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PORTS, NETWORKS, AND THE GEOGRAPHY OF TRADE

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PORTS, NETWORKS, AND THE GEOGRAPHY OF TRADE

*Global Maritime Flows, Regional Labour Markets,
Systemic Disruptions*

Marc-Antoine FAURE COLONNA D'ISTRIA

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« Il nous semble avoir vécu longtemps dans les lieux où nous avons vécu avec intensité. »

— MARGUERITE YOURCENAR, *Archives du Nord*

E quindi uscimmo a riveder le stelle

— DANTE ALIGHIERI, *Divina Commedia*, *Inferno* (XXXIV)

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Abstract

The aim of this thesis is to improve our understanding of the structure and impact of maritime trade. More specifically, it examines the impact of conflicts on the structure of global maritime trade, the evolution of international shipping flows over the long term, and the impact of port activity on local economic development.

The first chapter provides a systematic review of the recent literature on shipping networks. Using *natural language processing* algorithms, we identify the main trends in the field since 2007 and outline several avenues for future research. The remainder of the thesis aims to address some of the gaps identified in this first chapter.

In the second chapter, we examine the evolution of containerised shipping networks since the 1970s. Our objective is twofold: to provide a comprehensive overview of containerisation from its early years of internationalisation, and to assess the structural changes associated with microeconomic trade-offs, including alliance strategies and port development. We thus show a shift towards a multipolar and increasingly Asian-centred system at the macro level, as well as a transformation in the structure of the links connecting ports at the micro level.

The third chapter models and assesses the consequences of the Russia–Ukraine war for the Ukrainian maritime network. Using a multi-level approach, conducted at the levels of ports, flows and countries, we highlight the consequences of a high-intensity conflict for maritime trade and for the ability of a transport system to demonstrate resilience and adaptability several months after the initial shock. This study is one of the first to quantitatively assess the consequences of an armed conflict for the structure and level of activity of a maritime network.

The fourth and final chapter examines the link between port activity and local economic development. It explores how ports, as infrastructures connecting regions to international markets, can influence growth, employment and regional dynamics. To address the endogeneity issues associated with this relationship, we construct a historical instrumental variable. We also examine the spillover effects of maritime activity in the hinterland. Our results show that it remains difficult to accurately assess the local impact of maritime trade, even when using robust econometric methods.

Finally, we discuss the research perspectives opened up by the evaluation of the local impacts of port and maritime activity.

The approach and findings presented in this thesis thus aim to forge links between research themes and fields that remain insufficiently connected. Local issues relating to port activity are examined in the light of global and long-term transformations in maritime trade, while causal econometrics and network analysis methods are integrated into a unified analytical framework. The aim of this thesis is therefore not only to advocate an interdisciplinary approach to maritime trade, but to show that this integration of scales, methods and objects of analysis is a necessary condition for understanding contemporary transformations in port and maritime systems.

Résumé

Cette thèse a pour objectif d'améliorer la compréhension de la structure et de l'impact du commerce maritime. Plus précisément, elle étudie l'impact des conflits sur la structure du commerce maritime mondial, l'évolution de la structure des flux maritimes internationaux sur longue période, ainsi que l'impact de l'activité portuaire sur le développement économique local.

Le premier chapitre propose une revue systématique de la littérature récente sur les réseaux maritimes (*shipping networks*). À l'aide d'algorithmes de *natural language processing*, nous identifions les principales tendances du champ depuis 2007 et dessinons plusieurs perspectives de recherche pour le futur. La suite de la thèse vise à combler certaines des lacunes identifiées dans ce premier chapitre.

Dans le deuxième chapitre, nous étudions l'évolution des réseaux maritimes conteneurisés depuis les années 1970. Notre objectif est double : proposer une étude globale de la conteneurisation depuis ses premières années d'internationalisation et évaluer les changements structurels associés à des arbitrages microéconomiques, notamment les stratégies d'alliance et les développements portuaires. Nous montrons ainsi une bascule multipolaire et asiatique au niveau macro, ainsi qu'une transformation de la structure des liens unissant les ports au niveau micro.

Le troisième chapitre modélise et évalue les conséquences de la guerre Russie-Ukraine sur le réseau maritime ukrainien. À partir d'une approche multiniveau, menée à l'échelle des ports, des flux et des pays, nous mettons en évidence les conséquences d'un conflit de haute intensité sur le commerce maritime et sur la capacité d'un système de transport à se montrer résilient et adaptatif quelques mois après le choc initial. Cette étude est l'une des premières à évaluer quantitativement les conséquences d'un conflit armé sur la structure et le niveau d'activité d'un réseau maritime.

Le quatrième et dernier chapitre examine le lien entre activité portuaire et développement économique local. Il s'intéresse à la manière dont les ports, en tant qu'infrastructures de connexion aux marchés internationaux, peuvent influencer la croissance, l'emploi et les dynamiques territoriales. Pour traiter les problèmes d'endogénéité associés à cette relation, nous construisons une variable instrumentale historique. Nous étudions

également les effets de débordement de l'activité maritime dans l'hinterland. Nos résultats montrent qu'il demeure difficile d'évaluer précisément l'impact local du commerce maritime, même en utilisant des méthodes économétriques robustes. Enfin, nous discutons les perspectives de recherche ouvertes par l'évaluation des impacts locaux de l'activité portuaire et maritime.

L'approche et les résultats proposés dans cette thèse visent ainsi à développer des liens entre des thématiques et des champs de recherche encore trop peu connectés. Les enjeux locaux de l'activité portuaire sont étudiés à la lumière des transformations globales et de long terme du commerce maritime, tandis que les méthodes d'économétrie causale et d'analyse de réseaux sont intégrées dans un cadre analytique unifié. L'ambition de cette thèse n'est donc pas seulement de défendre une approche interdisciplinaire du commerce maritime, mais de montrer que cette articulation entre échelles, méthodes et objets d'analyse constitue une condition nécessaire pour comprendre les mutations contemporaines des systèmes portuaires et maritimes.

Contents

Acknowledgements	6
Remerciements	9
Abstract	12
Résumé	15
 General Introduction	 29
 Introduction Générale	 38
 CHAPTER 1 The Blue Connection	 49
 1 The Legacy of Pioneering Studies (1968-2007)	 53
 2 Corpus and Quantitative Methodology	 54
2.1 Size evolution	54
2.2 Disciplinary Background	55
2.3 Structural Topic Modeling	58
2.4 Selecting the Number of Topics	59
 3 Model Estimation	 61
3.1 Words and Topics	61
3.2 Covariates and Topic Proportion	63
 4 Detailed Discussion of the Topics	 66
4.1 Liner Shipping Connectivity and Trade	66
4.2 Hubs, Port Centrality and Competition	68
4.3 Vulnerability and robustness to disruptions	70
4.4 Communities and spatial structure	74
 5 Discussion: Missing Links?	 75
5.1 Environmental impacts	76
5.2 Socio-economic development	76
5.3 Shipping alliances	77
5.4 Network-analytical methods	78
 A Co-authorship Networks	 87

B	Topic Selection and Additional Estimations	89
B.1	The Metrics for Topic Selection	89
B.2	A Six-Topics Partition	90
B.3	Five and Ten Topics Partition – All Metrics	94
C	Corpus of Selected Shipping Network Studies, 2007-2025	98
CHAPTER 2	The World in a Box	125
1	Analysis of the Global Network Structure	127
1.1	Data and Methodology for Dynamic Analysis	127
1.1.1	Reconstructing the Dynamic Containership Network	127
1.1.2	Topological Indices of the GCSN in the Literature	130
1.2	Connectivity Evolution of the GCSN, 1977-2024	131
1.2.1	The Rise of Containers in Global Trade	131
1.2.2	Network Metrics	134
2	Hub Identification and Nodal Regions	139
A	Network metrics: definitions and computation	157
A.1	Unweighted metrics (Figure 4)	157
A.2	Weighted metrics (Figure 5)	158
A.3	Additional metrics (Figures 6 and 7)	158
CHAPTER 3	Shipping Trade and Geopolitical Turmoil	161
1	Historical Background and Geopolitical Context	164
2	Related Literature: Shipping Networks and Vulnerability	168
3	Data and Empirical Approach	175
3.1	<i>Lloyd's List</i> Data	175
3.2	A Multilevel 'Network' Strategy	175
3.3	A Grid Approach to Model Vessel Flows	176
4	Results	179
4.1	Global Network Topology and Hierarchy	179
4.2	Evolution of International Outflows at Country Level	192

4.3	Evolution of International Flows at Port Level	198
5	Discussion and conclusion	202
A	Degree centralities	214
B	Construction of the Ukrainian Maritime Network	225
C	Degree Distribution for Each Type of Vessels	226
C.1	Liquid Bulks	226
C.2	Solid Bulks	227
C.3	Containers	228
C.4	Passengers and Vehicles	229
D	Additional Metrics	230
D.1	Network Metrics for The Containers Network	230
D.2	Network Metrics for Solid Bulks	231
D.3	Network Metrics for General Cargo	232
D.4	Network Metrics for Liquid Bulks	233
D.5	Network Metrics for Passengers and Vehicles	234
D.6	Density in the Ukrainian - Foreign Ports Network	235
E	Additional Results on Network Hierarchy	236
E.1	Gini Coefficient	236
E.2	Power-law fitting diagnostics	237
F	International Flows of Ukrainian Ports	239
G	Additional maps on the connections of Ukrainian ports	242
H	Mathematical Details on Metrics	246
H.1	Distance and Diameter	246
H.2	Triangles, Triplets and Clustering Coefficient	246
CHAPTER 4	Wealth Comes from the Seas	249
1	Related Literature	252
1.1	Ports, Shipping and Spatial Structure: Theoretical Foundations	252
1.2	Empirical Evidences of the Local Impacts of Port Activity	254

1.3	Maritime Flows as Complex Systems	255
2	Data & Descriptive Statistics	256
2.1	Constructing the Good-specific Regional Port Activity	257
2.2	Regional Data	259
2.2.1	Employment	259
2.2.2	Population	259
2.2.3	Socio-economic Variables	260
2.2.4	Accessibility	260
2.3	Dynamics of the European Port System	261
2.4	Network Structure of European Maritime Trade	266
2.4.1	Constructing the Trade Network	266
2.4.2	Global and Local Dynamics	267
3	Identification Strategy	273
3.1	IV Strategy	273
3.1.1	Motivation	273
3.1.2	Methodology	275
3.1.3	Validity and Exclusion	277
3.2	Spillovers	278
4	Results	279
4.1	The Impact of Shipping in Port and Coastal Regions	279
4.1.1	Coastal Areas - OLS Estimates	280
4.1.2	Coastal Areas - IV estimates	284
4.2	Discussion on the Estimates	286
5	Discussion & Conclusion	287
A	Network Structure	294
B	Robustness Checks	295
B.1	First-stage regressions for the total DWT	295
B.2	Alternative Clustering of Standard Errors	298
B.3	Results for Container Shipping	301
B.4	Results for General Cargo Shipping	306
B.5	Port areas	309

B.6 Shipping and Spillovers	311
General Conclusion	315

List of Figures

General Introduction

Introduction Générale

CHAPTER 1 The Blue Connection

1	Evolution of the number of articles over time (2007 - 2025)	55
2	Top-10 most probable words for each topic	63
A.1	Co-authorship network (2007 – 2017)	87
A.2	Co-authorship network (2018 – 2025)	88
B.1	Diagnoses for 5-15 topics	89
B.2	Top-10 most probable words in a six-topics partition	93
B.3	Top-10 most probable words in a 10 topics partition	97

CHAPTER 2 The World in a Box

1	Space-L network topology	128
2	Space-P network topology	129
3	Global metrics for containerised trade	132
4	First set of metrics for the unweighted space-P network.	135
5	First set of metrics for the weighted space-P network.	136
6	Additional set of metrics for the unweighted space-P network.	137
7	Additional set of metrics for the weighted space-P network.	138
8	Illustration of single linkage analysis (SLA) and nodal regions.	140
9	Nodal regions in the weighted space-P GCSN using the SLA algorithm (1977 - 1984).	141
10	Nodal regions in the weighted space-P GCSN using the SLA algorithm (1985 - 1992).	143
11	Nodal regions in the weighted space-P GCSN using the SLA algorithm (1993 - 2000).	145
12	Nodal regions in the weighted space-P GCSN using the SLA algorithm (2001 - 2008).	147

13	Nodal regions in the weighted space-P GCSN using the SLA algorithm (2009 - 2016).	149
14	Nodal regions in the weighted space-P GCSN using the SLA algorithm (2017 - 2024).	151
 CHAPTER 3 Shipping Trade and Geopolitical Turmoil		
1	Ports in the Black Sea	165
2	The grid mapping vessel routes in the ocean	176
3	Global Ukrainian maritime flows following the grid.	177
4	Ukrainian maritime connections in Europe and the Mediterranean.	178
5	Ukrainian maritime connections weighting ports by tonnage.	178
6	Evolution of the network for each type of vessel.	179
7	Number of edges and vertices in the global Ukrainian network, starting in 2010.	181
8	Evolution of the network metrics for all the vessels.	182
9	Density in the Ukrainian network	183
10	Degree distribution for the Total Network	186
11	Evolution of the γ parameter for each type of vessel, 2010 – 2023.	188
12	Evolution of the σ coefficient of the Ukrainian Network, 2010-2023.	190
13	Evolution of the ω coefficient of the Ukrainian Network, 2010-2024.	191
14	Evolution of total cargo capacity (DWT) of dry bulk ships moving to foreign countries (first 20 countries).	194
15	Evolution of total cargo capacity (DWT) of general cargo ships moving to foreign countries. (First 20 countries)	196
16	Solid trade in 2022	200
17	Solid trade in 2023	201
18	Solid trade in 2024	202
C.1	Degree distribution of liquid bulks	226
C.2	Degree distribution of solid bulks	227
C.3	Degree distribution of containers	228
C.4	Degree distribution of passengers and vehicles	229
D.1	Topology of the container network of Ukrainian ports	230
D.2	Evolution of the network metrics for solid bulk.	231
D.3	Evolution of the network metrics for general cargo	232
D.4	Evolution of the network metrics for liquid bulks.	233

D.5	Evolution of the network for each type of vessel.	234
D.6	Evolution of the density for the Ukrainian-foreign ports network.	235
E.1	Lorenz Curve for Each Year.	236
E.2	Power-law and lognormal fits to the empirical CCDF of the DWT degree distribution.	238
F.1	Evolution of total cargo capacity (DWT) of containerhips moving to foreign countries. (First 20 countries)	239
F.2	Evolution of total cargo capacity (DWT) of liquid bulk ships moving to foreign countries. (First 20 countries)	240
G.1	Evolution of total dwt (2010-2024)	242
G.2	Evolution of solid trade (2010-2024)	243
G.3	Evolution of liquid trade (2010-2024)	244
G.4	Evolution of container trade (2010-2024)	245

CHAPTER 4 Wealth Comes from the Seas

1	From port-to-port ship movements to regional (NUTS) shipping flows.	258
2	Evolution of the DWT for bulk, containers, passengers and total (2000-2024)	261
3	Evolution of the traffic share for containers, liquid bulk, solid bulk, and passengers (2000-2024)	262
4	Top 3 - Total Regional Traffic	263
5	Top 3 - Containerised Regional Traffic.	264
6	Port regions in Europe	265
7	Constructing the European regional maritime trade network from raw vessel movements.	267
8	Network Density	268
9	Network Transitivity	269
10	Evolution of the degree of the five busiest port regions in 2024	270
11	Network Composition - Trade with non-European regions	271
12	Network Composition - intra-Europe trade 2020-2024	272
13	Port in Europe - 1880-1900	276
A.1	Network Composition - intra-Europe Trade per Period	294

General Conclusion

List of Tables

General Introduction

Introduction Générale

CHAPTER 1 The Blue Connection

1	Number of Articles by Journal and Period	56
2	Classification of Articles by Journal Background (2007–2025)	57
3	Classification of Articles by Geographic Area (2007–2025)	58
4	Top Words (Highest Probability) for Each STM Topic (K=5)	62
5	Beta Regression Results for Topics 1–5	65
B.1	Top Words from the STM model with 6 topics	90
B.2	Beta Regression Results for Topics 1–5 (Three-period specification) .	91
B.3	Beta Regression Results for Topics 1–6	92
B.4	Top Words from the STM model with 5 topics	94
B.5	Top Words from the STM model with 10 topics	95
B.6	Beta regression results for topic proportions (Topics 1–10)	96

CHAPTER 2 The World in a Box

1	Phases of containerisation & network effects	133
2	Major containerised trade lanes	134

CHAPTER 3 Shipping Trade and Geopolitical Turmoil

1	Research Overview of Container, Oil, and General Cargo Networks . .	170
2	Network properties	182
3	Inflow and Outflow of Various Cargo Types	192
A.1	Degree centralities (normalised) for the global network at port level (top 10 ports)	214
A.2	Degree centralities of liquid bulk by port	216
A.3	Degree centralities of solid bulk by port	219

A.4	Degree centralities of containers by port	222
E.1	Power-law fitting diagnostics for the total DWT network	237

CHAPTER 4 Wealth Comes from the Seas

1	Estimates — log-log baseline regressions without controls (paper setup + country-year FE variants)	280
2	Estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2)	282
3	Estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2, total DWT; <i>ac reg</i> + Conley)	283
4	IV (2SLS) estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2)	285
B.1	First-stage estimates — log-log regressions of total DWT on the excluded instrument with stepwise controls (coastal NUTS-2)	297
B.2	Estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2, total DWT; <i>ac reg</i> + Conley), common sample	299
B.3	First-stage (Conley) estimates — regressions of $\ln(\text{DWT total})$ on the excluded instrument with stepwise controls (coastal NUTS-2)	300
B.4	Estimates — log-log baseline regressions without controls (container DWT + country-year FE variants)	301
B.5	Estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2, container DWT)	302
B.6	Estimates — log-log regressions of employment with stepwise controls (persistent ports, container DWT)	303
B.7	First-stage regressions — instrument relevance for container flows (coastal NUTS-2)	304
B.8	IV (2SLS) estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2), container flows	305
B.9	Estimates — log-log baseline regressions without controls (general cargo DWT + country-year FE variants)	306
B.10	Estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2, general cargo DWT)	307
B.11	Estimates — log-log regressions of employment with stepwise controls (persistent ports, general cargo DWT)	308
B.12	Estimates — log-log baseline regressions without controls	309

B.13 Estimates — log-log regressions of employment with stepwise controls (persistent-port NUTS-2)	310
B.14 Estimates — log-log regressions of employment on spillovers (no con- trols)	312
B.15 Estimates — log-log regressions of employment on spillovers with con- trols	313

General Conclusion

General Introduction

Technical and organisational innovations associated with maritime transport were one of the driving forces behind the various waves of globalisation, and more broadly behind the mobility of the human species. From the Peopling of Oceania to the Great Discoveries of the 15th and 16th centuries, through the expansion of the Roman Empire in the Mediterranean and the prosperity of the republics of Genoa and Venice, the ability of humans to navigate, transport goods and develop connectivity systems were decisive factors in the construction of societies and civilisations. The two industrial revolutions accentuated this phenomenon by enabling the transition from sail to steam, which was fully completed in the 1920s and 1930s ([Bunel et al. 2017](#); [Ducruet and Itoh 2022](#))¹ and paving the way for longer voyages and larger, faster ships².

Despite the importance of maritime transport in ancient, medieval and modern economic history, research on shipping and port systems has remained relatively marginal outside of specialised journals in the field of maritime studies or, more recently, operational research journals. Slowly, over the last twenty years, maritime transport has become a more widely discussed subject of study in quantitative geography, applied economics and history. Methodological advances³ have made quantitative studies of maritime trade more relevant, as they have been accompanied by increased computing power, improved access to data⁴ and conceptual renewal⁵.

¹It should also be noted that numerous case studies have been published on the transition from sail to steam in local port economies: [Francaviglia \(1998\)](#) on Texas, [Loockx \(2022\)](#) on the maritime labour market in Antwerp, [Kapakakis and Delis \(2023\)](#) on Greek sailors, [Kaukiainen \(1980\)](#) on Finnish shipping between 1850 and 1914, [Cohn \(2005\)](#) on American immigration in the early 20th century.

²For additional details on the link between the transition from sail to steam and economic development, see [Pascali \(2017\)](#).

³We will return to this in depth in each chapter, but as a general remark, let us recall these methodological innovations: (i) development of simulation, partitioning and network measurement methods, (ii) improvement in the construction of geographic information systems (GIS) enabling the reconstruction of ship routes, (iii) progress in causal econometrics (instrumental variables, difference-in-differences, etc.) and international econometrics via gravity models.

⁴The widespread use of Automatic Identification System (AIS) data has led to a significant increase in the production of quantitative studies on maritime flows. See [Yang et al. \(2019\)](#) for a review of the use of AIS data in maritime research.

⁵Without being exhaustive, the theoretical contributions of the new economic geography ([Fujita and](#)

In this general introduction, we will briefly discuss some of the major dynamics of maritime trade and port systems, while linking the underlying concepts to the approaches, proposals and results of our four chapters.

Maritime Trade Throughout History

Maritime logistics is an ancient business, with traces dating back to antiquity. Maritime operators in the Mediterranean, between Rome, Alexandria, and Carthage, were already seeking to optimize maritime routes and modes of transport for goods. [DE GRAAUW \(2017\)](#) shows that the use of amphorae on ancient ships, and more broadly the organisation of shipping, can be compared to modern logistics processes. Between the end of the Middle Ages and the industrial revolutions, the prosperity of Northern Italy greatly benefited from the successive domination of Pisa, Genoa and Venice over the Mediterranean⁶. From the 18th century onward, falling ocean freight rates expanded the geographic scope of trade, deepened economic interdependence between regions, and enabled the long-distance movement of goods at unprecedented scale. These shifts contributed substantially to real GDP growth in Europe and the United States between the 18th and early 20th centuries ([North 1958](#)).⁷ This first wave of globalisation came to an end with the First World War; a second wave began in the early 1950s and saw sustained growth in maritime trade until the late 2000s. The shocks of this second period prompted local reorganisations and temporary slowdowns rather than halting the network's expansion at the global level. Since the early 2000s, organisational and geopolitical shifts have further accelerated trade and reshaped the structure of the network, even as major crises of various kinds have produced systemic disruptions with lasting effects on maritime trade. The following subsections introduce these phenomena in turn.

Mori [1996](#)), both in economics and geography, but also of spatial economics (see, for example, [Allen and Arkolakis \(2014\)](#)) have helped to operationalise technical and methodological advances.

⁶On Venice see [Lane \(1973\)](#) and [Fournier \(2015\)](#); on Genoa one can refer to [Tonizzi \(2006\)](#) and [Kirk \(2013\)](#); maritime republic of Pisa is covered in [Campopiano \(2022\)](#). [Carr \(2014\)](#) is analysing the role of Italian maritime republic during the First Crusade.

⁷This expansion of long-distance maritime trade was inseparable from the transatlantic slave trade and colonial systems of extraction, whose contribution to European growth and to the resulting global divergence is documented by a substantial economic-history literature ([Acemoglu, Johnson, and Robinson 2005](#); [Allen 2009](#); [Findlay and O'rourke 2009](#); [Heblich, Redding, and Voth 2022](#)), alongside the long-run costs imposed on extracting regions ([Nunn 2008](#)). The present discussion focuses on the technological and logistical dimensions of maritime transport, which should not be read as autonomous from that broader historical approach.

The Container Revolution

In the 1950s, the reconstruction of Europe, the development of global economic cooperation under the aegis of new governance institutions, and the spread of technical progress necessitated an intensification of maritime transport. At the end of the 1950s, containerisation first emerged as a solution to intermodal problems in freight transport. [Rodrigue \(2020\)](#) points out that Malcolm McLean's initial objective, when he placed 58 containers on the Ideal-X on 26 April 1956, was to create an integrated transport system in the United States in which maritime transport would complement road and rail transport.

During the 1960s, the main obstacle to the development of containers was the standardisation of norms and procedures. Containerisation thus remained confined to proprietary solutions that were difficult to interoperate between companies and modes of transport. The introduction of harmonised container standards in the 1960s, coupled with the intensification of transatlantic trade, facilitated the adoption of containers. The standardisation of loading units, intermodal integration and the establishment of regular services significantly reduced handling costs and port call times, while paving the way for increasing economies of scale in line operations. The containerisation of ports also significantly changed port activities by promoting automation, transshipment and the development of large areas dedicated to container storage.

[Guerrero and Rodrigue \(2014\)](#) and [Rodrigue \(2020\)](#) show that the adoption of containers follows a 'standard' diffusion curve in four stages: (i) adoption, from the 1960s to the early 1990s, (ii) acceleration until 2001, (iii) peak growth from 2001 to 2008, and (iv) maturity since 2009. From the 1970s onwards, the economies of scale offered by containerisation encouraged many operators to adopt it, and container terminals were built. During the 1990s, containers were the main means of international trade, with their spread accelerated by newly industrialised countries such as China. The post-crisis phase of 2008–2009 saw the adoption of containers reach maturity, with containerised trade stabilising worldwide. In Chapter 2, we revisit all of these concepts, showing how the emergence of China and regional players such as Brazil, South Korea and the Emirates is changing hierarchies and helping to shape the container diffusion curve.

Emergence of China, Vulnerability of Shipping Networks, and Organisational Changes

On 11 December 2001, China became a member of the WTO, thereby facilitating trade with Europe and the United States. It was also in the early 2000s that Chinese maritime

activity began to grow significantly, with major investments to modernise existing ports and build new ones, fuelled by the regulatory easing made possible by China's entry into the WTO. We discuss this issue in detail in Chapter 2, based on a study of global containerised maritime networks. The results on the global network and port hierarchy show how Asia, and more specifically China, became the heart of the containerised maritime network from the early 2000s onwards.

During the previous decades, there was steady growth in maritime trade, densification of networks and relative stability in the global network. Despite events that had significant consequences for political stability and global trade, such as the oil shocks of 1973 and 1979 and the fall of the USSR in 1991, the structuring of maritime networks was not slowed down (Zreik et al. 2017). The authors show that the fall of the USSR had no systemic effect on the global maritime network. The effect was regionalised (Baltic Sea, Black Sea) and limited in time (1991-1993). Vigarié (1995) suggests that socialist economies generally tended to develop continental trade relations, neglecting maritime development for a long time, although the USSR began to strengthen its maritime trade system from the late 1960s onwards (Vigarié 1995; Thorez 1998; Zreik et al. 2017). The first quarter of the 21st century offers a different reality in this regard. Several crises have already had systemic repercussions on global maritime trade: the 2008-2009 crisis⁸, the global Covid-19 pandemic⁹, the conflict in the Red Sea and Houthi attacks in the area, forcing ships to circumnavigate Africa to reach Europe, and lastly the blockade of the Strait of Hormuz.

The last quarter century has also seen major organisational changes. Following a profound change in the way goods are loaded via containers, it is the size of ships and the organisation of ports that have changed most significantly. The optimal size of ships is an important issue in maritime logistics¹⁰ as it involves a trade-off between efficiency at sea¹¹ and loss of efficiency on land¹² (Jansson and Shneerson 1982; Cullinane and Khanna 1999; Notteboom, Pallis, and Rodrigue 2022). By moving from 4,500 TEU to 25,000 TEU ships, the size of ships has increased approximately fivefold in 25 years. This

⁸See Ducruet (2023) for a specific study on the resilience of maritime networks in the case of the 2008-2009 financial crisis, and Ducruet, Cocuzza, and Ignaccolo (2023) for a comparative study of the resilience of maritime networks in the cases of the 2008-2009 crisis and Covid-19.

⁹Numerous articles focus on Covid-19, which has become one of the main topics that has shifted the study of shipping networks towards vulnerability and resilience, as we show in the first chapter of the thesis.

¹⁰There is a fairly extensive literature on the subject since the seminal paper by Jansson and Shneerson (1982). For recent references, see Ros Chaos et al. (2021) and Ge et al. (2021).

¹¹Quite intuitively: a larger ship allows for economies of scale by carrying more containers.

¹²A larger ship takes longer to unload, with greater constraints that can cause diseconomies of scale.

has had an impact on ports (larger quays have had to be built), on canals (canals have had to be widened to allow them to pass through) and on the organisation of maritime logistics (as the number of ports that can accommodate them is limited, this reinforces the hub-and-spoke system and the regionalisation of trade outside the main routes). In Chapters 2 and 4, we will see how these changes in port activity are reflected in the structure of maritime networks, city-port interaction, and local economic development.

Organisation of the Thesis

First Chapter. The first chapter of the thesis presents a systematic and quantitative literature review, notably using Natural Language Processing algorithms, of research on shipping networks. We note that no systematic literature review existed on this subfield of quantitative maritime studies. This chapter offers a long-term critical discussion of the field of shipping networks, based on pioneering studies published between the 1950s and 1970s, which represent a limited but conceptually and methodologically important corpus. On the conceptual side, this work introduces the notion of port systems, but also discussions on connectivity and hierarchy. This ties in with the methodological aspect: several articles in quantitative geography use concepts from graph theory to study maritime flows in limited areas and time frames. After several decades of incremental progress in the field of shipping networks, we show that a major shift took place in the early 2000s. Based on the corpus we are building from 2007 to 2024, we propose a quantitative approach coupled with critical discussion. This chapter thus opens the thesis with a twofold contribution to the literature: by identifying the major trends in research on shipping networks, and by offering a critical discussion identifying less-covered topics and prospects for future research.

Second Chapter. In this chapter, we continue with the ‘general’ aim of the first chapter. Here, we apply it to containerised networks through a quantitative study of the evolution of flows and hierarchies in global containerised networks. This chapter contributes to the literature in three ways. First, we reconstruct containerised flows from 1977 to 2024, thus providing an overview of almost the entire period of the container’s existence in global trade. Second, we propose a multilevel methodological framework for analysing containerised trade over a long period: reconstruction of the network via space-P topology, global network measures, local network measures, reduction of the network to the main links to study hierarchies. Thirdly, we discuss the results of these various quantitative analyses in relation to different concepts in port geography and economic

geography: the phenomenon of spatial agglomeration of trade links, the development of port systems, the evolution of hierarchies, and the geo-economic structuring of trade routes¹³. Thus, we build on the discussion in the first chapter on key contributions and research perspectives in the field of shipping networks by offering an in-depth analysis of the global containerised system.

The third and fourth chapters return to more localised issues, in which we can apply the generalisations from the first two chapters while exploring the subject in greater depth.

Third Chapter. In the third chapter, we examine the local impact of a conflict on maritime networks and its global spread. To study this issue, we focus on the impact of the war in Ukraine on Ukraine's maritime networks with the rest of the world. We begin by reviewing recent literature on the vulnerability of maritime networks, showing that the issue of conflict is rarely addressed, especially when considering the recent impact of conflicts on global maritime networks. We then propose a three-step approach: (i) reconstruction of the maritime routes of ships passing through a Ukrainian port using a global grid in a GIS, (ii) reconstruction of the shipping networks of Ukrainian ports and analysis of the dynamic evolution of their structures, (iii) analysis of bilateral trade in Ukrainian ports. Our analysis highlights several key findings: (i) the invasion of Crimea had a limited temporal and geographical impact, (ii) the large-scale invasion of Ukraine in 2022 had a major impact on maritime networks, reducing some trade to zero, (iii) maritime networks reorganised and quickly demonstrated effective resilience, notably by switching to the Dnieper River and redistributing traffic to less affected ports. Despite the highly specific nature of each conflict, our methodological approach and empirical conclusions have significant generalisable value and pave the way for a comparative study of conflicts in different areas and at different times to test the existence of such patterns.

Fourth Chapter. The last chapter addresses a long-standing question in regional and urban economics: what is the impact of maritime transport on local economic development? As we show in the literature review in this chapter, this is a question that has been discussed quite extensively in recent years. Most studies yield mixed results, showing that even when controlling for endogeneity in the relationship between employment

¹³This covers two sub-concepts: (i) the persistence of old ties (e.g. colonial ties) and (ii) the development of new hierarchies through strategies to expand economic influence (e.g. Chinese investment in African port systems)

and maritime trade, it remains difficult to draw conclusions about the impact at the local level. In this chapter, we pursue two objectives: (i) to analyse the evolution of the structure of maritime trade in European regions and (ii) to estimate the impact of maritime trade on local economic development. To contribute to the second objective beyond existing publications, we propose a new instrument to address the problem of endogeneity in maritime trade. We use port calls between 1880 and 1900 to estimate the “port size” of European regions in the past. We then make this metric time-varying by imposing the average trend over the period 2000-2024, excluding the region under consideration. We show, in line with previous results, that it is difficult to draw conclusions about the magnitude and sign of the impact of maritime trade on local employment, or at least that this impact is broadly indistinguishable from zero. We conclude by proposing some avenues for further research to improve our understanding of the relationship between port activity and economic development.

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Introduction Générale

Les innovations techniques et organisationnelles qu'a connues le transport maritime ont été l'un des moteurs des différentes vagues de mondialisation et, plus largement, de la mobilité de l'espèce humaine. Du peuplement de l'Océanie aux « Grandes découvertes » des XVe et XVIe siècles, en passant par l'expansion de l'Empire romain en Méditerranée et la prospérité des républiques maritimes de Gênes et de Venise, la capacité des humains à naviguer, à transporter des marchandises et à développer des systèmes de connectivité a constitué un facteur décisif dans la construction des sociétés et des civilisations. Les deux révolutions industrielles ont accentué ce phénomène en permettant la transition de la navigation à voile vers la vapeur, qui a été pleinement achevée dans les années 1920 ([Bunel et al. 2017](#); [Ducruet and Itoh 2022](#))¹, ouvrant la voie à des voyages plus longs ainsi qu'à des navires plus grands et plus rapides².

Malgré l'importance du transport maritime dans l'histoire économique ancienne, médiévale et moderne, la recherche sur les systèmes maritimes et portuaires est restée relativement marginale en dehors des revues spécialisées dans le champ des études maritimes ou, plus récemment, de la recherche opérationnelle. Progressivement, durant les vingt dernières années, le transport maritime est devenu un objet d'étude plus largement discuté en géographie quantitative, en économie appliquée et en histoire. Les avancées méthodologiques³ ont rendu les études quantitatives du commerce maritime plus pertinentes, dans la mesure où elles se sont accompagnées d'une augmentation

¹Il convient également de noter que de nombreuses études de cas ont été publiées sur la transition de la voile à la vapeur dans les économies portuaires locales : [Francaviglia \(1998\)](#) sur le Texas, [Looockx \(2022\)](#) sur le marché du travail maritime à Anvers, [Kapokakis and Delis \(2023\)](#) sur les marins grecs, [Kaukiainen \(1980\)](#) sur la navigation finlandaise entre 1850 et 1914, [Cohn \(2005\)](#) sur l'immigration américaine au début du XXe siècle.

²Pour plus de détails sur le lien entre la transition de la voile à la vapeur et le développement économique, voir [Pascali \(2017\)](#).

³Nous y reviendrons en profondeur dans chaque chapitre, mais à titre de remarque générale, rappelons ces innovations méthodologiques : (i) le développement des méthodes de simulation, de partitionnement et de mesure de réseaux, (ii) l'amélioration de la construction des systèmes d'information géographique (SIG) permettant la reconstruction des routes des navires, (iii) les progrès en économétrie causale (variables instrumentales, différences-en-différences, etc.) et en économétrie internationale via les modèles de gravité.

de la puissance de calcul, d'un meilleur accès aux données⁴ et d'un renouvellement conceptuel⁵.

Dans cette introduction générale, nous discutons brièvement des dynamiques majeures qui caractérisent le commerce maritime et les systèmes portuaires, tout en reliant les concepts sous-jacents aux approches, propositions et résultats de nos quatre chapitres.

Le commerce maritime dans l'histoire

La logistique maritime est une activité ancienne, dont les traces remontent à l'Antiquité. Les opérateurs maritimes méditerranéens, entre Rome, Alexandrie et Carthage, cherchaient déjà à optimiser les routes maritimes et les modes de transport des marchandises. [DE GRAAUW \(2017\)](#) montre que l'usage des amphores sur les navires antiques, et plus largement l'organisation de la navigation, peuvent être comparés à la logistique moderne. Entre la fin du Moyen Âge et les révolutions industrielles, la prospérité de l'Italie du Nord a largement bénéficié de la domination successive de Pise, Gênes et Venise sur la Méditerranée⁶.

Dès le XVIIIe siècle, la baisse des taux de fret maritime a élargi le champ géographique des échanges, approfondi l'interdépendance économique entre régions et permis le transport de marchandises sur de longues distances à une échelle sans précédent. Ces évolutions ont contribué de manière substantielle à la croissance du PIB réel en Europe et aux États-Unis entre le XVIIIe et le début du XXe siècle ([North 1958](#))⁷. Cette première vague de mondialisation s'est achevée avec la Première Guerre mondiale ;

⁴La généralisation de l'usage des données du Système d'Identification Automatique (AIS) a entraîné une augmentation significative de la production d'études quantitatives sur les flux maritimes. Voir [Yang et al. \(2019\)](#) pour une revue de l'utilisation des données AIS dans la recherche maritime.

⁵Sans prétendre à l'exhaustivité, les contributions théoriques de la nouvelle économie géographique ([Fujita and Mori 1996](#)), à la fois en économie et en géographie, mais aussi de l'économie spatiale (voir par exemple [Allen and Arkolakis \(2014\)](#)) ont contribué à l'opérationnalisation des avancées techniques et méthodologiques.

⁶Sur Venise, voir [Lane \(1973\)](#) et [Fournier \(2015\)](#) ; sur Gênes, on peut se référer à [Tonizzi \(2006\)](#) et [Kirk \(2013\)](#) ; la république maritime de Pise est traitée dans [Campopiano \(2022\)](#). [Carr \(2014\)](#) analyse le rôle des républiques maritimes italiennes durant la Première Croisade.

⁷L'essor du commerce maritime au long cours est indissociable de la traite transatlantique et des systèmes coloniaux d'extraction, dont la contribution à la croissance européenne et à la divergence économique mondiale qui en a résulté est documentée par une abondante littérature en histoire économique ([Acemoglu, Johnson, and Robinson 2005](#); [Allen 2009](#); [Findlay and O'rourke 2009](#); [Heblich, Redding, and Voth 2022](#)), de même que les coûts de long terme imposés aux régions soumises à cette extraction ([Nunn 2008](#)). Le présent travail porte sur les dimensions technologiques et logistiques du transport maritime, qui ne sauraient être considérées comme indépendantes de cette question historique plus large.

une seconde vague s'est amorcée au début des années 1950 et s'est traduite par une croissance soutenue du commerce maritime jusqu'à la fin des années 2000. Les chocs de cette seconde période ont entraîné des réorganisations locales et des ralentissements temporaires plutôt qu'un arrêt de l'expansion du réseau à l'échelle mondiale. Depuis le début des années 2000, des évolutions organisationnelles et géopolitiques ont encore accéléré les échanges et redessiné la structure du réseau, tandis que des crises majeures de natures diverses ont provoqué des perturbations systémiques aux effets durables sur le commerce maritime. Les sous-sections suivantes présentent successivement ces phénomènes.

La révolution du conteneur

Dans les années 1950, la reconstruction de l'Europe, le développement de la coopération économique mondiale sous l'égide de nouvelles institutions de gouvernance et la diffusion du progrès technique ont rendu nécessaire une intensification du transport maritime. À la fin des années 1950, la conteneurisation apparaît d'abord comme une solution aux problèmes d'intermodalité dans le transport de marchandises. [Rodrigue \(2020\)](#) souligne que l'objectif initial de Malcolm McLean, lorsqu'il installa 58 conteneurs sur l'Ideal-X le 26 avril 1956, était de créer, aux États-Unis, un système de transport intégré dans lequel le maritime viendrait compléter le transport routier et ferroviaire.

Au cours des années 1960, le principal obstacle au développement du conteneur tenait dans la standardisation des normes et procédures. La conteneurisation est ainsi restée confinée à des solutions propriétaires, difficilement interoperables entre entreprises et entre modes de transport. L'introduction de normes harmonisées pour les conteneurs dans les années 1960, couplée à l'intensification du commerce transatlantique, a facilité leur adoption. La standardisation des unités de chargement, l'intégration intermodale et la mise en place de services réguliers ont fortement réduit les coûts de manutention et les temps d'escale portuaire, tout en ouvrant la voie à des économies d'échelle croissantes dans les services de ligne. La conteneurisation des ports a significativement transformé leur activité en favorisant l'automatisation, le développement du transbordement et de vastes espaces dédiés au stockage des conteneurs.

[Guerrero and Rodrigue \(2014\)](#) et [Rodrigue \(2020\)](#) montrent que l'adoption des conteneurs suit une courbe de diffusion « standard » en quatre étapes : (i) l'adoption, des années 1960 au début des années 1990 ; (ii) l'accélération jusqu'en 2001 ; (iii) le pic de croissance de 2001 à 2008 ; (iv) et la maturité depuis 2009. À partir des années 1970, les économies d'échelle offertes par la conteneurisation ont encouragé de nombreux

opérateurs à l'adopter et des terminaux à conteneurs ont été construits. Au cours des années 1990, les conteneurs sont devenus le principal support du commerce international, leur diffusion étant accélérée par les nouveaux pays industrialisés, au premier rang desquels la Chine. La phase postérieure à la crise de 2008-2009 a vu l'adoption du conteneur atteindre sa maturité, avec une stabilisation du commerce conteneurisé à l'échelle mondiale. Dans le chapitre 2, nous revenons sur l'ensemble de ces concepts, en montrant comment l'émergence de la Chine et d'acteurs régionaux tels que le Brésil, la Corée du Sud et les Émirats arabes unis modifie les hiérarchies et contribue à dessiner la courbe de diffusion du conteneur.

Émergence de la Chine, vulnérabilité des réseaux maritimes et changements organisationnels

Le 11 décembre 2001, la Chine est devenue membre de l'OMC, facilitant ainsi les échanges avec l'Europe et les États-Unis. C'est également au début des années 2000 que l'activité maritime chinoise a commencé à croître de manière significative, avec d'importants investissements destinés à moderniser les ports existants et à en construire de nouveaux, alimentés par l'assouplissement réglementaire rendu possible par l'entrée de la Chine à l'OMC. Nous discutons cette question en détail dans le chapitre 2, à partir d'une étude des réseaux maritimes conteneurisés mondiaux. Les résultats portant sur le réseau mondial et la hiérarchie portuaire montrent comment l'Asie, et plus spécifiquement la Chine, est devenue le cœur du réseau maritime conteneurisé à partir du début des années 2000.

Au cours des décennies précédentes, le commerce maritime a connu une croissance régulière, une densification des réseaux et une relative stabilité de la structure mondiale. Malgré des événements ayant eu des conséquences importantes sur la stabilité politique et le commerce mondial, tels que les chocs pétroliers de 1973 et 1979 et la chute de l'URSS en 1991, la structuration des réseaux maritimes n'a pas été ralentie (Zreik et al. 2017). Les auteurs montrent que la chute de l'URSS n'a pas eu d'effet systémique sur le réseau maritime mondial. Son effet a été régionalisé, autour de la mer Baltique et de la mer Noire, et limité dans le temps, entre 1991 et 1993. Vigarié (1995) suggère que les économies socialistes ont généralement eu tendance à développer des relations commerciales continentales, en négligeant longtemps le développement maritime, bien que l'URSS ait commencé à renforcer son système de commerce maritime à partir de la fin des années 1960 (Vigarié 1995; Thorez 1998; Zreik et al. 2017). Le premier quart du XXI^e siècle offre, à cet égard, une réalité différente. Plusieurs crises ont déjà entraîné des

répercussions systémiques sur le commerce maritime mondial : la crise de 2008-2009⁸, la pandémie mondiale de Covid-19⁹, le conflit en mer Rouge et les attaques houthies dans la zone, qui contraignent les navires à contourner l'Afrique pour rejoindre l'Europe, et dernièrement le blocage du détroit d'Ormuz.

Le dernier quart de siècle a également été marqué par de profonds changements organisationnels. Après une transformation majeure de la manière dont les marchandises sont chargées grâce aux conteneurs, c'est surtout la taille des navires et l'organisation des ports qui ont changé de manière significative. La taille optimale des navires constitue une question importante en logistique maritime¹⁰, car elle implique un arbitrage entre l'efficacité en mer¹¹ et la perte d'efficacité à terre¹² (Jansson and Shneerson 1982; Cullinane and Khanna 1999; Notteboom, Pallis, and Rodrigue 2022). En passant de navires de 4 500 EVP à des navires de 25 000 EVP, la taille des navires a été multipliée par environ cinq en 25 ans. Cela a eu des répercussions sur les ports (il a fallu construire des quais plus grands), sur les canaux (il a fallu les élargir pour permettre leur passage) et sur l'organisation de la logistique maritime (le nombre de ports capables de les accueillir étant limité, cela renforce le système en étoile et la régionalisation des échanges en dehors des principales routes). Dans les chapitres 2 et 4, nous verrons comment ces transformations de l'activité portuaire se reflètent dans la structure des réseaux maritimes, dans l'interaction ville-port et dans le développement économique local.

Organisation de la thèse

Premier chapitre. Le premier chapitre de la thèse propose une revue systématique et quantitative de la littérature, mobilisant notamment des algorithmes de traitement automatique du langage naturel, portant sur les recherches consacrées aux réseaux maritimes. Nous avons constaté qu'aucune revue systématique de la littérature n'existait sur ce sous-champ des études maritimes. Ce chapitre propose une discussion critique

⁸Voir Ducruet (2023) pour une étude spécifique sur la résilience des réseaux maritimes dans le cas de la crise financière de 2008-2009, et Ducruet, Cocuzza, and Ignaccolo (2023) pour une étude comparative de la résilience des réseaux maritimes dans les cas de la crise de 2008-2009 et du Covid-19.

⁹De nombreux articles portent sur le Covid-19, devenu l'un des principaux sujets ayant orienté l'étude des réseaux maritimes vers les questions de vulnérabilité et de résilience, comme nous le montrons dans le premier chapitre de la thèse.

¹⁰Il existe une littérature relativement abondante sur le sujet depuis l'article fondateur de Jansson and Shneerson (1982). Pour des références récentes, voir Ros Chaos et al. (2021) et Ge et al. (2021).

¹¹De manière assez intuitive : un navire plus grand permet des économies d'échelle en transportant plus de conteneurs.

¹²Un navire plus grand met plus de temps à être déchargé, avec des contraintes plus importantes pouvant entraîner des déséconomies d'échelle.

de long terme du champ des réseaux maritimes, en s'appuyant sur les travaux pionniers publiés entre les années 1950 et 1970, qui constituent un corpus limité quantitativement mais important sur les plans conceptuel et méthodologique. Sur le plan conceptuel, ces travaux introduisent la notion de systèmes portuaires, ainsi que des discussions relatives à la connectivité et à la hiérarchie. Cela rejoint la dimension méthodologique : plusieurs articles de géographie quantitative mobilisent des concepts issus de la théorie des graphes pour étudier les flux maritimes dans des espaces et sur des périodes limités. Après plusieurs décennies de progrès incrémentaux dans le champ des réseaux maritimes, nous montrons qu'un tournant majeur s'est produit au début des années 2000. À partir du corpus que nous construisons pour la période 2007-2024, nous proposons une approche quantitative couplée à une discussion critique. Ce chapitre ouvre ainsi la thèse par une double contribution à la littérature : en identifiant les grandes tendances de la recherche sur les réseaux maritimes, et en proposant une discussion critique permettant d'identifier des thématiques moins couvertes et des perspectives pour les recherches futures.

Deuxième chapitre. Dans le deuxième chapitre, nous poursuivons l'objectif « généralisant » du premier chapitre. Nous l'appliquons ici aux réseaux conteneurisés à travers une étude quantitative de l'évolution des flux et des hiérarchies dans les réseaux conteneurisés mondiaux. Ce chapitre contribue à la littérature de trois manières. Premièrement, nous reconstruisons les flux conteneurisés de 1977 à 2024, offrant ainsi une vue d'ensemble de presque toute la période d'existence du conteneur dans le commerce mondial. Deuxièmement, nous proposons un cadre méthodologique multiniveau pour analyser le commerce conteneurisé sur longue période : reconstruction du réseau à partir d'une topologie en espace-P, mesures globales de réseau, mesures locales de réseau, réduction du réseau aux principaux liens afin d'étudier les hiérarchies. Troisièmement, Nous discutons des résultats de ces différentes analyses quantitatives au regard de plusieurs concepts de géographie portuaire et de géographie économique : le phénomène d'agglomération spatiale des liens commerciaux, le développement des systèmes portuaires, l'évolution des hiérarchies et la structuration géoéconomique des routes commerciales¹³. Nous nous appuyons ainsi sur la discussion du premier chapitre relative aux contributions clés et aux perspectives de recherche dans le champ des réseaux maritimes, en proposant une analyse approfondie du système conteneurisé

¹³Cela recouvre deux sous-concepts : (i) la persistance d'anciens liens (par exemple, les liens coloniaux) et (ii) le développement de nouvelles hiérarchies à travers des stratégies d'extension d'influence économique (par exemple, les investissements chinois dans les systèmes portuaires africains).

mondial.

Les troisième et quatrième chapitres abordent des enjeux plus localisés, auxquels nous pouvons appliquer les généralisations issues des deux premiers chapitres tout en explorant le sujet plus en profondeur.

Troisième chapitre. Dans le troisième chapitre, nous examinons l'impact local d'un conflit sur les réseaux maritimes et sa diffusion globale. Pour étudier cette question, nous nous concentrons sur l'impact de la guerre en Ukraine sur les réseaux maritimes ukrainiens avec le reste du monde. Nous débutons en passant en revue la littérature récente sur la vulnérabilité des réseaux maritimes, en montrant que la question des conflits est rarement traitée, en particulier lorsqu'il s'agit de considérer l'impact récent des conflits sur les réseaux maritimes mondiaux. Nous proposons ensuite une approche en trois étapes : (i) la reconstruction des routes maritimes des navires passant par un port ukrainien à l'aide d'une grille mondiale dans un SIG ; (ii) la reconstruction des réseaux maritimes des ports ukrainiens et l'analyse de l'évolution dynamique de leurs structures ; et (iii) l'analyse du commerce bilatéral dans les ports ukrainiens. Notre analyse met en évidence plusieurs résultats clés : (i) l'invasion de la Crimée a eu un impact temporel et géographique limité ; (ii) l'invasion à grande échelle de l'Ukraine en 2022 a eu un impact majeur sur les réseaux maritimes, réduisant certains échanges à zéro ; (iii) les réseaux maritimes se sont réorganisés et ont rapidement fait preuve d'une résilience effective, notamment par un basculement vers le Dniepr et par une redistribution du trafic vers les ports les moins affectés. Malgré le caractère très spécifique de chaque conflit, notre approche méthodologique et nos conclusions empiriques ont une valeur de généralisation significative et ouvrent la voie à une étude comparative des conflits dans différents espaces et à différentes périodes, afin de tester l'existence de tels schémas.

Quatrième chapitre. Le dernier chapitre aborde une question ancienne en économie régionale et urbaine : quel est l'impact du transport maritime sur le développement économique local ? Comme nous le montrons dans la revue de littérature de ce chapitre, cette question a été assez largement discutée ces dernières années. La plupart des études aboutissent à des résultats contrastés, montrant que, même en contrôlant l'endogénéité de la relation entre emploi et commerce maritime, il reste difficile de tirer des conclusions sur l'impact au niveau local. Dans ce chapitre, nous poursuivons deux objectifs : (i) analyser l'évolution de la structure du commerce maritime dans les régions européennes et (ii) estimer l'impact du commerce maritime sur le développement économique lo-

cal. Afin de contribuer au second objectif au-delà des publications existantes, nous proposons un nouvel instrument pour traiter le problème d'endogénéité du commerce maritime. Nous utilisons les escales portuaires entre 1880 et 1900 pour estimer la « taille portuaire » passée des régions européennes. Nous rendons ensuite cette mesure variable dans le temps en lui imposant la tendance moyenne observée sur la période 2000-2024, en excluant la région considérée. Nous montrons, conformément aux résultats précédents, qu'il est difficile de tirer des conclusions sur l'ampleur et le signe de l'impact du commerce maritime sur l'emploi local, ou du moins que cet impact est difficile à distinguer statistiquement de zéro. Nous concluons en proposant plusieurs pistes de recherche futures afin d'améliorer notre compréhension de la relation entre activité portuaire et développement économique.

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CHAPTER 1

The Blue Connection

A Systematic and Critical Review of Shipping Network Research

Abstract

Despite its early development by geographers, research on shipping networks long remained a narrow confine of academia. Since the late 2000s, however, this subfield is experiencing rapid growth, fueled by increased shipping data availability, computational power, renewed graph-theoretical methods, and a growing recognition that maritime connectivity matters for trade and socio-economic development. This research provides a bibliometric analysis of more than 300 peer-reviewed articles 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 coauthorships. Second, we use a natural language processing (NLP) approach, namely the structural topic model, to identify four main topics: trade and connectivity; hubs and centrality; vulnerability and robustness; and communities and spatial structure. Three emerging subthemes are identified, including environmental impacts, urban and regional development, and the strategies of shipping firms and alliances.

Keywords: bibliometric analysis; complex networks; graph theory; maritime transport; 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). Such a fact is familiar to human geographers, for whom ports and maritime transport are useful to "take the pulse of world trade and movement" (Ullman, 1949). Despite this importance, network analysis has been used relatively late to study maritime flows, compared to other networks, such as roads and railways (Ducruet and Beauguitte, 2014). After a long phase made of relatively scattered contributions, port and maritime research integrated graph theory, social network analysis, and the complex network framework in the late 2000s, leading to an exponential growth of studies of the kind in the 2010s and 2020s.¹ What have been the main themes and methods of shipping network research since the late 2000s? Did the integration of new analytical methods change the understanding of ports and shipping? How did shipping network research contribute to network science in general?

It is important to note that the integration of network-analytical methods in port and maritime research has been gradual.² Reviews of the fields of maritime logistics (Panayides 2006) and maritime economics (Panayides and Cullinane 2002; Heaver 2006) did not even mention the concept of 'network, like those of Woo et al. (2011), Pallis et al. (2011), Woo et al. (2013), and Notteboom et al. (2013) on port economics. Another example is the review by Talley (2013) of the literature published in the journals *Maritime Policy and Management* and *Maritime Economics and Logistics* since 2000, focusing on performance, management, and finance as the most important themes. The same applies to Shi and Li (2017) and Bai et al. (2021), focusing more on intermodal logistics, freight rates, port efficiency, economic impact, shipping finance, operations, and management (see also Xu et al. (2021), Munim and Saeed (2019), Chen et al. (2018), Wang and Peng (2023), and Dragović et al. (2024)). Other reviews on artificial intelligence (Xiao et al. (2024b)) and sustainable shipping (Zhou, Li, and Yuen (2023); Xiao et al. (2024a); Qi et al. (2024)) did not discuss the concept of shipping network. Still in economics, the same goes for reviews on shipping alliances (Ghorbani et al. (2022); Chen et al. (2022)) and port operations (Filom, Amiri, and Razavi (2022); Wang and Peng (2023)).

In geography, (Ng and Ducruet 2014; Ng et al. 2014) identified two topics related

¹We would like to draw the reader's attention to one important point: the blue references refer to the main bibliography of the article. Uncolored references refer to the corpus of articles used in this review. This corresponds to the appendix C.

²Section 2 details the constitution of the corpus.

to networks, namely ‘port connectedness’ and ‘ports’ place in shipping strategies and networks’. [Lau et al. \(2017\)](#) reviewed 294 articles published about container shipping between 1967 and 2013 based on title words, acknowledging the importance of ‘network design’ and ‘connectivity’ in the corpus. [Ducruet et al. \(2019\)](#) reviewed articles published in *Journal of Transport Geography* as well as geography and non-geography journals, highlighting the growing integration of network analysis in port and maritime research. Ducruet (2020a) proposed four arguments explaining the late emergence of shipping network analysis in geography and elsewhere: the lack of shipping data, the continental culture of scholars focusing on hinterlands, the consideration of seas and oceans as ‘empty spaces’, and the competitiveness of air transport for passenger travel since the second half of the 20th century. [Ducruet and Notteboom \(2023\)](#) found that maritime connectivity has recently become an important component of port system research.

Thus, reviews of shipping and port studies overlooked the growing application of network analysis in maritime transport research. This is rather surprising, given early discussions in economics on the absence of port centrality measures ([De Langen, Van der Lugt, and Eenhuizen 2002](#); [de Langen, Nidjam, and Van der Horst 2007](#)) and the position of ports in so-called scale-free shipping networks ([Le Marchand 2000](#); [Foschi 2002](#)).³ Other examples include [Bergantino and Veenstra \(2002\)](#) and [Caschili and Medda \(2012\)](#), focusing on maritime transport as a ‘complex system’. Reviews dedicated to the analysis of shipping networks gradually emerged, however, focusing on bilateral connectivity ([Ansorena 2018](#)), methods of shipping network analysis ([Kanrak, Nguyen, and Du 2019](#)), the complex network framework ([Álvarez, Adenso-Díaz, and Calzada-Infante 2021](#)), innovation in big data analysis ([Munim et al. 2020](#)), port and maritime disruptions ([Wendler-Bosco and Nicholson 2020](#); [Nguyen et al. 2023](#); [Zhang et al. 2024](#)), port dominance evaluation methods ([Wang et al. 2021](#)), vessel trajectory visualisation ([Liu et al. 2021](#); [Shankar et al. 2022](#)), and the reliability of maritime container transport networks [Yue and Mangan \(2024\)](#).

The field of shipping networks is thus scattered across the academic spectrum and, therefore, needs an up-to-date and comprehensive review. Our study is based on a corpus of 329 articles published in peer-reviewed journals between 2007 and 2025. 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’). Two further criteria guided the selection. We retained only empirical studies of real-world shipping networks, excluding both the theoretical literature in operations research and

³Class of network characterised by a few large hubs and a majority of small and secondary nodes.

engineering on ship routing, scheduling, and hub location, and the qualitative work in history, archaeology, anthropology, and linguistics. Tactical networks in maritime warfare were also excluded.

These exclusions define what this chapter takes a ‘shipping network’ to be. Operations research treats shipping networks as configurations to be optimised rather than as systems to be observed; historical, archaeological, and anthropological studies, conversely, reconstruct maritime connections from non-network sources and treat them as qualitative objects. The corpus retained here consists, by construction, of empirical, network-analytical studies of observed maritime connections among ports, regions, and countries.

The chosen methodology is to cluster the articles based on the words included in their title and abstract, using Natural Language Processing. Each cluster is destined to be a core topic in the corpus. We find four main thematic clusters (trade and liner shipping connectivity; hubs and centrality; vulnerability and robustness; space and community structure) as well as three under-researched areas.

This conceptual delimitation has methodological consequences that should be made explicit. Any corpus boundary shapes the topic structure that the STM ultimately recovers. Adding the operations research literature would probably surface a optimisation-and-routing topic; adding historical and archaeological studies would likely yield a long-run, historical-trade topic. We do not expect such additions to dissolve the main thematic clusters reported above, but the relative weights of topics, and the placement of borderline papers, would shift. The topic structure presented in Section 3 should therefore be read as conditional on the corpus boundary defined here, which is itself a substantive analytical choice rather than a purely operational filter.

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. Section 2 introduces the corpus gathered between 2007 and 2025 and describes its evolution from various angles, such as the growth of articles, the main academic journals represented, its disciplinary background, and the geographic specialization of studies. Section 3 presents the methodology of the text mining/NLP analysis of abstracts. Section 4 offers a critical review of the four main themes of the corpus, while we discuss in Section 5 the ‘missing links’ that appear in our analysis. The last section concludes on further research pathways for both maritime transport studies and network science.

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

The relational approach in port and maritime research has long relied on the concept of "port system", originating from the work of [Taaffe, Morrill, and Gould \(1963\)](#) on the evolution of transport corridors and port hierarchies in West Africa. Due to the strong emphasis of such research on hinterlands, [Rimmer \(1967a,b\)](#) argued that maritime links between ports should also be analyzed in port system studies. Thus, there had been a recognition that forelands, the overseas connections of ports, 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 geographic specialization of connections, without a network approach per se, while other transport modes, like roads and railways had already been the focus of graph theory since the early 1950s ([Ducruet and Beauguitte 2014](#)). It is only in 1968 that graph theory had been applied to a maritime network, by Ross [Robinson \(1968\)](#) in his Ph.D. dissertation. He mapped the connections among British Columbia ports to illustrate the central position of Vancouver in the system. Despite its innovative character, his work was never published in a journal and was not cited subsequently.

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 \(1983\)](#) and [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 analysis of the global container shipping network, using graph theory. Like Robinson's work, ports were characterized by their connectivity (degree) rather than throughput, while the cartography of the network illustrated the dominance of East Asia. Subsequent analyses focused on the strategies of shipping lines and alliances, 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](#)).

In general, shipping network research in the early period constitutes a minor field, mostly invested by geographers. It remained scattered, with long periods of inactivity, and methodological innovations were introduced relatively late compared to research on

other (transport) networks. The most innovative works had been unpublished Ph.D. dissertations, working papers, or conference proceedings, remaining relatively unknown to date. The goal of the next sections is to analyze 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. Corpus and Quantitative Methodology

2.1. Size evolution

By January 2025, the number of articles dealing with shipping networks had reached a total of 329 items, including nine articles for the year 2025⁴. As shown in Figure 1, the first decade (2007-2017) is characterized by a very modest publication rate, with an average yearly number of 5.5 articles. A second period can be 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 to 63 and 74 articles in 2022 and 2024, respectively. Multiple checks have ensured that such a drop was not caused by missing references. In general, this evolution is characterized by rapid growth in corpus size. This reflects the growing availability of shipping data, 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.

⁴We stopped collecting items on January 15, 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).

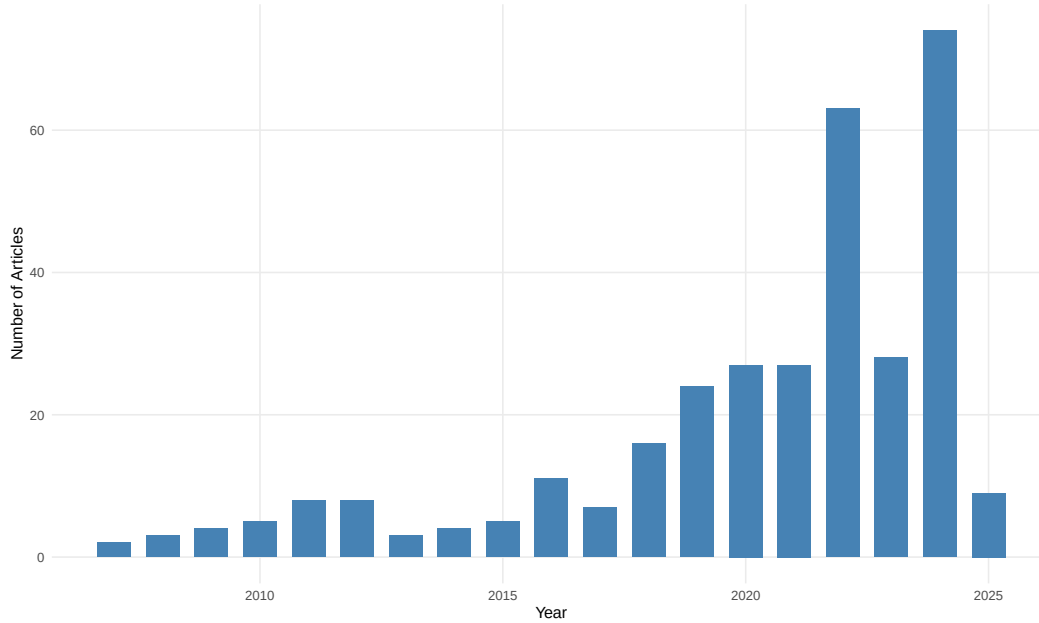


FIGURE 1. Evolution of the number of articles over time (2007 - 2025)

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 on the disciplinary and thematic focus of the corpus. The leading journal is *Journal of Transport Geography* (JTRG) which, contrary to other journals, is both disciplinary (geography) and thematic (transport) (Ducruet et al. 2019). This 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 Table 1, geography as a whole dominates other fields in Table 2, although it is 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

Maritime Policy and Management (MPM) as well as *Maritime Economics & Logistics* (MEL) can be considered the economic counterparts of JTRG, being the representative journals of the *International Association of Maritime Economists* (IAME). Together, they constitute the category of “shipping”, which is equal to 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 specialized field-journals. Physics was important in the early stage and maintained its rank afterward. Most of the 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. In general, the corpus can be divided between transport studies (144) and other studies (185), and its academic background has widened over time.

Table 3 presents a different distribution of articles, this time by geographic area of study. The global nature of maritime networks is well represented, with world-level

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

studies occupying half of the publications in the first period, one-third in the second period, and a little less than one-third in the total. This is followed by an overwhelming importance of studies in relation to Asia. In particular, studies of the Maritime Silk Road (MSR), which includes parts of Asia, Africa, and Europe, emerged in the second period, concentrating 10% of all studies, namely 20% when combined with China, and almost 30% together with the rest of Asia. Taken altogether, North and South America stagnated around 5-6 articles, while Europe witnessed a jump from 3 to 19 papers between the two periods, therefore ranking 5th in the total. Some categories went through a drastic increase in the second period, like the Arctic, Europe-Asia, Oceania/Pacific, and the Middle East.

TABLE 3. Classification of Articles by Geographic Area (2007–2025)

Area	2007–2017	2018–2025	Total
World	31	95	126
Rest of Asia	8	30	38
China	6	28	34
Maritime Silk Road	–	26	26
Europe	3	19	22
Americas	5	6	11
Arctic	–	10	10
Europe-Asia	1	6	7
Oceania/Pacific	1	6	7
Africa	2	3	5
Middle East	–	4	4
Atlantic	1	1	2
Antartica	–	1	1
Non-specified	2	34	36
Total	60	269	329

2.3. Structural Topic Modeling

To complement the description of corpus evolution, we build a corpus of abstracts for all the collected papers. 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 digitization 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 that aim to discover “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), 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 the 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 parameters⁵. 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.

2.4. 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 analyzing 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 framework developed by Roberts et al. (2013, 2014), Roberts, Stewart, and Airoldi (2016) and Roberts, Stewart, and Tingley (2019)⁶ provides

⁵For 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.

⁶We 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](#).

some directions on the selection of the number of topics⁷ and the in-depth analysis of topics' structures and determinants. The first metric is the 'semantic coherence' (Mimno et al. 2011)⁸. This criterion is maximized when the most probable words in a topic are also co-occurring together in the documents. 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* the the exclusivity of words to topics⁹.

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, five topics correspond to 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 we are dealing with abstracts¹⁰. 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.

We also believe that the relatively young field of maritime networks (less than two decades old) deserves attention for the major trends that characterise it. It is essential to identify these trends, as they enable us to understand the dynamics of the field and the major research issues that cut across it: trade, resilience, the environment, communities. For this reason, we are limiting the number of topics to five¹¹.

These exclusions are constitutive rather than residual: they define what this chapter takes a "shipping network" to be. Operations research treats shipping networks as con-

⁷This issue is also well-discussed, with some additional guidelines and good practices in Lindstedt (2019).

⁸For the figures, please check the appendix B.1.

⁹Figure B.1 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.

¹⁰Blei (2012), who review 17,000 academic articles published in *Science*, limit themselves to 50 to 100 topics.

¹¹In the appendix B, the results are presented for 6 (Table B.3) and 10 topics (Table B.6), but we lose clarity by allowing sub-themes to appear that are not relevant.

figurations to be optimised — through mathematical programming, simulation, and other prescriptive tools — rather than as systems to be observed; historical, archaeological, and anthropological studies, conversely, reconstruct maritime connections from non-network sources and treat them as qualitative objects. The corpus retained here is, by construction, the empirical, network-analytical study of observed maritime connections among ports, regions, and countries. Including either body of work would not enlarge this corpus but compose a different one, with a different object and different methods.

This conceptual delimitation has methodological consequences that should be stated openly. Any corpus boundary shapes the topic structure that the STM ultimately recovers, and ours is no exception. Adding the operations research literature would almost certainly surface a sizeable optimisation-and-routing topic, given the lexical homogeneity and volume of that body of work; adding historical and archaeological studies would likely yield a long-run trade-and-civilisation topic. We do not expect such additions to dissolve the main thematic clusters reported below — these capture the dominant strands of the empirical, network-analytical literature and remain recognisable across the alternative partitions explored in Appendix B — but the relative weights of topics, and the placement of borderline papers, would shift. The topic structure presented in Section 3 should therefore be read as conditional on the corpus boundary defined here, which is itself a substantive analytical choice rather than a purely operational filter.

3. Model Estimation

3.1. 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 4 brings together the ten most frequent occurrences for each of the four metrics, and for each topic¹². This partition then allows us to label the five selected topics, based on the top words in Table 4. We propose the following labels:

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

¹²Truncated 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.

TABLE 4. Top Words (Highest Probability) for Each STM Topic (K=5)

Topic	Highest Probability
1	<i>cruis, ship, vessel, oper, rout, arctic, use, model, emiss, data</i>
2	<i>connect, trade, region, contain, transport, liner, flow, develop, use, effect</i>
3	<i>contain, central, hub, connect, studi, degre, competit, use, develop, index</i>
4	<i>resili, vulner, disrupt, transport, impact, trade, studi, model, rout, attack</i>
5	<i>transport, trade, system, traffic, communiti, data, spatial, method, structur, use</i>

There are also terms such as connectivity and bilateral trade, which are more closely related to work in international economics and economic geography¹³. This transition from topological and structural issues to economic and political research questions suggests a maturing of the field.

¹³The 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)

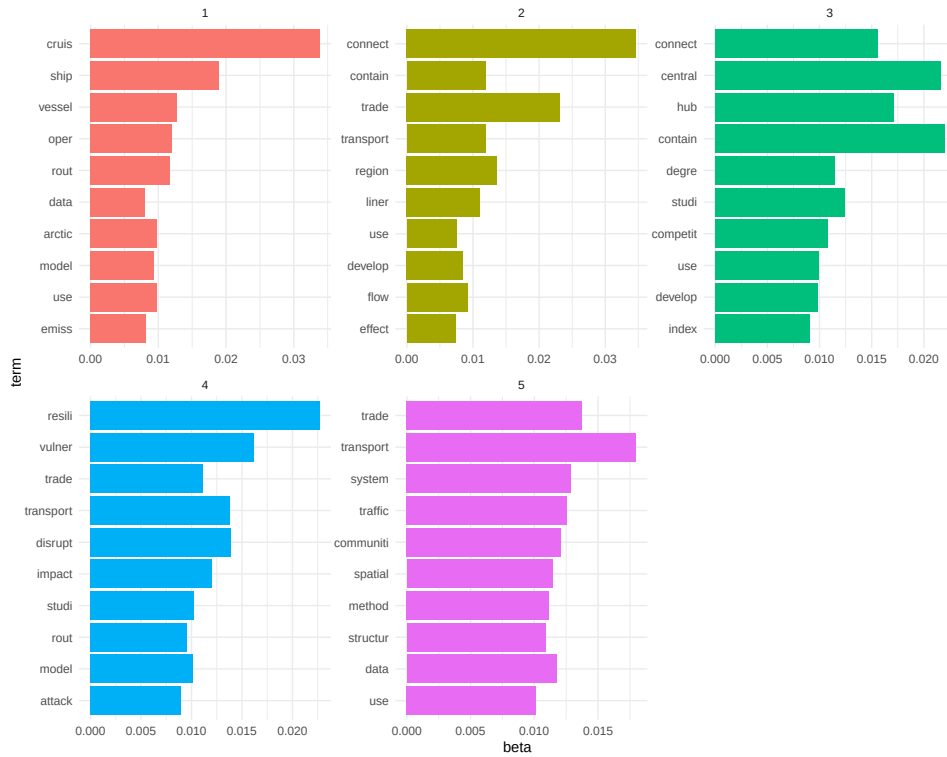


FIGURE 2. Top-10 most probable words for each topic

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

In the Figure 2 we observe the proportion of each word for the five topics. While topics 1 and 2 are rather uneven, with a predominance of cruises and connectivity, the other three topics are more evenly balanced. In topic three, connectivity is associated with centrality and hubs, while the fourth highlights the importance of terms associated with the subfield of network vulnerability (resilience, vulnerability, disruption, attack...).

3.2. Covariates and Topic Proportion

We now investigate how topic prevalence is shaped by specific covariates associated with the articles of the corpus. To properly account for the nature of topic proportions, we use a beta regression model (Ferrari and Cribari-Neti 2004).

We consider three main covariates: the publication period (2007-2019 vs. 2020-2025)¹⁴, the predominant geographic region of authors' affiliation¹⁵, and the disciplinary field

¹⁴The results are robust to the use of three periods (2007 - 2013, 2014 - 2019 and 2020 - 2025), see Table B.2.

¹⁵When two zones are at par, we used the zone of the first author.

of the journal in which the article i is published.

The output of the regressions in Table 5 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 all topics except the fifth. In the case of the first topic, for instance, the significant increase of researchers' interest probably corresponds to the opening of new shipping routes via the Arctic and environmental concerns, which relate to both these routes and cruises¹⁶. 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 conflicts¹⁷. We show in section 4 that network vulnerability and resilience became the central topic of interest of researchers in the recent years. Beyond its connection to current events (war in Ukraine, pandemic, conflict in the Red Sea), the growth of this theme is also associated with advances in methods for assessing network vulnerability in applied research fields (significantly positive coefficient in engineering, environment, and maritime sciences).

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, are negatively associated with the other journals compared with shipping ones.

¹⁶In 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, Sohler, and Lavissière (2020), Lin et al. (2023) and Qi et al. (2024) for reviews with a specific focus on arctic shipping.

¹⁷Polo-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 5. Beta Regression Results for Topics 1–5

	(1)	(2)	(3)	(4)	(5)
<i>Period</i>					
2020–2025	0.345**	-0.340**	-0.318**	0.313*	-0.258
<i>Origin (ref: Europe)</i>					
China	-0.300*	-0.328*	-0.917***	0.372*	1.086***
North America	0.204	-0.383	-0.063	0.523	-0.044
Rest of Asia	0.100	-0.305	-0.791***	-0.032	1.128***
<i>Background (ref: Shipping)</i>					
Economics	0.460	0.702	-0.104	0.507	-0.399
Engineering & data sciences	0.604*	-0.826***	0.003	0.536*	-0.258
Environment & energy	0.689*	-1.161***	-0.093	1.266***	-0.798*
Geography	0.012	0.116	0.353	0.116	-0.483*
Geosciences	0.670	-0.718*	0.448	0.271	-0.707*
Marine sciences	0.483	-0.559*	0.259	0.598*	-0.663**
Multidisciplinary	0.832**	-0.562*	0.152	0.311	-0.458
Networks & complex systems	0.279	-0.958***	1.418***	-0.065	-0.481
Physics & natural sciences	0.570	-0.776**	-0.016	0.160	0.237
Transport & logistics	-0.076	-0.349	0.263	0.480*	-0.179
Phi (precision)	1.804***	1.698***	1.911***	1.454***	1.975***
Pseudo R^2	0.200	0.267	0.274	0.234	0.356

Note: The dependent variable corresponds to the topic proportions in each element of the corpus. Coefficients are shown for each topic regression, with significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Baseline categories are *Europe* (Origin), *Shipping* (Background), and 2007–2019 (Period). Precision parameter (phi) and pseudo- R^2 at bottom. Only significant effects are highlighted.

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 a greater interest in resilience and transportation systems.

This succinct analysis, using regression based on the prevalence of topics, 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 disciplinary background of each article enables us to observe the links between certain fields and discussions in shipping research. Based on these findings, we will analyse in detail the 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. The creation of new ports and lines to cope with demand greatly modified the local and global structures of the shipping networks.

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, FREX reinforces this interpretation, with words such as 'bilateral' or 'freight' combining it with regional case studies ('north', 'vietnam', 'america'). Shipping networks are generally approached from a static point of view, and the dynamics of networks are essentially analyzed through the evolution of structural metrics such as betweenness and transitivity.

Since the end of the 2010s, several contributions have addressed the gravity aspect of shipping networks¹⁸. Fugazza and Hoffmann (2017) constructed the Liner Shipping

¹⁸Without explicitly mentioning '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 opening of the Suez Canal on global trade using a structural gravity model,

Bilateral Connectivity Index (LSBCI), a measure that brings together maritime (network) connectivity and international trade. The LSBCI includes a network framework¹⁹ 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 analyze the association between maritime connectivity and bilateral exports of containerizable goods. Fugazza and Hoffmann (2017) showed that improving maritime connectivity between partners significantly affects bilateral exports. For example, two countries sharing an additional common direct destination are associated with about 5% higher value of bilateral exports (see also Kosowska-Stamirowska, 2020)²⁰. Following Fugazza and Hoffmann (2017), Del Rosal (2024) estimated 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 macroregions and shows in particular that the effect of good connectivity is highly significant on long-distance routes.

Although Fugazza and Hoffmann (2017) and Del Rosal (2024) use the value of highly containerisable bilateral exports as a dependent variable, Ducruet, Itoh, and Berli (2020) directly exploit ship flows at the port city level²¹. They aggregated more than two million vessel movements between 1977 and 2016 at the city level and then ran a gravity model on space-L and space-P network topologies²². Their results confirmed the positive influence of city size (population) on the intensity of maritime trade and the growing friction of distance on such flows.

Ducruet and Yoon (2024) looked at the relationship between maritime connectivity and economic development in North Korea from 1977 to 2021. Notably, they show how the collapse of the USSR and the Eastern Block in the 1990s provoked a dramatic loss

thus approaching this research question with a ‘network-like’ approach. Those papers are not included in our corpus but are of particular interest to understand the structural dynamics of international (shipping) trade.

¹⁹It accounts for the number of transshipments required to get from j to k and the number of common direct connections for example.

²⁰It is directly connected to the concept of graph ‘communities’ discussed in section 4.4.

²¹Another interesting example of the combination - albeit without direct reference to shipping network literature - of Lloyd’s data and gravity models is Useche (2023).

²²Building 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: 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.

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, a ‘connectivity taker’ because of its size and geographical position, namely a small country with no real market power, relying almost entirely on foreign shipping companies. The ‘proximal market network’ is composed of ports through which New Zealand connects the rest of the world, such as Australian hubs, highlighting the risk of becoming peripheral (see Ducruet 2008 about the hub dependence concept and model). The regional development of maritime networks also goes hand in hand with questions of regional integration. Mohamed-Chérif and Ducruet (2016) observed that the multiplication of links across the Maghreb was better explained by traffic polarization around Tangier-Med than regional integration, which remains politically and economically limited. Calatayud et al. (2017a, 2017b) proposed a multilevel analysis of shipping networks at port level and trade networks at country level.

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 centrality²³ and betweenness centrality²⁴, concluding to a scale-free behaviour, as in the seminal work of [Barabási and Albert \(1999\)](#)²⁵. 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 (i.e., between -2 and -3).

²³Number of links connecting topologically adjacent nodes.

²⁴Number of occurrences of a node on all shortest paths in the network.

²⁵The “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 γ between 2 and 3.

Soon after, other physicists demonstrated that port centrality was significantly and positively correlated with container port throughput in TEUs²⁶ (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 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, as well as closeness centrality²⁷. 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).

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, highlighting the decline of Atlantic ports and the rise of Asia-Pacific ports, although container throughput kept growing 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 anal-

²⁶Twenty-Foot Equivalent Units, the standard measure of the volume of container handling at ports.

²⁷Also 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.

ysis. They identified Antwerp and Tanjung Pelepas as outliers due to their superior regional accessibility compared with their throughput.

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. In the case of links, the level of hub dependence corresponds to the share of the largest flow link in total port traffic (Ducruet, 2008). The higher the share, the more a port is vulnerable if the link is removed or perturbed (cf. Shenzhen and Hong Kong). Another study analyzed targeted link disruption, 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). Removing partially or completely canal-dependent links passing through Suez and Panama showed that European ports are the most

vulnerable in terms of betweenness loss (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” with some variants, such as clique percolation, network disintegration, and knock-on effects (Bai et al., 2024), the propagation of cascading failures based on betweenness and traffic (Cao et al., 2025; Ding et al., 2024), and the Copeland method (Dui et al., 2021). 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 either irreplaceability (Guo et al., 2024) or substitutability between adjacent ports in the advent of targeted attacks, in the latter case 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), and 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 density²⁸ 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

²⁸Network density refers to the share of actual links in the total maximum number of links.

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 the effects of this removal on the structure of the Northwest Pacific and northern Indian networks. 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 (in terms of throughput) and the vulnerability of hub ports (i.e., 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 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).

Lastly, another set of studies focused on the local and global impacts of real-world 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). 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. Some works looked at the impact of economic crises. For instance, Mesa-Arango et al. (2019) considered the 1997 Asian financial crisis 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, the East Coast of North America, and the Caribbean suffered 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, some 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 and spatial structure

The spatial nature of networks has been the subject of much research in theoretical and applied network science in recent years (Barthélemy 2011, 2022)²⁹. 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 between countries are highly dependent on maritime technology: steamships reduced shipping costs and time and allowed sailors to navigate without being subject - or to a lesser extent - to the winds. Containerization, by promoting hub-and-spoke network systems, also had a major effect on the spatial properties of the maritime network. The structure of shipping networks is not only explained by physical constraints³⁰, 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 when in proximity and to connect to the same large nodes. This process creates communities in the network and a whole field researched the best methods to identify these communities (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: neighboring ports are more likely to connect, especially when keeping smaller ships in the analysis. Industry factors, such as the emergence of transshipment ports and the containerization of cargo, greatly impacted the structure of

²⁹As 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).

³⁰It 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 the size of containerships.

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, dry bulk carriers, and oil tankers. Using a modularity-based approach ([Leicht and Newman 2008](#)) they found communities that correspond mainly to large geographical regions, with a few that are more dispersed. This result exemplifies an important limit of the application of modularity-based algorithms to networks, namely the ‘resolution limit’ ([Fortunato and Barthélemy 2007](#)). Modularity-based algorithms have been shown to fail in detecting small, specific communities. When analyzing shipping networks, this issue implies that we observe mainly geographical modules and fail to uncover the functional dimension of trading communities³¹.

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 other 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.

Thus, 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 such as dynamic stochastic block models (DSBM) should be pursued ([Matias and Miele 2017](#)).

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 could be identified within the corpus of articles published between 2007 and 2025: trade, centrality, vulnerability, and spatial structure, which comprise most of the articles. However, certain subfields remain strikingly small despite their core importance in

³¹Geographical communities are indeed existing in shipping networks, and clustering algorithms are useful in delineating them

port and maritime studies in general.

5.1. Environmental impacts

One of these subfields relates to environmental impacts. Some studies did not use network analysis or did not measure pollution. For example, Li et al. (2024) studied the South China Sea shipping network without measuring carbon emissions, while [Chen et al. \(2024\)](#) and Zhou et al. (2024a) did not use network analysis per se. Another example is Karountzos et al. (2023)³² who used a Geographical Information System (GIS) to examine the possible introduction of electric ferries in the Greek shipping network. Some studies went one step further, such as Tran and Lam (2024) analyzing the global network of CMA-CGM to reveal that in-port emissions concentrate in a small number of key hubs. Guo et al. (2023) concluded that container throughput, liner shipping connectivity, and trade openness have a positive impact on marine greenhouse gas (GHG) emissions at the country level. Some other studies used the complex network framework. Yue et al. (2024) estimated the carbon footprint of the Suez Canal disruption along the Europe-Asia route, while Kanrak et al. (2023) concluded that the best connected Caribbean ports tend to locate outside Emission Control Areas because the regulations are barriers for cruise ships entering the ports. Marine bioinvasions attracted peripheral interest from a network perspective, although they have enormous environmental, economic, cultural, and human health impacts. Kaluza et al. (2010) and 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, to measure the influence of centrality on the spread of non-indigenous species (NIS) between ports (Lenzen et al., 2023; Bereza et al., 2023; Song et al., 2024; Shi et al., 2024), with diverse outcomes.

5.2. Socio-economic development

Another striking deficiency of shipping network research is the subtheme of socio-economic development. This contrasts sharply 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.

³²See also [Karountzos et al. \(2024\)](#) and [Karountzos, Giannaki, and Kepaptsoglou \(2024\)](#)

Kanrak and Nguyen (2022) are one of the rare studies to consider node attributes in their analysis of the Asian-Australasian shipping network (location, number of attractions and visitors, rating score, popularity, and population). Guo and Qin (2022) studied the port-urban network system in China by combining cargo flows with people, capital, technology, and information flows to model the relationship between the coastal port system and its urban network. An original approach has been to measure the combined centrality of ports 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; Ducruet et al., 2011). This necessitated aggregating ports, stations, and airports at the level of urban agglomerations, often concluding that combined centrality is better correlated with city size than single centrality.³³ 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 causality.

5.3. Shipping alliances

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) looked at how major routes such as Europe-Asia have been reshuffled due to the rationalization of individual shipping lines and the growth of alliances. Liu et al. (2024b) found that the alliance shipping network is more robust than the one of individual companies. Yamamoto and Takebayashi (2024) concluded that hub-and-spokes systems are more profitable for carrier alliance. One of the most advanced approaches is that of Gou et al. (2024), offering a multilevel 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 COSCO and CSCL shipping networks before and after their merger. Complementarities were found before the merger, but afterward the merger also had the effect of strengthening the key hub ports of the network.

³³Two works outside of the corpus are worthy of investigation: [Ducruet and Itoh \(2015\)](#) and [Ducruet et al. \(2017\)](#) analyzed the centrality of subnational regions in combination with various socio-economic indicators, such as population density, unemployment rate, GDP per capita, and main economic sectors

5.4. Network-analytical methods

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 neglected if not ignored in the literature on shipping networks. 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 links, based on the assumption that the emergence of a relationship could be influenced by other relationships or individual characteristics (Kanrak and Nguyen, 2022b). However, no study has been done using this model, which 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 vast 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. It should not be forgotten that preferential attachment in a scale-free network is a process rather than a static property.

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 maritime transport. However, important issues related to globalization and regional integration processes, international trade patterns (e.g. gravity), and local socio-economic development 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 tonnage.

Moreover, focusing on the only 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 lack of data on the hinterland remains a major obstacle, forcing scholars to focus on the only 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.

Further research shall lean towards several possible directions. 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. Another avenue of research is on environmental impacts, including public health issues and pollution, to verify whether particular network structures 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. Lastly, massive extraction of historical shipping data may allow fine-grained analyses of past events and their influence on shipping network structures. The discovery of Lloyd's List records on vessel movements between world ports undoubtedly offered new possibilities to track multiple shocks that affected ports and shipping networks since the 19th century.

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A. Co-authorship Networks

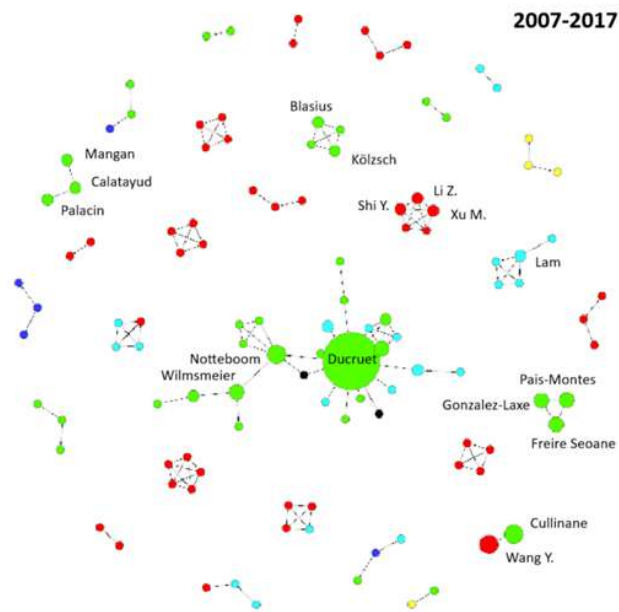


FIGURE A.1. Co-authorship network (2007 – 2017)

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 A.1), 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.

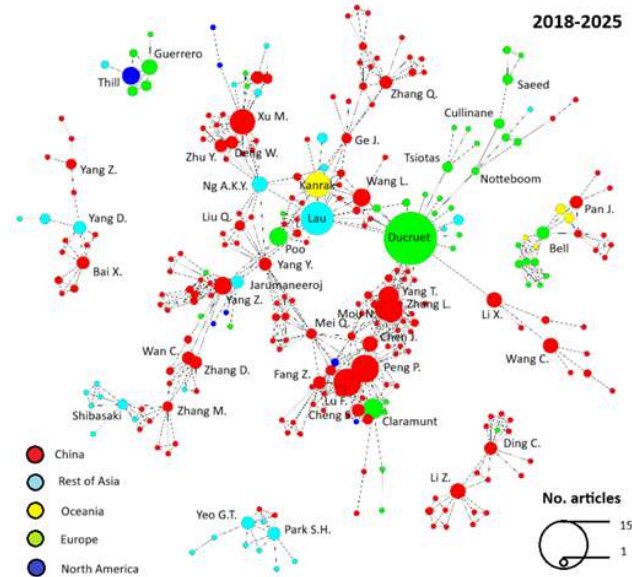


FIGURE A.2. Co-authorship network (2018 – 2025)

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

The second period (Figure A.2) 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.

B. Topic Selection and Additional Estimations

B.1. The Metrics for Topic Selection



FIGURE B.1. 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 model³⁴ strongly emphasise that these measures are imperfect and are no substitute for human validation of topics, in conjunction with subject consistency..

B.2. A Six-Topics Partition

TABLE B.1. Top Words from the STM model with 6 topics

Topic	Highest Prob	FREX	Lift	Score
1	<i>cruis, vessel, oper, ship, rout, arctic, use, emiss, chang, contain</i>	<i>emiss, cruis, arctic, suiez, asr, passag, itinerari, sea-son, voyag, water</i>	<i>acceler, contact, ice, in-ventori, murmansk, plant, prompt, summer, tonn, world-wid</i>	<i>cruis, arctic, itinerari, asr, passag, emiss, season, nis, dual-cor, visit</i>
2	<i>connect, trade, region, contain, liner, use, model, transport, econom, effect</i>	<i>bilater, export, freight, product, period, connect, variabl, partner, demand, africa</i>	<i>agenda, best, bilater, calibr, capita, contract, country-level, crise, eight, endogen</i>	<i>bilater, -go, trade, coun-try', lsbc, capita, partner, output, freight, canari</i>
3	<i>contain, central, hub, con-nect, competit, develop, studi, servic, region, degre</i>	<i>hong, asian, kong, busan, singapor, competit, cen-tral, shanghai, hub, al-lianc</i>	<i>fierc, hole, late, latest, penang, qingdao, sub-hub, topsi, alphabet, arrang</i>	<i>busan, competit, hong, asian, kong, singapor, hacc, tier, alphabet, cosco</i>
4	<i>resili, vulner, disrupt, impact, transport, trade, model, studi, assess, attack</i>	<i>resili, failur, cascadi, at-tack, disrupt, conflict, vul-ner, robust, critic, risk</i>	<i>aid, catastroph, confid, conflict, encount, fail, faster, fragil, hazard, intent</i>	<i>resili, cascadi, failur, attack, disrupt, conflict, glsn, reliabl, crude, risk</i>
5	<i>structur, spatial, trans-port, communiti, trade, system, flow, region, traf-fic, studi</i>	<i>urban, communiti, citi, spatial, linkag, articl, inter-, function, strateg, coupl</i>	<i>airport, australia, bipar-tit, bodi, chosen, clarifi, communic, compil, con-nect, convent</i>	<i>communiti, urban, spa-tial, citi, gmn, updat, inter-, multiplex, socioe-conom, linkag</i>
6	<i>rout, transport, ship, method, use, data, road, node, model, link</i>	<i>msr, silk, road, shortest, path, algorithm, advan-tag, tanker, bulk, edg</i>	<i>abstract, allevi, billion, blockag, bottleneck, foot-print, heavy-tail, hope, msr, neighbourhood</i>	<i>msr, silk, tanker, advan-tag, ship, chart, waypoint, oil, bulk, road</i>

TABLE B.2. Beta Regression Results for Topics 1–5 (Three-period specification)

	(1)	(2)	(3)	(4)	(5)
<i>Period</i>					
2007–2013	0.173	0.289	0.147	-0.168	-0.239
2020–2025	0.441**	-0.253	-0.210	0.352*	-0.548***
<i>Origin (ref: Europe)</i>					
China	-0.381*	-1.251***	1.010***	0.334*	0.123
North America	-0.145	-0.602	-0.109	0.484	0.594
Rest of Asia	0.481*	-1.173***	1.284***	-0.125	-0.514*
<i>Background (ref: Shipping)</i>					
Economics	0.746	-0.665	0.037	0.492	-0.374
Engineering & data sciences	-0.377	-0.852***	-0.617*	0.622*	0.717**
Environment & energy	0.466	-0.874**	-1.026**	1.124**	-0.076
Geography	0.005	0.086	-0.321	0.069	0.170
Geosciences	0.426	-0.889**	-0.996**	0.077	1.354***
Marine sciences	0.291	-0.390	-0.788**	0.623*	0.444
Multidisciplinary	0.810**	-0.581*	-0.614*	0.223	0.124
Networks & complex systems	-0.030	0.038	-0.997**	-0.101	0.920**
Physics & natural sciences	0.102	-1.097***	-0.203	0.217	0.854**
Transport & logistics	-0.355	-0.028	-0.263	0.512*	0.066
Phi (precision)	2.120***	2.212***	2.056***	1.516***	2.111***
Pseudo R^2	0.320	0.447	0.336	0.276	0.248

Note: Coefficients are shown for each topic regression, with significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Baseline categories are *Europe* (Origin), *Shipping* (Background), and 2014–2019 (Period). Precision parameter (phi) and pseudo- R^2 at bottom. Only significant or near-significant effects are highlighted.

TABLE B.3. Beta Regression Results for Topics 1–6

Variable	Topic					
	(1)	(2)	(3)	(4)	(5)	(6)
(Intercept)	-2.230***	-0.280	-1.362***	-2.008***	-0.876***	-1.725***
2020–2025	0.618***	-0.011	-0.379**	0.426**	-0.488***	-0.324*
China	-0.174	-0.948***	0.907***	0.280	-0.466**	0.454**
North America	-0.182	-0.377	-0.211	0.479	-0.130	0.413
Rest of Asia	0.646**	-1.029***	1.510***	-0.070	-0.734***	-0.235
Economics	0.656	-0.237	0.206	0.399	-0.226	0.661
Engineering & data sciences	-0.636**	-0.789**	-0.928***	0.590*	-0.034	1.308***
Environment & energy	0.498	-0.791*	-1.069**	1.266***	-0.114	-0.156
Geography	0.077	-0.281	-0.221	0.051	0.557**	-0.166
Geosciences	-0.125	-0.734*	-0.854*	0.121	1.049**	0.595
Marine sciences	0.060	-0.449	-0.788**	0.524*	0.163	0.700**
Multidisciplinary	0.851***	-0.551*	-0.680**	0.222	0.138	0.247
Networks & complex systems	0.158	0.042	-0.905**	-0.144	0.647	0.252
Physics & natural sciences	0.167	-0.730*	-0.738*	0.324	0.496	0.917**
Transport & logistics	-0.407	-0.056	-0.245	0.517*	0.084	0.175
Phi (precision)	2.008***	1.829***	2.279***	1.484***	1.890***	2.050***
Pseudo R^2	0.463	0.334	0.377	0.267	0.254	0.353

Note: Columns (1), (2), (3), (4), (5), and (6) show coefficients for Topics 1, 2, 3, 4, 5, and 6, respectively. Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, for $p < 0.15$. Baseline categories are *Europe* (Origin), *Shipping* (Background), 2007–2019 (Period). Precision parameter (phi) and pseudo- R^2 at bottom. Only significant effects are highlighted.

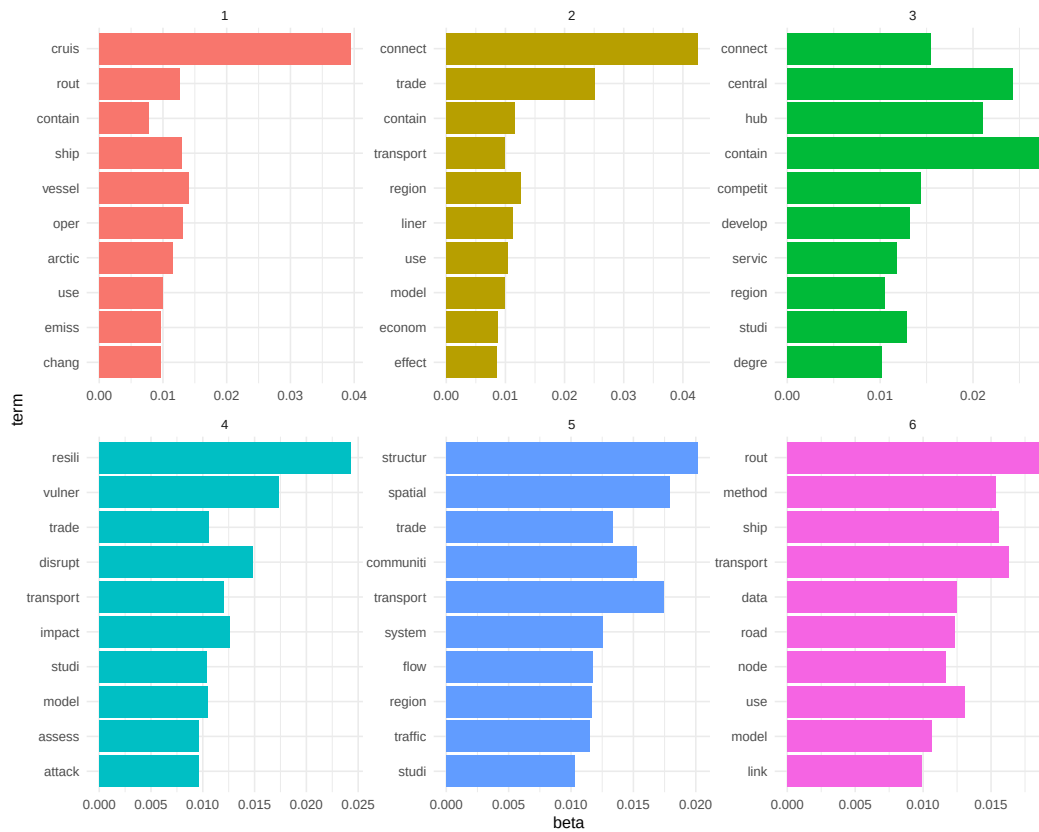


FIGURE B.2. Top-10 most probable words in a six-topics partition

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.3. Five and Ten Topics Partition – All Metrics

TABLE B.4. Top Words from the STM model with 5 topics

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

TABLE B.5. Top Words from the STM model with 10 topics

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

TABLE B.6. Beta regression results for topic proportions (Topics 1–10)

Variable	Topic									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(Intercept)	-2.20036***	-0.90316***	-1.54150***	-1.98598***	-1.35758***	-2.04161***	-2.27121***	-1.33283***	-2.25221***	-2.30221***
2020–2025	0.23061*	0.03132	-0.43583**	-0.44995**	-0.17244	-0.32027*	0.22932	-0.19475	0.45343***	0.26342*
China	0.38202*	-0.50396**	0.66231***	0.35851*	-0.21705	0.80117***	0.37793*	-1.04901***	-0.10680	-0.57838***
North America	-0.31235	-0.62810*	-0.23478	0.76999*	-0.02496	0.23524	0.19182	-0.16161	-0.42106	0.58744
Rest of Asia	0.70162**	-0.35749	1.17182***	-0.23592	-0.67220**	0.25489	0.01116	-0.75451***	0.21100	-0.10473
Economics	-0.48254	-0.30760	0.07487	0.07450	-0.39358	-0.21336	0.33865	0.10050	0.06351	1.30185*
Engineering & data sciences	-0.77869**	-0.67444**	-0.72712**	0.39060	-0.35013	0.60526*	0.48936*	0.50956*	-0.18578	0.54951*
Environment & energy	-0.39940	-0.98080**	-0.93409**	1.24086***	-0.46691	-0.60974	0.33007	-0.16714	-0.24633	1.19297***
Geography	-0.04488	-0.31608	-0.41521*	0.13919	0.31603	-0.34688*	-0.00813	0.41327*	0.20510	-0.19996
Geosciences	-0.49026	-1.10968**	-0.84941*	0.15552	-0.12745	0.05646	-0.00043	1.35702***	-0.24827	0.48374
Marine sciences	-0.41335*	-0.42465*	-0.64470**	0.21408	-0.13183	0.38775	0.66739**	0.45436	0.47341	0.35231
Multidisciplinary	0.21387	-1.00253***	-0.61901*	0.55618*	-0.09140	-0.07956	0.17463	-0.06394	0.12030	0.61239*
Networks & complex systems	0.12697	-0.25232	-1.00381**	0.54769	0.58575	0.26784	-0.03986	0.08788	-0.36266	0.05987
Physics & natural sciences	-0.55635*	-0.69215*	-0.99624***	-0.01788	0.29121	1.11169***	0.45301	0.02704	-0.15942	0.43151
Transport & logistics	-0.54424*	0.04135	-0.27110	-0.23202	-0.03760	0.15889	0.55496*	0.40381	0.06067	0.11788

Note: Coefficients are from beta regression models for each topic (1 to 10). Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Baseline categories: *Europe* (origin), *Shipping* (background), and 2007 – 2019 (period).



FIGURE B.3. Top-10 most probable words in a 10 topics partition

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CHAPTER 2

The World in a Box

Structure and Dynamics of the Global Container Shipping Network, 1970s-2020s

Abstract

Container shipping has become a cornerstone of global supply chains, regional integration, and port-city development. The globalization of trade and, at the same time, the increased vulnerability of supply chains have created a more efficient yet fragile system. In this chapter, using a unique dataset of more than four million ship movements, we uncover the local and global dynamics of container flows. Starting in the 1970s, with the diffusion of container technology in international trade, we analyse fifty years of global trade through the lens of network structures and community detection. We document (i) an almost continuous expansion in nodes and links with improving topological efficiency up to the mid-2010s, followed by (ii) the consequences of recent shocks, such as COVID-19, Red Sea disruptions, and the Panama Canal drought, which highlights the vulnerability of the container shipping network. Using single linkage analysis, we also show the evolution of trade dependencies, the emergence of China particularly towards Africa over the last decade, and the persistence of certain port systems such as the European system around Rotterdam. We open a new avenue of research by combining global and local, systemic and long-term quantitative analyses to understand the dynamics of international trade.

Keywords: complex networks; international trade; container shipping

A shorter version of this paper will be published in the forthcoming *Research Handbook on Maritime Logistics*, co-authored with César Ducruet. Preliminary results of this paper have been presented at the ‘Young scholars’ group on shipping and ports’ in Le Havre in December 2025. The research leading to these results received financial support from the French National Research Agency (ANR) through the research project MAGNETICS No. ANR-22-CE22-0002.

Introduction

It is now widely recognized that container shipping occupies a central place in global trade, carrying no less than 70% of the value of commercial exchanges (UNCTAD, 2024). In addition, containerization is considered to be not only an innovation but also a revolution, since its emergence in the United States back in the 1950s. [Jacks, Meissner, and Novy \(2008\)](#) recalled that containerisation boosted international trade by 471% during the Second Wave of globalization (1944-1971) and reduced transport costs by 16%¹. Although the early days of containerisation faced numerous technical, organizational, and cultural challenges, it has gradually boosted port productivity (ship turnaround times), enhanced voyage regularity and safety through liner shipping schedules, and fostered hinterland expansion via intermodal connectivity ([Palmer 1999](#); [Stopford 2008](#); [Kaukiainen 2012](#)). Such changes are quite comparable to those that took place in the 19th century, with the introduction of the steamship, which fostered economies of scale in shipping and ports, the integration with railways, port selection, and competition, albeit more in nature than in scale ([Marnot 2024](#)). Ultimately, global shipping networks became increasingly optimized through the rationalization of services and the centralization of traffic around main hubs and gateways ([Cullinane and Khanna 2000](#)). Here again, the process is not entirely new, considering the important literature depicting port system concentration in past centuries ([Ducruet and Notteboom 2023](#)).

The unpublished PhD dissertation of [Joly \(1999\)](#) is the first-ever analysis of the global liner shipping network. It used graph theory to calculate the degree centrality of ports and mapped the main routes to demonstrate the dominance of East Asia in the system. It also constitutes the first use of Lloyd's List data, namely the "Voyage Record", which provides information on successive vessel movements among ports of the world. It was only ten years later that other scholars proposed analyzes of the global shipping network from a complex network perspective in physics ([Hu and Zhu 2009](#); [Wei-Bing et al. 2009](#)).

Our chapter is an empirical and quantitative analysis of the evolution of the global container shipping network (GCSN) between 1977 and 2024. It uses the Lloyd's List database that covers a total of 4,073,112 inter-port containership movements, based on the months of March, June, September, and December each year.

This chapter is organised around four empirical propositions. First, the expansion of containerisation should be associated with a long-run densification and geographical widening of the global container shipping network. Second, the centre of gravity of the GCSN should progressively shift from the historical North Atlantic and Japan-centred configuration toward East and Southeast Asian port systems. Third, the development of hub-and-spoke architectures should increase the hierarchical organisation of the network, with a limited number of ports

¹On shipping and trade costs, one can also refer to [Jacks, Meissner, and Novy \(2010\)](#) and [Jacks and Pendakur \(2010\)](#).

concentrating a large share of connectivity. Fourth, recent systemic shocks and organisational changes should be reflected in greater network fragility, visible through changes in centrality, density, and nodal-region structures.

The first part of the analysis applies graph theory and the complex network framework to describe the changing topological structure of the GCSN over time, with various global-level measures and indices. The shape of the network is a good indicator telling how carrier strategies and trade patterns affected the overall structure, notwithstanding the influence of various shocks such as economic crises and the pandemic.

The second part focuses on the identification of hubs and the geographic extent of their connectivity, in terms of dominance and network centralization. Here also, the goal is to detect the role of changing carrier schedules and trade patterns, but also the effects of local and national port policies, port selection mechanisms, as well as the possible factors of port resilience. Moving from a macro and general analysis to a micro one, in which specific port-to-port interactions are identified, is also one of the contributions of the paper. The chapter ends with a discussion and conclusion about the implications of the results for port competition and governance.

1. Analysis of the Global Network Structure

The question of scale is central to the modelling and analysis of maritime networks. While trade flows are generally studied at the inter-country level, or more rarely at the inter-regional level, maritime movements allow flows to be tracked at very disaggregated levels. At the same time, network analysis enables us to construct a “system” and study its overall properties. Finally, having several periods available in a harmonised manner allows us to study how the properties of the system evolve over time.

1.1. Data and Methodology for Dynamic Analysis

1.1.1. Reconstructing the Dynamic Containership Network

Lloyd’s List data. To uncover the structural properties of maritime trade, we construct a dynamic graph of vessel movements. Let us consider a graph $\mathcal{G}(V, E)$ with V the vertices, or nodes, of the graph, and E the edges (links) that are connecting vertices. In the case of a shipping network, the vertices are the ports and the edges are the movements of ships from one port to another. Then, we introduce the dynamic part of the analysis, which is simply the collection of the static networks.

The Lloyd’s data are structured as follows: in the first dataset, we have the movements of ships. Each line corresponds to a ship N and its route between port A and port B . Each port is designated by a unique identifier. In a second dataset, we have all the information about

these ports. The identifier is associated with various pieces of information: port type, port name, geographical coordinates, country, continent, geographical area. Finally, we have a third dataset structured in a similar way for ships: ship type, IMO identifier, DWT, etc. First, we select container ships. Then, we reconstruct the Space-P network as follows: two ports A and B are connected if there is a sequence of movements of a ship N connecting these two ports². In other words, and this applies particularly to the container industry, two ports are connected when they belong to the same line. The number of calls on this line is used to weight the links.

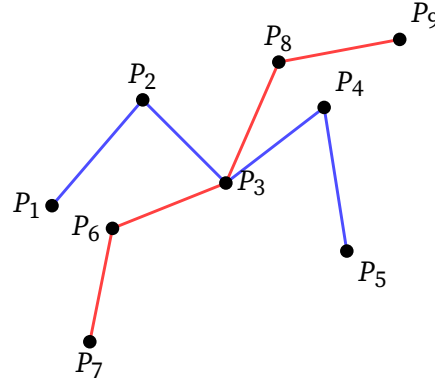


FIGURE 1. Space-L network topology

Notes: The blue edges represent the main chain $P_1-P_2-P_3-P_4-P_5$; the red edges represent the additional connections P_6-P_3 , P_6-P_7 and $P_3-P_8-P_9$. Two ports are connected if there is a direct journey between them by ship.

Figure 1 shows a space-L topology for the maritime network. Using that topology, two nodes are considered connected if there is a *direct* connection between them. To put it another way: Shenzhen and Rotterdam will never be considered connected using this topology. This is because a container ship operating on this route will make a number of stops between these two ports. Shenzhen will therefore only be connected to the first port of call and Rotterdam to the last one. This is an interesting topology for studying the structure of short-distance shipping and the development of local structures, such as those of large regional hubs. This advantage comes with a major drawback: local hubs are overestimated and, particularly in the case of community detection, we end up with regional clusters.

Another way to model the GCSN is to consider the shipping lines rather than the direct connections. This topology is called the space-P network. In that case, we consider that a port

²When rebuilding a transport network, two topologies can be adopted, giving a different view of connectivity. In a space-L network, two ports are considered connected if there is a direct link, i.e. a voyage by ship, between them. In the space-P topology, two ports are considered connected if they belong to the same line. There is therefore a voyage between these two ports, but it may include intermediate stops.

that does P_1 to P_5 is connecting *all* those ports, because they belong to the same operating shipping route. If P_1 is Shenzhen, and P_5 is Rotterdam, then Shenzhen and Rotterdam are considered to be *connected*.

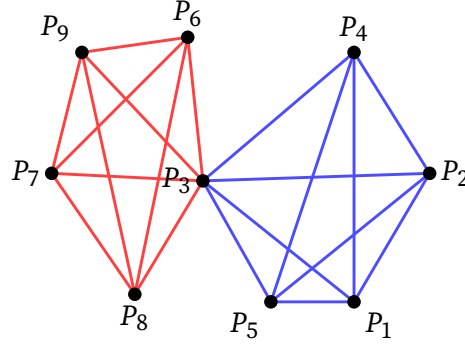


FIGURE 2. Space-P network topology

Notes: The blue edges represent the main chain $P_1 - P_2 - P_3 - P_4 - P_5$, while the red edges represent the additional links $P_6 - P_3$, $P_6 - P_7$ and $P_3 - P_8 - P_9$. Two ports are connected if there is a line between them. In the space-P topology, a connection does not require a direct voyage between two ports, but rather that they belong to the same overall shipping route.

The space-P topology (Fig. 2) is particularly relevant in the case of global and long-term analyses. In this paper, we model and analyse the emergence of *hubs* and the expansion of major hubs to growing regions such as East Africa. For this reason, we focus our analysis on this topology. This allows us to analyse both short- and long-distance relationships. It also avoids a serious bias that can affect large-scale maritime network analysis: by focusing solely on direct connections, excessive weight is given to regional trade networks in international trade. These are indeed important; if we consider the Mediterranean or China, there is a high density of regional connections, and these are increasing over time. However, this does not reflect the economic and strategic organisation of shipping companies and global maritime trade³.

A potential limitation of the dataset is that it is based on four months per year (March, June, September, and December) rather than on the full annual sequence of vessel movements. This sampling design may introduce seasonal bias if container services, port calls, or temporary route adjustments are systematically concentrated in other months. This concern is particularly relevant for short-run analyses. However, the present chapter focuses on long-run structural transformations of the GCSN rather than on intra-annual fluctuations. Container shipping is also organised through regular liner services, which reduces, although does not eliminate, the

³To give a simple example: when analysing the global maritime network as a collection of direct connections between ports, Shenzhen and Rotterdam are considered to be unconnected. The same applies to all large hubs that are relatively distant from each other, even within the same continent. However, the links between these ports are essential and, although separated by numerous stops, they reflect the evolution of the structure and hierarchies in international trade.

likelihood that the core topology of the network is driven by unobserved seasonal movements. The use of four quarters per year, the long time span from 1977 to 2024, and the focus on relative hierarchies and repeated structural indicators mitigate this issue.

1.1.2. Topological Indices of the GCSN in the Literature

The study of maritime networks quickly adopted the methods introduced by the field of complex systems in the late 1990s and early 2000s (Watts and Strogatz 1998; Barabási and Albert 1999; Albert and Barabási 2002). Foschi (2002, 2003), Xu, Hu, and Liu (2007), and Hu and Zhu (2009) were the first to introduce this theoretical and empirical framework into the analysis of maritime flows. Maritime transport remains less studied than air or rail transport Ducruet (2020) and, within maritime transport, a fairly large number of literature reviews do not pay specific attention to the application of “complex” network analysis methods to maritime flows⁴. Polo-Martin et al. (2025) and Faure and Ducruet (2025) are two notable recent exceptions. While the former offered a discussion of the literature on the vulnerability of maritime network, the latter proposed the first systematic review of work on shipping networks⁵.

An initial phase of work, beginning with Robinson (1968) and continuing until the early 2000s, introduced some elements of graph theory and focused on maritime networks and connectivity between ports. However, this work remained confined to maritime geography, within a limited field of research. From 2007 to 2019, a first series of articles applied the methods and theoretical framework of complex networks to analyse maritime flows. During this period, the study of maritime networks focused on issues of connectivity, hubs, and communities. This corresponded to methodological advances in complex networks during this period: (i) improved understanding of network connectivity, (ii) reassessment of hierarchies, and (iii) detection of communities. These three themes saw a decline in interest from 2019/2020 onwards in favour of issues related to resilience, vulnerability and risk mitigation in networks. The various recent crises (Covid-19, war in Ukraine, Houthis attacks in the Red Sea) may explain part of this renewed interest in the field.

Nevertheless, there are several limitations in the field of maritime networks, and several avenues of research remain to be explored. Firstly, port management performance is rarely questioned in the literature on shipping networks, even though it is a central issue in the structure of trade between ports. Some studies have discussed the long-term dynamics of maritime trade, but the field still lacks comprehensive and systematic approaches to the evolution of shipping

⁴See, for example, Shi and Li (2017), Bai et al. (2021), and Dragović et al. (2024).

⁵It is important to note that a significant number of papers dealing with “maritime networks” have been published in the field of operations research. These articles also use the concept of maritime networks, focusing on the optimization of various processes in maritime transport. In this respect, we do not reference this literature.

over several decades. In this article, covering almost the entire period of global containerisation⁶, we attempt to fill this gap in the literature.

1.2. Connectivity Evolution of the GCSN, 1977-2024

1.2.1. The Rise of Containers in Global Trade

Having defined the main methodological choices, we now turn to the long-term evolution of connectivity in the global network. As already mentioned in the introduction, the containerisation of shipping trade started in the 1950s in the United States. The spread of containerisation, like any innovation process, took some time and became particularly visible from the 1970s onwards. Containerisation did not only mechanise cargo handling, it standardised the transport unit and enabled seamless sea–rail–road intermodality, reducing port time and transport frictions. In network terms, this transformation should increase the extensive margin (ports and links), shorten shipping distances, and reinforce hierarchy and spatial-concentration due to hub-and-spoke structures.

⁶As a reminder, the first containerised voyages took place in the United States in the late 1950s. Containerisation developed gradually, first in the United States and then in Europe in the 1960s. The 1970s saw wider adoption worldwide. Thus, by covering all ports listed from 1977 to 2024, we can construct a fairly accurate picture of the long-term global dynamics of container transport.

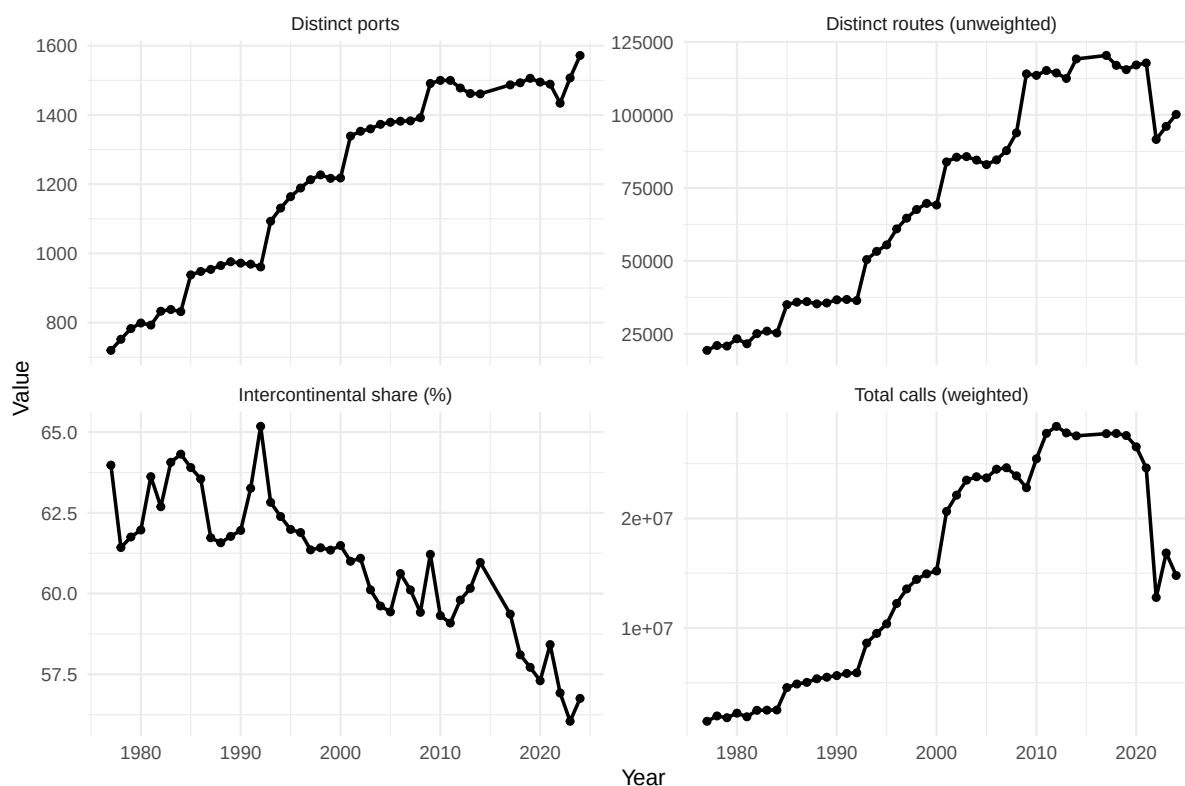


FIGURE 3. Global metrics for containerised trade

Notes: This figure shows four metrics on global containerised trade. We computed the number of distinct ports, distinct routes (connections from a port A to a port B), the share of intra-continental trade and the total of calls. The number of calls differs from the number of routes because several ships may have taken the same route in a given year.

The number of ports and routes has continuously increased from the 1970s onwards. As shown in Fig. 3 the number of ports receiving container ships has risen from around 800 to almost 1,600, while the number of connections has increased fivefold. The reduction in intercontinental traffic can be explained by the development of hub-and-spoke structures and, more broadly, by the growth in Asian traffic and regional integration processes in other areas as well. On these routes, ships make short journeys and stop at the many major ports in the region, in China, South Korea, and Singapore. The number of calls increased significantly from the 1990s onwards. There was also a sharp increase between 2000 and 2001, coinciding with China's entry into the WTO. While the number of ports does not seem to have been affected by Covid-19, the number of routes and, even more so, the number of calls have been severely affected by the pandemic. As a result, the number of calls globally has not returned to its pre-pandemic level. It should be noted that this does not necessarily mean that less cargo is being transported, but rather that value chains are operating differently. Larger ships or a concentration of connections

to major ports followed by road connections to the hinterland previously served by smaller ports may explain the reduction in the number of port calls.

TABLE 1. Phases of containerisation & network effects

Period	Structural & organisational changes	Network & topology effects	Empirical impacts in shipping data	Institutional and organisational milestones ^a
1956-late 1960s	Early experiments; first dedicated services; standardisation begins; geographically limited	Sparse networks; limited port set; weak hierarchy	Few links; strong measurement noise; comparability issues across ports/series	First container voyages and early international services; initial standard-setting
1970s-mid 1980s	Diffusion and infrastructure build-out; dedicated terminals; intermodal integration	Rapid densification; declining effective distances; emergence of hubs and regular liner patterns	Growth of extensive margin (nodes/links) and intensive margin (calls/TEU); rising concentration in gateways	Wider adoption of ISO standards; terminalisation accelerates
late 1980s-1990s	Scale and consolidation: larger vessels, service rationalisation; early alliance logic; corridor strengthening	Stronger hierarchy; hub-and-spoke deepens; higher betweenness of transshipment hubs	Faster growth of degree/centrality dispersion; modular structure becomes clearer (regional subnetworks)	Post-Panamax threshold; early generations of alliances
2000s	Global supply-chain integration; China-driven trade boom; port system reconfiguration	Further hub concentration on main East-West trades; increasing assortativity among top nodes (core-periphery)	Structural break in volumes and centralities; strongest gains on trunk lines; rising transshipment shares	Trade boom; rapid hub growth in Asia and Mediterranean interfaces
2010s	ULCV era; mature alliances; schedule optimisation	Higher vulnerability to chokepoint; more pronounced “trunk + feeder” architecture; potential over-reliance on hubs	Topological stability with increasing capacity; alliance networks	ULCV diffusion; consolidation into a small set of global alliances
2020s	Polycrisis regime: pandemic, chokepoint disruptions, climate constraints, re-routing	Temporary re-wiring, higher path lengths, increased regionalisation	Volatility in connectivity metrics; centrality shifts	COVID shock; Red Sea disruption; Panama drought constraints

Table 1 summarizes the evolution of the container sector and its impacts on networks, institutions, and organizations. Regarding "waves of containerization" and their effects, [Guerrero and Rodrigue \(2014\)](#) offers an in-depth analysis showing that the development of container ports follows a cyclical pattern corresponding to the Kondratieff wave.

TABLE 2. Major containerised trade lanes

Lane	Commercial / Structural importance	impor-	Main risks / shocks	Typical effects
Asia-North Europe	Largest East-West trunk		Suez/Red Sea; mega-hub congestion; fuel/regulatory cost shocks	Cape rerouting; longer transit; freight-rate spikes
Asia-Mediterranean	Dense markets; key transshipment interface		Suez/Red Sea; hub disruption; labour/port strikes	Call disruption; feeder delays; intra-Europe connectivity stress
Trans-Pacific	Core Asia-US corridor; high scale economies		Port labour; weather; demand/capacity swings	Intermodal congestion; equipment/empty shortages
Asia-US East Coast	Canal-dependent alternative gateways		Panama constraints; hurricane season; Suez exposure	Route switching; higher variance in transit times; cost increases
Trans-Atlantic	Mature lane; industrial supply chains		Weather; strikes; cyber/IT risks	Moderate delays; sector-specific supply disruptions
Intra-Asia	Backbone of regional production + feedering into trunks		SCS/Taiwan geopolitics; typhoons; port shutdowns	Regional ripple effects; feeder disruptions; hub substitution
Asia-Middle East / ISC	Gulf hub role; inputs + consumer goods		Hormuz; Red Sea spillovers; sanctions/insurance	Risk premia; re-optimised routings; inventory delays
Asia-LatAm Africa	/ Growth corridors; high sensitivity to rates and capacity		Canal constraints; port productivity; weather/security	Higher import costs; reliability shocks

In table 2, we provide additional information on the major containerised trade lanes in recent years. It complements the previous table by showing the challenges major container lanes are currently facing, due to geopolitical turmoil, climate change, and commercial tension.

1.2.2. Network Metrics

In the previous subsection, we discussed some major trends in containerised transport based on ship flows from 1977 to 2024. To refine this analysis, we examine the structure and evolution of the maritime network. Based on the binary and weighted space-P topology⁷. We thus produce two series of four metrics for unweighted and weighted networks. These metrics aim to trace the major structural trends in the global network, but also to detect more subtle elements related to crises, market transformations, or the emergence of new players⁸.

⁷When the network is unweighted, the adjacency matrix contains only 0s and 1s. If two ports i and j are connected, then $a_{i,j} = 1$. For the weighted network, each link takes as its value the number of calls between the two ports i and j .

⁸Additional details on the metrics are provided in appendix A.

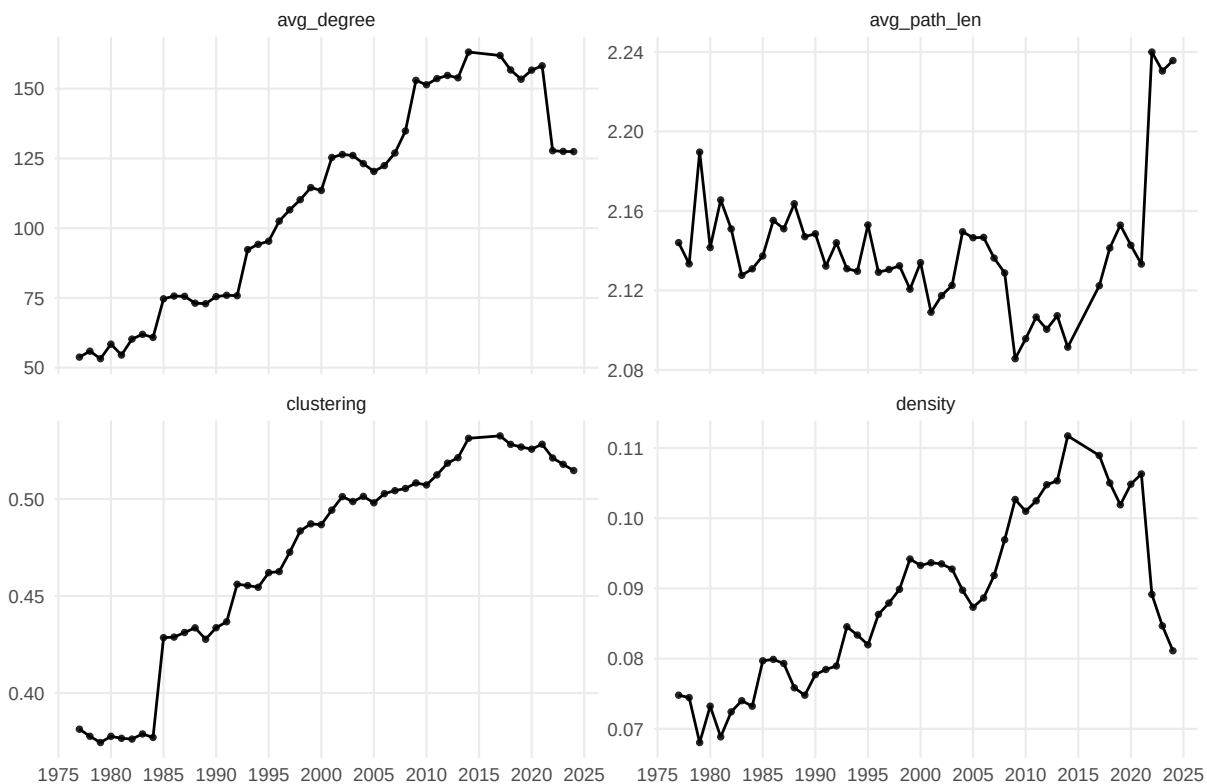


FIGURE 4. First set of metrics for the unweighted space-P network.

Notes: we computed four metrics for the global, unweighted, space-P network of containerised trade. The average degree is computed as the arithmetic mean of the number of connections each port has. The average path length shows the length of all the shortest paths from or to the vertices in the network. It is computed on the largest connected component of the graph. The transitivity measures the probability that the adjacent vertices of a vertex are connected. It is thus related to the regionalisation of maritime trade. The density of the network is the ratio of the actual number of edges and the largest possible number of edges in the graph.

This first figure presents four metrics for the unweighted space-P network. The average degree in the network increases steadily until the mid-2010s. It then reaches a plateau until the years following Covid-19, whose lockdowns particularly affected Asian ports. The impact of Covid-19 and the recent global disruption of value chains⁹ also had a significant effect on the average shortest-path length between ports. From 1977 to the mid-2010s, the network generally gained in efficiency: higher degree, shorter paths, rising clustering¹⁰, greater density. Over the last five to ten years, depending on the metric considered, new challenges have emerged to

⁹Several phenomena likely explain the recent disruption of global value chains: first and foremost Covid-19 and lockdowns, Houthi attacks, and the drought in the Panama Canal.

¹⁰More triangles and local redundancy in the network's topology. The increased branching reflects a more complex network in which containers become integrated across all segments of maritime freight.

which the global system has struggled to adapt.

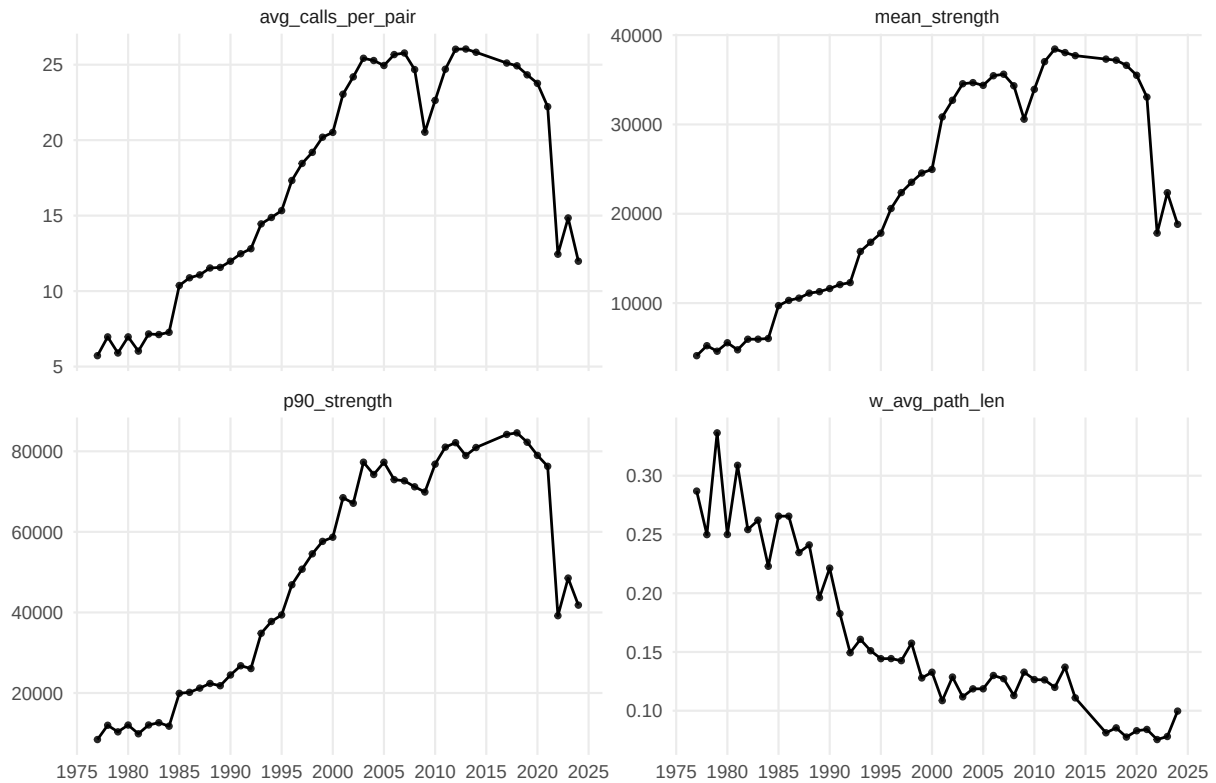


FIGURE 5. First set of metrics for the weighted space-P network.

Notes: in this figure, we computed four metrics for the global, weighted, space-P network of containerised trade. The average calls per pair corresponds to the arithmetic mean of the number of journeys between two ports A and B . The average strength is computed as the mean of the node strength. The strength is calculated summing up the edge weights of the adjacent edges for each vertex. We also compute it for the top 10% of the ports. Finally, we calculated a weighted version of the average path length.

The weighted network¹¹ (Fig. 5) suggests broadly similar dynamics. One important difference is the drop corresponding to the 2008–2009 crisis. The average number of calls per pair drops sharply at that time before returning to its early-2000s plateau. Overall, the period 1977–2008 corresponds to a strong expansion of (i) maritime trade and (ii) the containerisation of seaborne flows. China’s opening up through its WTO accession, technological progress, and the emergence of large hub-and-spoke networks supported this dynamic¹². The concentration of traffic along major corridors between large hubs drives a continued reduction in the weighted average path length over the whole period. The de-intensification of flows associated with recent disruptions

¹¹Each edge is weighted with the number of calls.

¹²There are certainly many other factors, including market concentration and alliances between carriers, the emergence of many Asian countries, and the pacification of certain maritime areas.

to maritime supply chains, therefore, does not prevent the maintenance of efficient routes.

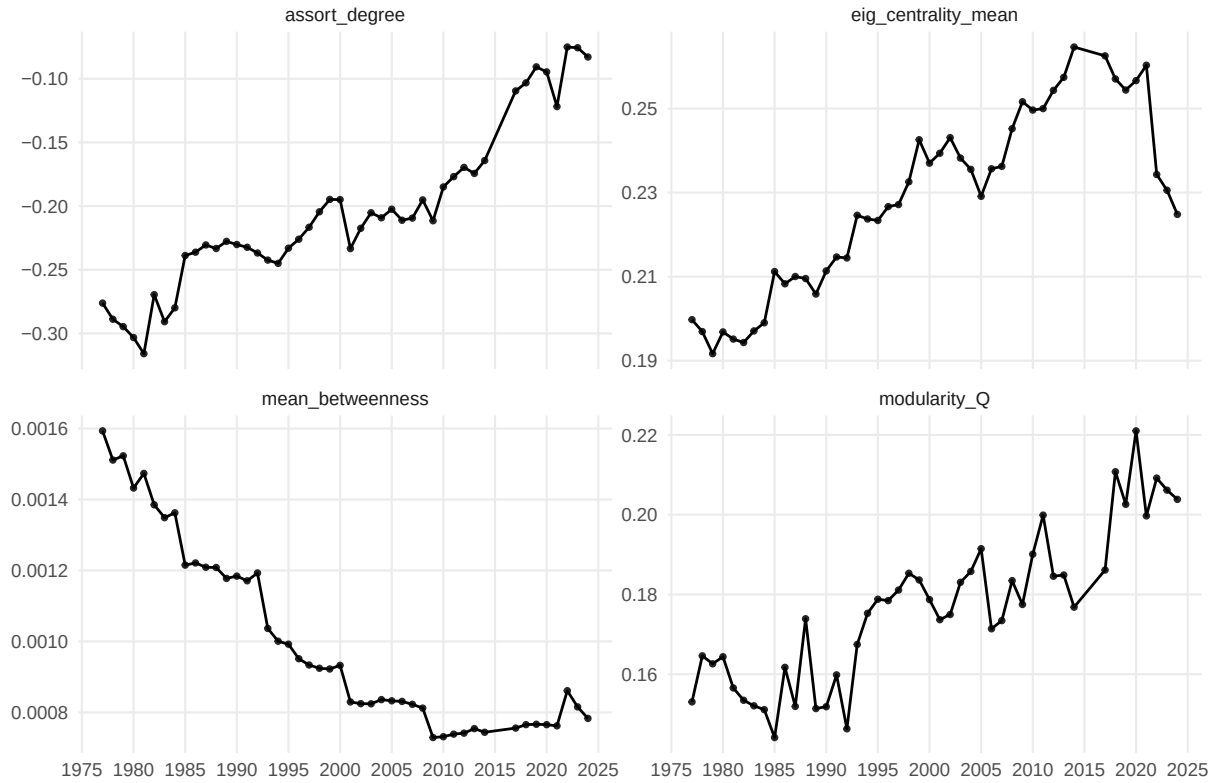


FIGURE 6. Additional set of metrics for the unweighted space-P network.

Notes: In this figure, we provide a set of additional metrics for the unweighted GCSN. The assortativity measures the level of homophily of the network. In the case of assortativity degree, the value assigned to vertices is their degree. The network is said assortative when nodes of comparable degree connect each other on average (positive correlation), and disassortative in the opposite case. The evolution of the average of the eigenvector centrality gives an idea of the distribution of the centrality in the network. If it increases, it means that more ports have access to central nodes in the network. The mean betweenness shows the number of alternative paths within the network. Its decrease indicates that the number of alternatives has grown and that dependency on a few pivotal hubs has weakened. The modularity (Q) provides information about the community structure of the graph. The increase in community structure can be related to dense, local links, and thus a process of regionalisation in the GCSN.

In Figure 6 and Figure 7, four additional metrics are added for unweighted and weighted space-P networks. These metrics allow us to further discuss the structural changes in global containerised networks over a long period of time. For weighted and unweighted space-P networks, the evolution of assortativity is broadly similar. Over time, the network becomes less assortative. This means that despite the permanence of hub-and-spoke structures, the intensification of connections between hubs reduces the propensity within the network for

ports to connect with other dissimilar ports. However, it should be noted that this reduction in disassortativity is more moderate in the case of the weighted network, and has even decreased again in recent years. This can be explained by recent disruptions that make long-distance connections more difficult and favour the intensification of shorter lines around hubs. Average betweenness and modularity both show similar trends.

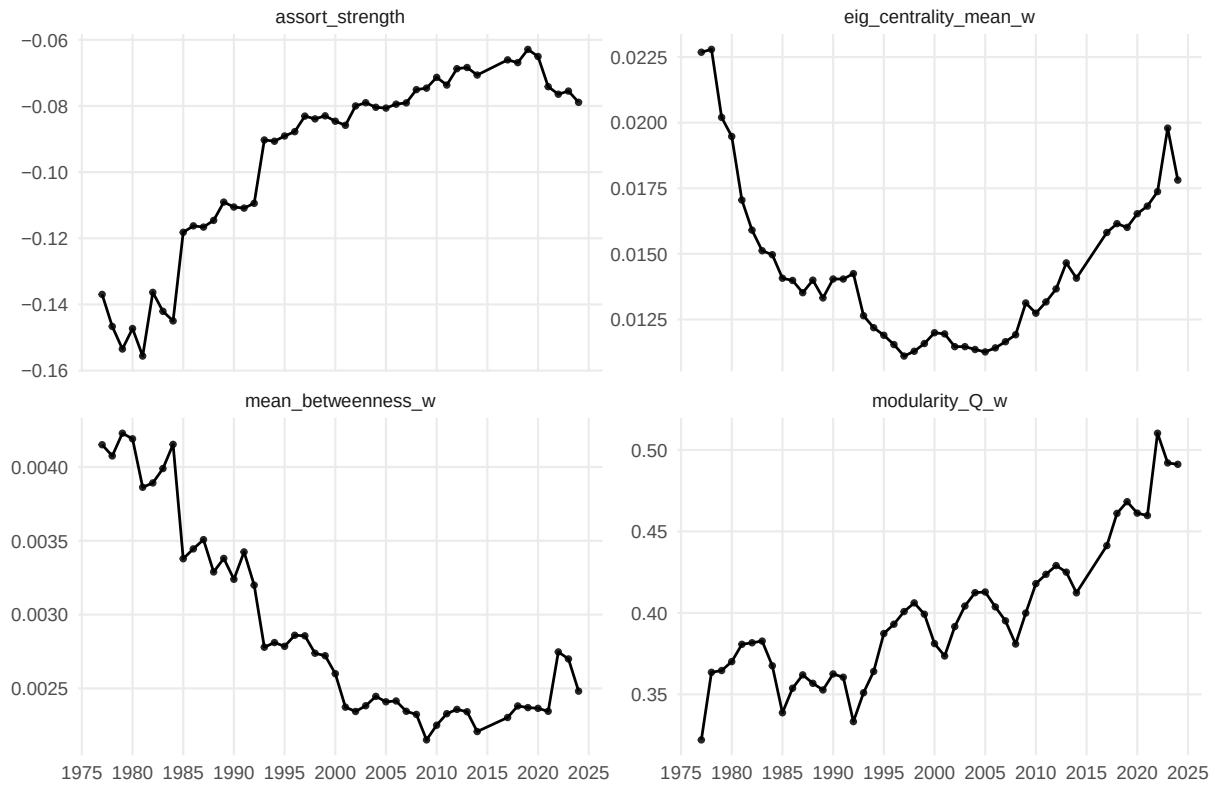


FIGURE 7. Additional set of metrics for the weighted space-P network.

Notes: This figure presents the same set of topological metrics computed on the weighted space-P GCSN. The assortativity by strength indicates the tendency of ports with similar traffic intensity to connect with each other. The average eigenvector centrality (weighted) captures how connectivity to central ports contributes to overall network influence once link intensity is considered. The weighted average centrality accounts for the number of calls between ports, thus reflecting the weighted intermediary of each node in the network. The average of the betweenness is calculated by taking into account the number of calls between ports. The modularity (Q_w) measures the strength of community structure when edge weights are included.

The decrease in betweenness indicates that the average number of alternative paths in the network is increasing. The network is becoming less dependent on a few major routes and offering alternative lines to connect large maritime areas. This can be interpreted as a reduction in the overall structural vulnerability of the network. However, it should be noted that

the decline in betweenness stopped around 2010 and has even tended to rise slightly in recent years. Recent tensions at several key maritime transport chokepoints (Red Sea, Panama) may explain this stagnation. The growth in modularity is reflected in the regionalisation of maritime flows, particularly in Asia. The densification of maritime networks, the growth in the number of triangles (cliques) in the network and the development of regional port systems in different basins (Northern Europe, South-East Asia, Western Mediterranean, etc.) are promoting the growth of the community structure of the global maritime network.

The difference in eigenvector centrality is also an interesting point to note, as it reveals the importance of different network structures. In the case of the unweighted network, eigenvector centrality grew significantly between 1977 and 2020. The upward trend in eigenvector centrality from 1977 to the end of the 2010s can be explained by a densification of the network: ports are connecting more with other ports that are already well connected, promoting the development of areas of attraction around the main ports. In the case of the weighted network, the increase in the number of containerised lines and their intensity, with calls spread over a larger number of lines, explains the decrease in average eigenvector centrality. From the 2010s onwards, several factors pushed average eigenvector centrality upwards, explaining the U-shaped curve. Market consolidation, the increase in ship size, and shock-driven reroutings (e.g., Red Sea or Panama constraints) forced a reconcentration of calls on a more limited number of routes. Based on this dual evolution of eigenvector centrality, we can interpret the structural evolution of containerised trade in two ways: (i) there has been a historical diffusion of topological centrality and (ii) a more recent repolarisation of usage on major shipping routes. The unweighted ‘skeleton’ of the network has expanded and become denser, while the dispersion of volumes reflects the dilution of the weighted average centrality. The 2010s saw traffic flows channeled back towards major corridors and hubs, without any additional densification of the network.

2. Hub Identification and Nodal Regions

The identification of hubs in this section was made possible using the algorithm first proposed by [Nystuen and Dacey \(1961\)](#) in their analysis of intercity communication flows in Oregon. This algorithm is relatively straightforward; it retains for each (port) node its largest flow link to another (port) node. Although this creates a massive loss of information in the case of ports having numerous links, it has the advantage of illuminating the hierarchy of hubs and the spatial extent of their dominance. Early applications of this methodology to maritime networks proved to be effective ([Wang and Wang 2011](#); [Cullinane and Wang 2012](#); [Ducruet and Notteboom 2012](#); [Wang and Cullinane 2014](#)), although they remained static and focused on recent years only. We performed this ‘single linkage analysis’ on the space-P topology, so that it considers both local and long-distance linkages. Due to the long-term period under investigation, we chose to

divide it by six sub-periods of eight years. The weight of links and nodes is the total number of vessel calls, a measure of voyage frequency at and between ports. The so-called “nodal regions” correspond to the extent of node dominance, not only through direct connections but also indirect ones through “transitivity”. For instance, if a given port C is dominated by port B, and port B is dominated by port A, then port C is also dominated by port A.

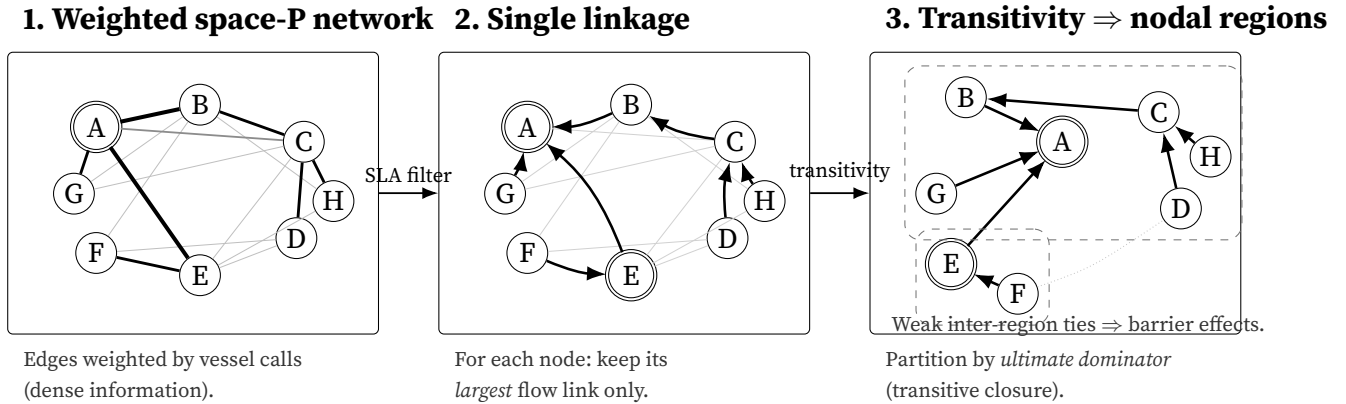


FIGURE 8. Illustration of single linkage analysis (SLA) and nodal regions.

Notes: The diagram illustrates the workflow used to construct nodal regions from the weighted space-P network. Panel (1) represents the original weighted graph (edge weights = vessel calls). Panel (2) applies single linkage analysis (SLA): for each port, only its largest flow link is retained (directed toward the dominant port). Panel (3) derives nodal regions by transitivity (dominance closure): if C is dominated by B and B by A, then C belongs to A’s nodal region. Dashed envelopes indicate the resulting partitions; dotted cross-links stylise weaker inter-region ties (‘barrier effects’).

The resulting nodal regions can be understood as port communities or “port systems”, namely groups of ports having dense maritime interactions internally ([Ducruet and Notteboom 2022](#)). The division of the whole network into nodal regions is also a revelation of “barrier effects” between port communities, caused by a variety of factors such as spatial frictions (e.g., physical distance as a cost, seas and basins closed by straits or canals), trade patterns (e.g., regionalization of trade exchanges), and network configurations (e.g., coastal and short sea shipping, hub-and-spokes) [Ducruet and Zaidi \(2012\)](#). The ability of a port to extend its dominance outside its region or even on other continents is revelatory of a strong centrality and intermediacy ([Fleming and Hayuth 1994](#)), despite physical distance increasingly impeding global container flows in the past decades. It was also demonstrated that the bulk of container shipping traffic occurs over the shortest distances ([Ducruet and Notteboom 2012](#)), while the geographic layout of port communities is highly influenced by geographic proximity ([Kaluza et al. 2010](#); [Sun, Zheng, and Hu 2012](#)). In the following figures, each port is colored according to its world region (continent) of belonging. The results are not projected geographically, but thanks to the Gem-Frick visualization algorithm using TULIP software. This visualization is a

core-periphery pattern putting the most central/dominant nodes in the center and the secondary nodes at the extremes.

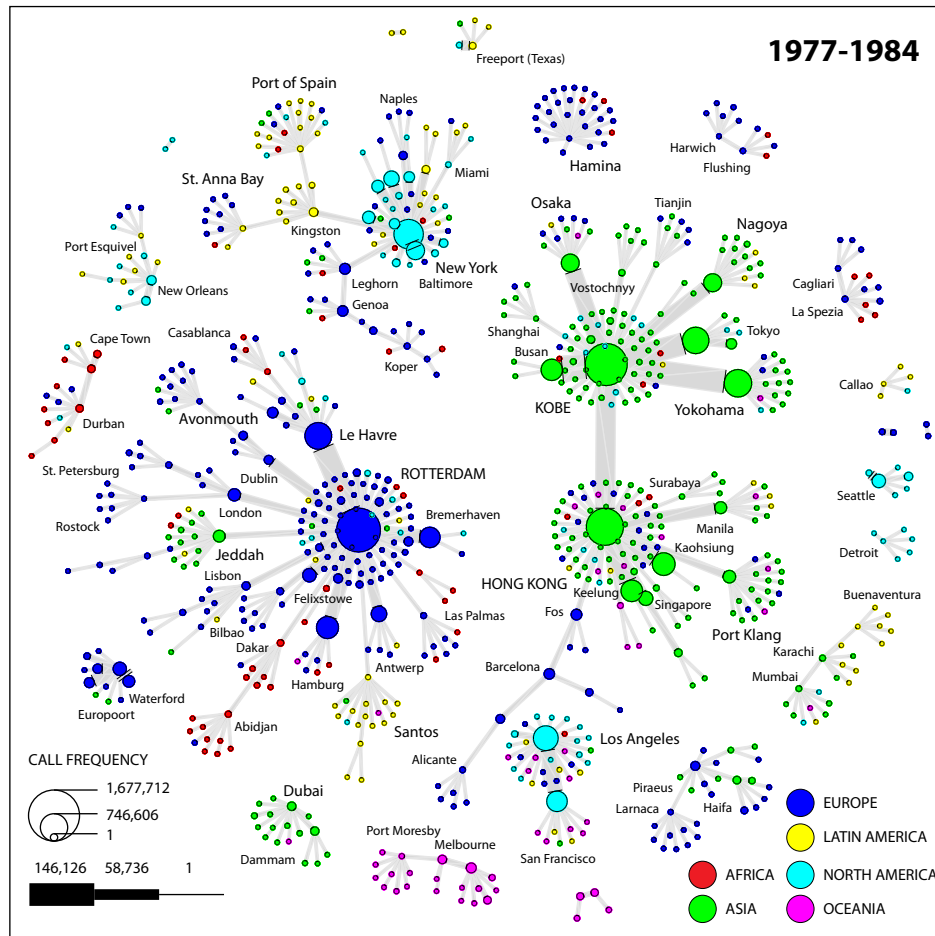


FIGURE 9. Nodal regions in the weighted space-P GCSN using the SLA algorithm (1977 - 1984).

Notes: Each figure displays the nodal regions identified using single linkage analysis on the weighted space-P network for the 1977 - 1984 period. Node size is proportional to the total number of vessel calls, and edges reflect the strongest connections between ports within each sub-period. Colours correspond to each port's continent or macro-region. The spatial layout is produced with the GEM-Frick force-directed algorithm (TULIP software), which places the most central ports near the core and peripheral nodes toward the outer layers.

Our analysis starts with the first period (1977-1984, Fig. 9) which is, according to (Guerrero and Rodrigue 2014), encompassing successive “waves” of containerisation: the pioneers (1970s), early adopters (mid-1970s), and diffusion (mid/late 1970s). New York, Rotterdam, Hong Kong and Kobe are the leading hubs, revelatory of the triadic configuration of the global economic system. Kobe dominates a number of Northeast Asian satellites (Busan, Shanghai, Tianjin,

Vostochnyy), but is principally a domestic transshipment hub, centralizing the flows of major Japanese gateways (Osaka, Nagoya, Tokyo, Yokohama). This “super-port” position in the national port system will later become a weakness following the Hanshin earthquake (1995), motivating a more balanced port development in Japan ([Shinohara 2009](#)). Hong Kong is more oriented towards the polarization of Southeast Asia. It had just started to play the role of re-export center for Chinese trade, due to the lack of container handling facilities in Chinese ports. Political factors also influenced shipping patterns. In 1979, China suggested the launch of cross-strait communications in trade, shipping and mail with Taiwan, which rejected the project, forcing traffic to be redirected via a third port, especially Hong Kong, until 2008 ([Wang, Hong, and Lin 2017](#)). Rotterdam is the unbeatable hub in North Europe, with extensions towards the Iberian peninsula, Brazil, West Africa, and the Red Sea. At that period, Le Havre (France) had a much stronger position than Antwerp, with the advantage of being the first and last port of call at the entrance of the English Channel. While Piraeus is the oldest container hub in the Mediterranean, together with Cyprus, the West Med gateways are polarized by New York on one side (Leghorn, Genoa, Naples) and Hong Kong on the other (Fos, Barcelona, Alicante). In the Caribbean, the pioneering hub is Kingston (Jamaica), together with Port of Spain, well connected to New York and the U.S. East Coast for transshipment ([McCalla 2008](#)).

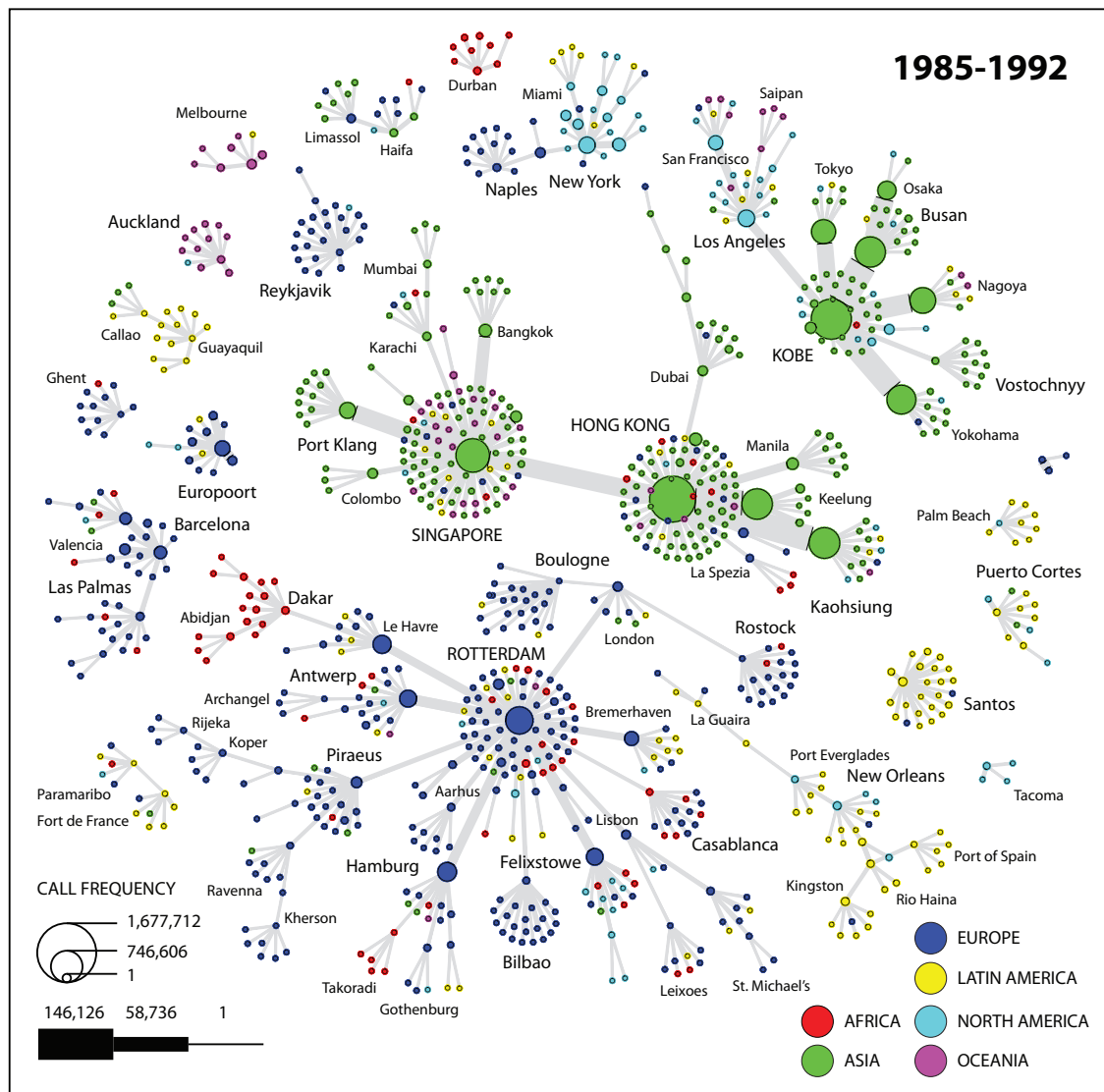


FIGURE 10. Nodal regions in the weighted space-P GCSN using the SLA algorithm (1985 - 1992).

Notes: Each figure displays the nodal regions identified using single linkage analysis on the weighted space-P network for the 1985 - 1992 period. Node size is proportional to the total number of vessel calls, and edges reflect the strongest connections between ports within each sub-period. Colours correspond to each port's continent or macro-region. The spatial layout is produced with the GEM-Frick force-directed algorithm (TULIP software), which places the most central ports near the core and peripheral nodes toward the outer layers.

The second period (1985-1992) witnessed impressive evolutions among the so-called “global hub port cities” (Lee, Song, and Ducruet 2008), as seen with the decline of New York and the rise of Singapore. The latter has the highest number of connections, thanks to the construction of Keppel and Brani container terminals in the 1980s, becoming the dominant hub for Southeast Asia and the Indian Ocean (Tan 2007; Akhavan 2017). The prime connection of Hong Kong is not anymore Kobe but Kaohsiung (Taiwan) for cross-strait transit trade. Kobe is still a major domestic hub, also connecting Los Angeles/San Francisco in the U.S., while Busan (South Korea) is still under its influence but gained significant centrality. Busan is mainly a gateway port serving the growing South Korean economy, as only 5% of its container throughput was dedicated to transshipment in 1989 (Fremont and Ducruet 2005). There are also major changes in Europe and the Americas. For instance, Hutchinson Port Holdings (Hong Kong) acquired its first stake in Felixstowe (U.K.) in 1991, making it the first European port investment for HPH, and over time HPH increased its stake to full ownership. The growth of Felixstowe also corresponds to the shift of U.K. port dynamics towards Southeast England, in a context of growing European integration, which had the effect of moving Europe’s centre of gravity closer to mainland (Overman and Winters 2005). European integration also favoured the growth of Antwerp and Hamburg as part of the “Northern Range” with Rotterdam and Le Havre, altogether constituting the new core of the concentrating European port system Notteboom (1997). Except for Naples, linked with New York, Mediterranean ports now form independent communities based on geographic proximity and respectively dominated by Piraeus (East Med) and Barcelona (West Med). Some relatively minor European ports are preserved from the centralization of major hubs, as seen with the multiplication of their connections: Boulogne (France), Rostock (Germany), Bilbao (Spain), Reykjavik (Iceland).

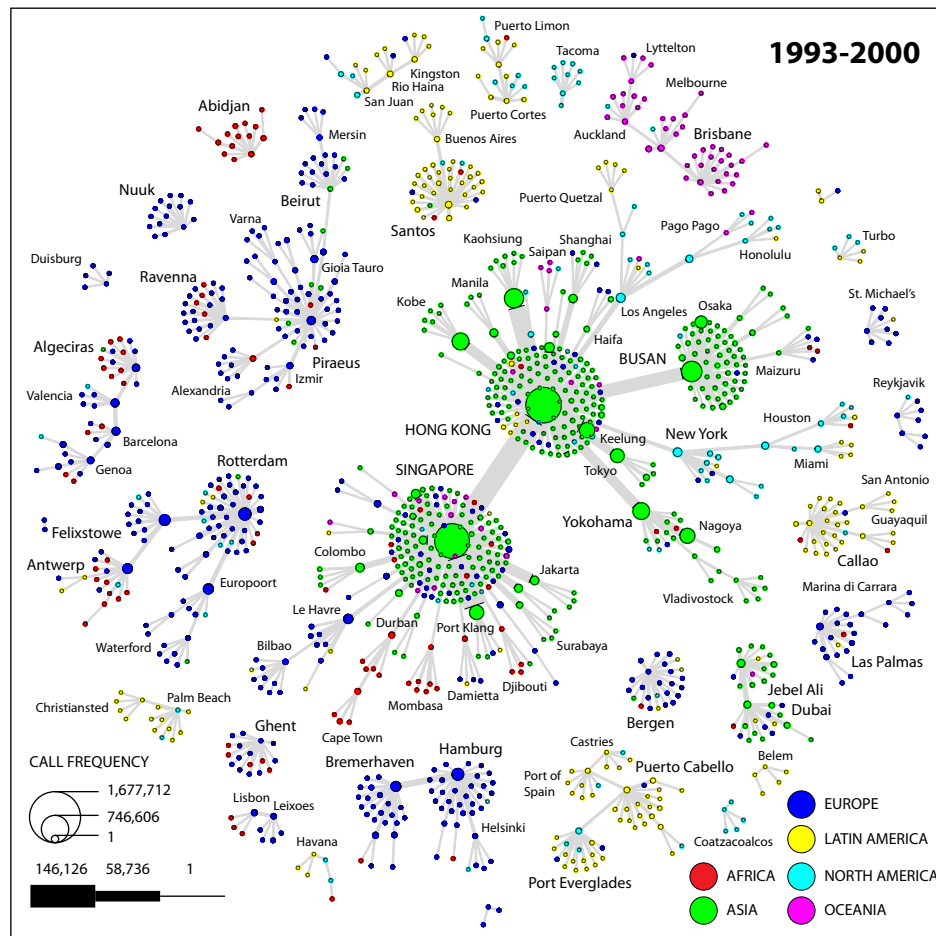


FIGURE 11. Nodal regions in the weighted space-P GCSN using the SLA algorithm (1993 - 2000).

Notes: Each figure displays the nodal regions identified using single linkage analysis on the weighted space-P network for the 1993 - 2000 period. Node size is proportional to the total number of vessel calls, and edges reflect the strongest connections between ports within each sub-period. Colours correspond to each port's continent or macro-region. The spatial layout is produced with the GEM-Frick force-directed algorithm (TULIP software), which places the most central ports near the core and peripheral nodes toward the outer layers.

The third period (1993-2000) marks a turning point, with the growing centralization of the global network by Asian ports, and notably the emergence of the “East Asian maritime corridor” (Singapore – Hong Kong – Busan). The connections of Singapore now penetrate the Mediterranean and even reach Le Havre/Bilbao. Kobe is not anymore a hub, mainly due to the Hanshin earthquake (1995), which had the effect of shifting traffic to Busan (Xu and Itoh 2018), whose transshipment function grew to 25% of total throughput in 1999. Other factors explain the growth of Busan as a hub, of which its central position in Northeast Asia and proximity to major

sea lanes, its lower port costs and less cumbersome labor relations than Japan ([Fremont and Ducruet 2005](#)). Major Japanese ports are now dependent on Hong Kong and Busan to access the network. Hong Kong maintained and even increased its centralization, while the growth of Pearl River Delta ports in mainland China is not yet visible ([Wang 1998](#); [Song 2002](#)). Rotterdam has, in relative terms, become a secondary hub at the global scale, notably because the Northern Range has become divided internally, with German ports being apart. Piraeus, corporatized in 1999, has become a stronger hub for the East Med, while the West Med maintained its importance. Elsewhere, local hubs largely owe their unique position to a large, nearby metropolitan area, like Santos (Sao Paulo) and Callao (Lima) in Latin America.

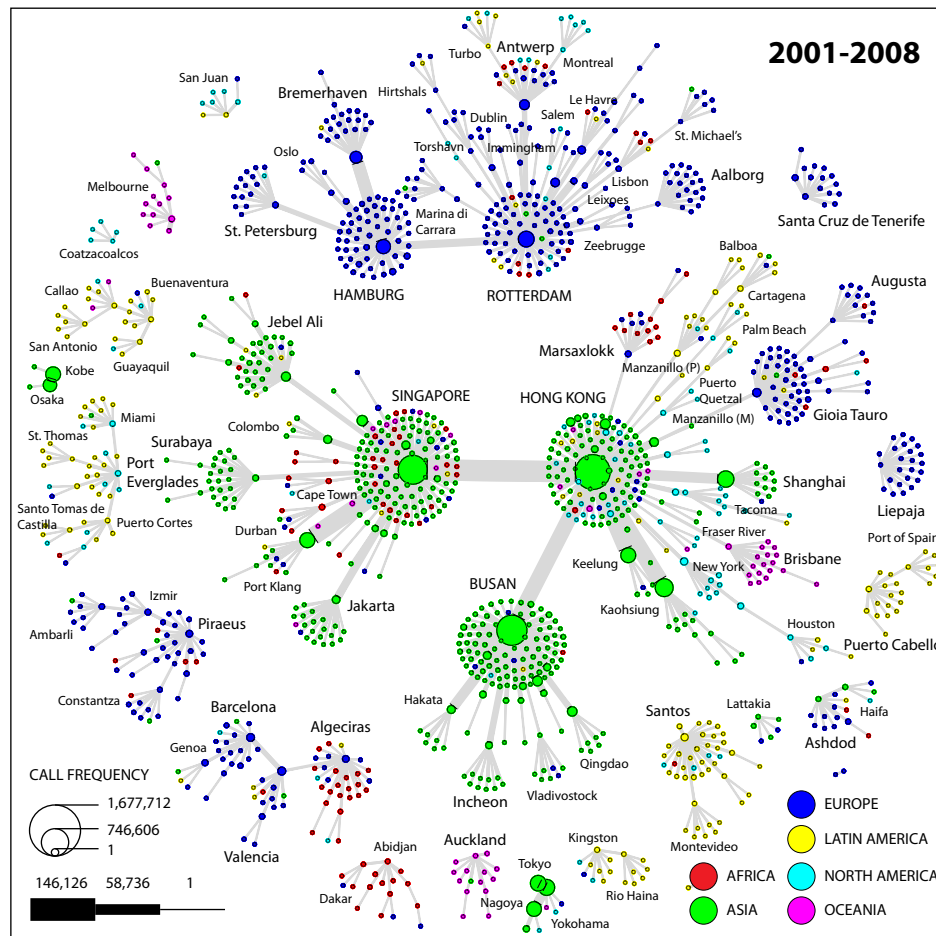


FIGURE 12. Nodal regions in the weighted space-P GCSN using the SLA algorithm (2001 - 2008).

Notes: Each figure displays the nodal regions identified using single linkage analysis on the weighted space-P network for the 2001 - 2008 period. Node size is proportional to the total number of vessel calls, and edges reflect the strongest connections between ports within each sub-period. Colours correspond to each port's continent or macro-region. The spatial layout is produced with the GEM-Frick force-directed algorithm (TULIP software), which places the most central ports near the core and peripheral nodes toward the outer layers.

In the fourth period (2001-2008), the East Asian maritime corridor still occupies a very central place in the global system. Hong Kong in particular extends its dominance towards the Caribbean, the Mediterranean, the U.S. East Coast, and Australia. Jakarta and Surabaya have emerged as pivotal ports for Indonesian domestic shipping, but they still rely on Singapore to access global shipping, due the government's reluctance to create an international hub in the country (KAWASAKI et al. 2019). Another noticeable growth is Jebel Ali (UAE), following the merger between Dubai Ports Authority (DPA) and Dubai Ports International (DPI) to form

Dubai Ports World (DP World), launched as a global terminal operator in 2005 ([Jacobs and Hall 2007](#)). Kobe, Osaka, Tokyo, Nagoya and Yokohama have all lost their hub functions, remaining large gateways but at the periphery. New Mediterranean hubs have emerged, such as Algeciras (Spain), Marsaxlokk (Malta) and Gioia Tauro (Italy), launched in the mid-1990s in a context of growing ship sizes and route optimization by shipping lines, and best positioned on the main trunk lines ([Zohil and Prijon 1999](#)). This explains the relative decline of Piraeus, with a connectivity shrinking around Turkey and the Black Sea, and the disappearance of several West Med gateways, except Barcelona and Valencia, notably thanks to successive port reforms in Spain ([Castillo-Manzano et al. 2018](#)).

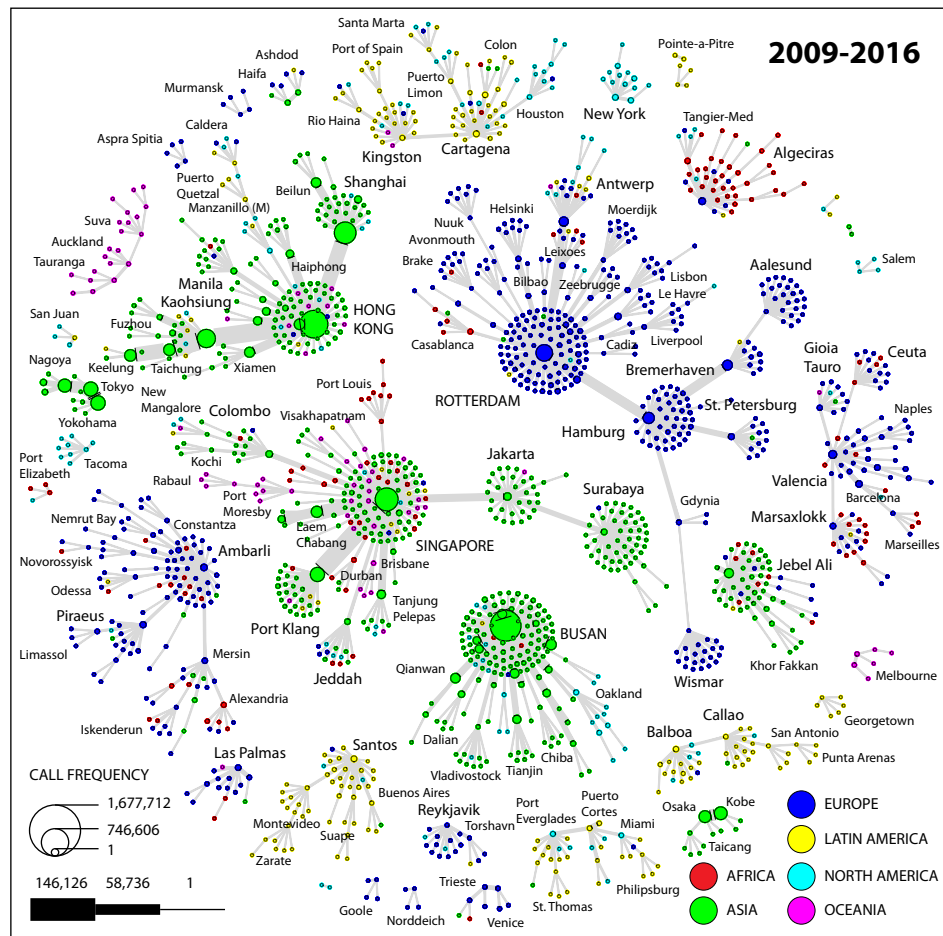


FIGURE 13. Nodal regions in the weighted space-P GCSN using the SLA algorithm (2009 - 2016).

Notes: Each figure displays the nodal regions identified using single linkage analysis on the weighted space-P network for the 2009 - 2016 period. Node size is proportional to the total number of vessel calls, and edges reflect the strongest connections between ports within each sub-period. Colours correspond to each port's continent or macro-region. The spatial layout is produced with the GEM-Frick force-directed algorithm (TULIP software), which places the most central ports near the core and peripheral nodes toward the outer layers.

The penultimate period (2009-2016) is consistent with the former, given the maintained dominance of Hong Kong, Singapore, and Busan, although they are not any more connected by their respective largest links, which indicates a stronger hub-and-spokes function locally. Busan expanded its influence on Northern Chinese ports, such as Dalian and Tianjin, while more Chinese ports have appeared connected to Hong Kong: Fuzhou and Xiamen in the South, but most importantly, Shanghai at the mouth of the Yangtze River Delta (YRD). The spread of containerisation across the YRD had been gradual but vital for Shanghai, of which 50%

total traffic emanates from river shipping. The growth of Shanghai as a “multilayered gateway-hub” (Wang and Ducruet, 2012) has been possible based on two concomitant dynamics: the polarization of inland river ports, by building logistics bases in the YRD and purchasing shares; and the launch of Yangshan offshore hub in 2005, connected to mainland by truck through the Donghai Bridge. Despite the continued reliance of Chinese ports on Hong Kong in the figure, their growth largely explains the relative decline of Hong Kong, since they became able to connect the network through direct calls from major shipping lines. Another reason for Hong Kong’s reduced position is its transformation from hub port city to “global supply chain management center” (Wang and Cheng 2010), focusing increasingly on advanced tertiary functions rather than physical distribution functions. While Kingston, Piraeus, Gioia Tauro and Marsaxlokk have maintained their centrality, they have become dominated by a larger hub in their respective regions. This is due to the emergence of Cartagena (Colombia), Valencia (Spain), and Ambarli (Turkey) as new hubs, going beyond their gateway functions. Valencia, traditionally a gateway port, was selected in 2002 as a Mediterranean hub by the shipping company MSC, “leading to a percentage of transshipment over 50% after 2009” and a +20% increase of transshipment volumes between 2007 and 2015 (Grifoll 2019). Ambarli, situated in the giant Istanbul metropolis, has become the prime East Med and Black Sea hub, following two decades of port devolution, attraction of domestic and global investors, and improvement of port infrastructures (Esmer and Duru 2017), notwithstanding the emergence of smaller Turkish ports like Mersin, Iskenderun, and Nemrut Bay. Cartagena benefited from a favourable context, as “the geographical distribution of transshipment in the Caribbean has shifted towards the Isthmus of Panama” (Rodrigue 2021), just before the expansion of the canal in 2016.

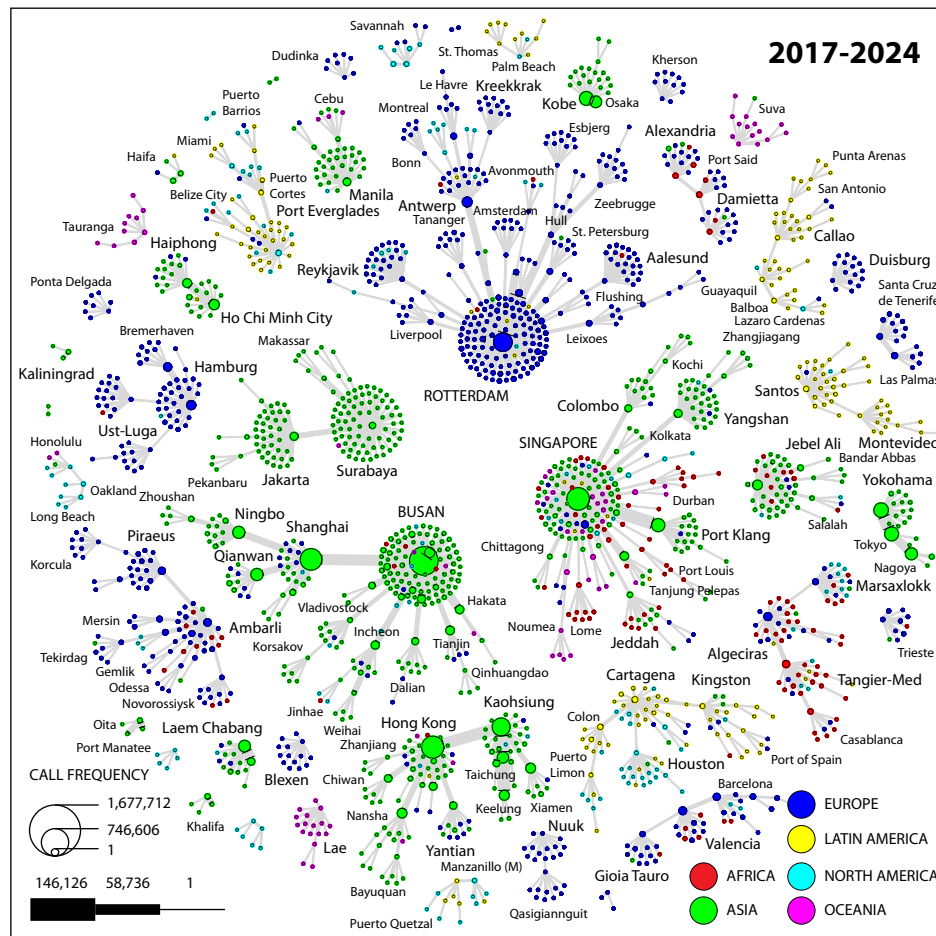


FIGURE 14. Nodal regions in the weighted space-P GCSN using the SLA algorithm (2017 - 2024).

Notes: Each figure displays the nodal regions identified using single linkage analysis on the weighted space-P network for the 2017 - 2024 period. Node size is proportional to the total number of vessel calls, and edges reflect the strongest connections between ports within each sub-period. Colours correspond to each port's continent or macro-region. The spatial layout is produced with the GEM-Frick force-directed algorithm (TULIP software), which places the most central ports near the core and peripheral nodes toward the outer layers.

The last and most recent period (2017-2024) is very similar to the former for the overall structure and port hierarchy. Most of the previously mentioned hubs have maintained their position in the network. A number of medium-sized hubs have emerged, however, such as Ho Chi Minh City and Haiphong (Vietnam), Laem Chabang (Thailand), Manila (Philippines), Yangshan (China), and Tangier-Med (Morocco). The rise of Yangshan cannot be isolated from the growth of other Chinese ports, including Shanghai itself, which dominates Ningbo and Qianwan (Qingdao's new port), but also Shenzhen ports (Chiwan, Yantian) dominated by Hong

Kong in the Pearl River Delta. As underlined by a former study, mainland Chinese ports still fail to become international transshipment hubs, given the priority given by shipping lines to “capitalist” hubs like Busan, Hong Kong, and Singapore (Ducruet, Lee, and Ng 2010). To be noted is the growing number of African ports being dominated by Singapore. This is an illustration of the actual linkages between China and Africa, as seen with the connection with Lome (Togo), in view of China’s increasing economic involvement in the development of the African continent (Chen, Xu, and Haralambides 2020). The inclusion of small European ports in the nodal regions of several Chinese ports is revelatory of the linkages created by the New Maritime Silk Road project launched in 2013 by the Chinese government (Wang et al. 2018). However, the effects of China’s overseas investments in European port operations remain only superficially visible, especially given the stagnation of Piraeus as a hub, despite the involvement of COSCO in the port, with a majority acquisition in 2016, and the completion of full controlling stake in 2021. Our analysis corroborates the findings of Koenig et al. (2023), who found that the privatization and acquisition of Piraeus by COSCO increased the ports’ attractiveness mainly for COSCO vessels, while “the use of Piraeus by the vessels of other operators remains relatively unchanged”.

Discussion and Conclusion

In this article, we have attempted to analyse the dynamics of containerised transport from its emergence on the global stage to the present day. Invented in 1956 in the United States, containerised transport gradually spread from the 1960s onwards, particularly in Europe, and has grown significantly since the 1970s. In 2024, it is the main mode of maritime freight transport, carrying almost half of global trade, all modes of transport combined. Between 1977, the first year of our sample, and 2024, global trade underwent major upheavals: the emergence of China and regional Asian powers, the fall of the USSR, and European regional integration, to name but a few major trends.

The first part of our quantitative analysis focuses on global trends in containerised maritime trade over the period. We show that the almost continuous growth in trade volumes, as well as in the number of connections and active ports in the network, has been accompanied by both an improvement in network efficiency and more complex phenomena. As such, the maritime network can hardly be compared to the networks initially studied in the field of complex systems. Physical constraints (straits, canals), geopolitical constraints (armed conflicts, territorial disputes) and commercial constraints (competition between carriers, customs duties) limit the emergence of the scale-free and small-world properties that characterise many complex systems. It should also be noted that the hub-and-spoke dimension of the network is variable; the intensification of links between major ports on the world’s main routes, but also the densification of regional connections between smaller ports, moderate the overall hierarchical

structure of the network.

The second part of our quantitative exploration of global containerised trade aims precisely to identify the structure and nature of hierarchies in the maritime network. Using a single linkage analysis algorithm over the entire period allows us to study (i) the evolution of vertical hierarchies in container transport and (ii) the identification of the main maritime regions. The use of space-P topology, which traces transport lines and not just direct connections, avoids over-spatialisation of the network. We therefore propose an empirical approach to detect the structure and dynamics of functional maritime trade communities by ‘erasing’ geographical barriers¹³. From the first to the last period, three major changes can be identified in the network: (i) the shift from a New York-Rotterdam-Kobe/Hong Kong triad to a dominant Singapore-Hong Kong-Busan corridor; (ii) the multipolarisation of the network from 2000 onwards with the emergence of regional hubs (Jebel Ali, Algeciras, Marsaxlokk, Gioia Tauro, Valencia, Ambarli) and the fragmentation of associated traffic; and (iii) the stabilisation of the hierarchy coupled with a densification of regional connections and an extension of the influence of Asian hubs over Africa. The dominance of Asian hubs has thus resulted in the integration of African ports into the sub-network dominated by Singapore over the last ten years. It is also noteworthy that over the period 2017-2024, Rotterdam has not disappeared from the network but has become regionalised, dominating a mainly European system.

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¹³This is one of the major challenges of community detection in maritime networks. By taking direct connections into account, the density of local networks highlights purely geographical communities. These are separated by straits, canals and continents, and simply recreate the major Asian, Mediterranean and Atlantic basins.

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A. Network metrics: definitions and computation

This appendix details the network indicators reported in Figures 4–7. We consider a port-level undirected space-P network $G = (V, E)$ with $n = |V|$ ports and $m = |E|$ links.¹⁴ In the unweighted version, links are encoded by an adjacency matrix $A = (a_{ij})$ with $a_{ij} = 1$ if ports i and j are connected and 0 otherwise. In the weighted version, each link $(i, j) \in E$ carries a weight $w_{ij} \geq 0$ equal to the number of calls between i and j over the period considered.

A.1. Unweighted metrics (Figure 4)

Average degree.. The degree of port i is $k_i = \sum_{j \neq i} a_{ij}$. The average degree is

$$\bar{k} = \frac{1}{n} \sum_{i \in V} k_i = \frac{2m}{n}.$$

Network density.. Density is defined as the fraction of realised links among all possible links:

$$\delta = \frac{2m}{n(n-1)}.$$

Transitivity (global clustering).. Let T denote the number of triangles and W the number of connected triples (two-paths). Global transitivity is

$$C = \frac{3T}{W}.$$

Average path length.. Let $d(i, j)$ be the unweighted geodesic distance between ports i and j . We compute the average path length on the largest connected component (LCC):

$$\bar{\ell} = \frac{2}{|V_{\text{LCC}}|(|V_{\text{LCC}}| - 1)} \sum_{i < j \in V_{\text{LCC}}} d(i, j).$$

¹⁴In each year, multiple observations for a given dyad are aggregated into a single edge. Self-loops are removed.

A.2. Weighted metrics (Figure 5)

Average calls per connected pair. Let $W = \sum_{(i,j) \in E} w_{ij}$ be the total weight across edges. The average calls per connected pair is

$$\bar{w} = \frac{1}{m} \sum_{(i,j) \in E} w_{ij} = \frac{W}{m}.$$

Node strength and average strength. The strength of port i is

$$s_i = \sum_{j \neq i} w_{ij},$$

and $\bar{s} = \frac{1}{n} \sum_{i \in V} s_i$. We also report the mean strength among the top 10% ports by strength.

Weighted average path length. To compute distances in a weighted graph, we convert weights into edge lengths using a monotone decreasing transform. We set

$$\ell_{ij} = \frac{1}{\max(w_{ij}, \varepsilon)},$$

with a small $\varepsilon > 0$ to avoid division by zero. The weighted shortest-path distance $d_w(i, j)$ is the minimum sum of edge lengths along all paths between i and j . We compute:

$$\bar{\ell}_w = \frac{2}{|V_{\text{LCC}}|(|V_{\text{LCC}}| - 1)} \sum_{i < j \in V_{\text{LCC}}} d_w(i, j).$$

A.3. Additional metrics (Figures 6 and 7)

Assortativity. Degree assortativity is the Pearson correlation between the degrees at both ends of an edge. In the weighted case, we compute the Pearson assortativity of node strengths across edges.

Eigenvector centrality. In the unweighted case, eigenvector centrality x satisfies $Ax = \lambda x$. In the weighted case, A is replaced by the weighted adjacency matrix $W = (w_{ij})$. We report the average eigenvector centrality across nodes.

Betweenness centrality. Betweenness of node i is

$$b_i = \sum_{s \neq i \neq t} \frac{\sigma_{st}(i)}{\sigma_{st}}.$$

We report average betweenness. In the weighted case, shortest paths are computed using edge lengths ℓ_{ij} as defined above (*i.e.*, using calls-based costs).

Modularity. For a partition c_i , unweighted modularity is

$$Q = \frac{1}{2m} \sum_{i,j} \left(a_{ij} - \frac{k_i k_j}{2m} \right) \mathbf{1}_{\{c_i = c_j\}}.$$

Weighted modularity is

$$Q_w = \frac{1}{2W} \sum_{i,j} \left(w_{ij} - \frac{s_i s_j}{2W} \right) \mathbf{1}_{\{c_i = c_j\}}, \quad W = \sum_{(i,j) \in E} w_{ij}.$$

Implementation notes. All metrics are computed on annual port-level networks. Average path length (unweighted and weighted) is computed on the LCC.

CHAPTER 3

Shipping Trade and Geopolitical Turmoil

The Case of the Ukrainian Maritime Network

Abstract

Conflicts, whether political, commercial or military, affect transport networks. In the context of large-scale conflicts, operators seek to avoid the most tense areas or reconsider certain routes. Certain links can be disrupted in case of local geopolitical tensions, which can have a significant global impact. The article is devoted to studying Ukraine's maritime network and identifying changes in these structures because of the armed confrontation that started in 2014. The purpose of the paper is to quantify, model and visualise the main changes in the Ukrainian seaport system and maritime forelands from 2010 until the most recent data available (December 2024). To this end, we propose a threefold strategy based on network models, bilateral trade analyses and route simulation. The results emphasise three (dynamic) processes characterising the Ukrainian seaport system: significant short-term impact, disruption - mostly on distant connections - and resilience of the network through reallocation to other routes and transport modes.

Keywords: Black Sea, Complex networks, Shipping Trade, Russian-Ukrainian War

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Introduction

In the last few decades, scientific research on ports and shipping has predominantly and increasingly insisted on the importance of market forces and the role of global players in value and logistics chains. Yet, in his major contribution entitled *The Sea and the Geostrategy of Nations*, the French geographer [Vigarié \(1995\)](#) expressed a nuanced - if not alternative - viewpoint:

A commercial operation always has a certain political significance. Commodities or economic activities for the exchange of goods are rarely neutral. They carry the print of the society where they come from, which possesses its own rules of external relations, its forms and its domains of production; they vehicle their linguistic and cultural characteristics; they are witnesses of a form of civilisation; they are the expression of interests that all partners do not share; they express a policy, which means a dynamic of insertion in the outside world: liberal, socialist. . . Trading is thus expressing certain behaviour; and the sea, with the ports, constitutes one of the most important vectors for transmitting this cultural, economic and political background.

However, explicit research on politics and trade in a port context remains limited and scattered. [Notteboom, Ducruet, and de Langen \(2009\)](#) underlined the existence of publications on naval warfare, coastal shipping policies, and the influence of local merchant elites, to name but a few. They particularly shed light on two sets of research developed in geography: a) ports as institutions embedded in a territorial structure where power relations are fundamental; and b) the tension between global and local, economics and politics in maritime network distribution. Changing political regimes and borders received particular attention in recent studies of ports and shipping networks in a communist ([Zreik et al. 2017](#); [Ducruet and Yoon 2022](#); [Yoon 2024](#)) or colonial context ([Castillo and Ducruet 2017](#); [Tsubota, Kidwai, and Ducruet 2017](#)).

Studies on military events such as wars remain, in comparison, very few¹. War impacts on shipping networks can be classified in a broader category of shocks, defined by the partial or complete destruction of transport infrastructure, and may require more time to recover compared to other types of shocks. Military operations include bombings on port terminals and anchored ships, to undermine durably a country's capacity to trade. Such a category also includes natural disasters like hurricanes and earthquakes as well as terrorist attacks. In comparison, economic crises, civil wars, inter-oceanic canal disruptions, pandemics, and embargoes should have less severe impacts on port nodes and maritime routes, but this depends on their duration and depth. As will be presented below, scholars analysed such events through a wide variety of themes and methods.

The research proposed in this article is particularly challenging, as it deals with the ongoing war between Ukraine and Russia at the time of writing. The study period starts in 2010, before

¹One can see [Walker \(1989\)](#) for an early study.

the annexation of Crimea by Russia (2014), to look at the impacts of this border change, until the invasion of Ukraine that took place in 2022, followed by military events up to late 2023. Our analysis has the advantage of being documented by a third-party data source, namely the Lloyd's List Intelligence database on daily vessel movements among ports of the world. As Lloyd's insures most of the world's fleet, and documents the ship movements of other insurers, this allows a very complete, precise, and neutral source of information not depending on local statistics.

As underlined by [Gruchevska, Notteboom, and Ducruet \(2017\)](#), *'the political and economic instability of the Black Sea states (mainly Russia and Ukraine) could counter-work global trends and prevent the region from potential dynamic development'*. The authors already recalled that important volumes of Ukrainian container throughput had been lost to Hamburg, Baltic ports, and Constanta (Romania) from 2012 onwards, due to regulatory changes in customs procedures. The annexation of Crimea and the armed confrontation at the border with Russia already provoked a 14% drop in container throughput in 2014. The analysis of the Black Sea container shipping network between 1977 and 2015 ([Gruchevska, Notteboom, and Ducruet 2017](#)) revealed important trends, such as the growing internal connectivity of the region, and the increasing share of Turkey in this connectivity, but without a (hub) port concentration process. This is mainly due to the nautical limitations of the Bosphorus Strait, which favour traffic concentration at external hubs, in the Eastern Mediterranean.

This research intends to examine the more recent period with a methodology based on network properties. It proposes a global and region-wide analysis of shipping connectivity, this time including bulk shipping, which is traditionally a major component of Ukraine's and other Black Sea countries' trade. The analysis shall explore how border changes and military events affected several dimensions of the Black Sea port system, such as its internal maritime connectivity and port hierarchy, the so-called "ego-network" (*i.e.*, foreland) of Ukrainian ports, and the pattern of recovery - if any - in late 2024. We shall focus on Ukraine's possible external hub concentration as a "constrained economy" ([Ducruet 2008](#)). How have certain ports and connections been resilient to change? Can we observe stability in the spatial design of the port hierarchy and shipping network? Does this military event witness known regularities in the field of network vulnerability?

The remainder of the article is as follows. The first section sets the scene by depicting the evolution of the Ukrainian economy since the collapse of the Soviet Union in 1991. The second section reviews the scientific literature about shipping networks, with a particular focus on vulnerability issues. It is followed by section 3, which presents the data and methodology to analyse the connectivity of Ukrainian ports between 2010 and 2024. Section 4 is devoted to results, followed by some conclusions in section 5. Additional results, tables and figures can be found in the appendix.

1. Historical Background and Geopolitical Context

Ukraine declared its independence from the Soviet Union in August 1991, following a failed coup against Soviet leader Mikhail Gorbachev. The dissolution of the Soviet Union led to the emergence of independent states, including Ukraine and Russia. The current war has transformed Ukraine's economic landscape and regional trade dynamics, with significant implications for global economic relations and energy security.

After independence, the country experienced significant economic reforms, such as the transition to a market economy, privatization, and the attraction of foreign investment, particularly in agriculture, energy, and telecommunications ([Aidis \(2003\)](#), [Berkowitz and DeJong \(2005\)](#), [Brown, Earle, and Álmos Telegdy \(2006\)](#), [Estrin et al. \(2009\)](#)).

Political and economic relations between Ukraine and Russia experienced a first significant disruption in 2014 following the Maidan Square protests after the suspension of the signing of an Association Agreement with the EU by the Ukrainian President Viktor Yanukovich and his ousting. Following this, the onset of armed confrontation in the separatist regions of Lugansk and Donetsk and Russia's annexation of Crimea, condemned by Ukraine and the international community ([Dumont \(2007\)](#), [Dumont and Verluise \(2009\)](#), [Dumont \(2023\)](#)[Sokoloff \(2014\)](#)), have resulted in a drastic reduction in the economic relations hitherto retained by the two countries.

The armed confrontation then turned into an open war in February 2022 when Russian President Vladimir Putin decided to invade Ukraine, heavily impacting the population, the economy ([Orcier \(2022\)](#), [Dräger, Gründler, and Potrafke \(2025\)](#)) and the infrastructures of the country. The maritime transport of Ukraine, that is the focus of this paper, has been subject to a deep disruption since the start of the war. The Russian naval blockade on Ukrainian ports, interrupted only during the Grain Initiative promoted by the United Nations from July 2022 to July 2023 to preserve the cereal export of the countries, and attacks on port infrastructures determine a huge reduction of maritime activity and of the maritime trade.

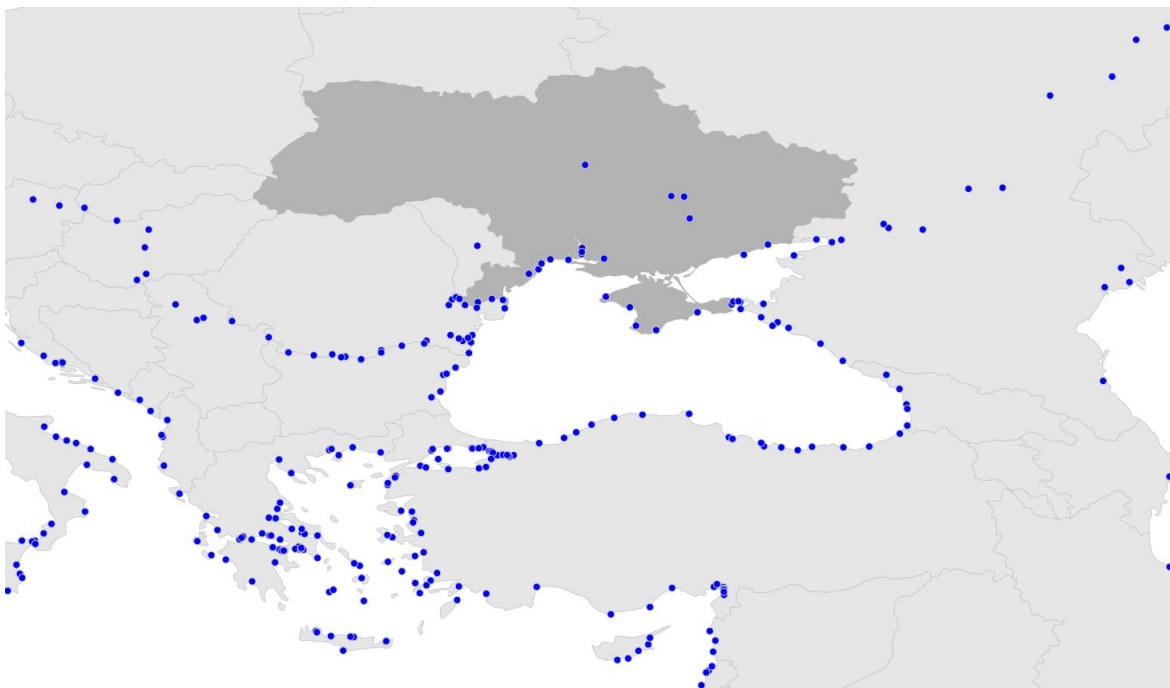


FIGURE 1. Ports in the Black Sea

Notes: All the ports identified in the *Lloyd's List* database are plotted in this map. After 2014 the Crimean ports are considered as Russian by *Lloyd's*. It does not affect a lot the commercial flows considering that they mainly have military purposes. We also represent the river ports and the ports of the Marmara Sea and Eastern Mediterranean.

In the case of trade, Ukraine's port development has been a significant aspect of its economic strategy since this independence, given its extensive coastline along the Black Sea and access to major international shipping routes. Ukraine's port development has been an important component of its efforts to leverage its geographical location and natural resources to drive economic growth and strengthen its position in regional and international trade networks. Continued investment in port infrastructure and reforms to improve efficiency and competitiveness will be essential for realising these objectives.

Before, Ukraine had invested in modernising and expanding its port infrastructure to enhance efficiency and capacity. This includes dredging and deepening of harbour channels to accommodate larger vessels, upgrading cargo handling equipment, and improving logistics and transportation networks. Ukraine's ports, particularly Odesa, Mariupol, and Yuzhny, are strategically important for trade with Europe, Asia, and the Middle East. These ports provide access to the Black Sea and, via the Bosphorus and Dardanelles straits, to the Mediterranean Sea, and the Atlantic via the Strait of Gibraltar, or in the Indian Ocean via the Suez Canal.

Ukraine's ports play a crucial role in the country's export-oriented economy, particularly for grain, steel, iron ore, and other bulk commodities. Grain exports, in particular, have been a

major focus, with Ukraine being one of the world's largest producers of grains such as wheat, corn, and barley. In the same way, mining products, such as iron ore, of which the country was the fourth largest producer in 2022, and pig iron, of which it was the second largest producer in the world, as well as other metal products, were a key component of maritime exports before the war.

Thanks to that important production, Ukraine has sought closer integration with European markets before the war, through initiatives such as the EU-Ukraine Association Agreement. Improving port infrastructure and aligning with European standards are, right now, crucial for facilitating trade and enhancing Ukraine's economic ties with the EU. However, the country suffered the loss of important ports in its network due to the annexation of Crimea in 2014. Kerch, Eupatoria, Krym, Sevastopol and Yalta came under the control of Russia². This situation must also be inserted in a long-term strategy of Russia, started in mid-2010, to improve their geostrategic position in the Black Sea taking control of the maritime trade in the area, with Odessa and Mykolaiv as a key priority for Russian military planner (TO Dispute DS512).

In that way, Ukraine endured increasingly severe restrictions on its coastal state rights and freedom of navigation in the Black Sea, the Sea of Azov, and the Kerch Strait. These limitations have undermined Ukraine's control over key maritime zones and access to international waters. The "Kerch Strait clash" of November 2018, during which Russian forces seized three Ukrainian naval vessels in international waters south of the strait, represented a significant flashpoint in a long-standing maritime dispute that had been intensifying for years ([Atland 2021](#)). This confrontation underscored the broader geopolitical struggle, as Russia simultaneously began fortifying Crimea, enhancing its military presence and infrastructure in the region ([Sukhanin 2017](#)). This militarization further solidified Russian control over the peninsula, limiting Ukraine's ability to operate in the area.

From the start of the war, the main target of Russian missiles had been Ukraine's critical power infrastructures in densely populated regions. The Black Sea Grain Initiative of 2022–2023, facilitated by the UN, was the first significant effort to leverage mediation strategies that had been thought during the armed confrontation phase between Ukraine and Russia since 2014. These strategies were instrumental in addressing the complex dynamics of the ongoing war and were applied to secure a temporary agreement allowing grain exports despite the broader war ([Mackinnon 2022](#))([Kormych, Averochkina, and Kormych 2024](#)). The success of this initiative deal was clear during the first six months, when approximately 14 million tons of Ukrainian grain exports were loaded, demonstrating the resilience of the supply chain ([Karakas et al. 2024](#))

It is only in July 2023, after withdrawing from the deal, that Russia attacked port infrastruc-

²As already mentioned in the note of Fig. 1 this does not affect considerably the volume handled by Ukrainian ports. The port of Sevastopol is a strategic port for military reasons but not a major commercial port. Consequently, it probably affects the structure of the Ukrainian network in terms of geostrategy, which is not the focus of this paper.

ture – the first being a grain terminal in Odesa as well as trucks and railway tracks (Kottasova et al. 2023; South China Morning Post 2023; Meduza 2023), followed by Mykolaiv (Reuters 2023a). Russian air strikes later targeted Ukraine's Danube ports (e.g., Reni, Izmail), which had become a vital export route, thereby damaging grain silos, oil storage tanks, and other buildings (Reuters 2023b). Russian strikes on ports and civilian vessels in the Odesa region intensified after the retreat from the deal, with over 85% of all attacks occurring after July 2023. As described by (Diakun 2025), repeated attacks by Russian forces on port infrastructure and a period of intense strikes on the Odesa ports has not slowed deep-sea port trade in 2024. Following the collapse of the UN-brokered Black Sea Initiative in July 2023, vessel traffic resumed from January 2024 onwards thanks to a temporary maritime corridor set by Ukraine. Throughout 2024, 2705 vessels called at Ukrainian ports (79.9 million deadweight tons), compared with 1028 in 2022 (38.2 million dwt) and 759 in 2023 (32.4 million dwt). This trend for 2024 occurred despite the attack on Odesa and Izmail ports' infrastructure in early October via missiles and drones (Polishchuk and Vlas 2024). As a whole, between 24 February 2022 and 11 October 2024, Russian forces damaged 22 foreign civilian vessels, while 38 events of Russian missiles and drones targeting port infrastructure and civilian vessels in the Odesa region were recorded. Another type of attack from Russia has been the bombing of civilian vessels, on top of grain silos and port infrastructure, with about 20 ships damaged since the start of the war (Rainsford and Kirby 2024). This recent shift constitutes a new strategy for Russia, which is to weaken the Ukrainian economy and undermine its exports while becoming more competitive on the global grain market to buy more weapons (Marsi 2024).

The armed confrontation in Eastern Ukraine, particularly in regions like Donetsk, Luhansk, and Mykolaivska regions and alongside the Danube River has affected port operations and logistics (Bank 2024). Security concerns, including the risk of military escalation and disruptions to transportation routes, have impacted trade flows and investment in the region. Also, the war has prompted Ukraine to diversify its trade routes and reduce its dependence on Russian-controlled infrastructure, including ports. Ukraine has sought to strengthen trade ties with other countries, such as Turkey, Georgia, and countries in the European Union, to mitigate the impact of disruptions caused by the war. Such changes led to an increasing focus on accessing Western markets, including Europe and North America, to offset the loss of trade with Russia and the Commonwealth of Independent States (CIS). This shift has led to the development of new trade routes and the expansion of port facilities to accommodate increased trade with Western partners.

After the start of the war, the role of Ukraine as a provider of producer goods has changed. The situation has affected not only bilateral relations but also energy security in Europe. Indeed, the war has transformed the global economic model of world economic relations, specifically maritime trends.

Russia enforced a comprehensive naval blockade, inflicting significant damage on Ukraine's

economy, which had previously relied on maritime exports for 70% of its trade. In essence, if Russia were to gain control of Ukraine's remaining coastline, it would deprive Kyiv of its last operational ports and key infrastructure, effectively removing Ukraine as a maritime competitor and cementing Russian dominance over the Black Sea region (Kollakowski 2023). Understanding this strategic risk, the Ukrainian military demonstrated foresight by recognizing the critical importance of controlling Odessa in any major war, well before the escalation of the 2022 Russo-Ukrainian War. Navigation in the Black Sea has also been significantly affected by the presence of drifting mines. These explosive devices make commercial shipping dangerous and can have significant long-term effects on maritime safety in the region.

Due to this development of the war, Ukrainian neighbours have helped reconfigure the international trade network. Romanian and Polish seaports have absorbed the bulk of Ukraine's transit needs for agricultural goods, handling 80% and 10% of the traffic, respectively (Melnyk 2023). As a result, the war prompted a reassessment of infrastructure policies within the Three Seas Initiative (Black, Baltic, and Adriatic Seas), driving its expansion. This growth has been both geographic—with Ukraine gaining partner status—and strategic, as planning now encompasses the reconstruction and development of Central and Eastern Europe in the post-Russo-Ukrainian war era (Kivalov 2023).

Also, as part of actions taken by the European Union to pressure the Russian government to cease hostilities and seek a resolution to the war, while also supporting Ukraine's sovereignty and territorial integrity, sanctions at different levels have been promoted. Among these actions, we find trade restrictions and export control, which result in a trade network's reconfiguration. However, despite being quite effective, Russia has regained a bit of control creating a shadow fleet from the latter half of 2022. A common violation involves disabling the Automatic Identification System (AIS) when vessels enter ports for loading Hilgenstock, Hrybanovskii, and Kravtsev (2024).

Since the Ukraine-Russia negotiations in Saudi Arabia in early 2025, the end of military activities in the Black Sea had been approved, at the condition that western powers lift the sanctions on Russian grain and fertilizer exports Quénelles and Ricard (2025).

2. Related Literature: Shipping Networks and Vulnerability

Due to limited data availability about maritime flows, shipping networks have long attracted peripheral interest compared with other transport and communication networks (Ducruet 2020). It is only in the late 2000s and early 2010s that the structure of shipping networks started to be well documented, especially by physicists (Hu and Zhu 2009; Kaluza et al. 2010), before a rapid multiplication of such studies in the 2020s (Polo-Martín and Ducruet 2024). In parallel, various crises and changes affecting ports have been investigated by numerous studies (Wendler-Bosco

and Nicholson 2020; Wang et al. 2021; Nguyen and Kim 2022) and visualised (Liu et al. 2018)³.

The recent review of over 200 journal articles on shipping networks (2007-2022) (Ducruet 2023) observed that nearly 20% of the corpus had been devoted to the theme of network vulnerability and robustness. Table 1 provides an overview of such studies, with more than 40 articles published in peer-reviewed journals between 2008 and 2024⁴. Nearly half of these studies focus on global maritime networks, followed by Asia (including China, Europe-Asia, and Maritime Silk Road). A great majority deals with liner (container) shipping, the study of bulk shipping being relatively rare. One-third uses graph theory and complex networks, and the rest of the methods are very diverse. The developed themes concern the Covid-19 pandemic (Li, Wang, and Ducruet 2020; Wan et al. 2020; March et al. 2021; Jin et al. 2021; Dirzka and Acciaro 2022; Ferrari, Persico, and Tei 2022; Guerrero, Letrouit, and Pais-Montes 2022; Kanrak, Nguyen, and Du 2022), natural disasters and climate change (Shen et al. 2019; Rousset and Ducruet 2020; Poo and Yang 2024), and the simulation of targetted attacks (Earnest, Yetiv, and Carmel 2012; Ducruet 2016; Viljoen and Joubert 2016; Calatayud, Mangan, and Palacin 2017; Achurra-Gonzalez et al. 2019a; Wu et al. 2019; Xie 2019; Xu et al. 2022).

³It is worth mentioning that the very first paper using complex networks in shipping economics is Foschi (2002) which has been then partly ignored by the rest of the literature.

⁴We extended the review proposed in Ducruet (2023) including the most recent studies on shipping networks' resilience and vulnerability.

TABLE 1. Research Overview of Container, Oil, and General Cargo Networks

Author(s)	Theme	Network	Method/Data	Region
Achurra-Gonzalez et al. (2019a)	Resilience	Container	Attacker-defender model	World
Achurra-Gonzalez et al. (2019b)	Cargo routing	Container	Optimisation techniques	Asia
Alderson, Funk, and Gera (2020)	Multiplex network	Container	Flow-based model	World
Bai, Ma, and Zhou (2023)	Resilience assessment	Container	Clique percolation, network disintegration, knock-on simulation model	World
Calatayud, Mangan, and Palacin (2017)	Multiplex network	Container	Attack simulation	Americas
Dirzka and Acciaro (2022)	Covid-19	Container	Carrier schedules	World
Ducruet (2008)	Hub dependence	Total	Foreland linkages	Asia
Ducruet (2016)	Interoceanic canals	Container	Complex networks	World
Dui, Zheng, and Wu (2021)	Resilience	Total	Optimal resilience model	World
Earnest, Yetiv, and Carmel (2012)	Contagion	Intermodal	Attack simulation	Transpacific
Fang et al. (2018)	War, sanctions, elections	Container, tanker, bulk	Spatiotemporal modeling	Asia
Ferrari, Persico, and Tei (2022)	Covid-19	Container	Customs data	Europe
Guerrero, Letrouit, and Pais-Montes (2022)	Covid-19	Container	AIS	World
Guo et al. (2024)	Geographic factors	Container	Irreplaceability model	World
Guo et al. (2017)	Hub centrality	Container	Complex networks	Asia

Continued on next page

TABLE 1 – *Continued from previous page*

Author(s)	Theme	Network	Method/Data	Region
He et al. (2022)	Resilience	Container	Complex networks	China
Liupeng et al. (2024)	Cascading failure	Container	Attack simulation	Maritime Silk Road
Jin et al. (2021)	Covid-19	Container	AIS	China
Kanrak and Nguyen (2022)	Covid-19	Cruise	Complex networks	Oceania
Li et al. (2024)	Covid-19	Container	Complex networks	World
Li, Wang, and Ducruet (2020)	Covid-19	Cruise	Carrier schedules	World
Liu et al. (2018)	Multi-centrality	robustness models	Container (Maersk)	Europe-Asia
Laxe, Seoane, and Montes (2012)	Port hierarchies and areas	Container	Graph theory	World
March et al. (2021)	Covid-19	Total	AIS	World
Mei et al. (2024)	Robustness	LNG	Graph deep learning approach	Europe
Montes, Seoane, and Laxe (2012)	Emergent routes	Container & general cargo	Graph theory	World
Mou et al. (2020)	Resilience	Oil	Complex networks	Maritime Silk Road
Pan, Zhang, and Fan (2022)	Covid-19	Container	Graph theory, gravity model	World
Pan et al. (2021)	Bottlenecks	Container	Recursive spectral bi-partitioning	Maritime Silk Road
Poo, Yang, and Lau (2024)	Climate extremes	Container	Regional vulnerability index	World
Poo and Yang (2024)	Climate vulnerability	Container	Composite centrality	World

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TABLE 1 – *Continued from previous page*

Author(s)	Theme	Network	Method/Data	Region
Qin et al. (2023)	Resilience	Container	Three-dimensional econometric model	China
Rousset and Ducruet (2020)	Natural disasters & terrorist attacks	Total	Complex networks	USA & Japan
Saito et al. (2022)	Interoceanic canals	Container	Graph theory	Europe-Asia
Shen et al. (2019)	Tropical cyclones	Total	Complex networks	Oceania
Stergiopoulos et al. (2018)	Congestion interdependencies	Container	Risk-based interdependency analysis	World
Viljoen and Joubert (2016)	Link disruption	Container	Complex networks	World
Wan et al. (2020)	Covid-19	Container	Carrier schedules	China
Wan et al. (2023)	Suez Canal blockage	Container & tanker	Targeted (canal) and random attacks	World
Wan et al. (2022)	Resilience & recovery	Container	Resilience loss triangle model	Maritime Silk Road
Wang et al. (2016)	Robustness	Container	Complex networks	World
Wang et al. (2024)	Typhoons	Container	Complex networks	China
Wei, Xie, and Zhou (2022)	Robustness	Oil	Attack simulation	World
Wen et al. (2022)	Multiscale centralities	Total	Entropy	Europe-Asia
Wu et al. (2019)	Main channels	Container	Carrier schedules	World
Wu et al. (2024)	Covid-19	Container	Collapse threshold, geospatial connectivity	World
Xie (2019)	Robustness	Container, tanker, bulk	Attack simulation	Maritime Silk Road

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TABLE 1 – *Continued from previous page*

Author(s)	Theme	Network	Method/Data	Region
Xiao et al. (2024a)	Ukraine war	LNG	Attack simulation	World
Xu et al. (2024)	Cascading failure	Container	Motter-Lai overload model	World
Xu et al. (2024a)	Multiple disruptions	Container	Efficiency metric	World
Xu et al. (2022)	Cascading failure	Container	Attack simulation	World
Xu et al. (2023)	Robustness	Container	Motif analysis	World
Xu et al. (2024b)	Cyclones	Container	Path-dependency	North Pacific
Yang and Liu (2022)	Resilience	Container	Transmissibility and diversity	Maritime Silk Road

Other important themes are resilience and robustness, multiplex networks, and congestion. In particular, [Fang et al. \(2018\)](#) documented how wars, lifted economic sanctions, and government elections affected South Asian shipping networks. The basic material of the study is massive AIS data between 2013 and 2016 comprising 20,864 vessels and 3,685 ports worldwide. The authors used a spatio-temporal analytic framework to understand maritime network dynamics and to assess possible indirect effects within a network. More specifically, the research employed a multivariate local polynomial fitting approach (LOESS) and autoregressive moving average (ARMA) models. It also made use of a K-means clustering method to group links having similar behaviour. Regarding military issues, the case study focused on the India-Pakistan armed confrontation in 2015. The authors explored the evolution of the top 20 maritime connections between India and other countries before and after this event by type of ship (tanker, container, bulk). The main results indicated that shipping between India and its connected countries all declined by more than 69% after August 2015. Yet, the study remains at the country level, with each link and each traffic category being more or less resilient to the event.

Much earlier, studies were conducted on the case of North Korea ([Ducruet, Roussin, and Jo 2009](#)), which is still a country at war in the absence of a peace treaty with South Korea since the armistice of 1953. This country experienced huge impacts of sanctions (embargo), economic crisis (famine), natural disasters (floods), and political transition after the collapse of the USSR (1991) and the death of former president Kim Il-Sung (1994). *Lloyd's List* data allowed us to map and analyse the evolution of North Korean ports' connectivity, marked by a shrinking foreland, ageing vessel fleet, increased berthing time, and the concentration of its external connections at the South Korean hub, notably for containers. This phenomenon was defined as a "hub dependence" process whereby a constrained economy is forced to connect the global maritime network through a neighbouring external hub, being not able to receive direct ship calls for the aforementioned reasons. A hub dependence model was proposed by [Ducruet \(2008\)](#), depicting successive phases of increased vulnerability, potentially applicable to any constrained economy. It is one objective of this paper is to investigate whether such a model corresponds to the case of Ukraine.

Regarding the war between Russia and Ukraine, most of the existing literature about the impacts of this war over the network is qualitative [Zhao, Duan, and Chang \(2023\)](#). Quantitative assessments are specialized on a single commodity such as liquid gas [Xiao et al. \(2024b\)](#), [Zhang, Wang, and Ng \(2024\)](#) or look at the global scale only [L. et al. \(2024\)](#). So, another objective of this article is to show, for the first time, the impact of the war on the network on a general level as well as regarding different types of commodities.

3. Data and Empirical Approach

3.1. *Lloyd's List* Data

In our study of Ukrainian maritime networks, we used shipping data sourced from the *Lloyd's List* corpus, which documents vessel movements between ports of the world. We focused on traffic by calculating the tonnage of port nodes and inter-port flows (*i.e.*, frequency of vessel calls multiplied by ship capacity) in deadweight tonnes (DWT)⁵. Traffic is differentiated amongst main cargo types, of which we retain bulk (solid and liquid) and containers⁶, between 2010 and 2024⁷.

3.2. A Multilevel 'Network' Strategy

Network analysis plays a crucial role in understanding international trade by uncovering and quantifying the underlying structural properties of networks. It offers a comprehensive approach to examining the relationships and interactions between countries in terms of their trade flows. By delving into the connectivity and clustering of trade relations among nations, as well as considering factors like geographic proximity and centrality, network analysis provides valuable insights into the patterns and dynamics of global trade. We divide this approach into two stages: network topology, which analyses the evolution of basic structures, and network models, which provide a more detailed analysis of structural changes in the network.

This analytical framework facilitates the identification of key players - influential ports and countries - in the international trade landscape. Moreover, it enables the tracking of changes and evolution in trade networks between 2010 and 2024. Utilising network analysis techniques and random network models, we can gain a deeper understanding of the intricate structure of the Ukrainian trade situation⁸. This helps reevaluate the effects of global shocks and opens the discussion on relevant strategies to build resilient trade networks.

Moreover, analysing maritime data by type of ship is crucial for understanding various aspects of international trade and economic activities (containers, liquid and solid bulk). A deep analysis of the different types of trades allows for a forecast of economic trends at both national and global levels. Trends in the trade of specific goods can provide early indicators of broader economic developments, such as emerging market opportunities, shifts in industrial production, or changes in consumption patterns. This information is essential for assessing the

⁵For additional information on the *Lloyd's List*, one can refer to [Ducruet and Zaidi \(2012\)](#); [Ducruet, Cuyala, and El Hosni \(2018\)](#); [Ducruet et al. \(2024\)](#) among others.

⁶For some analyses, we also included general cargo and passengers/vehicles.

⁷The objective was to capture the Annexation of Crimea by the Russian Federation in 2014 and the war which started in 2022.

⁸Additional details on the method are provided in section 4.1 and appendix H

overall competitiveness of domestic industries and identifying areas where shocks may exist.

The foreland maritime links were also analysed in an aggregated manner by country. To help us interpret the evolution of connections, the Observatory of Economic Complexity (OEC) TreeMap Tool was used⁹, which provides bilateral trade statistics between states based on UN ‘COMTRADE’ databases¹⁰ [World Trade Organization \(n.d.\)](#).

3.3. A Grid Approach to Model Vessel Flows

When it comes to visualise the results, cartography is the key. But representing flows is not as easy as it seems. When we initially create routes from one point (port) to another on any GIS software, the paths are straight. For that reason, a grid to act as a conductor of flows is necessary. Besides, this grid must avoid incompleteness owing to the method of map creation in every software due to the representation in a 2D space as a 3D surface. For that reason, the natural hole that appears between the two parts was fixed ([Polo-Martín and Ducruet 2024](#)).

In Grass software, to this mesh, ports were added using a 1.5-degree tolerance to connect ports on islands, optimising the system for the mainland coast (Fig. 2). This setup enables the study of connectivity, accessibility, and centrality measures.

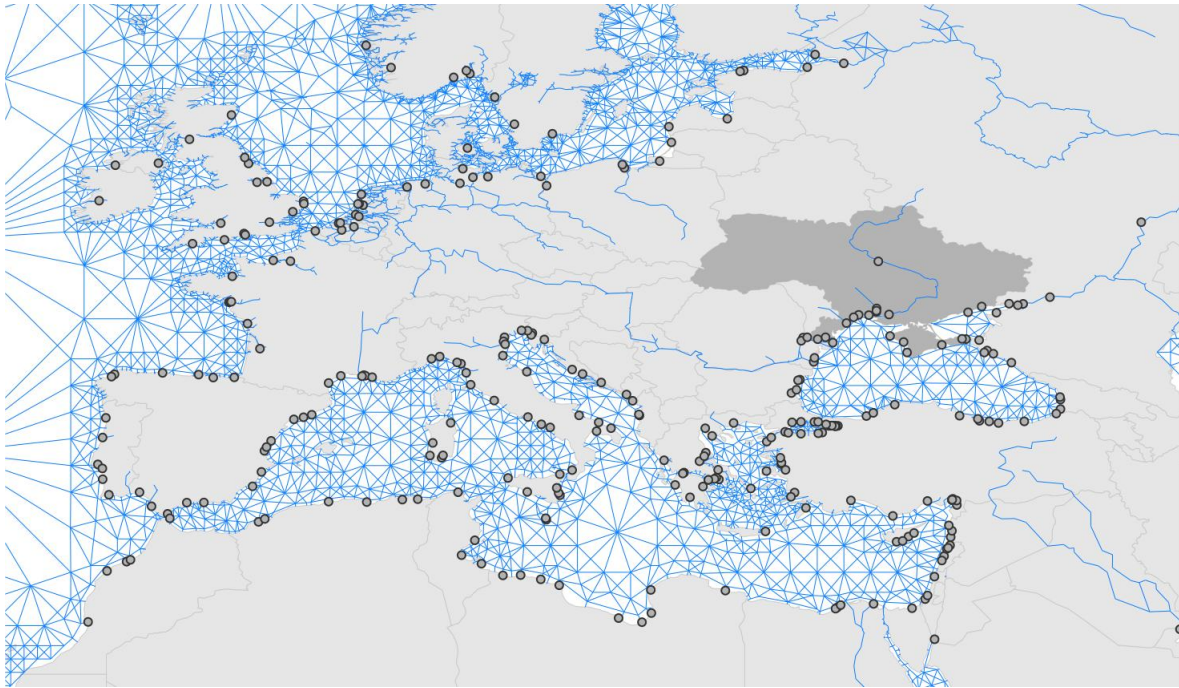


FIGURE 2. The grid mapping vessel routes in the ocean

⁹The ‘TreeMap Tool’ can be accessed at the following link: [click here](#).

¹⁰The United Nations ‘Comtrade’ database contains detailed annual and monthly statistics on world trade by product and by trading partner for use by governments, universities, research institutes and businesses. It can be accessed at the following address: [click here](#).

For each edge, we measured the distance as a cost and excluded certain shortest paths that were impractical for maritime transport of goods, such as specific rivers (e.g., the Rhine), the Dead Sea, and the Arctic. Because the exported vector of the mesh is not continuous—nobody can traverse the world continuously as it has "extremes"—we repeated the previous steps with the inverse vector. For instance, we analysed the American continent first from one end and then from the opposite end (Fig. 3).

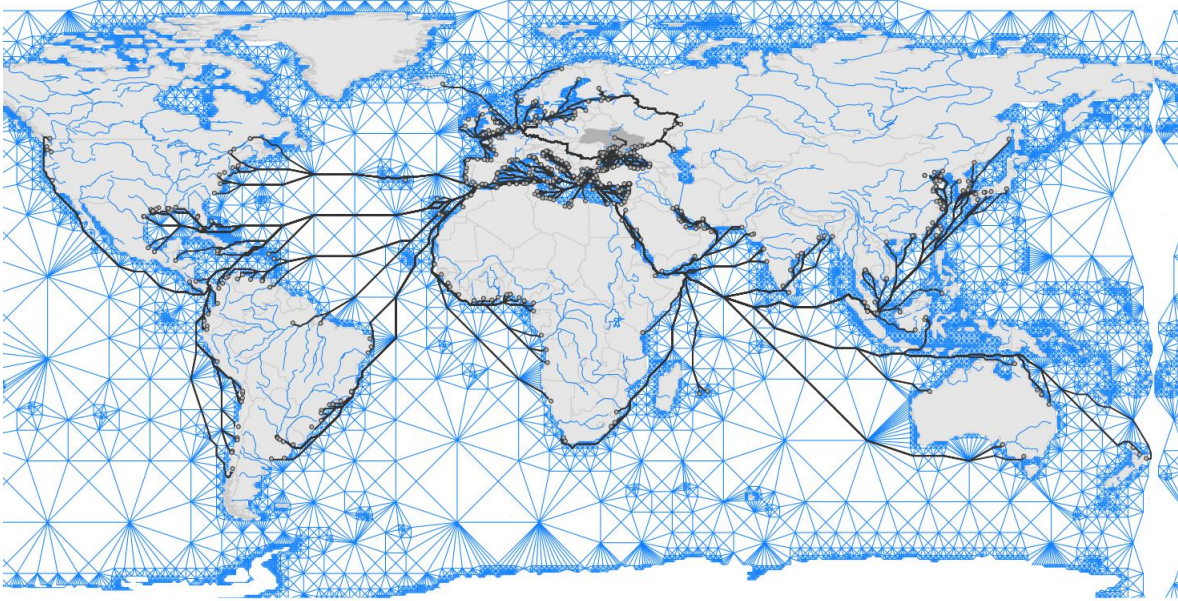


FIGURE 3. Global Ukrainian maritime flows following the grid.

Once we settled the mesh with nodes and edges (Fig. 4), it was possible to add centrality measures, determined by colour¹¹. The size of the ports was determined by the tonnage as well as that of one of the flows (Fig. 5).

¹¹This analysis is performed in section 4.3

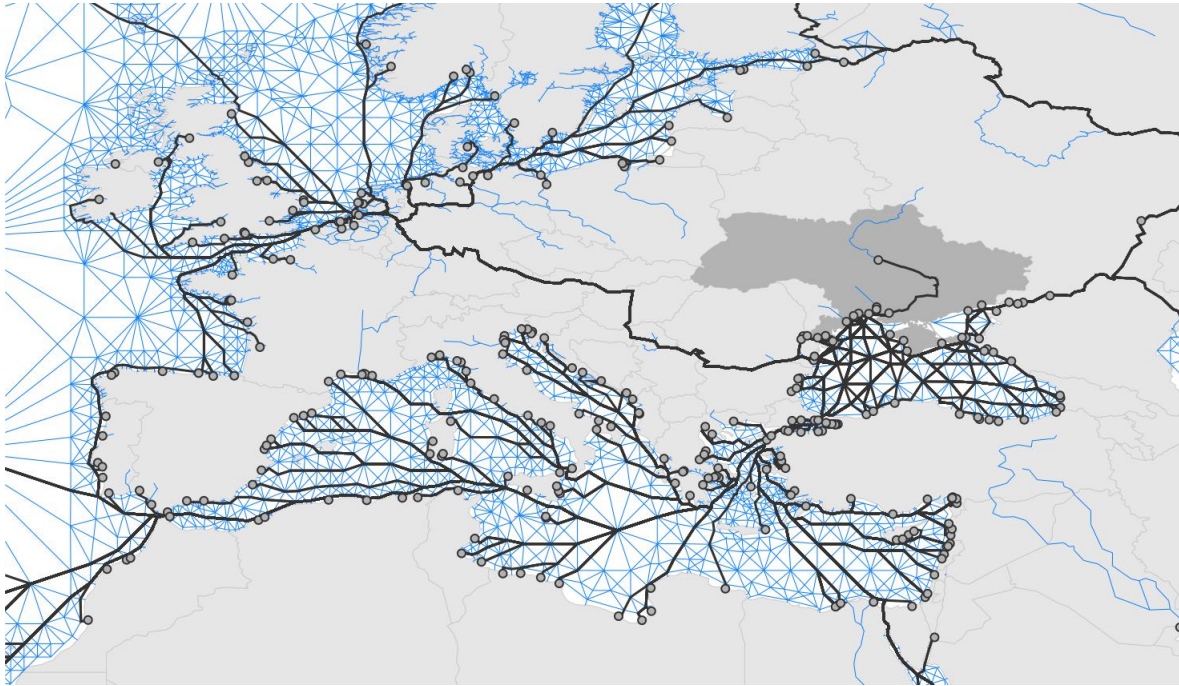


FIGURE 4. Ukrainian maritime connections in Europe and the Mediterranean.

Thanks to that grid, the flows follow straight paths. By using Drake's method in Grass, we were able to smooth the lines, resulting in routes that naturally curve through the oceans and seas.

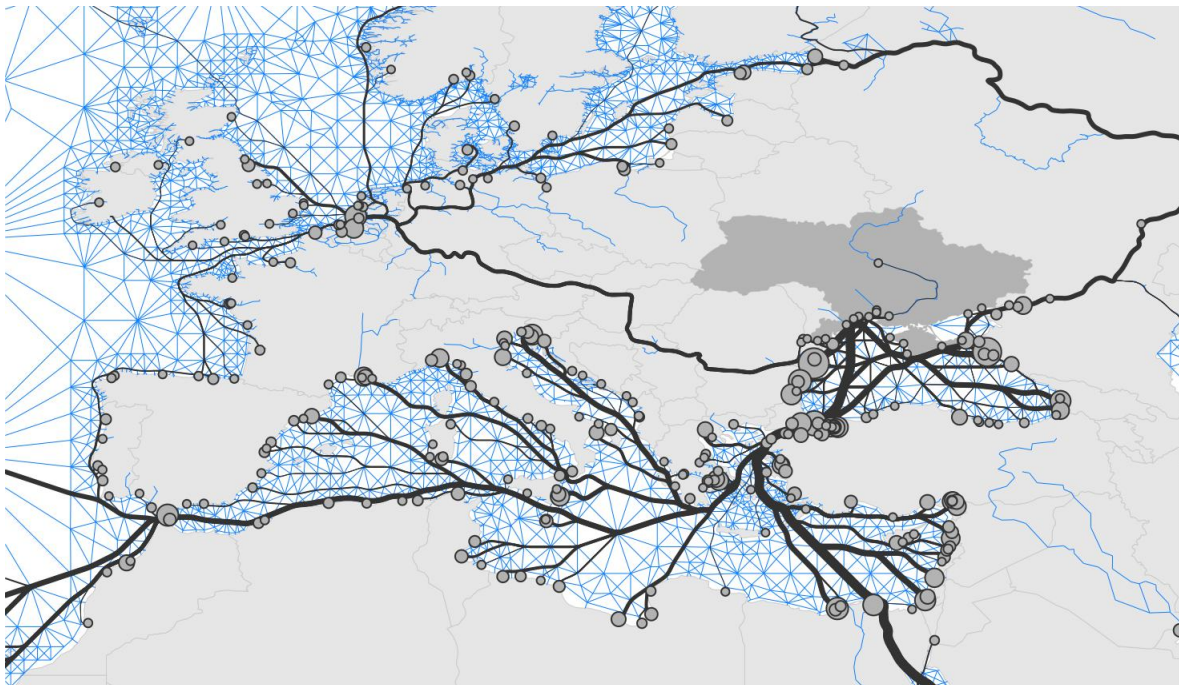


FIGURE 5. Ukrainian maritime connections weighting ports by tonnage.

4. Results

This section follows the organisation proposed in 3.3. We start by discussing the evolution of the Ukrainian network structure, then discuss the interactions between Ukraine and other countries and end with the evolution of outflows at the port level using a GIS and a route simulation analysis. It allows us to propose a global, quantitative and spatial analysis of the evolution of Ukrainian international trade over almost 15 years.

4.1. Global Network Topology and Hierarchy

Evolution of the network structure. As we have pointed out, different network properties of Ukraine over different years (2010, 2015, 2021, 2022, 2023 and 2024) have been examined to see the shocks provoked by the war (Table 4.1). The results show a clear effect - disappearance or change of linkages- of the armed confrontation from 2014 until nowadays over Ukrainian trade (Figure 6).

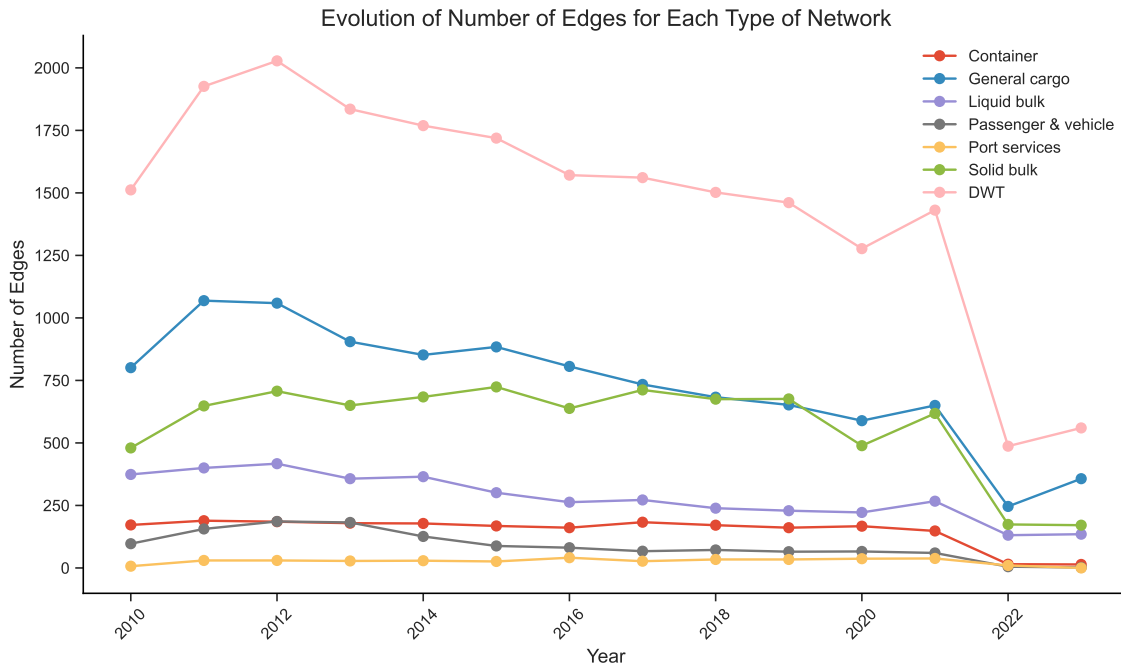


FIGURE 6. Evolution of the network for each type of vessel.

Notes: We computed the size of the network (*i.e.* the number of edges) for each type of goods (Container, liquid bulk, etc.) and the total network, *i.e.* taking into account all types of vessels.

In Fig. 6, we have calculated the sum of the edges (*i.e.* the ‘size’¹² of the network), for each

¹²‘Size’ typically refers to the scale or magnitude of the network, often measured by the number of

network, from 2010 to 2024¹³. While there is a declining trend, albeit relatively moderate, over the period 2010-2021, the fall in 2022 is particularly marked. The invasion of Ukraine, by making it difficult to move goods, isolating certain regions and destroying port infrastructures, has significantly affected capacity and therefore Ukrainian maritime traffic. It is also interesting to note that the annexation of Crimea in 2014 did not significantly affect the reduction in the number of connections from Ukrainian ports. The port of Sevastopol, which went over to the Russian side, is an important port infrastructure for Crimea as it is deep-water and facilitates access to the Sea of Marmara. It was already leased to Russia for 32 years from 2010. Traffic in Ukraine's main Black Sea ports was therefore unaffected by the annexation of Crimea, whereas the strikes on the Black Sea port of Odessa and the seizure of the ports of Berdyansk and Mariupol considerably affected Ukraine's maritime capacities¹⁴.

If we focus on the total network, *i.e.* including all the ships, we obtain the figure 7 in which we computed the number of edges and vertices for the total network, *i.e.*, for the network $\mathcal{G}^U(V, E)$. The trend is even clearer here, with a massive fall in 2022. The disruption of traditional trade routes, the destruction of port infrastructures and the reconfiguration of Ukrainian value chains all help to explain why traffic has remained at a very low level.

vertices (devices or entities) within the network and the number of connections (edges) between those vertices. The network landscape, encompassing scalability, topology, bandwidth, latency, reliability, manageability, security, interoperability, and resource allocation, has undergone significant shifts at different key moments throughout the Russia-Ukraine war.

¹³Considering the Ukrainian network $\mathcal{G}^U(V, E)$, an edge E exists between two vertices (ports) V if we observe a direct connection between the two ports. It corresponds to the so-called 'space- L ' network topology (Hu and Zhu 2009; Ducruet, Itoh, and Berli 2020).

¹⁴It should also be noted that we are interested here in the number of connections, disregarding tonnages, which are dealt with at port level and aggregate level in the following sections.

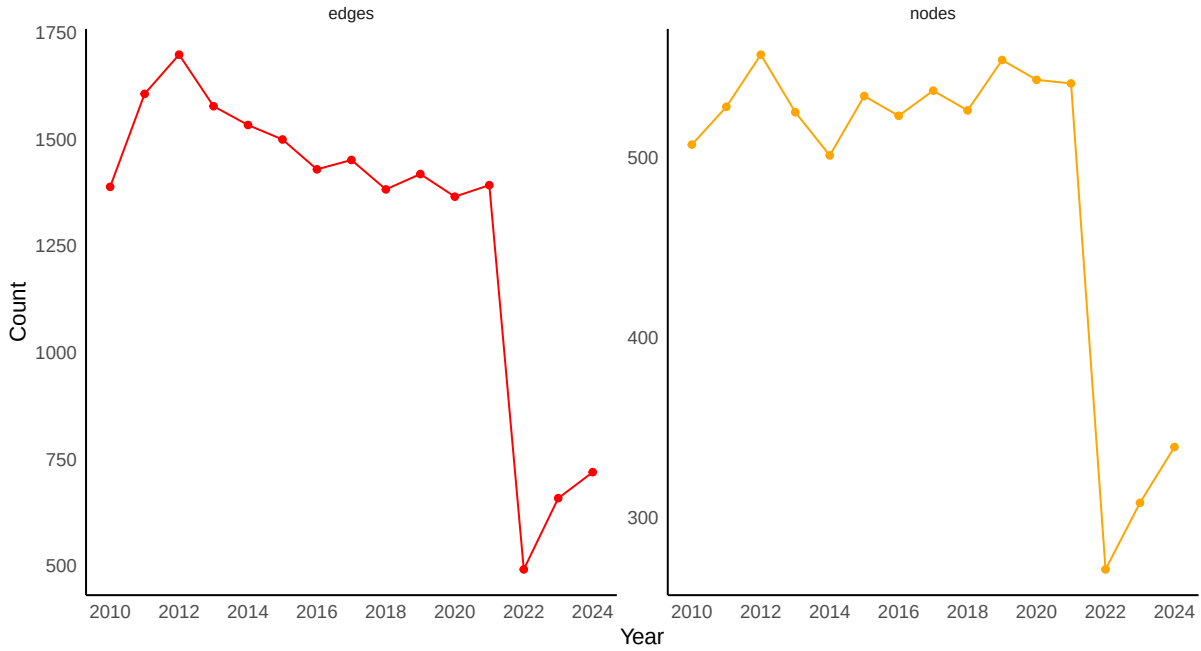


FIGURE 7. Number of edges and vertices in the global Ukrainian network, starting in 2010.

Notes: For each year, we computed the sum of the total number of edges (connections between ports) and vertices (ports) for all types of vessels. It allows us to emphasise the shock of 2022, but also the downward that ended in 2012. We also observe the slow recovery in active ports and connections in 2023 and 2024.

Building on this general overview, we can investigate in more detail the changes in the structure of the Ukrainian maritime network¹⁵ based on a series of network metrics. In Fig. D.1 we decided to focus on a particular network, namely the container one. Today, a very large part of world trade is carried out in containers and has become a crucial part of supply chains and the organization of maritime trade (Ganapati, Wong, and Ziv 2021; Do et al. 2024). The average degree¹⁶ (*i.e.* the number of connections of each port) follows the same trend as the number of edges and vertices, and so does the number of triangles¹⁷ in the network (see Fig. 8).

¹⁵Which includes both intra-country flows, *i.e.* amongst Ukrainian ports, and inter-country flows, *i.e.* from or to a port of Ukraine.

¹⁶For a network $\mathcal{G}(V, E)$ the j 's neighbours of a vertex i are defined as $\mathcal{V}(i) = \{j \in V; \{i, j\} \in E\}$. The degree of the vertex i is $d_i = |\mathcal{V}(i)|$ and the average degree is computed as the sum of the degrees divided by the number of vertices, *i.e.* $\bar{d} = \frac{1}{|V|} \sum_{i \in V} d_i$.

¹⁷A 'triangle' in a network is a motif defined by the connection between vertices i and j , j and k and i . It is a common structure in complex networks, which could be linked to the increased regionalisation in the case of transportation networks.



FIGURE 8. Evolution of the network metrics for all the vessels.

Notes: We computed the size of the network (*i.e.* the number of edges) for each type of goods (Container, liquid bulk, etc.) and the ‘full network’. The downward trend is strongly accentuated in 2022, with a minimal recovery in 2023 and 2024. In each figure, ‘complete’ means that we computed the metric on the total network and ‘LCC’ means that we computed the metric on the largest connected component.

The disruption of the network in 2022 significantly affects the number of connections and recorded ports, while the effect on the other metrics is ambiguous. As shown in Fig. 8 and Tab. 4.1, the evolution of the diameter and the average distance seems difficult to link with the invasion of Ukraine.

TABLE 2. Network properties

	2010	2015	2021	2022	2023	2024
Size	1388	1499	1392	491	658	719
Density	0.0108	0.0105	0.009	0.0134	0.0139	0.0125
Diameter	4	5	4	5	5	6
Average distance	2.44	2.49	2.49	2.54	2.45	2.43
Average strength	5.47	5.61	5.14	3.62	4.27	4.24

Notes: the ‘size’ of the network represents the number of direct connections from Ukrainian ports. Between 2021 and 2022, there is a massive drop in connections, and a limited recovery in 2023 and 2024. The ‘density’ corresponds to the ratio between the number of existing edges and the number of possible edges. The ‘diameter’ is the topological length of the longest shortest path. The ‘average distance’ is the average shortest path length in the network. Finally, the ‘average strength’ is the average of the ratio between the degree and the number of vertices. Again, we observe the massive drop in 2022 and the slow recovery in 2023 and 2024.

When considering the full tonnage network of Ukrainian ports, it appears that the network is very sparse (with a density of ≈ 0.01) and this property seems not to be affected by the war. In Fig. 9, we computed the density of the Ukrainian, ‘national network’, *that is*, taking into account the connections between Ukrainian ports only. We observe that the density of the national connections is much higher, with a decreasing trend over time. Again, while considering a ‘dense network’, compared to the total network, the evolution of the density does not seem to be explained by the geopolitical situation in Ukraine. The increase in 2022 and 2024 could be interpreted as a loss of efficiency, corroborating the findings of [Rousset and Ducruet \(2020\)](#) on the ego networks of Kobe (Hanshin earthquake), New Orleans (Hurricane Katrina) and New York (Twin Towers).

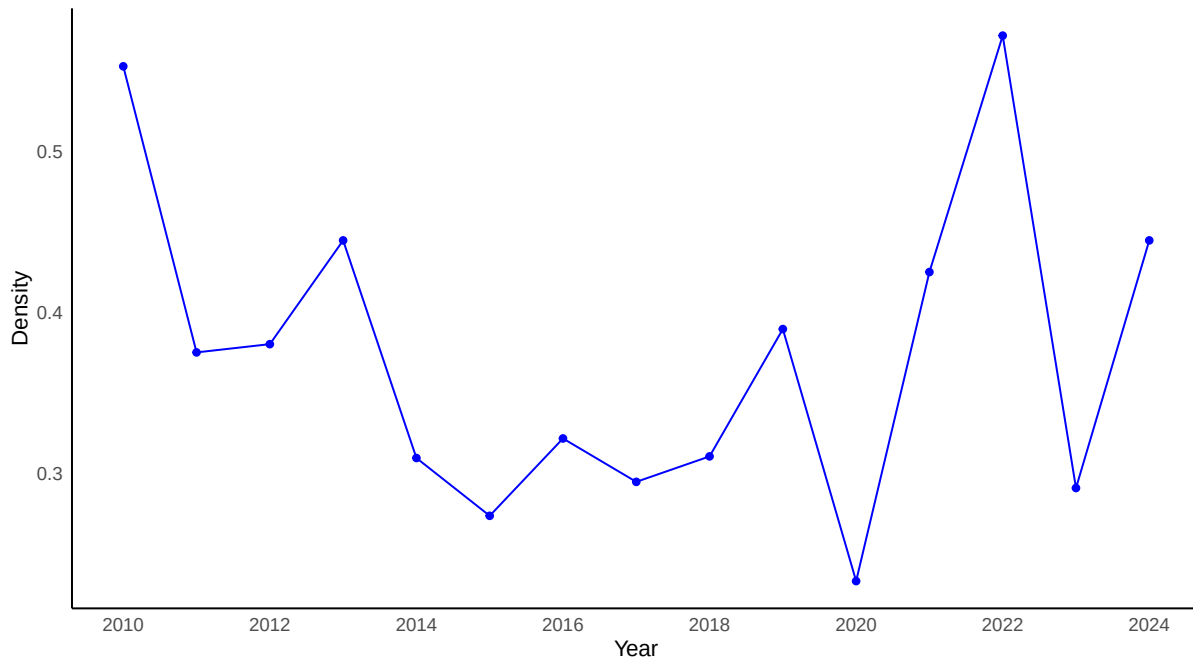


FIGURE 9. Density in the Ukrainian network

Notes: We computed the evolution of the density in the network composed only of Ukrainian ports. The ‘density’ is computed as $\frac{m}{\frac{n(n-1)}{2}}$ where m is the number of edges and n the number of vertices. $\frac{n(n-1)}{2}$ corresponds to the number of possible edges in an undirected network.

In that case, the diameter provides valuable information about the scale and connectivity of a network. From 2010, a key year for the commercial development of Ukraine after its independence, to 2023, the diameter did not change much, oscillating between 4 and 7. However, in 2024 the diameter increased. The difficulty in interpreting the results in terms of network structure and simple metrics can be explained by several factors. Firstly, the Ukrainian network has been reorganized, starting in 2014 and then more strongly in 2022, to adapt to a tense geopolitical situation, followed by war. This has probably compensated for some of the loss of efficiency in the network, which could have affected the metrics presented here. Secondly, from 2022 onwards, Ukraine received foreign aid to rebuild its ports, which made up for some of the destruction. Thirdly, the reduction in maritime traffic has affected the number of connections, but also the number of ports involved in trade. This double movement also helps to explain why these metrics are ‘noisy’ and do not clearly show the various shocks experienced by Ukraine since 2014. Finally, we analyse direct connections from Ukrainian ports. In this respect, the reorganisation of global value chains, in which the Ukrainian production system can be integrated, also has a background effect. This type of reorganisation does not appear in the port-to-port analysis¹⁸.

The average shortest path length is closely related to other network properties such as diameter and density. In that case, we find that the average distance does not vary over time. The average strength of the network has a different trend, with a marked fall from 2022 and continuing into 2023. Of the network metrics presented here, except for the number of connections, this is the only one to undergo significant variation from the invasion of Ukraine. Considering that the average strength represents the average of the sums of the weights of the neighbouring edges for all the vertices in the graph, a drop in this metric is explained here by a reduction in exchanges in the network.

Analysis of the basic network topology shows a significant reduction in network size. Despite this shock, metrics such as density and diameter do not appear to have changed significantly. The fact that the shock was mitigated by the reorganisation of value chains, the reduction in both the number of connections and the number of ports involved, and the geographical specificity of Ukraine¹⁹ may explain the limitations of the analysis in terms of network topology. Before looking at the global analysis of the network and the evolution of trade trajectories, we will approach the topology of the network via the distribution of degrees and the phenomena of ‘small world’ and ‘scale-free’ networks.

¹⁸If we were to consider a ‘space-P’ type of network (Hu and Zhu 2009; Ducruet, Itoh, and Berli 2020) organisation, which considers that two ports are connected if they are visited by the same ship during its journey, then this type of effect could appear more significantly. We leave this aspect aside in this paper, but it could be a perspective for future research.

¹⁹For an in-depth analysis of the global geography of trade links, please check the sub-section 4.3.

Degree distribution. Basic metrics are a good way of analysing the network as a whole and tracking changes in its topology over time. It also allows us to observe the impact of a major shock on the structure, and therefore the efficiency, of the network. In the case of a transport network, this implies potential disruptions to the movement of goods and consequences for value chains. We can also observe network resilience, meaning that players adapt to disruptions and reconfigure their routes to avoid losing efficiency. To investigate the evolution of the Ukrainian maritime network further, we will now briefly look at the evolution of its hierarchy. Fig. 10 represents the frequency for each value of vertex degree. A vast majority of ports have a low degree (< 10) while very few ports are above 30 and, still, some are directly trading with more than 100 other ports. The bottom-right panel of the figure 10 highlights the concentration of degrees to lower values, the vast majority being concentrated around 1 to 5 and no port exceeding 150. The number of ports in the network has also decreased. This corresponds to the total network for 2022, which has been severely affected by the war in Ukraine, the destruction of certain ports and the disruption of trade in the Black Sea²⁰.

²⁰Check the appendix C for the degree distribution for each type of vessel. The shock of 2022 is visible and significant in each case. The shock on the container network, as shown in figure C.3, is probably the most significant. This is revelatory of the more footloose character of container shipping compared with bulk shipping, notably in terms of port infrastructure. The power-law distribution disappeared in 2022, with a flat distribution of degree on low values.

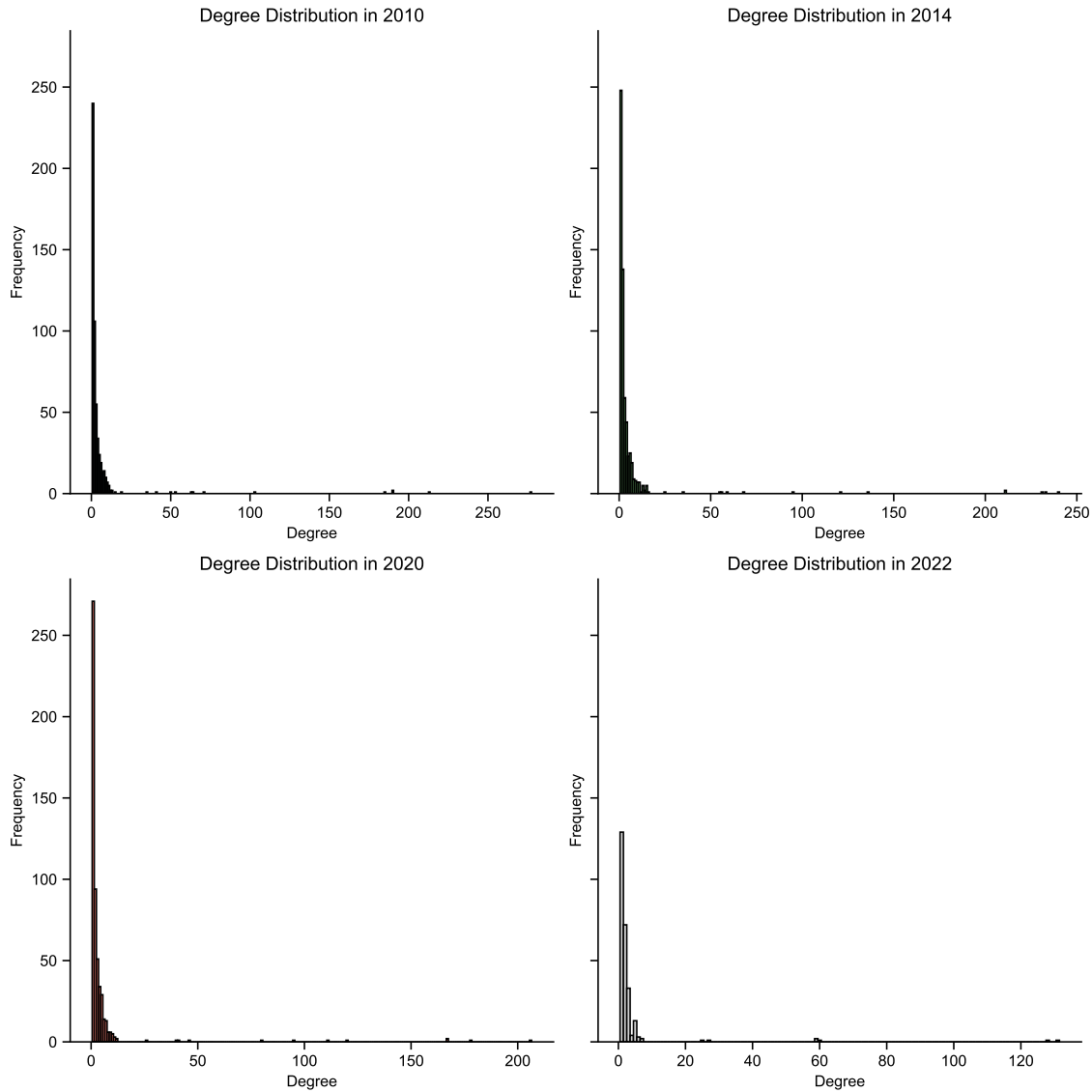


FIGURE 10. Degree distribution for the Total Network

Notes: We computed the 2010, 2014, 2020 and 2022 degree distribution.

Common network structures in terms of hierarchy and distribution of connections have been investigated through the lens of ‘small-world phenomenon’ ([Watts and Strogatz 1998](#)) and ‘scaling’ ([Barabási and Albert 1999](#)). It has been shown that a significant number of real-world networks are characterised by a ‘scale-free’ property ([Barabási and Albert 1999](#); [Albert and Barabási 2002](#); [Barabási 2009](#); [Lhomme 2012](#)), which means that their degree distribution follows, or can be

approximated, by a power-law²¹. We can write it in the following terms:

$$(1) \quad P(k) = Ck^{-\gamma}$$

In the equation 1 $P(k)$ is the fraction of vertices having k connections with other vertices in the network and C is a constant²². A network is considered as ‘scale-free’ when the exponent γ ranges between 2 and 3²³. These networks are highly hierarchical and determined by a few large vertices. In the case of maritime networks, this corresponds to the presence of large hubs (Ducruet and Zaidi 2012; Ducruet and Notteboom 2012; Ducruet, Cuyala, and El Hosni 2018; Liu, Wang, and Zhang 2018), which centralise both traffic volumes and the distribution of traffic to smaller ports. This is what is known as a hub-and-spoke network (Fremont 2007; Gelareh and Pisinger 2011; Wang and Wang 2011; Xu et al. 2020), in which the hubs, integrated into the major international trade routes, redistribute traffic to smaller ports serving local markets and acting as feeders.

²¹For each yearly network, we estimate the power-law exponent from the distribution of node degrees. The estimation focuses on the upper tail of the distribution, that is, on the most connected ports. The lower threshold $k_{\min}$ is not fixed arbitrarily; it is selected from the data by choosing the value that provides the best fit between the empirical distribution and the fitted power law. The estimated exponent should therefore be read as an indicator of network hierarchy rather than as proof that the entire network follows a strict power-law distribution.

²²Following Pósfai and Barabási (2016), the constant C is defined by the normalisation condition $\sum_{k=1}^{\infty} p_k = 1$.

²³In the case of power-law distribution, there is no ‘typical’ scale. It can be opposed to Bell-Shaped distribution, in which most individuals are close to the average value.

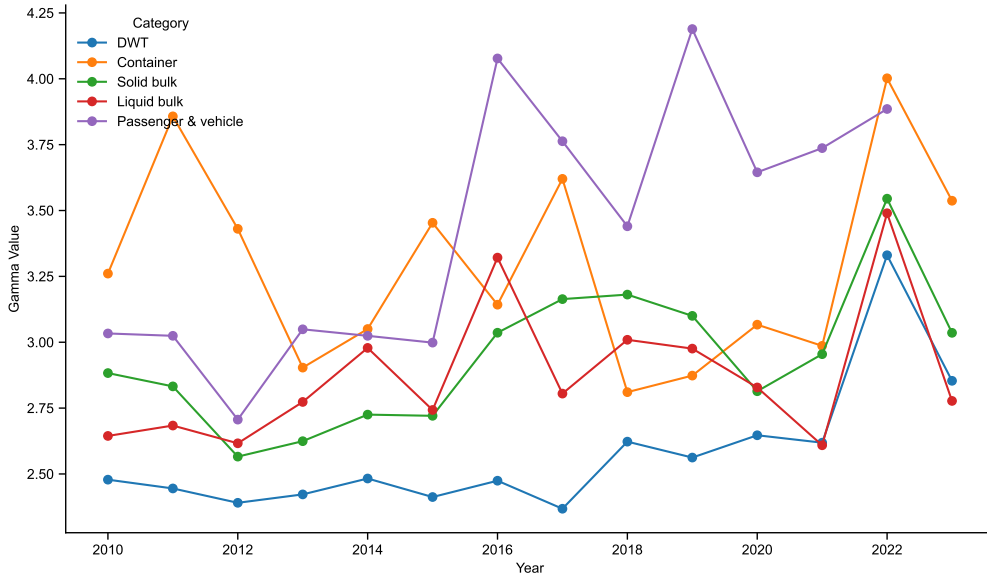


FIGURE 11. Evolution of the γ parameter for each type of vessel, 2010 – 2023.

Notes: We fitted a power-law to each distribution for each year and then extracted the γ value. To determine the best minimal value for power law fit²⁴. It allows us to avoid misfitting since power-law behaviour often does not extend to the entire range of degrees, especially at the lower end.

In Fig. 11, we observe the evolution of the γ defined in Eq. 1. For the 2010 – 2024 the γ ranges from 2 to ≈ 4 for each type of vessel. For each type of goods, we observe a peak in 2022, coinciding with the invasion of Ukraine. As γ increases, extreme values become rarer. There are fewer very large ports, in terms of different connections, in the network. The variation in the γ coefficient makes, therefore, possible to discuss the modification of the network hierarchy²⁵. The network becomes progressively less hierarchical as the coefficient increases. This is easily interpreted in the context of Russia's invasion of Ukraine: the disruption caused by the war in 2022 reduced maritime trade, paralysing or destroying some of the network's major ports such as Odessa and Mariupol. In this context, distribution homogenised around lower values. The drop in 2023 can be interpreted as the resuming of maritime traffic to certain ports and reconstruction, encouraged by foreign financial aid. It can also be considered that the reorganisation of the maritime network into a smaller number of ports is encouraging the emergence of a new hierarchy, bringing γ down to values around 3 for most types of goods.

The 'small-world phenomenon'²⁶, originally proposed by [Milgram \(1967\)](#) and [de Sola Pool](#)

²⁵Additional results on the evolution of network hierarchy based on the power-law approach are provided in the appendix E.

²⁶Additional details on the theoretical and statistical properties of the 'small-world' networks can be

and Kochen (1978), states that sparse and decentralised networks are usually characterised by two main properties: a high clustering coefficient and a short average distance (Watts 1999). To characterise the ‘small-worldliness’ of the networks and its evolution from 2010 to 2024, we computed the σ and ω coefficients (Humphries, Gurney, and Prescott 2006; Humphries and Gurney 2008; Telesford et al. 2011). The σ coefficient can be written in the following way:

$$(2) \quad \sigma_{\mathcal{G}} = \frac{\mathcal{C}}{\frac{\mathcal{C}_r}{L_r}}$$

Where $\mathcal{C}$ is the average clustering coefficient (see Eq. 4) and L is the average shortest path of the network. The subscript r indicates shows the metrics computed for the random network²⁷.

The clustering coefficient measures the extent to which a network tends to be organised in a (quasi)-cluster, *i.e.* a network where “*my friends’ friends are also my friends*”. Considering a graph $\mathcal{G}(V, E)$ with V the number of vertices (here, ports) and E the number of edges (the connections between ports), λ_i the number of triangles in the network and τ_i the number of triplets, the clustering coefficient at the vertex level can be written as follow²⁸:

$$(3) \quad \mathcal{C}_i = \begin{cases} \frac{\lambda_i}{\tau_i} & \text{if } d_i \geq 2 \\ 0 & \text{otherwise} \end{cases}$$

At the network level we thus have:

$$(4) \quad \mathcal{C}(\mathcal{G}) = \frac{1}{|V'|} \sum_{i \in V'} \mathcal{C}_i$$

In Eq. 44, $V' = \{i \in V : d_i \geq 2\}$ is the subset of vertices such that $\mathcal{C}_i > 0$. To discuss the evolution of the ‘small-worldliness’ of the Ukrainian network we thus need (i) to compute the clustering coefficient and compare it to the random counterparts of our real networks and (ii) to compare our network to a lattice graph²⁹.

Fig. 12 represents the evolution of the sigma coefficient (Eq. 2) for the Ukrainian network. It is quite surprising to see that the coefficient is slightly below 1 from 2010 to 2020. Following Watts and Strogatz (1998) it means that the network is not ‘small-world’. Nevertheless, we can see the shock of 2022 and the apparent resilience of the Ukrainian maritime network from 2023.

found in Watts (1999) and Albert and Barabási (2002).

²⁷To randomise each network we used the Maslov and Sneppen (2002) method.

²⁸For mathematical details please check the appendix H.2.

²⁹To achieve these tasks we use the NetworkX package in Python, to compute the random networks and the ω and σ coefficients.

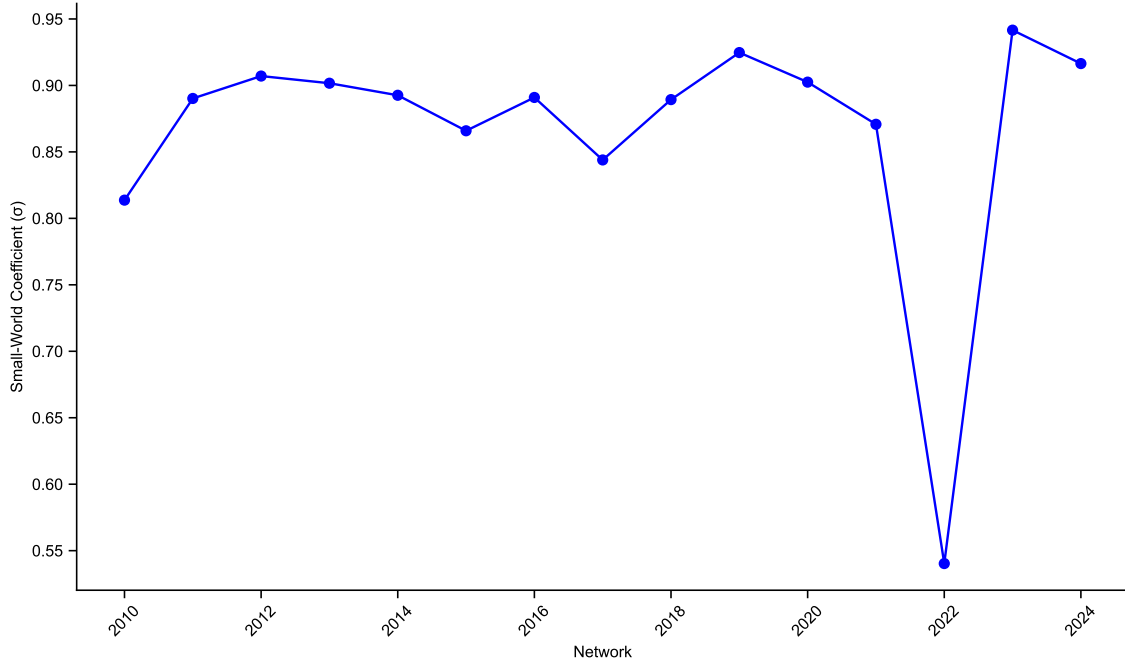


FIGURE 12. Evolution of the σ coefficient of the Ukrainian Network, 2010-2023.

Notes: We computed the σ coefficient, as expressed in Eq. 2 for the total network of Ukrainian ports from 2010 to 2024. When the total network was not connected, we used the largest connected component, usually accounting for - almost - all nodes.

This metric, which is useful as an initial approach, has several limitations, particularly because it is not very adaptable to different network topologies. To overcome this problem, we use the ω coefficient proposed by Telesford et al. (2011) which quantifies the small-world properties of networks more accurately, avoiding the biases introduced by the double σ ratio ³⁰.

We thus use the omega coefficient³¹ which can be expressed as follows:

$$(5) \quad \omega_{\mathcal{G}} = \frac{L_r}{L} - \frac{\mathcal{C}}{\mathcal{C}_\ell}$$

The ω coefficient compares the ratios of average shortest paths and the average clustering coefficient. The important difference with the σ coefficient is the use of the lattice network in the second part of the equation, instead of a random one. This approach makes the measurement less sensitive to the fluctuations of the average clustering coefficient of a random network

³⁰One can read the discussion proposed by Telesford et al. (2011) on the issues related to the use of the σ coefficient for additional details.

³¹ L , L_r and $\mathcal{C}$ are equivalent to the 2 ones, $\mathcal{C}_\ell$ is the average clustering coefficient of an equivalent lattice graph. In addition, the lattice networks are computed following the method proposed by Sporns and Zwi (2004).

Telesford et al. (2011)³².

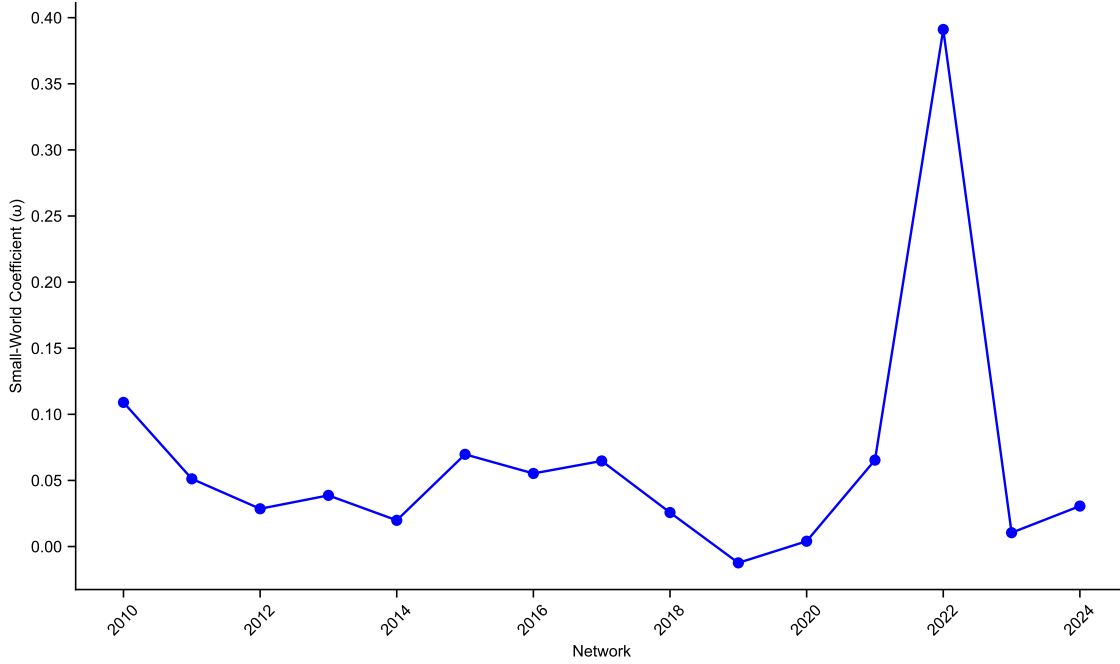


FIGURE 13. Evolution of the ω coefficient of the Ukrainian Network, 2010-2024.

Notes: We computed the ω coefficient, as expressed in Eq. 5 for the total network of Ukrainian ports from 2010 to 2024. When the total network was not connected, we used the largest connected component, usually accounting for - almost - all nodes.

From 2011 to 2021 we observe that the ω coefficient is close to 0, slightly varying but not exceeding 0.1. Telesford et al. (2011) showed that for values close to 0 the network exhibits ‘ideal small-world properties’, *i.e.*, path length of the network is as close to random as clustering is to a lattice. This relates in particular to the notion of network efficiency (Watts and Strogatz 1998; Amaral et al. 2000; Opsahl et al. 2017), which has been significantly affected since Russia invaded Ukraine. We have discussed both the 2022 shock to Ukrainian ports and the gradual resilience from 2023 in previous sections. Here we see this phenomenon clearly in the structural characterisation of the network based on the ω coefficient. In 2022, this increases sharply to 0.4, approaching the values associated with random networks and characterising the loss of organisation, and consequently efficiency, of the maritime network. The destruction of ports and the disruption of traffic in the Sea of Azov and the Black Sea explain this disorganisation of

³²As emphasised by Telesford et al. (2011) the value of the clustering coefficient of the random network greatly impacts the value of σ . This can lead to networks with very different structures but identical σ values, because of the position of $\mathcal{C}_r$ in the formula. It should also be noted that larger networks with similar clustering and shortest path tend to have a higher σ , which also introduces a bias into the interpretation of the measure.

the Ukrainian network, in line with what is known about the evolution of transport networks in times of war.

We explored the topology of the Ukrainian network and its evolution over time. In particular, we showed how the war affected both local and global properties in the network, reducing its size, isolating it from international connections and harming its efficiency. The results also emphasised the limitation of an approach that would be exclusively focused on the network structure. To deal with this issue we now analyse the Ukrainian shipping trade through the lens of international outflows, *i.e.*, focusing on international partnerships and traded volumes at both country and port levels.

4.2. Evolution of International Outflows at Country Level

This section provides a general overview of the results regarding Ukraine’s direct maritime connections with other countries. It analyses the most important outgoing connections for different segments of maritime transport for the years 2010, 2015, 2021, 2022, 2023 and 2024. To conduct the analysis at the country level, the outward flows from Ukrainian ports to all ports in each of the different countries were aggregated.

TABLE 3. Inflow and Outflow of Various Cargo Types

Year	Solid Bulk		Container		Liquid Bulk		General Cargo	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
2010	65	64	29	30	51	50	54	53
2015	77	80	34	32	44	43	49	58
2021	69	70	31	31	38	40	41	47
2022	33	32	5	6	24	25	33	36
2023	24	29	6	2	24	24	31	36
2024	38	49	7	9	19	25	27	31

Notes: This table represents the number of countries connected, inflow and outflow, by various cargo types for the period 2010-2024. A connection between two country *A* and *B* means a *direct* link, *i.e.* a vessel doing the journey from Country *A* to Country *B*.

Table 3 shows the number of direct maritime connections with the rest of the world for Ukraine, divided by type of transport and by incoming or outgoing connections. An analysis of all vessel types shows that international connections are already decreasing between 2015 and 2021, with bulk and general cargo vessels being particularly affected. The most drastic reduction, however, occurred after the Russian invasion in 2022. A reduction that continues to affect the solid bulk in particular but also has a strong impact on container transport. In 2023, there are no

particular signs of a recovery in the number of international connections, which instead suffer a slight decrease or stability compared to 2022. The year 2024 showed a slightly stronger recovery only in Solid Bulk transport with more countries connected than in the previous two years. Container transport, on the other hand, remains the most heavily penalised even though it has recovered slightly since 2023. Before the start of the war, dry bulk was the type of vessel that provided the largest number of direct international connections but, by 2023, this number tends to align with that of liquid bulk and general cargo. The strong decrease in container shipping, as said earlier, may correspond to a deviation of this traffic through Hamburg and the Baltic.

In terms of total cargo capacity, the dry bulk transport was the most important in volume (DWT) for the Ukrainian ports. In the years leading up to the war, China remained in the first two positions for outgoing direct connections (See [14](#)). Since 2010, Ukraine's main exports to China have been iron ore and, since 2015, cereals as well. Given the bulk nature of these products, this justifies the strong dry bulk carriers connection.

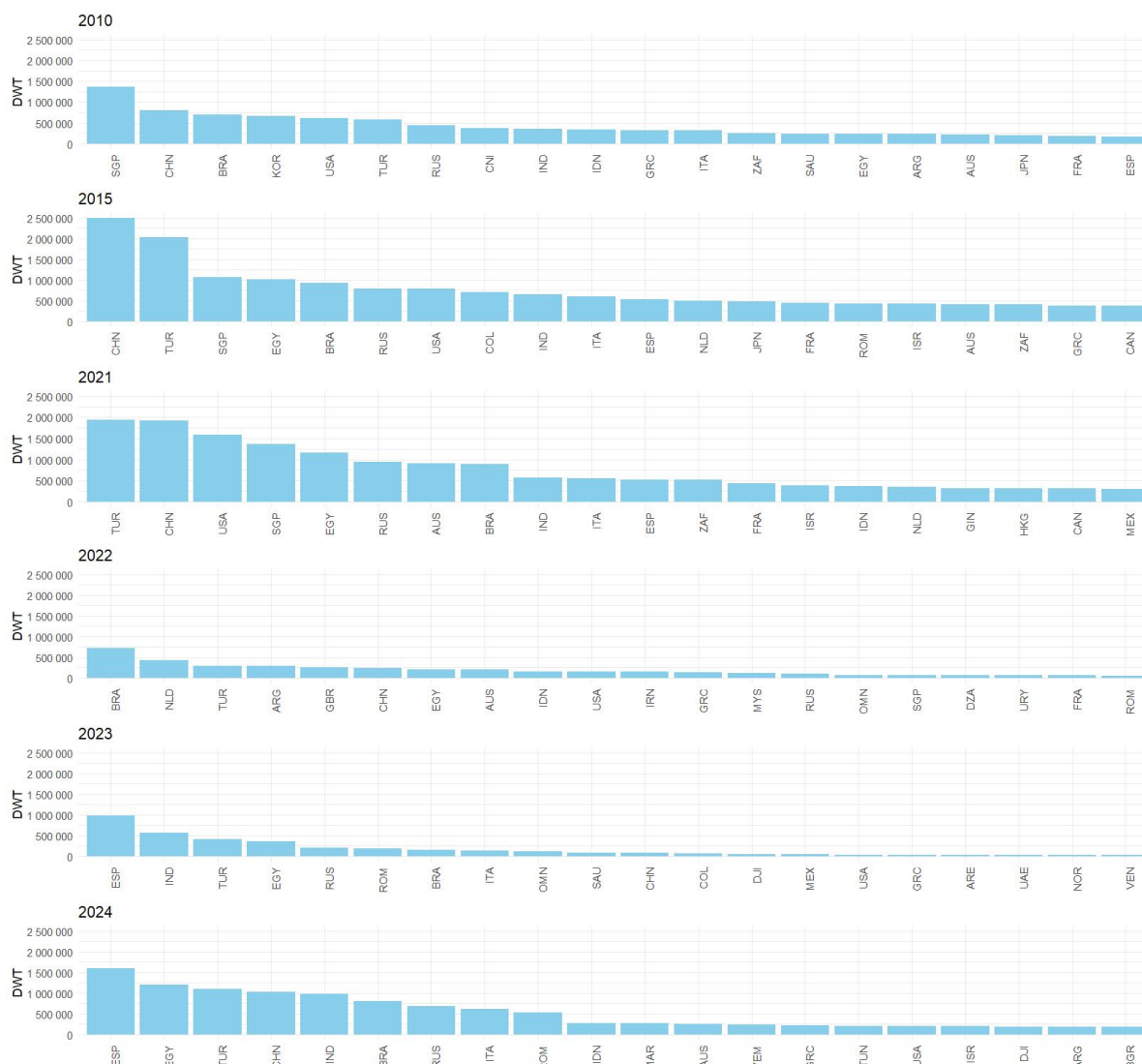


FIGURE 14. Evolution of total cargo capacity (DWT) of dry bulk ships moving to foreign countries (first 20 countries).

Notes: We summed the volumes of ships in DWT departing from Ukrainian ports and arriving in Ukrainian ports from a foreign country. This figure takes into account dry bulk ships only.

However, the volumes directed to this country have declined in 2021 compared to 2015 as shown in Fig. 14, probably influenced by the COVID-19 outbreak, which had a strong impact on Chinese demand and maritime logistics³³. Despite the importance of trade with China, the start of this war led to a drastic reduction in volumes in 2022 and 2023 reappearing only in 2024

³³Volume data may differ from other international freight export databases due to the temporal sampling of the database, which covers daily maritime trade, at ship level, but does not necessarily include every month. One can also refer to data from the United Nations *Black Sea Grain Initiative* for annual, aggregated, coverage of the grain trade.

among the top destinations.

But Ukraine was not the only country connected to the Far East to be heavily affected. One of the Four Tigers, Singapore, also suffered a drastic reduction in its connections with Ukraine. Singapore was in the top four direct connections in the first three years of the survey. This country has established itself in recent decades as a maritime hub (Ducruet,2013) for various types of commodities flows (Jacob, Ducruet and De Langen,2010), as well as hosting the main iron ore exchange (Haris and Tao,2016). However, this link, as well as all direct links to the Far East, seems to have almost disappeared after 2022. It echoes the study of North Korea whereby a crisis has the effect of shrinking long-distance shipping through intermediate hubs as shown by [Ducruet \(2008\)](#).

Another very significant phenomenon is the increase in volumes directed to Turkey from 2015. This confirms the important role of the country in the Black Sea region, which remains among the top three connections even after the start of the war in 2022. Its centrality in the Grain Initiative certainly influenced the dry bulk connection to its ports. Turkey served in fact as a neutral place for the inspection of the cargoes of the ships, granted by the agreements (i.e., the Black Sea Grain Initiative Agreement). Since 2015, Egypt has also been an important partner, particularly for grain trade. It becomes the first destination for direct trade with Africa, a relationship that will weaken after the start of the war in 2022, but regaining importance in 2023 probably thanks to the cereals agreement.

The only significant impact of the Russian annexation of Crimea that can be traced back to analysing the volumes between 2015 and 2021 is the connection to the U.S. From 2015 to 2021, the country moved from being the seventh-largest connection by volume to the third. These flows are mainly attributed to the increased imports of pig iron and ferrous metal products by the U.S. to support the Ukrainian economy. However, this flow almost disappeared after the start of the war ([U.S. Embassy Kyiv 2022](#)). Despite the escalating geopolitical and military tensions from 2014 onwards, volumes to Russia have increased until 2021. In that year the country became the sixth destination for Ukrainian ports. The outbreak of war in 2022 drastically reduced these volumes, but did not cut the link between the two countries. In 2022 and 2023 there are some residual volumes moving to Russian ports, but they return to growth in 2024.

The outbreak of war meant that certain European ties became stronger and more important for Ukrainian maritime trade. This was the case with the Netherlands and Spain. The former is undoubtedly enhanced by the more secure river trade link via the Danube, which allows it to bypass the maritime blockade in the Black Sea. The latter was boosted by the Grain Initiative Agreement, which made it a significant vertex for Ukrainian grain exports. In the last two years of the analysis, Spain consolidates and confirms its role as the first connection. However, both connections seem to show greater support from EU countries for trade with Ukraine during the war.

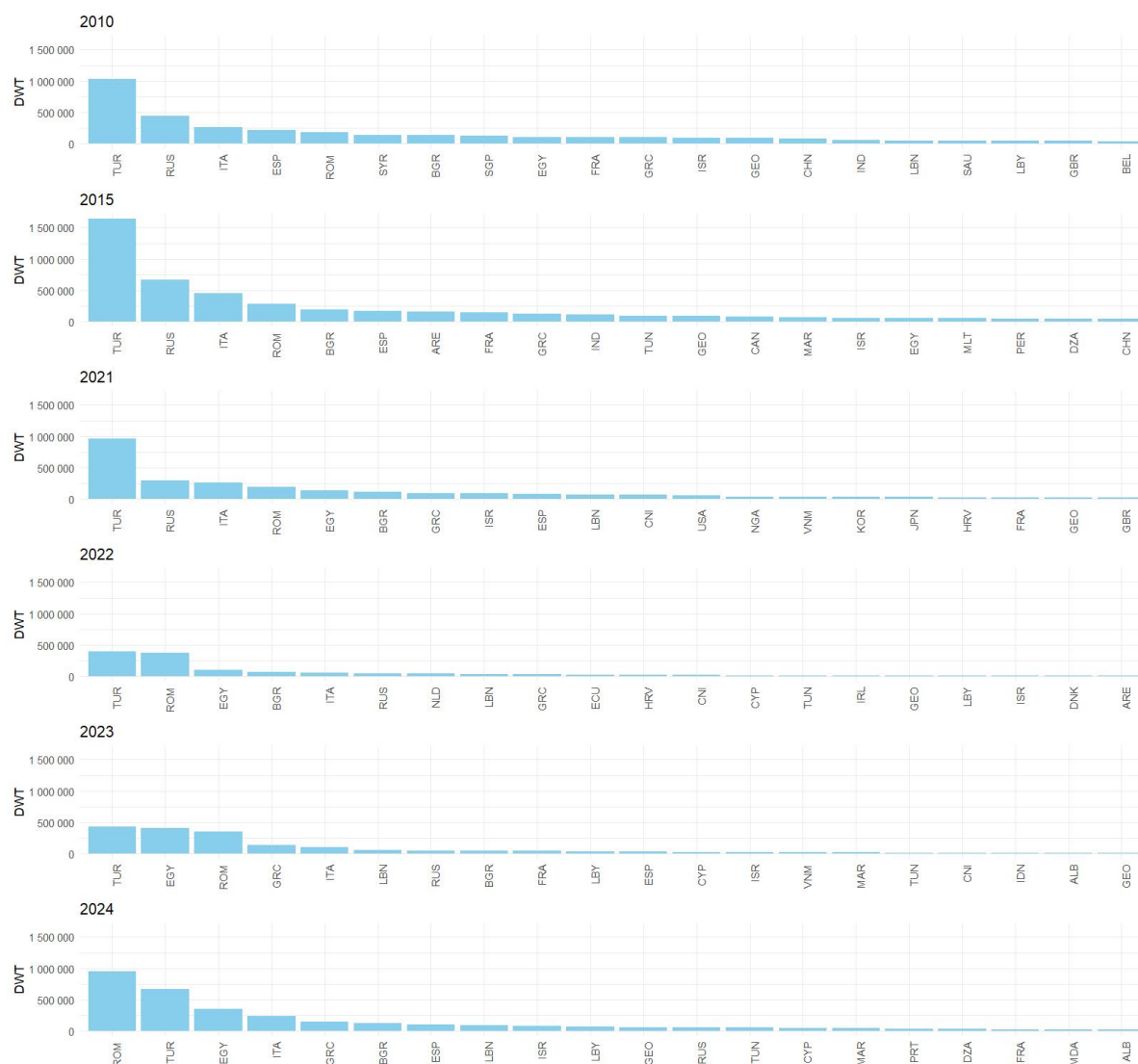


FIGURE 15. Evolution of total cargo capacity (DWT) of general cargo ships moving to foreign countries. (First 20 countries)

Notes: We summed the volumes of ships in DWT leaving from Ukrainian ports and arriving in Ukrainian ports from a foreign country. This figure considers general cargo ships only.

The analysis of general cargo transport seems to show, in contrast to solid bulk, greater stability in the hierarchies of the countries connected to Ukrainian ports. In general, the total volume of traffic is certainly lower than for dry bulk. There was a volume increase between 2010 and 2015, followed by a general decline in 2021. This decline became drastic since the start of the war in 2022 but showed a small recovery in 2023 that continued also in 2024. For the first five years, Turkey remains the most important connection. However, if until 2021 it concentrated the largest outgoing volumes, from 2022 onwards there is a sharp reduction in these volumes

and a greater distribution of volumes to other connections as well. The nation between the Black Sea and the Mediterranean Sea however became the second connection in 2024 despite an increase from the year before. In 2022, Romania augmented its volumes and remained just below Turkey. In 2023, these two main connections were joined by Egypt with volumes similar to the other two countries. In 2024 the increase of Romania volumes and its emergence as the first country in volume reached by general cargo ships in 2024 suggest a redistribution of flows to closer ports. Russia remains the second-largest country in terms of volumes from Ukraine until 2021. However, already in 2021, there is a significant reduction compared to 2015. (see Fig. 15). The increased importance of close neighbours recalls the principle of the aforementioned hub dependence model.

At a general level, liquid bulk appears to be the type of transport most affected by Russia's annexation of Crimea. Compared to 2010, there was a drastic reduction in 2015. From that year onwards, Turkey became the main destination of outflows. In 2021, outbound volumes from Ukraine were mainly concentrated towards Turkey, which saw its volumes increase compared to 2015. However, from 2022 onwards, liquid bulk suffered another further decline like the other modes of transport and a reallocation of volumes to nearer countries like Romania. This country became the first connection for Ukraine in 2022 and 2023 but the second in 2024 just behind Greece. Examining trade between Ukraine and Russia, despite the reduction in volumes between 2010 and 2015 following the annexation of Crimea, these links have not ended and the country has become the second largest in terms of volumes until 2021. In 2022 and 2023, this connection remains but with extremely low volumes³⁴ and disappear completely in 2024.

Finally, the analysis of container transport shows that the only drastic reduction in volumes occurred after 2022. From 2010 to 2021 there was no big change in total outbound volume but the distribution between countries changed. China was the first direct connection in both 2010 and 2015; however, in 2021 it disappeared from the top 20 connections. In its place, Turkey gained importance by concentrating the largest volume. However, the start of the war in 2022 practically eliminated this type of transport from Ukrainian ports, reducing outbound volumes to almost zero. The few connections in 2022 and 2023 are probably mainly due to container ships that have been trapped in Ukrainian ports since the beginning of the war. In 2024 there seems to be a very slight recovery with Romania again as the first link. This analysis shows that this type of transport was the least able to restructure itself after the beginning of the war. On the one hand, the causes could be found in the impossibility of developing scheduled services typical of this type of maritime transport. On the other, container transport may have benefited from an intermodal redirection of the flows via North European ports³⁵.

³⁴For additional details on liquid bulk, please check Fig. F.2 in the Appendix F.

³⁵For additional details on container transport, please check Fig. F.1 in the Appendix F.

4.3. Evolution of International Flows at Port Level

Regarding the network at the port level, from 2015, the value of total DWT (table F.1) confirms that Ukraine is taking steps to reduce its economic dependence on Russia or to lessen its economic ties with Russia. This could involve various strategies or actions aimed at diversifying trade partners, reducing reliance on Russian imports or exports, or strengthening economic relations with other countries or regions. Specifically, Ukraine's association agreement with the European Union (EU) and participation in the Deep and Comprehensive Free Trade Area (DCFTA) provide opportunities for closer economic integration with EU member states. Strengthening economic ties with the EU can help Ukraine reduce its reliance on Russian markets and enhance its access to European markets. However, while political tensions between Ukraine and Russia undoubtedly impact their economic relations, various factors contribute to the continued commerce between Ukraine and Russia, as we can appreciate with the port of Novorossiysk or the ports located in the Volga River.

While Ukraine may seek to diversify its trade routes and reduce its dependence on Russia, alternatives may be limited, especially in the short term. Developing new trade relationships and infrastructure takes time and resources, and until viable alternatives are established, commerce with Novorossiysk may continue. This situation could be explained because Novorossiysk is located relatively close to the southern regions of Ukraine, particularly those bordering the Black Sea. This proximity makes it a convenient and cost-effective port for Ukrainian businesses to export and import goods. This geographical advantage confers to Novorossiysk an essential role in broader international trade routes, connecting not only Ukraine and Russia but also other countries in the region and beyond.

Besides, both Ukraine and Russia have economic dependencies on each other: Ukraine exports various goods to Russia, including agricultural products, metals, and machinery. Similarly, Ukraine imports energy resources, such as natural gas, from Russia. Novorossiysk serves as a crucial point for facilitating this trade. When it comes to trade by ship types, at level port we can see the tendency of Ukraine to reduce the relationships with Russia and strengthen them with European Union or NATO countries since the annexation of Crimea, and overall, after the beginning of the war in 2022.

Regarding the liquid bulk trade, Ukraine had sought to reduce its dependence on Russian energy imports, including oil (gasoline) from the beginning of the war. This move is part of a broader strategy to enhance energy security and reduce vulnerability to geopolitical tensions between Ukraine and Russia. One significant event contributing to this was the annexation of Crimea by Russia in 2014 and the subsequent armed confrontation in eastern Ukraine³⁶, which heightened concerns about the reliance on Russian energy supplies. To mitigate this dependency, Ukraine, since 2022, has been exploring various avenues such as diversifying

³⁶Considering that the global Russo-Ukrainian war started in 2022.

its energy sources, increasing domestic production, and seeking alternative suppliers. This includes importing petroleum from other countries or producing it domestically where possible.

The degree of liquid bulk at the port level shows this tendency (see Table F.2). In 2010, before Crimea's annexation, the Russian ports of Kerch, Rostov and Novorossiysk were the most important in liquid bulk trade with Ukraine. After the annexation, Russia maintained the two first positions in the list with Rostov and Kavkaz until 2021, when only Rostov and Temryuk ports appeared in the first ten positions, but not as the most important ones. When the war broke out, Rotterdam, Ereğli in the Sea of Marmara and Seville were the most important ports to trade liquid bulk; changing last year for Romanian ports like Constanta, Sulina, and Bitter Lakes in Egypt. Russian ports have almost disappeared as points of liquid bulk trade.

In terms of solid bulk, Ukraine is one of the world's major producers and exporters of cereals, including wheat, barley, and corn. The country's agricultural sector plays a crucial role in its economy, and cereal exports are a significant component of its international trade. Ukraine's cereal trade involves exporting its products to various countries around the world, including countries in the Middle East (Jeddah in Saudi Arabia or Bandar Imam Khomeini in Iran), North Africa (Alexandria and Bitter Lakes in Egypt), Europe (Rotterdam in Netherlands, Piraeus in Greece, Ravenna in Italy, Algeciras, Tarragona and La Canal in Spain or Iskenderun and Ereğli in Turkey) and Asia (Singapore or Tartous in Syria). The list of the top ports of solid bulk includes Novorossiysk as one of the most important ports even during the current war, because of the aforementioned reasons (see table A.4 in appendix A).

The same situation for container trade occurs. The analyses at the port level let us appreciate the change in relationships after Crimea. In 2010 the relationships diversified, having ports from Africa (Alexandria in Egypt), Asia (Shanghai or Qingdao in China, Singapore, Ashdod in Israel or Port Klang in Malaysia) and Europe. However, after the annexation of Crimea in 2014 until now, we have observed a transformation of trade relationships between Ukraine and the rest of the world, where Europe is the central receptor of trade - Novorossiysk is the only Russian port remaining. Only Egyptian and Tunisian ports, such as Alexandria or Zarzis, remain important ports outside Europe. However, the most striking is the fact that only these nine ports had container trade with Ukraine³⁷.

With the start of the global invasion, maritime trade via the Black Sea encountered significant disruptions (Figure G.1). Grain exports, a crucial economic activity facilitated through the Black Sea, faced persistent threats from Russian assaults, particularly during the heaviest onslaught between February and July of 2022. Following the invasion, Ukraine relinquished full control of the Mariupol port in May 2022, after Russia's occupation initiated on February 24, 2022. Among the remaining four vital ports, Mykolaiv ceased operations due to the comprehensive invasion by Russia, while Chornomorsk, Pivdennyi, and Odessa ports have been functioning at reduced

³⁷Please check Tab. F.1 in appendix.

capacity since February 2022.

For this reason, in May 2022, the European Commission introduced the ‘Solidarity Lanes action plan’ to facilitate the movement of goods to and from Ukraine. The ‘EU-Ukraine Solidarity Lanes’ initiative offers alternative logistics routes to Ukraine’s seaports, encompassing rail, road, and inland waterways. According to the World Bank, by July 2023, nearly 33 million metric tons of grain and other foodstuffs had been exported via the Black Sea Grain Initiative, representing approximately half of the pre-invasion export volume (See Fig. G.2). Concurrently, Ukraine facilitated the import of vital commodities such as fuel, while ensuring the unimpeded flow of military and humanitarian aid (See Fig. G.3). However, container trade has almost disappeared (Figure G.4), probably due to the shift mentioned by Gruchevska, Notteboom, and Ducruet (2017) towards Hamburg and Baltic Sea ports.

In July 2022, Russia, Ukraine, Turkey, and the United Nations collaborated to establish the ‘Black Sea Grain Initiative’. This initiative aimed to provide partial security for Ukraine’s grain exports via the Black Sea ports of Odessa, Chornomorsk, and Pivdennyi for one year. Since August 2022, the initiative has facilitated the shipment of 32 million metric tons of Ukrainian grain and foodstuffs worldwide. Additionally, it enabled Ukraine to export more than 36 million metric tons of non-agricultural goods such as iron, steel, ores, and wood. However, Russia terminated the agreement in July 2023, leading to a resumption of heavy attacks on Ukraine’s port infrastructure (See Fig. 16).

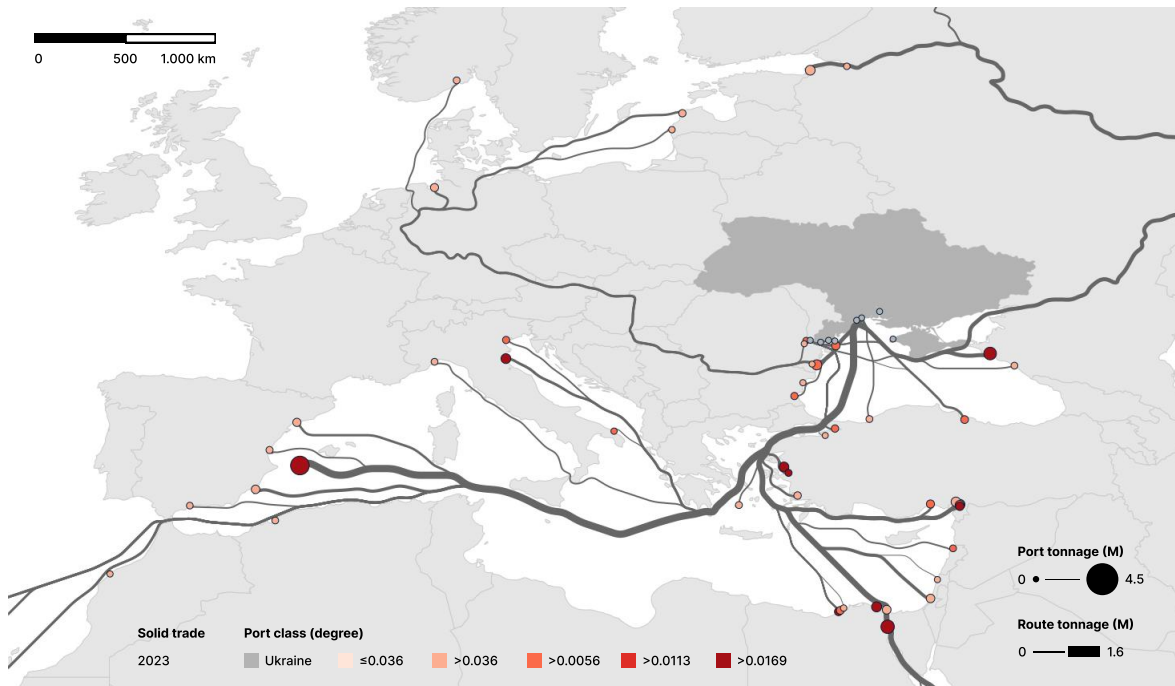


FIGURE 16. Solid trade in 2022

So, as a response, in August 2023, Ukraine initiated its own alternative Black Sea corridor, with support from its Western allies. This corridor connecting Ukrainian ports to the Bosphorus Strait has demonstrated effectiveness. Ships now navigate along the western coast of the Black Sea, along Romanian and Bulgarian territorial waters. Additionally, Ukraine has expanded its grain export activities through the ports of Reni and Izmail, situated along the Danube River and the Mediterranean Sea up to Spain (See Fig. 17). In December 2023, Ukraine asserted that it had exported around seven million metric tons of cargo through its seaports, with five million metric tons consisting of Ukrainian agricultural products. In 2024 (Fig. 18), Ukraine's trade sector demonstrated significant resilience and recovery, as detailed in the April 2024 report . (Bandura, Timtchenko, and Robb 2024).

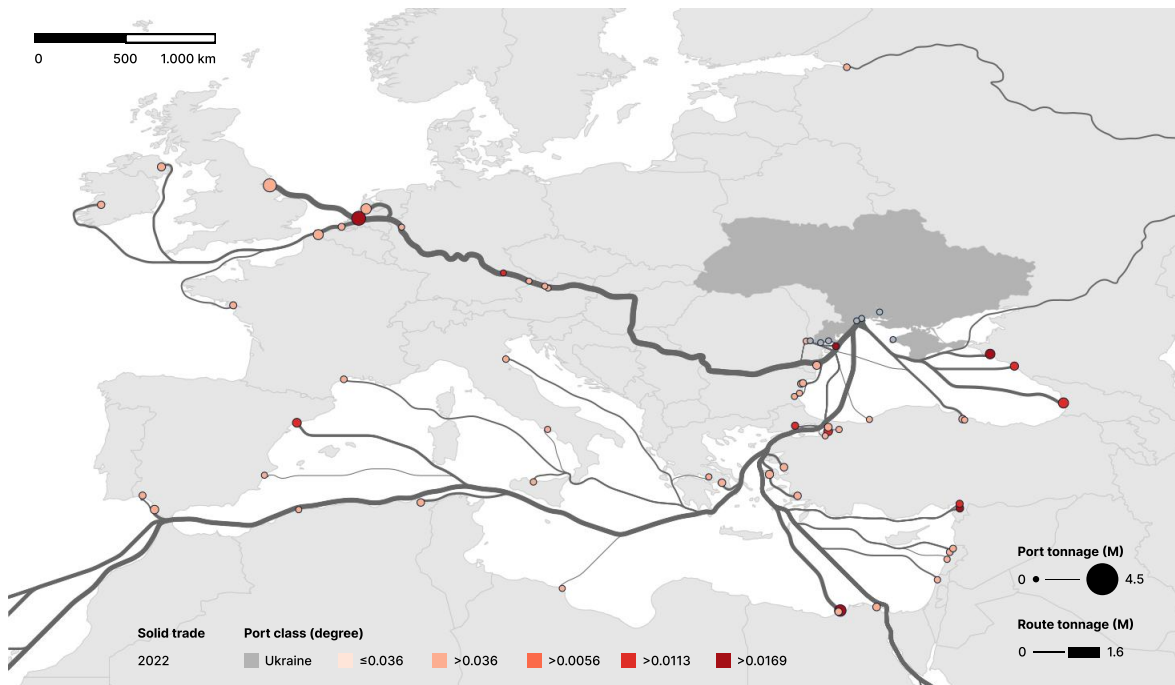


FIGURE 17. Solid trade in 2023

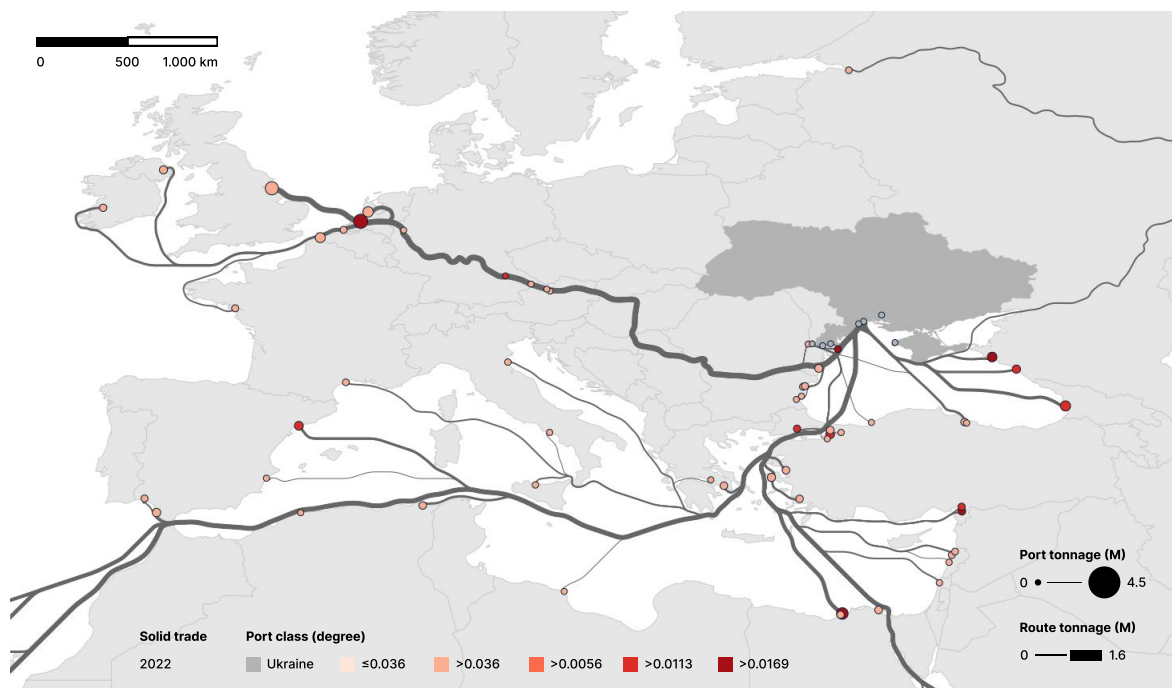


FIGURE 18. Solid trade in 2024

5. Discussion and conclusion

Since gaining independence from the Soviet Union in 1991, Ukraine has undergone significant changes across various aspects of its society, economy, and politics. However, the ongoing war with Russia and its implications on international relations will likely continue to influence Ukraine's trade patterns. Shifts in alliances, sanctions, and political developments have impacted trade agreements and partnerships.

Ukraine's association agreement with the European Union (EU) has led to increased trade with EU countries as we have seen through our analyses. Continued efforts towards integration and compliance with EU standards could further boost trade volumes, particularly in sectors like solid or liquid bulks.

The quantitative analysis deployed at three levels - network models, bilateral trade, and trade route modelling - highlighted the magnitude of the shock and the gradual resilience experienced by Ukraine in 2022 and 2023. We have also shown how this shock affects different types of goods in different ways. Ukraine's role as a transit country for natural gas has been significant historically. Still, the current situation has provoked a shift in Ukraine's trade dynamics related to energy markets, including changes towards renewable energy sources and changes in gas transit routes. These factors, along with any unforeseen events or developments, will collectively shape the evolution of Ukrainian trade in 2024. Continuous monitoring of economic indicators and geopolitical dynamics will be necessary to assess the actual trajectory of Ukrainian trade

throughout the year.

However, we are aware that inland corridors have gained weight during the war³⁸. Before the full-scale invasion, non-marine modes of transportation accounted for 37% of Ukraine's trade turnover, while seaports were responsible for approximately 63% [State Customs Service of Ukraine \(2021\)](#). At the start of the war, in 2022, the cargo volumes showed that 60.36 million tons were transported through land borders with the EU, 13.61 million tons with CIS countries, and 76.85 million tons through sea checkpoints. In 2023, these numbers changed slightly to 64.13 million tons with the EU, 5.81 million tons with CIS countries, and 76.37 million tons via sea checkpoints [State Customs Service of Ukraine \(2023\)](#).

The contribution of this paper is twofold. To the best of our knowledge, it is the first detailed analysis of the impact of the Russian invasion on the structure and dynamics of Ukrainian maritime trade flows. Most of the literature of this war is qualitative, made of discussions about shipping sustainability for instance ([Zhao, Duan, and Chang 2023](#)). In addition, it makes a broader contribution to the literature, which is still fairly thin, on the impact of war on maritime networks.

Although the literature about maritime network vulnerability is well-developed, most of it remains theoretical or addresses other types of shocks, such as natural disasters (cyclones, hurricanes, typhoons, climate extremes), or focus on unintended disruptions (*e.g.*, COVID-19, canal blockade, bottlenecks) and estimate the degree of network's resilience. Our study is relatively unique, as it deploys an empirical analysis based on actual vessel movements. The paper is the only one that use of *Lloyd's List* corpus for the reconstruction maritime network of Ukraine instead of AIS data. Furthermore, an innovative combination of quantitative techniques has been used to model and quantify the disruption of the Ukrainian maritime network. We also innovate by analysing the network at different geographic scales, and covering various types of cargo, unlike more specialized studies focusing on a single commodity such as liquid gas ([Xiao et al. 2024b](#)) or looking at the global scale only ([L. et al. 2024](#)).

This chapter does not estimate a formal counterfactual trajectory of Ukrainian maritime trade in the absence of war. This choice is deliberate. The 2022 full-scale invasion affected port operations, hinterland routes, insurance conditions, security constraints, commodity markets, and trade policy simultaneously, making the construction of a credible untreated comparison network difficult. Instead, the analysis relies on a multilevel event-based approach. To provide a descriptive benchmark, Appendix D reports the evolution of key network metrics relative to their 2010-2021 pre-war average. This benchmark should not be interpreted as a causal counterfactual, but it helps quantify the magnitude of the post-2022 disruption relative to the pre-invasion structure of the Ukrainian maritime network.

³⁸Specifically focusing on Ukraine, this is an important point for a future research agenda: combining shipping with inland flows and model/quantify the multimodal impact of the Ukrainian war.

We identified two promising paths for further research. First, one shall investigate the impact of this war with a higher time granularity³⁹. This granular approach could be completed with a more in-depth analysis of bilateral flows: combining network models with gravity techniques⁴⁰ might lead to interesting results on the impact of the Ukrainian war on trade. The second path for research is to focus on vulnerability and resilience. This is a relatively new field in shipping network analysis. Considering that conflicts have a long-lasting and significant impact on trade, researching the *ex-ante* vulnerability and *ex-post* resilience of shipping networks could help researchers and practitioners anticipate and mitigate crises by focusing on vulnerable areas of the network.

³⁹*Lloyd's List* provides data at the day level for all the ships recorded in the database. In this paper, we decided to aggregate it at the port and year level for a global overview

⁴⁰[Herman \(2022\)](#) combined Exponential Random Graph Models (ERGMs) with standard gravity estimates to explore the network effect in the structure of international trade.

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A. Degree centralities

TABLE A.1. Degree centralities (normalised) for the global network at port level (top 10 ports)

	degree	country	port
2010			
	0.028195489	RUS	Rostov
	0.02443609	ROM	Constantza
	0.02443609	TUR	Diliskelesi
	0.022556391	RUS	Novorossiysk
	0.022556391	GEO	Poti
	0.022556391	TUR	Gebze
	0.020676692	TUR	Zeytinburnu
	0.020676692	TUR	Iskenderun
	0.018796992	BGR	Bourgas
	0.018796992	TUR	Nemrut Bay
2015			
	0.024604569	TUR	Gebze
	0.021089631	TUR	Nemrut Bay
	0.021089631	TUR	Bandirma
	0.021089631	ROM	Constantza
	0.021089631	TUR	Samsun
	0.019332162	RUS	Novorossiysk
	0.019332162	BGR	Bourgas
	0.019332162	RUS	Rostov
	0.019332162	BGR	Varna
	0.017574692	GRC	Thessaloniki
2021			

Continued on next page

TABLE A.1 – *Continued from previous page*

degree	country	port
0.020637899	TUR	Bandirma
0.020637899	ROM	Constantza
0.018761726	EGY	Damietta
0.018761726	RUS	Novorossiysk
0.018761726	TUR	Nemrut Bay
0.018761726	TUR	Izmir
0.018761726	TUR	Hereke
0.016885553	BGR	Bourgas
0.016885553	EGY	Alexandria (EGY)
0.016885553	TUR	Eregli
2022		
0.023715415	EGY	Alexandria (EGY)
0.023715415	TUR	Yalova
0.019762846	RUS	Novorossiysk
0.019762846	NLD	Rotterdam
0.019762846	TUR	Mersin
0.019762846	ROM	Constantza
0.019762846	BGR	Varna
0.019762846	TUR	Tuzla
0.015810277	SGP	Singapore
0.015810277	GEO	Poti
2023		
0.02166065	EGY	Damietta
0.02166065	RUS	Novorossiysk
0.02166065	TUR	Nemrut Bay
0.02166065	ROM	Sulina
0.02166065	ROM	Constantza

Continued on next page

TABLE A.1 – *Continued from previous page*

degree	country	port
0.02166065	TUR	Yesilyurt
0.018050542	EGY	Bitter Lakes
0.018050542	EGY	Alexandria (EGY)
0.018050542	TUR	Tekirdag
0.018050542	TUR	Izmir
2024		
0.023489932	GRC	Eleusis
0.023489932	BGR	Burgas
0.023489932	TUR	Gemlik
0.023489932	ROM	Constantza
0.020134228	RUS	Novorossiysk
0.020134228	EGY	El Dekheila
0.020134228	BLK	Poti
0.020134228	EGY	Alexandria (EGY)
0.0201342281	TUR	Tekirdag
0.0201342281	TUR	Mersin

Note: For each year, the table reports the ten ports with the highest normalised degree centrality in the corresponding network. Degree centrality is computed on the port-level graph and values are comparable within years.

TABLE A.2. Degree centralities of liquid bulk by port

Degree	Country	Port
2010		
0.015037594	RUS	Rostov
0.011278195	RUS	Novorossiysk
0.011278195	ROM	Midia

Continued on next page

TABLE A.2 – *Continued from previous page*

Degree	Country	Port
0.009398496	SGP	Singapore
0.009398496	GEO	Poti
0.009398496	ROM	Sulina
0.009398496	TUR	Diliskelesi
0.009398496	ROM	Constantza
0.009398496	TUR	Aliaga
0.009398496	ROM	Constantza
2015		
0.010544815	RUS	Rostov
0.008787346	RUS	Kavkaz
0.007029877	TUR	Nemrut Bay
0.007029877	ROM	Sulina
0.007029877	GRC	Aspropyrgos
0.007029877	GEO	Batumi
0.007029877	TUR	Diliskelesi
0.005272408	RUS	Novorossiysk
0.005272408	SGP	Singapore
0.005272408	GRC	Eleusis
2021		
0.00750469	TUR	Eregli
0.00750469	RUS	Rostov
0.00750469	GRC	Agioi Theodoroi
0.00750469	EGY	Alexandria (EGY)
0.00750469	TUR	Nemrut Bay
0.00750469	ROM	Constantza
0.00750469	GRC	Aspropyrgos
0.00750469	RUS	Temryuk

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TABLE A.2 – *Continued from previous page*

Degree	Country	Port
0.00750469	EGY	Port Fouad
0.005628518	NOR	Porsgrunn
2022		
0.011857708	NLD	Rotterdam
0.011857708	TUR	Eregli
0.011857708	ESP	Seville
0.007905138	ITA	Monopoli
0.007905138	NLD	Amsterdam
0.007905138	LVA	Riga
0.007905138	TUR	Dortyol
0.007905138	ROM	Galatz
0.007905138	EGY	Alexandria
0.007905138	TUR	Mersin
2023		
0.018050542	ROM	Constantza
0.014440433	ROM	Sulina
0.010830325	EGY	Bitter Lakes
0.010830325	TUR	Eregli
0.010830325	GRC	Eleusis
0.010830325	ITA	Ravenna
0.010830325	GEO	Batumi
0.010830325	TUR	Diliskelesi
0.007220217	EGY	Damietta
0.007220217	BEL	Antwerp
2024		
0.023489932	GRC	Eleusis

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TABLE A.2 – *Continued from previous page*

Degree	Country	Port
0.013422818	TUR	Dortyol
0.013422818	TUR	Mersin
0.013422818	ITA	Ravenna
0.013422818	TUR	Rota (TUR)
0.010067114	ITA	Monopoli
0.010067114	EGY	Damietta
0.010067114	ROM	Galatz
0.010067114	EGY	Alexandria
0.010067114	ESP	Huelva

Note: For each year, the table reports the ten ports with the highest normalised degree centrality in the corresponding network. Degree centrality is computed on the port-level graph and values are comparable within years.

TABLE A.3. Degree centralities of solid bulk by port

Degree	Country	Port
2010		
0.011278195	SGP	Singapore
0.009398496	RUS	Novorossiysk
0.009398496	SYR	Tartous
0.009398496	NLD	Rotterdam
0.009398496	EGY	Alexandria
0.009398496	SAU	Jeddah
0.009398496	TUR	Iskenderun
0.007518797	GRC	Piraeus
0.007518797	ESP	Algeciras
0.007518797	GEO	Poti

Continued on next page

TABLE A.3 – *Continued from previous page*

	Degree	Country	Port
2015			
	0.014059754	RUS	Novorossiysk
	0.012302285	EGY	Alexandria
	0.012302285	ITA	Ravenna
	0.008787346	EGY	Damietta
	0.008787346	ESP	Algeciras
	0.008787346	SGP	Singapore
	0.008787346	EGY	El Dekheila
	0.008787346	BGR	Bourgas
	0.008787346	ESP	Castellon
	0.008787346	TUR	Dortyol
2021			
	0.013133208	RUS	Novorossiysk
	0.011257036	EGY	Damietta
	0.011257036	SGP	Singapore
	0.011257036	EGY	El Dekheila
	0.011257036	TUR	Iskenderun
	0.011257036	ROM	Constantza
	0.009380863	BGR	Bourgas
	0.009380863	EGY	Alexandria
	0.009380863	BRA	Santos
	0.009380863	TUR	Eregli
2022			
	0.015810277	EGY	Alexandria
	0.011857708	RUS	Novorossiysk
	0.011857708	NLD	Rotterdam

Continued on next page

TABLE A.3 – *Continued from previous page*

Degree	Country	Port
0.011857708	TUR	Iskenderun
0.007905138	ROM	Sulina
0.011857708	ESP	Tarragona
0.007905138	GEO	Poti
0.007905138	TUR	Dortyol
0.007905138	BRA	Paranagua
0.007905138	TUR	Tekirdag
2023		
0.018050542	EGY	Bitter Lakes
0.014440433	EGY	Damietta
0.010830325	RUS	Novorossiysk
0.010830325	TUR	Sariseki
0.010830325	ESP	La Canal
0.010830325	EGY	El Dekheila
0.010830325	TUR	Nemrut Bay
0.010830325	TUR	Izmir
0.007220217	ITA	Ravenna
0.007220217	IRN	Bandar Imam
2024		
0.013422818	EGY	Alexandria (EGY)
0.013422818	TUR	Bandirma
0.013422818	TUR	Hereke
0.013422818	ROM	Constantza
0.013422818	EGY	Abu Kir
0.010067114	EGY	Bitter Lakes
0.010067114	EGY	Damietta
0.010067114	RUS	Novorossiysk

Continued on next page

TABLE A.3 – *Continued from previous page*

Degree	Country	Port
0.010067114	NLD	Rotterdam
0.010067114	ESP	Huelva

Note: For each year, the table reports the ten ports with the highest normalised degree centrality in the corresponding network. Degree centrality is computed on the port-level graph and values are comparable within years.

TABLE A.4. Degree centralities of containers by port

Degree	Country	Port
2010		
0.007518797	EGY	Alexandria
0.005639098	RUS	Novorossiysk
0.005639098	CHI	Shanghai
0.005639098	ISR	Ashdod
0.003759398	MYS	Port Klang
0.003759398	NLD	Rotterdam
0.003759398	SGP	Singapore
0.003759398	GRC	Thessaloniki
0.003759398	CHI	Qingdao
0.003759398	TUR	Ambarli
2015		
0.007029877	RUS	Novorossiysk
0.007029877	TUR	Nemrut Bay
0.005272408	ESP	Barcelona
0.005272408	TUR	Ambarli
0.005272408	MLT	Marsaxlokk
0.005272408	TUR	Evyap

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TABLE A.4 – *Continued from previous page*

Degree	Country	Port
0.003514938	GRC	Piraeus
0.003514938	SGP	Singapore
0.003514938	USA	Charleston
0.003514938	BGR	Bourgas
2021		
0.00750469	TUR	Nemrut Bay
0.005628518	ESP	Algeciras
0.005628518	TUR	Ambarli
0.005628518	ROM	Constantza
0.003752345	RUS	Novorossiysk
0.003752345	GRC	Piraeus
0.003752345	NLD	Rotterdam
0.003752345	GRC	Thessaloniki
0.003752345	EGY	El Dekheila
0.003752345	BGR	Bourgas
2022		
0.007905138	TUR	Tuzla
0.007905138	TUR	Diliskelesi
0.003952569	ITA	Barletta
0.003952569	RUS	Novorossiysk
0.003952569	TUR	Ambarli
0.003952569	TUN	Zarzis
0.003952569	EGY	Alexandria
0.003952569	TUR	Gemlik
0.003952569	ROM	Sulina
0.003952569	TUR	Hereke

Continued on next page

TABLE A.4 – *Continued from previous page*

Degree	Country	Port
2023		
0.018050542	ROM	Sulina
0.014440433	RUS	Novorossiysk
0.010830325	ESP	Castellon
0.010830325	TUR	Zonguldak
0.010830325	EGY	Alexandria
0.010830325	GRC	Nea Karvali
0.010830325	TUR	Nemrut Bay
0.010830325	ROM	Constantza
0.007220217	TUR	Diliskelesi
2024		
0.010067114	ROM	Sulina
0.010067114	ROM	Constantza
0.006711409	TUR	Gemlik
0.006711409	TUR	Nemrut Bay
0.006711409	ROM	Braila
0.003355701	GRC	Piraeus
0.003355704	GRC	Suda Bay
0.003355704	TUR	Eregli
0.003355704	LBN	Tripoli
0.003355704	ARE	Abu Dabhi

Note: For each year, the table reports the ten ports with the highest normalised degree centrality in the corresponding network. Degree centrality is computed on the port-level graph and values are comparable within years.

B. Construction of the Ukrainian Maritime Network

To build Ukraine's maritime network, we used data provided by Lloyd's List. This data tracks the movement of ships daily for four months of the year (one per quarter). In this way, it is possible to cover all the mechanisms at work over a year while maintaining a computationally acceptable amount of data.

In graph theory, a network denoted $\mathcal{G}(V, E)$ is composed of nodes, or vertices, V , and links, or edges, E . To reconstruct the Ukrainian maritime network we combine the monitoring of the movement of ships, and the identification of ports and we quantify the quantities transported using a third file containing the size of the ships.

We thus reconstruct the ship routes (from point to point). Each link, between two ports, therefore, receives a size (corresponding to the quantity of goods transported on this link) and each port is weighted by the traffic it receives.

C. Degree Distribution for Each Type of Vessels

C.1. Liquid Bulks

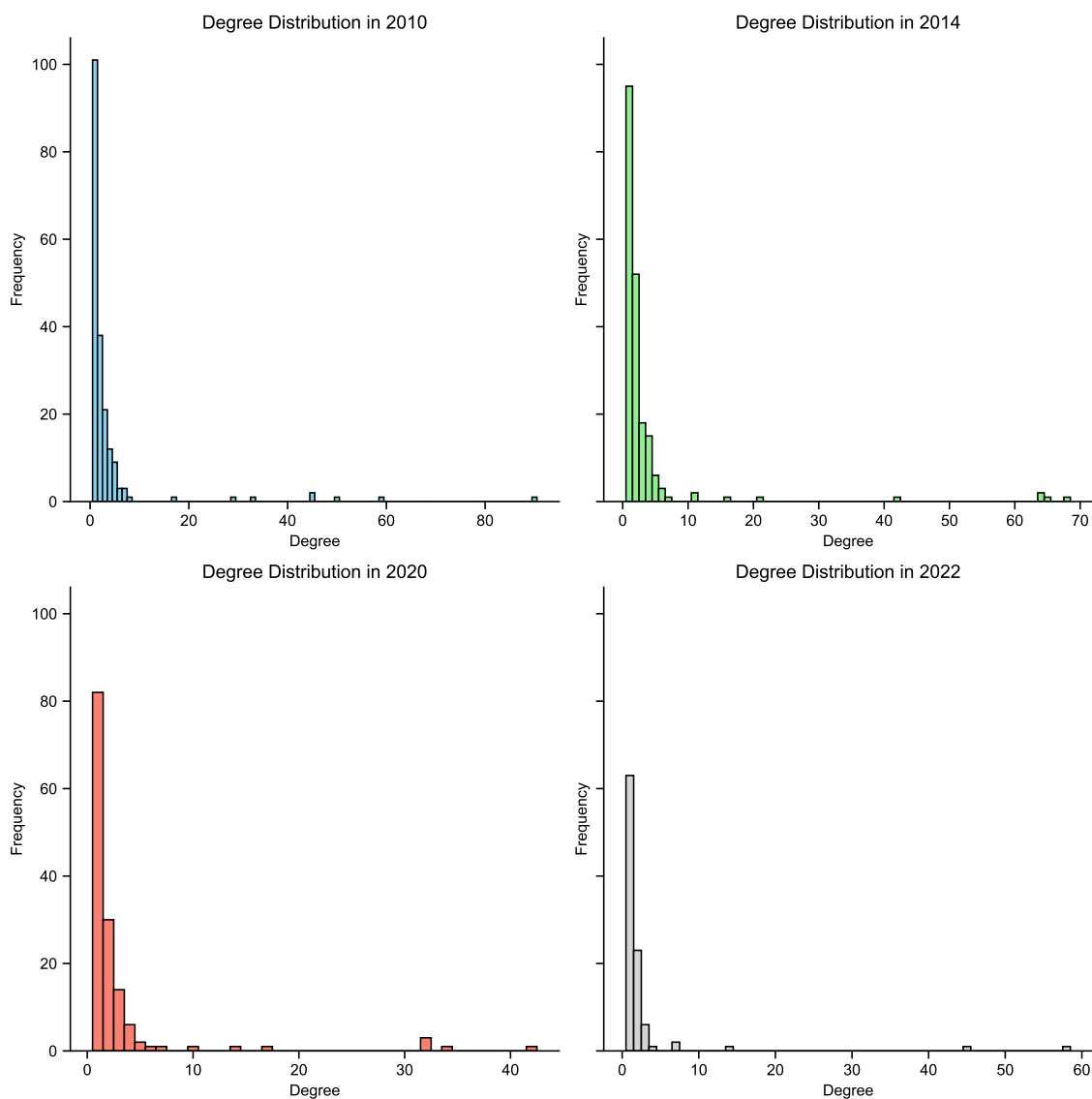


FIGURE C.1. Degree distribution of liquid bulks

Notes: We computed the degree distribution for the Ukrainian network of liquid bulks. We did this operation for four years: 2010, 2014 (annexation of Crimea), 2020 and 2022 (invasion of Ukraine).

C.2. Solid Bulks

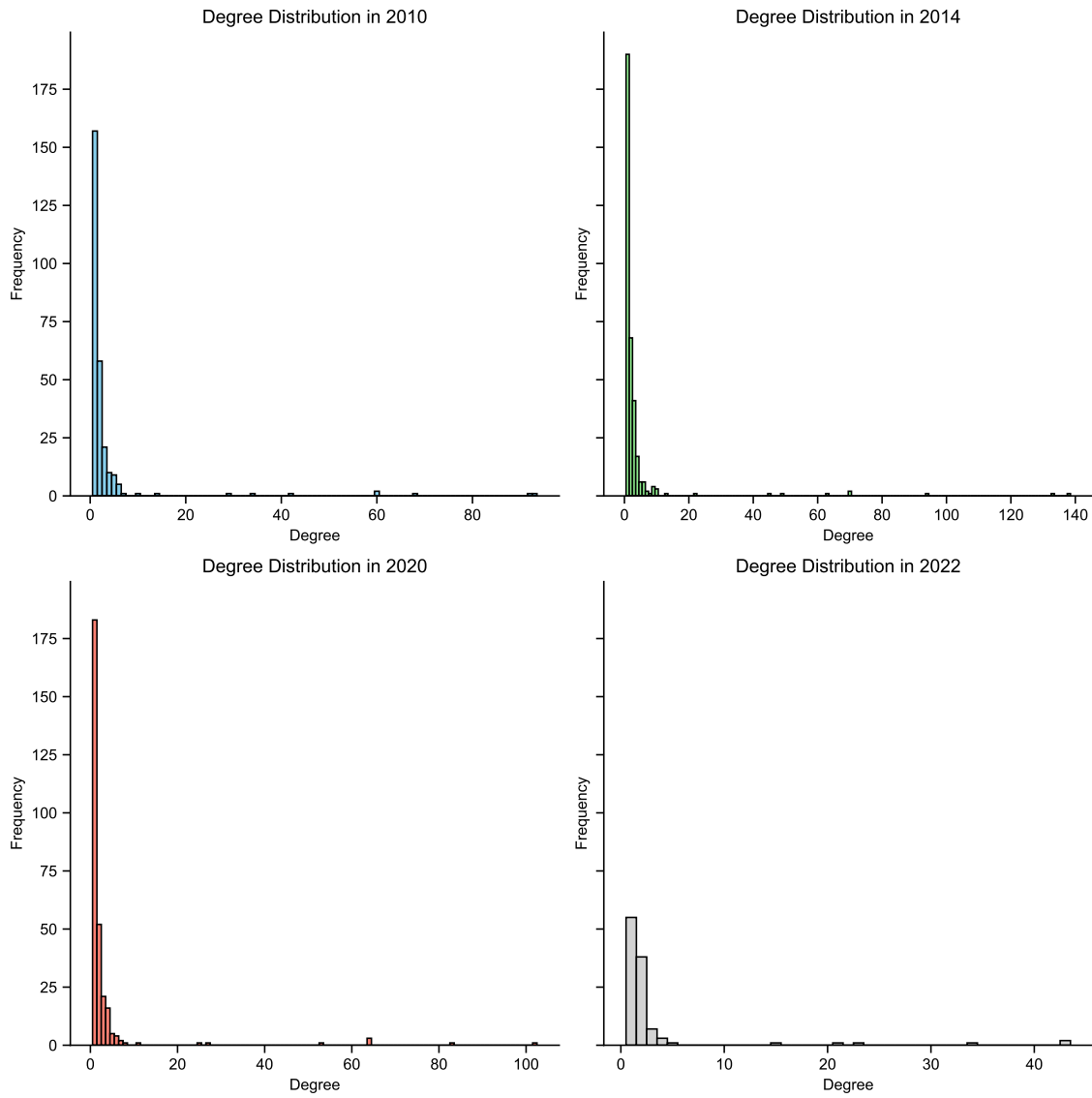


FIGURE C.2. Degree distribution of solid bulks

Notes: We computed the degree distribution for the Ukrainian network of solid bulks. We did this operation for four years: 2010, 2014 (annexation of Crimea), 2020 and 2022 (invasion of Ukraine).

C.3. Containers

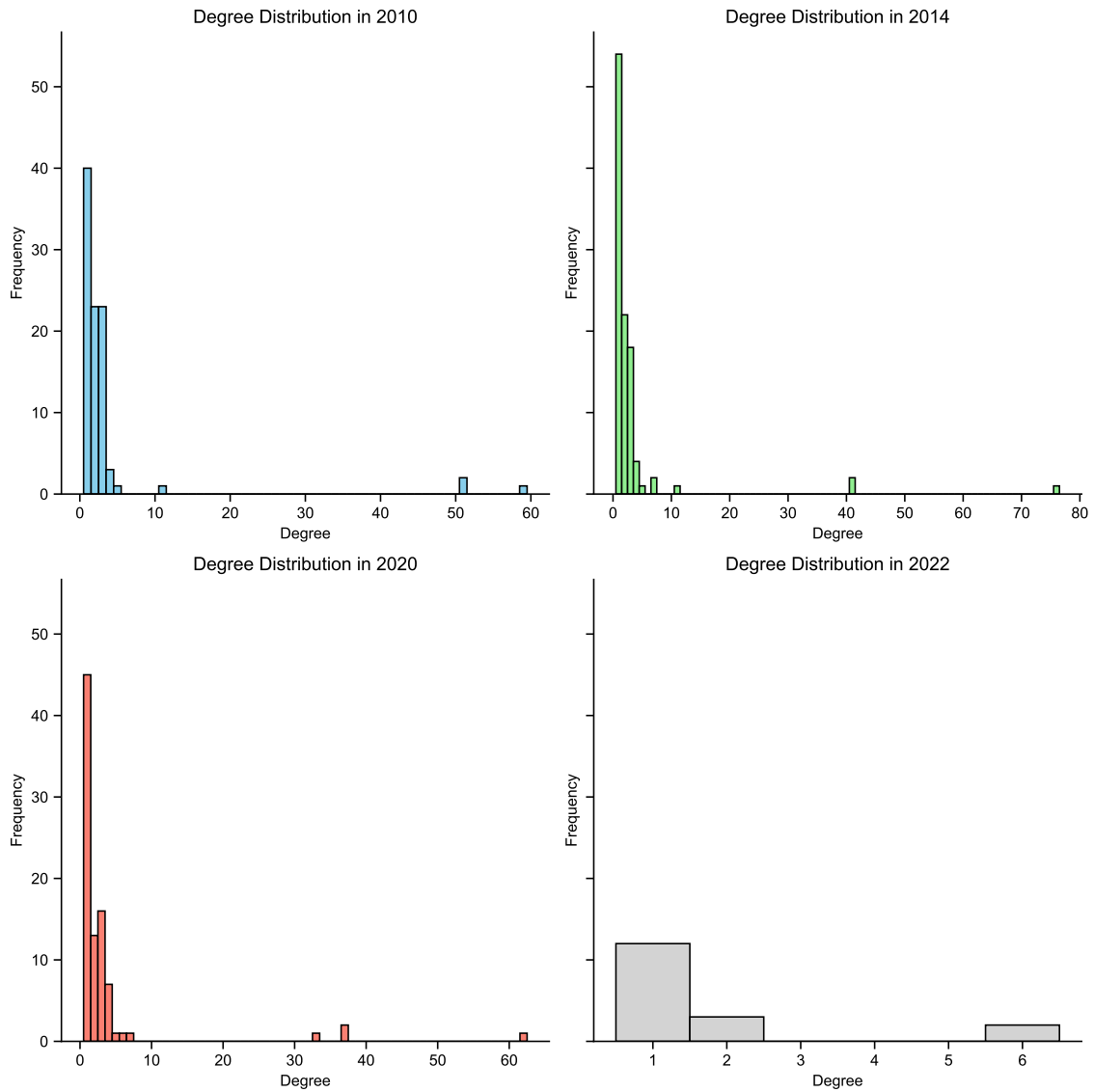


FIGURE C.3. Degree distribution of containers

Notes: We computed the degree distribution for the Ukrainian network of container ships. We did this operation for four years: 2010, 2014 (annexation of Crimea), 2020 and 2022 (invasion of Ukraine).

C.4. Passengers and Vehicles

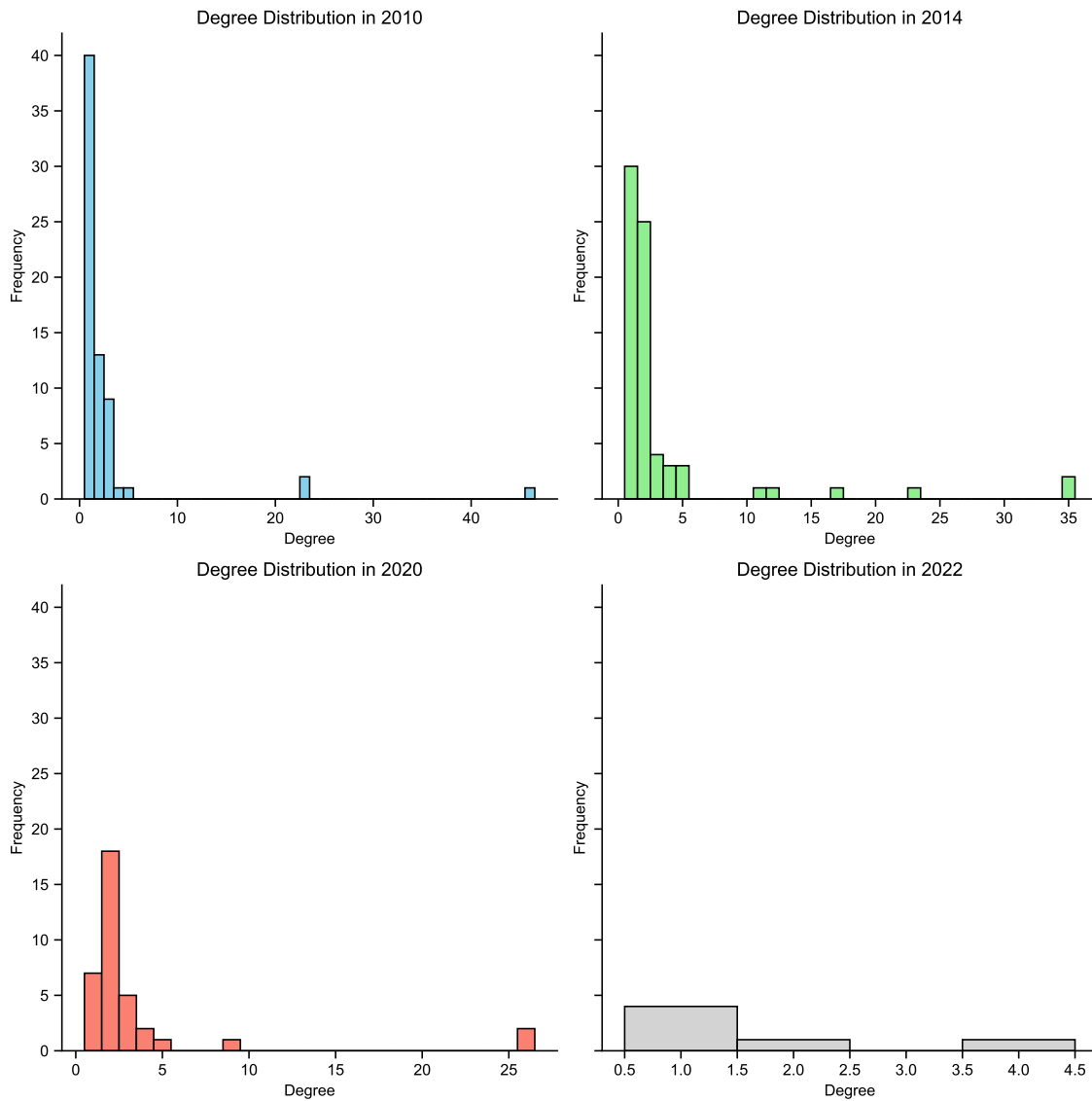


FIGURE C.4. Degree distribution of passengers and vehicles

Notes: We computed the degree distribution for the Ukrainian network of passengers and vehicles ships. We did this operation for four years: 2010, 2014 (annexation of Crimea), 2020 and 2022 (invasion of Ukraine).

The flows for passengers and vehicles, as represented in figure C.4 tell something that is not significantly visible for the other types: the annexation of Crimea in 2014 seems to impact the traffic. In 2010, we observe the standard power-law shape with some high values and the distribution is progressively flattened, starting in 2014. Similarly to the

containers' traffic, the distribution is almost flat in 2022 with the highest value for the degree at 4.5 while we observe values above 45 in 2010.

D. Additional Metrics

In this appendix, we provide additional metrics, including various types of goods (complementing Fig. D.1) and additional networks (complementing 9).

D.1. Network Metrics for The Containers Network

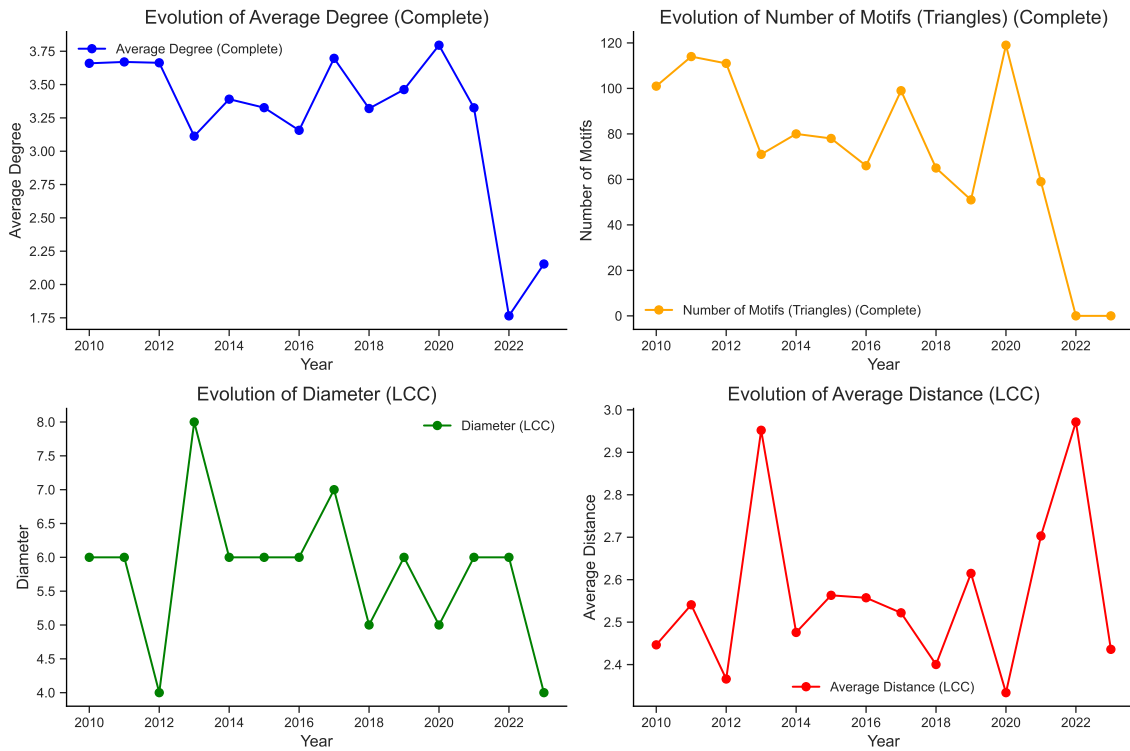


FIGURE D.1. Topology of the container network of Ukrainian ports

Notes: The average degree is computed as the average of the number of connections of each port (*i.e.* the ‘degree’). The triangle metric computes the sum of all the K_3 graphs in the network. The diameter and the average distance are computed on the largest connected component each year, to avoid infinite values due to disconnected sub-graphs.

D.2. Network Metrics for Solid Bulks

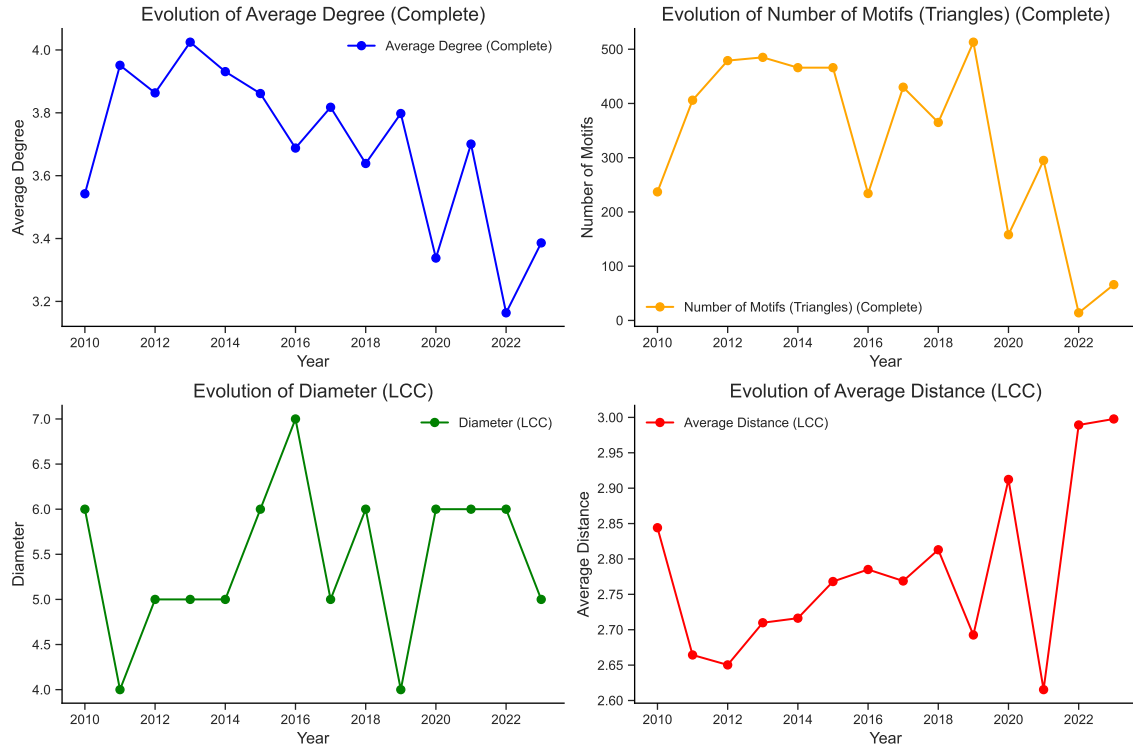


FIGURE D.2. Evolution of the network metrics for solid bulk.

Notes: The average degree is computed as the average of the number of connections of each port (*i.e.* the ‘degree’). The triangle metric computes the sum of all the K_3 graphs in the network. The diameter and the average distance are computed on the largest connected component each year, to avoid infinite values due to disconnected sub-graphs.

D.3. Network Metrics for General Cargo

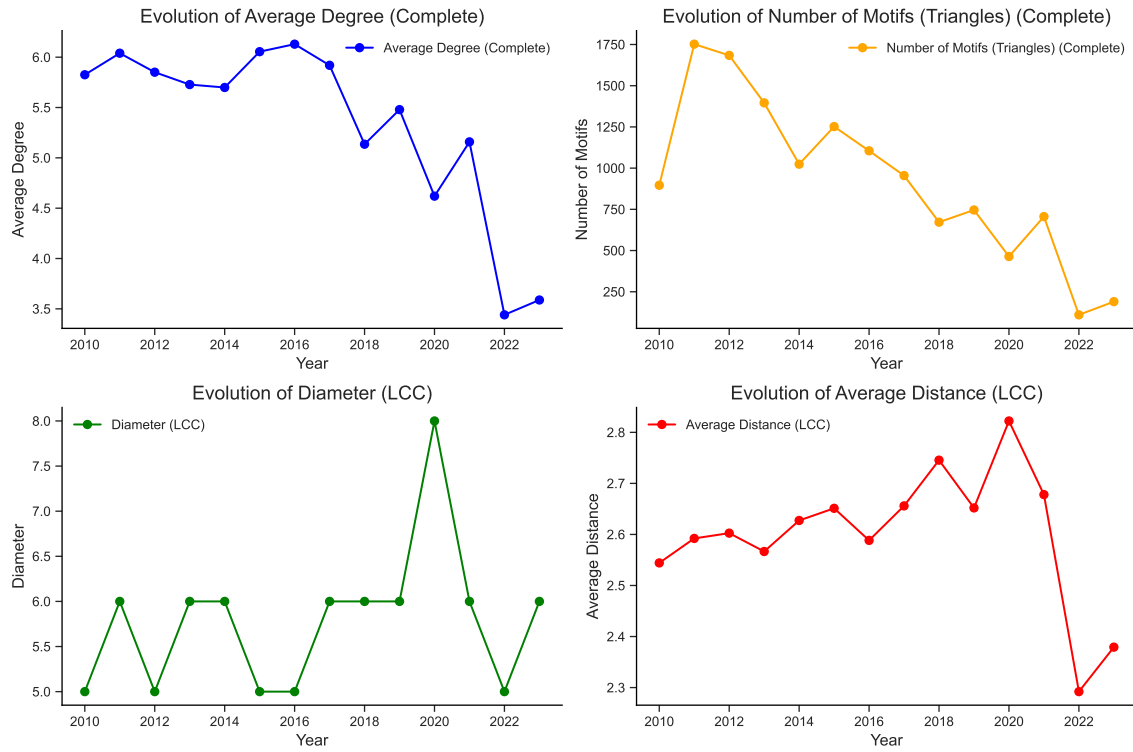


FIGURE D.3. Evolution of the network metrics for general cargo

Notes: The average degree is computed as the average of the number of connections of each port (*i.e.* the ‘degree’). The triangle metric computes the sum of all the K_3 graphs in the network. The diameter and the average distance are computed on the largest connected component each year, to avoid infinite values due to disconnected sub-graphs.

D.4. Network Metrics for Liquid Bulks

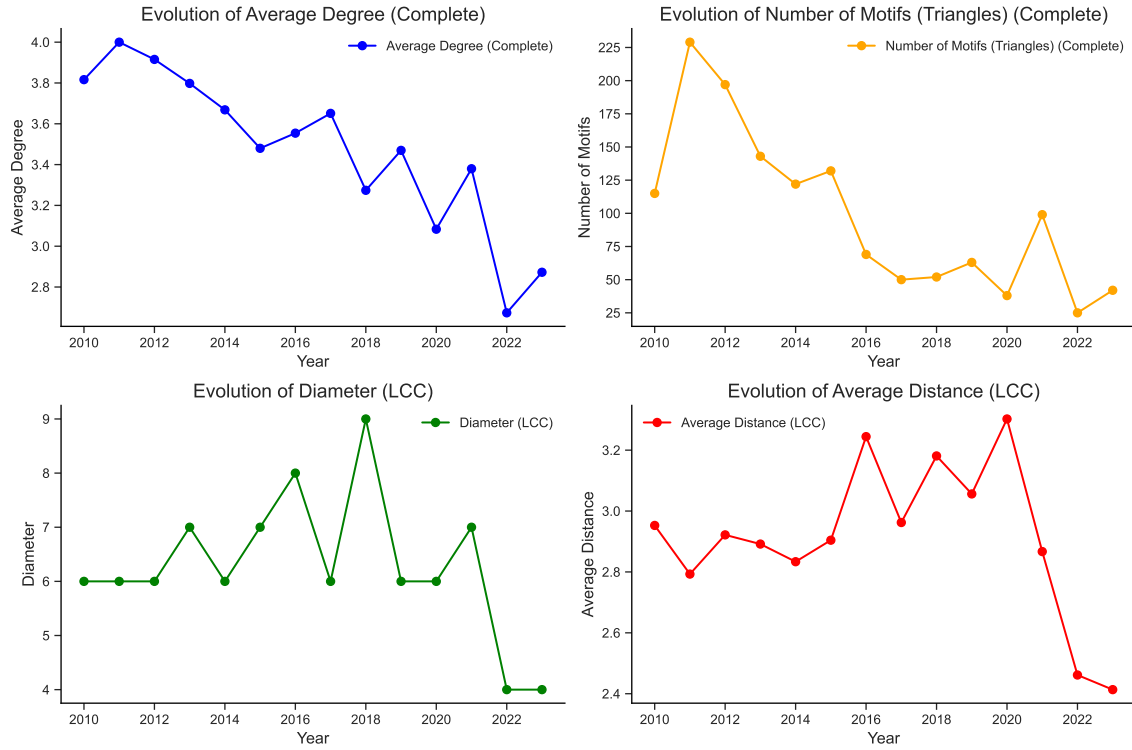


FIGURE D.4. Evolution of the network metrics for liquid bulks.

Notes: The average degree is computed as the average of the number of connections of each port (*i.e.* the ‘degree’). The triangle metric computes the sum of all the K_3 graphs in the network. The diameter and the average distance are computed on the largest connected component each year, to avoid infinite values due to disconnected sub-graphs.

D.5. Network Metrics for Passengers and Vehicles



FIGURE D.5. Evolution of the network for each type of vessel.

Notes: The average degree is computed as the average of the number of connections of each port (*i.e.* the ‘degree’). The triangle metric computes the sum of all the K_3 graphs in the network. The diameter and the average distance are computed on the largest connected component each year, to avoid infinite values due to disconnected sub-graphs.

D.6. Density in the Ukrainian - Foreign Ports Network

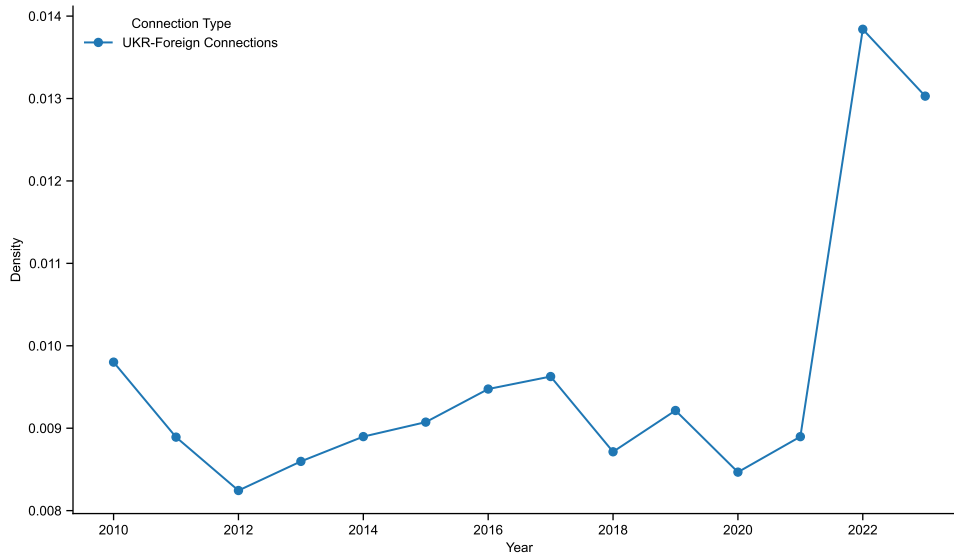


FIGURE D.6. Evolution of the density for the Ukrainian-foreign ports network.

Notes: We created a - kind of - bipartite network with Ukrainian ports on one side and foreign ports and the other side. It is not easy to explain the sudden increase in density that we have identified in 2022. There may be two explanations: a reorganisation of the routes from the preserved ports outwards, making the network more compact; and an overall reduction in the size of the network mechanically favouring density, dominating the disruption effect.

E. Additional Results on Network Hierarchy

E.1. Gini Coefficient

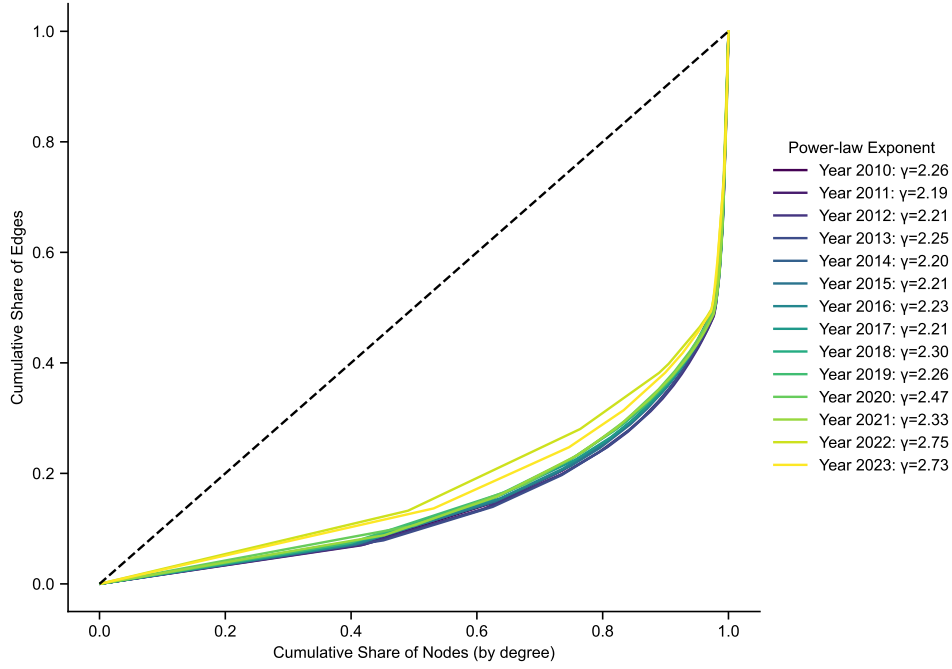


FIGURE E.1. Lorenz Curve for Each Year.

Notes: We computed the Gini coefficient of each network and the associated Lorenz curve, demonstrating that the less hierarchical network is the 2022 one, closely followed by 2023. We draw inspiration from the work of [?](#), who discussed the relationship between power-law distribution and hierarchy in networks.

E.2. Power-law fitting diagnostics

TABLE E.1. Power-law fitting diagnostics for the total DWT network

Year	Nodes	Edges	$k_{\min}$	n_{tail}	$\hat{\alpha}$	KS	Boot. p	Lognormal	Exponential	Trunc. PL
2010	546	1498	2	306	1.993	0.075	0.905	n.s.	PL***	n.s.
2014	615	1749	2	367	2.019	0.056	0.990	n.s.	PL***	n.s.
2020	540	1262	2	267	2.041	0.077	0.874	n.s.	PL***	n.s.
2022	262	478	2	131	2.399	0.106	0.442	n.s.	PL***	n.s.
2023	287	550	2	133	2.220	0.071	0.849	n.s.	PL***	n.s.

Notes: The table reports diagnostics for the degree distribution of the total DWT network. *Nodes* and *Edges* refer to the size of the yearly network. $k_{\min}$ is the lower threshold above which the power-law fit is estimated. n_{tail} is the number of observations with degree greater than or equal to $k_{\min}$. $\hat{\alpha}$ is the estimated power-law exponent. KS is the Kolmogorov-Smirnov distance between the empirical distribution and the fitted power law. Boot. p is the bootstrap goodness-of-fit p-value; high values indicate that the power-law approximation is not rejected. The last three columns report likelihood-ratio comparisons between the power-law model and alternative distributions. PL*** means that the power law is significantly preferred at the 1% level. n.s. means that the power law is not statistically distinguishable from the alternative distribution. Trunc. PL refers to the truncated power-law distribution.

The diagnostics provide two main messages. First, the bootstrap goodness-of-fit p -values are high in all selected years, meaning that the power-law approximation cannot be rejected for the upper tail of the DWT degree distribution. Second, the likelihood-ratio comparisons systematically favour the power-law model over the exponential distribution, confirming that the Ukrainian maritime network has a heavy-tailed rather than exponentially declining degree structure. However, the power law is not statistically distinguishable from the lognormal or truncated power-law alternatives. The results should therefore be interpreted as evidence of a hierarchical heavy-tailed network, not as a robust proof of a strict scale-free topology. The estimated exponent remains close to 2 before the full-scale invasion, increases to 2.399 in 2022, and then declines to 2.220 in 2023. This increase in 2022 suggests a compression of the upper tail of the distribution, consistent with the disruption of highly connected nodes during the shock. The partial decline in 2023 points to some re-emergence of hierarchical structure, although the network remains much smaller than before the invasion. Overall, these diagnostics support the use of the power-law exponent as a descriptive indicator of changing network hierarchy.

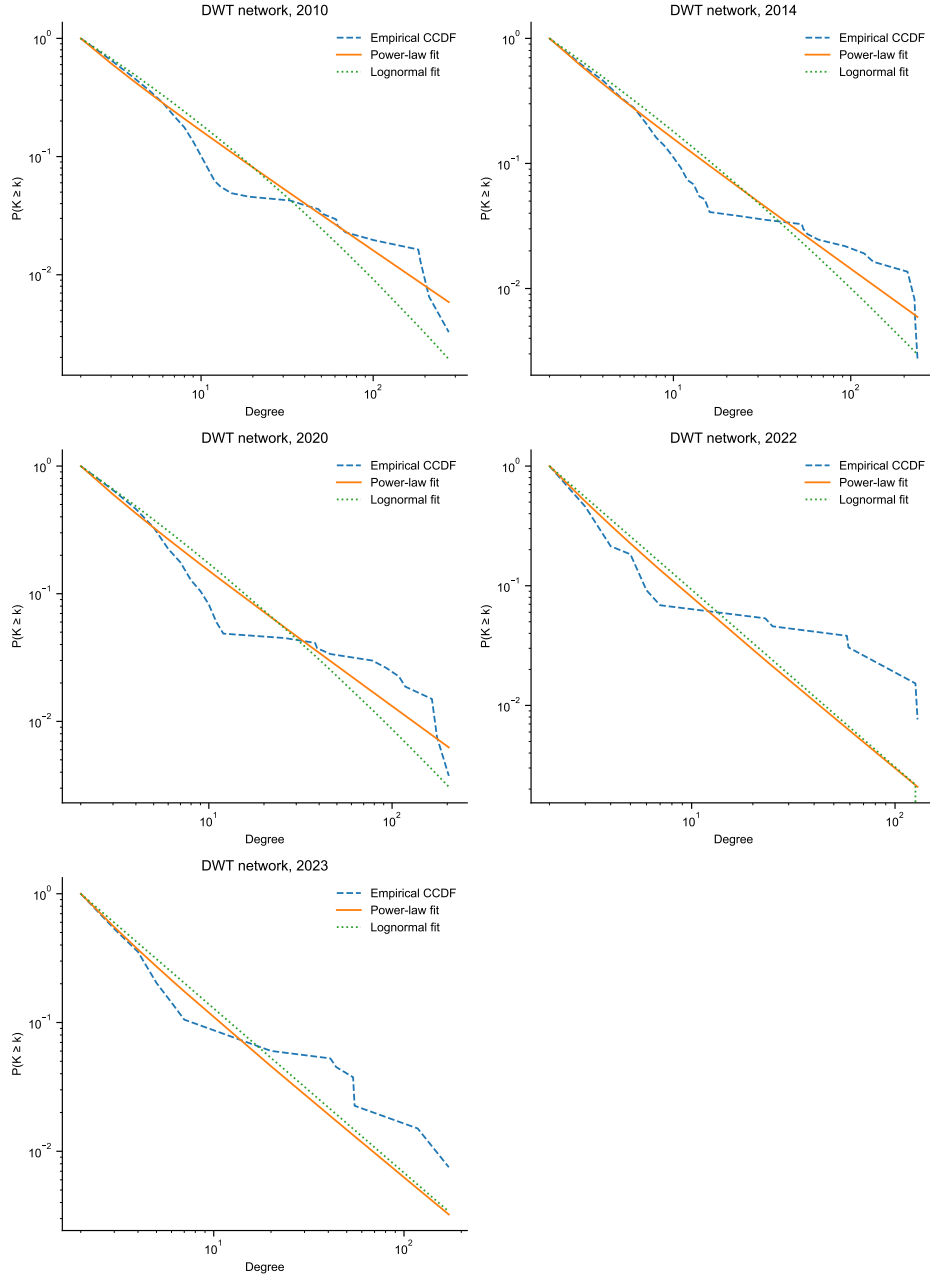


FIGURE E.2. Power-law and lognormal fits to the empirical CCDF of the DWT degree distribution.

Notes: The figure plots the empirical complementary cumulative distribution function (CCDF) of node degrees for the total DWT network in selected years. The power-law and lognormal fits are estimated on the positive degree sequence. Both fitted curves are shown to assess whether the upper tail of the degree distribution is consistent with a heavy-tailed structure. The comparison should be read together with the diagnostics reported in Table E.1. Deviations between the empirical CCDF and the fitted curves reflect finite-sample variation and the fact that the network does not necessarily follow a strict power law over the full degree distribution.

F. International Flows of Ukrainian Ports

This section provides additional results and figures related to the section 4.2.

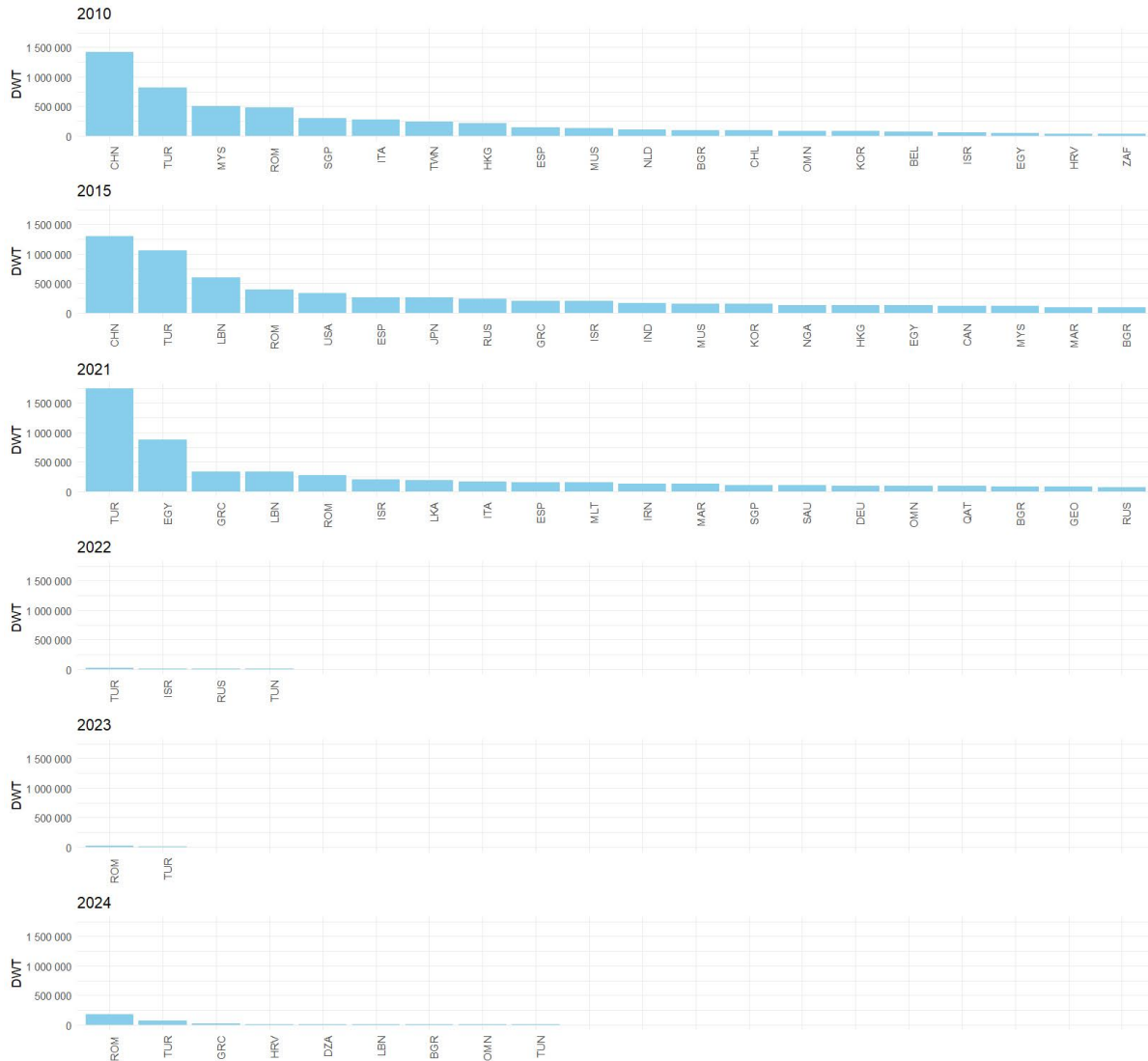


FIGURE F.1. Evolution of total cargo capacity (DWT) of containerships moving to foreign countries. (First 20 countries)

Notes: We computed the container flows in terms of cargo capacity (DWT) of Ukraine and its evolution over time. As we can see, it almost disappeared (in volume) in 2022 and 2023. It also concentrated on neighbouring partners (Turkey, Romania) rather than long-distance journeys. The container trade seems to be the most affected by the war with volumes going to (almost) 0.

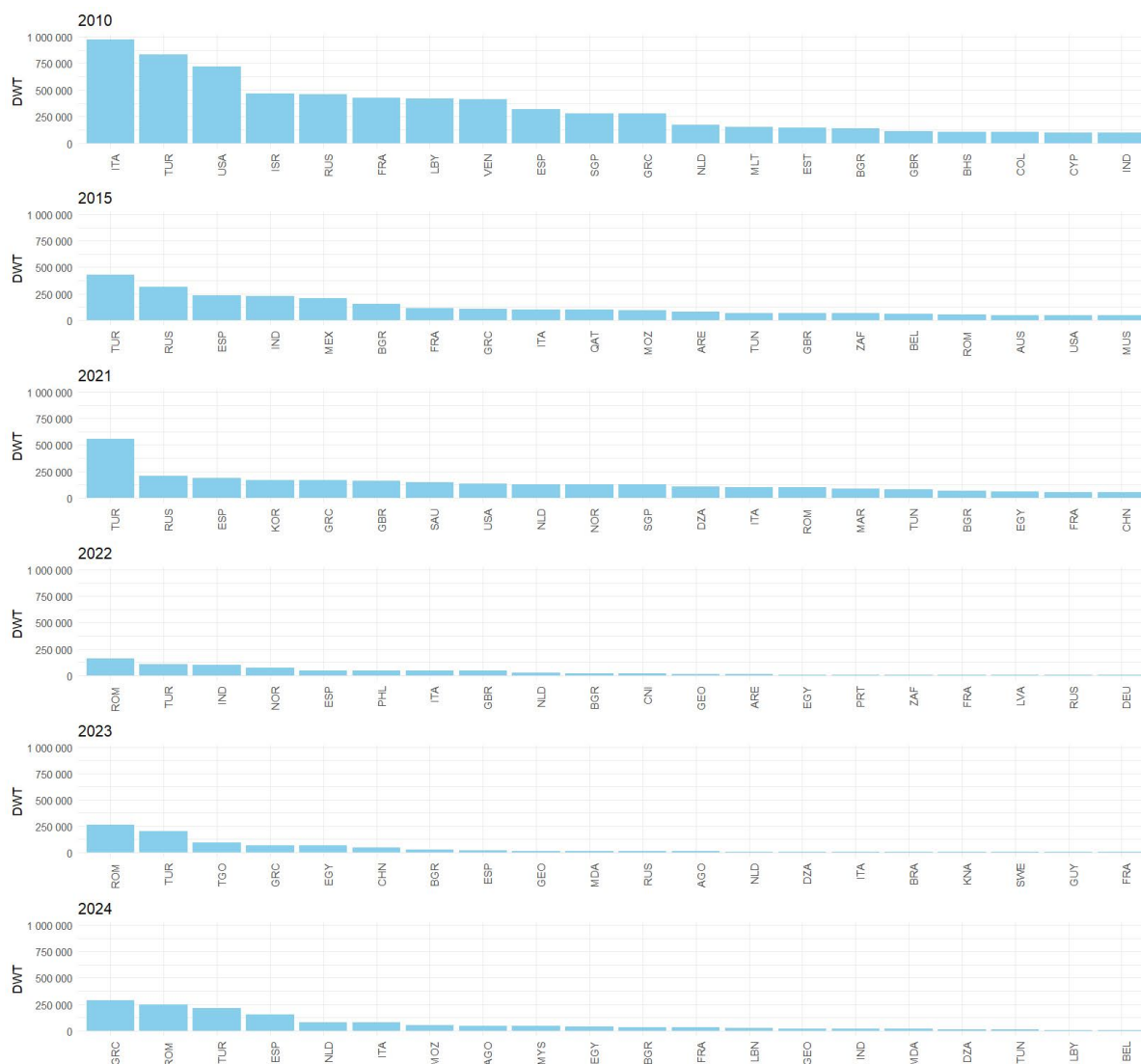


FIGURE F.2. Evolution of total cargo capacity (DWT) of liquid bulk ships moving to foreign countries. (First 20 countries)

G. Additional maps on the connections of Ukrainian ports

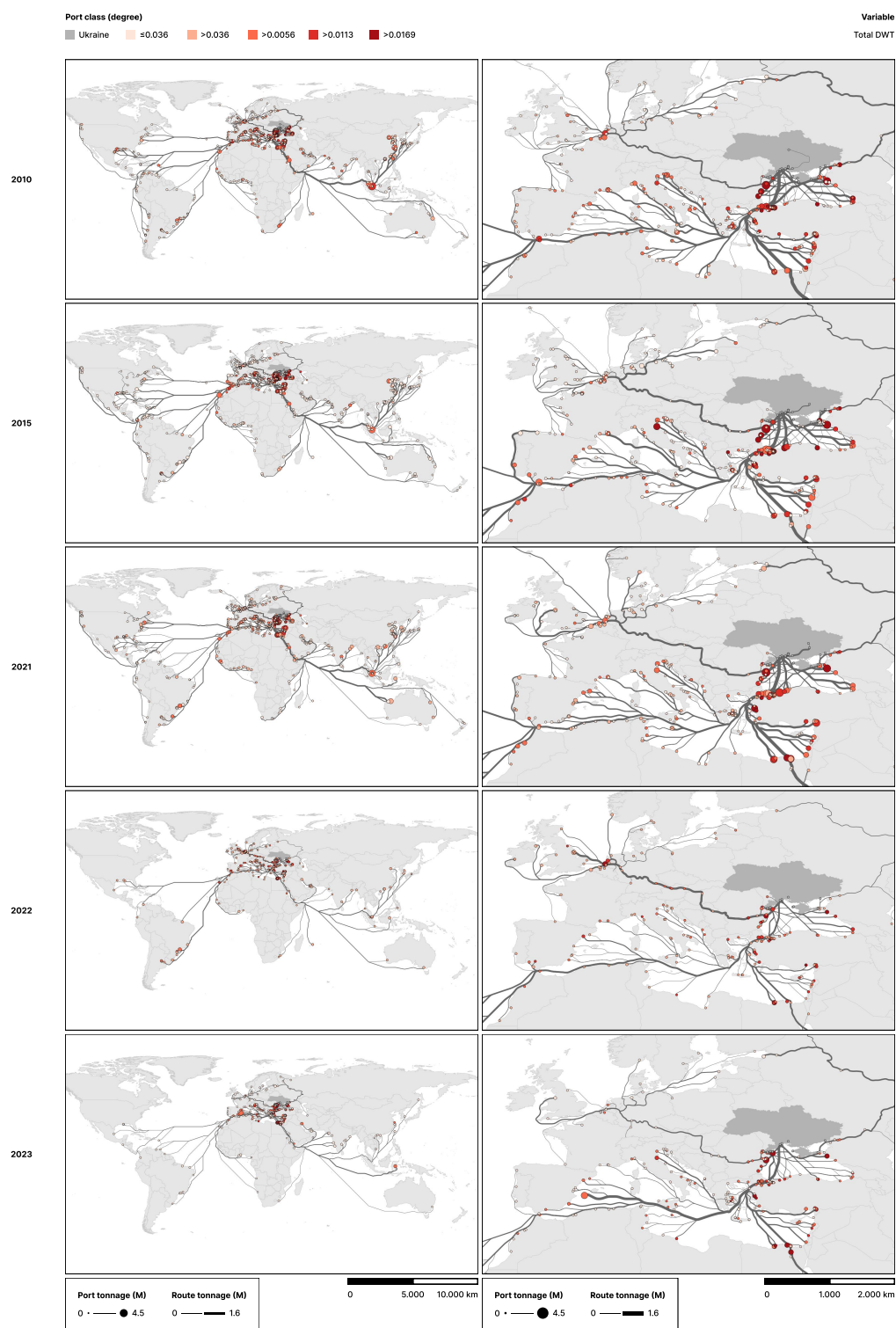


FIGURE G.1. Evolution of total dwt (2010-2024)

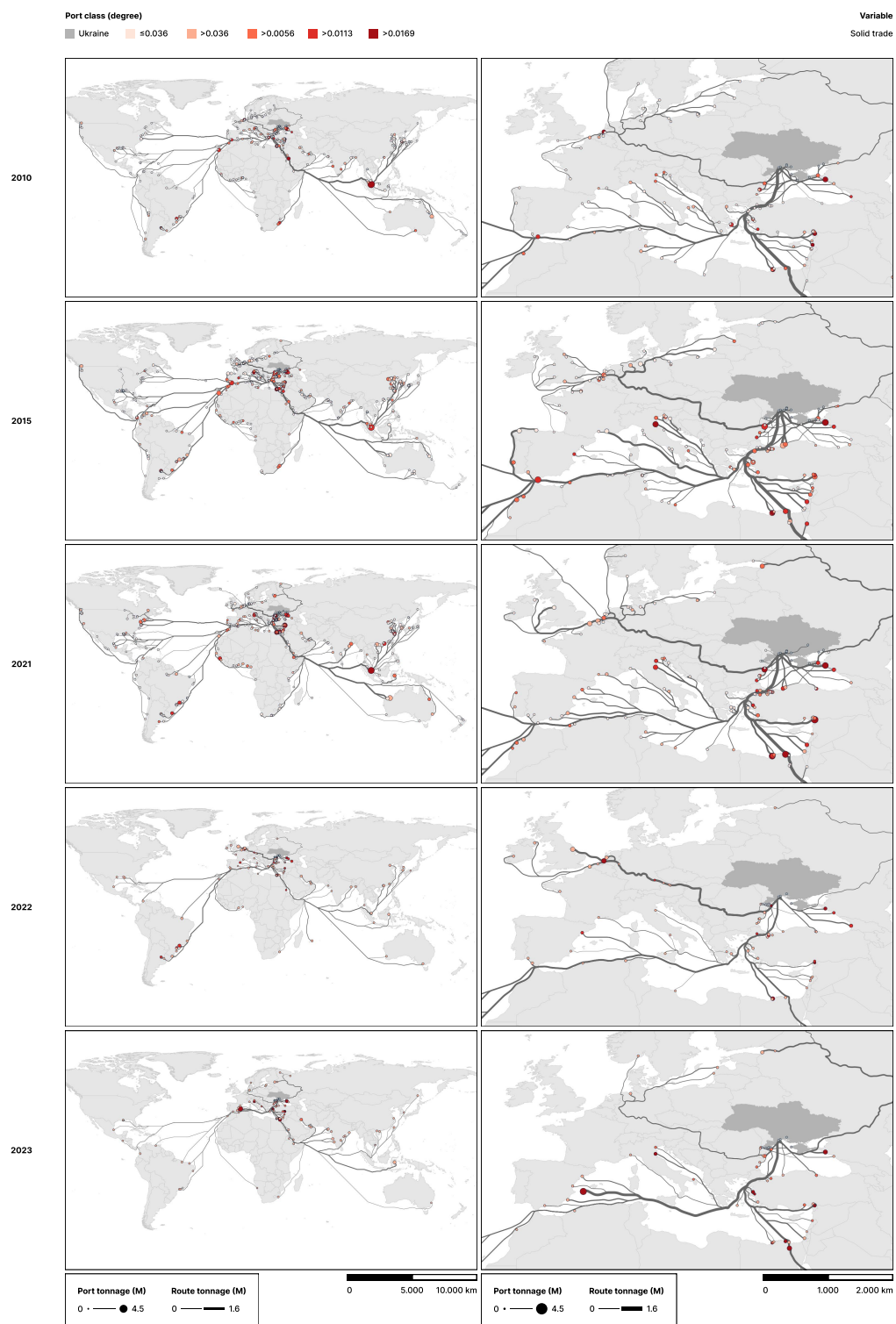


FIGURE G.2. Evolution of solid trade (2010-2024)

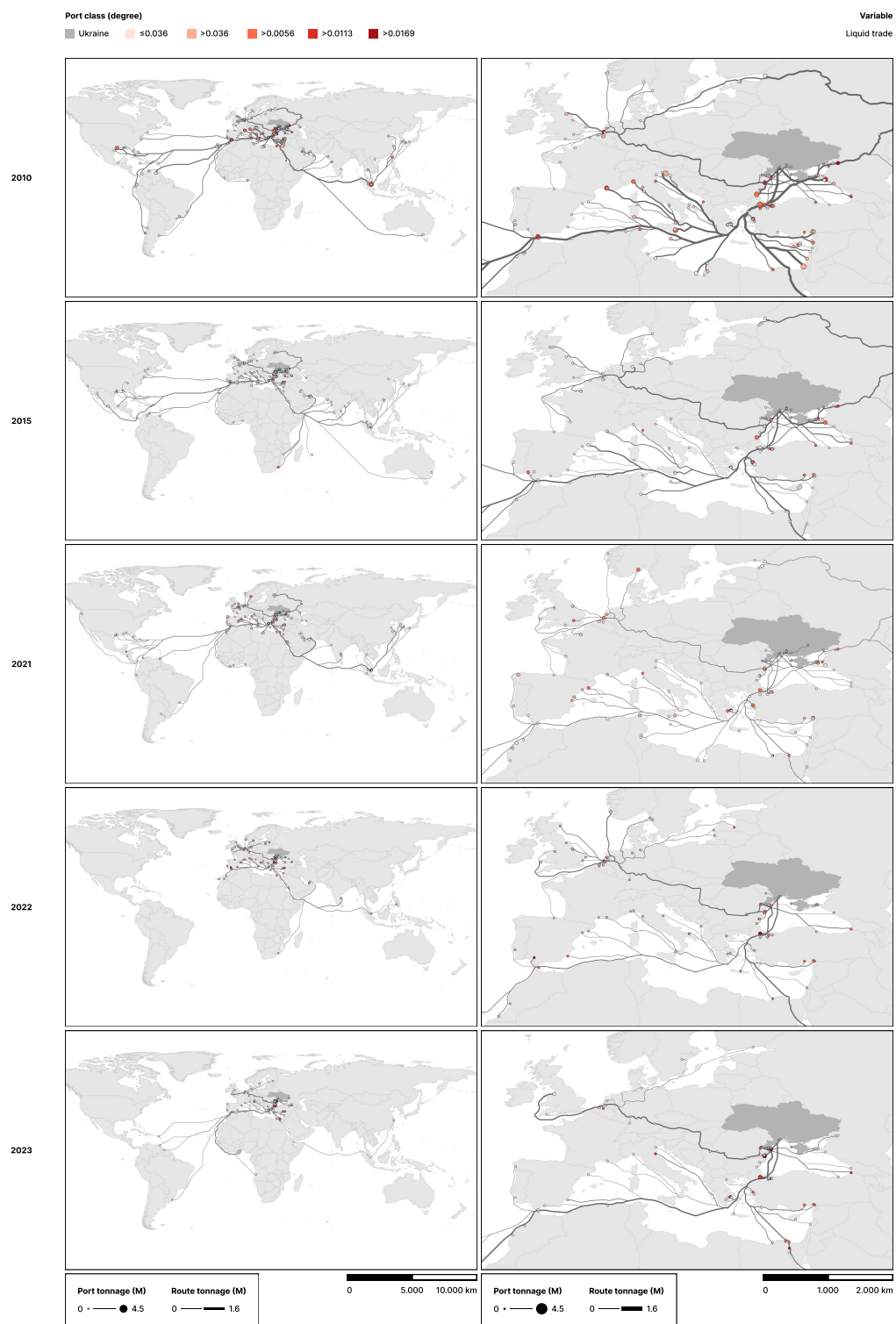


FIGURE G.3. Evolution of liquid trade (2010-2024)

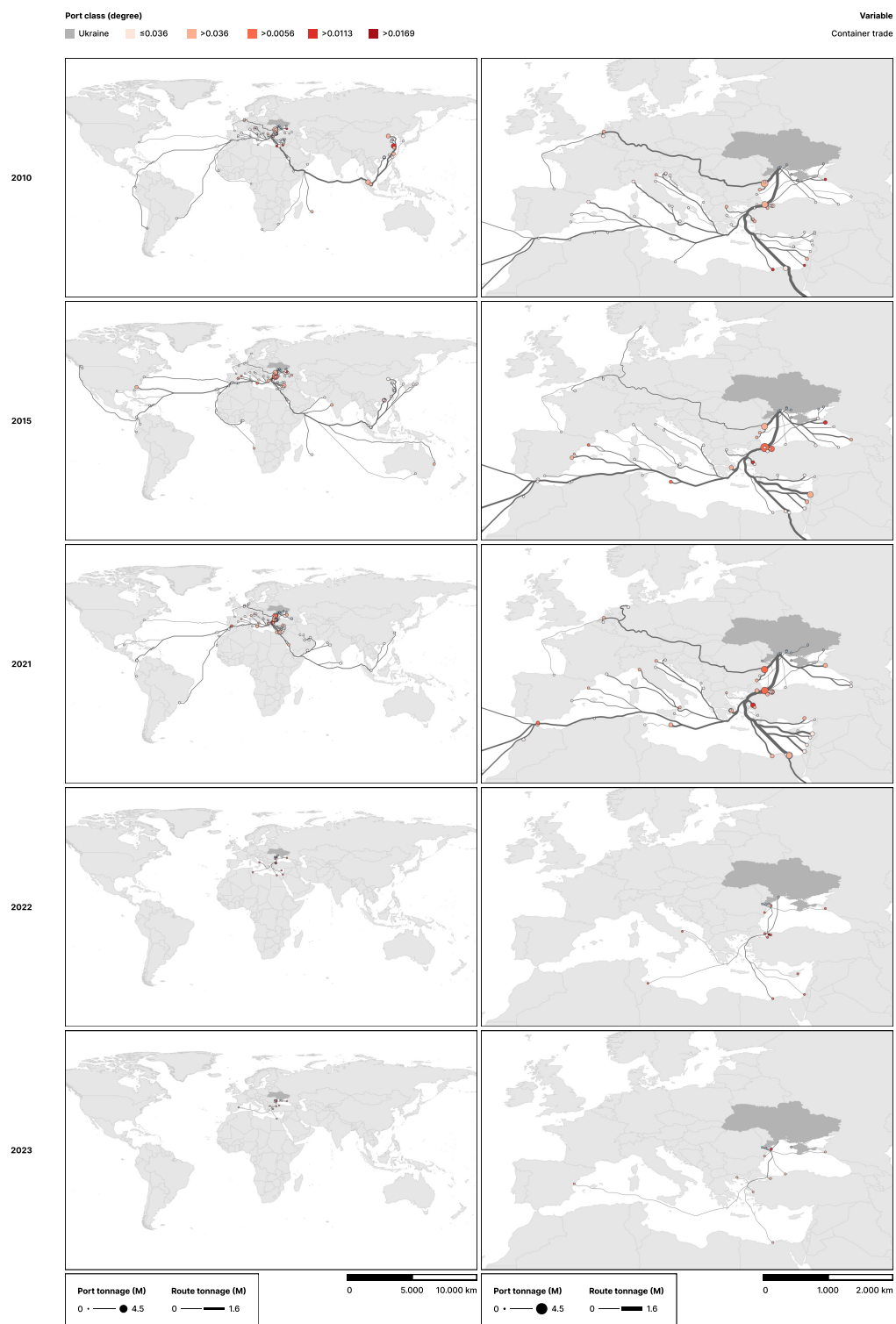


FIGURE G.4. Evolution of container trade (2010-2024)

H. Mathematical Details on Metrics

In this section, we provide a more detailed development of the different network metrics used in this paper. This makes it possible to observe the articulation between the metrics. We mainly base ourselves on the mathematical expressions as proposed by ?.

H.1. Distance and Diameter

In a graph $\mathcal{G}(V, E)$ the *distance* ℓ_{ij} between two vertices i and j is the shortest path connecting these two vertices. The average distance is thus defined as:

$$(1) \quad \bar{\ell} = \frac{1}{n(n-1)} \sum_{i=1}^n \sum_{j=1}^n \ell_{ij} = \frac{2}{n(n-1)} \sum_{i,j; i < j} \ell_{ij}$$

From Eq. 1 we can derive the diameter:

$$(2) \quad \text{diam}(G) = \max \{ \ell_{ij}; i, j \in V \}$$

The diameter gives a first indication of the efficiency of the network. In the case of a small diameter, the network is compact and circulation occurs smoothly and quickly.

H.2. Triangles, Triplets and Clustering Coefficient

Let us consider an undirected and unweighted graph $\mathcal{G}(V, E)$ with V the number of vertices and E the number of edges. λ_i measures the number of triangles to which the vertex i belongs and at the network level we can write:

$$\lambda(\mathcal{G}) = \frac{1}{3} \sum_{i=1}^n \lambda_i$$

Following the notations of ?, we now consider the induced subgraph $\tilde{\mathcal{G}}_i = (\mathcal{V}(i) \cup \{i\}, \tilde{E}_i)$ of $\mathcal{G}$ containing the vertex i and its neighbours $\mathcal{V}(i) = \{j \in V; \{i, j\} \in E\}$.

Let us recall that the other metric involved in computing the clustering coefficient $\mathcal{C}(i)$ is the number of triplets. A triplet is a set of 3 vertices such that the subgraph induced by these 3 vertices is connected. We can define τ_i as the number of triplets containing the vertex i in $\tilde{\mathcal{G}}_i$ and $\tau(\mathcal{G}) = \sum_{i=1}^n \tau_i$ the number of triplets in $\mathcal{G}$. The number

of triplets involving the vertex i can be expressed as follows:

$$(3) \quad \tau_i = \frac{d_i(d_i - 1)}{2}$$

The equation 3 gives the τ_i used in the equation 3. As emphasised by ?, the clustering coefficient $\mathcal{C}$ corresponds to the density of the subgraph $\bar{\mathcal{G}}_i()$ $\mathcal{V}(i), \bar{E}_i$ induced by i 's neighbours. In other words, the clustering coefficient C_i can be interpreted as the triangles' density within the subgraph induced by the neighbours of the vertex i . In mathematical terms, we can reformulate the clustering coefficient such that:

$$(4) \quad C_i = \text{dens}(\bar{\mathcal{G}}_i) = \frac{2|E_i|}{d_i(d_i - 1)}$$

CHAPTER 4

Wealth Comes from the Seas

Port Activity and Local Economic Development

Abstract

Maritime trade is an important element of regional development, shaping urban form, access to international markets, and local labour demand. While ports consume scarce coastal land and generate environmental externalities, they may also foster employment in both tradable and non-tradable activities. We quantify the causal impact of maritime activity on regional labour markets in Europe. We assemble a novel panel dataset that matches 1,530 ports and more than one million ship movements to NUTS-2 coastal regions over the last two decades. We start by discussing the structure of European maritime trade by building the dynamic graph of flows at the regional level. Then, we construct measures of port throughput at the regional level. To address the endogeneity of maritime flows, we propose an instrumental-variable strategy in line with recent work on transport infrastructure and trade. Our results show that increases in maritime activity are associated with modest to null employment gains at the regional level, while the estimates are not uniformly stable across specifications. IV estimates typically point to positive effects, but their magnitude remains limited and sensitive to the spatial scope of analysis and the time horizon. We also find suggestive evidence that part of the economic effects of port activity is spatially diffuse, consistent with the idea that benefits can accrue to wider hinterlands. Overall, the chapter indicates that port activity is not an automatic engine of local job creation: its regional impact is heterogeneous and conditional on local contexts, notably hinterland connectivity.

A previous version of this chapter has been presented at the kick-off workshop of the MAGNETICS (ANR-22-CE22-0002) project. The research leading to these results received financial support from the French National Research Agency (ANR) through the research project MAGNETICS No. ANR-22-CE22-0002. This chapter has benefited from the precious guidance and supervision of Anna Bottasso and Maurizio Conti.

Introduction

The Meloria battle in 1284 marked the beginning of the decline of the city of Pisa ([Sarti, Bini, and Giacomelli 2010](#); [Airaldi 2012](#); [Quertier 2022](#)) and the new prosperity of the Republic of Genoa, from the western Mediterranean to the Byzantine East. A century later, the Hanseatic League was born in northern Europe, and its importance in the northern range and central European hinterland can still be seen today ([Pedersen 2006](#)). Today's major American, European and Chinese cities have often benefited from an initial 'lock-in effect' ([Fujita and Mori 1996](#)) due to their openness to the sea. These three examples highlight the importance of maritime space as a factor in prosperity, not only for coastal regions but also for hinterland regions.

The relationship between urban and regional prosperity and openness to the sea has long been an open question in the social sciences, particularly in history, geography and economics. The initial intuition is that easy access to the sea is a factor in economic development. It is easier to export local products, import raw materials, semi-finished goods, and develop tourism. At the same time, the development of a port, especially since the advent of the container, requires a lot of space on the seafront, creating a crowding-out effect for other activities. The impact of tourism is not easy to quantify, given that the positive externalities of local consumption and infrastructure development are counterbalanced by negative externalities such as pollution, the over-specialisation of certain areas and the sector's exposure to international economic and political risks.

To answer the question of the regional impact of maritime transport, this paper is structured in three main parts. The first part provides a literature review summarising the main theoretical and empirical findings on the question. We draw on three distinct fields of literature, which communicate very little. Firstly, transport geography, whose numerous theoretical and empirical works over the last few decades have produced a wide range of intuitions and results on the structure and regional impact of port activity. The second body of literature belongs to the field of economic geography. Following Krugman's pioneering work ([Krugman 1991, 1992, 1997](#)), several authors have applied this new family of theoretical models to the birth and development of port cities. More recent contributions have renewed the use of geographical and spatial models in the analysis of the relationship between local economies and ports. The last field, into which this paper is mainly integrated, aims at the econometric estimation of the impact of port activity. These studies estimate the contribution of maritime traffic

and port infrastructures on a local or national scale, and use a variety of methods and data structures, from standard panel econometrics to gravity models and more recent impact assessment methods.

Following the literature review, we focus on data construction and descriptive statistics. The data used in this paper was constructed based on three areas: (i) collection and harmonisation of regional data, (ii) harmonisation, processing and aggregation of maritime flow data¹, and (iii) construction of the instrumental variable².

We then detail the econometric strategy adopted in the paper. Estimating the impact of infrastructure poses various empirical challenges, including the treatment of missing data and the endogeneity of certain control variables. Our econometric estimation also attempts to take into account the spillover effects of maritime traffic from coastal regions to inland areas. These spillover effects are a function of two main parameters: the distance to the coastal region hosting ships and the size—in terms of tons transported—of this region. We therefore propose a direct approach that is easy to implement, making it possible to assign a ‘port spillover’ value to all the non-coastal regions in the sample. As we shall see, the flexibility of this measure allows for several refinements and weightings that make it easier to assess its robustness.

To address these issues empirically, we build an original dataset that links European regional economic outcomes to maritime activity. Starting from ship-level movement records—each observation corresponding to a voyage between two ports—we reconstruct annual port-to-port flows and aggregate them to the regional scale by geocoding ports and assigning them to NUTS polygons. This data structure allows us to measure both local port activity in coastal regions and inland exposure through a ‘port spillover’ index that depends on (i) distance to the coastline/port regions and (ii) the scale of maritime traffic handled by those regions. Finally, to mitigate concerns about reverse causality between regional development and port activity, we complement fixed-effects panel estimates with an instrumental-variable approach that exploits plausibly exogenous variation in natural port characteristics, proxied by historical regional port activity³.

¹Maritime flows are provided at ship level, with each line corresponding to a movement from one port to another. We need to aggregate movements at port level and then at regional level.

²The instrumental variable strategy used in this paper is detailed in the section 3.

³The same strategy is applied to historical ports: using the coordinates, we aggregate the ports at the NUTS-2 level to have a measure of the historical port activity of the given regions.

1. Related Literature

Shipping remains relatively understudied within the social sciences on transport infrastructures and flows, especially when compared to road and rail transport. [Ducruet \(2020\)](#) proposes a quantitative study for transport geography, pointing out that X times fewer articles are published on shipping than on rail and Y times fewer than on road transport. A quick examination of publications in *Regional Science and Urban Economics*, *Journal of Regional Science* or *Journal of Urban Economics* shows that the same trend exists in the case of economics. However, in recent years, there has been renewed interest in the impact of maritime transport on local economic development and the structure of international trade in economics, regional science, and quantitative geography⁴.

1.1. Ports, Shipping and Spatial Structure: Theoretical Foundations

[Krugman \(1991, 1992, 1997\)](#) proposed a significant renewal of spatial interactions in theoretical economics via the new economic geography (NEG). Based on several works aimed at unifying monocentric city models and integrating them into the NEG framework ([Krugman 1993](#); [Fujita and Krugman 1995](#); [Fujita and Mori 1997](#)), [Fujita and Mori \(1996\)](#) developed a model of port cities representing the counterpart of international trade models with increasing returns⁵. They highlighted the conditions for the existence of a ‘lock-in effect’: port cities develop an initial comparative advantage which persists over time and enables them to remain important cities, even once their initial advantage no longer has any effect. This ‘hub’ effect of the port contributes to the phenomenon of agglomeration as described by Krugman in the context of a NEG model. [Fujita and Mori \(1996\)](#) also show that the transfer of economic activities from the core to the periphery - and consequently spillovers from the port and developed regions to the hinterland - can only be achieved by ‘protecting’ the periphery through temporary isolation in terms of transport infrastructure.

[Fujita and Mori \(1996\)](#)’s contribution has remained an orphan within the New Economic Geography and has never been empirically tested. Nevertheless, this paper has influenced maritime geography—essentially quantitative—via the intuitions it formalises,

⁴[Faure and Ducruet \(2025\)](#) conducted a systematic review of contributions relating to the quantitative study of maritime networks.

⁵The earlier models of port cities, represented by [Mills \(1972\)](#), [Goldstein and Moses \(1975\)](#), [Schweizer and Varaiya \(1976\)](#) and [Schweizer and Varaiya \(1977\)](#) among others, are the counterpart of neoclassical theories of international trade. In these models, comparative advantage determined the existence of a port city. [Fujita and Mori \(1996\)](#) revised this condition, showing that there are port cities that remain prosperous even after the comparative advantage of cheap access to water has been exhausted

which can be seen quite clearly in the structure of today's city networks (Ducruet, Cuyala, and El Hosni 2018; Ducruet, Notteboom, and De Langen 2016; Ducruet 2020; Ducruet and Notteboom 2023). Shipping has regained popularity in theoretical economics in the wake of the renewal of spatial economics in the early 2010s. Allen and Arkolakis (2014) have developed a general equilibrium model that allows the spatial distribution of economic activities to be studied for a very wide panel of topography. The general and flexible nature of the model has allowed it to be applied to the development of port cities and regions. Ducruet et al. (2024)

The quality of transport infrastructure is a key factor in regional economic development. Congestion in transport flows can have a significant impact on well-being at both local and global levels. Based on the theoretical framework developed by Allen and Arkolakis (2022), Heiland et al. (2023) study the expansion of the Panama Canal in 2016 and the consequences of this improvement of a nodal point for maritime trade. The combination of this theoretical framework and satellite data tracking container ship movements suggests an increase in bilateral trade between nodes using the Panama Canal and an overall revenue gain three times greater than Panama's revenue gains. Koenig et al. (2023) emphasised the role played by port ownership. The takeover of the port of Piraeus by COSCO in 2016 led to a significant increase in the use of the port by the Chinese operator's ships. The takeover has made Piraeus COSCO's main transshipment hub, without crowding out other European ports in any way.

Other recent contributions have updated older models by integrating a port component. For instance, Bonadio (2022) developed a model of international trade inspired by Krugman (1980). He estimated the contribution of ports and roads to regional access to international markets. As transport costs play an important role in the integration of regional economies into international trade, the quality of transport infrastructure, particularly ports, has a significant impact on local economic development. Bonadio (2022) also pointed out that the contribution of ports to improving openness to international markets is significantly higher than that of roads; their overall impact on welfare⁶ is similar to that of roads. Finally, the effect of ports and roads diverges according to the geographical location of the region: coastal areas benefit relatively more from port improvements while inland regions benefit relatively more from road investments.

In the same vein, Brooks, Gendron-Carrier, and Rua (2021) constructed a spatial equilibrium model *à la* Rosen (1979) and Roback (1982) describing the impact of con-

⁶Brancaccio, Kalouptsi, and Papageorgiou (2024) showed that investment in port infrastructure can lead to substantial welfare gains, provided that it is correctly targeted and sized. They also showed that for the United States the net gain in costs is positive for only a few ports.

tainerisation on the population and employment of American coastal cities. In their model, containerisation affects population change via three channels: local consumer amenities, local production amenities and access to international markets. The negative externalities of ports (noise, pollution, landscape degradation) will adversely affect local consumer amenities. The spatial equilibrium model of [Brooks, Gendron-Carrier, and Rua \(2021\)](#) predicts a positive effect of containerisation on total factor productivity in counties neighbouring ports ⁷. This effect is assumed to be particularly pronounced in the case of transport and storage service industries. The third point of impact of containerisation on the local population relates to domestic and international trade costs. The evolution of these two trade costs produces opposing effects which make it difficult to formulate an unequivocal theoretical prediction.

1.2. Empirical Evidences of the Local Impacts of Port Activity

Our work is mainly in the field of applied transport economics, and more specifically the econometric estimation of the impact of transport flows on regional economic development. [Brooks and Liscow \(2021\)](#) and [Ducruet et al. \(2024\)](#), which we mentioned earlier because of their theoretical approaches, estimated the impact of containerisation on the population of port cities - in the United States for [Brooks, Gendron-Carrier, and Rua \(2021\)](#) and in the world, over a long period, for [Ducruet et al. \(2024\)](#). They use a 'cost-shifter' instrument linking the initial depth of ports to the introduction of containerisation⁸. [Brooks, Gendron-Carrier, and Rua \(2021\)](#) demonstrated that containerisation is significantly associated with population gains in second-tier agglomerations, benefiting from space and low-cost land⁹.

Considering the development of cities over the long term, and throughout the world, [Ducruet et al. \(2024\)](#) also stressed the importance of having abundant and cheap land available for developing container terminals. The effects on economic development are mixed, and the authors suggest that the scarcity - and consequent high cost - of land around the world's major port cities is a major source of tension in global value chains. On a normative level, they raise the question of the 'optimal' position of ports in

⁷This second intuition is in line with the intuition in our paper: the - potentially - positive effect of port activity 'spills over' to neighbouring spatial units. We will discuss this in the rest of the paper, but the second part of our intuition is that this effect is naturally stronger when considering small spatial units. If we wish to test the existence of spillover effects, too large regions are likely to absorb most of the effect.

⁸This is due to the structure of container ships and the need for dredging operations in shallow ports

⁹This is the second particularity of containerisation: as container storage requires a lot of space - and is difficult to reduce - it is a very space-intensive mode of transporting goods. Low-cost, low-development areas therefore have a comparative advantage when it comes to receiving containers.

space¹⁰.

In the same field, the contribution of this paper draws inspiration from [Bottasso et al. \(2013, 2014\)](#). The authors focused on the relationship between maritime traffic and local economic development in the case of European regions using panel econometric models ([Bottasso et al. 2013](#)) and spatial econometric models ([Bottasso et al. 2014](#)). More precisely, [Bottasso et al. \(2013\)](#) analysed the impact of major ports¹¹ on OECD-LT regions¹². Following on from this paper, [Bottasso et al. \(2014\)](#) studied the link between the economic development of TL-3 regions and the port activities of major European ports using a series of spatial econometric models, to measure maritime traffic spillovers.

1.3. Maritime Flows as Complex Systems

Maritime flows and the structure of trade between ports have been a recurring theme in quantitative transport geography since at least the 1960s ([Ducruet 2020](#)). The concept of the ‘port system’ originated in the work of [Taaffe, Morrill, and Gould \(1963\)](#), who sought to model the evolution of port corridors in West Africa. This was followed by the work of [Rimmer \(1967,?\)](#), which was part of an already active literature on the link between port activities and hinterlands [Weigend \(1952\)](#); [Britton \(1965\)](#); [Robinson \(1970\)](#). This work remains essentially descriptive but lays the theoretical foundations for approaches used

The first application of graph theory to port flows can be found in [Robinson \(1968\)](#) analysis of British Columbia’s ports. This contribution was not widely followed, as it took almost fifteen years for new contributions to use graph theory tools to study maritime flows ([Marti 1981](#); [Marti and Krausse 1983](#)). The 1980s and 1990s saw the publication of several important contributions to the field: [McCalla \(1986\)](#) made explicit use of graph theory to study Canadian coastal shipping, while [Dick and Rimmer \(1993\)](#) focused on containerised systems in Asia-Pacific.

The availability of large-scale data, the theoretical foundations necessary for more systematic studies, and the associated computing capabilities thus limited these studies to small geographical areas during the early decades. [Joly \(1999\)](#) was the first analysis of the global containerised network, combining graph theory, spatial analysis and

¹⁰The examples of Long Beach and Singapore are put forward: in highly urbanised centres, where available land is scarce and extremely expensive, [Ducruet et al. \(2024\)](#) question whether it is desirable to pursue an intense port activity. We may note that this raises the question of urban persistence ([Brooks and Lutz 2019](#)) and a certain form of path dependency in the development of cities.

¹¹All ports must have handled an average of three million tonnes of goods or one million passengers over the period considered.

¹²The OECD proposes a sub-national breakdown of member countries, which for European countries is similar to Eurostat’s NUTS regions.

cartography¹³.

The late 1990s marked a major theoretical and methodological break with the contributions of [Watts and Strogatz \(1998\)](#) and [Barabási and Albert \(1999\)](#). In the field of shipping networks, [Foschi \(2002, 2003\)](#), [Xu, Hu, and Liu \(2007\)](#) and [Wei-Bing et al. \(2009\)](#) were the first to apply methods from the field of ‘complex networks’ to maritime flows. The 2010s were characterised by a wider adoption of these methods in the study of shipping networks. It was with the onset of Covid-19 and the geopolitical shocks of the early 2020s that the field of shipping network studies began to develop rapidly ([Faure and Ducruet 2025](#)). Thematically, the field has gradually structured itself around four main themes: (i) liner shipping connectivity and trade; (ii) hubs, centrality and competition; (iii) vulnerability and robustness to disruptions; and (iv) communities and spatial structures. While the field of shipping networks and the economics of ports and maritime flows are rarely cited, we argue that it is relevant to use methods from the field of complex systems to study regional maritime flows. In particular, this sheds light on the mechanisms of hierarchisation in the European maritime network, and thus the potential economic impact of ports according to their position in the network.

Based on this review of the literature, which, without claiming to be exhaustive, offers a broad and rarely done survey of theoretical and applied economics work on the link between economic development - national and local - and port and maritime activity, we can now turn to the methodology of this paper. The relationship between transport infrastructure development and local prosperity is complex and often the result of a multiplicity of causes. Using a cautious, multi-level approach that reduces the spatial problem to simple components, we attempt to contribute to this still-open question.

2. Data & Descriptive Statistics

We now try to discuss in quite an extensive way the data construction, *i.e.* the ‘creation’ of the regional maritime networks and the data collection for the regional panels. Then, we provide a discussion on the main dynamics of the European port system based on descriptive statistics and network metrics¹⁴.

¹³In the years that followed, other analyses focused on regional networks of alliances, strategies and shipping lines ([McCalla, Slack, and Comtois 2004](#); [McCalla 2004](#); [Veenstra, Mulder, and Sels 2005](#)) and port networks ([Comtois and Wang 2003](#); [Rimmer and Comtois 2005](#); [Frémont and Soppé 2005](#)).

¹⁴There is a real challenge for transport economics as a field, and more specifically for maritime economics, to combine standard econometric approaches (panel econometrics, causal inference, gravity

2.1. Constructing the Good-specific Regional Port Activity

Eurostat open data sources provide NUTS-2 data for passengers and goods for a set of main ports and without distinction between goods. It is a useful source because it covers a fairly long period of time, but it lacks granularity in terms of both the goods transported and the regional dimension. As the information is aggregated at NUTS-2 level, the routes taken by the various ports are not known. Nor is it possible to differentiate between major type of goods - e.g. identifying the impact of containerisation - or to disaggregate the analysis at the port level. To fill this gap in the literature, we reconstruct European regional maritime traffic for 5 types of goods from 2000 to 2024 for NUTS-2¹⁵.

In this paper, we are looking for a disaggregated approach, at both good and spatial levels. *Lloyd's List* is a unique source of information for global shipping on long periods¹⁶. In this article, we limit the analysis period to 2000–2024, but other studies have gone back much further in time with this type of data (Polo-Martín and Ducruet 2024; Ducruet et al. 2025; Polo-Martín, Castillo-Hidalgo, and Ducruet 2026; Ducruet and Faure 2026).

To construct regional shipping flows, we proceeded in three steps. The first step is to identify European ports and associate them with geographical coordinates that will then be used to identify the region to which they belong. To do this, we use two data sources: a flow database, which consists of ship movements, and a port database, which stores information (country, continent, coordinates, etc.) for each port. Once this first step has been completed, we can identify European ports quite easily, as they have the label 'Europe' in the 'Continent' column.

models) with network analysis and graph models. In this paper, we build our analysis on both empirical strategies to provide a structural and 'policy evaluation' discussion.

¹⁵We thus build the dynamic networks and the panels for the total DWT, containers, general cargo, liquid, and solid bulks.

¹⁶We do not use AIS data in this paper, even if it became a very common practice in the literature. AIS data are very precise, and can be used for high-frequency analyses, but it is quite hard, and sometimes impossible, to construct long-term time-series.

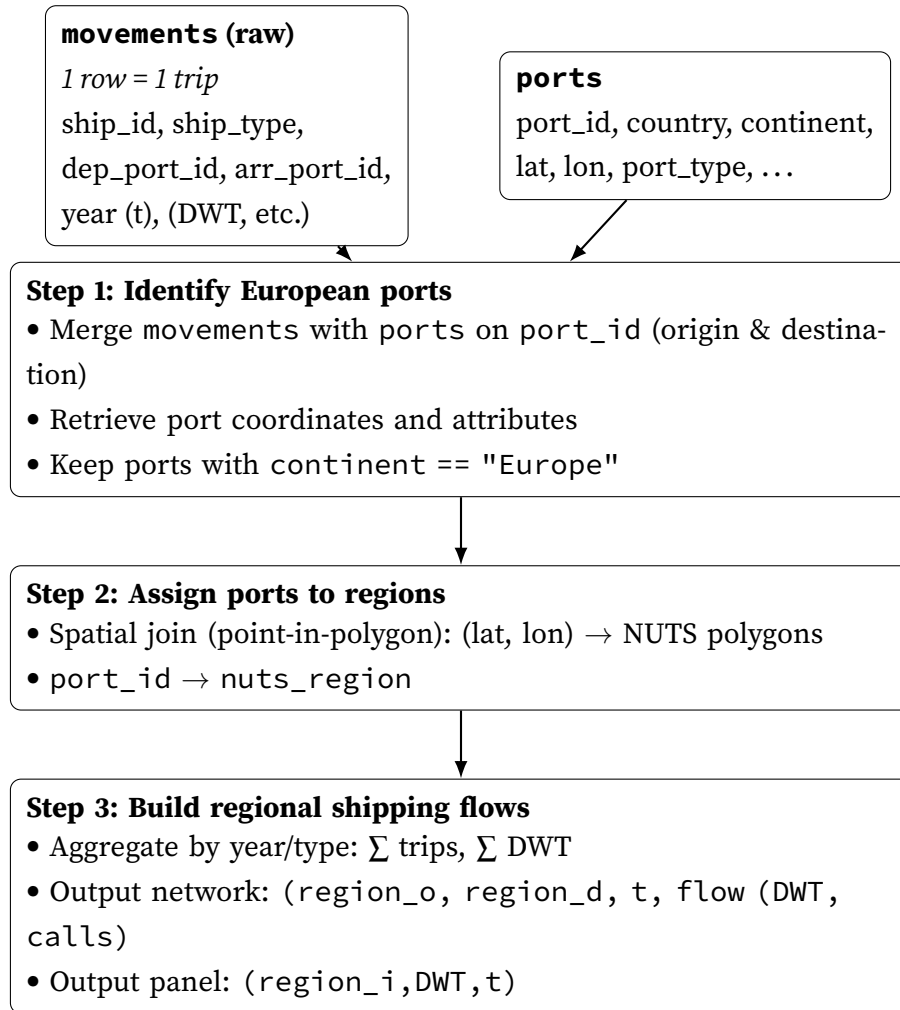


FIGURE 1. From port-to-port ship movements to regional (NUTS) shipping flows.

The structure of the raw dataset is shown in table 1. Several key pieces of information are stored in the ‘movements’ table: the ID of the ship, the type of the ship (containers, oil, general cargo, etc.), the ID of the sailing port, and the ID of the arrival port. Each line thus corresponds to one trip, from port A to port B. In a second dataset we have information on ports: ID, type, coordinates, country, continent... In the section 3, notably with the Fig. 13, we provide additional details on the challenges associated to the selection of ‘European’ ports in construction the historical port activity of NUTS-2 regions.

2.2. Regional Data

To estimate the impact of shipping on regional activity, and to control for socio-economic, demographic, and geographic factors, we use several sources for European regional economies.

2.2.1. Employment

The employment data for the NUTS-2 level come from the Annual Regional Database of the European Commission (ARDECO). This platform provides access to harmonised data from 1980 to 2024 for different levels of spatial disaggregation, from country to metropolis. The ARDECO database has the advantage of having a very low proportion of missing data, which facilitates estimation by limiting imputation to a few rare cases. In addition, the temporal coverage of the data enables us to construct a detailed and credible base of employment in medium-sized regions over the period. We use the number of jobs in thousands and apply a logarithmic transformation to the econometric estimates. We also collected sector employment to compute agriculture/industry/services shares in total employment for NUTS-2 ¹⁷.

2.2.2. Population

In a similar way to employment, population is derived at NUTS-2 level from ARDECO data. These data cover the same period (2000 - 2024). We also log-transform the population data. The sample of NUTS regions we use corresponds strictly to the regions available in the ARDECO harmonised data, in their 2021 version¹⁸. We also applied a linear trend on the 2000 population for each region¹⁹. Finally, we computed the area of the NUTS regions, thanks to the polygons, which is then used to calculate the density of each region. The ‘linear trend’ procedure is also applied to the density of regions in 2000.

¹⁷ARDECO uses a 10 NACE sectors typology. We considered A as the primary sector, B-F for secondary sector and G-U for ‘services’.

¹⁸It implies that we miss some European ports if they are in a, geographically speaking, European land that is not included in ARDECO dataset.

¹⁹Doing so, we eliminate the major issues related to reverse causality in the employment-population relation.

2.2.3. Socio-economic Variables

Beyond employment and population, we control for a set of regional socio-economic characteristics that are standard determinants of local labour-market dynamics and may correlate with port activity. First, we use regional output measures from ARDECO, including gross domestic product (GDP) and gross value added (GVA). In the baseline specifications, these variables are included in logarithms (or per-capita form) to control for the size of the regional economy and long-run development patterns. We also exploit the sectoral composition of economic activity. In particular, we compute the shares of agriculture, industry, and services in total employment (and, when available, in total value added) to account for differences in specialisation that may shape both shipping activity and employment dynamics.

Second, we account for labour-market conditions using standard indicators such as the unemployment rate and participation-related measures. These variables are useful to capture cyclical conditions and persistent regional labour-market frictions. Third, we include demographic structure controls (e.g., age composition) as ageing and working-age shares affect both labour supply and medium-run employment trajectories.

Finally, we introduce slow-moving institutional and human-capital proxies (e.g., regional quality of government indices and/or education attainment measures)²⁰.

2.2.4. Accessibility

A crucial factor in regional development, and even more in the case of measuring the spillovers of port activities, is regional accessibility. This can be measured as the length of highways, roads, railways..., in the region, or using composite indicators for multimodal accessibility. *Eurostat* provides data for regional transport infrastructure at the regional level, such as the length of highways, navigable canals, and railways. However, there is a non-negligible number of missing years and regions. In addition, the European Spatial Planning Observation Network (ESPON) has constructed several indicators for accessibility and regional transport endowment. We primarily rely on the ESPON's multimodal potential accessibility indicator. When the accessibility series is observed for a few years, we harmonised it to the annual panel frequency using interpolation between available points. As a robustness check, we also considered infrastructure-based measures (when sufficiently observed) to verify that our results

²⁰It should be noted that one of the main problems with this last control set is the number of missing regions. This results in the loss of a lot of information, which makes our coefficients particularly unstable.

are not driven by a specific definition of accessibility.

2.3. Dynamics of the European Port System

In this section, we review the evolution of port activities in European regions, from 2000 to 2024. Regional traffic is constructed as detailed in subsection 2.1 for NUTS-2 regions.

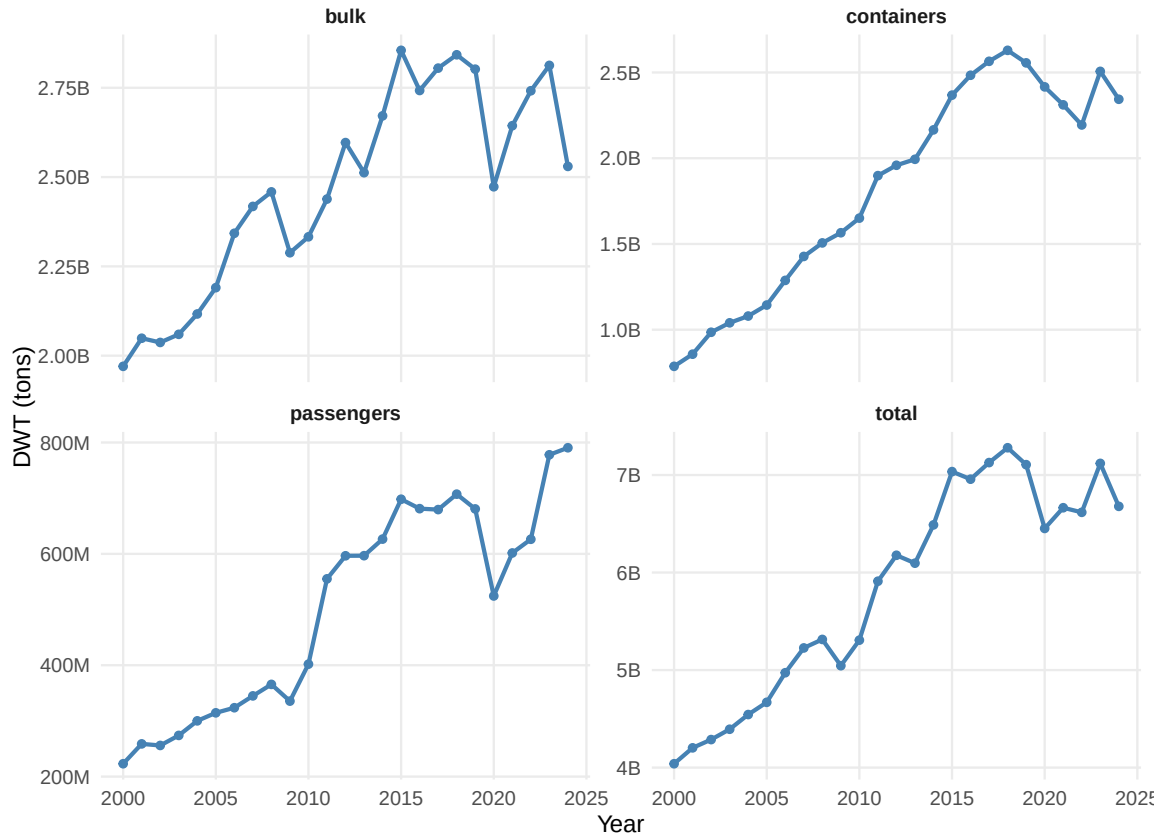


FIGURE 2. Evolution of the DWT for bulk, containers, passengers and total (2000-2024)

Notes: The plot shows the total dead-weight tonnage (DWT), each year, for each type of goods. It has been computed by summing all the movements of ships arriving and departing from European ports. The ‘bulk’ category includes liquid and solid bulks. Passengers includes cruises and ferry/Ro-Ro ships carrying passengers.

In the figure 2 we computed the evolution of DWT for bulks²¹, containers, passengers

²¹We summed liquid and solid bulk cargoes for simplicity. Bulk cargo refers to commodities shipped unpackaged in large quantities. The distinction between the two categories is physical and operational: solid bulk consists of dry commodities handled by grabs, conveyors, and storage yards or silos (e.g., coal, iron ore, cereals/grains, fertilizers, cement, bauxite), whereas liquid bulk consists of fluids handled through tanks and pipelines (e.g., crude oil and refined petroleum products, LNG/LPG, chemicals, vegetable oils).

and the total²². Bulk shipping is the most volatile category, while containers and total grew at a ‘smooth’ pace. Passenger numbers rose sharply at the beginning of the 2010s and we also observe the impact of Covid-19. Lockdowns and travel restrictions have had a considerable impact on the tourism and cruise sectors, which has directly translated into a decline in passenger numbers in European regions.

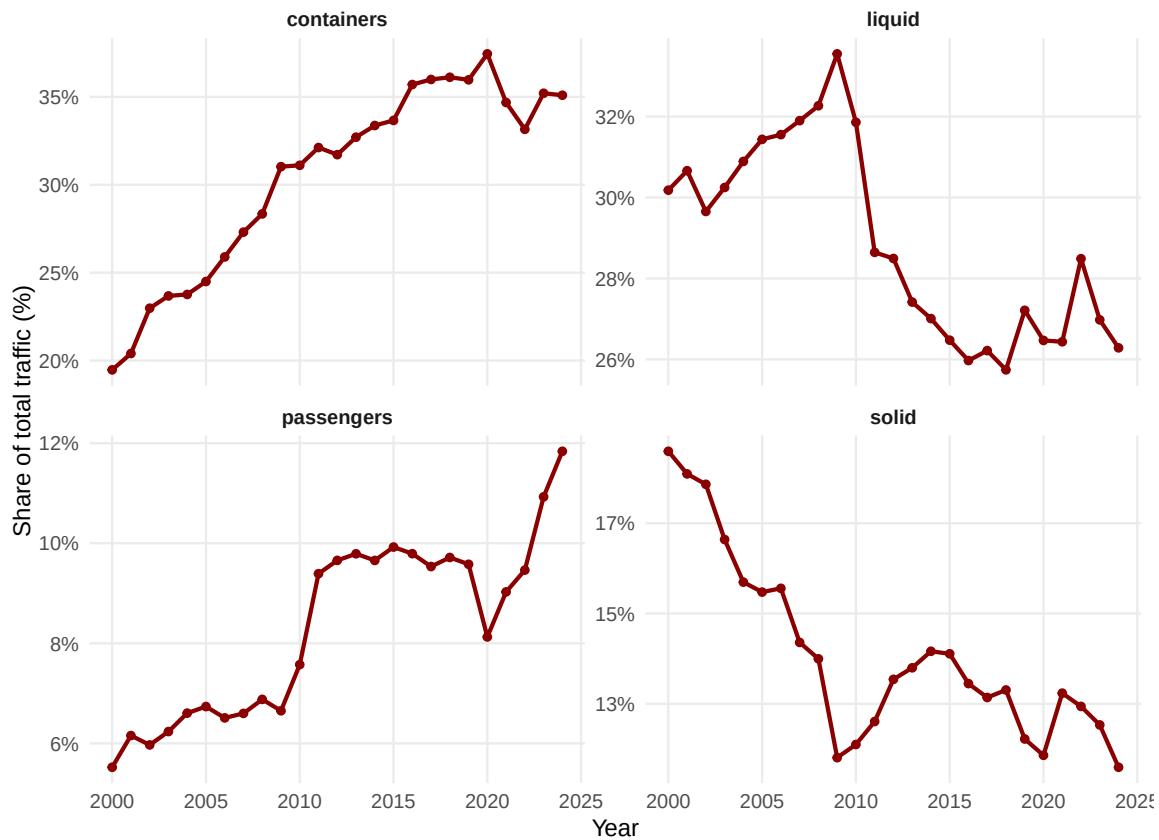


FIGURE 3. Evolution of the traffic share for containers, liquid bulk, solid bulk, and passengers (2000-2024)

Notes: The figure reports the annual composition of European maritime traffic by cargo category. For each year, we aggregate traffic over all ports in the sample by type of goods (containers, liquid bulk, solid bulk, passengers) and compute each category's share in the total. Traffic is measured using DWT.

This second figure provides another interesting point of view on the European port system. Here, we computed the evolution of the share of each type of goods in the total. We are seeing a significant increase in the number of containers in European ports, while liquid and solid bulk cargoes are losing market share. We also see a stabilisation

²²Which also includes port services, roll-on/roll-off and general cargo. We focused here on the goods that we considered most relevant to the rest of our analysis.

of containers' market share since 2015, suggesting that containers have reached relative maturity in the structure of European flows. In the case of bulk cargo, the trend is less obvious and warrants specific attention. In the case of liquids, it is conceivable that the development of pipelines may explain part of this decline. Overall, for both solids and liquids, it seems that this decline in market share is mainly explained by the strong and sustained growth of container traffic and the very steady growth in passenger traffic. With regard to the latter, the development of cruises, but also the existence of short-distance regional connections, helps to explain the dynamics of passenger traffic.

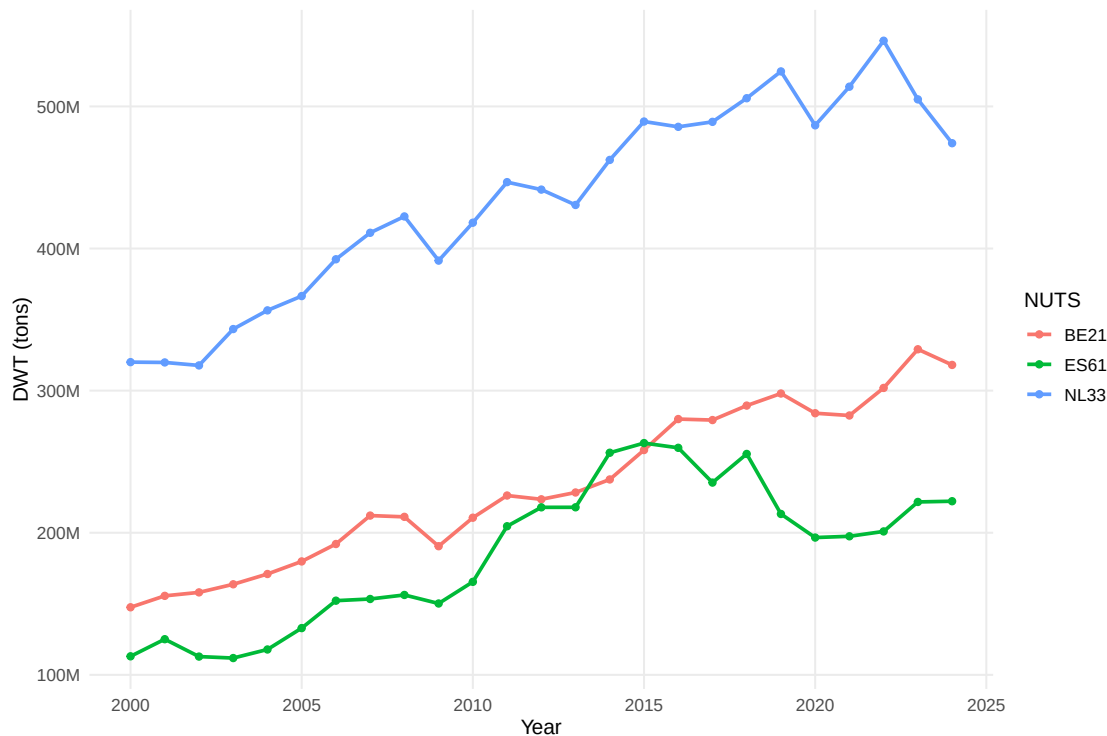


FIGURE 4. Top 3 - Total Regional Traffic

Notes: The figure plots annual total maritime traffic for the three NUTS-2 coastal regions with the highest activity in 2023. Traffic is constructed by aggregating port-level movements to the regional level (NUTS-2) and includes all cargo categories (containers, general cargo, and bulk). Values are expressed in DWT and correspond to the measure used in the main estimations.

The evolution of the three regions with the highest port activity in 2023 is represented in figure 5. The region 'NL33' is, by far, the largest one. It notably contains the port of Rotterdam. The second region is BE21, including the Antwerp-Bruges port complex (notably Antwerp and Zeebrugge terminals). We can see that the BE21 region has been quite resilient to the Covid crisis, with a recovery that has almost brought it back to its

pre-Covid growth trajectory. For the ES61 region (including Algeciras), the impact of Covid has not been overcome and the disruption has had a lasting effect on the decline in traffic and the difficulties of post-pandemic recovery.

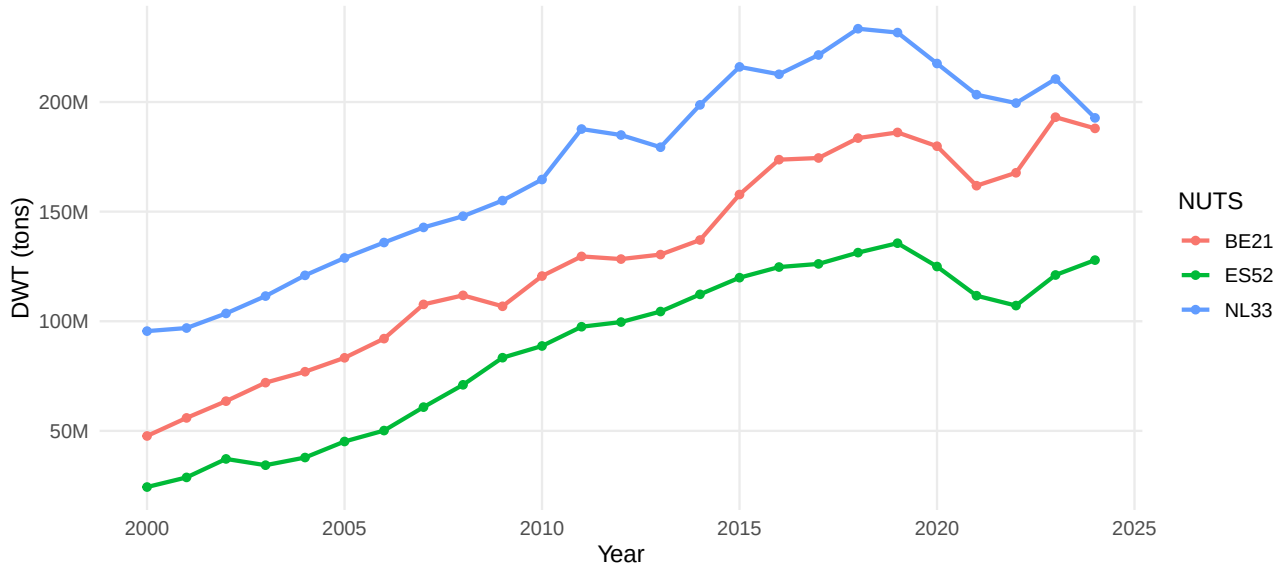


FIGURE 5. Top 3 - Containerised Regional Traffic.

Notes: The figure plots annual maritime traffic for the three NUTS-2 coastal regions with the highest activity in 2023. Traffic is constructed by aggregating port-level movements to the regional level (NUTS-2) and includes only container activity. Values are expressed in *DWT* and correspond to the measure used in the main estimations.

It is interesting to note that containerisation, which was already broadly adopted at the beginning of the 2000s, has had steady growth in top regions for 20 years. Since Covid-19, and even a little before, container traffic has reached a plateau. The post-Covid recovery is quite clear for total traffic (figure 2), while in the case of the top 3, the shock was more moderate and so was the recovery. In the figure 6 we show the ‘port’ regions in our dataset. It emphasises the port activity that takes place in the hinterland of seaports. We notably see the ‘arc’ from Marseilles to Paris and Le Havre, which is already emphasised as the major French hinterland in Guerrero (2014).

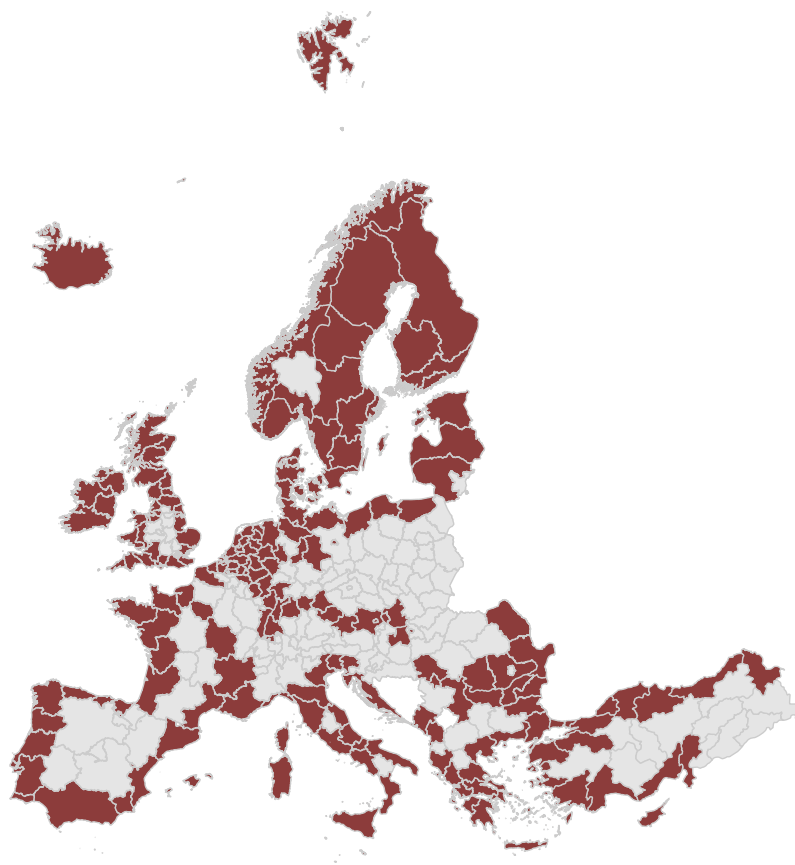


FIGURE 6. Port regions in Europe

Notes: In this map, we show the ‘port regions’, which can be coastal regions with seaports or inland regions with a river port. A region is considered as ‘port region’ if it has at least five years with a positive maritime activity from 2000 to 2024. Using this threshold, we avoid measurement errors and very small, insignificant, port activity.

The map in figure 6 shows a slightly different situation of port activity in Europe: it is limited to coastal regions, either maritime or not. Very few European regions are coastal and not maritime²³. On the contrary, a lot of regions are ‘port regions’ while being hundred kilometers away from the coast. In processing data, we are able to collect river port activity. This is interesting and innovative in two respects. Firstly, because it allows us to cover a wider range of port regions and therefore estimate the impact of port activity more accurately than was previously possible. Secondly, when estimating the spillover effects of port activity, we are once again covering a larger number of regions. This increases the magnitude of spillover effects on regions neighbouring large

²³Especially because we consider a large quantity of ports in our dataset. In Eurostat, some small ports are not included. In our case, due to the fact that we aggregate ports from ship movements directly, we cover a large, in fact almost exhaustive, set of ports.

river ports, which might not have been taken into account if we had limited ourselves to coastal regions.

2.4. Network Structure of European Maritime Trade

In this section, we approach the structure and dynamics of European maritime trade through a different strategy. By constructing an annual list of European maritime traffic graphs and using metrics derived from the study of networks or complex systems, we enrich our preliminary discussion on the structure of port activity in European regions²⁴.

2.4.1. Constructing the Trade Network

To build the European maritime trade network, we use raw maritime movement data from Lloyd's List. Knowing the route of each ship, we consider each port - European or not-European - as a vertex V in the network, and the route between two ports as an edge E . For each year, we thus have a graph $G = (V, E)$, where V is the number of ports in the network and E is the number of links. To ensure consistency with the regional focus of the rest of the paper, European ports are aggregated at the NUTS-2 level. In practice, all ports located within the same NUTS-2 region are represented by a single regional node. This aggregation reflects the fact that the economic impacts of maritime activity materialize at the regional level, through port systems and their hinterlands, rather than at the level of individual ports. Ports located outside the European Union are instead kept as individual nodes, as no comparable regional classification is available and as they primarily serve to capture the external connectivity of European regions. As a result, edges in the network connect either two European regions or a European region to an extra-European port²⁵.

²⁴Additional details on the construction of the database are provided in subsection [2.1](#)

²⁵This construction implies that the network captures the structure of European regional maritime connectivity within the global shipping system, rather than a detailed hierarchy of individual European ports.

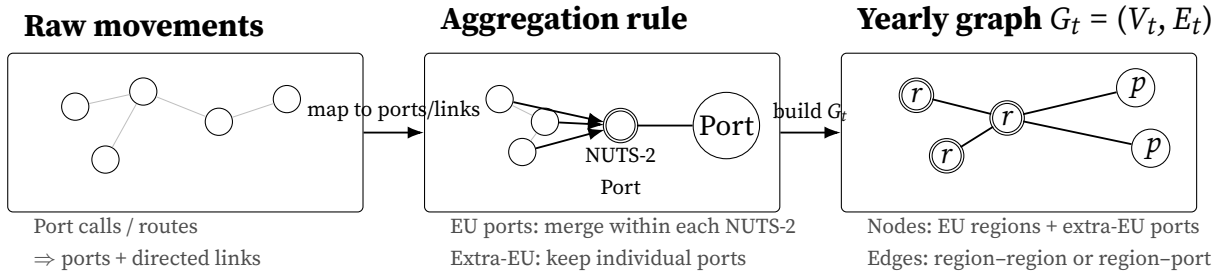


FIGURE 7. Constructing the European regional maritime trade network from raw vessel movements.

We repeat the same procedure for each year from 2000 to 2024. This enables us to construct temporal indicators, at both individual and network level, to measure the evolution of the European maritime system.

2.4.2. Global and Local Dynamics

We begin with a series of standard metrics at the global network level, without distinguishing between European ports and the rest of the world. These network metrics, such as betweenness or transitivity, allow us to assess structural changes in European maritime trade more accurately than simple descriptive statistics. They are designed to capture the overall properties of connectivity, hierarchy and cohesion within the system, taking into account not only the number of links, but also their relative organisation and the strategic position of nodes within the network as a whole. They thus provide a comprehensive overview of long-term changes in the European maritime system, highlighting dynamics of centralisation, diffusion or fragmentation that are not necessarily observable from aggregated volumes or purely bilateral indicators.

Macrostructures of the Shipping Trade Network. Figure 8 shows the evolution of network density over the period. It can be seen that network density, which remained stable until 2010–2011, then began to decline rapidly and relatively continuously until 2024. The downward trend in network density indicates that the growth of the European maritime system has been mainly extensive, through the addition of new nodes and connections, rather than proportional strengthening of existing links. In other words, the number of edges is increasing less rapidly than the number of potential connections, reflecting a gradual dilution of the network’s relative connectivity. This development is consistent with a process of geographical and functional expansion of European maritime trade, marked by diversification of routes and partners rather than a uniform intensification

of relations. It also suggests that the growing integration of the network is not leading to saturation of links, but to a more extensive and less dense structure, characteristic of continuously expanding networks.

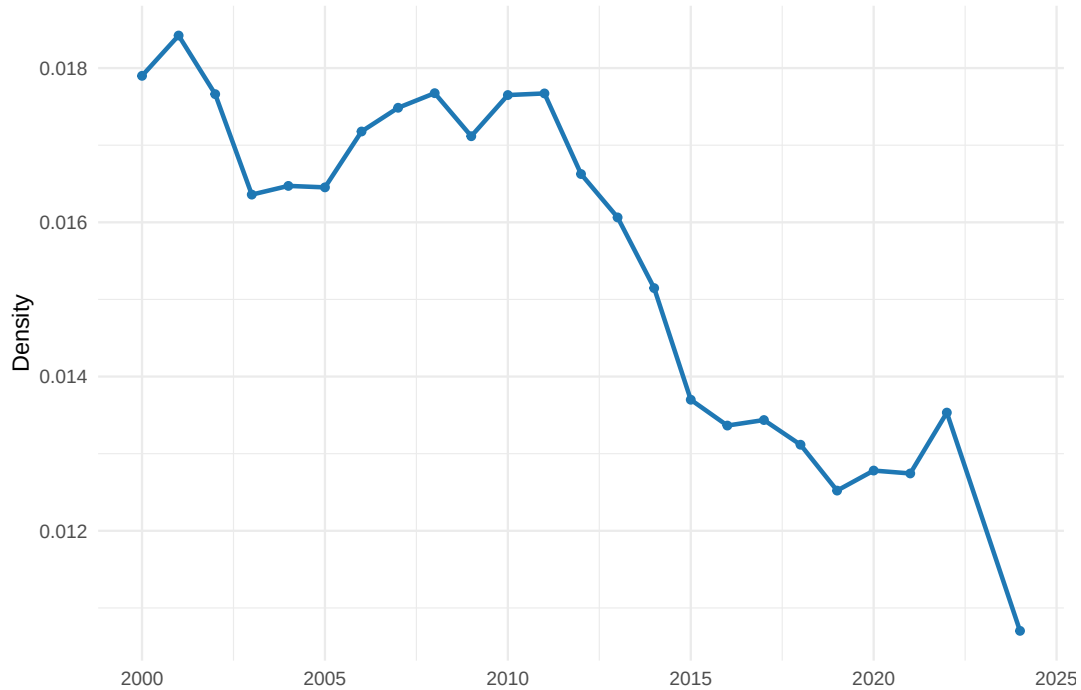


FIGURE 8. Network Density

Notes: Network density is computed on the annual (binary) regional maritime trade network as the ratio of observed links to all possible links between nodes (loops excluded). A link is recorded when a positive connection between two regions is observed in a given year (see Data section for the construction of links).

The downward trend can also be observed for transitivity (Figure 9), this time over the entire period. The gradual decline in transitivity indicates a decrease in the propensity of regions to form closed triangles, suggesting an erosion of highly interconnected local structures. This evolution reflects a shift from a network organised around dense and redundant subsets to a structure based more on extended logistics chains and longer-range connections.

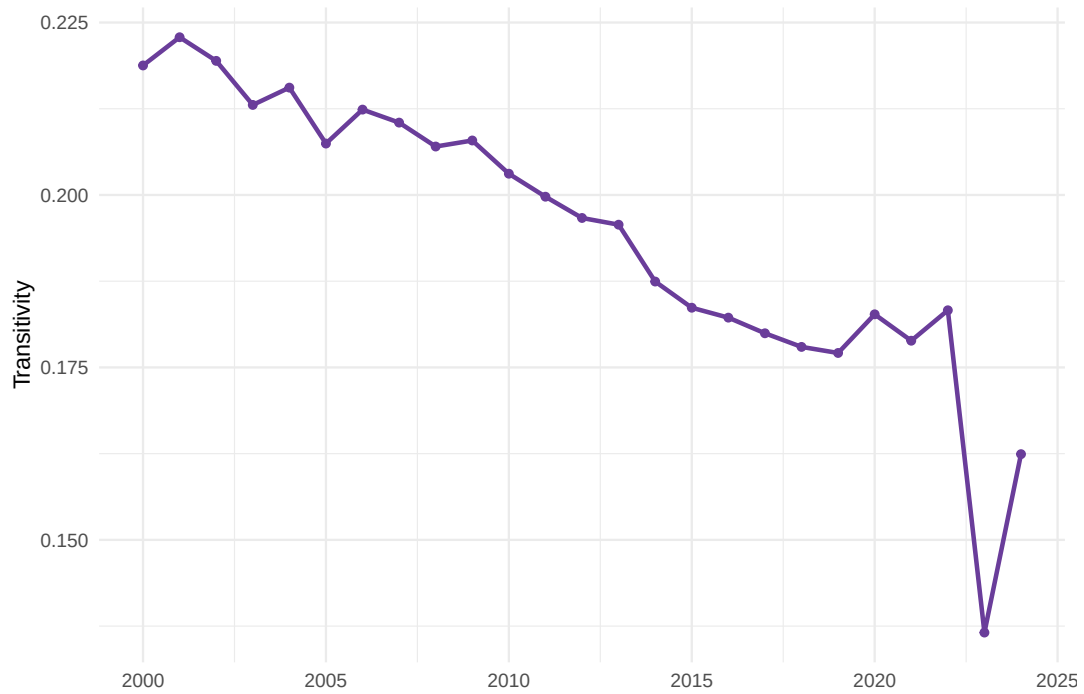


FIGURE 9. Network Transitivity

Notes: Transitivity (global clustering) is computed on the annual (binary) regional maritime trade network as the share of closed triplets among all connected triplets, capturing the tendency of regions to form triangles. Loops are excluded and the measure is computed year-by-year on the same network definition as in Figure 8.

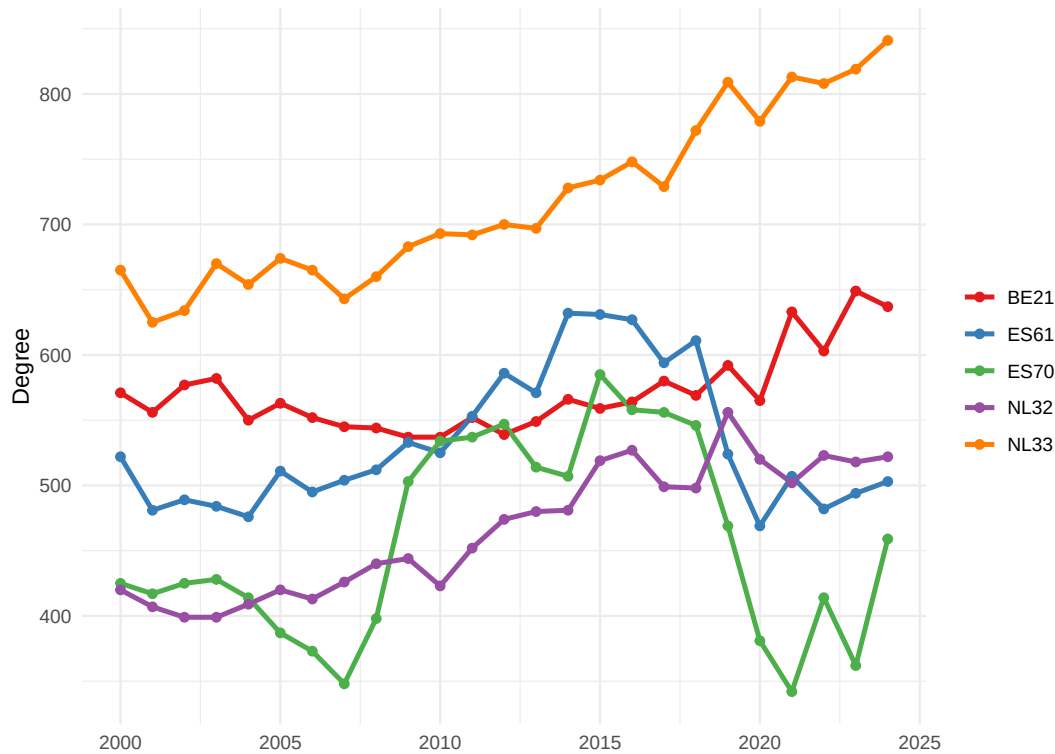


FIGURE 10. Evolution of the degree of the five busiest port regions in 2024

Notes: The figure reports the yearly evolution of total degree (number of distinct maritime trade partners) for the five NUTS-2 regions with the highest degree in 2024. Degree is computed on the annual network, counting a partner whenever a positive connection exists in either direction in a given year. Region identifiers correspond to NUTS-2 codes.

Structure and Dynamics of the Regional Maritime Trade Network. The figure 10 illustrates the evolution of connectivity levels in the five most connected European regions in 2024. Some regions, such as NL33, show almost continuous growth in connectivity, suggesting a structural strengthening of their integration into the European maritime network. Others experience more volatile dynamics, marked by phases of expansion followed by temporary declines, particularly around recent shocks. For instance, the Spanish regions (ES61 and ES70) appear to have been severely affected by Covid-19, although it should be noted that the decline had already begun in previous years²⁶. Growth in the NL33 region is mainly driven by the port of Rotterdam; the refocusing of the European maritime system in favour of northern ports²⁷ is directly linked to

²⁶In the case of ES70 (Canary Islands), it can be hypothesised that the sharp decline in the degree since the late 2010s reflects a reconfiguration of ocean routes and an increased concentration of flows on a smaller number of major platforms.

²⁷A dynamic that also benefits the BE21 (Antwerp) and NL32 (Amsterdam) regions.

the macro mechanisms described in the previous subsection: a growing proportion of the links at the top of the hierarchy (long containerised journeys, hub-and-spoke structures) are concentrated on the ports of northern Europe.

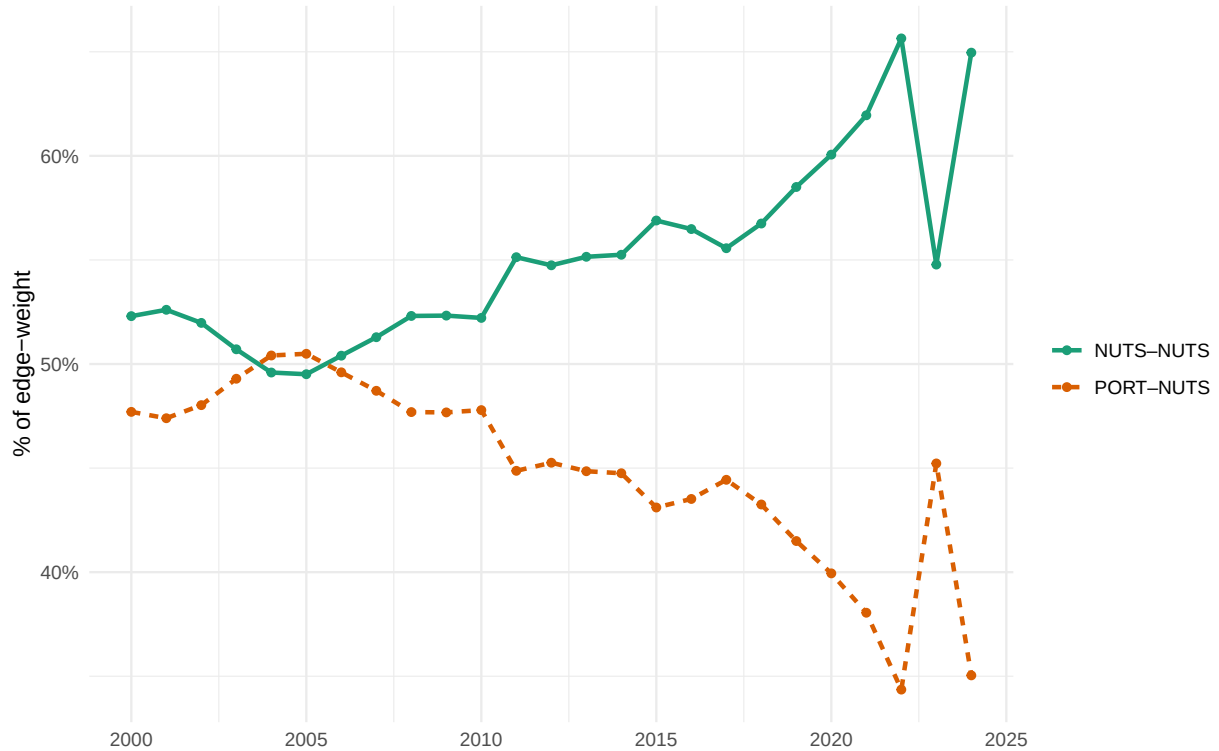


FIGURE 11. Network Composition - Trade with non-European regions

Notes: The figure decomposes total weighted connectivity in the European maritime network into (i) NUTS-NUTS links, *i.e.* connections between European NUTS-2 regions (intra-European component), and (ii) PORT-NUTS links, *i.e.* connections between non-European ports and European NUTS-2 regions (extra-European component). For each year, values are expressed as shares of total link weight (summing to one).

The above figure (Fig. 11) highlights a gradual restructuring of connections within the European maritime network. Over the period as a whole, the share of NUTS-NUTS connections has tended to increase, rising from just over half of weighted connections in the early 2000s to a clearly dominant proportion from the mid-2010s onwards. This development is accompanied by a symmetrical decline in the share of PORT-NUTS links, indicating a relative decrease in the dependence of European regions on direct connections with non-European ports.

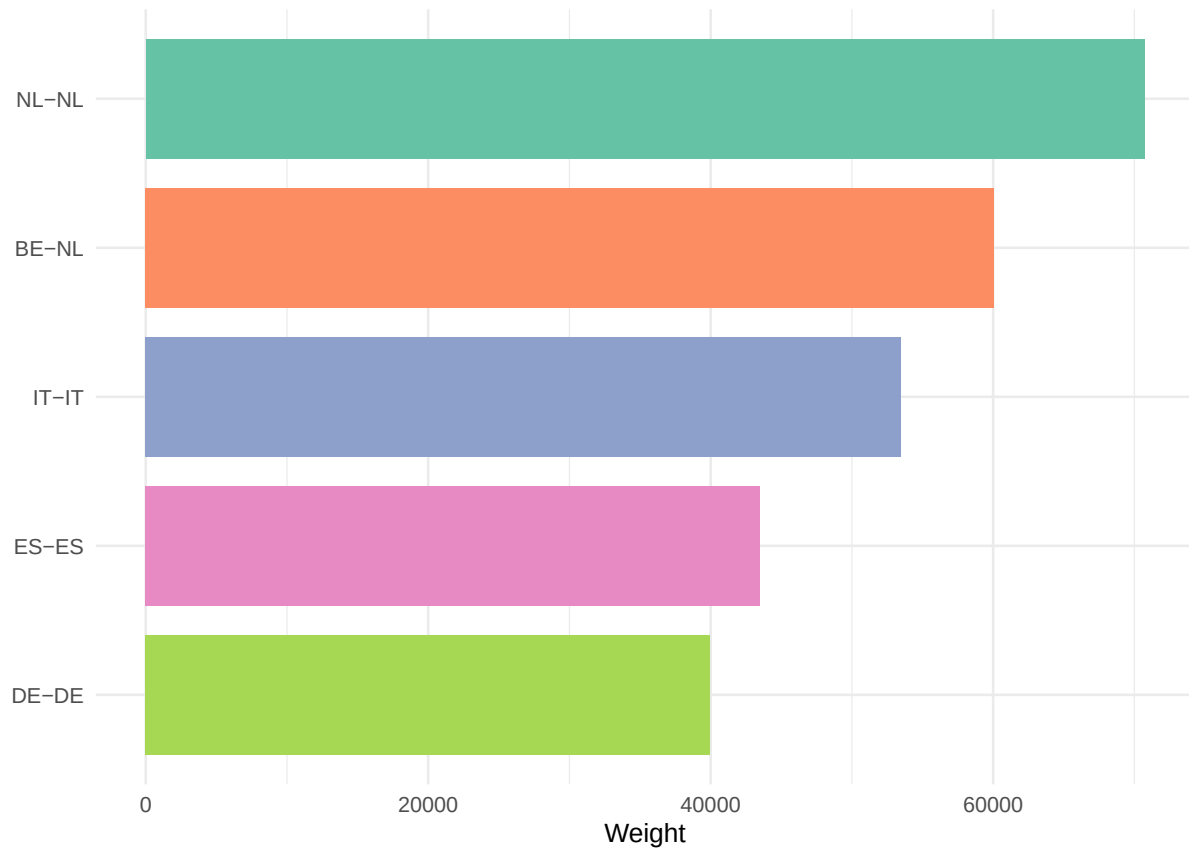


FIGURE 12. Network Composition - intra-European trade 2020-2024

Notes: The figure focuses on intra-European trade over 2020–2024 and aggregates NUTS–NUTS links by country pair (based on the country code of each NUTS-2 region). Cell values represent the share of total intra-European link weight accounted for by each country pair over the period (directions aggregated). Diagonal entries capture domestic (within-country) connections.

Figure A.1 emphasizes the high concentration of intra-European trade around a limited number of country pairs over the period 2020–2024. NL–NL connections dominate, highlighting the central role of the Dutch port system and the density of trade associated with the Rotterdam hub. The BE–NL and IT–IT pairs confirm the importance of integrated regional corridors, respectively within the Northern Range and the Italian port system. The ES–ES and DE–DE links, although significant, appear to be less intense, reflecting more fragmented and specialised national structures. Overall, these results suggest that recent European maritime integration is based primarily on a small core of highly connected national systems.

3. Identification Strategy

The literature review in section 1 proposes a precise overview of prior contributions and of the issues linked to the complex relationships between the development of regions - coastal and hinterland - and port activity. The loading and unloading of ships, whether carrying passengers or goods, has consequences for local economic activity. also for the development of neighbouring regions²⁸. Moreover, we can reasonably assume that spillovers are a function of the size of the port - at least in many cases.

The existence of spillovers, from coastal and port regions to hinterland regions, is at the root of the second main challenge of this paper. Without using a spatial econometric model, which raises other methodological problems that we do not tackle in this paper, we need to find an effective way of capturing this effect. We detail the econometric methodology and the different axes that motivate the specifications presented in section 3.2 and among the robustness checks in appendix B.

We begin by presenting the rationale behind our three-step approach: (i) OLS, (ii) IV, (iii) spillovers. This also allows us to justify the limitations, in the case of the European economy, of the approaches adopted in previous studies. We then present in detail our strategy for constructing an instrumental variable for maritime traffic in European regions. Finally, we detail the approach chosen in the paper to estimate the impact of maritime traffic on neighbouring regions.

3.1. IV Strategy

In this section, we introduce a novel instrument to estimate the impact of port activity on economic activity. We first discuss the previous instruments used in the literature, explaining why they did not work in our case, and propose a novel approach based on a historical measure of regional ‘maritime size’.

3.1.1. Motivation

The estimation of the impact of transport infrastructures on local economic development poses one main challenge: the reverse causality in the relationship between economic development and transport flows. In the case of ports and maritime flows, the

²⁸ [Ducruet et al. \(2024\)](#) show that the introduction of containerisation has an ambiguous local impact: improved market access and the attractiveness of the area have a positive impact on the population. At the same time, the costs associated with containerisation and the space required by container terminals offset some of the positive effects.

direction of the causality is not clear. The - plausibly exogenous - development of ports is certainly a source of economic growth. Port activity generates employment, promotes infrastructure development, and opens up opportunities for international trade. At the same time, economic development, industrial activity, or population growth may attract new ships or - for inland regions - generate spillovers by fuelling the development of shipping in coastal areas. To ensure the robustness of our estimates, we thus need to find an instrument for port activities in European regions.

Breidenbach and Mitze (2016), Brooks, Gendron-Carrier, and Rua (2021), and Ducruet et al. (2024) proposed three instruments for port activities in the case of local economic development. Breidenbach and Mitze (2016) developed a long-run instrument, by using the German ports built before the Industrial Revolution as an instrument for current German infrastructures, considering that they are exogenous to the economic development of the past few decades. Brooks, Gendron-Carrier, and Rua (2021) and Ducruet et al. (2024) approached the problem with a completely different idea: they considered that the ‘naturally deep’ harbours are more likely to welcome large ports²⁹. Following this statement, they used two different strategies to estimate the ‘naturally endowed depth’ of ports. Brooks, Gendron-Carrier, and Rua (2021) use the *World Port Indexes* from 1953 and 2015 to access a wide variety of information, including a classification of ports according to their depth. Ducruet et al. (2024) adopt a different strategy, using bathymetric surveys that indicate depth by grid square. This allows them to delineate areas around ports where the depth is natural and thus ensure the exogeneity of their instrument.

We first tried a long-run instrument strategy *à la* Breidenbach and Mitze (2016), using the De Graauw (2022) dataset that provides the coordinates of ancient ports and harbours. The results were not very successful³⁰, probably because major ports were located in the Mediterranean Sea during that period, while actual major ports are in the Netherlands, Belgium, and Germany, with only a few in the Mediterranean³¹. We then explored the possibility of a depth-based instrument. To this end, we used a strategy similar to the one used by Ducruet et al. (2024). We first extracted a grid of depth around Europe. Then, we counted the number of cells with a depth greater than ten meters in a ‘ring’ of one to five kilometres around each port. Finally, we merged this count at

²⁹Under this logic, variation in ‘naturally endowed depth’ provides a plausibly exogenous component of port capacity and connectivity.

³⁰At the end, as detailed in subsection 3.1.2, we adopted a historical instrument based on the ports with activity in Europe at the end of the 19th century.

³¹It should also be noted that major container ports in the Mediterranean, like Gioia Tauro, are recent and highly specialised in transshipment, further weakening the relevance of this instrument.

the NUTS-2 and NUTS-3 levels to have regional depth. While this instrument worked quite well for [Ducruet et al. \(2024\)](#) it did not provide a robust first stage in our case. The reason for this failure could be as follows: in the Mediterranean, we observe extremely deep ports with a very small traffic, especially around the islands such as Corsica and Sardinia. On the contrary, the North Sea, the English Channel, and the Baltic Sea are shallow areas, yet they have very high volumes of port activity. In addition, the regional level does not offer enough variation to capture the dynamics of shipping flows, while in the case of [Ducruet et al. \(2024\)](#) the city level is well-suited to this method³².

3.1.2. Methodology

To treat the endogeneity of port activity due to the reverse causality in the relationship with local economic development, we introduce a ‘historical’ instrument. We exploit the port activity from 1880 to 1900 to compute the ‘port size’ of each European region. To compute this ‘port size’ we use OCRised data from *Lloyd’s List*. This dataset has been used by [Ducruet et al. \(2024\)](#) to estimate the long-run effect of containerisation on population in a large panel of cities³³.

³²Both methods, and the third one that we will introduce in the next paragraph, are producing ‘static’ instruments. Considering that we work on panel data, we must make this instrument time-varying. [Ducruet et al. \(2024\)](#) do that too, and we detail in the next paragraph how we create variation in the instrument.

³³[Ducruet et al. \(2025\)](#) provide additional details on data collection and processing.

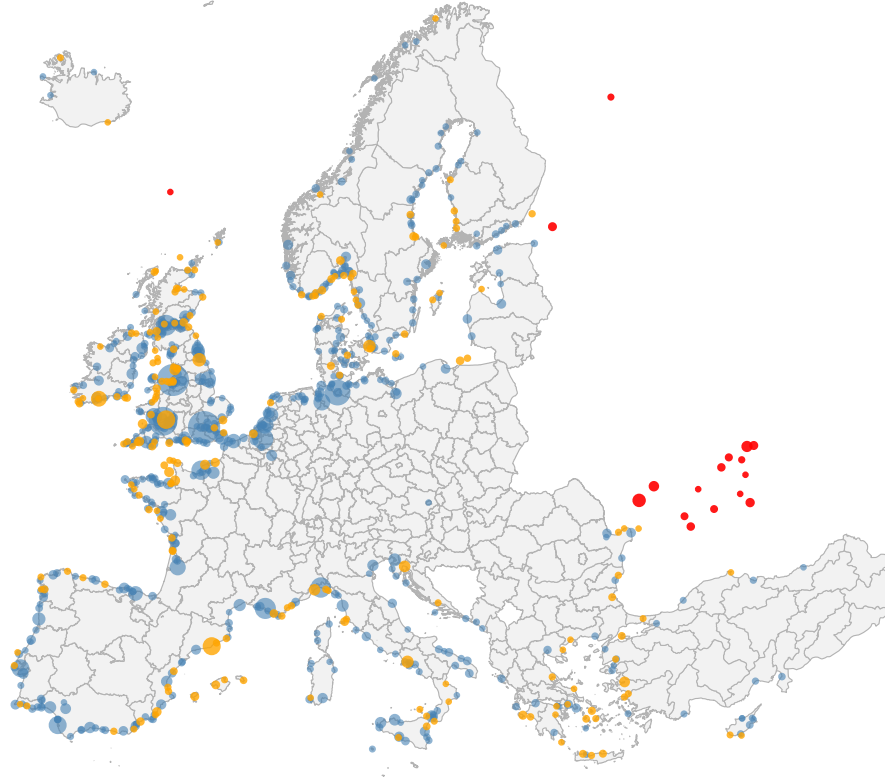


FIGURE 13. Port in Europe - 1880-1900

Notes: The figure illustrates the spatial distribution of ports with observed activity between 1880 and 1900. Port–region matching follows a three-step classification. Ports whose coordinates lie within a NUTS-2 polygon are assigned directly (blue). Ports located outside but within 60 km of the nearest NUTS-2 region are assigned using a nearest-neighbour rule (orange). Ports located farther than 60 km from any NUTS-2 region are classified as non-European or insufficiently geolocated and are excluded from the sample (red).

First, we identify European ports by merging the spatial polygons of NUTS regions with the coordinates of ports that have been active in any year from 1880 to 1900. Some ports have coordinates that place them slightly in the sea and are therefore not matched with the corresponding regions³⁴. In that case, we collected the ports in a buffer around the regions and assigned them to the nearest region by computing the distance from the point to the coast. We did that for each available year from 1880 to 1900³⁵ and then

³⁴As shown in Fig. 13 the unmatched ports are of two types: orange (within 60 km of the nearest NUTS-2 region) and red (farther than 60 km from any NUTS-2 region). We remove the red ports from the dataset to focus only on ports that are ‘Europeans’ *i.e.* associated to a NUTS-2 region.

³⁵The *Lloyd’s List* dataset provides information on port calls every five years on this period. We thus

summed the *port calls*³⁶. At the end of the process, we have the *port size* of European regions (NUTS-2 and NUTS-3) for the end of the 19th century. In other words, this is a historical measure of port development in the regions concerned. The *port size* of region i can be written in the following terms:

$$(5) \quad \text{maritime_size}_{i,t} = \sum_{t=1880}^{1900} \sum_p \text{calls}_{p,t}$$

The metric in Eq. 5 is a *static* measure of port development in the regions. However, panel data requires a time-varying metric. It raises a new issue: how can we create a time-varying, realistic, measure of port development that is exogenous? We follow Garcia Lopez et al. (2024)³⁷ by interacting our static measure with the growth rate of port activity from 2000 to 2020 in all regions of the country c excluding the region i ³⁸. Formally, it gives us the following equation for the first stage:

$$(6) \quad \text{IV}_{i,t}^{\text{tot}} = \left(\sum_p \sum_{\tau=1880}^{1900} \text{calls}_{p,\tau} \right)_i \times \frac{\left(\sum_{j \in c(i), j \neq i} \text{tot_DWT}_{j,t} \right)}{\left(\sum_{j \in c(i), j \neq i} \text{tot_DWT}_{j,2000} \right)}$$

3.1.3. Validity and Exclusion

The exclusion restriction requires that late-nineteenth-century port activity affects current regional employment only through contemporary maritime activity. Three families of threats merit scrutiny, and the design addresses each at a distinct margin. Time-invariant persistence is the most obvious concern. Historical port activity may capture first-nature geography, such as natural harbours, estuaries, or sheltered bays, but also early industrialisation, administrative centrality, long-run market access, and complementary infrastructure accumulated by historically central ports, including railways, warehouses, logistics facilities, and industrial districts. These channels are absorbed by region fixed effects: identification exploits within-region variation, net of

have 1880, 1885, 1890, 1895 and 1900.

³⁶The ‘call’ corresponds to a ship’s stopover in port. This dataset is thus approximating flows by counting the number of ships entering the port each year.

³⁷This is the most recent paper using this technique, but this approach is quite popular in the research dealing with transportation and economic development. For instance, it can be found in Baum-Snow (2007), García-López (2019), and ? Ducruet et al. (2024) are also using a similar technique.

³⁸We also tried to instrument the current dynamics of each region by using the 1880-1900 time series of calls, interpolating the missing years. It led to unreported results.

the cumulative historical advantages captured by the α_i .

Common time-varying shocks, including national maritime cycles, trade-policy episodes, and macroeconomic dynamics, are absorbed by country-year fixed effects. These specifications therefore compare regions within the same national and temporal environment. The more binding threat concerns persistent local trends correlated with both historical centrality and contemporary employment dynamics. The instrument addresses this concern by interacting historical port capacity with a leave-one-out contemporary maritime trend. A region's predicted exposure therefore depends on its nineteenth-century port capacity and on shocks affecting the rest of the maritime network, while excluding the region's own contemporaneous maritime evolution. Demographic, socio-economic, and accessibility controls further narrow the residual channel.

Two limitations remain explicit. The exclusion restriction cannot be tested directly, as in any IV design. Moreover, the instrument is, by construction, less informative for late-twentieth-century transshipment hubs whose rise reflects containerisation, terminal specialisation, and carrier strategies rather than nineteenth-century maritime centrality. This limitation mainly affects the scope of interpretation and the strength of the first stage for some types of modern port development, rather than the overall logic of the historical instrument.

3.2. Spillovers

Shipping impacts the economic organisation of coastal regions: development of port infrastructures, ships' maintenance, warehousing... But it also has an impact on the economic development of neighbouring, inland, regions. Firstly, goods and passengers arriving at the port are then distributed throughout the surrounding regions. In areas immediately adjacent to port regions, we can also observe the development of services such as storage, finance and logistics³⁹. Our discussion on the economic impact of shipping thus needs to be enlarged to non-coastal, neighbouring, regions.

To consider the spillover effects of port activity on non-coastal regions⁴⁰, we adopt a simple strategy of weighting traffic according to the distance between the neighbour's centroid and the port region. This can be written in the following terms:

³⁹For example, financial services such as maritime brokerage are present in Milan. Many support functions are therefore located in large non-coastal cities, but close to major port regions.

⁴⁰It implies that we compute the spillovers for inland regions with river ports. Compared with the traffic of coastal NUTS-2 (or even NUTS-3) regions, this traffic is often marginal and related to specific goods, such as cement or cereals.

We construct spillovers at three levels, corresponding to buffer areas around the centroids of port regions, ranging from 100 to 500 kilometres. In this way, we want to check the effect of distance on the spillovers, with the hypothesis that longer distance has an attenuation effect. We also check for non-linear impact, considering that larger ports might have a significant and bigger impact, even hundreds of kilometres away⁴¹. Another approach to spillovers and measuring the influence of ports could have been to consider the neighbourhood: a spillover limited to the neighbour, then adding the neighbours of the neighbours, and so on⁴². This approach would have posed a problem in the case of NUTS regions: depending on the country, the size of NUTS regions varies greatly. In France, NUTS-2 regions cover an area of 24,000 km², in Belgium 2,780 km², in the Netherlands 3,100 km², and in Germany 9,400 km². In the case of France, neighbours of neighbours make it possible to go from Perpignan to Dreux, near Paris, whereas in the Netherlands or Germany this greatly limits the ‘distance’ impact of spillovers.

The spillover impact is estimated through OLS. The results are included in the appendix B.6; they suggest some interesting results

4. Results

We have divided the assessment of shipping’s impact on local economic development into several strata. First, we assess the impact on coastal and port regions, including OLS and IV estimates. Next, we estimate the impact – via spillovers – on non-coastal/non-port regions⁴³.

4.1. The Impact of Shipping in Port and Coastal Regions

Our first set of estimates focuses on the port coastal regions. We thus identify the ‘direct’ impact of shipping and port activities on local areas. We make the distinction between ‘port region’ and ‘coastal region’ because in the first case we include regions such as Paris⁴⁴ while in the second case it is restricted to strictly coastal areas.

⁴¹For instance, the impact of Rotterdam, Antwerp and Le Havre on Paris is well documented.

⁴²This would be like Amdaoud et al (2022)’s approach. The main difference is that Amdaoud et al. (2022) focus on France, avoiding this issue of size heterogeneity.

⁴³This allows us to test both (i) spillovers strictly from coastal regions to other regions, even if they are river ports, and (ii) spillovers from regions with port activity to other regions. In the second case, considering the buffers used, we can go much further into the hinterland.

⁴⁴The ‘Ile-de-France’, *i.e.*, the region surrounding Paris, has the biggest river port in Europe. We can thus consider that a river port may have an impact on the employment/population in the area. Paris is obviously a particular case, considering the size and importance of the economic area, but in other cases

4.1.1. Coastal Areas - OLS Estimates

The estimation of the impact of shipping on coastal regions is organised in three blocks: (i) baseline regressions for NUTS-2 regions, (ii) OLS with a set of controls to account for geography, socio-economic and accessibility factors and (iii) IV estimates at NUTS-2 level. We estimate the impact of shipping for the total amount of goods that stopped in the given region, and for containers⁴⁵.

TABLE 1. Estimates — log-log baseline regressions without controls (paper setup + country-year FE variants)

Model	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	Employment	Employment	Population	Population	Employment	Population
Port activity	0.011 (0.009)	0.209** (0.082)	0.008 (0.006)	0.200*** (0.067)	-0.006 (0.006)	0.001 (0.004)
Model Setup						
Observations	3,580	3,580	3,569	3,569	3,385	3,374
Time Periods	25	25	25	25	25	25
NUTS-2 FE	✓		✓		✓	✓
NUTS-1 FE		✓		✓		
Time FE	✓	✓	✓	✓		
Country-year FE					✓	✓
Clusters	NUTS-2	NUTS-1	NUTS-2	NUTS-1	NUTS-2	NUTS-2

Notes: Coefficients are reported with robust standard errors clustered at the regional level (in parentheses). Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All models are restricted to coastal NUTS-2 regions (*coast_n2* = 1). Columns (1)–(4) include regional and year fixed effects (NUTS-2 or NUTS-1, plus year). Columns (5)–(6) replace year fixed effects with country-year fixed effects (*cy_fe*) and include NUTS-2 fixed effects. The independent variable is the log of total deadweight tonnage (*log_tot_dwt*).

The baseline results in Table 1 show that for level and log equations, the impact of shipping on local employment is positive but not significant at any level with fixed effects and clustered standard errors at NUTS-2 level. Equations 3 and 4 test the impact on population, and we mostly find the same results with NUTS-2 fixed effects. When we include NUTS-1 fixed effects instead of NUTS-2, the coefficients are positive and significant for employment and population. We focus here on *coastal* regions, excluding inland port regions. In the table below, we ran again the regression without controls river ports are central in the region's economy.

⁴⁵In the robustness checks we also provide estimates for cargo and containers.

but for *port* regions, which includes inland port cities such as Paris. The results are of the same nature: coefficients are all positive, but significant only in the case of NUTS-1 fixed effects.

We will now introduce control variables at NUTS-2 level, to account for quite a large set of economic and geographic determinants of employment dynamics. We computed the trend of density, GDP, multimodal accessibility⁴⁶.

We see that the ‘global picture’ remains the same: the impact of shipping is positive in the regression, but it does not reach any significant p-value. This may seem surprising at first glance, as one might expect, even in the presence of endogeneity, to observe a significant relationship for employment or population. However, this result is broadly in line with recent literature. As we noted earlier, recent studies generally conclude that the effect is weak and rarely significant.

In the specification using log-log regression and controlling for density, GDP, education and multimodal accessibility, the coefficient is positive and significant at the 5% level. When we include the share of the GVA in services, the coefficient remains positive, but it loses it becomes non-significant. While the positivity of the coefficient is robust to many specifications, its significance is much more sensitive.

⁴⁶We focused on the multimodal indicator, instead of using motorways, rails, canals etc., to simplify the regression and avoid overfitting.

TABLE 2. Estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2)

Variable	Model										
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
ln(DWT Total)	0.0112 (0.0081)	0.0198* (0.0109)	0.0197* (0.0109)	0.0396** (0.0172)	0.0346** (0.0161)	0.0124 (0.0118)	0.0095 (0.0115)	0.0083 (0.0118)	−0.0116 (0.0085)		
L.ln(DWT Total)										0.0089 (0.0113)	−0.0118 (0.0083)
NUTS	177	132	132	102	102	79	79	61	60	61	60
Years	25	25	25	25	21	21	21	21	21	20	20
NUTS-2 FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗
Country×Year FE	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓
Clusters	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2

Note: Robust standard errors clustered at the NUTS-2 level in parentheses. Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All regressions are restricted to coastal NUTS-2 regions (*coast_n2* = 1). Unless otherwise stated, controls enter as trends. Accessibility is measured by *potacmu_projection* from column (b) onward.

Controls by column — (a) density trend, GDP trend; (b) (a) + accessibility; (c) (b) + education; (d) (c) + industrial GVA share (*gva_gu_trend*); (e) (d) + business/services GVA share (*gva_be_trend*) and gross fixed capital formation (GFCF); (f) (e) + working-age population (15–64) trend; (g) (f) + total GHG emissions; (h) (g) + institutional quality (EQI); (i) same controls as (h) with country×year fixed effects in addition to NUTS-2 fixed effects (year FE are redundant when country×year FE are included); (j) same controls as (h) but using the lagged maritime variable *L1[ln(DWT total)]* with NUTS-2 and year fixed effects; (k) same as (j) with country×year fixed effects in addition to NUTS-2 fixed effects (year FE redundant).

Reading: Positive and significant effects emerge mainly once structural controls are enriched (d–e). With country×year fixed effects (i, k), identification relies on within-country/within-year variation; coefficients become statistically weaker or change sign accordingly. Lagged specifications (j–k) address timing but remain broadly consistent with the patterns observed under stricter fixed effects.

TABLE 3. Estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2, total DWT; acreg + Conley)

Variable	Model							
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
ln(Total DWT)	0.0186*** (0.0051)	0.0260*** (0.0071)	0.0265*** (0.0070)	0.0512*** (0.0103)	0.0471*** (0.0097)	0.0110 (0.0078)	0.0076 (0.0076)	0.0080 (0.0082)
Obs.	3502	2808	2807	2266	1914	1508	1508	1193
NUTS	136	—	—	—	—	—	—	—
Years	25	—	—	—	—	—	—	—
NUTS-2 FE	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓
Country×Year FE	✗	✗	✗	✗	✗	✗	✗	✗
SE (Conley)	✓	✓	✓	✓	✓	✓	✓	✓
DistCutoff / LagCutoff	500 / 5 (Bartlett)							

Note: Spatial HAC (Conley) standard errors in parentheses from acreg using `distcutoff(500)` and `lagcutoff(5)` (Bartlett kernel). All regressions are restricted to coastal NUTS-2 regions (`coast_n2 = 1`) with non-missing coordinates. Models include NUTS-2 and year fixed effects (`pfe1(nuts_id)` and `pfe2(year)`). Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Controls by column — (a) density trend, GDP trend; (b) (a) + accessibility (`potacmu_projection`); (c) (b) + education (`edu_58_trend`); (d) (c) + GVA structure (GU trend: `gva_gu_trend`); (e) (d) + BE trend (`gva_be_trend`) and investment trend (`gfcf_trend`); (f) (e) + working-age population trend (`pop_1564_trend`); (g) (f) + total GHG emissions (`ghg_emission_tot`); (h) (g) + institutional quality (`eqi_final`).

Reading: Under variable-sample stepwise controls, the estimated elasticity of employment to total DWT is positive and statistically significant in (a)–(e), but becomes small and statistically indistinguishable from zero once the control set expands and the usable sample shrinks (f)–(h). This pattern is consistent with substantial sample selection induced by later controls and/or diminishing identifying variation once richer covariates are included.

Table 3 reports coastal NUTS-2 log-log estimates of employment on total DWT using `acreg` with Conley (spatial HAC) standard errors, which relax the usual i.i.d. assumption by allowing for spatial dependence within 500 km and serial correlation up to five years. In the first specifications (a)–(e), the estimated elasticity is positive and modest (roughly 0.02–0.05), consistent with the baseline fixed-effects association between maritime traffic and coastal employment. However, once the control set expands to include working-age population, emissions, and institutional quality (f)–(h), the coefficient collapses toward zero and becomes statistically indistinguishable from zero. Later specifications also entail a substantial contraction of the usable sample due to missing values in the additional covariates, so the change in estimates conflates conditioning on richer correlates of local employment dynamics with a shift in sample composition and identifying variation. Overall, the Conley correction does not overturn the qualitative message from conventional clustered inference in previous models.

4.1.2. Coastal Areas - IV estimates

In the last table in this section (4), we report 2SLS estimates based on our historical instrument, following the identification strategy described in Section 3. In light of recent literature, this approach using a historical instrumental variable should be seen as an attempt to construct a robust and relatively comprehensive methodology for identifying the impact of port activity on regional economic activity.

Across specifications (a-c), the instrument is reasonably robust and estimates are positive, suggesting that higher maritime activity is associated with higher regional employment even after accounting for underlying structural trends. As the controls are gradually enriched (d-e), the estimates remain positive, but the strength of the first stage deteriorates, indicating that the variation becomes increasingly limited once the correlated long-term dynamics (sectoral composition, investment, demographics) are partially eliminated. This weakening implies that part of the correlation between port activity and employment may be driven by slow local fundamentals, which are difficult to separate from the historical component captured by the instrument. It should also be noted that including these variables results in a significant loss of data. This is related to the regions for which these statistics were produced by Eurostat.

TABLE 4. IV (2SLS) estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2)

Variable	Model										
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
In(DWT Total)	0.1703*** (0.0501)	0.1945*** (0.0659)	0.2010*** (0.0652)	0.4261*** (0.1558)	0.3922*** (0.1660)	-0.5768 (0.9918)	-0.5013 (0.7881)	-1.1020 (2.6871)	-0.0240 (0.0157)		
L.ln(DWT Total)										-1.0094 (2.2395)	-0.0222 (0.0156)
K-P rk Wald F (1st stage)	21.57	15.50	15.83	7.67	5.94	0.39	0.48	0.17	73.53	0.21	78.69
Observations	3307	2629	2629	2092	1764	1386	1386	1155	1155	1100	1100
NUTS-2 (clusters)	136	108	108	84	84	66	66	55	55	55	55
Years (in-sample)	25	25	25	25	21	21	21	21	21	20	20
NUTS-2 FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Country×Year FE	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Clusters	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2

Note: 2SLS estimates from `ivreghdfe` on coastal NUTS-2 regions (`coast_n2 = 1`). Robust standard errors clustered at the NUTS-2 level in parentheses. Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The excluded instrument is `log_iv_nat_tot` (or `L1.log_iv_nat_tot` in lagged specifications). Reported first-stage strength is the Kleibergen–Paap rk Wald F statistic (cluster-robust). Accessibility is measured by `potacmu_projection` from column (b) onward.

Controls by column — (a) density trend, GDP trend; (b) (a) + accessibility; (c) (b) + education; (d) (c) + industrial GVA trend component (`gva_gu_trend`); (e) (d) + business/services GVA trend component (`gva_be_trend`) and gross fixed capital formation trend (`gfcf_trend`); (f) (e) + working-age population (15–64) trend (`pop_1564_trend`); (g) (f) + total GHG emissions (`ghg_emission_tot`); (h) (g) + institutional quality (`eqi_final`); (i) same controls as (h) with country×year fixed effects (year FE redundant); (j) same controls as (h) but using `L1[ln(DWT total)]` instrumented by `L1[log_iv_nat_tot]` with NUTS-2 and year FE; (k) same as (j) with country×year fixed effects (year FE redundant).

The richer specifications (f-h) and the lagged model (j) should therefore be interpreted with caution. In these columns, the Kleibergen–Paap statistics indicate weak identification, and the second-stage coefficients become unstable, as might be expected under weak instruments. Rather than contradicting the previous results, these results mainly reflect a loss of usable variation and a substantial reduction in sample size due to the availability of additional controls (notably environmental and institutional measures), which mechanically inflates standard errors and undermines the precision of the first stage.

A useful benchmark is provided by specifications with fixed country×year effects (i) and (k). By absorbing national shocks and common trends at the country level each year, these models restrict identification to interregional differences within the country, within the year. In this demanding context, the instrument remains robust, but the elasticity of employment with respect to maritime activity becomes close to zero and statistically indistinguishable from it. This result can be interpreted in two non-mutually exclusive ways: (i) once contemporary national shocks are eliminated, the residual variation in port activity may limit short-term employment content at the NUTS-2 level; and (ii) the effects on employment may operate through largely national (or synchronised within countries) channels rather than through purely local differences linked to national conditions for the year.

Overall, Table 4 reinforces the credibility of the empirical framework in three respects. First, it shows that the historical instrument can generate significant variation in the first stage of standard specifications and remains powerful under strict national year controls. Second, it clarifies the empirical limits of identification: adding slow structural controls and rapidly reducing the sample pushes the design towards a weak instrument, where inference must be cautious. Third, it suggests that any positive effect on port activity employment is likely to be modest, or mediated by broader structural dynamics, rather than a robust reduced-form elasticity that survives each tightening of controls.

4.2. Discussion on the Estimates

As shown in Table 4⁴⁷, the use of a historical instrumental variable does not lead to a statistically meaningful improvement in the results. Overall, it therefore remains difficult to draw firm conclusions regarding the magnitude, the sign, or the statistical

⁴⁷Table B.2 in the Appendix report additional estimates obtained by modifying the clustering of standard errors. The results are broadly similar.

significance of the impact of port activity on regional development.

A qualitative economic intuition helps to shed light on the obstacles encountered in the quantitative analysis. The development of port areas in coastal regions is, at first glance, expected to generate positive economic effects through two main channels: (i) the creation of local employment linked to port and logistics activities, and (ii) an increase in regional attractiveness through greater exposure to international trade and improved land connectivity with the hinterland. However, port growth may also generate negative effects on the quantity of employment through displacement mechanisms, which are further reinforced by technological progress in cargo handling and logistics.

First, containerisation is highly land intensive and may crowd out alternative economic activities that are denser in employment, thereby reducing local job creation. Second, the progressive automation of loading and unloading operations and of port-related services such as customs clearance, transport, and storage has made port activities increasingly capital intensive relative to labour, potentially generating an additional negative effect on local employment. The interaction of these opposing forces, combined with the rapid evolution of maritime networks and port hierarchies, weak political coordination, and intense competition among European ports, contributes to making the identification of a clear and unambiguous effect of maritime transport on local employment particularly challenging, even beyond the standard endogeneity issues affecting the relationship between port activity and regional outcomes.

The introduction of spillover effects (Tab. B.6 in the robustness checks) in combination with the instrumental variable nonetheless provides useful insights into this discussion and helps clarify some of the difficulties highlighted in the existing literature when estimating the local impact of port activity⁴⁸.

5. Discussion & Conclusion

Contributions. In this paper, we proposed a generalisation and an extension of the discussion on the regional impact of shipping. We have contributed to the literature on European transport networks by reconstructing regional maritime trade for different

⁴⁸The spillover results reported in Appendix B.6 suggest that the economic effects of maritime activity may not be confined to coastal or immediately adjacent regions. In the baseline regressions, the estimated association between DWT spillovers and employment is positive and increases with the radius considered. Once controls are introduced, the coefficients are not statistically different from zero at 100 km and 300 km, but become positive and weakly significant at 500 km. This pattern should be interpreted cautiously, but it is consistent with the idea that port activity may operate through broader logistics corridors, hinterland integration, and interregional market-access effects.

types of goods over the last 25 years. To our knowledge, this paper is the first to undertake this exercise and apply it in the context of a network analysis using metrics derived from graph theory. Then, combining standard OLS estimation with historical instruments and an extensive review of the literature, we tried to understand why it is so difficult to estimate the impact of shipping on local economic activity. Although we found some evidence of limited, positive effects, it largely remains an open question. This difficulty in stabilising robust orders of magnitude is not simply a statistical artefact: it reflects the very nature of the ‘treatment’ under study (ports and flows): a set of ‘complex’ networks, multi-sectoral object, whose effects are felt as much through channels of accessibility and commercial integration as through mechanisms of spatial reallocation and local costs.

Ports as a major policy and geo-economic issue. Nevertheless, it is an important issue that deserves attention. Port development is a key economic, urban, cultural, and social policy issue. It affects local economic activity, but also the landscape, health, and access to housing. Port activity is not limited to the development of port infrastructure. Financial, storage, and transport services are also an important part of this industry. Finally, we must not forget the international issues at stake, which concern not only ports but also the major shipping companies that compete fiercely in strategic oligopolies.

Estimation challenges and real economic impacts. This chapter highlights two main messages. First, the impact of maritime flows on regional economic activity is neither automatic nor uniformly strong: at best, we observe a positive but modest effect, while most regressions have led to a zero effect. Secondly, this conclusion is itself informative: it indicates that the average causal effect on standard regional aggregates is likely to be weak, heterogeneous, and partially displaced outside administrative boundaries, making estimates sensitive to specification, spatial scope, and time horizon.

Our approach largely follows the work of [Bottasso et al. \(2013, 2014\)](#) and, more recently, [Brooks, Gendron-Carrier, and Rua \(2021\)](#) and [Ducruet et al. \(2024\)](#). These latter two articles also estimate the impact of port activity on local development using an instrumental variable strategy. In their case, as in ours, it is clear that obtaining stable and consistently positive coefficients is not easy. Beyond the estimation challenges, this also reflects an economic reality: the local effect of ports is uncertain, dependent on local contexts, and often diffuse, extending from nearby areas to very distant hinterlands.

On the econometric side, we identify three difficulties: (i) Residual endogeneity may

remain, as demand for port services responds to economic dynamics that are not fully absorbed by the usual fixed effects and controls. (ii) Spatial disaggregation is crucial: the economic area actually affected by a port (hinterland, logistics corridors, employment areas) does not necessarily coincide with administrative units, and some of the benefits may materialise in the form of spillovers beyond the port region. (iii) Finally, on the question of relevance: identifying an exogenous variation that is sufficiently strong while remaining economically interpretable requires compromises. In this context, the contribution of this work is not to claim to definitively resolve the identification issue, but to clarify why it is difficult, to propose an empirical strategy consistent with these constraints, and to deliver cautious orders of magnitude.

Future contributions. These results open a research agenda for future contributions. A first avenue is to better align the spatial unit of analysis with the relevant economic object⁴⁹, or at least to propose a multilevel estimation framework that captures heterogeneous effects across spatial scales. In the European context, this can be pursued thanks to data available at the metropolitan, NUTS-3 and NUTS-2 levels⁵⁰. A second line of work is to focus on outcomes that are closer to the underlying mechanisms: sectoral composition, the creation of logistics firms, land prices, pollution and congestion, in order to better characterise the net local balance of gains and costs. Finally, recent disruptions and reroutings highlight the importance of a systemic perspective: regional resilience depends on institutions' and firms' ability to internalise externalities and coordinate investments beyond administrative boundaries. Along these lines, we also suggest strengthening a multidisciplinary approach that combines standard econometric designs with tools from network analysis, as we have attempted to do in this chapter.

⁴⁹Administrative regions and functional hinterlands are usually quite different and we do not capture the 'real' local effect of ports by proxying the boundaries of their associated hinterlands.

⁵⁰Access to data remains a major constraint: few control variables are consistently available across the three levels of aggregation, so comparisons will necessarily rely on econometric specifications that are not fully identical.

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A. Network Structure

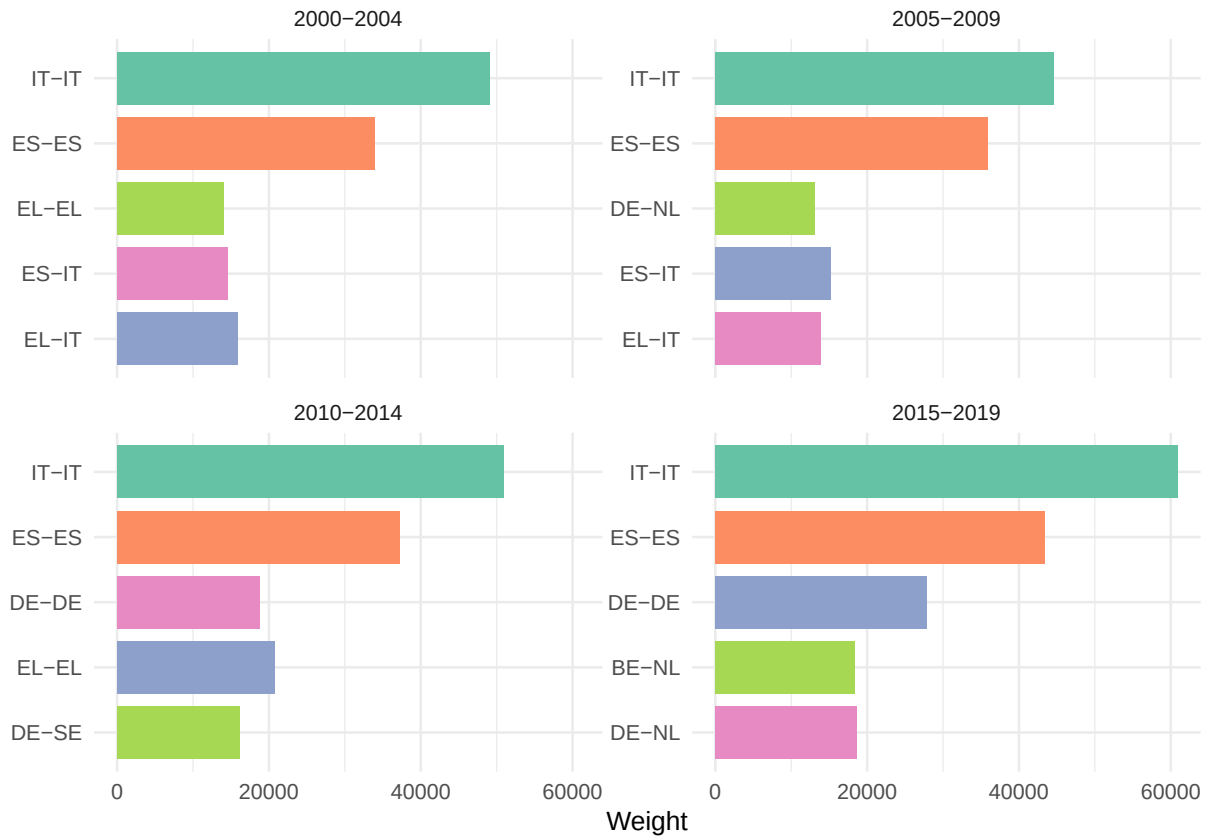


FIGURE A.1. Network Composition - intra-Europe Trade per Period

Notes: 'intra-Europe' refers to connections where both endpoints are European (NUTS-2) regions in the constructed network. Values are computed from link weights (vessel calls) aggregated within each period, and can be read as the changing composition of internal European connectivity over time at the country level.

B. Robustness Checks

B.1. First-stage regressions for the total DWT

First stage (total DWT). Table B.1 indicates that the excluded instrument $\ln(\text{IV nat tot})$ is relevant in the reference specifications: in columns (a-c), its coefficient is positive (approximately 0.65-0.68) and statistically significant, with F statistics (excluded instrument, robust and NUTS-2 clustered) between 15 and 22. This result is consistent with the structural interpretation of the instrument as capturing a component of variation exogenous to the regions (aggregate transport demand/supply shocks), which is transmitted to maritime activity observed at the NUTS-2 level, once unobserved invariant determinants (FE NUTS-2) and common shocks (FE year) have been neutralised⁵¹. Overall, (a-c) validate the relevance of the instrument for core specifications.

Sensitivity to controls and sample. As the block of controls (sectoral trend components, investment, demographics, emissions, institutional quality) is enriched, the instrument-DWT relationship weakens and then becomes statistically indistinguishable in (f-h), with F values below 1. Two non-exclusive interpretations are possible. First, certain controls (*e.g.*, sector dynamics, investment, demographic trends) may absorb a substantial portion of the structural variation through which aggregate shocks translate into regional maritime volumes: the first stage then becomes mechanically weak because part of the transmission channels are ‘closed’. Second, the sample shrinks significantly across columns (3,307 $\rightarrow$ 1,155 observations), which changes the country $\times$ year composition and may reduce accuracy and usable variance⁵².

Country $\times$ Year FE. Columns (i) and (k), which replace year FEs with country $\times$ year FEs, restore a very strong first stage ($F \approx 73$ -79) but with a negative sign and high magnitude. This change in sign should not be interpreted as mere instability: the inclusion

⁵¹The empirical motivation is classic: port activity (and, more broadly, maritime flows) is potentially endogenous to the regional economic situation via the demand for port services, which biases naive estimates. Contributions on the economics of ports explicitly highlight this risk of reverse causality and the difficulty of finding external instruments, hence the use of rich fixed effects and additional controls. See, for example, the discussion on the endogeneity of port activity and the value of dedicated identification strategies in Bottasso et al. (2014), Brooks, Gendron-Carrier, and Rua (2021), and Ducruet et al. (2024).

⁵²Consequently, specifications (f-h) should be interpreted as stress tests rather than reference columns: when $F < 10$, we favour robust inference with weak instruments (Anderson–Rubin/CLR tests, or LIML/Fuller estimators) and avoid over-interpreting conventional t -statistics.

of country×year FEs modifies the identification by basing it on an intra-country and intra-year comparison (relative reallocation of flows between coastal regions of the same country), rather than on co-variation with common aggregate shocks. In a context of competition between gateways, reconfiguration of maritime services, and expansion of hinterlands, a ‘national’ increase in flows may be accompanied by relative losses for certain historically exposed regions; hence, a potentially negative sign. This interpretation is consistent with the idea that the benefits (and geography) of port activity can spread and be reconfigured beyond port regions⁵³.

⁵³The literature highlights both (i) the spatial diffusion of benefits linked to port activity and (ii) the difficulties of identification linked to reverse causality (growth → demand for port services). [Bottasso et al. \(2014\)](#) explicitly discussed these issues and showed that control/fixed effects choices can aim to limit biases related to national cycles and omitted variables. Furthermore, the use of ‘predetermined’ instruments (*e.g.*, pre-industrial port infrastructure) illustrates a similar strategy: the objective is to extract a variation that is exogenous to recent economic activity, while recognising that causality may remain difficult to establish definitively ([Breidenbach and Mitze 2016](#)).

TABLE B.1. First-stage estimates — log-log regressions of total DWT on the excluded instrument with stepwise controls (coastal NUTS-2)

Variable	Model										
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
ln(IV nat tot)	0.650*** (0.140)	0.682*** (0.173)	0.681*** (0.171)	0.404*** (0.146)	0.370** (0.152)	-0.104 (0.168)	-0.117 (0.169)	-0.0831 (0.200)	-2.871*** (0.335)		
L1.ln(IV nat tot)										-0.0877 (0.192)	-2.869*** (0.324)
F excl. IV (robust)	21.56	15.50	15.83	7.67	5.93	0.39	0.48	0.17	73.45	0.21	78.60
Observations	3307	2629	2629	2092	1764	1386	1386	1155	1155	1100	1100
NUTS-2 (clusters)	136	108	108	84	84	66	66	55	55	55	55
Years (in-sample)	25	25	25	25	21	21	21	21	21	20	20
NUTS-2 FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Country×Year FE	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Clusters	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2

Note: First-stage regressions corresponding to the 2SLS specifications in Table 4. Robust standard errors clustered at the NUTS-2 level in parentheses. Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The excluded instrument is $\log_iv_nat_tot$ (or $L1.\log_iv_nat_tot$ in lagged specifications). “F excl. IV (robust)” reports the cluster-robust excluded-instrument F-statistic.

Controls by column — (a) density trend, GDP trend; (b) (a) + accessibility; (c) (b) + education; (d) (c) + industrial GVA trend component (gva_gu_trend); (e) (d) + business/services GVA trend component (gva_be_trend) and gross fixed capital formation trend ($gfcf_trend$); (f) (e) + working-age population (15–64) trend (pop_1564_trend); (g) (f) + total GHG emissions ($ghg_emission_tot$); (h) (g) + institutional quality (eqi_final); (i) same controls as (h) with country×year fixed effects (year FE redundant); (j) lagged first stage for $L1[\ln(DWT\ total)]$ using $L1[\log_iv_nat_tot]$ with NUTS-2 and year FE; (k) same as (j) with country×year fixed effects (year FE redundant).

B.2. Alternative Clustering of Standard Errors

This appendix subsection assesses the sensitivity of our baseline coastal estimates to alternative assumptions about the error structure and the composition of the panel. In maritime systems, unobserved shocks are unlikely to be independent across neighbouring regions: common demand fluctuations, corridor-level disruptions, and port-network reconfigurations can generate spatial correlation in residuals.

Standard clustering at the NUTS-2 level addresses serial correlation within regions but does not, by itself, account for cross-sectional dependence across nearby coastal economies. To relax this assumption, we re-estimate the log-log employment specifications using `acreg` with Conley (spatial HAC) standard errors, allowing residual dependence within 500 km and up to five years (Bartlett kernel).

Because stepwise controls induce non-trivial changes in sample composition, we use a common-sample version that fixes the panel to the intersection defined by the richest specification. The common-sample table is particularly informative for distinguishing genuine covariate sensitivity from mechanical changes driven by missingness. Finally, we also report a specification with country×year fixed effects, which absorbs national shocks and policies common to all regions within a country in a given year.

TABLE B.2. Estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2, total DWT; acreg + Conley), common sample

Variable	Model								
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
ln(Total DWT)	0.0078 (0.0092)	0.0094 (0.0090)	0.0082 (0.0084)	0.0083 (0.0084)	0.0065 (0.0081)	0.0104 (0.0083)	0.0074 (0.0080)	0.0080 (0.0082)	−0.0104* (0.0058)
Obs.	1193	1193	1193	1193	1193	1193	1193	1193	1193
NUTS	57	57	57	57	57	57	57	57	57
Years	21	21	21	21	21	21	21	21	21
NUTS-2 FE	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✗
Country×Year FE	✗	✗	✗	✗	✗	✗	✗	✗	✓
SE (Conley)	✓	✓	✓	✓	✓	✓	✓	✓	✓
DistCutoff / LagCutoff	500 / 5 (Bartlett)								

Note: Common sample imposed by the richest specification (h): *coast_n2* = 1, non-missing lat/lon, and non-missing RHS variables in (h). Spatial HAC (Conley) standard errors in parentheses. Column (i) uses country×year fixed effects (pfe2 (cy_fe)) instead of year fixed effects; NUTS-2 fixed effects are always included. Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Controls by column — (a) density trend, GDP trend; (b) (a) + accessibility; (c) (b) + education; (d) (c) + GU trend; (e) (d) + BE trend and GFCF trend; (f) (e) + working-age population trend; (g) (f) + total GHG emissions; (h) (g) + institutional quality (EQI); (i) same controls as (h) with country×year fixed effects (year FE redundant).

Reading: Once the sample is held fixed, the elasticity of employment to total DWT is small and statistically null across (a)–(h). Under country×year fixed effects (i), the point estimate turns negative and marginally significant, suggesting that identification within countries over time (net of national shocks) yields no robust positive association between port activity and employment in this coastal subsample.

TABLE B.3. First-stage (Conley) estimates — regressions of $\ln(\text{DWT total})$ on the excluded instrument with stepwise controls (coastal NUTS-2)

Variable	Model										
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
$\ln(\text{IV nat tot})$	−0.0704 (0.1287)	−0.0934 (0.1336)	−0.1121 (0.1349)	−0.1178 (0.1342)	−0.1094 (0.1427)	−0.0453 (0.1432)	−0.0699 (0.1417)	−0.0831 (0.1421)	−2.8706*** (0.1878)		
$L1.\ln(\text{IV nat tot})$										−0.0877 (0.1445)	−2.8688*** (0.1861)
Wald χ^2 excl. IV (Conley)	0.30	0.49	0.69	0.77	0.59	0.10	0.24	0.34	233.61	0.37	237.57
Observations	1172	1172	1172	1172	1172	1172	1172	1172	1172	1100	1100
NUTS-2 units	??	??	??	??	??	??	??	??	??	??	??
Years (in-sample)	21	21	21	21	21	21	21	21	21	20	20
NUTS-2 FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Country×Year FE	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓

Note: First-stage regressions estimated with `acreg` using Conley (spatial HAC) standard errors with `distcutoff = 500` and `lagcutoff = 5`. The dependent variable is `Log_tot_dwt`. All specifications include NUTS-2 fixed effects and either year fixed effects (a–h, j) or country×year fixed effects (i, k). The excluded instrument is `Log_iv_nat_tot` (or its lag in j–k). The reported “Wald χ^2 excl. IV” corresponds to the post-estimation test of the excluded instrument under Conley SE.

Controls by column — (a) density trend, GDP trend; (b) (a) + accessibility; (c) (b) + education; (d) (c) + industrial GVA trend component (`gva_gu_trend`); (e) (d) + business/services GVA trend component (`gva_be_trend`) and gross fixed capital formation trend (`gfcf_trend`); (f) (e) + working-age population (15–64) trend (`pop_1564_trend`); (g) (f) + total GHG emissions (`ghg_emission_tot`); (h) (g) + institutional quality (`eqi_final`); (i) same controls as (h) with country×year fixed effects (year FE redundant); (j) same controls as (h) but using `L1[ln(DWT total)]` and `L1[Log_iv_nat_tot]` with NUTS-2 and year FE; (k) same as (j) with country×year fixed effects (year FE redundant).

Reading: Under NUTS-2 and year fixed effects (a–h), the excluded instrument is close to zero and statistically insignificant once Conley corrections are applied (Wald $\chi^2 \approx 0$ –0.8). In contrast, under country×year fixed effects (i, k) the first stage is extremely strong and precisely estimated (Wald $\chi^2 \approx 234$ –238), implying that identification comes from within-country-year cross-sectional variation in exposure to the national instrument.

B.3. Results for Container Shipping

TABLE B.4. Estimates — log-log baseline regressions without controls (container DWT + country-year FE variants)

Model	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	Employment	Employment	Population	Population	Employment	Population
ln(Container DWT)	0.0012 (0.0008)	0.0536*** (0.0151)	−0.0006 (0.0008)	0.0531*** (0.0150)	0.0003 (0.0006)	−0.0007 (0.0005)
Model Setup						
Observations	4,445	4,445	4,433	4,433	4,225	4,213
Time Periods	25	25	25	25	25	25
NUTS-2 FE	✓		✓		✓	✓
NUTS-1 FE		✓		✓		
Time FE	✓	✓	✓	✓		
Country-year FE					✓	✓
Clusters	NUTS-2	NUTS-1	NUTS-2	NUTS-1	NUTS-2	NUTS-2

Notes: Coefficients are reported with robust standard errors clustered at the regional level (in parentheses). Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All models are restricted to coastal NUTS-2 regions ($coast_n2 = 1$). Columns (1)–(4) include regional and year fixed effects (NUTS-2 or NUTS-1, plus year). Columns (5)–(6) replace year fixed effects with country-year fixed effects (cy_fe) and include NUTS-2 fixed effects. The independent variable is the log of container deadweight tonnage ($log_container_dwt$).

TABLE B.5. Estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2, container DWT)

Variable	Model										
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
In(Container DWT)	0.0014* (0.0008)	0.0019* (0.0010)	0.0020** (0.0010)	0.0021* (0.0013)	0.0012 (0.0013)	0.0002 (0.0011)	0.0001 (0.0010)	−0.0004 (0.0010)	−0.0003 (0.0009)	−0.0004 (0.0006)	−0.0004 (0.0006)
L.In(Container DWT)											−0.0000 (0.0010)
NUTS	178	132	132	102	102	79	79	61	61	60	61
Years	25	25	25	25	21	21	21	21	21	21	21
NUTS-2 FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Country×Year FE	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Clusters	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2

Note: Robust standard errors clustered at the NUTS-2 level in parentheses. Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All regressions are restricted to coastal NUTS-2 regions (*coast_n2 = 1*). Accessibility is measured by *potacmmu_projection* from column (b) onward (with the 2000 value set to zero to avoid dropping year 2000 when *potacmmu_projection* starts in 2001).

Controls by column — (a) density trend, GDP trend; (b) (a) + accessibility; (c) (b) + education; (d) (c) + industrial/services GVA share (*gva_gu_trend*); (e) (d) + business/services GVA share (*gva_be_trend*) and gross fixed capital formation (GFCF); (f) (e) + working-age population (15–64) trend; (g) (f) + total GHG emissions; (h) (g) + institutional quality (EQI); (i) (h) + R&D trend (*ln_rd_fte_trend*); (j) same controls as (h) with country×year fixed effects in addition to NUTS-2 fixed effects (year FE redundant); (k) same controls as (h) but using the lagged maritime variable *L1[ln(container DWT)]* with NUTS-2 and year fixed effects; (l) same as (i) but with country×year fixed effects in addition to NUTS-2 fixed effects.

Reading: Container port activity is weakly positive (marginally significant) in intermediate specifications (a–d), but the coefficient collapses toward zero and turns slightly negative once the control set is enriched and the sample contracts (e–i), and it remains statistically null under country×year fixed effects (j, l). The lagged specification (k) does not reveal delayed effects in this setup.

TABLE B.6. Estimates — log-log regressions of employment with stepwise controls (persistent ports, container DWT)

Variable	Model										
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
ln(Container DWT)	0.0019* (0.0010)	0.0022* (0.0012)	0.0023* (0.0012)	0.0021 (0.0013)	0.0016 (0.0012)	0.0006 (0.0012)	0.0004 (0.0012)	−0.0002 (0.0012)	−0.0005 (0.0007)		
L.ln(Container DWT)										0.0001 (0.0013)	−0.0006 (0.0007)
Obs.	3,141	2,540	2,540	2,242	1,890	1,449	1,449	1,092	1,071	1,040	1,020
Clusters (NUTS-2)	128	103	103	90	90	69	69	52	51	52	51
NUTS-2 FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗
Country×Year FE	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓
Clusters	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2

Note: Robust standard errors clustered at the NUTS-2 level in parentheses. Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All regressions are restricted to the persistent-port sample for containers (*port_persist_cont* = 1). Accessibility is measured by *potaccmu_projection* (with the 2000 value set to zero to avoid dropping year 2000 when *potaccmu_projection* starts in 2001).

Controls by column — (a) density trend, GDP trend; (b) (a) + accessibility; (c) (b) + education; (d) (c) + GVA trend (*gva_gu_trend*); (e) (d) + *gva_be_trend* and *gfcf_trend*; (f) (e) + working-age population (15–64) trend; (g) (f) + total GHG emissions; (h) (g) + institutional quality (EQI); (i) same controls as (h) with country×year fixed effects (year FE redundant); (j) same controls as (h) but using the lagged maritime variable $L1[\ln(\text{container DWT})]$ with NUTS-2 and year fixed effects; (k) same as (j) but with country×year fixed effects.

Reading: The container coefficient is weakly positive in parsimonious specifications (a–c), then attenuates to zero as controls become more demanding and the sample shrinks. With country×year fixed effects and in lagged models, estimates are close to zero and statistically indistinguishable from zero.

TABLE B.7. First-stage regressions — instrument relevance for container flows (coastal NUTS-2)

Excluded instrument	Model										
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
ln(IV nat container)	0.4279 (0.2862)	0.5319* (0.3028)	0.5216* (0.3051)	0.3990 (0.3130)	0.2292 (0.3104)	0.0603 (0.3482)	0.0327 (0.3399)	0.1511 (0.3774)	−2.3348*** (0.7881)		
L.ln(IV nat container)										0.2060 (0.3890)	−2.4264*** (0.8528)
K-P rk Wald F (excluded instr.)	2.23	3.09	2.92	1.62	0.55	0.03	0.01	0.16	8.78	0.28	8.09
Observations	3307	2629	2629	2092	1764	1386	1386	1155	1155	1100	1100
NUTS-2 (clusters)	136	108	108	84	84	66	66	55	55	55	55
Years (in-sample)	25	25	25	25	21	21	21	21	21	20	20
NUTS-2 FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗
Country×Year FE	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓

Note: First-stage regressions from `ivreghdfe`. The dependent variable is `ln(Container DWT)` in (a)–(i) and `L1[ln(Container DWT)]` in (j)–(k). Robust standard errors clustered at NUTS-2. Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The reported first-stage strength is the Kleibergen–Paap rk Wald F statistic (cluster-robust).

TABLE B.8. IV (2SLS) estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2), container flows

Variable	Model										
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
ln(Container DWT)	0.1036 (0.0716)	0.0942* (0.0566)	0.1022 (0.0617)	0.1535 (0.1223)	0.2329 (0.3180)	0.6377 (3.6452)	1.1417 (11.7833)	0.2904 (0.7011)	−0.0136*** (0.0043)		
L.ln(Container DWT)										0.2436 (0.4416)	−0.0128*** (0.0039)
K-P rk Wald F (1st stage)	2.23	3.09	2.92	1.62	0.55	0.03	0.01	0.16	8.78	0.28	8.09
Observations	3307	2629	2629	2092	1764	1386	1386	1155	1155	1100	1100
NUTS-2 (clusters)	136	108	108	84	84	66	66	55	55	55	55
Years (in-sample)	25	25	25	25	21	21	21	21	21	20	20
NUTS-2 FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Country×Year FE	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Clusters	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2

Note: 2SLS estimates from `ivreghdfe` on coastal NUTS-2 regions (`coast_n2 = 1`). Robust standard errors clustered at the NUTS-2 level in parentheses. Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The excluded instrument is `log_iv_nat_container` (or `L1.log_iv_nat_container` in lagged specifications). Reported first-stage strength is the Kleibergen-Paap rk Wald F statistic (cluster-robust). Accessibility is measured by `potaccmu_projection` from column (b) onward.

Controls by column — (a) density trend, GDP trend; (b) (a) + accessibility; (c) (b) + education; (d) (c) + industrial GVA trend component (`gva_gu_trend`); (e) (d) + business/services GVA trend component (`gva_be_trend`) and gross fixed capital formation trend (`gfcf_trend`); (f) (e) + working-age population (15–64) trend (`pop_1564_trend`); (g) (f) + total GHG emissions (`ghg_emission_tot`); (h) (g) + institutional quality (`eq1_final`); (i) same controls as (h) with country×year fixed effects (year FE redundant); (j) same controls as (h) but using `L1[ln(Container DWT)]` instrumented by `L1[log_iv_nat_container]` with NUTS-2 and year FE; (k) same as (j) with country×year fixed effects (year FE redundant).

B.4. Results for General Cargo Shipping

TABLE B.9. Estimates — log-log baseline regressions without controls (general cargo DWT + country-year FE variants)

Model	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	Employment	Employment	Population	Population	Employment	Population
ln(General cargo DWT)	−0.0003 (0.0023)	0.0687** (0.0322)	0.0011 (0.0021)	0.0670** (0.0314)	−0.0022 (0.0018)	−0.0016 (0.0015)
Model Setup						
Observations	4,445	4,445	4,433	4,433	4,225	4,213
Time Periods	25	25	25	25	25	25
NUTS-2 FE	✓		✓		✓	✓
NUTS-1 FE		✓		✓		
Time FE	✓	✓	✓	✓		
Country-year FE					✓	✓
Clusters	NUTS-2	NUTS-1	NUTS-2	NUTS-1	NUTS-2	NUTS-2

Notes: Coefficients are reported with robust standard errors clustered at the regional level (in parentheses). Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All models are restricted to coastal NUTS-2 regions (*coast_n2* = 1). Columns (1)–(4) include regional and year fixed effects (NUTS-2 or NUTS-1, plus year). Columns (5)–(6) replace year fixed effects with country-year fixed effects (*cy_fe*) and include NUTS-2 fixed effects. The independent variable is the log of general cargo deadweight tonnage (*log_generalcargo_dwt*).

TABLE B.10. Estimates — log-log regressions of employment with stepwise controls (coastal NUTS-2, general cargo DWT)

Variable	Model										
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
In(General cargo DWT)	0.0007 (0.0027)	0.0022 (0.0023)	0.0023 (0.0023)	0.0028 (0.0036)	0.0028 (0.0040)	-0.0023 (0.0023)	-0.0024 (0.0023)	-0.0036* (0.0018)	-0.0034* (0.0017)	-0.0016 (0.0011)	-0.0015 (0.0011)
L.In(General cargo DWT)											-0.0032* (0.0018)
NUTS	178	132	132	102	102	79	79	61	61	60	60
Years	25	25	25	25	21	21	21	21	21	21	21
NUTS-2 FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Country×Year FE	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Clusters	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2

Note: Robust standard errors clustered at the NUTS-2 level in parentheses. Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All regressions are restricted to coastal NUTS-2 regions (*coast_n2 = 1*). Accessibility is measured by *potacmmu_projection* on from column (b) onward (with the 2000 value set to zero to avoid dropping year 2000 when *potacmmu_projection* starts in 2001).

Controls by column — (a) density trend, GDP trend; (b) (a) + accessibility; (c) (b) + education; (d) (c) + industrial/services GVA share (*gva_gu_trend*); (e) (d) + business/services GVA share (*gva_be_trend*) and gross fixed capital formation (GFCF); (f) (e) + working-age population (15–64) trend; (g) (f) + total GHG emissions; (h) (g) + institutional quality (EQI); (i) (h) + R&D trend (*ln_rd_fte_trend*); (j) same controls as (h) with country×year fixed effects in addition to NUTS-2 fixed effects (year FE redundant); (k) same controls as (h) but using the lagged maritime variable *L1[ln(general cargo DWT)]* with NUTS-2 and year fixed effects; (l) same as (i) but with country×year fixed effects in addition to NUTS-2 fixed effects.

Reading: Unlike containers, the general cargo coefficient turns negative once the specification becomes more demanding and the sample shrinks (f–i), with borderline significance around (h–i). The lagged model (k) suggests a weakly negative delayed association. Under country×year fixed effects (j, l), estimates remain negative but are no longer statistically distinguishable from zero.

TABLE B.11. Estimates — log-log regressions of employment with stepwise controls (persistent ports, general cargo DWT)

Variable	Model										
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
ln(General cargo DWT)	0.0005 (0.0008)	−0.0001 (0.0008)	0.0000 (0.0008)	−0.0004 (0.0008)	0.0010 (0.0008)	0.0002 (0.0006)	0.0002 (0.0006)	0.0001 (0.0008)	0.0001 (0.0007)		
L.ln(General cargo DWT)										−0.0001 (0.0008)	0.0003 (0.0007)
Obs.	4,191	3,368	3,368	2,840	2,394	1,911	1,911	1,407	1,365	1,340	1,300
Clusters (NUTS-2)	171	137	137	114	114	91	91	67	65	67	65
NUTS-2 FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Country×Year FE	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Clusters	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2

Note: Robust standard errors clustered at the NUTS-2 level in parentheses. Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All regressions are restricted to the persistent-port sample for general cargo (*port_persist_gc* = 1). Accessibility is measured by *potaccmu_projection* (with the 2000 value set to zero to avoid dropping year 2000 when *potaccmu_projection* starts in 2001).

Controls by column — (a) density trend, GDP trend; (b) (a) + accessibility; (c) (b) + education; (d) (c) + GVA trend (*gva_gu_trend*); (e) (d) + *gva_be_trend* and *gfcf_trend*; (f) (e) + working-age population (15–64) trend; (g) (f) + total GHG emissions; (h) (g) + institutional quality (EQI); (i) same controls as (h) with country×year fixed effects (year FE redundant); (j) same controls as (h) but using the lagged maritime variable *L1[ln(general cargo DWT)]* with NUTS-2 and year fixed effects; (k) same as (j) but with country×year fixed effects.

Reading: In the persistent-port sample, the general cargo coefficient is consistently close to zero and never statistically distinguishable from zero across stepwise controls, country×year fixed effects, and lag specifications. The most salient changes across columns relate to sample contraction and the behavior of non-maritime controls (notably EQI and macro controls), rather than the maritime variable.

B.5. Port areas

In this section, we include inland regions with a river port. It allows us to consider the impact of ports on regional economic activity with a larger scope. For instance, [Bottasso et al. \(2013, 2014\)](#) focused on coastal ports and their impact on local and neighbouring zones. Covering river ports allow us to go quite far in the hinterland. In the table [B.12](#) we include baseline regression for employment and population, and we controlled for economic, demographic and geographic factors.

TABLE B.12. Estimates — log-log baseline regressions without controls

Model	(1)	(2)	(3)	(4)
Dependent variable	Employment	Employment	Population	Population
ln(DWT Total)	0.0095602 (0.0089982)	0.0494992** (0.0231312)	0.007855 (0.0067079)	0.0498927** (0.0219155)
Model Setup				
Observations	4,066	4,066	4,055	4,055
Time Periods	25	25	25	25
NUTS-2 FE	✓	7	✓	7
NUTS-1 FE	7	✓	7	✓
Time FE	✓	✓	✓	✓
Clusters	NUTS-2	NUTS-1	NUTS-2	NUTS-1

Notes: Coefficients are reported with robust standard errors clustered at the regional level (in parentheses). Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All models include regional and time fixed effects as indicated. The dependent variable is the log of employment (columns b–c) or the log of population (columns d–e). The independent variable is the log of total deadweight tonnage ($\log_tot_dwt$), aggregated at the NUTS-2 regional level. Regressions are restricted to persistent port regions ($port_persist = 1$).

We see that in the case of baseline regression, the logarithm of employment does not reach any level of significance, while population (in log) is significant at the 5% level.

TABLE B.13. Estimates — log-log regressions of employment with stepwise controls (persistent-port NUTS-2)

Variable	Model										
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
ln(DWT Total)	0.0214** (0.00848)	0.0298** (0.01218)	0.0299** (0.01212)	0.0488*** (0.01655)	0.0451*** (0.01484)	0.00845 (0.00985)	0.00546 (0.00946)	0.00801 (0.01179)	−0.0104 (0.00873)		
L.ln(DWT Total)										0.00823 (0.01123)	−0.0108 (0.00853)
NUTS	144	114	114	91	91	72	72	56	55	56	55
Years	25	25	25	25	21	21	21	21	21	20	20
NUTS-2 FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗
Country×Year FE	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓
Clusters	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2	NUTS-2

Note: Robust standard errors clustered at the NUTS-2 level in parentheses. Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All regressions are restricted to persistent-port NUTS-2 regions (*port_persist* = 1). Controls enter as trends unless otherwise stated. Specifications (i) and (k) include country×year fixed effects, so year FE are redundant.

Controls by column — (a) density trend, GDP trend; (b) (a) + accessibility (*potacmu_projection*); (c) (b) + education; (d) (c) + GVA trend (*gva_gu_trend*); (e) (d) + *gva_be_trend* and *gfcf_trend*; (f) (e) + working-age population trend (*pop_1564_trend*); (g) (f) + total GHG emissions; (h) (g) + institutional quality (EQI); (i) same controls as (h) with country×year fixed effects; (j) same controls as (h) but using *L1[ln(DWT total)]* with year FE; (k) same as (j) with country×year fixed effects.

When adding controls (Tab. B.13), the coefficient on $\ln(\text{DWT total})$ remains positive and statistically significant in the more parsimonious specifications (a)-(e), with coefficients ranging from about 0.02 to 0.05. The point estimate increases when additional economic controls are introduced (notably in (d)-(e)), consistent with the idea that omitting local economic dynamics can bias the baseline association between maritime activity and employment.

However, once we condition on broader demographic and structural trends, in particular the working-age population trend and the subsequent blocks (emissions and institutional quality), the estimated elasticity shrinks markedly and loses statistical significance (f)-(h). In the most demanding specifications, where country $\times$ year fixed effects absorb all common national shocks in a given year (i), the coefficient turns small and slightly negative, indicating that the remaining identifying variation is essentially within-country-year reallocation across regions. Using a lagged measure of maritime activity (j)-(k) does not restore statistical significance.

Overall, the stepwise OLS evidence suggests a positive correlation between maritime traffic and employment in simpler specifications, but limited robustness once rich trend controls and country $\times$ year shocks are absorbed, motivating the instrumental-variable strategy introduced next.

B.6. Shipping and Spillovers

Economic activities that are highly concentrated in specific areas such as ports, airports, and plants generally have a structurally broader economic impact than their own area of activity⁵⁴. In our case, we consider that shipping, especially in large ports, could have a significant impact on economic activity outside the port area. Once again, we estimate our baseline and OLS models at the NUTS-2 and NUTS-3 levels. We perform the estimates at each level of spatial disaggregation for two samples: (i) all regions, including maritime traffic for port regions and spillovers for others, and (ii) non-port regions with spillovers only.

If we follow Bottasso et al. (2013, 2014)'s findings, we could expect a significant effect, which would be greater than in coastal regions. Intuitively, this can be explained by the absence of the spatially intensive nature of the port. Indeed, the crowding-out effect of port infrastructure, and even more so of container terminals, can have an effect that counteracts the positive local effects. In regions further away from the port, economic

⁵⁴The general idea is quite simple: this type of infrastructure has a limited location but aims to serve larger areas, whether for the supply of goods, services, or the influx of tourists.

activity can benefit from port development without suffering from the crowding-out effects associated with the space required to develop port terminals.

TABLE B.14. Estimates — log-log regressions of employment on spillovers (no controls)

Model	(1)	(2)	(3)
Dependent variable	Employment	Employment	Employment
ln(Spillovers DWT)	0.0524** (0.0259)	0.0890*** (0.0286)	0.1537*** (0.0461)
Model Setup			
Observations	3,474	3,474	3,474
Time Periods	25	25	25
NUTS-2 FE	✓	✓	✓
Time FE	✓	✓	✓
Clusters	NUTS-2	NUTS-2	NUTS-2
Radius	100 km	300 km	500 km

Notes: Coefficients are reported with robust standard errors clustered at the NUTS-2 level (in parentheses). Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All models include NUTS-2 and time fixed effects. The dependent variable is the log of employment. The independent variable is the log of total DWT spillovers computed within the indicated radius (100, 300, 500 km).

With the Table B.14 we follow a similar strategy as the one presented in section 3.2. We first derive ‘intuition’ from the baseline regression and then introduce some controls. With the baseline regressions, we observe an interesting thing: it seems that the (significant, positive) impact is increasing with distance.

TABLE B.15. Estimates — log-log regressions of employment on spillovers with controls

Model	(1)	(2)	(3)
Dependent variable	Employment	Employment	Employment
ln(Spillovers DWT)	-0.0202 (0.0177)	0.0314 (0.0270)	0.0722* (0.0381)
Model Setup			
Observations	2,598	2,598	2,598
Time Periods	25	25	25
NUTS-2 FE	✓	✓	✓
Time FE	✓	✓	✓
Clusters	NUTS-2	NUTS-2	NUTS-2
Radius	100 km	300 km	500 km

Notes: Coefficients are reported with robust standard errors clustered at the NUTS-2 level (in parentheses). Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All models include NUTS-2 and time fixed effects. Additional controls: population density trend, GDP trend, potential accessibility projection, and education (share of cohort with higher education).

Table B.15 introduces various controls for non-coastal regions to estimate the impact of spillovers on local employment. The coefficient on ln(Spillovers DWT) is not statistically different from zero for the 100 km and 300 km radii, but becomes positive and weakly significant when spillovers are measured within a 500 km radius (column (3)).

The absence of effects at 100-300 km suggests that very local spillovers are limited once common trends and observable socio-economic dynamics are controlled for. The emergence of a positive association at 500 km is consistent with broader network and corridor effects -e.g., employment responses driven by interregional logistics chains, hinterland reallocation, and market access improvements that operate beyond immediate adjacency.

General Conclusion

The four chapters of this thesis address four main questions: How has the literature on maritime networks evolved since the development of ‘complex networks’? How are global maritime networks structured? What is the impact of conflicts on local maritime networks? These questions are at the heart of related but rarely linked fields: quantitative transport geography on the one hand, and urban and regional economics on the other. By establishing a common theme between the different chapters, rooted in a discipline that could be broadly described as ‘maritime studies’, this thesis sought to strengthen and deepen these links, combining a variety of empirical strategies with large databases and deliberately targeted issues.

A common thread: measuring, describing and identifying in maritime systems

The first point linking all the chapters together relates to the very subject of the thesis: maritime transport is a spatial system connecting nodes (ports) via links (maritime routes) and producing hierarchical structures, dependencies and propagation effects. This systemic dimension, which is both multi-level (port, region, country) and dynamic, justifies the focus on both network analysis and spatial and regional economics. Thus, the dynamics of maritime agglomeration and hierarchy cannot be completely disconnected from issues of market access and hinterland formation. The second general point linking the chapters concerns the articulation between three complementary empirical objectives. The first is to measure maritime transport and construct the associated statistical objects: static and dynamic maritime networks, connectivity indicators, panels, and multilevel aggregation of port activity. The second empirical objective is to describe the structures and dynamics of maritime transport: changes in the hierarchy and structure of global networks, the impact of conflicts, and the transformation of regional coastal economies. Finally, the third empirical objective, which is the subject of the last chapter, focuses on identifying the causal impacts of maritime transport on regional economic development. In each case, we also discuss the methodological and conceptual limitations of our approaches and suggest some avenues for future research.

Main contributions of the four chapters

Chapter 1 - structuring a fragmented field. In the first chapter, we developed a conceptual and empirical framework for conducting a critical and comprehensive literature review of the field of “maritime networks”. This literature review highlights two main periods: the “pioneering” era and the “revolution” of complex systems. The first period has its origins in quantitative geography, which, recognising the network structure of maritime flows at the micro level, applied empirical measurements and a conceptual framework inspired by graph theory. These contributions remained rare and received limited attention when they were published. The late 1990s marked a significant break in the quantitative treatment of complex systems: increased computing power, theoretical advances and the availability of large-scale data made it possible to address problems that had previously been relatively absent from the literature. The structure and dynamics of transport networks were among the main beneficiaries of these technical and theoretical advances. As Ducruet (2020) points out, compared to air and rail networks, maritime networks remained relatively unexplored during the first decade of the 2000s. This is mainly due to the difficulty researchers encountered in building large databases covering several periods.

The widespread use of AIS data and the development of other sources ² enabled researchers specialising in maritime transport to apply network analysis methods to ship flows from the late 2000s and early 2010s.

In this chapter, we have chosen to limit our quantitative analysis to articles using methods derived from complex network analysis. Our corpus begins in 2007 and ends in February 2025, comprising 328 articles published in generalist journals on transport, geography and economics, as well as in the main journals in the field of maritime studies. For the sake of conceptual consistency, we have excluded some publications strictly related to operational research when they focus mainly on optimising operations and programming without any perspective on network structuring or multi-scale interdependencies.

This mapping highlights not only the quantitative expansion of the field, but also its fragmentation: disciplinary communities (geography, applied economics, statistical physics, transport studies) still cite each other relatively little, which limits the dissem-

²In this thesis, we constructed our panels, static and dynamic networks, from raw ship movement data provided by *Lloyd's List*; the data sources are divided into two periods: 1880–1977, with digitised data covering limited periods for each year, and 1977 – 2024, with digital data covering a larger part of each year, as well as a larger set of ports and goods.

ination of tools and results. Using structural topic modelling and co-author network analysis, we also show how the field has evolved over time, with one major development: the emergence of studies on the vulnerability and resilience of maritime networks since COVID-19. This emergence of a new subfield focuses not only on pandemics, but also on the risks associated with climate change, social tensions, armed conflicts, and their political and economic consequences.

Chapter 2 - fifty years of containerisation: global dynamics, dependencies, changing hierarchies. The second chapter continues the general discussion on maritime trade, offering a study of global containerised flows from 1977 to 2024. The possibility of beginning the analysis in the 1970s is particularly relevant: this was the period when the use of containers in freight transport gradually became widespread. In other words, we cover almost the entire history of international containerised trade and can document in detail the formation of port hierarchies, the evolution of connectivity structures, and the rise of network architectures associated with hub emergence and major intercontinental routes.

By exploiting millions of ship movements between several thousand ports over the period, we aim for a form of exhaustiveness and can study the evolution of hierarchies through the gradual emergence of new competitors in port systems. The use of big data poses several methodological and conceptual challenges. Based on the reconstruction of networks using two specific topologies³ we attempt to trace the geography of containerised trade over a long period and its links with the political and economic transformations and shocks of recent decades.

In this chapter, we adopted a dual quantitative approach: the first was global, based on metrics derived from the study of complex systems, and the second was “micro”, allowing us to study hierarchies and changes in the system’s centres of gravity. At the “global” level, we studied the temporal evolution of the global containerised system using metrics applied to the entire network. We thus highlighted major structural changes: globalisation of the containerised system, development of the hub-and-spoke system, and increased vulnerability to crises. At the local level, the single linkage analysis (SLA) approach allows us to visualise (i) the emergence of Asia, and mainly China, (ii)

³The space-P topology connects two ports if they are connected by the same containerised line (see Fig. (ref)). This topological approach, rarely used in the literature, makes it possible to reconstruct much more realistic connectivity in the case of containers, as these ships follow specific routes. The second, known as “single linkage analysis”, summarises the links between a port and its main link, promoting the emergence of hierarchies and allowing for a more detailed study of hubs.

the spatialisation of maritime hubs, (iii) the permanence of European containerised networks around Rotterdam, and (iv) the growth of African networks, which are closely linked to Chinese ports.

By explicitly discussing the transition from ship movements to links, then to interpretable network indicators, we propose a framework for linking robust stylised facts to broader economic questions about globalisation, trade concentration and the role of logistics hubs. This article thus enables us to study one of the major revolutions in modern trade, the introduction of the container, and its links with transformations in global geo-economic hierarchies.

Chapter 3 - conflicts, disruption, resilience (Ukraine, 2010 - 2024). The last two chapters transition to ‘localised’ issues. In the third chapter, we study the impact of Russia’s invasion of Ukraine on maritime trade in Ukrainian ports. The article quantifies, models and visualises the transformations in the system using a three-pronged strategy: network models, bilateral trade analyses and route simulation. The results highlight three dynamic processes: (i) a significant short-term impact, (ii) disruption affecting certain connections in particular, especially long-distance ones, and (iii) a form of network resilience through reallocation to other routes and modes of transport.

Beyond the Ukrainian case, this chapter highlights an essential property of contemporary maritime networks: they are adaptive systems, capable of redirecting part of the flows, but at the cost of logistical costs, increased dependence on certain hubs, and marked distributional effects. In other words, the ‘resilience’ observed at the aggregate level does not imply territorial neutrality or the absence of losses, and refers to concrete trade-offs between redundancy, concentration, and route security.

Finally, analysis of the Ukrainian case sheds light on how a geopolitical shock simultaneously reconfigures the geography of trade and the hierarchy of logistics hubs: the conflict acts as a catalyst for revealing pre-existing dependencies and accelerating reallocations that would have been slower under normal circumstances. The chapter thus highlights that the vulnerability of a national port system is not limited to its port capacity or its aggregate trade integration, but depends on network properties: concentration of links, redundancy, dependence on crossing points, and capacity to reconfigure. This interpretation brings discussions on supply chain resilience closer to network geography approaches and provides a useful framework for analysing other episodes of major disruptions affecting maritime trade.

Chapter 4: Maritime activity, European networks, and regional development. Finally, the fourth chapter explicitly places maritime transport and port activity within a central issue for the regional economy: how do flows and port infrastructure shape local development trajectories? Using a novel panel that links maritime/port activity to regional economic outcomes, the chapter quantifies the impact of maritime activity on regional labour markets while explicitly addressing the endogeneity of both flows and infrastructure.

The main contribution lies in the articulation between a detailed measurement of maritime activity and identification strategies adapted to spatial panel data (fixed effects, rich controls, and extensive robustness checks), making it possible to move beyond the classic opposition between the port as a ‘driver’ of development and the port as a ‘symptom’ of an already favourable regional dynamic. To tackle endogeneity more directly, we propose an instrumental-variable strategy grounded in historical maritime geography and recent approaches in the infrastructure-and-trade literature. We reconstruct regional maritime activity in Europe at the end of the nineteenth century, and interact this predetermined exposure with an exogenous, time-varying national component of maritime growth. Using a leave-one-out construction to purge mechanical correlation, this yields a dynamic instrument for contemporary regional port activity that varies over time while remaining anchored in historical port prominence.

The empirical results suggest that maritime flows are an economically significant determinant of regional labour-market dynamics, but that the magnitude of the effect depends on structural conditions (hinterlands, density, productive structure) and may be accompanied by local externalities that call for nuanced interpretations in terms of welfare and policy trade-offs.

The findings in this chapter, which generally point to difficulties in identifying a clearly positive effect, are consistent with previous findings using similar methods. They also point the way towards new research avenues, in particular by integrating causal estimation and regional integration via spillovers into a single research framework. Finally, in the European case, it could be useful to estimate these impacts at different levels of spatial disaggregation.

Articulating interdisciplinarity: contributions and perspectives within the MAGNET-ICS project

On a general level, the primary aim of this thesis was to provide a methodological and theoretical synthesis of the fields of quantitative economic geography and economics

applied to maritime transport. The second aim, limited to a few specific issues, was to contribute to methodological progress, to propose answers to key questions in the field, and to suggest new avenues for research.

A major difficulty, documented throughout the thesis, is the fragmentation of scientific production on maritime transport. Quantitative studies are spread across several fields – quantitative geography, operational research, applied economics, statistical physics, transport studies – which cite each other relatively little and, as a result, benefit marginally from methodological advances in neighbouring fields. This segmentation results in differences in language, evaluation criteria and sometimes empirical objects (data, definitions of flows, choice of scale), which limit the cumulativeness of results. One of the cross-disciplinary contributions of the thesis is therefore to clarify these links: to specify what network analysis tools bring to regional economic issues, and conversely what the requirements of identification and economic interpretation impose on the choice of network measurement and modelling.

This thesis offers a more general reflection on the place of maritime transport in global economic systems and regional governance. By combining different quantitative strategies with large databases and relatively narrow issues, The limitations of this work are part of the same tension between transdisciplinary ambition and empirical constraints. A first set of limitations concerns measurement: definition of flows and links, data granularity, spatial and temporal coverage, and choice of multilevel aggregation (port-region-country). A second set of limitations concerns identification: despite the use of fixed effects, rich controls and instrumental strategies, several channels may coexist (productive specialisation, regional policies, urban dynamics), and certain dimensions - in particular environmental externalities and fine distributional effects - call for dedicated developments. These limitations do not reduce the scope of the results; they clarify the conditions for interpretation and define a set of natural extensions.

Finally, the work proposed in this thesis aims to continue the scientific discussion initiated within the MAGNETICS project and to open up new avenues of research. For interdisciplinarity to be more than just a slogan with no concrete future, it must be integrated into a research programme with specific objectives. The use of network analysis methods⁴, language analysis and applied econometrics are all part of the same research programme and are based on a set of empirical observations and theoretical discussions. In this context, the interactions between maritime activities and coastal

⁴Here we broadly group together the calculation of metrics derived from graph theory, random network simulation, the construction of maritime flows using GIS and route simulation, clustering methods and the selection of relevant links.

development, and between coastal development and regional integration, can benefit from further exploration of this interdisciplinarity. Finally, we wish to continue our work on estimating the local causal impact of port activity and develop new approaches that will complement the results of the last chapter.

