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# Shipping Network Research: A Systematic and Quantitative Review

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# Shipping Network Research

## A Systematic and Quantitative Review

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### Abstract

Once developed by geographers, shipping network research has long remained a peripheral subfield of academia. Increased shipping data availability and computational power, combined with renewed graph-theoretical methods, caused an unprecedented growth of shipping network studies since the late 2000s. This article provides an in-depth bibliometric analysis of no less than 329 peer-reviewed papers published between 2007 and 2025. First, it describes the gathered corpus from diverse angles, such as the growth of papers, the main journals, its disciplinary background, and the pattern of co-authorships. Second, we use a natural language processing (NLP) approach, namely the structural topic model, to undertake an in-depth analysis based on the contents of abstracts. We identify four main topics, of which trade and connectivity; hubs and centrality; vulnerability and robustness; and communities and spatial structure, which are discussed according to their innovative character compared with wider research on ports, maritime transport, and network science. Three additional subgroups received peripheral attention despite their core importance: environmental issues (of which, marine bioinvasions), socio-economic development, and the role of shipping alliances. We conclude that network science methods still have important potential in shipping network port and maritime studies, and propose several pathways for further research.


**Keywords:** bibliometric analysis; complex networks; graph theory; maritime transport; scientometrics; shipping network; social network analysis; structural topic modeling

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## Introduction

In a world where more than 80% of global trade volumes are supported by sea transport (UNCTAD, 2024), maritime connectivity plays an essential role in socio-economic development (Gallup et al., 1999; Lane and Pretes, 2020). Major international organizations pay close attention to maritime connectivity, such as the Organization for Economic Cooperation and Development (OECD), the World Bank, and the International Monetary Fund (IMF)[1], notwithstanding more specialized bodies like the International Maritime Organization (IMO), the International Association of Ports and Harbors (IAPH), and the European Sea Ports Organization (ESPO). However, the analysis of maritime networks *per se* remained of peripheral interest in academia since the 1950s compared with other transport networks, due to the lack of maritime data and a traditional preference given to hinterland dynamics (Ducruet 2020a).

In the related literature, a maritime or shipping network is commonly defined as a set of ports (nodes, or vertices) connected by vessel voyages (links, or edges). Since the links are made of flows of moving objects (*i.e.*, vessel trajectories) rather than physical infrastructure, the network is an abstraction due to the ephemeral nature of maritime connectivity. Interestingly, the term "maritime network" is more employed in history and archaeology, to discuss patterns of migration and merchandise trade, while geographers, economists, and other scientists rather use "shipping network", to analyse the more recent period, with a dominant focus on container shipping. This article uses shipping network hereafter.

The literature review undertaken in this article[2] shows that quantitative research on shipping networks remained very scarce before the late 2000s. From being a negligible subpart of port and maritime geography, the empirical analysis of shipping networks has become a research field on its own (Ducruet 2015; Kanrak, Nguyen, and Du 2019; Álvarez, Adenso-Díaz, and Calzada-Infante 2021; Shankar et al. 2022). Wider shipping data availability and computational power permitted innovation in the domain of big data (Munim et al. 2020). Several reviews have recently been proposed, about port and maritime disruptions (Wendler-Bosco and Nicholson 2020; Nguyen et al. 2023; Zhang et al. 2024), bilateral connectivity in liner shipping networks (Ansorena 2018), evaluation

[1]See for instance the *PortWatch* platform developed by the IMF, aimed at monitoring and simulating disruptions on maritime flows.

[2]We would like to draw the reader's attention to one important point: the blue references refer to the main bibliography of the article. Uncoloured references refer to the corpus of articles used in this review. This corresponds to the appendix C.

methods of port dominance (Wang et al. 2021), and the visualization of vessel trajectory data (Liu et al. 2021).

This increasing interest in shipping networks resulted in an unprecedented multiplication of publications, which has not been fully reviewed yet, however, through a systematic bibliometric analysis. What have been the main themes and methods of shipping network research since the late 2000s? Is there an academic community emerging, beyond disciplinary boundaries? Has network analysis allowed a better understanding of the port and maritime sector? How did shipping network research contribute to network science in general?

The early 21$^{st}$ century has been a time of important changes in maritime and port research: scholars were trying to build a new research agenda at the crossroads of maritime logistics (Panayides 2006) and maritime economics (Panayides and Cullinane 2002; Heaver 2006). This combined effort to review the evolution of the field in the 1980s and 1990s and to open new perspectives for the future has been an important contribution to the development of innovative research. However, technical and conceptual advances, particularly in network science, which is the subject of our study in this article, have modified the field in an unprecedented way. This phenomenon, combined with the growth in the number of papers published in the 2000s and 2010s, has made it necessary to publish new literature reviews, both general and exploring the subfields under development. Hence, during the 2010s, a significant number of reviews have been published on port and maritime research, reflecting the maturity of the field in terms of conceptual and technical developments. Woo et al. (2011) and Pallis et al. (2011) are among the first to propose a structured literature review of maritime research, with the aim of discussing several decades of academic contributions. One important question asked in our present research can be summarised in the following terms: has shipping network research been identified as an emerging subfield?

Some reviews focused on specific journals, such as Woo et al. (2013) and Notteboom et al. (2013) for *Maritime Policy and Management* and Ducruet et al. (2019) for *Journal of Transport Geography*. Lau et al. (2017) reviewed 294 articles published about container shipping between 1967 and 2013 based on title words. They highlighted the co-occurrence between 'network design' and 'container service' in the first period (1967-1982), the absence of 'network' in the second period (1983-1998), but a strong importance of 'network design' in the last period (1999-2013), in relation with 'ports', as well as a connection between 'ports' and 'connectivity'. The contribution of (quantitative) geographers also aimed to build bridges between human geography and transport studies by focusing on port areas (Ng and Ducruet 2014; Ng et al. 2014). In particular, Ng and Ducruet (2014) identified two subthemes related to networks, namely 'port connectedness' and 'ports' place in shipping strategies and networks', the latter having grown rapidly in size over time. According to Ducruet and Notteboom (2023)), maritime connectivity recently became an important subtheme of port system research, discussing the belonging of ports to tightly connected clusters in the shipping network. Ducruet (2020a) also emphasised the fact that the spatial dimension of these networks[3] is currently under-researched[4].

Yet, existing reviews on maritime research rarely mention shipping networks as a field of research[5]. For example, Talley (2013) reviewed the literature published in *Maritime Policy and Management* and *Maritime Economics and Logistics* between 2000 and 2012, underlining that the most frequent keywords and approaches were shipping/port performance and management and shipping finance, while proposing five key directions for further research: maritime shippers, maritime transport chains, maritime transportation as a service, the quality of maritime transportation, and research on maritime theoretical propositions. Notteboom et al. (2013) classified 267 papers published in *Maritime Policy and Management* since its inception in 1973, resulting in 7 main themes: terminal studies; ports in transport and supply chains; port governance; port planning and development; port policy and regulations; port competition and competitiveness; and spatial analysis of seaports, with little reference to networks in such categories. Shi and Li (2017) did not find 'network' as an important keyword in their survey, compared to port management, service, performance, efficiency, and competitiveness, as well as shipping market, industry, freight rate, economic impact, and terminal studies. Bai et al. (2021) reviewed 3199 articles[6], from 1991 to 2020, on maritime transport, but they mention shipping networks twice[7], and only when talking about liner shipping

[3]On spatial networks, one can refer to Barthélemy (2011, 2022). Barthélemy (2015), Ducruet (2020b) and Rousset and Ducruet (2020) are good references for a more specific focus on maritime networks.

[4]In spatial economics, some papers studied the impact of maritime activity on the distribution of economic activity; among others: Bottasso et al. (2014), Brooks, Gendron-Carrier, and Rua (2021), Ducruet et al. (2024) and Bonadio (2024).

[5]A challenging dimension of our review is to successfully reconcile the analysis of themes and methods that relate to the field of shipping networks. The term "network" can be used without directly referring to network methods, and similarly these methods are sometimes used without direct reference to the term "shipping network". Section 2 details the constitution of the corpus.

[6]Bai et al. (2021) is also of a particular interest for us considering that they also use structural topic model to analyse maritime research. We try, in the present paper, to push further this empirical strategy, focusing on a specific theme, *i.e.*, shipping networks.

[7]As we shall see in the rest of this article, shipping network research is a recent field, and one that has been extremely dynamic over the last three to four years. This partly explains why this field, which was

issues, which are more closely related to operational research[8]. More likely subthemes included intermodal logistics, port efficiency, shipping finance and, to a lesser extent, regional development, with a focus on operations and management.

The majority of recent literature reviews focus on specific aspects of shipping operations: Xiao et al. (2024b) reviewed the application of artificial intelligence in the shipping industry; Zhou, Li, and Yuen (2023), Xiao et al. (2024a) and Qi et al. (2024) discussed the issues related to sustainable transport and environmental issues[9]; Ghorbani et al. (2022) and Chen et al. (2022) focused on alliances among shipping companies; Filom, Amiri, and Razavi (2022) and Wang and Peng (2023) identified the contributions related to port operations, including topics such as efficiency, automation, quayside operations[10]; health and port-source pollution have been reviewed by Mueller, Westerby, and Nieuwenhuijsen (2023). Some reviews did not mention the shipping network as an important topic, such as Xu et al. (2021) on port and shipping research in management science, Munim and Saeed (2019) on seaport competitiveness research and Chen et al. (2018) on port and maritime transport system researches. The review by Wang and Peng (2023) on port logistics also did not identify 'network' as an important keyword or theme, compared with model, management, systems, performance, transport, supply chain, optimization, simulation, transportation, location, ports-hinterland, supply chain management, service, allocation, policy, and integration[11]. To more precisely cover this vast body of recent publications, Dragović et al. (2024) proposed a review of 'Maritime Bibliometric Studies' (MBS) published in the last decade (2014 – 2024). They identified seven main research topics covered by MBS: maritime shipping, seaports and terminals, maritime logistics, maritime accidents, maritime risks, maritime human factors, and maritime environment.

Thus, the intersection of shipping flows and network science[12] is hardly discussed

in its infancy at the time and still relatively limited, received little attention in the reviews published a few years ago.

[8]We excluded the field of operational research from our review because it is a quite independent field with its very own literature.

[9]There is a flourishing literature in the past three years reviewing academic research on shipping and environmental issues, we thus selected some articles without seeking to be exhaustive.

[10]The literature in operations research that deals with port efficiency, scheduling, containers' operations etc. is extremely large. For example, Weerasinghe, Perera, and Bai (2024) reviewed 1,768 articles related to container terminal operations

[11]This is one of the special features of our review compared with many others: we limit the scope of the study ex ante to articles that are part of the field of network studies as practised since the late 1990s (Watts and Strogatz 1998; Barabási and Albert 1999). Within this literature, questions of management, integration or system performance can be addressed, but this is done on the basis of a common conceptual and empirical framework.

[12]We call 'network science' all the concepts and techniques using graph structures and dynamics to

at all in reviews of the field. Notable exceptions are Bergantino and Veenstra (2002), Caschili and Medda (2012)[13], Álvarez, Adenso-Díaz, and Calzada-Infante (2021)[14] and Yue and Mangan (2024). The first two papers are dealing with the application of the so-called 'complex networks' framework to maritime flows, while Yue and Mangan (2024) are focusing on the reliability of maritime container transport networks. Kanrak, Nguyen, and Du (2019) reviewed the methods and applications of network analysis to maritime transport, while Ducruet (2020a) showed that this field witnessed the highest growth rate of publications among all transport network studies between the 2000s and the 2010s.

Conceptual and technical progresses in network analysis have also attracted the interest of researchers working on other transport modes. For instance, Zanin and Lillo (2013), de Oliveira, Lohmann, and Oliveira (2022) and Zanin and Wandelt (2023) reviewed the literature on air transport networks. Zanin and Wandelt (2023) recall that the literature on the network properties of the aviation system is, as is the case for shipping networks, the product of the conceptual advances of the 2000s with the emergence of a modern network science focused on so-called 'complex networks'. The resilience of overhead networks is a more established topic than in shipping research; for example, Sun and Wandelt (2021) discuss fifteen years of research into the resilience of overhead networks, while the resilience of shipping networks was still a peripheral theme. Network resilience is thus a research theme common to many transport networks, since there is also work on street networks (Sharifi 2019) and rail networks (Bešinović 2020; Wen et al. 2025). A more general approach is proposed by Wan et al. (2018) and Pan et al. (2021), who review the research on network resilience for transport systems. Moreover, from the results of Pan et al. (2021) we note that there are fewer studies on the resilience of maritime networks than for rail or air, confirming Ducruet (2020a)'s observation and fuelling the research prospects discussed by Polo-Martín et al. (2024) and redeveloped in the rest of our article.

The field of shipping networks therefore needs an up-to-date and systematic review[15]; we combine qualitative analysis, social network analysis and generative models to propose a review that is both systematic and comprehensive. To approach this field

analyse the shipping industry.

[13]To be more specific, Caschili and Medda (2012) reviewed the maritime container shipping industry, approaching it as a 'complex system'.

[14]This paper collected 97 articles using complex network analysis, from 2002 to 2019.

[15]Although maritime / shipping network analyses only accounted for 2.26% of all transport network analyses in the 2010s, they witnessed the highest growth rate between the 2000s and the 2010s (Ducruet 2020a).

in all its aspects, we also propose a review of ‘pioneer’ works: although they do not fit exactly into the field of ‘networks’ as understood since the early 2000s, they have nonetheless proposed approaches that are similar and conceptually seminal.

This study is based on a corpus of no less than 329 articles published in peer-reviewed journals between 2007 and 2025[16]. Such articles have in common the term ‘maritime network’ or ‘shipping network’ in their title and/or abstract, as well as possible variants (*e.g.*, ‘maritime transport network’). Several other criteria guided article selection. First, they all are empirical studies of real-world shipping networks, contrary to the theoretical literature in operations research and engineering, which deploys mathematical programming and modeling to optimize ship routing and scheduling and hub-location[17]. Second, we excluded the works in history, archaeology, anthropology, and linguistics dealing with shipping networks, because such disciplines have a more qualitative approach. Other works such as tactical networks in maritime warfare were also excluded.

The remainder of this article is developed as follows. Section 1 reviews the pioneering literature on shipping networks, published before 2007, and discusses its legacy for the subsequent decades. Section 2 introduces the corpus gathered between 2007 and 2025 and describes its evolution from various angles, such as the growth of papers, the main academic journals represented, its disciplinary background, and the pattern of co-authorships. Section 4 dives into the contents of the corpus through a text mining/NLP analysis of title words and abstracts, to reveal semantic patterns and trends over the period. We discuss in Section 6 the “missing links” that appear in our analysis, while section 7 concludes about further research pathways for both maritime transport studies and network-analytical studies.

## 1. The Legacy of Pioneering Studies (1968-2007)

The relational approach in port and maritime research long relied on the analysis of “port systems”, a core concept in port and maritime geography originating from the work of Taaffe, Morrill, and Gould (1963) about the evolution of transport corridors and related port hierarchies in West Africa. Due to the strong emphasis of port system

[16]This choice makes it possible to have a structured corpus (the abstracts of articles). In addition, limiting ourselves to articles published in journals makes disciplinary classification easier and more transparent.

[17]See in-depth reviews by Tran and Haasis (2015) and Christiansen et al. (2020). A systematic review using structural topic modeling in the case of shipping networks and operations research would be an important contribution in identifying the main trends and research opportunities for the future.

studies on hinterlands, Rimmer (1967a,b) argued in favor of the integration of maritime linkages between ports. There had been a recognition that forelands matter as much as hinterlands for the understanding of port activities (Weigend 1952; Britton 1965; Robinson 1970)notably through the concept of "port triptych" (hinterland-port-foreland) (Vigarié 1979).

But empirical studies of forelands mainly consisted in measuring the share and specialization of connections, without a network approach per se, despite the wide use of graph theory in geography and regional science since the 1950s (Ducruet and Beauguitte 2014). The application of graph theory to a maritime network was first proposed by Ross Robinson (1968) in his PhD dissertation. He mapped the connections among British Columbia ports to illustrate the very central position of Vancouver in the system. Despite its innovative character, his work was never published in a journal, and was not cited subsequently. At the same time, graph theory, which was so popular during the *quantitative revolution* – the introduction of mathematical tools in geography – started to lose ground with the subsequent *behavioural turn*. Recalling the main steps of his career evolution, Robinson (2015) recognized that port research at that time had to adapt to changing contexts by becoming more applied and practical.

It is only about 15 years later that other analyses were proposed. Marti (1981) described the pattern of US-Canada container flows, while Marti and Krausse (1983) as well as Helmick (1994) searched for load center development in the North Atlantic liner shipping network. The works of McCalla (1986) on Canadian coastal shipping and Dick and Rimmer (1993) on Asia-Pacific container flows explicitly made use of network analysis, the first using graph theory and the latter arguing that such methods should be 'revived'. The work of Joly (1999) constitutes the first-ever analysis of the global container shipping network, using graph theory. Like in Robinson's work, ports were characterized by their connectivity (degree) rather than throughput, while the cartography of the network illustrated the domination of East Asia. Subsequent analyses focused on the strategies of shipping lines and shipping alliances, by mapping regional networks (McCalla 2004; McCalla, Slack, and Comtois 2004, 2005; Veenstra, Mulder, and Sels 2005) or individual port networks (Comtois and Wang 2003; Rimmer and Comtois 2005; Frémont and Soppé 2004).

At the beginning of the 2000s, maritime economists questioned the striking absence of port centrality measures (De Langen, Van der Lugt, and Eenhuizen 2002; de Langen, Nidjam, and Van der Horst 2007) as well as the position of ports in maritime scale-free networks (Le Marchand 2000; Foschi 2002). A few years later, (Čišić, Komadina, and

Hlača 2007) used social network analysis (SNA) to measure the centrality of Mediterranean container ports, while Tian et al. (2007) were the first to publish a complex network analysis of a shipping network.

Overall, shipping network research in the early period constitutes a minor field, mostly invested by geographers. Such a field remained scattered, with long periods of inactivity, and methodological innovations were introduced relatively late compared with research on other (transport) networks. The most innovative works had been unpublished PhD dissertations, working papers or conference proceedings remaining relatively unknown to date. The goal of the next sections is to analyse how shipping network research has been conducted in the more recent period, to the point of constituting a field in its own right. Given the subsequent exponential growth of related studies, we decided to approach this in a systematic and quantitative way.

# 2. Describing the Corpus

## 2.1. Size evolution

As of late December 2024, the number of articles dealing with shipping networks had reached a total of 329 items, including nine articles for the year 2025[18]. As shown in Figure 1, the first decade (2007-2017) is characterized by a very modest rate of publication, with an average yearly number of 5.5 articles. A second period can be distinguished, defined as the "take-off", with an average number of 23.5 articles published between 2018 and 2021. If we merge 2024 and 2025, the late period 2022-2025 is characterized by an average number of no less than 55 articles. The year 2023 marks an exception, with only 28 articles, compared with 63 and 74 articles in 2022 and 2024, respectively. Multiple checks have insured that such a drop was not caused by missing references. On the contrary, this exception is better explained by a sudden concentration of papers in 2022 and 2024 for specific reasons. As it will be demonstrated later on in this study, such years constitute peaks of research on special events like the Covid-19 pandemic, the Red Sea crisis, and the Russia-Ukraine conflict, together with numerous works about the 21st century Maritime Silk Road. Overall, this evolution is characterized by a rapid growth of the corpus' size. This directly reflects the growing availability of shipping data,

[18] We stopped collecting articles on 15 January 2025. The gap between the other (complete) years and the year 2025 will not pose a problem for the estimation of the structural topic model in section 3 because we are grouping the years into periods: 2007 - 2019 and 2020-2025 (see section 2.3 for details on the methodology).

the popularization of network-analytical methods in the field of maritime research, and the increased recognition that sea transport is a vital component of global trade and economic development. Such a fact has been a gradual discovery for non-maritime specialists coming from various disciplines across the academic spectrum.

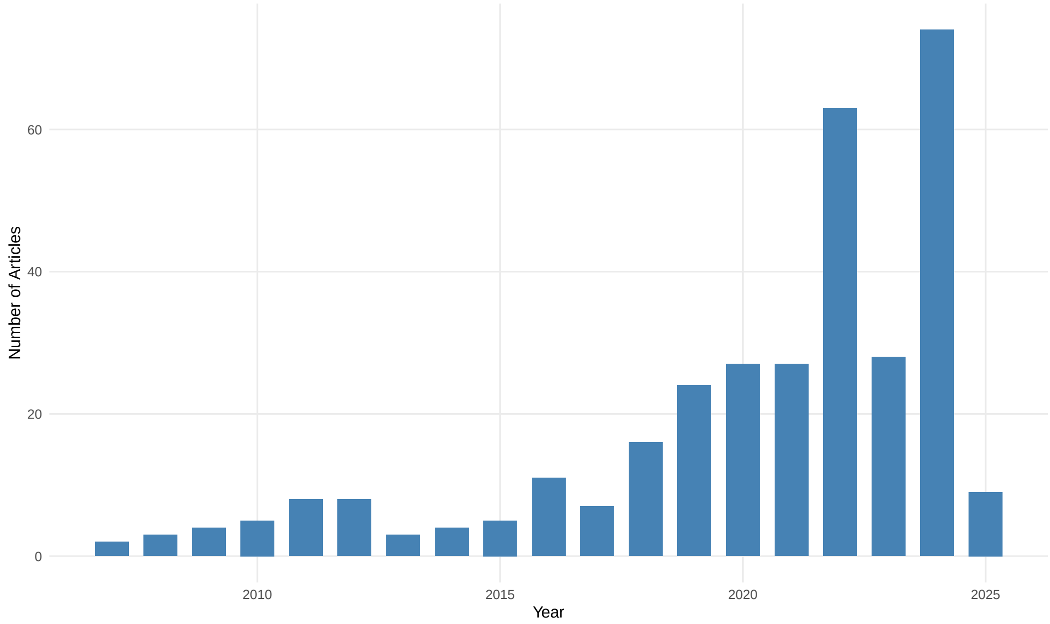


FIGURE 1. Evolution of the number of articles over time (2007 - 2025)

*Notes:* We plot the number of articles per year. We observe a significant increase of publications starting in 2017. We included 2025 as we then analyse periods and not only years.

## 2.2. Disciplinary Background

The distribution of articles by journal (Table 1) and journal background (Table 2) offers useful evidence about the disciplinary and thematic focus of the corpus. The leading journal is *Journal of Transport Geography* (JRTG) which, contrary to other journals, is both disciplinary (geography) and thematic (transport) (Ducruet et al. 2019). Such an importance confirms the early role of geographers in the analysis of shipping networks as discussed in section 2. Although *Geojournal* is the only other geography journal in 1, geography as a whole dominates other fields in Table 2, despite being slightly below "shipping" and "transport & logistics" in the second period. This analysis may underestimate the real importance of geography, since (transport) geographers increasingly published in transport journals, in their quest to better address operational logics, while leaving behind core issues of human geography (Ng and Ducruet 2014).

TABLE 1. Number of Articles by Journal and Period

| **Journal** | **2007–2017** | **2018–2025** | **Total** |
|---|---|---|---|
| Journal of Transport Geography | 12 | 22 | 34 |
| Maritime Policy and Management | 5 | 23 | 28 |
| Ocean and Coastal Management | – | 16 | 16 |
| Maritime Economics & Logistics | 5 | 9 | 14 |
| Sustainability | 1 | 12 | 13 |
| Transport Policy | 2 | 9 | 11 |
| Journal of Marine Science and Engineering | – | 9 | 9 |
| Physica A | 2 | 6 | 8 |
| Transportation Research Part E | 4 | 4 | 8 |
| Networks and Spatial Economics | 1 | 6 | 7 |
| Transportation Research Part D | – | 7 | 7 |
| GeoJournal | 3 | 2 | 5 |
| International Journal of Shipping and Transport Logistics | – | 5 | 5 |

In comparison, *Maritime Policy and Management* (MPM) as well as *Maritime Economics & Logistics* (MEL) can be seen as the economic counterparts of JTRG, being the representative journals of the *International Association of Maritime Economists* (IAME). Put together, they constitute the category of "shipping", which equals geography for the whole period. They are closely followed by general transport journals, which are not specialized in shipping, while general economic journals have the lowest number of articles (3). This means that shipping network research in geography and economics is mostly published in specialised, field-journals. Physics is important in the early stage and has maintained its rank afterwards. Most of other papers were published in transdisciplinary journals, especially in the second period, such as marine sciences, geosciences, environment and energy, and networks and complex systems. The category "multidisciplinary" includes journals such as *Sustainability*, *Nature Scientific Reports, Nature Communications, PNAS,* and *Plos One,* which cover a very wide diversity of topics. Overall, the corpus can be divided between transport studies (144) and other studies (185), and its academic background has widened over time.

TABLE 2. Classification of Articles by Journal Background (2007–2025)

| Background | 2007–2017 | 2018–2025 | Total |
|---|---|---|---|
| Geography | 20 | 37 | 57 |
| Shipping | 11 | 46 | 57 |
| Transport & logistics | 11 | 43 | 54 |
| Marine sciences | – | 38 | 38 |
| Engineering & data sciences | 3 | 31 | 34 |
| Multidisciplinary | 5 | 25 | 30 |
| Physics & natural sciences | 7 | 10 | 17 |
| Environment & energy | – | 16 | 16 |
| Geosciences | – | 13 | 13 |
| Networks & complex systems | 1 | 11 | 12 |
| Economics | – | 3 | 3 |
| **Total** | 60 | 269 | 329 |

### 2.3. Structural Topic Modeling

To complete the first two stages of our analysis (descriptive examination and analysis of co-authorship networks) we build a corpus of abstracts for all the papers published from 2007 to 2025[19]. Using this corpus and the associated metadata, we estimate a series of structural topic models (henceforth STM) with two main objectives: explore the topical structure of shipping network research and estimate the impact of some variables, such as the period, the field or the affiliation of authors on the proportion of each topic.

Text is frequently used as data by social science researchers (Bail 2014; Lindstedt 2019), both through qualitative (surveys, interviews) and quantitative studies. With the rapid digitisation of academic resources, a large amount of metadata has been made available to researchers interested in the evolution of scientific production. Topic modeling is a set of methods aimed at discovering "hidden" topics in text data (Lindstedt 2019). Mixed-membership topic modeling has been first developed by Blei, Ng, and Jordan (2003), and is usually designated as 'Latent Dirichlet Allocation' (LDA). Blei, Ng, and Jordan (2003) assumed that each document in the corpus is a mixture of topics and each topic is a distribution of words. The second step in the development of topic modeling (Lindstedt 2019) is the "structural topic model" (Roberts et al. 2013, 2014),

[19] For 2025 we included the papers published in January. This difference in the number of articles between the other years and 2025 does not affect the analysis, as we then group the abstracts in the corpus by period.

which was developed to overcome one of the main limitations of topic modeling via LDA: topics were assumed to be independent within each document, which is rarely the case when dealing with complex documents. In STM, the topic proportions for documents are drawn from a logistic-normal distribution. This approach takes into account the dependence between topic distributions and allows for the inclusion of covariates in the estimation. For each document in the corpus (*i.e.*, each article abstract) we define a data generating process and then use the data to find the most likely values for the parameters. The generative process for each document $d$ with a vocabulary of size $V$ and $K$ topics can be divided into three blocks (Roberts, Stewart, and Tingley 2019):

a. $\theta_d$ is drawn from a logistic-normal generalised linear model based on a vector of document covariates $X_d$:

$$\theta_d \mid X_{d\gamma}, \Sigma \sim \text{Logistic-Normal}\left(\mu = X_{d\gamma}, \Sigma\right) \tag{1}$$

With $X_d$ a $1\times p$ vector, $\gamma$ a $p\times K-1$ matrix of coefficients and $\Sigma$ a $K-1\times K-1$ covariance matrix.

b. The model estimates the document-specific distribution over words for each topic is given by:

$$\beta_{d,k} \propto \exp\left(m + \kappa_k^{(t)} + \kappa_{y_d}^{(c)} + \kappa_{y_d,k}^{(i)}\right) \tag{2}$$

Where $m$ is the baseline word distribution in the document, $\kappa_k^{(t)}$ is the topic-specific deviation, $\kappa_{y_d}^{(c)}$ the covariate group deviation and $\kappa_{y_d,k}^{(i)}$ the interaction[20]. We use STM to explore the corpus at two levels. At the global level, we want to understand how the shipping network literature is structured *i.e.,* labelling the topics; at the topic-level we want to estimate the impact of a basic set of covariates on topic proportion. This second objective allows us to observe and quantify the evolution of topics' popularity over time, and the geographical and field determinants of each topic.

[20] For additional details, one can refer to Roberts, Stewart, and Tingley (2019) (with applications in R); Brunetti, Joëts, and Mignon (2024) and Candelon, Joëts, and Mignon (2024) for an application of STM to review the econometric literature.

# 3. Model Estimation

## 3.1. Selecting the Number of Topics

Before presenting the results of our quantitative analysis of shipping network studies, let us briefly discuss model selection, focusing particularly on determining the "desirable" number of topics. The development of automated text analysis came with the attractive promise of considerably reducing the costs of analysing large amount of text data (Grimmer and Stewart 2013). This potential is associated with a non-negligible pitfall: the trade-off between "statistical" quality - coming from quantitative diagnoses - and human-based interpretability (Lindstedt 2019). To be more precise, there is no consensus on the means for selecting the number of topics that produces both interpretable results and "optimal" properties (Roberts et al. 2014; Farrell 2016; Lindstedt 2019; Roberts, Stewart, and Tingley 2019). The theoretical and empirical framework developed by Roberts et al. (2013, 2014), Roberts, Stewart, and Airoldi (2016) and Roberts, Stewart, and Tingley (2019)[21] provide some directions on the selection of the number of topics[22] and the in-depth analysis of topics' structures and determinants.

The first metric, computed in Fig. 2 for 5 to 15 topics, is the 'semantic coherence' (Mimno et al. 2011). This criterion is maximized when the most probable words in a topic are also co-occurring together in the documents. This criterion is computed as follows:

$$C_k = \sum_{i=2}^{M} \sum_{j=1}^{i-1} \log \left( \frac{D\left(v_i, v_j\right) + 1}{D\left(v_j\right)} \right) \tag{3}$$

Roberts et al. (2014) show that semantic coherence is biased by the fact that it is relatively easy to reach a high value when considering few topics with dominant words. To deal with this issue and improve topic partition, they propose to use the FREX metric (Bischof and Airoldi 2012; Airoldi and Bischof 2016). This second criterion accounts for the frequency *and* and the the exclusivity of words to topics. The FREX is given by the

[21] We use the `stm` package to perform the quantitative analysis of the corpus. The most recent version of the R-package can be found here: here.

[22] This issue is also well-discussed, with some additional guidelines and good practices in Lindstedt (2019).

following expression:

$$\text{FREX}_{k,v} = \left( \frac{\omega}{\text{ECDF}\left(\beta_{k,v}/\sum_{j=1}^{K}\beta_{j,v}\right)} + \frac{1-\omega}{\text{ECDF}\left(\beta_{k,v}\right)} \right)^{-1} \tag{4}$$

In the equation 4 'ECDF' is the empirical CDF and ω is the weight[23]. Figure 2 shows three other metrics associated with the set of topics tested: held-out likelihood, residuals, and lower bound. The evolution of these different metrics also illustrates the difficulty of choosing the number of topics that satisfies both the consistency and statistical quality of the model. After various qualitative analyses of the different partitions, we decided to segment the corpus into five topics; this partition corresponds to the most coherent structure.

There are several reasons for choosing a limited number of topics. Firstly, if we look at Figure 2, this is a number of topics with the greatest semantic consistency. We end up with fairly large topics dominated by a few key words, which tend to generate this type of result. In the case of a literature review, it seems to us that this also corresponds to what is expected of a score: to identify the major trends that structure the field and its division into sub-fields. This argument is reinforced by the fact that our corpus is relatively small, with 329 articles, and composed of elements that are themselves small in size, since they are abstracts. Blei (2012), who review 17,000 academic articles published in *Science*, limit themselves to 50 to 100 topics. Roberts et al. (2014) support this point by insisting on the importance of the size and variety - or what the researcher considers it to be - of the corpus on the choice of the number of topics.

Beyond the number of elements in the corpus and their length, we also defend the idea that the field of shipping networks being relatively young (less than two decades) is interesting to identify the major trends. These trends are structuring because they allow us to understand the dynamics of the field and to identify the major research questions that run through it: trade, resilience, environment, communities, ... For this reason, we are limiting the number of topics. In the appendix B, the results are presented for 6 and 10 topics, but we lose clarity by allowing sub-themes to appear that are not relevant to detach from the broader themes to which they are attached.

[23] Roberts, Stewart, and Tingley (2019) fixed ω to 0.7 to favor 'exclusivity'.


FIGURE 2. Diagnoses for 5-15 topics

*Notes:* We ran a structural topic model for each number of topics from 5 to 15. From left to right and top to bottom, the figure plots the evolution of : semantic coherence, held-out likelihood, residuals and 'lower bound'. We decided to focus on semantic coherence after analysing the output of each model[24] strongly emphasise that these measures are imperfect and are no substitute for human validation of topics, in conjunction with subject consistency..

### 3.2. Words and Topics

The first output of the structural topic model is the partition of the corpus into topics. Four metrics are used to define each topic: the occurrences with the highest probability, the 'FREX', the 'Lift' and the Score.

The table A3 brings together the ten most frequent occurrences for each of the four metrics, and for each topic[25]. This partition then allows us to label the six topics. We propose the following labels:

a. Topic 1: cruises, arctic shipping and operations;
b. Topic 2: connectivity, bilateral trade and regional development;

[25] Truncated terms such as 'cruis', 'resili' or 'connect' bring together all the terms derived from this basic structure. For 'cruis' this could be 'cruise', 'cruises', 'cruising'... allowing us to cover all the grammatical uses and functions of this term within a sentence

c. Topic 3: container operations, hubs and Asian shipping networks;
d. Topic 4: resilience, vulnerability and risk mitigation;
e. Topic 5: spatial structure, network communities and port systems.

These five topics correspond to our intuitions: they suggest a disciplinary and thematic partition. First of all, they group together terms that are associated with the "premises" of the field: network structure, hubs, communities, connectivity. The analysis of shipping networks was made possible by advances in complex networks in the early 2000s, and the early years of the field are integrated into the issues arising from this work. There are also terms such as connectivity and bilateral trade, which are more closely related to work in international economics and economic geography[26]. This transition from topological and structural issues to economic and political research questions suggests a maturing of the field.

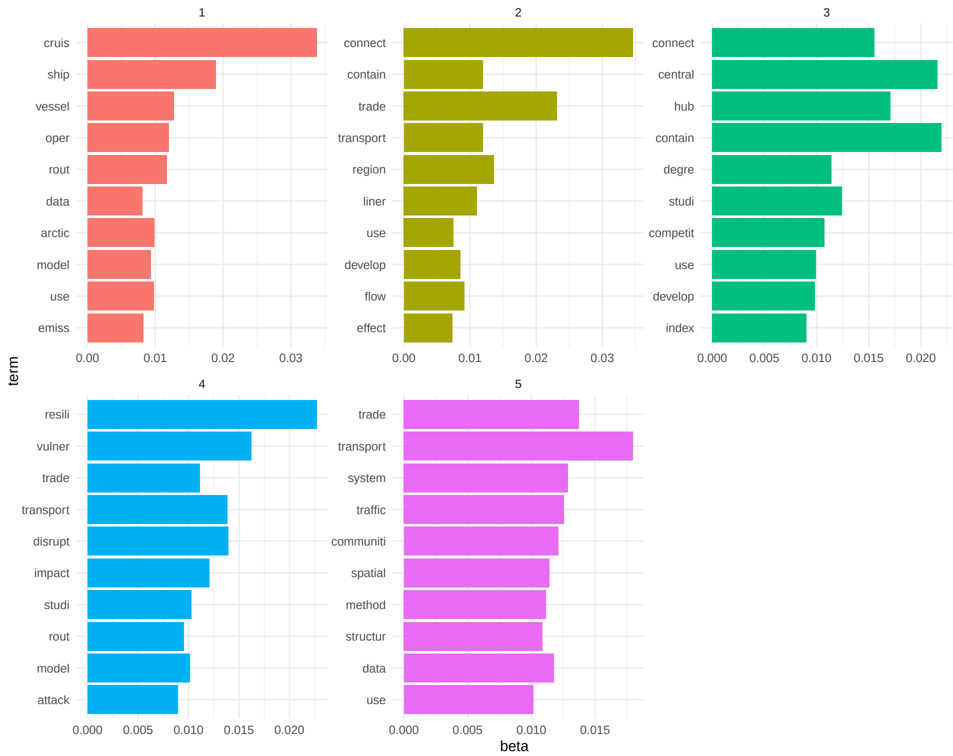


FIGURE 3. Top-10 most probable words for each topic

*Notes:* The figure shows the most probable words for each topic. It is used to label the topics.

[26]The study of network resilience and vulnerability is a recent trend in the study of networks. We find both simulations of network 'attacks' and studies of real shocks, such as earthquakes and hurricanes (Rousset and Ducruet, 2020), the war in Ukraine (Polo-Martin et al., 2024; Ke et al., 2024) or the development of the maritime silk road and regional development associated with maritime activity (Liupeng et al., 2024)

Table 3. Top Words from the STM model with 5 topics

| Topic | Highest Prob | FREX | Lift | Score |
|---|---|---|---|---|
| **1** | *cruis, ship, vessel, oper, rout, arctic, use, model, emiss, data* | *emiss, invas, itinerari, speci, cruis, arctic, water, environment, asr, passag* | *-call, acceler, aquat, arriv, bioinvas, classif, contact, ecosystem, emiss, flag* | *cruis, arctic, emiss, itinerari, asr, season, nis, flag, passag, invas* |
| **2** | *connect, trade, region, contain, transport, liner, flow, develop, use, effect* | *bilater, freight, north, export, inter-, vietnam, literatur, period, america, connect* | *-go, accept, accommod, add, adequ, agenda, amongst, best, bilater, boom* | *bilater, trade, vietnam, korean, inter-, capita, country', export, -go, lsbci* |
| **3** | *contain, central, hub, connect, studi, degre, competit, use, develop, index* | *hong, asian, kong, busan, central, degre, shanghai, cluster, competit, singapor* | *alphabet, bbv, believ, bohai, claim, colombo, coronavirus, cyclic, decemb, dissemin* | *busan, asian, competit, hong, kong, tier, between, rank, singapor, central* |
| **4** | *resili, vulner, disrupt, transport, impact, trade, studi, model, rout, attack* | *resili, failur, cascad, recoveri, oil, attack, disrupt, vulner, glsn, conflict* | *accid, aid, blockag, cancel, cascad, catastroph, confid, conflict, encount, failur* | *resili, cascad, failur, attack, disrupt, glsn, reliabl, conflict, crude, recoveri* |
| **5** | *transport, trade, system, traffic, communiti, data, spatial, method, structur, use* | *communiti, msr, silk, road, tanker, bulk, traffic, detect, advantag, extract* | *assumpt, billion, bottleneck, communic, continuum, flexibl, gmn, greec, heavy-tail, insular* | *silk, communiti, msr, bulk, tanker, gmn, waypoint, advantag, road", socioeconom* |

### 3.3. Covariates and Topic Proportion

We then estimate the impact of various covariates on the *i*'s topic proportion, which corresponds to the following equation:

$$y_i = \beta_0 + \phi^{'}\mathbf{X}_i + \varepsilon_i \quad (5)$$

Where $y_i$ is the proportion of topic $i$ in the structural topic model, $\beta_0$ the intercept and $\mathbf{X}_i$ a set of covariates. We included the period in which this article was published[27], the majoritarian geographic area[28] in the authors' affiliations and the field to which the articles belong[29].

The output of the regressions in Table A2 offers some interesting insights on the evolution of shipping network research. We first observe that topic proportion is significantly impacted by the transition from 2007 - 2019 to 2020 - 2025 for topics 1, 3 and 5. Topic 1 focuses on Arctic routes, operational challenges and pandemics, it is thus quite expected[30]. Topic 4 is also significantly and positively affected by the recent period : it includes research interests around resilience, vulnerability, disruption… which is correlated to pandemics and wars[31].

We decided to consider "Shipping" as the reference for the background; this is a fairly broad and general category, which is well represented in terms of articles, allowing us to see how more specialised fields, which have also emerged more recently, position themselves in relation to 'generalist-shipping' research and journals. Shipping "background" includes journals such as *Maritime Economics and Logistics*, *Maritime Policy and Management* and *Journal of Shipping and Trade*. The traditional themes of shipping research (connectivity, trade, formation of hubs, etc.), which correspond to topics 2 and 3, are negatively associated with the other journals compared with shipping ones.

[27] The results are robust to the use of three periods (2007 - 2013, 2014 - 2019 and 2020 - 2025) and year dummies

[28] When two zones are at par, we used the zone of the first author.

[29] Determined from the journals in which they were published

[30] In the remainder of this article, we have decided not to include a discussion of this topic. It is in fact limited to a few references (the Covid-19 theme is dealt with more extensively in the resilience topic) and with scattered concerns. Nevertheless, we wanted to mention it because of the interest it may present. See Lavissière, Sohier, and Lavissière (2020), Lin et al. (2023) and Qi et al. (2024) for reviews with a specific focus on arctic shipping.

[31] Polo-Martín et al. (2024) emphasised that networks' vulnerability became a popular research theme in recent years, following major disruptions such as Covid-19, Ukrainian war and Red Sea crisis.

TABLE 4. Regression Results for Topics 1–5 (Updated Model)

| | Topic | | | | |
|---|---|---|---|---|---|
| **Variable** | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** |
| **(Intercept)** | 0.059801 | 0.51360*** | 0.18878*** | 0.01900 | 0.21754*** |
| **2020–2025** | 0.11202*** | -0.07046· | -0.03721 | 0.10856** | -0.11237** |
| **China** | -0.07967* | -0.27018*** | 0.22455*** | 0.08668· | 0.03921 |
| **North America** | -0.03092 | -0.14936 | -0.00482 | 0.06353 | 0.12260 |
| **Rest of Asia** | 0.08880· | -0.24683*** | 0.29796*** | -0.02784 | -0.11254* |
| **Economics** | 0.21921 | -0.10118 | -0.01826 | 0.00121 | -0.10440 |
| **Engineering & data sciences** | -0.03197 | -0.16452* | -0.11152 | 0.14104· | 0.16903* |
| **Environment & energy** | 0.14341· | -0.17385* | -0.23243* | 0.25379* | 0.00905 |
| **Geography** | 0.00095 | 0.04062 | -0.08237 | 0.00950 | 0.03170 |
| **Geosciences** | 0.07629 | -0.16029· | -0.25321** | 0.02982 | 0.30650** |
| **Marine sciences** | 0.06481 | -0.08556 | -0.19272** | 0.13309· | 0.07990 |
| **Multidisciplinary** | 0.19237** | -0.12341· | -0.12722· | 0.03063 | 0.02717 |
| **Networks & complex systems** | 0.02450 | 0.03949 | -0.22858* | -0.05876 | 0.22638* |
| **Physics & natural sciences** | 0.03590 | -0.18884* | -0.03360 | 0.03880 | 0.14549 |
| **Transport & logistics** | -0.06706 | 0.02116 | -0.06936 | 0.11617· | -0.00152 |

*Note:* Columns (1), (2), (3), (4), and (5) show coefficients for Topics 1, 2, 3, 4, and 5, respectively. Significance codes follow the R summary: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Baseline categories are *Europe* (Origin), *Shipping* (Background) and 2007 – 2019 (Period).

The geography of authors' affiliation also provides some information on the structure of the corpus. These results show how different regions are linked to different research interests. For instance, China and the rest of Asia stand out in particular in the context of central hubs, while North America shows greater interest in resilience and transportation systems.

This succinct analysis, using regression based on the prevalence of topics given by the STM, gives us a first glimpse of the overall structure of the corpus. It shows the temporal evolution of topics, with the emergence of new interests linked to recent geopolitical and health crises. The geography of affiliations also yields results that inform us about differentiated trends from one region of the world to another. Lastly, the background to each article enables us to observe the links between certain disciplinary fields and discussing collaborative networks in shipping research, and then, giving some insight into the determinants and dynamics that structure the field, we will now analyse in detail the five topics corresponding to the selected partition.

## 4. Detailed Discussion of the Topics

### 4.1. Liner Shipping Connectivity and Trade

Liner shipping networks are critical in the design and efficiency of global supply chains (Ducruet and Notteboom 2012). Studying the evolution of their structure helps to understand the major changes that affected international trade in the last few decades: containerisation, emergence of Asian hubs, and various shocks such as armed conflicts and pandemics. Network analysis, focusing on the interaction of the nodes through the edges, is particularly well suited to understand the structure and dynamics of shipping activities. As Ducruet and Notteboom (2012) emphasized in their conclusion, shipping networks are characterized by dynamic processes both in temporal and spatial terms. The creation of new ports and lines to cope with demand greatly modified the local and global structures of the shipping networks. In their work, Wan et al. (2023) studied the impact of the Suez blockage on global shipping networks. The authors show the heterogeneous impact of the Suez blockage across continents and goods. In particular, Africa and containerships were the most affected, while Asia and Europe demonstrated more resilient supply chains. The Russo-Ukrainian war (Polo-Martin et al. 2024; Zhang, Wang, and Ng 2024; Xiao et al. 2025) and Houthis attacks in the Red Sea (Yap and Yang 2024) have also attracted some interest. Yap and Yang (2024) emphasised the "footloose" nature of Mediterranean and Red Sea transshipment hubs. They also provide interesting evidence on the various resilience strategies pursued by shipping companies.

This topic is related to the connectivity of shipping networks and its impact on international trade and regional economic development. The keywords with the highest probability of occurrence refer to maritime connectivity ('connect', 'liner', 'flow') and economic matters ('trade', 'develop', 'econom'). In addition, the FREX reinforces this interpretation, with words such as 'bilateral' or 'freight' combining it with regional case studies ('north' stands for North Korea, 'vietnam', 'america'). We have noted that a relatively small number of authors attempt to make the link between shipping networks and the gravity mechanisms of international trade. Shipping networks are generally approached from a static point of view and the dynamics of networks are essentially analysed through the evolution of structural metrics such as betweenness and transitivity. However, since the end of the 2010s, several contributions have addressed the gravity aspect of shipping networks[32]. As a matter of fact, Fugazza and Hoffmann (2017) have constructed the Liner Shipping Bilateral Connectivity Index (`LSBCI`), which is a measure that brings together maritime (network) connectivity and international trade. The `LSBCI` includes a network framework[33] and 'industry' metrics like the level of competition on services that connect country pairs and the size of the largest ship on the weakest route. They combine the `LSBCI` with a standard gravity model to analyse the association between maritime connectivity and bilateral exports of containerisable goods. Fugazza and Hoffmann (2017) showed that improving maritime connectivity among partners significantly impact the bilateral exports. For instance, two countries sharing an additional common direct destination is associated with about 5% higher value of bilateral exports[34]. Following on from Fugazza and Hoffmann (2017), Del Rosal (2024) estimates the impact of the `LSBCI` on bilateral exports for 22 classes of manufactured goods (ISIC classification). Thanks to a rich set of estimations, he explores in detail the heterogeneous effects between trade routes and macro-regions and shows in particular that the effect of good connectivity is highly significant on long-distance routes.

While Fugazza and Hoffmann (2017) and Del Rosal (2024) use the value of highly

[32] Without explicitly building their empirical strategy on 'shipping networks', Jacks and Pendakur (2010) studied the 'gravitational' impact of technological progress on shipping trade. More recently, Jacks, Meissner, and Wolf (2024) discussed the impact of the Suez canal opening on global trade using a structural gravity model, thus approaching this research question with a 'network-like' approach. Those papers are not included in our corpus but are of a particular interest to understand structural dynamics of international (shipping) trade.

[33] It accounts for the number of transhipments required to get from $j$ to $k$ and the number of common direct connections for example.

[34] It is directly connected to the concept of graph 'communities' discussed in section 4.4.

containerisable bilateral exports as a dependent variable, Ducruet, Itoh, and Berli (2020) directly exploit ship flows at port city level[35]. They aggregate more than two million inter-port vessel movements between 1977 and 2016 at the port and city level and then run gravity model on space-L and space-P network topologies[36]. Inter-port vessel movements are assigned to about 9000 ports and 4600 cities to run a gravity model on two different network topologies. Their results highlight the decisive impact of location parameters (coastal city vs. downstream city, for example), distance between partners, and city size on the intensity of maritime trade. The authors show that the effect of distance on maritime trade is increasing over time and explain this by the emergence of containerisation and hub-and-spoke network structures.

Ducruet and Yoon (2024) provides one of the first in-depth study of the maritime network and shipping trade of North Korea, by reconstructing the shipping network of the country from 1977 to 2021. Notably, they show how the collapse of the USSR and the Eastern Block in the 1990s provoked a dramatic loss in maritime connectivity and isolated North Korea from the rest of the world, China remaining the only exception. While Ducruet and Yoon (2024) studied one of the most closed countries in the world, Trent et al. (2024) focused on New Zealand, an insular country which heavily relies on international trade for both imports and exports. Trent et al. (2024) construct dynamic graphs and discuss the maritime connectivity of New Zealand. The authors refer to New Zealand as a 'connectivity taker' because of its size and geographical position: it is a small country with no real market power, relying almost entirely on foreign shipping companies. They developed the concept of the 'proximal market network', which limits the network to ports that call a New Zealand directly. Their analysis, combining complex network measures with time-series, allows the authors to identify the main 'candidates' among the ports with which New Zealand trades, and to highlight the risk of becoming peripheral by depending essentially on local hubs in Australia for their international trade. The regional analyses thus have a clearer focus on the 'public policy' dimension of port activity: shipping networks are an essential element in the international trade of countries and are at the heart of many development issues. The regional development

[35] Another interesting example of the combination - albeit without direct reference to shipping network literature - of Lloyd's data and gravity models is Useche (2023)

[36] Building on the idea of Sen et al. (2003), Hu and Zhu (2009) proposed two topologies for the global shipping network : space-L and space-P. In the space-L topology, two ports are connected if and only if there is a *direct* vessel connection between them. The space-P topology is less restrictive and considers that two ports are connected if they are on the same line. Let us take the example of the pendulum route such as Hamburg – Shanghai (Ducruet, Itoh and Berli, 2020): in the space-L topology, those two ports are not considered as 'connected' while in space-P they are, because they constitute two elements of the same shipping line.

of maritime networks also goes hand in hand with questions of regional integration. Mohamed-Chérif and Ducruet (2016) develop this issue using the Maghreb as a case study. They show that this is a region whose shipping networks are poorly integrated regionally, despite several projects underway. The polarisation of traffic around Tanger-Med and the development of transshipment are improving the region's connectivity but at the same time making regional integration difficult, in the context of limited political and economic integration. Geographical proximity plays a definite role in the structure of shipping networks, but this is reinforced by regional integration processes (Ducruet and Notteboom, 2012). The development of containerised lines, associated with the hub-and-spoke system, and the increase in connectivity within trading communities are the two main phenomena structuring global shipping networks(Ducruet and Notteboom, 2012; Guo et al., 2024)[37].

### 4.2. Hubs, Port Centrality and Competition

This theme includes important keywords which form a coherent whole, of which hub, centrality, degree, container, development, and competition. Overall, it corresponds to the comparison of ports using rankings of various centrality measures, to assess their function in the network and their competitiveness. The theme has a strong affinity with Asia, where ports compete for transshipment, and which includes the largest ports of the world.

The early works of physicists focused on the statistical distribution of centrality measures, to summarize the topology of the network and prove the existence of hubs. For instance, Xu et al. (2007) and Cui (2014) applied conventional complex network methods, plotting the log-log distribution of degree centrality[38] and betweenness centrality[39], concluding to a scale-free behaviour, as in the seminal work of Barabási and Albert (1999)[40]. Such an analysis was repeated in many subsequent works, but without always reaching satisfactory results, as the exponent of the power-law line in the plot often scored below the expected threshold.

Soon after, other physicists demonstrated that degree centrality was significantly

[37] See also Rimmer (2004)

[38] Number of links connecting topologically adjacent nodes.

[39] Number of occurrences of a node on all shortest paths in the network.

[40] The "scale-freeness" of a network is a topological property shared by many complex systems in biology, transport, information technology and so on. A network is considered scale-free when the distribution of vertex degrees follows a power law. This relationship is usually written as $P(k) \sim k^{-\gamma}$ with $\gamma$ between 2 and 3.

and positively correlated with port throughput in TEUs[41] (Deng et al., 2009; Hu and Zhu, 2009). Such a correlation between centrality and size has long been observed in the case of urban networks of all kinds (see Li and Neal 2024). Degree centrality in the space-*P* topology better illustrates the trade relationships of ports, especially gateway ports, as it includes their long-distance connections, which are ignored in space-*L*. Shenzhen in China, a very large port by its throughput, is overshadowed by the Hong Kong hub in space-L, while in space-P it deploys numerous indirect connections with ports on all continents (Ducruet et al., 2010). Singapore is more central in the space-L network due to its hub function, but it is less central in the space-P network than Shanghai, which is more a gateway port (Duan et al., 2024). The inverse relationship between clustering coefficient and throughput is because hub ports are usually large and polarize their neighbours, with few connexions among them (low clustering coefficient). The low correlation of betweenness centrality with throughput stems from the fact that it is a global accessibility measure, showing an important bridge function between densely connected regions, but without necessarily creating important traffic.

The great majority of related works described port rankings based on various centrality measures, based on pure network topology, often concluding that the most central ports locate in East Asia, Western Europe, and North America (Liu et al., 2018a, 2018b). Certain works, however, proposed alternative metrics or pushed further the comparison between centrality and throughput. Bartholdi et al. (2016) adapted the UNCTAD's Liner Shipping Connectivity Index (LSCI) at the port level to create the Container Port Connectivity Index (CPCI), a composite indicator that is more in line with trade. The CPCI was decomposed by Jarumaneeroj et al. (2023) to study the impact of Panama Canal expansion and of the Hanjin bankruptcy on global port connectivity. Other scholars used the eigenvector accessibility to compare ports (Wang and Cullinane, 2008; Kölzsch and Blasius, 2011; Doshi et al., 2012; Pan et al., 2019; Cheung et al., 2020) as well as closeness centrality[42] (Wang and Cullinane, 2016; Wang et al., 2022). Zhao et al. (2014) proposed a joint analysis of degree, betweenness, closeness, and eigenvector centralities to differentiate global, regional, and sub-regional hub ports (see also Zheng and Shao, 2022), while other works analyzed such centralities independently (see Kanrak and Nguyen (2022a) and Kanrak and Nguyen (2022b)).

Most of the time port centrality is envisaged in a static way. Ducruet and Notteboom (2012) analyzed the evolution of degree and betweenness between 1996 and 2006,

[41]Twenty-Foot Equivalent Units, the standard measure of the volume of container handling at ports.

[42]Also known as the *Shimbel index*, closeness centrality is the inverse of the number of links between a node and its farthest node in the network.

highlighting the decline of Atlantic ports and the rise of Asia-Pacific ports, although container throughput grew everywhere in the same period. The work of Kang and Woo (2017) is a rare example of research looking at the impact of centrality on throughput based on panel data. Their analysis of 20 global ports between 2006 and 2011 concluded that eigenvector centrality positively affects throughput, like berth length, while betweenness had no apparent effect. Conversely, Bai et al. (2022) analyzed how throughput determines connectivity, using graph theory and principal component analysis. They identified Antwerp and Tanjung Pelepas as outliers due to their superior regional accessibility compared with their throughput. Tovar and Wall (2022) demonstrated a strong correlation between port connectivity and efficiency for Spanish ports.

Another approach has been to compare the centrality of ports at different network scales. Fraser et al. (2016) for instance highlighted the peripherality of South African ports in the global container shipping network despite their hub position regionally. Liu et al. (2022) observed that Piraeus (Greece) ranks high in the Europe-China network by its closeness centrality but remains under Northern Range ports in the intra-European network by its degree and betweenness. The multilayer dimension of the global maritime network, decomposed by main types of vessels (container, general cargo, solid bulk, liquid bulk, passengers and vehicles) was first explored by Ducruet (2013), showing a striking increase of all centrality measures with the number of layers (see also Ducruet, 2017a, 2022; Alderson et al., 2020; Peng et al., 2023). Some scholars considered the multi-level structure of the maritime network, looking at the connectivity of ports at different levels of community structures (Ducruet et al., 2010b), including port-level and country-level linkages (Calatayud et al., 2017a, 2017b), disaggregating the network by shipping companies (Xu et al., 2024e), or coined the network multi-scale for their analysis (Kojaku et al., 2019; Liu et al., 2024b). Parent works looked at the centrality of ports in the hypergraph, a network where one single link (edge) can connect multiple nodes (vertices) (Tocchi et al., 2022; Tinessa et al., 2022; Yu et al., 2022; Li et al., 2024).

### 4.3. Vulnerability and robustness to disruptions

This subfield of shipping network research is one of the most developed in the literature, comprising no less than one-third of the whole corpus. It is very diverse internally, from topological assessments of vulnerability, reaction to economic crises, wars and geopolitical conflicts, as well as natural disasters, the Covid-19 pandemic, main channel disruptions, and targeted attacks.

The topological approach wishes to determine whether a given maritime network is easy to collapse under a variety of attacks on nodes or on links. At the node level, an early study proposed the concept of hub dependence to assess port vulnerability, which is the share of the main traffic link in total port traffic (Ducruet, 2008). The higher the share, the more a port depends on one or a few links to access the network, making it highly vulnerable if the link is removed or perturbated (cf. Shenzhen and Hong Kong). Surprisingly, only one study analyzed targeted link disruption, despite its wide use in wider network research, concluding that removing links of highest betweenness resulted in a reduction of transshipment and dynamic re-routing potential amongst the busiest port regions (Viljoen and Joubert, 2016). A parent study removed partially and completely canal-dependent traffic links (Suez, Panama) from the global liner shipping network, to observe the impact on port betweenness, concluding to the higher vulnerability of European ports (Ducruet, 2016).

At the network level, most analyses simulate attacks on nodes through successive iterations to verify which strategies are more efficient to make the network collapse rapidly. Simulations evaluated the vulnerability of the maritime network under theoretical disruptions (Earnest et al., 2012; Achurra-Gonzalez et al., 2019a, 2019b). Several studies proposed a "resilience assessment framework" albeit with some variants. For instance, Bai et al. (2024) used a clique percolation method to identify key ports, a network disintegration method, and a knock-on effect simulation model to predict the impact of major disruptions. Cao et al. (2025) measured port importance to investigate the propagation of cascading failures through the global container shipping network based on betweenness, weight, and connectivity. Ding et al. (2024) constructed a network cascading failure model to compare the robustness of the Belt and Road land–sea transport network and the Maritime Silk Road under deliberate attacks. Dui et al. (2021) used the Copeland method to rank the importance of ports and routes and proposed an optimal resilience model to assess residual resilience. Fang et al. (2018) used a spatiotemporal analytic framework to measure the impact of various disruptions in South Asia, including military conflict, lifted economic sanctions, and government elections. Guo et al. (2024) proposed an irreplaceability model based on the port's geographical location to bring the vulnerability assessment results of shipping networks closer to reality. Many other simulations at the network level were provided, often concluding that the disruption of large ports is detrimental (Yang and Liu, 2022; Liu et al., 2023b; Jiang et al., 2024; Liu et al., 2024d; Lu et al., 2024) as well as main channels or chokepoints such as Malacca, Suez, and Panama (Wu et al., 2019). Other studies envisaged the substitutability between adjacent ports in the advent of targeted attacks, making the network more robust (Wang et al., 2016; Yang and Sun, 2024). The global container shipping network was studied from the perspective of port congestion propagation (Xu et al., 2022b), maritime traffic redistribution to other routes and ports to improve network resilience (Xu et al., 2024a; Xu et al., 2024d), concluding that targeted attacks on betweenness are more efficient than random attacks (He et al., 2022; Liu et al., 2018c; Xia et al., 2024).

One important particularity of ports and shipping networks is their vulnerability to natural disasters. Existing studies have looked at the impact of tsunamis and rising sea levels (Chua et al., 2024), cyclones (Chen et al., 2019; Huang et al., 2024; Poo et al., 2024; Xu et al., 2024c), typhoons (Mou et al., 2024; Wang et al., 2024ca), extreme weather (Poo and Yang, 2024), hurricanes and earthquakes (Rousset and Ducruet, 2020), and natural hazards (Verschuur et al., 2022). However, few of the mentioned studies provided an analysis of a real-world event, compared with those using prediction and simulation tools. Rousset and Ducruet (2020) compared Kobe's Hanshin Earthquake (1995), New Orleans' Hurricane Katrina (2004), and the Twin Towers attack in New York (2001). In all cases, the density[43] of the network increased after the event, with container traffic being the most affected, and a common pattern of traffic re-routing was observed at the periphery of the respective port systems. Another example is Huang et al. (2024) who analyzed the effects of Typhoon Ma-on on the container shipping network using over 776 million Automatic Identification System (AIS) trajectory signals, with the goal to enhance the effectiveness of disaster prevention and mitigation policies.

Although Mou et al. (2024) only looked at the probability of port failure under typhoon risk, they also discussed how to safeguard crucial ports, find alternative ports, optimize shipping routes, and improve the reliability of maritime networks. Poo and Yang (2024) measured the maritime transportation system's recent and future climate risks by integrating climate risk indicators, centrality assessment, and a shipping routing model for a sample of 136 port cities worldwide. Poo et al. (2024) analyzed how five major Chinese ports may resist to tropical cyclones, in order to strengthen infrastructure, improve emergency responses, and adopt climate-resilient policies to make them more sustainable and resilient to climate threats. Wang et al. (2024a) established a centrality ranking of Chinese ports in the global shipping network to estimate their robustness to typhoon risks, concluding that performance loss caused by multiple ports is higher than that of a single port. Shen et al. (2019) proposed a theoretical framework based on which they removed the ports most exposed to tropical cyclones and observed

[43]Network density refers to the share of actual links in the total maximum number of links.

the effects of this removal on the structure of the Northwest Pacific and northern Indian oceans. Another theoretical framework was provided by Verschuur et al. (2022b) to enhance system-wide resilience, alongside port adaptation, to prevent exacerbation of supply chain losses. Xu et al. (2024c) established a framework considering both direct and indirect impacts of tropical cyclones in the Northwest Pacific, from the perspective of path redundancy.

Contrary to natural disaster studies where empirical investigations are relatively scarce, analyses of the covid-19 impacts on ports and shipping networks have mostly been data-driven. Another difference with natural disasters is that the covid-19 had a global magnitude. Dirzka and Acciaro (2022) used data on liner shipping schedule cancellations as distress signals of the pandemic's impact on global supply chains. While network disruptions first clustered in Asia before rippling along main trade routes, the agility of shipping companies prevented the collapse of the global maritime transport network. Some studies provided convergent results, such as the robustness of large ports (throughput) and the vulnerability of hub ports (betweenness, degree) (Guerrero et al., 2022; Ferrari et al., 2022; Li et al., 2024e; Nguyen and Kim, 2024). Jin et al. (2022) analyzed 55 mainland Chinese ports during January-September 2019 and 2020 based on AIS data, with different outcomes depending on main routes and to the role of external hubs. The study by Pan et al. (2022) used graph theory and a gravity model to add new links and strengthen the container shipping network connectivity. Wu et al. (2024a) concluded to an improved tolerance of the global liner shipping network to deliberate attacks, notwithstanding a decline in port efficiency. Yue et al. (2024a) used a disruption risk propagation model to uncover the hub-and-spokes structure of the global container shipping network. Zhou et al. (2024b) applied a microscopic simulation model to the global port network using AIS data, concluding that the effect of quarantine policies were both direct (port skipping) and indirect (network interaction). Arpin et al. (2024) used network analysis and route dynamic assessment in two different scenarios to show the moderate adaptability of the global liner shipping network to substantial disruptions. Some other works focused more on cruise shipping networks (Kanrak et al., 2022; Li, 2024; Poo et al., 2024), since passenger shipping had been among the most impacted sectors during the pandemic (see Verschuur et al., 2022a).

Another set of studies focused on the local and global impacts of specific shocks, such as the Red Sea crisis (Yap and Yang, 2024; Wang et al., 2024), the Russia-Ukraine conflict (Xiao et al., 2024; Cong et al., 2024; Polo Martin et al. 2024; Zhang et al., 2024; Ke et al., 2024; Xiao et al., 2025), and the Suez Canal blockage (Saito et al., 2022; Wan et al., 2023;

Tran et al., 2025). A few works looked at the impact of economic crises. For instance, Mesa-Arango et al. (2019) considered the 1997 Asian financial crisis, the 2000–01 dot-com bubble, the removal of textile and apparel export quotas by developed countries in 2005, and the great recession from 2007 to 2009, based on a multicommodity bilateral network among countries. Pais Montes et al. (2012) compared the degree centrality of global ports across three periods (2008-2009, 2009-2010, 2010-2011) to reveal the impact of the global financial crisis and the pattern of recovery, with a divergence between throughput evolution and centrality evolution (see also Gonzalez-Laxe et al., 2012; Freire Seoane et al., 2013). Ducruet et al. (2023) provided a detailed analysis of the global financial crisis, showing that New York, North America East Coast, and Caribbean had the highest loss of betweenness centrality in 2009. The longer-term North Korean crisis was documented with precision using vessel movement data available since the 1970s (Ducruet et al., 2009; Ducruet and Yoon, 2024). Last but not least, a few works considered other sectors than container shipping, looking at the vulnerability of the LNG maritime supply chain network (Mei et al., 2024), the crude oil maritime network (Mou et al., 2020), the tanker and dry bulk maritime networks (Xie, 2019), and the global agricultural trade network (Wei et al., 2024; Wei et al., 2025).

### 4.4. Communities, spatial structure and port-city systems

This topic combines three main research branches[44]: the study of maritime and port systems, the detection of communities in the shipping networks and the methodological aspects of shipping network reconstruction. The spatial nature of networks has been the subject of much research in theoretical and applied network science in recent years (Barthélemy 2011, 2022)[45]. Understanding the evolution of transport networks cannot be achieved without considering that they are grounded in space. Planar (roads, rails) and non-planar (airlines, shipping lines) transport networks are designed according to spatial constraints. In the case of shipping, the distance between ports is determinant but not sufficient to explain the structure of the network; Pascali (2017) showed that trade distances among countries are highly dependent on maritime technology:

[44] Fig 3 contains the most probable words for this topic. They suggest that it is highly related to the spatial properties of the shipping network, the transportation system and the community structure of the network. It is also interesting to observe the occurrence of 'method' and 'data': until recent years accessing shipping data at a large scale was extremely difficult, especially for long-term analyses.

[45] As emphasized in section 4.4 and recalled by Barthélemy (2011) the 'spatiality' of networks was already an object of study of quantitative geographers in the 1960s. However, we consider 'networks' in the modern way, following the major conceptual and technical progresses of the 1990s (Watts and Strogatz 1998; Barabási and Albert 1999).

steamships reduced shipping costs and time and enabled sailors to navigate without being subject - or to a lesser extent - to the winds. Containerisation, by promoting hub-and-spoke network systems, has also had a major effect on the spatial properties of the maritime network. The structure of shipping networks is not only explained by physical constraints[46], but also by meteorological phenomena, technological advances and organizational changes, which affect the definition of the space in which ships operate (Ducruet and Notteboom, 2012; Ghorbani et al., 2022; Ducruet and Itoh, 2022; Xu et al., 2024).

Transport networks – like many other complex systems – are characterized by a phenomenon of preferential attachment (Newman 2001; Vázquez 2003). It implies that some nodes - *e.g.* ports - are very likely to connect with each other and to connect to the same other nodes in the network. This process creates communities in the network and a whole field researched the best methods to identify communities in the networks (Newman and Girvan 2004; Fortunato 2010; Fortunato and Newman 2022). In the case of maritime networks, this property implies that ports are integrated into 'trade communities'; these clusters are explained by various factors such as geography, history, trade agreements and port functions. The geographical rationale of maritime communities is highly related to distance: neighbouring ports are more likely to connect, especially when considering all the ships without filtering small units. Industry factors such as the emergence of transshipment ports along with the containerization of shipping greatly impacted the structure of shipping networks (Rodrigue and Notteboom 2013; Guerrero and Rodrigue 2014; Cosar and Demir 2018; Tsiotas and Ducruet 2021).

Kaluza et al. (2010) and Sun et al. (2012) were the first to explore community structures in shipping networks using clustering algorithms. Kaluza et al. (2010) built three global shipping networks, for container ships, bulk dry carriers and oil tankers. Using a modularity-based approach (Leicht and Newman 2008) they found communities that mostly correspond to geographical entities with a few one that are more dispersed. The communities are very large and specific clusters such as oil-producing regions do not appear in the results. This result exemplifies an important limit of the application of modularity-based algorithms to networks, namely the 'resolution limit' (Fortunato and Barthélemy 2007). It has been shown that modularity-based algorithms fail to detect

[46] It should be noted, however, that this remains an important parameter in the structure of shipping networks. Particularly in the case of containerisation, the size of ships and port facilities have a strong impact on the network (see Brooks, Gendron-Carrier, and Rua (2021), Ducruet et al. (2024) on the impact of port depth and Malchow (2017) and Ge et al. (2021) on operational challenges related to containerships' size.

small, specific, communities. When analysing shipping networks, this issue implies that we mostly observe geographical modules and fail to uncover the functional dimension of trading communities[47].

The variety of strategies pursued by shipping companies and the differences in trading communities between companies are explored by Xu et al. (2024) within the framework of a multiplex network. Certain hubs form communities that are very specific to certain shipping companies, and disappear when several ones are considered. The authors highlight the critical role of certain ports for specific players, while other ports have a central position for the Global Container Shipping Network (GCSN) as a whole. The 'multi-criticality' of the different port infrastructures and the competition between them is thus approached at different levels of aggregation in the shipping industry.

The 'Lift' and the 'Score' indicate that the port-city system is very rare in other topics – and thus quite distinctive of this one. The way in which ports integrate into cities (and their hinterlands) is a complex and multifactorial research issue. The economic impact of the port, although difficult to measure precisely, affects the structure of local and regional logistics chains and the urbanisation dynamics of neighbouring areas. Investigating quantitatively the port-city relationship is a challenging task due to the issues related to data accessibility and the nature of shipping flows and cities' activity[48]. Guo and Qin (2022) provide some answers to this question by studying the coupling of the port-urban network system. To achieve this, they combine cargo flows with people, capital, technology and information flows to model the relationship between the coastal port system and its urban network. In particular, the authors show that as ports diversify, logistics integration with other flows becomes a necessary condition for network efficiency. They also point out that port cities - in the case of China - have moved from a model of competition to a form of 'coopetition', with the development of hub-and-spoke maritime networks between cities and more independent urban networks.

This topic also highlights the major methodological efforts made by the researchers in the analysis of shipping networks. These efforts are linked to the difficulty of reconstructing shipping networks due to several factors: difficult access to large-scale temporal, limited temporal coverage... The progress of AIS (automated identification

[47] Geographical communities are indeed existing in shipping networks, and clustering algorithms are useful in delineating the

[48] Fujita and Mori (1996) developed an economic geography model of port-city development. In transport geography, one can also refer to Debrie and Raimbault (2016) and Raimbault (2019) who studied port-city relationships through the lens of port governance.

system)[49] data collection is viewed as an appealing and accessible solution to this issue. Wang et al. (2019) reconstruct a Global Shipping Network (GSN) at terminal, port and country level from historical ship AIS data. Combining clustering and semantic approaches to identify terminals and ports in the sequence of ship movements and applying this bottom-up method to containerships in 2015 they show how to reconstruct and analyse the network properties of the global container shipping network (GCSN) from individual AIS data points. Machine-learning methods also prove their ability to be used in the reconstruction of global shipping networks from AIS data: Liu et al. (2023) extracted bulk carriers shipping networks for 2018, covering 2769 berthing areas over the world and demonstrating how this strategy can actually improve route planning methods. Filipiak et al. (2020) used an evolutionary algorithm to reconstruct a GSN; Yu et al. (2019) introduced several additional levels of complexity by modelling a dynamic and multi-layer (bulk, container and tanker) network of global vessel trajectories. Beyond the methodological scope, Yu et al. (2019) also discuss policy implications of GSN reconstruction such as ports' cooperation, shipping lines adaptation to changing environment and economic integration of transportation flows. Finally, other researchers have attempted to reconstruct navigation routes using different algorithmic methods, making it possible to go further back in time without having real data on the position of ships (Polo-Martin and Ducruet, 2024; Polo-Martin et al., 2024; Robertsa et al., 2024).

Some avenues for future research specific to this topic can be identified. Firstly, efforts to apply clustering models should be directed towards a better understanding of the temporal and functional dynamics of maritime networks. Now that the spatial dimension is well understood, the exploration of new methods[50] will provide a better understanding of preferential attachment mechanisms. The understanding of port systems also deserves in-depth study, particularly in terms of their interactions with other networks (road, rail). Conceptual and empirical work on port systems, the communities they form, and their interactions with other transport systems are therefore the main perspectives for the future of this sub-field.

## 5. Discussion: Missing Links?

This study reviewed the research trends of shipping network research since the original application of graph theory to a maritime network by Robinson (1968). Four main themes

[49] See Artikis and Zissis (2021) for a specific in-depth study on maritime informatics.
[50] Such as dynamic stochastic block models (DSBM) (Matias and Miele 2017).

could be identified within the corpus of articles published between 2007 and 2025: trade, centrality, vulnerability, and spatial structure, comprising most of the papers. Nevertheless, other subfields remain strikingly small despite their core importance in port and maritime studies in general.

One of these subfields relates with environmental impacts[51]. For instance, Tran and Lam (2024) analysed the global network of CMA-CGM to reveal that hub-and-spoke patterns influence the skewed distribution of in-port emissions, which concentrate in a small number of key hubs that attract substantial vessel calls. In their analysis of the South China Sea shipping network, Li et al. (2024) discussed the reduction of carbon emissions but without measuring them. For the Bohai Rim region, Chen et al. (2024) explored the possibilities of shifting transport modes from land to sea to reduce emissions, but without using network analysis *per se*. Similarly, Zhou et al. (2024a) proposed an optimization model to investigate the carrier's economic viability and CO2 emissions under the maritime emission trading scheme without reference to graph theory. Instead, Karountzos et al. (2023)[52] used a Geographical Information System (GIS) to examine whether the Greek shipping network can be restructured by the introduction of zero-emission sub-networks operated by electric ferries calling at new transshipment port hubs located in the islands. The study of eight Northern European countries between 2005 and 2017 concluded that container throughput, liner shipping connectivity, and trade openness have a positive impact on marine greenhouse gas (GHG) emissions. A few other studies employed the complex network framework. Yue et al. (2024) estimated the carbon footprint of Suez Canal disruption along the Europe-Asia route, while Kanrak et al. (2023) focused on the Caribbean basin, concluding that the best connected ports tend to locate outside Emission Control Areas because the regulations are barriers for cruise ships entering the ports.

Marine bioinvasions is another topic which attracted peripheral interest from a network perspective. This is rather surprising, given that it is specific to shipping and has enormous environmental, economic, cultural, and human health impacts. Kaluza et al. (2010) as well as Kölzsch and Blasius (2011) provided the first analyses of the kind using a complex network framework. They particularly used betweenness centrality and community detection to estimate how invasive species can travel through the global shipping network, carried by ballast water. It is only much later that other studies were conducted. Lenzen et al. (2023) traced the origins and destinations of

[51] See Artikis and Zissis (2021) for a specific indpeth on maritime informatics.
[52] See also Karountzos et al. (2024) and Karountzos, Giannaki, and Kepaptsoglou (2024)

seaborne trade connections, and the nature of the traded commodities, to predict the strength of shipping vectors and associated marine biosecurity risks. Bereza et al. (2023) compared the respective port visit durations and voyage sailing times of Ultra Large Container Vessels (ULCV) and small vessels, concluding that major shipping hubs were not necessarily major invasion hubs. Song et al. (2024) included shipping flux density, distance between ports, trade flow, and centrality measures of transportation hubs in a gravity model to predict the spread of non-indigenous species (NIS) between ports. Shi et al. (2024) employed automatic identification system (AIS) data, ballast water data, and water temperature and salinity data to construct the species invasion network (SIN) and the global shipping network (GSN), concluding that closeness centrality is most highly correlated to the invasion risk.

Another striking deficiency of shipping network research is the subtheme of local socio-economic development. This stands in sharp contrast with the abundant literature on port-city relationships and port economic impacts. Very few works put port centrality in relation with the socio-economic attributes of nodes. Wan et al. (2021) included port city GDP and throughput in their classification of container ports along the Maritime Silk Road. Kanrak and Nguyen (2022) are one of the rare studies considering node attributes in their analysis of the Asian-Australasian shipping network (location, number of attractions and visitors, rating score, popularity, and population). The way in which ports integrate into cities (and their hinterlands) is a complex and multifactorial research issue. Investigating quantitatively the port-city relationship is a challenging task due to the issues related to data accessibility and the nature of shipping flows and cities' activity[53]. Guo and Qin (2022) provide some answers to this question by studying the coupling of the port-urban network system. To achieve this, they combine cargo flows with people, capital, technology and information flows to model the relationship between the coastal port system and its urban network. In particular, the authors show that as ports diversify, logistics integration with other flows becomes a necessary condition for network efficiency.

An original approach has been to measure a combined port centrality in road, railway, and maritime networks simultaneously (Berli et al., 2018; Indriastiwi and Hadiwardoyo, 2021; Jung and Thill, 2022; Polo Martin and Ducruet, 2024; Da Costa et al., 2025), as well as air-sea connectivity (Parshani et al., 2011). This necessitated aggregating ports, stations, and airports at the level of urban agglomerations, thereby concluding

[53] Fujita and Mori (1996) developed an economic geography model of port-city development, but it is not applied in this literature or elsewhere despite its relevance.

that combined centrality is better correlated with city size than single centrality. Two works outside of the corpus are worthy of investigation. For instance, Ducruet and Itoh (2015) analyzed the Asia-Pacific maritime network with subnational regions as nodes, characterized by traffic, centrality, and various socio-economic indicators (population density, unemployment rate, GDP per capita, and main economic sectors). A similar approach was proposed by Ducruet et al. (2017), looking at the socio-economic similarity of connected port regions in the OECD area. They underlined a strong correlation between traffic volume, network centrality, interaction range, demographic and economic size, population density, GDP per capita, specialization in the tertiary sector and in container as well as vehicle flows, the most valued commodities. Despite these advances, we still lack of an analysis that would address the issue of endogeneity, as maritime connectivity and local socio-economic development occur through reverse causation.

Last but not least, we found only a few works on the influence of shipping alliances on maritime networks. Wilmsmeier and Notteboom (2011) soon discussed the effects of shipping lines' strategies and the role of alliances on the connectivity between Europe and South America. Yap and Zahraei (2018) look at how major routes like Europe-Asia had been reshuffled due to the rationalization of individual shipping lines and the growth of alliances. Liu et al. (2024b) found that the shipping network of alliances is more robust than individual route or port disruption. Yamamoto and Takebayashi (2024) concluded that hub-and-spokes systems are more profitable to carrier alliance. One of the most advanced approaches is the one of Gou et al. (2024), offering a multi-level analysis of the global liner network with two layers (shipping lines and alliances), concluding that alliances ease competition, while making the network more efficient, denser, and stable, supporting shipping network integration. Finally, Wang et al. (2020) analyzed the shipping networks of COSCO and CSCL before and after their merger. Complementarities were found before the merger, but afterwards, the merger also had the effect of strengthening the key hub ports of the network.

In terms of methods, since the review by Kanrak, Nguyen, and Du (2019) of the analytical methods applied to shipping networks, many network models have in fact been much neglected if not ignored in the shipping network literature. The random graph or Erdős and Rényi model combines graph theory and probability theory, functioning as a benchmark to study the topology and connectivity of a network (Kanrak and Nguyen, 2022a). The exponential random graph model (ERGM) is a statistical model of social networks that explains the formation of networks, network links and relationships, based on the assumption that the emergence of a relationship might be influenced by other relationships or individual characteristics (Kanrak and Nguyen, 2022b). However, no study has been done using such a model in shipping network research. This is rather surprising, given that shipping networks witness a highly hierarchical structure that echoes the processes of rich-club (most central nodes connecting each other, or assortativity) and preferential attachment (new nodes and links primarily connected high degree nodes, in a scale-free network). The great majority of studies used descriptive statistics instead, such as local measures of centrality (degree, clustering coefficient), global accessibility measures (betweenness, closeness, eigenvector), and network-level indices to summarize the structure of the network (diameter, average shortest path length, density, degree distribution), but without a modeling approach, despite its wide use in other domains. In terms of network dynamics, although fine-grained shipping data is increasingly available, very few works have proposed a detailed temporal approach of centrality, except for Guinand and Pigné (2015) looking at daily, weekly, and monthly centrality in the global container shipping network. The discovery of Lloyd's List archives on daily vessel movements between ports of the world undoubtedly offered new possibilities to track multiple shocks affecting ports and shipping networks back in the 19th century.

## Conclusion

Without a doubt, shipping network research is a buoyant field today, given the rise of publications and the diversity of approaches. Like in many other fields and across all scientific disciplines, port and maritime research experienced a massive integration of the complex network framework in the 2000s, offering new ways to compare ports and understand shipping. This recalls the adaptation of graph theory from mathematics to geography to study transport and urban networks in the 1950s-1960s (Ducruet and Beauguitte 2014). The overwhelming importance given to methodological aspects carries, however, the risk for scholars to remain *"stuck in the narrow confines of network structures and flows"* (Keeling 2007). This is particularly true for shipping network research, where we observed that a majority of studies remained relatively abstract, *i.e.,* providing a description of network topology for the sake of applying the complex network framework, thereby ignoring spatial structure, socio-economic embedding, and governance issues. Regional integration processes and international trade patterns (e.g., gravity) remain poorly discussed in the literature on shipping networks. The exact meaning of port centrality is rarely discussed as well, although it provides in some cases interesting deviations from the more classic ranking of ports according to throughput, revealing the specific functions of ports. In addition, we found many misinterpretations of the Barabasi-Albert model in the shipping network literature. Several authors claimed that the network is scale-free, although the exponent of the power-law line remained much below the theoretical threshold. It must not be forgotten that preferential attachment in a scale-free network is a process rather than a static property.

Moreover, focusing on the sole shipping network tended to ignore the fact that ports and maritime transport are only one component of the overall supply and value chain (Robinson 2002). The absence of hinterland data remains a major impediment, forcing scholars to focus on the sole road or rail infrastructure in combination with the shipping network. This explains the drastic absence of empirical studies on the vertical integration of maritime networks. As mentioned above, other promising research themes include the relationships between maritime connectivity and ship emissions, marine bioinvasions, local socio-economic development, and shipping alliances. In our review, we have focused on the most original contributions, implying that a great majority of studies were satisfied by simply applying the most conventional graph-theoretical tools to given datasets.

Further research shall lean towards several possible directions, with reference to the various research agendas proposed by earlier reviews of port and maritime studies. One of them is the deeper analysis of port performance and competitiveness, where port centrality should be included as one factor among others, to test its relative influence, and to elucidate the respective roles of various types of centrality at different scales from the local to the global. Another research avenue is about environmental impacts, including public health issues and pollution, to verify whether particular network structures may reinforce or lower such impacts, also considering the technical characteristics of vessels and their navigation patterns. Economic development in general is a promising theme, should it be about cities, regions, or countries, given its very close relationship with trade and maritime transport. Further linking shipping network analysis with hinterland and other territorial data is a prerequisite for advancing knowledge about such interactions. Lastly, the massive extraction of historical shipping data may allow fine-grained analyses of past events and their influence on shipping network structures.

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# Appendix A. Co-authorship Networks

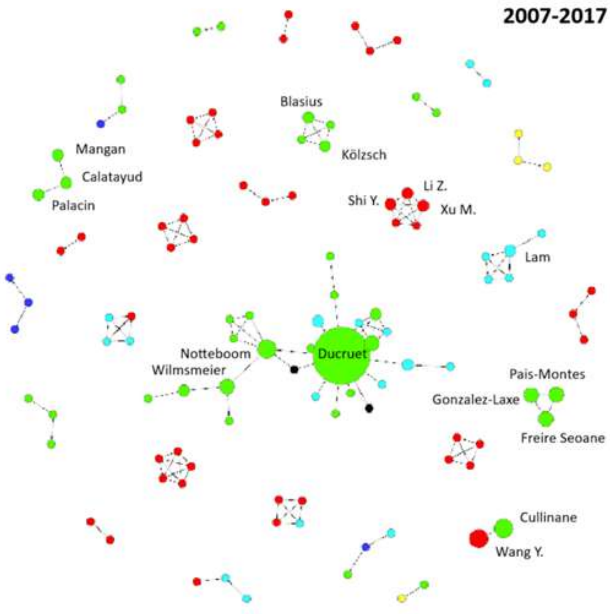


FIGURE A1. Co-authorship network (2007 – 2017)

*Notes:* Two authors are connected if they have written an article together.

The configuration of co-authorships is relatively scattered in the first period (Figure A1), mainly due to the low number of articles. Interregional collaborations are near to non-existent, except for the dyad between Cullinane (Europe) and Wang (China). European scholars concentrate the bulk of publications, with Ducruet-Notteboom-Wilmsmeier as the core community.

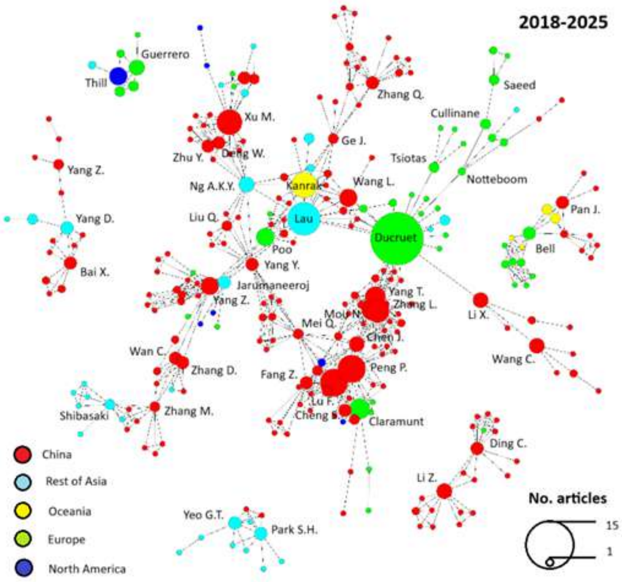


FIGURE A2. Co-authorship network (2018 – 2025)

*Notes:* Two authors are connected if they have written an article together.

The second period (Figure A2) witnesses a fully different pattern , with multiple cores and more interregional connexions. Europe is still in a relatively central position with Ducruet-Notteboom, but China clearly dominates most of the communities. In the core community, Poo and Claramunt (Europe) have emerged through intensive collaborations with Chinese scholars, as well as Kanrak (Oceania), Lau and Ng (Hong Kong), Jarumaneeroj (Indonesia), and Shibasaki (Japan). The most publishing Chinese authors are Xu M., Yang T., Zhang L., Mou N., Peng P., and Lu F., while Wang L., Mei Q., and Yang Y. occupy important bridge roles to make this core community interconnected.

# Appendix B. Additional Estimations

## B.1. A Six-Topics Partition

TABLE A1. Top Words from the STM model with 6 topics

| Topic | Highest Prob | FREX | Lift | Score |
|---|---|---|---|---|
| **1** | *cruis, vessel, oper, ship, rout, arctic, use, emiss, chang, contain* | *emiss, cruis, arctic, suez, asr, passag, itinerari, season, voyag, water* | *acceler, contact, ice, inventori, murmansk, plant, prompt, summer, tonn, world-wid* | *cruis, arctic, itinerari, asr, passag, emiss, season, nis, dual-cor, visit* |
| **2** | *connect, trade, region, contain, liner, use, model, transport, econom, effect* | *bilater, export, freight, product, period, connect, variabl, partner, demand, africa* | *agenda, best, bilater, calibr, capita, contract, country-level, crise, eight, endogen* | *bilater, -go, trade, country', lsbci, capita, partner, output, freight, canari* |
| **3** | *contain, central, hub, connect, competit, develop, studi, servic, region, degre* | *hong, asian, kong, busan, singapor, competit, central, shanghai, hub, allianc* | *fierc, hole, late, latest, penang, qingdao, sub-hub, topsi, alphabet, arrang* | *busan, competit, hong, asian, kong, singapor, hacc, tier, alphabet, cosco* |
| **4** | *resili, vulner, disrupt, impact, transport, trade, model, studi, assess, attack* | *resili, failur, cascad, attack, disrupt, conflict, vulner, robust, critic, risk* | *aid, catastroph, confid, conflict, encount, fail, faster, fragil, hazard, intent* | *resili, cascad, failur, attack, disrupt, conflict, glsn, reliabl, crude, risk* |
| **5** | *structur, spatial, transport, communiti, trade, system, flow, region, traffic, studi* | *urban, communiti, citi, spatial, linkag, articl, inter-, function, strateg, coupl* | *airport, australia, bipartit, bodi, chosen, clarifi, communic, compil, connector, convent* | *communiti, urban, spatial, citi, gmn, updat, inter-, multiplex, socioeconom, linkag* |
| **6** | *rout, transport, ship, method, use, data, road, node, model, link* | *msr, silk, road, shortest, path, algorithm, advantag, tanker, bulk, edg* | *abstract, allevi, billion, blockag, bottleneck, footprint, heavy-tail, hope, msr, neighbourhood* | *msr, silk, tanker, advantag, ship, chart, waypoint, oil, bulk, road* |

TABLE A2. Regression Results for Topics 1–6 (Updated Model)

| Variable | Topic (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| **(Intercept)** | 0.02369 | 0.39416*** | 0.17719*** | 0.01703 | 0.28595*** | 0.10200* |
| **2020–2025** | 0.11341*** | -0.00270 | -0.06031· | 0.11080** | -0.09880** | -0.06255· |
| **China** | -0.02373 | -0.20694*** | 0.18153*** | 0.06725 | -0.11060** | 0.09258* |
| **North America** | -0.02683 | -0.11109 | -0.00152 | 0.10650 | -0.04424 | 0.07638 |
| **Rest of Asia** | 0.15072** | -0.22830*** | 0.31065*** | -0.02693 | -0.17163** | -0.03592 |
| **Economics** | 0.11645 | -0.08334 | -0.02469 | -0.02042 | -0.11176 | 0.12096 |
| **Engineering & data sciences** | -0.09225· | -0.15229* | -0.16267* | 0.13061· | -0.01142 | 0.28656*** |
| **Environment & energy** | 0.10782 | -0.15236· | -0.20551* | 0.29789** | -0.01486 | -0.03333 |
| **Geography** | 0.01326 | -0.04273 | -0.06036 | -0.00673 | 0.12195* | -0.02461 |
| **Geosciences** | -0.01974 | -0.15374· | -0.19289* | 0.03740 | 0.22512* | 0.10403 |
| **Marine sciences** | 0.01766 | -0.11488· | -0.16735** | 0.09616 | 0.01751 | 0.15063* |
| **Multidisciplinary** | 0.16326* | -0.12160· | -0.14088* | 0.02379 | 0.03606 | 0.03894 |
| **Networks & complex systems** | 0.05010 | -0.00999 | -0.18866* | -0.04923 | 0.14299 | 0.05632 |
| **Physics & natural sciences** | 0.02751 | -0.15812· | -0.16115* | 0.03981 | 0.06392 | 0.18914* |
| **Transport & logistics** | -0.07604 | -0.00015 | -0.05151 | 0.10628· | -0.00817 | 0.03019 |

*Note:* Columns (1), (2), (3), (4), (5), and (6) show coefficients for Topics 1, 2, 3, 4, 5, and 6, respectively. Significance codes follow the R summary: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Baseline categories are *Europe* (Origin), *Shipping* (Background) and 2007 – 2019 (Period).

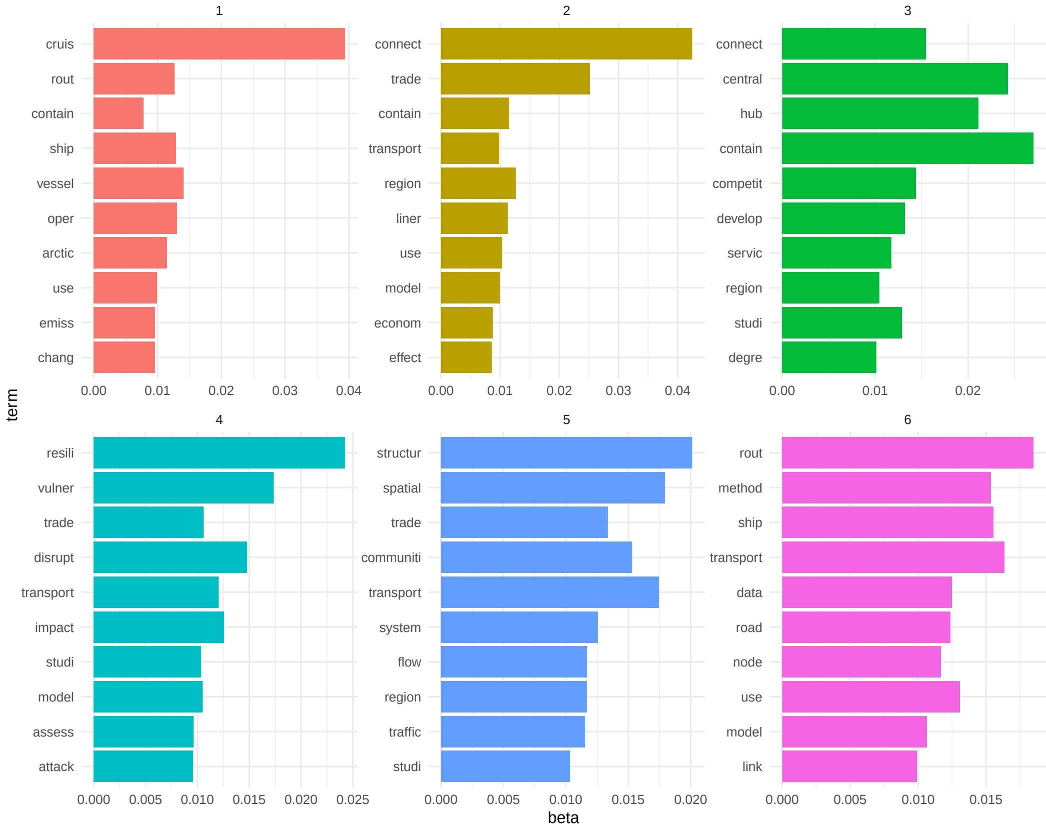


FIGURE A3. Top-10 most probable words in a six-topics partition

The most probable words in a six-topics partition also reveal some interesting results: in particular, it makes it possible to create a new topic focusing on methodological issues (with words such as method, link, data). However, this methodological question is outside the scope of our more thematic analysis. This also reinforces the coherence of an approach with a limited number of topics focusing on the major trends in the field over the years.

## B.2. A Ten-Topics Partition

TABLE A3. Top Words from the STM model with 10 topics

| Topic | Highest Prob | FREX | Lift | Score |
|---|---|---|---|---|
| **1** | *cruis, arctic, connect, studi, rout, ship, oper, chang, line, use* | *cruis, arctic, itinerari, asr, passag, season, voyag, core, line, allianc* | *acceler, branch, murmansk, dual-cor, latitud, medium, one-way, round-trip, cruis, asr* | *cruis, itinerari, arctic, asr, dual-cor, passag, season, caribbean, murmansk, acceler* |
| **2** | *connect, trade, liner, region, servic, effect, use, contain, measur, indic* | *bilater, connect, africa, partner, liner, variabl, export, posit, servic, african* | *bilater, capita, endow, -go, agenda, brief, country', gross, longitudin, lsbci* | *bilater, -go, lsbci, country', export, liner, african, capita, trade, variabl* |
| **3** | *central, hub, contain, competit, connect, studi, develop, region, liner, use* | *hong, busan, shanghai, kong, singapor, asian, central, hub, competit, southeast* | *hacc, hole, qingdao, subhub, topsi, alphabet, believ, cyclic, dalian, hub-* | *busan, asian, hong, kong, competit, alphabet, singapor, hacc, shanghai, sna* |
| **4** | *trade, transport, oil, intern, countri, use, bulk, data, tanker, flow* | *oil, tanker, bulk, energi, trade, crude, lng, price, strait, volum* | *add, annual, apart, clean, earthquak, food, mass, modul, repeat, dri* | *oil, tanker, bulk, energi, crude, trade, modul, lng, dri, price* |
| **5** | *structur, communiti, spatial, transport, citi, system, connect, flow, contain, studi* | *communiti, citi, urban, spatial, linkag, inter-, function, articl, hierarchi, strateg* | *communic, gmn, multiplex, revisit, stake, bipartit, chosen, geomat, lloyd', non-planar* | *communiti, urban, citi, updat, gmn, inter-, hierarchi, socioeconom, linkag, multiplex* |
| **6** | *method, road, china, silk, rout, msr, studi, construct, traffic, use* | *silk, road, msr, china, along, plan, advantag, belt, method, extract* | *waypoint, wmtn, barabási-albert, bri, cambodia, chart, data-driven, digit, match, rich-club* | *msr, silk, road, vietnam, wmtn, chart, belt, advantag, coeffici, extract* |
| **7** | *resili, vulner, node, disrupt, transport, attack, failur, studi, robust, impact* | *failur, attack, vulner, resili, robust, glsn, critic, cascad, disrupt, deliber* | *failur, interfer, suscept, well-connect, compens, cyclon, system', transmiss, typhoon, tropic* | *resili, failur, cascad, attack, glsn, well-connect, deliber, disrupt, vulner, cyclon* |
| **8** | *transport, model, region, use, contain, graph, differ, flow, rout, trade* | *databas, graph, freight, limit, methodolog, demand, literatur, korean, discuss, occur* | *aris, contract, frontier, interfac, understood, complement, gis, hand, immedi, interv* | *principl, korean, gis, freight, databas, reliabl, review, hypergraph, frontier, interv* |
| **9** | *contain, rout, covid-, impact, chang, model, pandem, transport, indic, disrupt* | *recoveri, covid-, pandem, emiss, cost, decreas, carrier, carbon, individu, reduct* | *black, catastroph, consum, green, inventori, manila, profit, tax, -day, accomplish* | *covid-, recoveri, accomplish, emiss, pandem, carbon, black, conflict, profit, cancel* |
| **10** | *ship, risk, vessel, model, water, data, invas, use, rout, suppli* | *invas, speci, nis, water, risk, spread, propag, biosecur, ship, delay* | *aquat, arriv, bioinvas, high-risk, nis, non-indigen, ballast, biofoul, biosecur, ecoregion* | *arriv, nis, invas, water, biosecur, speci, risk, visit, flag, bioinvas* |

## Table A4. Regression Results for Topics 1–10 (Updated Model)

| Variable | Topic (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| **(Intercept)** | 0.03288 | 0.25676$^{***}$ | 0.14770$^{***}$ | 0.07875$^{*}$ | 0.18857$^{***}$ | 0.03938 | -0.01318 | 0.19857$^{***}$ | 0.03936 | 0.03218 |
| **2020–2025** | 0.05046$^{\cdot}$ | 0.01473 | -0.06434$^{*}$ | -0.08296$^{**}$ | -0.03323 | -0.03818 | 0.05705$^{\cdot}$ | -0.03909 | 0.09114$^{**}$ | 0.04288$^{\cdot}$ |
| **China** | 0.06935$^{*}$ | -0.11362$^{**}$ | 0.11693$^{***}$ | 0.07530$^{*}$ | -0.04862 | 0.13673$^{***}$ | 0.07565$^{*}$ | -0.18707$^{***}$ | -0.02647 | -0.09733$^{***}$ |
| **North America** | -0.03892 | -0.15430$^{\cdot}$ | 0.00428 | 0.15820$^{\cdot}$ | 0.01136 | 0.03668 | 0.01383 | -0.05565 | -0.09302 | 0.12048 |
| **Rest of Asia** | 0.13278$^{**}$ | -0.07877 | 0.20632$^{***}$ | -0.02493 | -0.14339$^{**}$ | 0.04513 | 0.00156 | -0.15523$^{***}$ | 0.03578 | -0.01721 |
| **Economics** | -0.09898 | -0.01721 | 0.01132 | -0.01172 | -0.12032 | -0.03815 | 0.01910 | 0.00546 | -0.03305 | 0.28908$^{*}$ |
| **Engineering & data sciences** | -0.12548$^{*}$ | -0.12529$^{*}$ | -0.11549$^{\cdot}$ | 0.06586 | -0.08225 | 0.12521$^{*}$ | 0.11660$^{\cdot}$ | 0.08354 | -0.05142 | 0.10800$^{*}$ |
| **Environment & energy** | -0.04831 | -0.15712$^{*}$ | -0.14239$^{\cdot}$ | 0.24047$^{**}$ | -0.08485 | -0.08956 | 0.09128 | -0.01240 | -0.03409 | 0.23584$^{**}$ |
| **Geography** | -0.01554 | -0.05808 | -0.07075 | 0.02349 | 0.06615 | -0.04328 | 0.00209 | 0.07013 | 0.04386 | -0.01777 |
| **Geosciences** | -0.08028 | -0.18034$^{*}$ | -0.14759$^{\cdot}$ | 0.02120 | -0.00932 | 0.04946 | 0.00001 | 0.28463$^{**}$ | -0.04707 | 0.10760 |
| **Marine sciences** | -0.08370 | -0.11155$^{\cdot}$ | -0.12337$^{*}$ | 0.00916 | -0.04337 | 0.07230 | 0.10810$^{\cdot}$ | 0.05976 | 0.06387 | 0.04962 |
| **Multidisciplinary** | 0.05377 | -0.17616$^{**}$ | -0.09436 | 0.11541$^{\cdot}$ | -0.02848 | -0.02276 | 0.03031 | -0.01639 | 0.02274 | 0.11556$^{*}$ |
| **Networks & complex systems** | 0.01574 | -0.06879 | -0.15057$^{*}$ | 0.09134 | 0.10128 | 0.06417 | -0.00642 | 0.02614 | -0.07093 | -0.00116 |
| **Physics & natural sciences** | -0.10406 | -0.14617$^{*}$ | -0.19286$^{**}$ | -0.01152 | 0.04980 | 0.23249$^{**}$ | 0.12330 | 0.00069 | -0.03365 | 0.07886 |
| **Transport & logistics** | -0.10101$^{*}$ | 0.01392 | -0.05694 | -0.04689 | -0.02800 | 0.02074 | 0.11750$^{*}$ | 0.06305 | -0.00438 | 0.02051 |

*Note:* Columns (1), (2), (3), (4), (5), (6), (7), (8), (9), and (10) show coefficients for Topics 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10, respectively. Significance codes follow the R summary: $^{***}$ $p < 0.01$, $^{**}$ $p < 0.05$, $^{*}$ $p < 0.1$. Baseline categories are *Europe* (Origin), *Shipping* (Background) and 2007 – 2019 (Period).

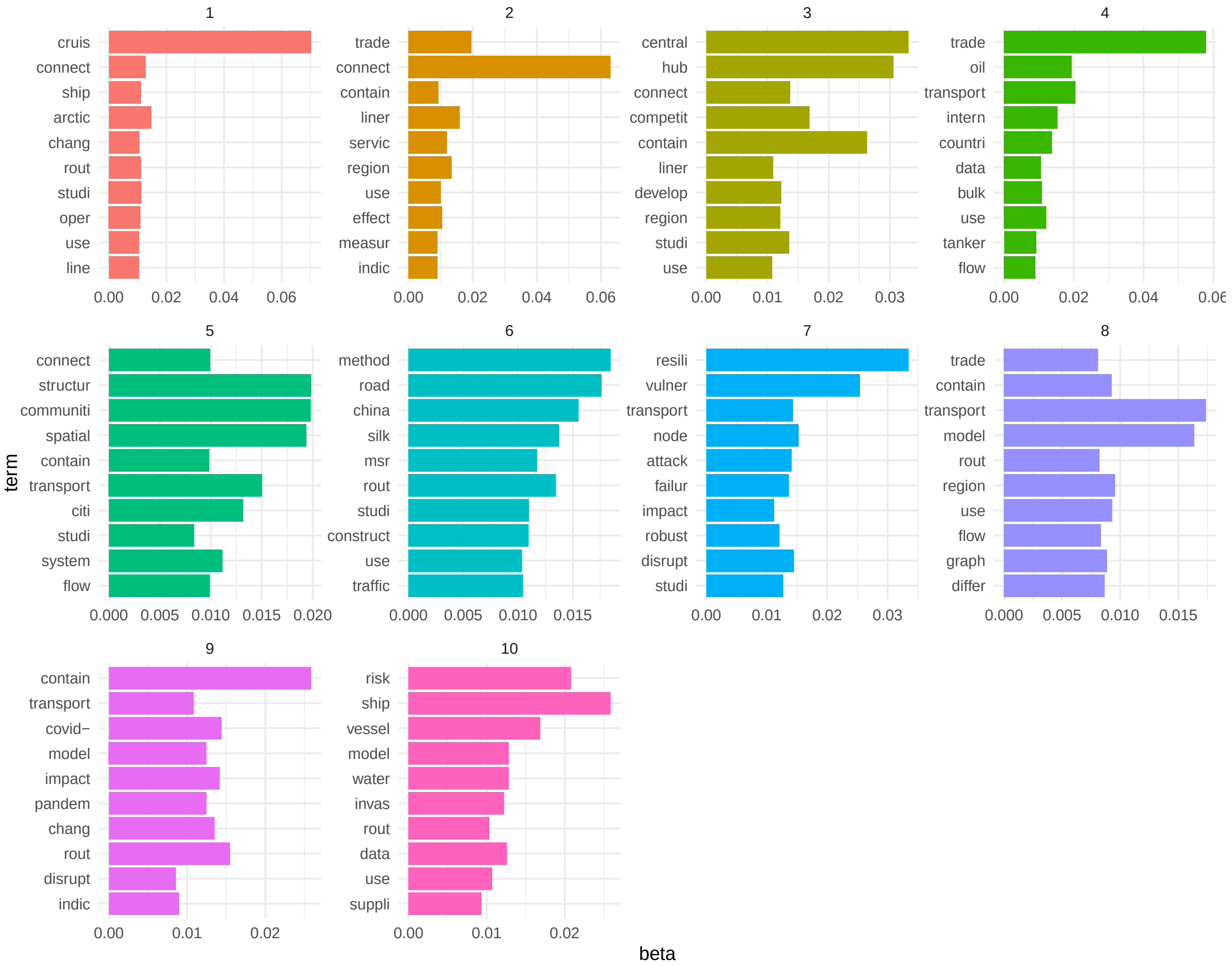


FIGURE A4. Top-10 most probable words in a 10 topics partition

## Appendix C. Corpus of Selected Shipping Network Studies, 2007-2025

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