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Shipping trade and geopolitical turmoil
The case of the Ukrainian Maritime network

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A R T I C L E I N F O

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A B S T R A C T

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.

0. Introduction

In the last decades or so, scientific research on ports and shipping has, dominantly 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 et al. (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 et al., 2017).

Studies on military events such as wars remain, in comparison, very few.[23] 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

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[23] One can see Walker (1989) for an early study.

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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 war between Ukraine and Russia, which is still ongoing at the time of writing. The study period starts in 2010, before 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 et al. (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 et al., 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 Bosporus 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, privatisation, and the attraction of foreign investment, particularly in agriculture, energy, and telecommunications (Aidis, 2003; Berkowitz and DeJong, 2005; Brown et al., 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 Yanukovych 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 et al., 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.

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 Russia.[24] This

[24] As 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.

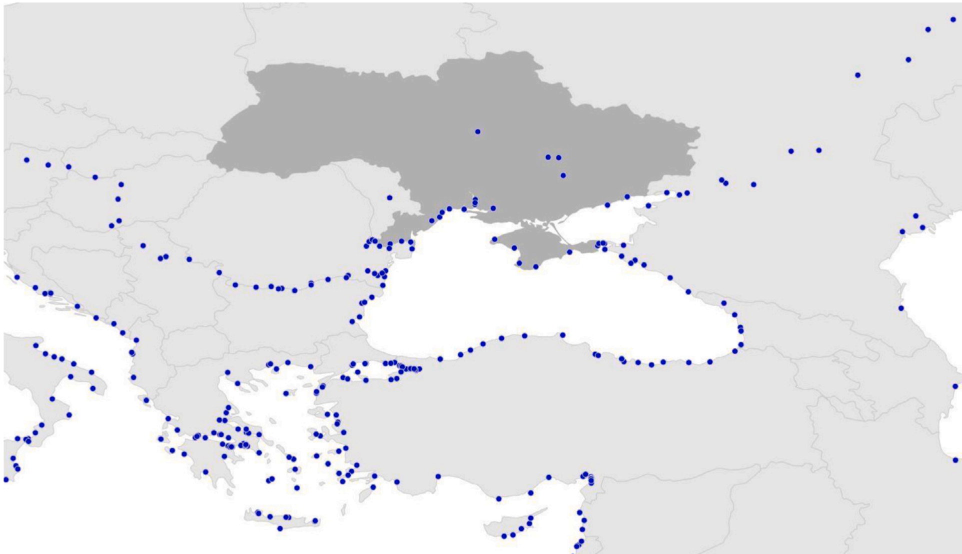

Fig. 1. Ports in the Black Sea.
Notes: All the ports identified in the *Lloyd's List* database are plotted in this map. After 2014 the Crimean ports are considered as Russian by *Lloyd's*. It does not affect a lot the commercial flows considering that they mainly have military purposes. We also represent the river ports and the ports of the Marmara Sea and Eastern Mediterranean.

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 militarisation 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 et al., 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 infrastructure — 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 recognising 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 et al., 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 fertiliser exports (Quénelle 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., 2018a).[25]

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 2024.[26] 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 et al., 2020; Wan et al., 2020; March et al., 2021; Jin et al., 2021; Dirzka and Acciaro, 2022; Ferrari et al., 2022; Guerrero et al., 2022; Kanrak et al., 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 et al., 2012; Ducruet, 2016; Viljoen and Joubert, 2016; Calatayud et al., 2017; Achurra-Gonzalez et al., 2019a; Wu et al., 2019; Xie, 2019; Xu et al., 2022).

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 et al., 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 et al., 2023). Quantitative assessments are specialised on a single commodity such as liquid gas (Xiao et al., 2024a; Zhang et al., 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).[27] Traffic

[25] It 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.

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

[27] For additional information on the Lloyd's List, one can refer to Ducruet and Zaidi (2012), Ducruet et al. (2018, 2024) among others.

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 et al. (2020)	Multiplex network	Container	Flow-based model	World
Bai et al. (2023)	Resilience assessment	Container	Clique percolation, network disintegration, knock-on simulation model	World
Calatayud et al. (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 et al. (2021)	Resilience	Total	Optimal resilience model	World
Earnest et al. (2012)	Contagion	Intermodal	Attack simulation	Transpacific
Fang et al. (2018)	War, sanctions, elections	Container, tanker, bulk	Spatiotemporal modelling	Asia
Ferrari et al. (2022)	Covid-19	Container	Customs data	Europe
Guerrero et al. (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
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 et al. (2020)	Covid-19	Cruise	Carrier schedules	World
Liu et al. (2018a)	Multi-centrality	robustness models	Container (Maersk)	Europe-Asia
Laxe et al. (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 et al. (2012)	Emergent routes	Container & general cargo	Graph theory	World
Mou et al. (2020)	Resilience	Oil	Complex networks	Maritime Silk Road
Pan et al. (2022)	Covid-19	Container	Graph theory, gravity model	World
Pan et al. (2021)	Bottlenecks	Container	Recursive spectral bi-partitioning	Maritime Silk Road
Poo et al. (2024)	Climate extremes	Container	Regional vulnerability index	World
Poo and Yang (2024)	Climate vulnerability	Container	Composite centrality	World
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 et al. (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
Xiao et al. (2024b)	Ukraine war	LNG	Attack simulation	World
Xu et al. (2024a)	Cascading failure	Container	Motter-Lai overload model	World
Xu et al. (2024b)	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. (2024c)	Cyclones	Container	Path-dependency	North Pacific
Yang and Liu (2022)	Resilience	Container	Transmissibility and diversity	Maritime Silk Road

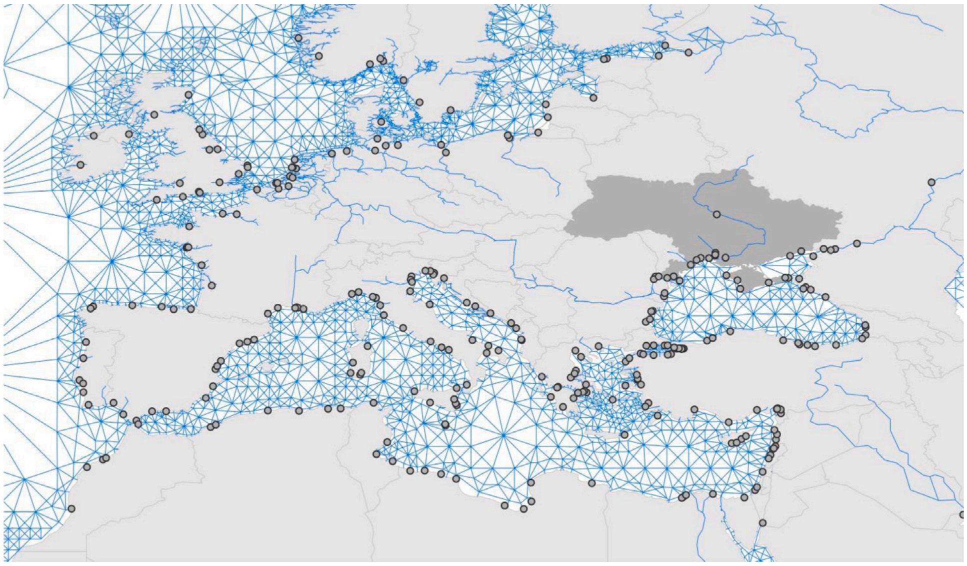

Fig. 2. The grid mapping vessel routes in the ocean.

is differentiated amongst main cargo types, of which we retain bulk (solid and liquid) and containers,[28] between 2010 and 2024.[29]

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 situation.[30] 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 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 used,[31] which provides bilateral trade statistics between states based on UN 'COMTRADE' databases[32] (World Trade Organization, 2024).

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.

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).

Once we settled the mesh with nodes and edges (Fig. 4), it was possible to add centrality measures, determined by colour.[33] The size of the ports was determined by the tonnage as well as that of one of the flows (Fig. 5).

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.

[28] For some analyses, we also included general cargo and passengers/vehicles.

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

[30] Additional details on the method are provided in Section 4.1 and Appendix D.

[31] The 'TreeMap Tool' can be accessed at the following link: click here.

[32] The 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.

[33] This analysis is performed in Section 4.3.

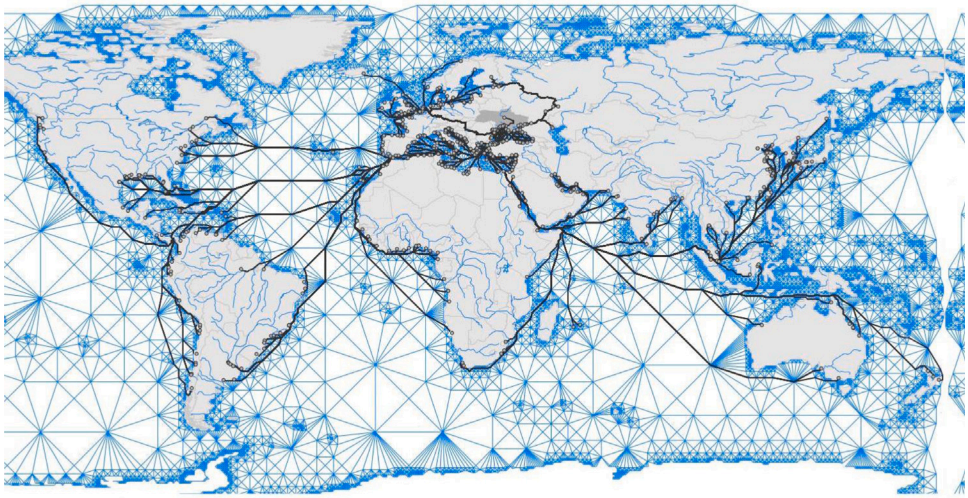

Fig. 3. Global Ukrainian maritime flows following the grid.

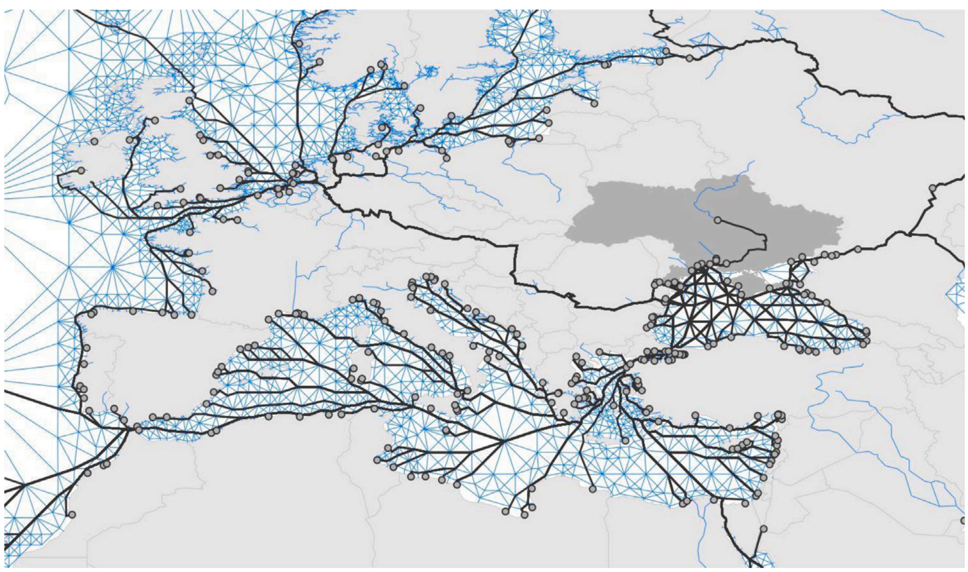

Fig. 4. Ukrainian maritime connections in Europe and the Mediterranean.

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 2). The results show a clear effect — disappearance or change of linkages — of the armed confrontation from 2014 until nowadays over Ukrainian trade (Fig. 6).

In Fig. 6, we have calculated the sum of the edges (*i.e.* the 'size'[34] of the network), for each network, from 2010 to 2024.[35] 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

[34] 'Size' typically refers to the scale or magnitude of the network, often measured by the number of 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.

[35] Considering 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 et al., 2020).

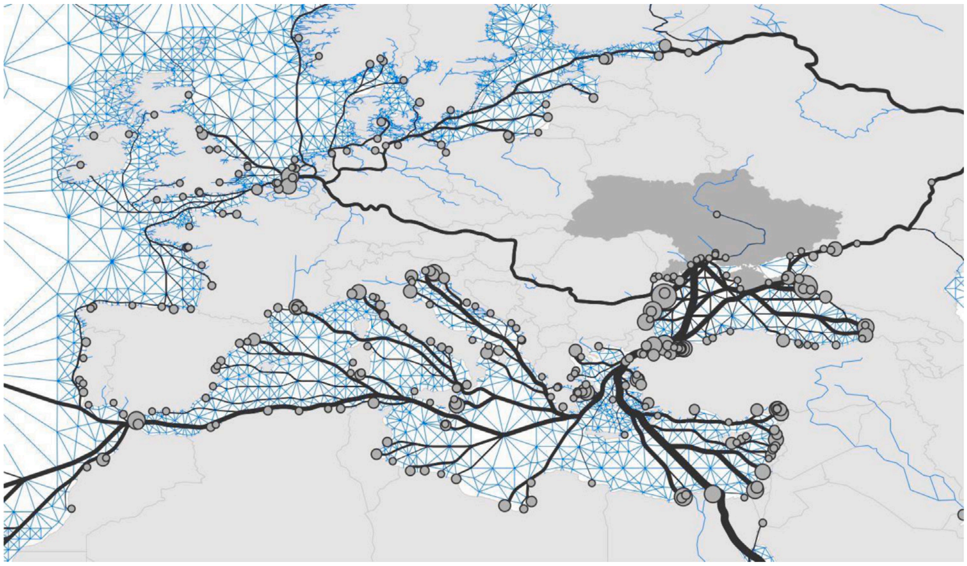

Fig. 5. Ukrainian maritime connections weighting ports by tonnage.

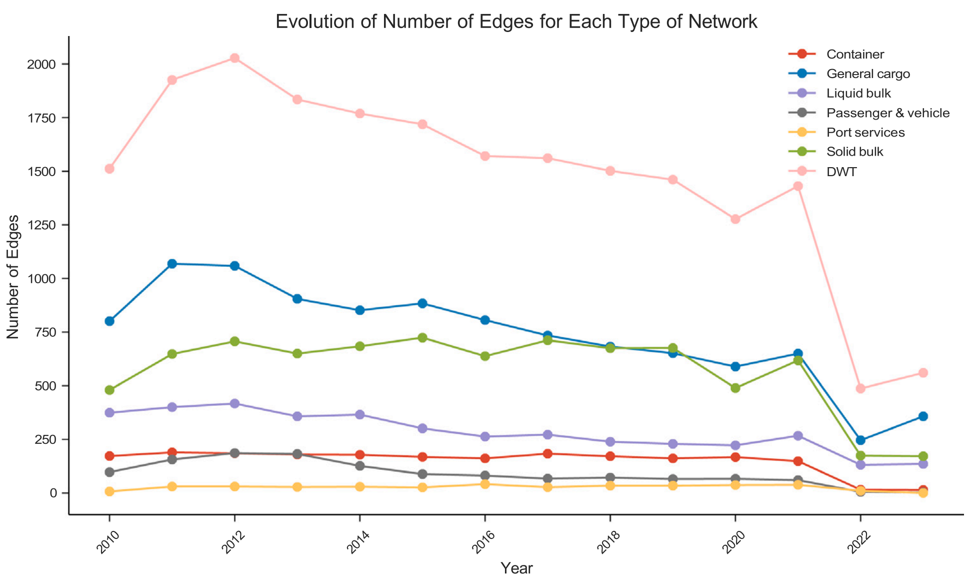

Fig. 6. Evolution of the network for each type of vessel.
Notes: We computed the size of the network (*i.e.* the number of edges) for each type of goods (Container, liquid bulk, etc.) and the total network, *i.e.* taking into account all types of vessels.

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 capacities.[36]

If we focus on the total network, *i.e.* including all the ships, we obtain Fig. 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.

Building on this general overview, we can investigate in more detail the changes in the structure of the Ukrainian maritime network[37] based on a series of network metrics. In Fig. E.5 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 organisation of maritime trade (Ganapati et al., 2021; Do et al., 2024). The average degree[38] (*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 triangles[39] in the network (see Fig. 8).

[36] It 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.

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

[38] For 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.* $\bar{d} = \frac{1}{|V|}\sum_{i \in V} d_i$.

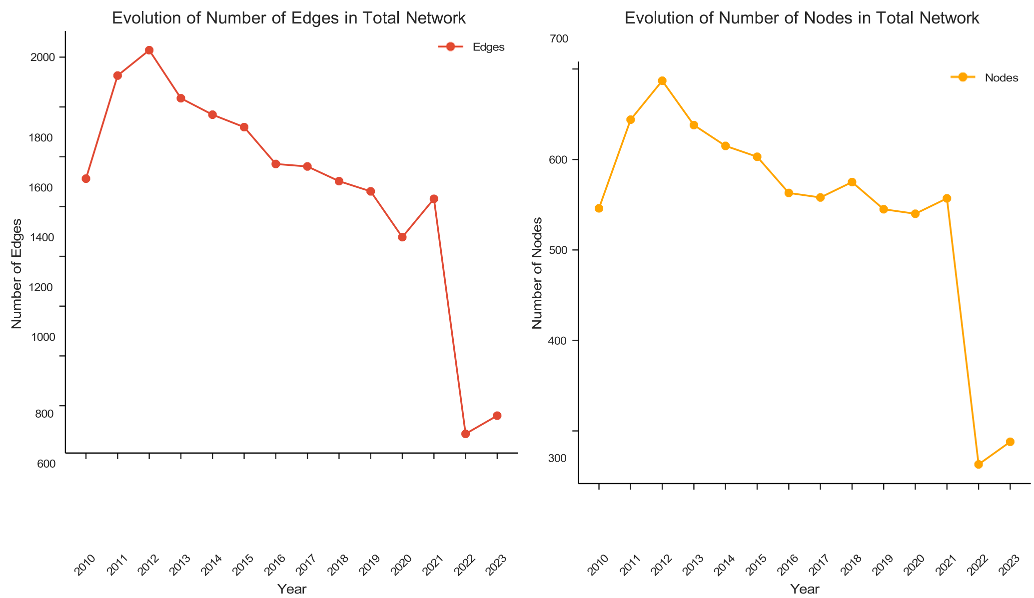

Fig. 7. Number of edges and vertices in the global Ukrainian network, starting in 2010.
Notes: For each year, we computed the sum of the total number of edges (connections between ports) and vertices (ports) for all types of vessels. It allows us to emphasise the shock of 2022, but also the downward that ended in 2012. We also observe the slow recovery in active ports and connections in 2023 and 2024.

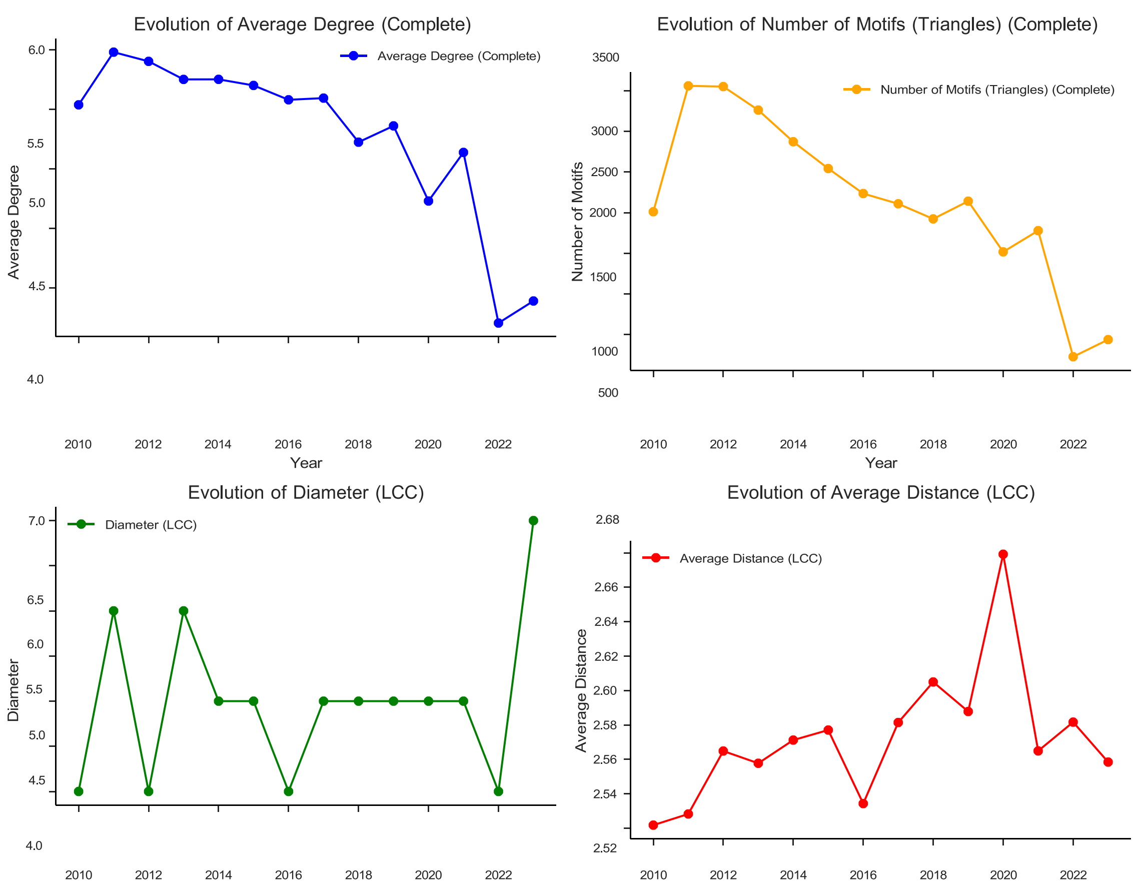

Fig. 8. Evolution of the network metrics for all the vessels.
Notes: We computed the size of the network (*i.e.* the number of edges) for each type of goods (Container, liquid bulk, etc.) and the 'full network'. The downward trend is strongly accentuated in 2022, with a minimal recovery in 2023 and 2024. 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.

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.

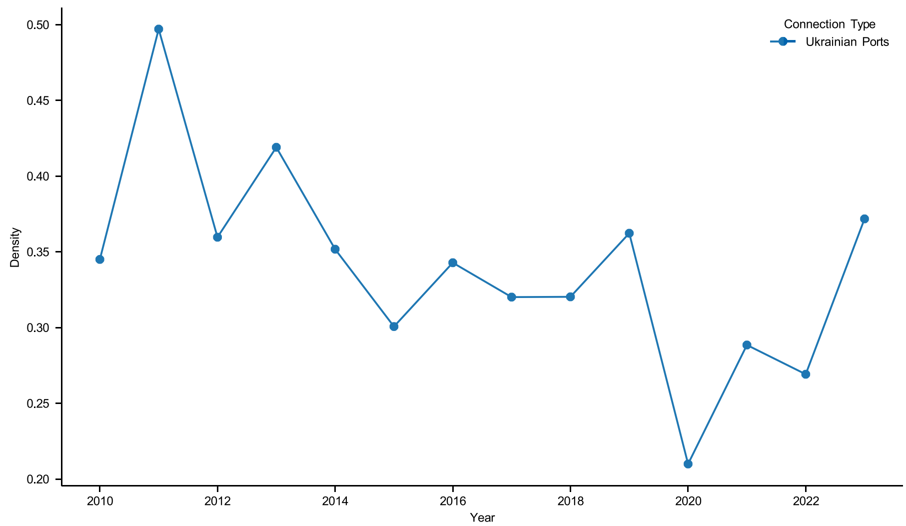

Fig. 9. Density in the Ukrainian network.
Notes: We computed the evolution of the density in the network composed only of Ukrainian ports. The ‘density’ is computed as $\frac{m}{\frac{n(n-1)}{2}}$ where m is the number of edges and n the number of vertices. $\frac{n(n-1)}{2}$ corresponds to the number of possible edges in an undirected network.

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 Table 2, the evolution of the diameter and the average distance seems difficult to link with the invasion of Ukraine.

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).

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 reorganised, 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 analysis.[40]

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

[39] A ‘triangle’ in a network is a motif defined by the connection between vertices i and j, j and k 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.

[40] If we were to consider a ‘space-P’ type of network (Hu and Zhu, 2009; Ducruet et al., 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.

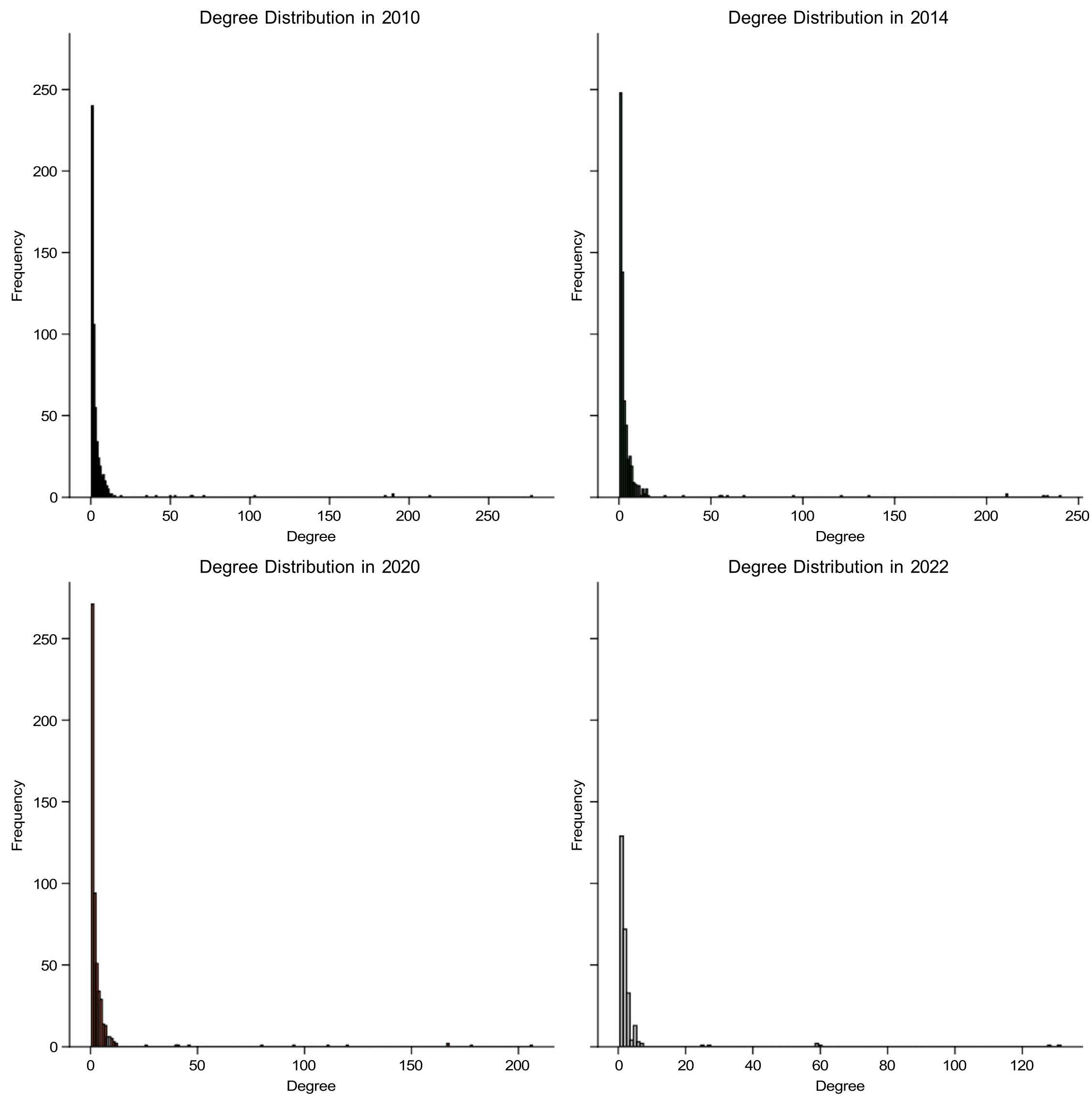

Fig. 10. Degree distribution for the Total Network. *Notes:* We computed the 2010, 2014, 2020 and 2022 degree distribution.

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 Ukraine.[41] 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.

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 Fig. 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 Sea.[42]

[41] For an in-depth analysis of the global geography of trade links, please check the Section 4.3.

[42] Check 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 Fig. 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

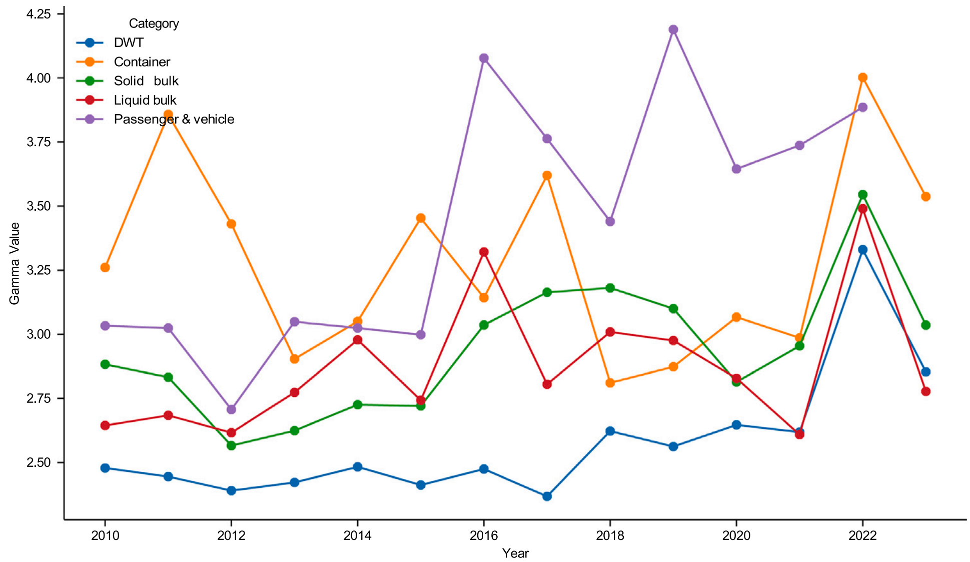

Fig. 11. Evolution of the γ parameter for each type of vessel, 2010 – 2023.
Notes: We fitted a power-law to each distribution for each year and then extracted the γ value. To determine the best minimal value for power law fit.[23] It allows us to avoid misfitting since power-law behaviour often does not extend to the entire range of degrees, especially at the lower end.

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-law. We can write it in the following terms:

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

In Eq. (1) $P(k)$ is the fraction of vertices having k connections with other vertices in the network and C is a constant.[43] A network is considered as 'scale-free' when the exponent γ ranges between 2 and 3.[44] 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 et al., 2018; Liu et al., 2018b), 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.

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 hierarchy.[24] 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',[25] originally proposed by Milgram (1967) and de Sola Pool 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 et al., 2006; Humphries and Gurney, 2008; Telesford et al., 2011). The σ coefficient can be written in the following way:

$$\sigma_{\mathcal{G}} = \frac{\frac{C}{C_r}}{\frac{L}{L_r}} \tag{2}$$

Where 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 network.[26]

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 follow[27]:

$$C_i = \begin{cases} \frac{\lambda_i}{\tau_i} & \text{if} \quad d_i \geq 2 \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

distribution disappeared in 2022, with a flat distribution of degree on low values.

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

[44] In 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.

[23] We use the `powerlaw.Fit` from the `powerlaw` Python's package.

[24] Additional results on the evolution of network hierarchy based on the power-law approach are provided in Appendix F.

[25] Additional details on the theoretical and statistical properties of the 'small-world' networks can be found in Watts (1999) and Albert and Barabási (2002).

[26] To randomise each network we used the (Maslov and Sneppen, 2002) method.

[27] For mathematical details please check Appendix D.2.

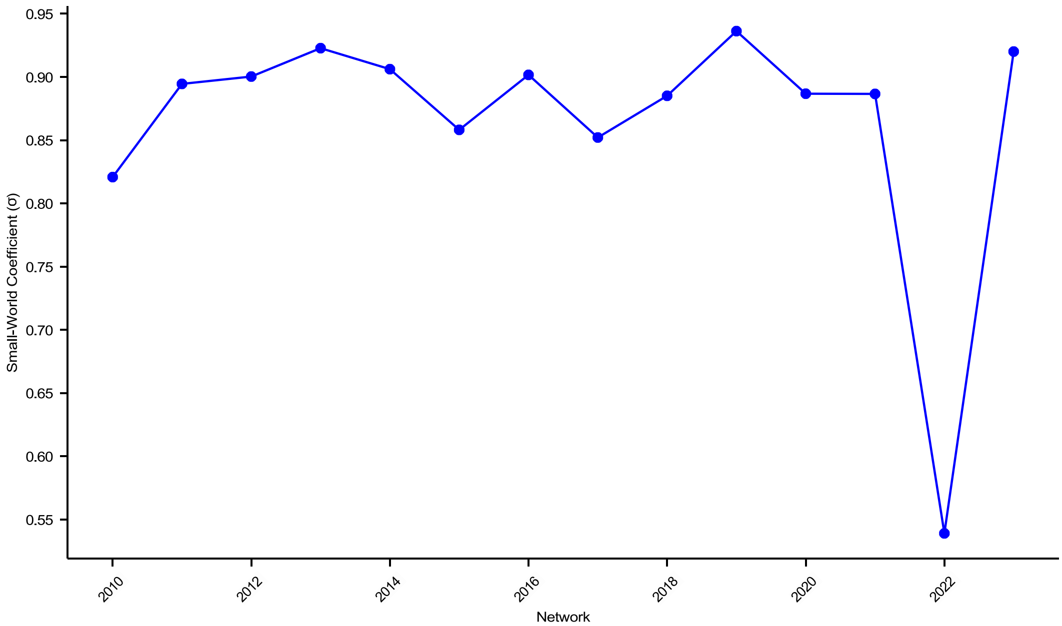

Fig. 12. Evolution of the σ coefficient of the Ukrainian Network,2010–2023.
Notes: We computed the σ coefficient, as expressed in Eq. (2) for the total network of Ukrainian ports from 2010 to 2024. When the total network was not connected, we used the largest connected component, usually accounting for — almost — all nodes.

At the network level we thus have:

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

In (4), $V' = \{i \in V : d_i \geq 2\}$ is the subset of vertices such that $C_i > 0$. 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 graph.[28]

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.

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.[29]

We thus use the omega coefficient[30] which can be expressed as follows:

$$\omega_{\mathcal{G}} = \frac{L_r}{L} - \frac{C}{C_{\ell}} \tag{5}$$

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 (Telesford et al., 2011).[31] (See Fig. 13).

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 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

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

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

[30] L, L_r and C are equivalent to the (2) ones, C_{ℓ} 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).

[31] As 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 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.

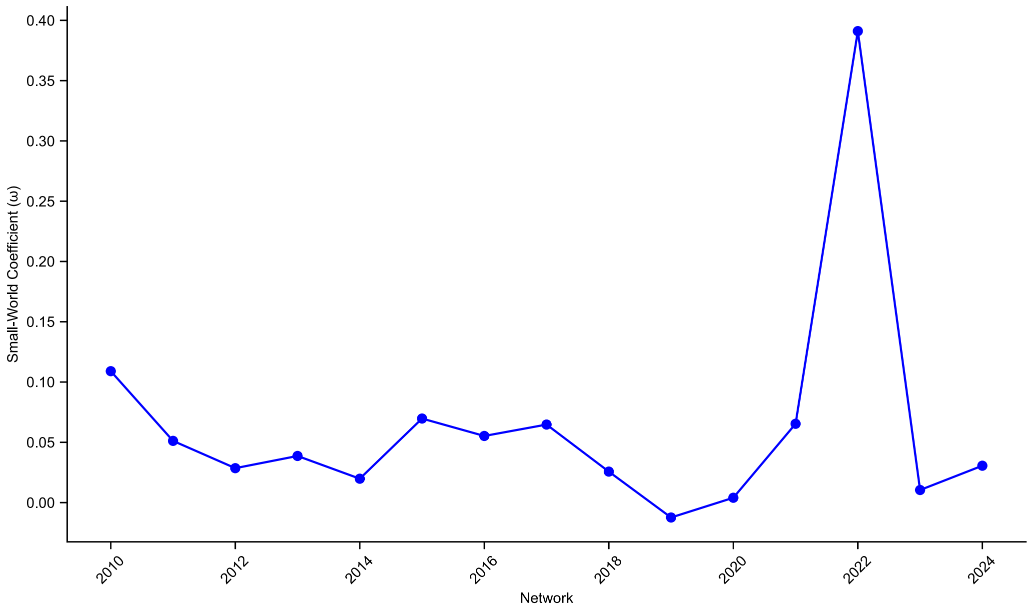

Fig. 13. Evolution of the ω coefficient of the Ukrainian Network, 2010–2024.
Notes: We computed the ω coefficient, as expressed in Eq. (5) for the total network of Ukrainian ports from 2010 to 2024. When the total network was not connected, we used the largest connected component, usually accounting for — almost — all nodes.

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*.

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 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 Fig. 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.

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 logistics.[32] 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 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

[32] Volume 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.

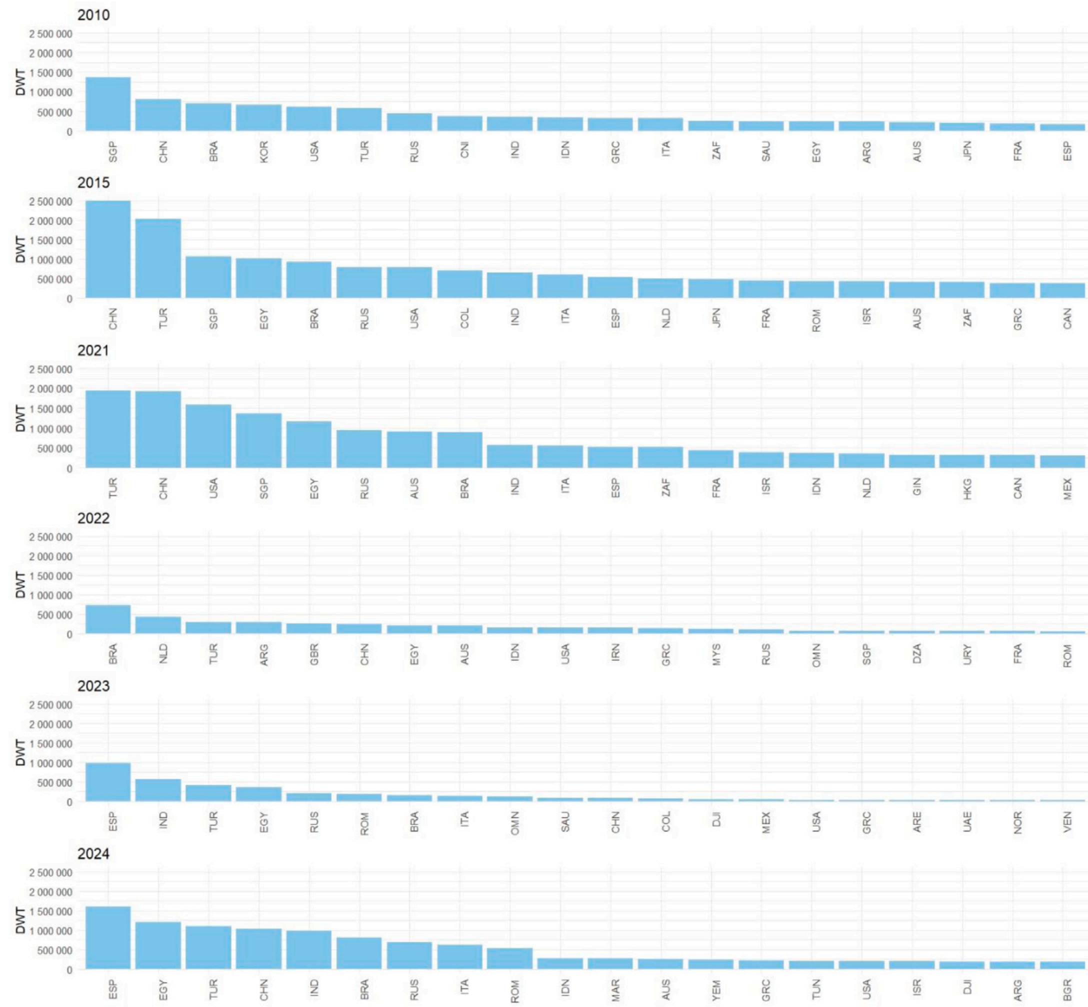

Fig. 14. Evolution of total cargo capacity (DWT) of dry bulk ships moving to foreign countries (first 20 countries).
Notes: We summed the volumes of ships in DWT departing from Ukrainian ports and arriving in Ukrainian ports from a foreign country. This figure takes into account dry bulk ships only.

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 (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.

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

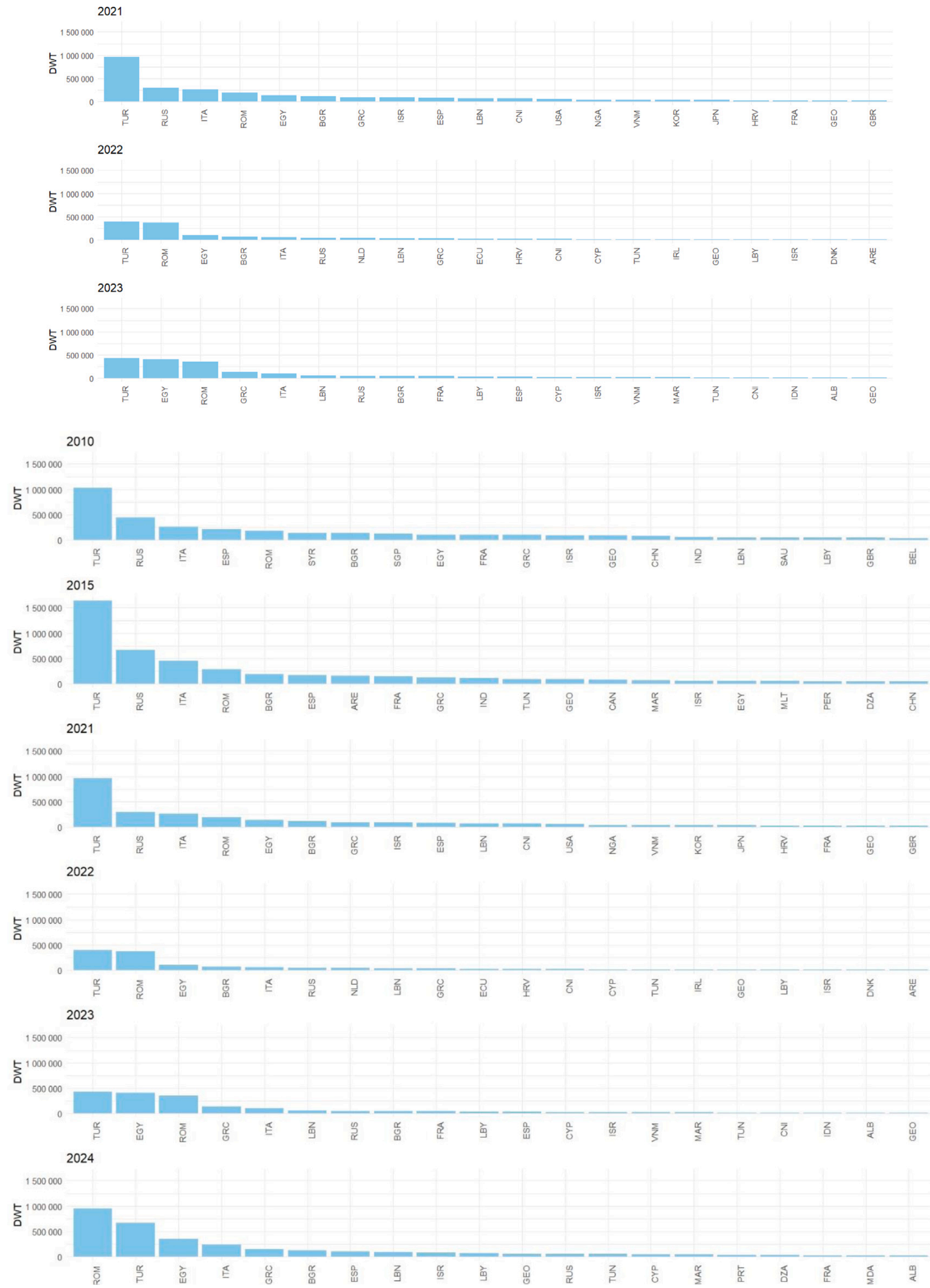

Fig. 15. Evolution of total cargo capacity (DWT) of general cargo ships moving to foreign countries. (First 20 countries).
Notes: We summed the volumes of ships in DWT leaving from Ukrainian ports and arriving in Ukrainian ports from a foreign country. This figure considers general cargo ships only.

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 volumes[33] 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 ports.[34]

4.3. Evolution of international flows at port level

Regarding the network at the port level, from 2015, the value of total DWT (Fig. G.12) 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 Ukraine,[35] 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 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 Fig. G.13). 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, Eregli 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 Eregli 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 Ukraine.[36]

With the start of the global invasion, maritime trade via the Black Sea encountered significant disruptions (Fig. H.14). 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,

[33] For additional details on liquid bulk, please check Fig. G.13 in Appendix G.

[34] For additional details on container transport, please check Fig. G.12 in Appendix G.

[35] Considering that the global Russo-Ukrainian war started in 2022.

[36] Please check Fig. G.12 in appendix.

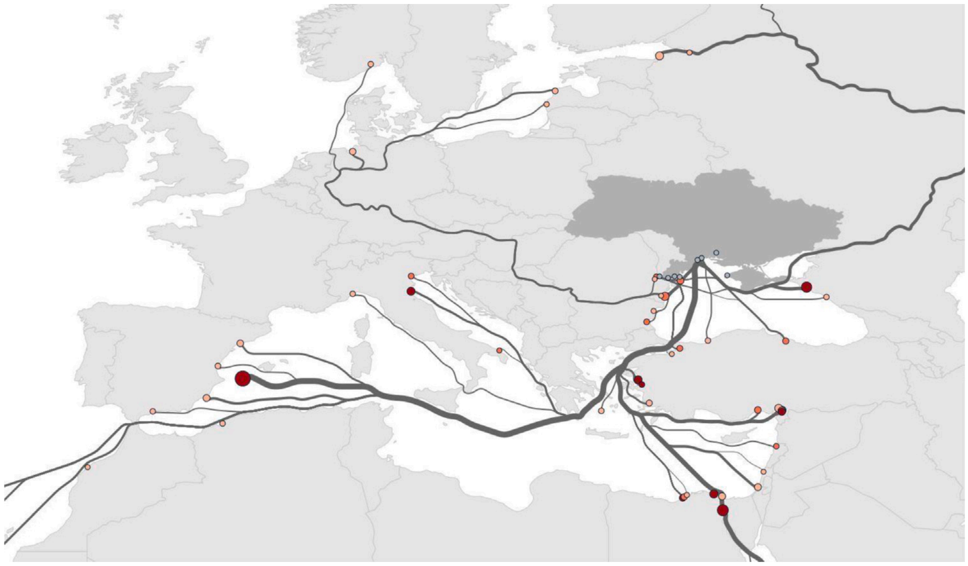

Fig. 16. Solid trade in 2022.

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 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. H.15). Concurrently, Ukraine facilitated the import of vital commodities such as fuel, while ensuring the unimpeded flow of military and humanitarian aid (See Fig. H.16). However, container trade has almost disappeared (Fig. H.17), probably due to the shift mentioned by Gruchevska et al. (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).

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 Bosporus 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 et al. (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 war.[37] 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).

[37] Specifically 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.

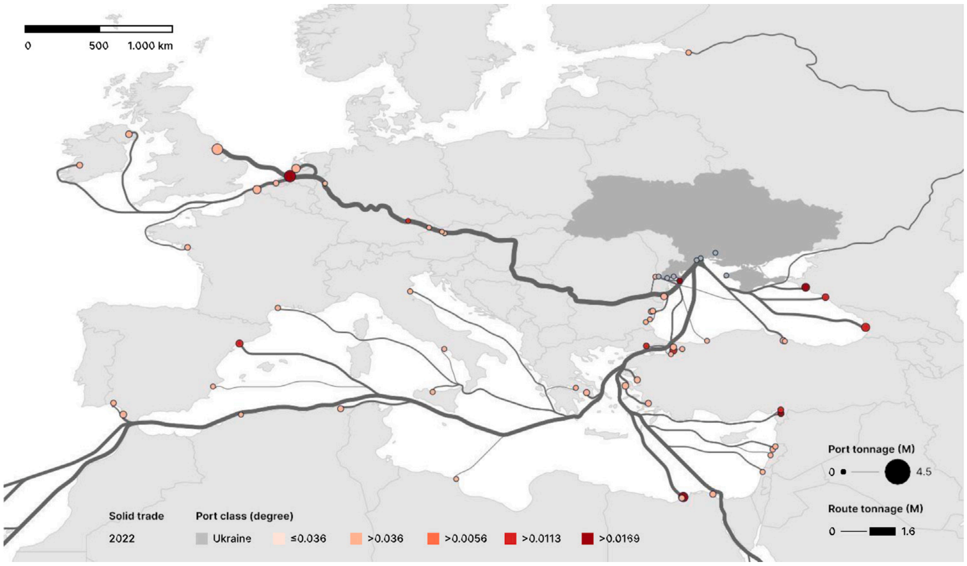

Fig. 17. Solid trade in 2023.

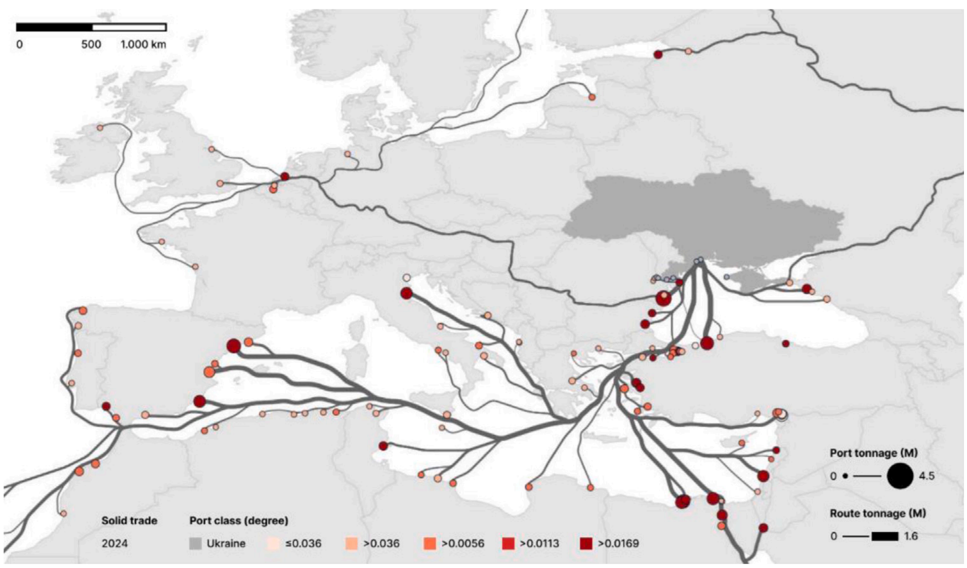

Fig. 18. Solid trade in 2024.

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 et al., 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 specialised studies focusing on a single commodity such as liquid gas (Xiao et al., 2024a) or looking at the global scale only (L. et al., 2024).

We identified two promising paths for further research. First, one shall investigate the impact of this war with a higher time granularity.[38] This granular approach could be completed with a more in-depth analysis of bilateral flows: combining network models with gravity techniques[39] 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

[38] *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.

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

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	GCR	Thessaloniki
2021			
	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	NDL	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
	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	GCR	Eleusis
	0,023489932	TUR	Bourgas
	0,023489932	ROM	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

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

Year	Degree	Country	Port
2010	0.015037594	RUS	Rostov
	0.011278195	RUS	Novorossiysk
	0.011278195	ROM	Midia
	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
	0.00750469	EGY	Port Fouad
	0.005628518	NOR	Porsgrunn
2022	0.011857708	NDL	Rotterdam
	0.011857708	TUR	Eregli
	0.011857708	ESP	Seville
	0.007905138	ITA	Monopoli
	0.007905138	NDL	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	GCR	Eleusis
	0,013422818	TUR	Dortyol
	0,013422818	TUR	Mersin
	0,013422818	IT	Ravenna
	0,013422818	TUR	Rota (TUR)
	0,010067114	ITA	Monopoli
	0,010067114	TUR	Damietta
	0,010067114	ROM	Galatz
	0,010067114	EGY	Alexandria
	0,010067114	ESP	Huelva

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.

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

Year	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
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	BRG	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
	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
	0,010067114	NLD	Rotterdam
	0,010067114	ESP	Huelva

Table A.4
Degree centralities of containers by port.

Year	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
	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
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

CRediT authorship contribution statement

Bárbara Polo Martin: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marc-Antoine Faure:** Writing – original draft, Methodology, Investigation, Formal analysis. **Fabio Cremaschini:** Writing – original draft, Resources, Investigation, Formal analysis, Data curation. **César Ducruet:** Writing – original draft, Validation, Funding acquisition, Conceptualization.

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Appendix A. Degree centralities

See Tables A.1–A.4.

Appendix 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.

Appendix C. Degree distribution for each type of vessels

C.1. Liquid bulks

See Fig. C.1.

C.2. Solid bulks

See Fig. C.2.

C.3. Containers

See Fig. C.3.

C.4. Passengers and vehicles

The flows for passengers and vehicles, as represented in Fig. 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.

Appendix D. 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 Rebafka (2021).

D.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:

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

From Eq. (D.1) we can derive the diameter:

$$\mathrm{diam}(G) = \max \left\{ \ell_{ij}; i, j \in V \right\} \tag{D.2}$$

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.

D.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 Rebafka (2021), we now consider the induced subgraph $\tilde{\mathcal{G}}_i = \left(\mathcal{V}(i) \cup \{i\}, \tilde{E}_i\right)$ 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 $C(i)$ 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:

$$\tau_i = \frac{d_i \left(d_i - 1\right)}{2} \tag{D.3}$$

The Eq. (D.3) gives the τ_i used in Eq. (3). As emphasised by Rebafka (2021), the clustering coefficient C_i 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:

$$C_i = \mathrm{dens}\left(\bar{\mathcal{G}}_i\right) = \frac{2|E_i|}{d_i \left(d_i - 1\right)} \tag{D.4}$$

Appendix E. Additional metrics

In this appendix, we provide additional metrics, including various types of goods (complementing Fig. E.5) and additional networks (complementing 9).

E.1. Network metrics for the containers network

See Fig. E.5.

E.2. Network metrics for solid bulks

See Fig. E.6.

E.3. Network metrics for general cargo

See Fig. E.7.

E.4. Network metrics for liquid bulks

See Fig. E.8.

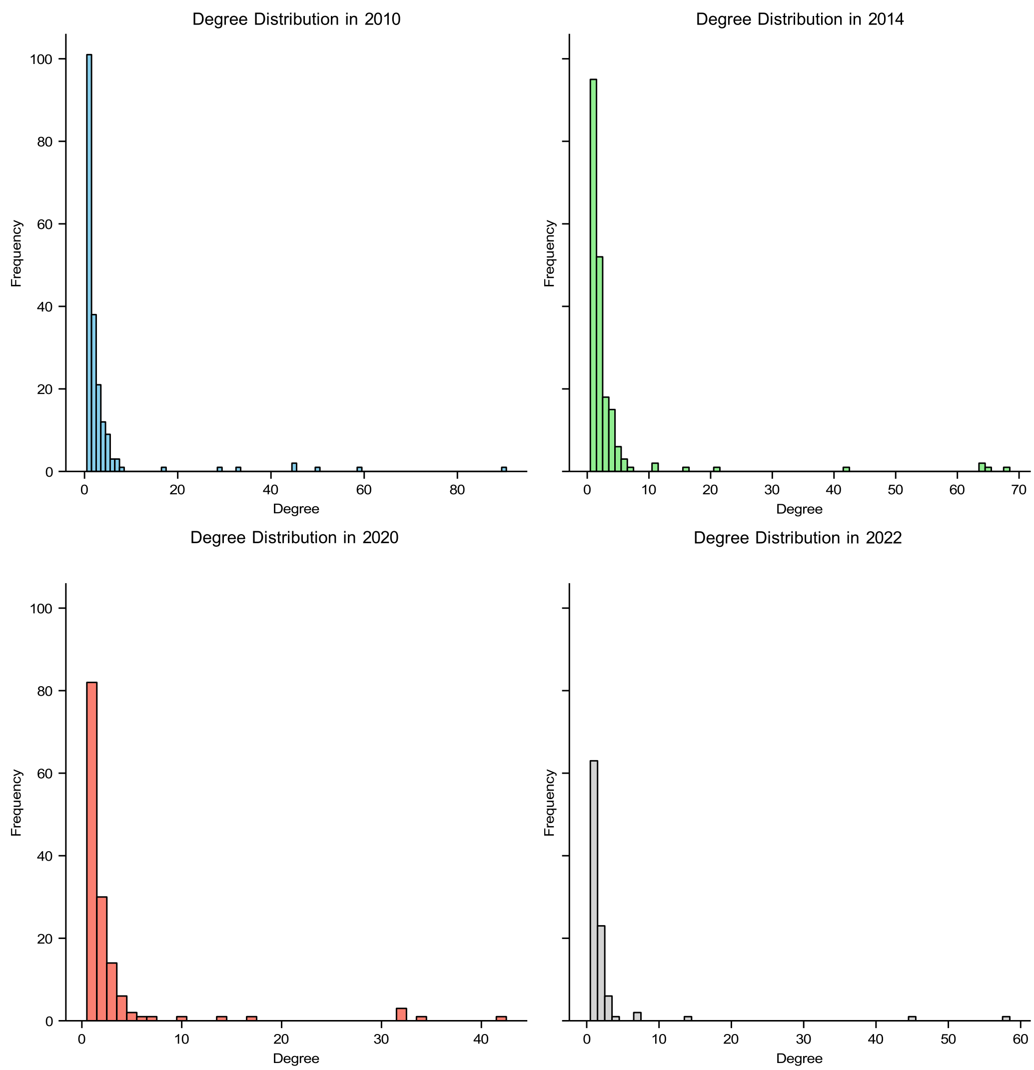


Fig. C.1. Degree distribution of liquid bulks.
Notes: We computed the degree distribution for the Ukrainian network of liquid bulks. We did this operation for four years: 2010, 2014 (annexation of Crimea), 2020 and 2022 (invasion of Ukraine).

E.5. Network metrics for passengers and vehicles

See Fig. E.9.

E.6. Density in the Ukrainian - foreign ports network

See Fig. E.10.

Appendix F. Additional results on network hierarchy

See Fig. F.11.

Appendix G. International flows of Ukrainian ports

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

Appendix H. Additional maps on the connections of Ukrainian ports

See Figs. H.14–H.17.

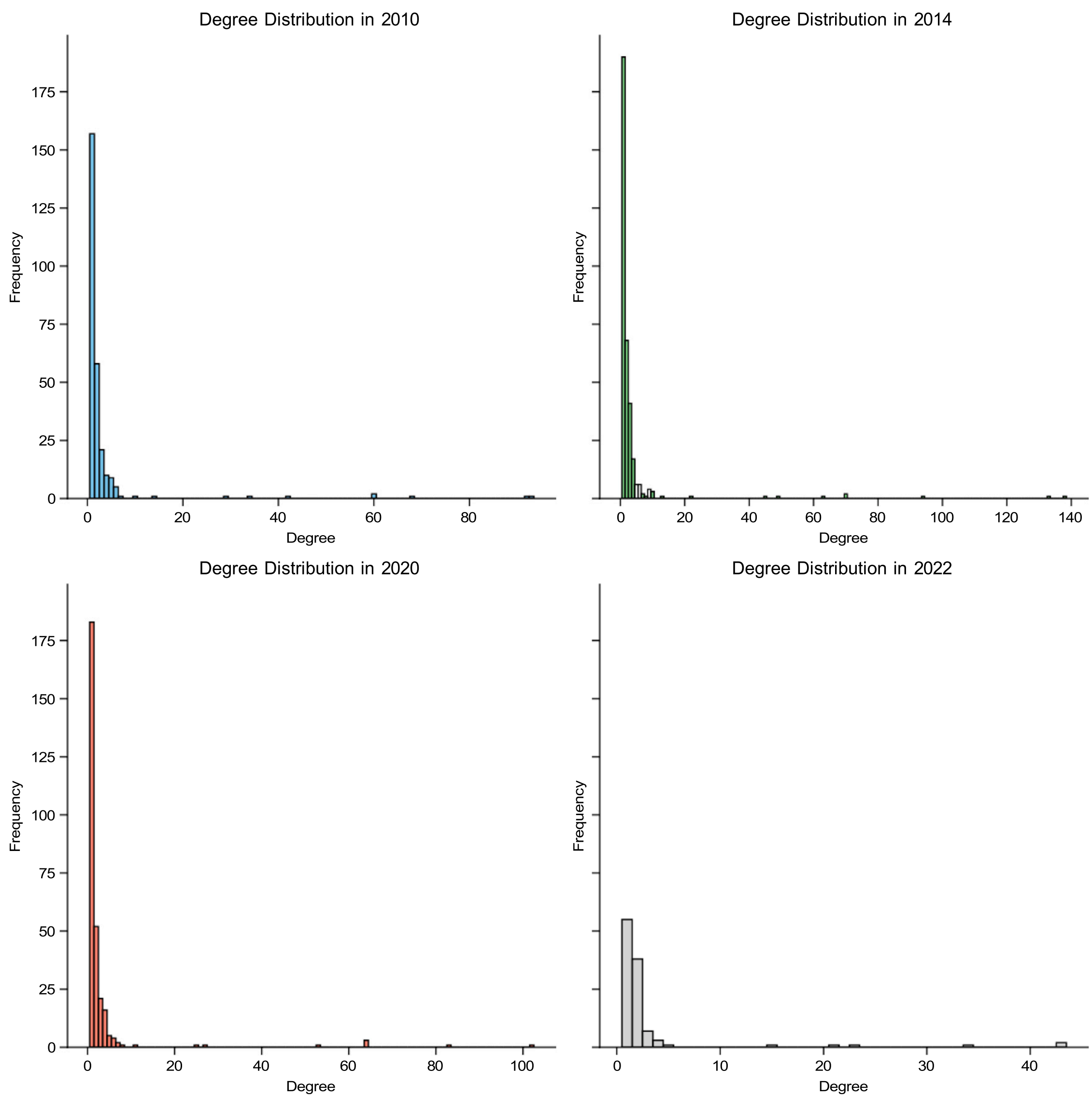


Fig. C.2. Degree distribution of solid bulks.
Notes: We computed the degree distribution for the Ukrainian network of solid bulks. We did this operation for four years: 2010, 2014 (annexation of Crimea), 2020 and 2022 (invasion of Ukraine).

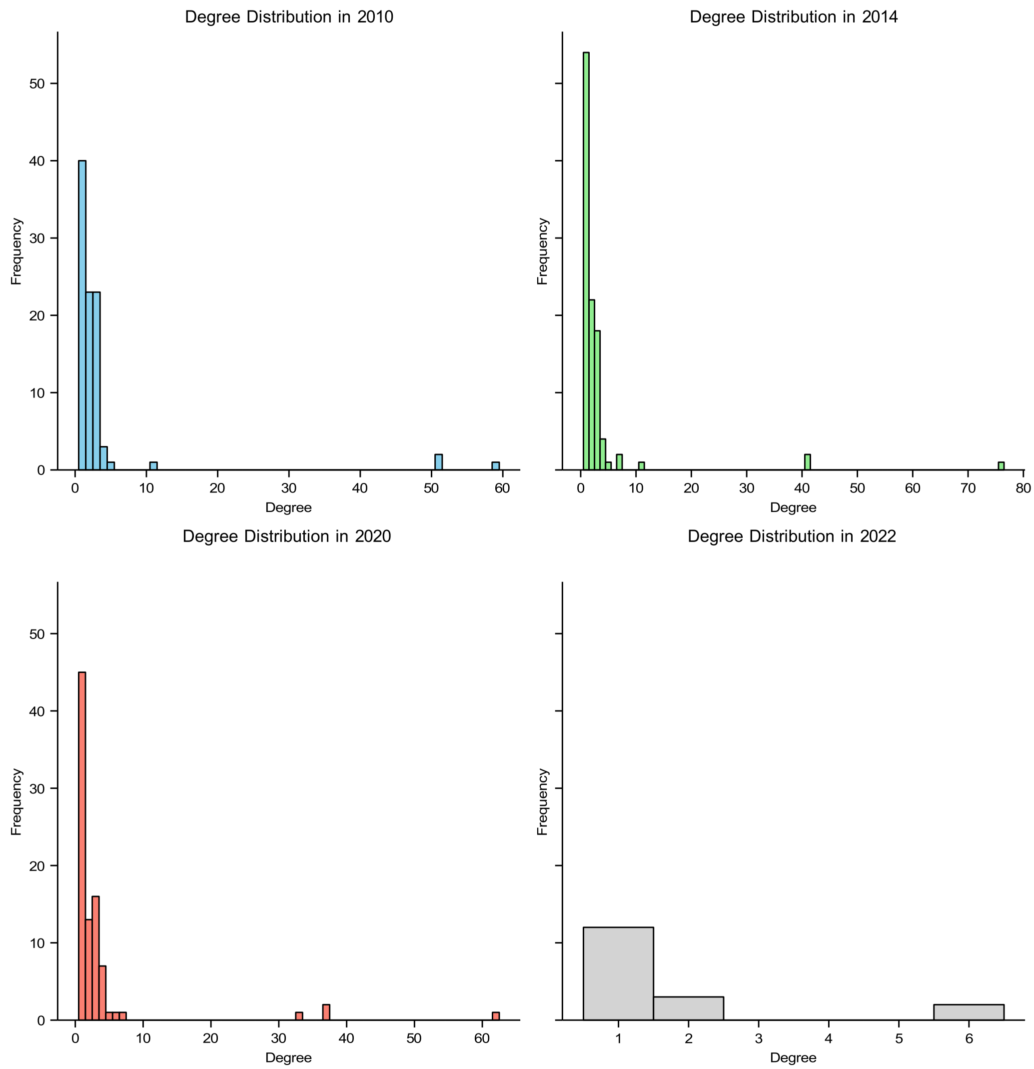


Fig. C.3. Degree distribution of containers.
Notes: We computed the degree distribution for the Ukrainian network of container ships. We did this operation for four years: 2010, 2014 (annexation of Crimea), 2020 and 2022 (invasion of Ukraine).

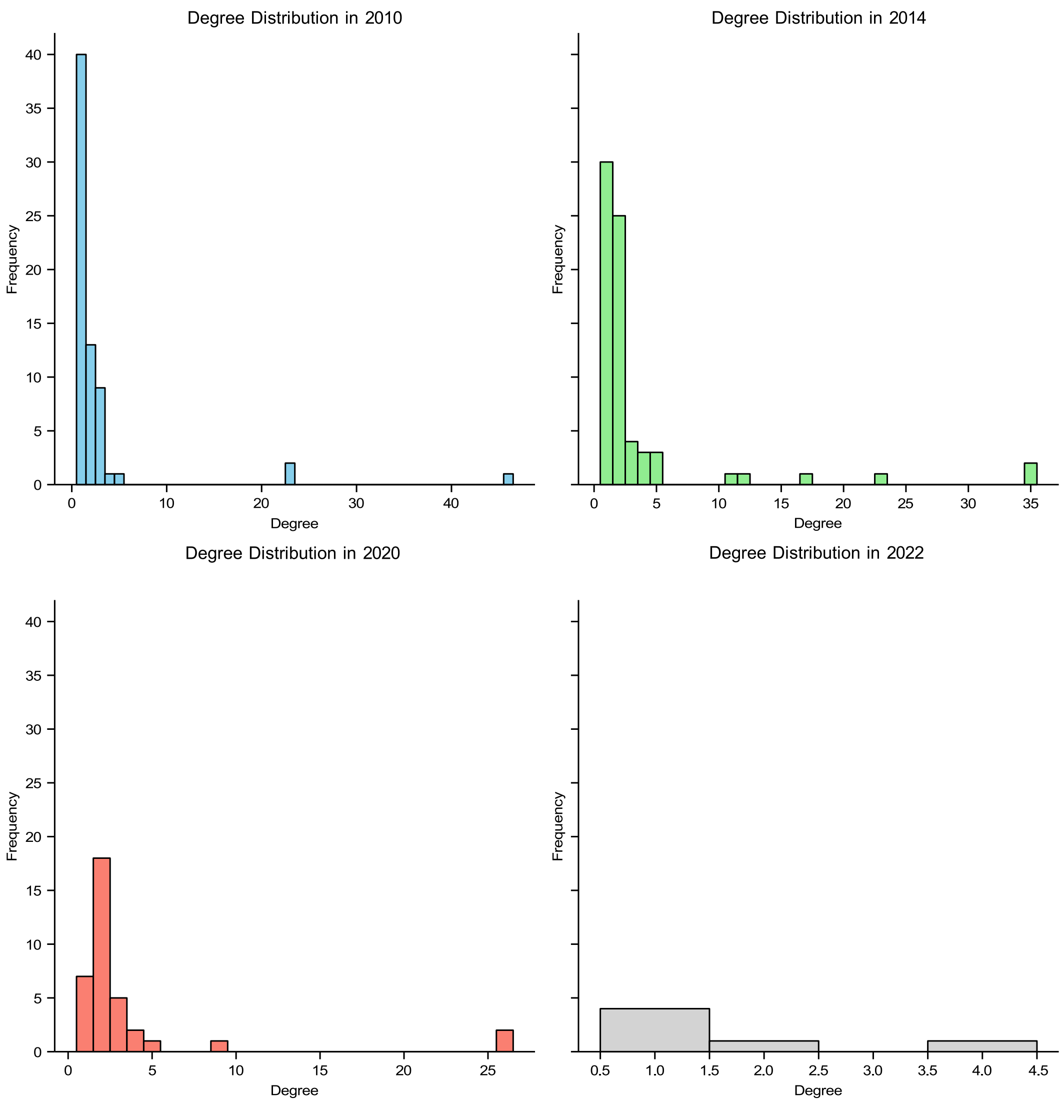


Fig. C.4. Degree distribution of passengers and vehicles.
Notes: We computed the degree distribution for the Ukrainian network of passengers and vehicles ships. We did this operation for four years: 2010, 2014 (annexation of Crimea), 2020 and 2022 (invasion of Ukraine).

Fig. E.5. 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.

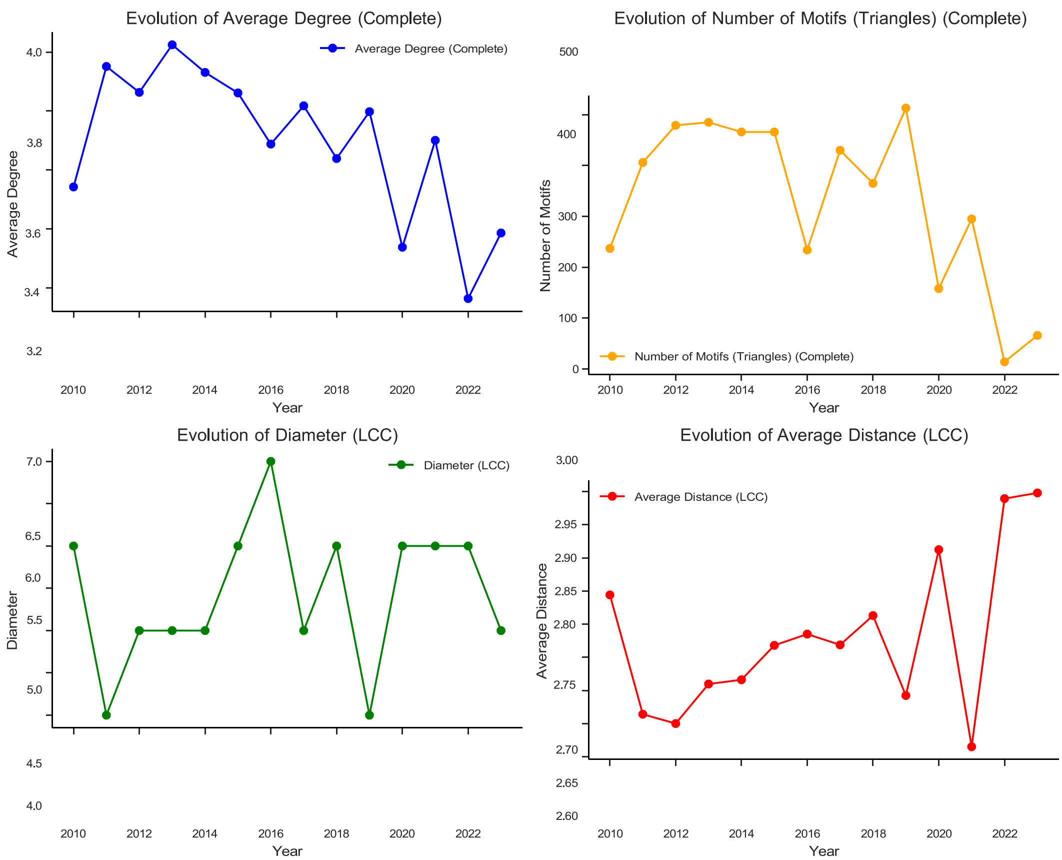


Fig. E.6. Evolution of the network metrics for solid bulk.
Notes: The average degree is computed as the average of the number of connections of each port (*i.e.* the 'degree'). The triangle metric computes the sum of all the K_3 graphs in the network. The diameter and the average distance are computed on the largest connected component each year, to avoid infinite values due to disconnected sub-graphs.

Fig. E.7. 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.

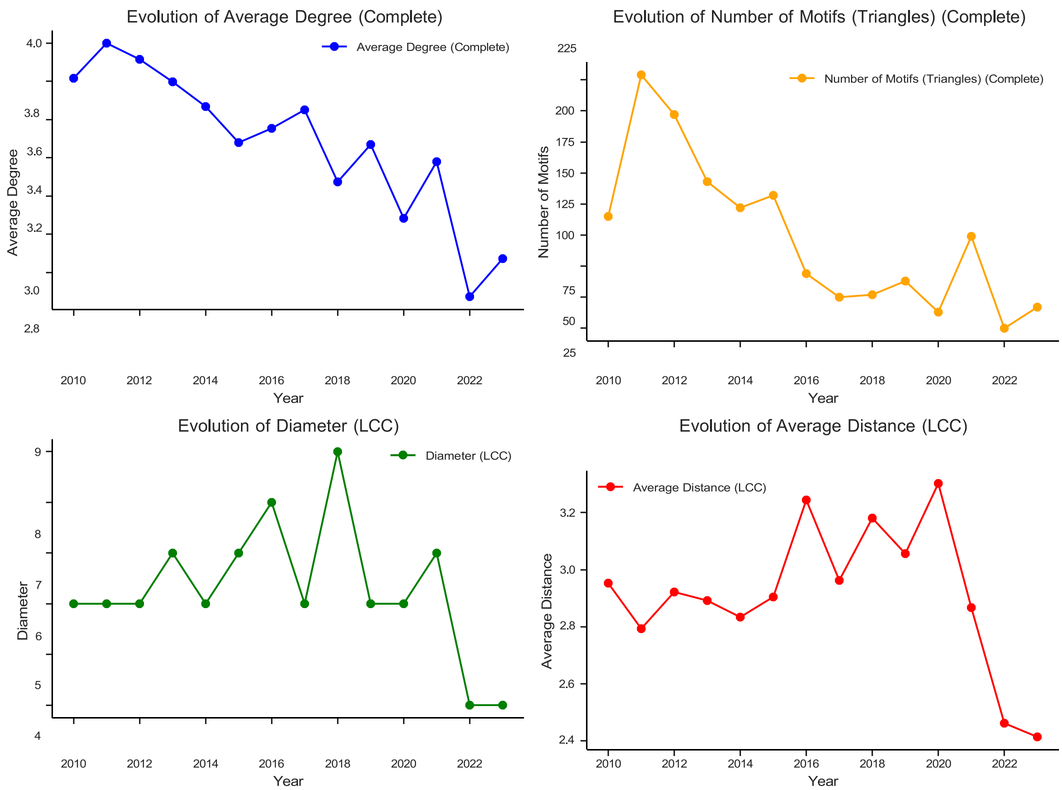


Fig. E.8. Evolution of the network metrics for liquid bulks.
Notes: The average degree is computed as the average of the number of connections of each port (*i.e.* the 'degree'). The triangle metric computes the sum of all the K_3 graphs in the network. The diameter and the average distance are computed on the largest connected component each year, to avoid infinite values due to disconnected sub-graphs.

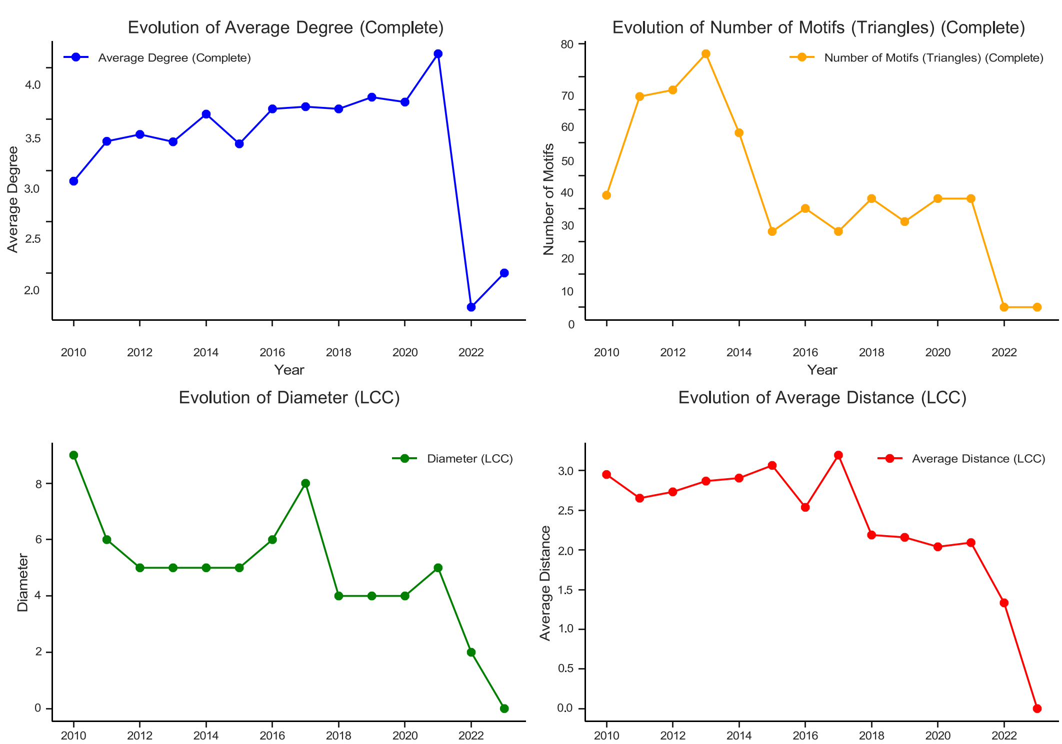


Fig. E.9. Evolution of the network for each type of vessel.
Notes: The average degree is computed as the average of the number of connections of each port (*i.e.* the 'degree'). The triangle metric computes the sum of all the K_3 graphs in the network. The diameter and the average distance are computed on the largest connected component each year, to avoid infinite values due to disconnected sub-graphs.

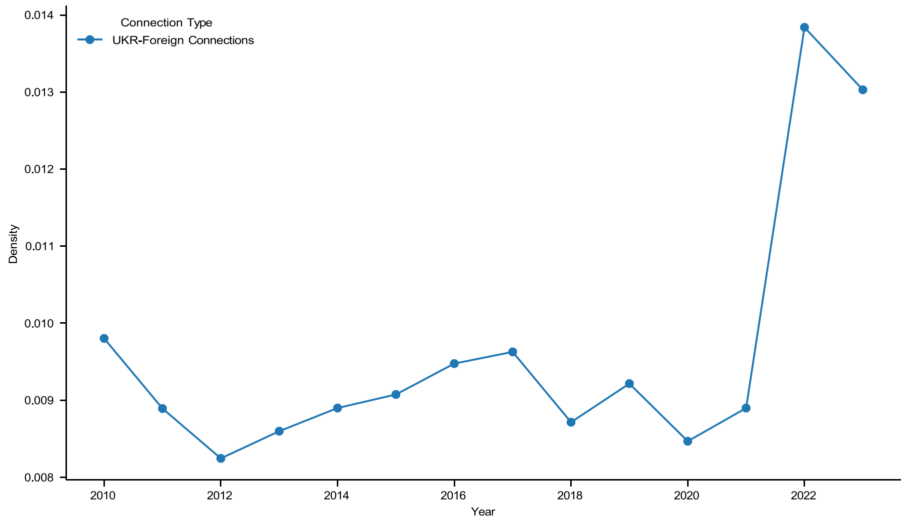


Fig. E.10. Evolution of the density for the Ukrainian-foreign ports network.
Notes: We created a — kind of — bipartite network with Ukrainian ports on one side and foreign ports and the other side. It is not easy to explain the sudden increase in density that we have identified in 2022. There may be 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.

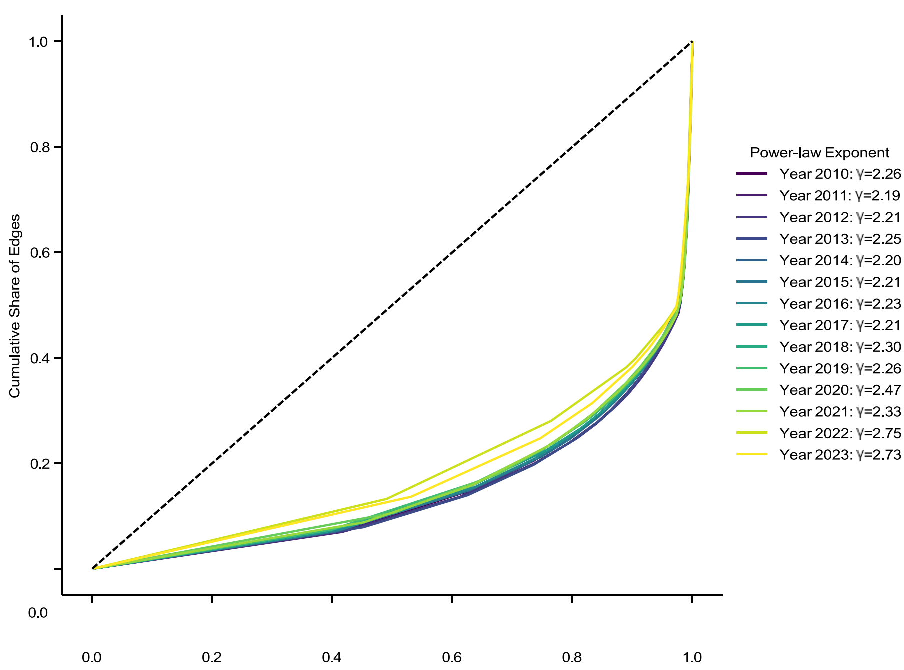


Fig. F.11. Lorenz curve for each year.
Notes: We computed the Gini coefficient of each network and the associated Lorenz curve, demonstrating that the less hierarchical network is the 2022 one, closely followed by 2023. We draw inspiration from the work of Kunegis and Preusse (2012), who discussed the relationship between power-law distribution and hierarchy in networks.

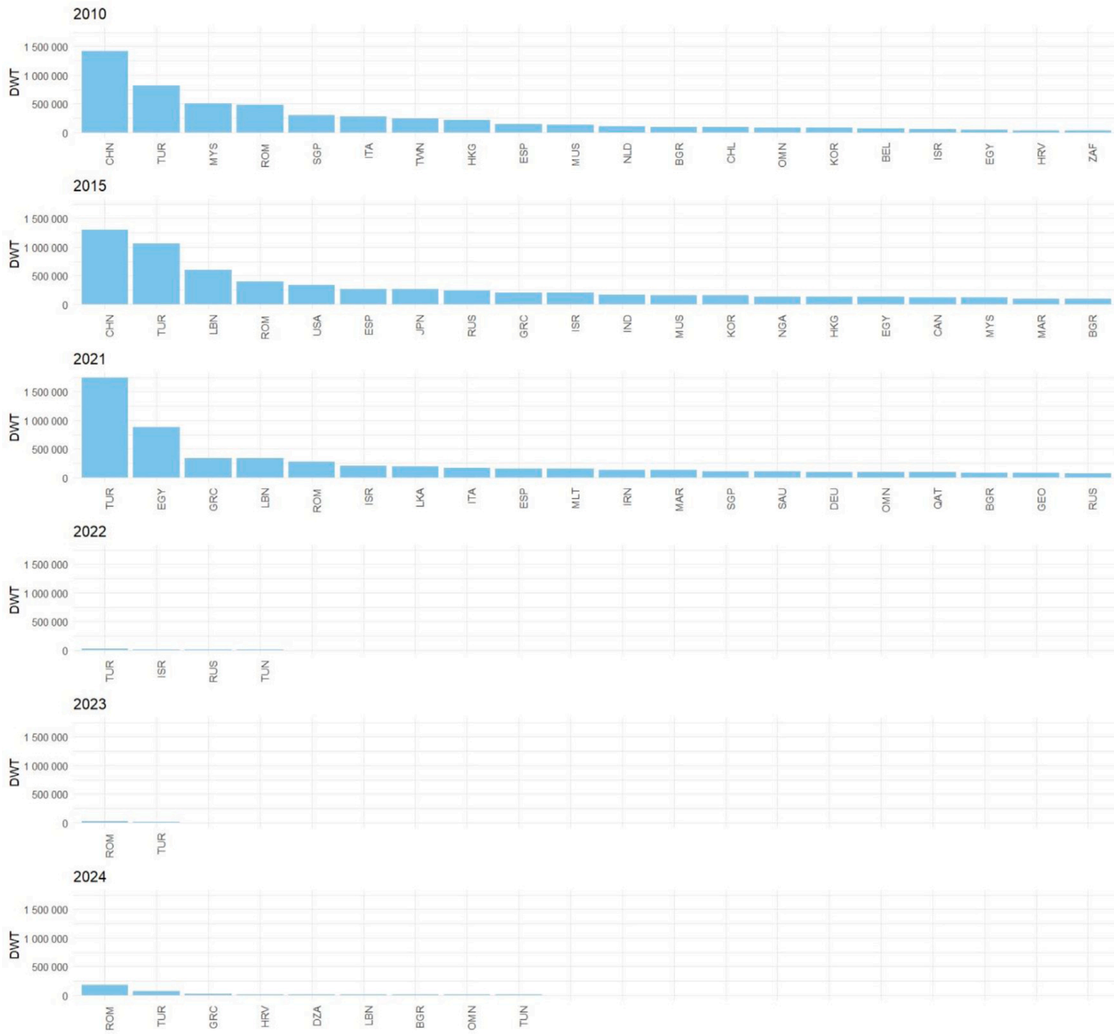
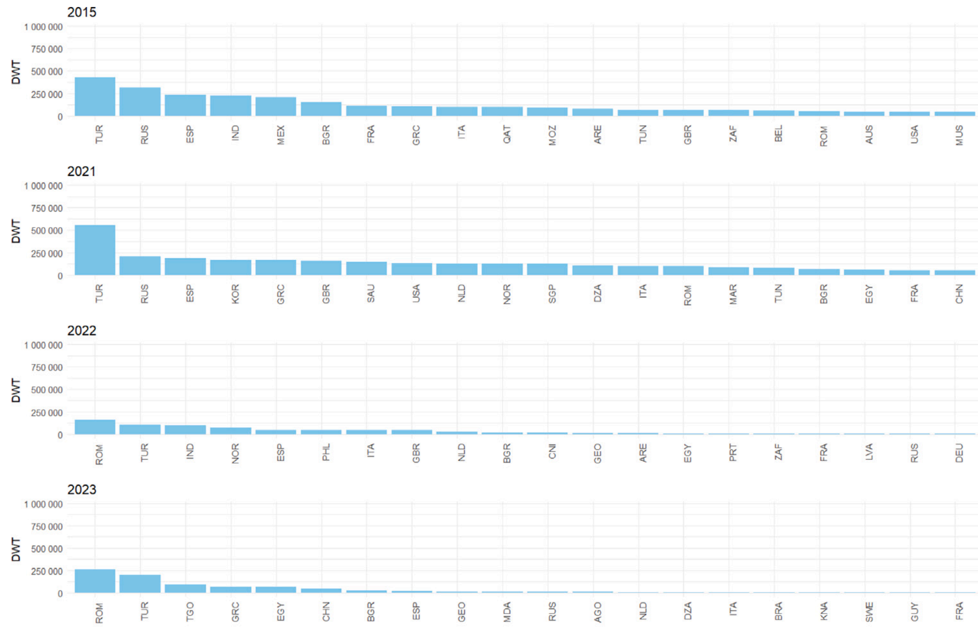


Fig. G.12. Evolution of total cargo capacity (DWT) of containerships moving to foreign countries. (First 20 countries).

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.



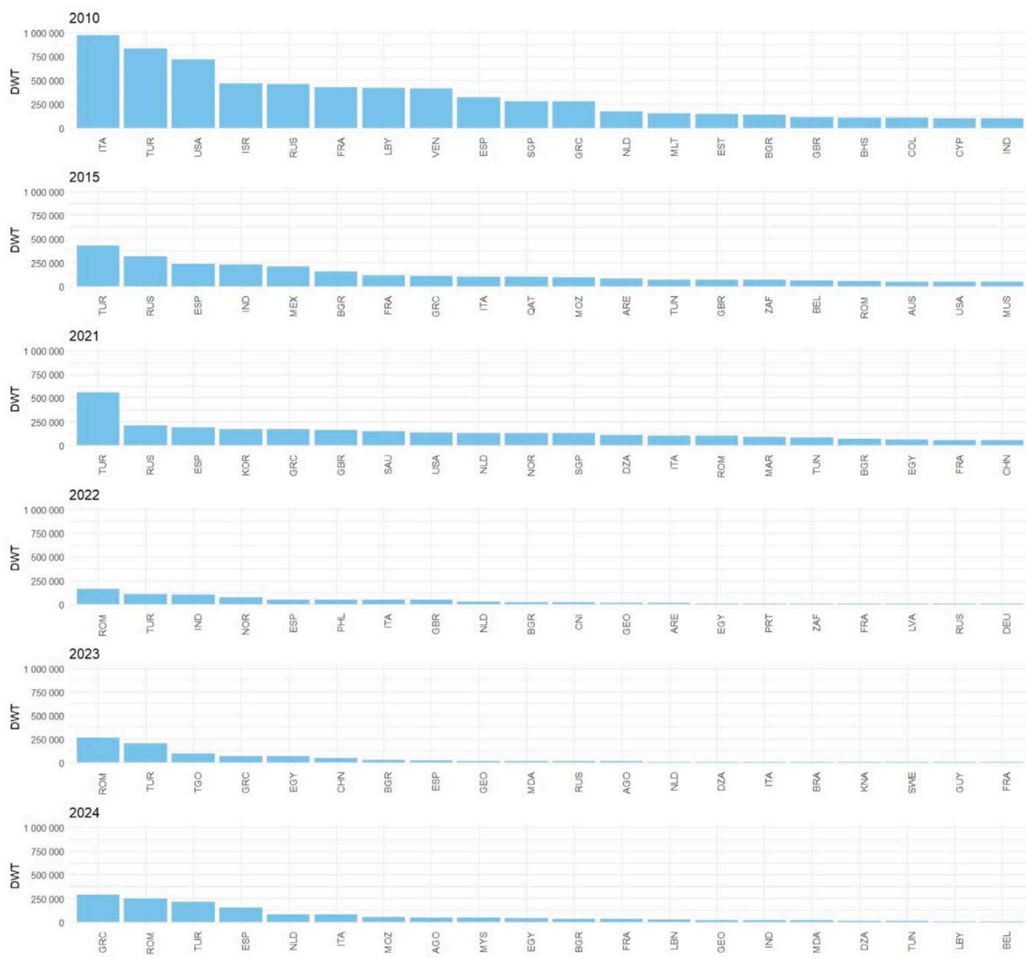


Fig. G.13. Evolution of total cargo capacity (DWT) of liquid bulk ships moving to foreign countries. (First 20 countries).

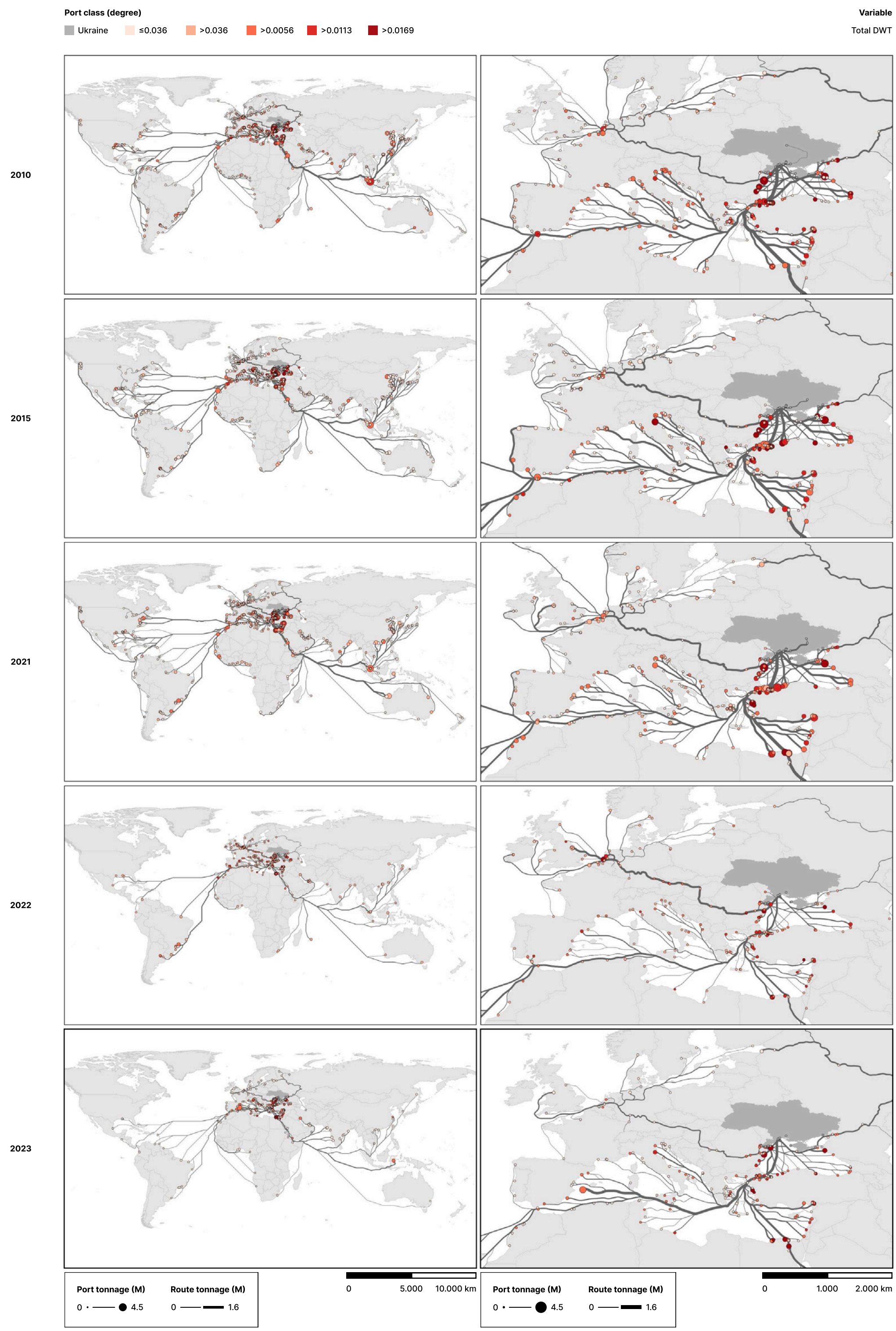


Fig. H.14. Evolution of total dwt (2010–2024).

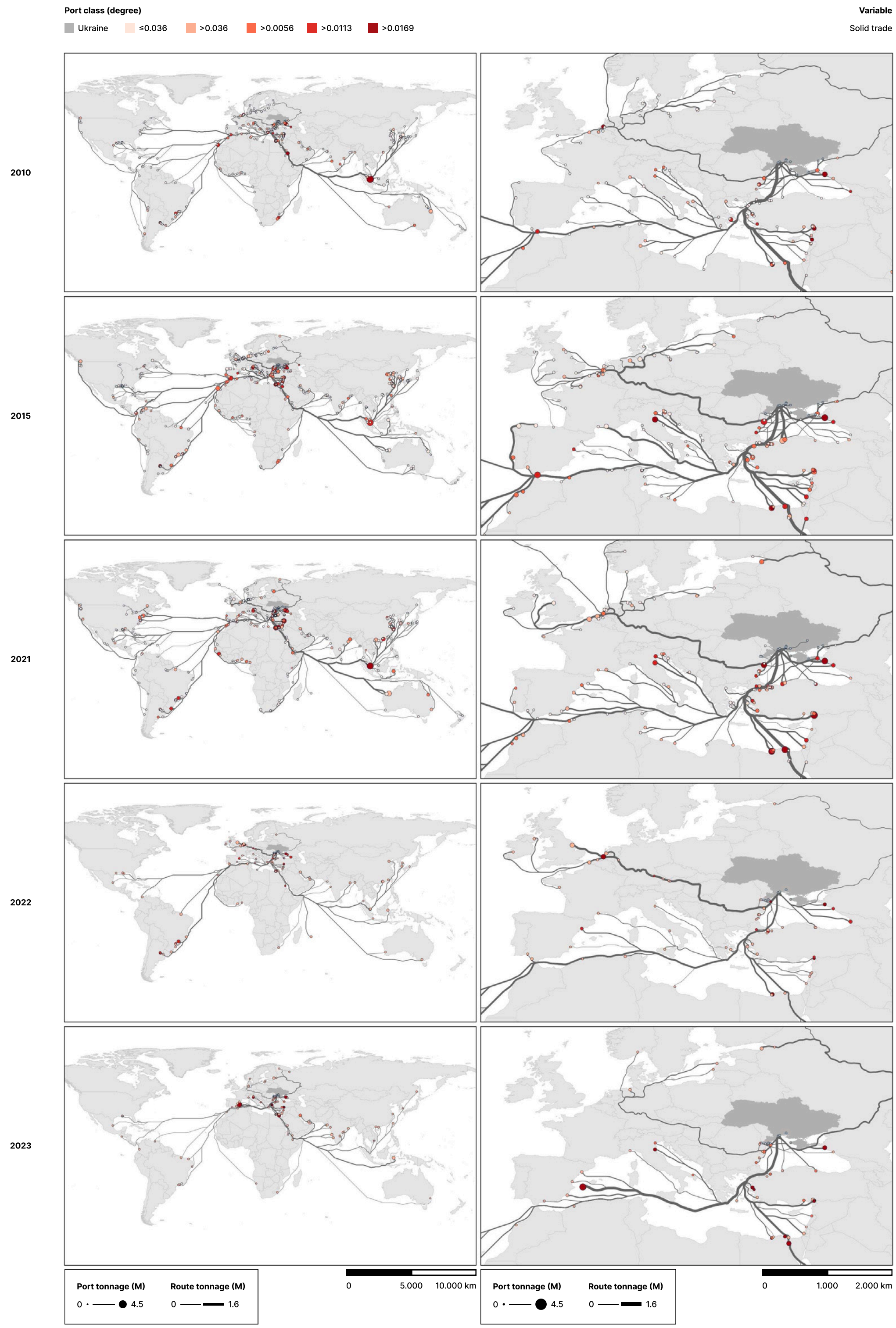


Fig. H.15. Evolution of solid trade (2010–2024).

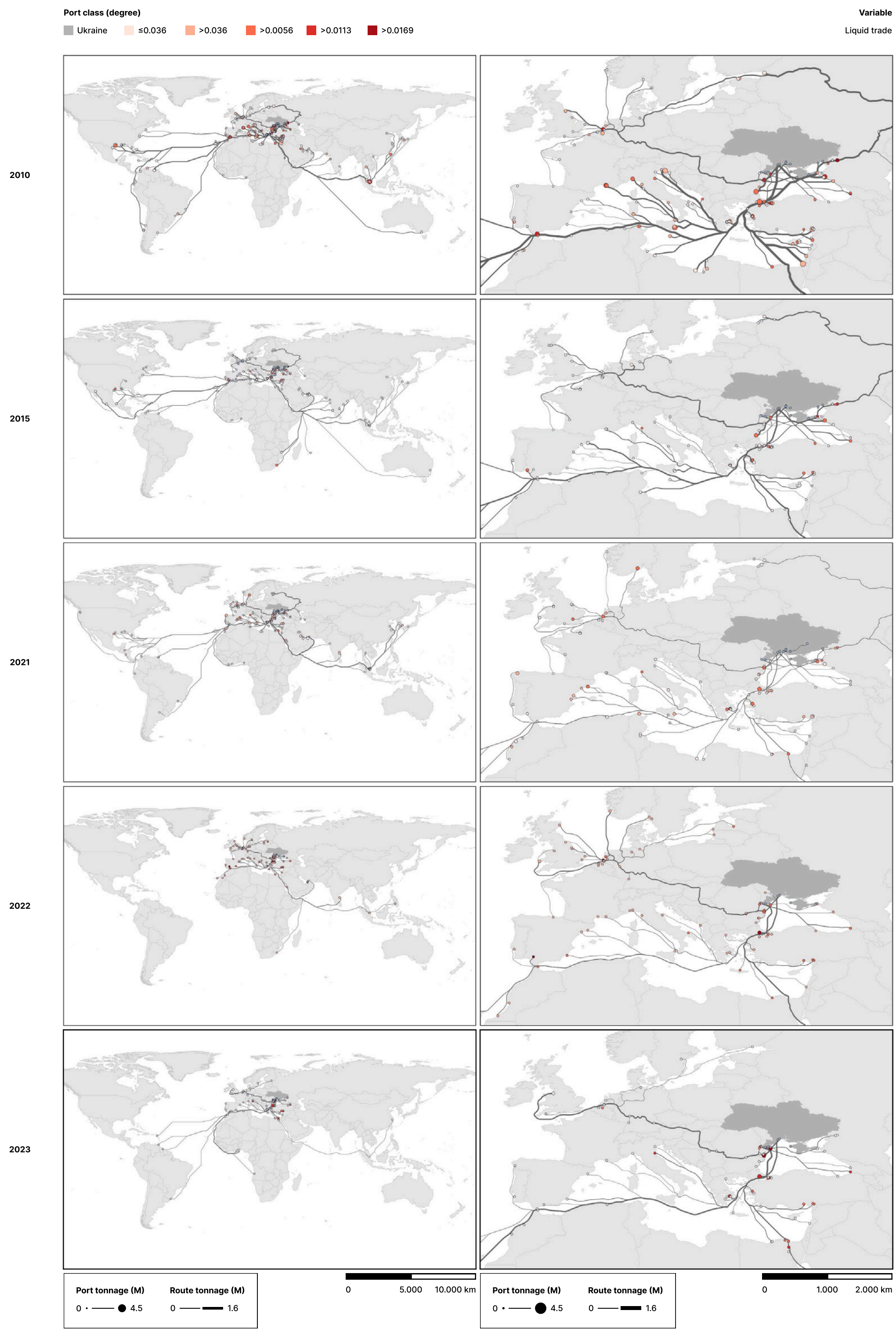


Fig. H.16. Evolution of liquid trade (2010–2024).

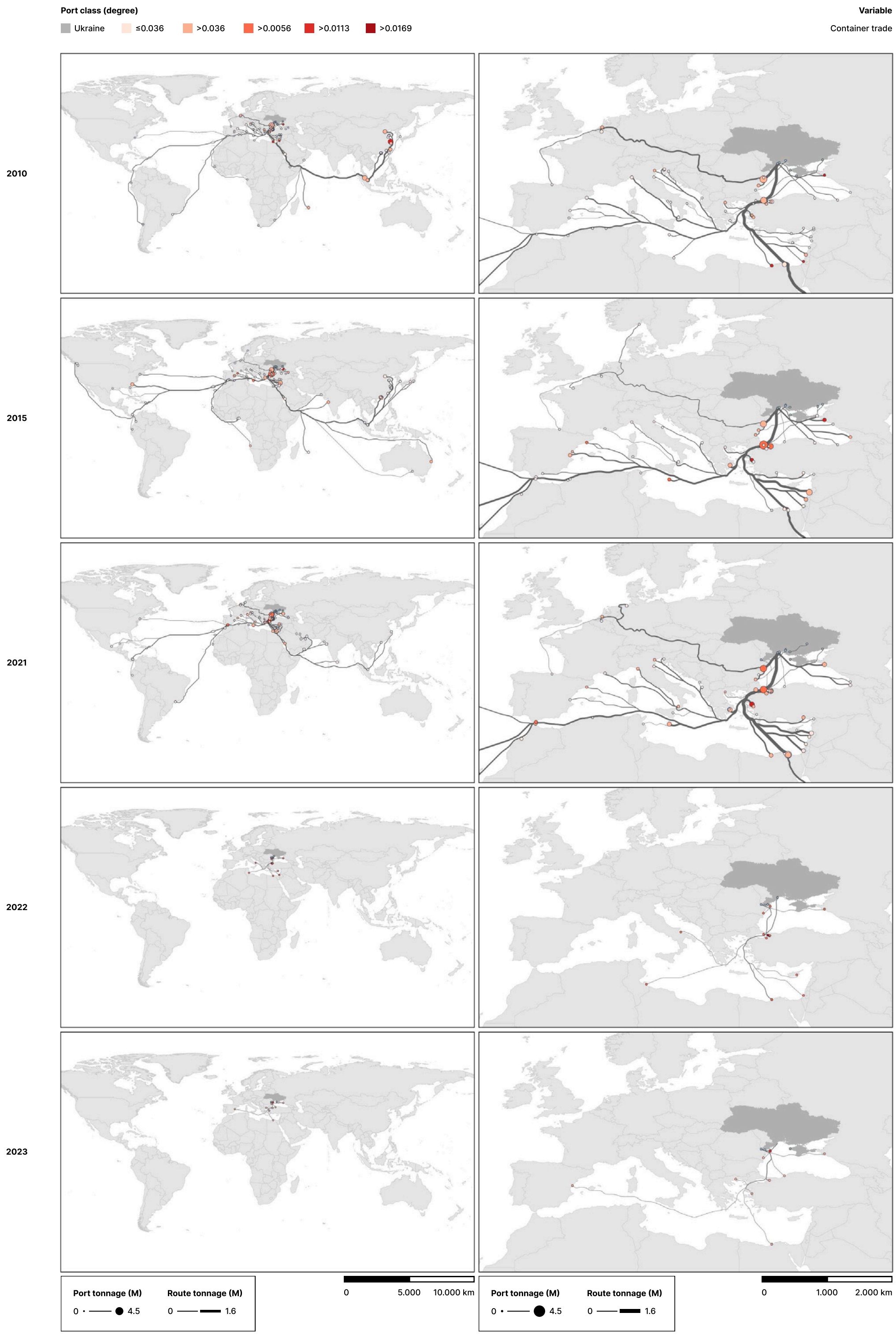


Fig. H.17. Evolution of container trade (2010–2024).

Data availability

The data used in this study was obtained through a single-user licence and therefore is not publicly available due to copyrights, except in aggregated format upon reasonable request.

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