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The container transport system during Covid-19: An analysis through the prism of complex networks

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Abstract

This paper analyses the changes on the maritime network before and after the Covid-19 outbreak. Using a large sample of vessel movements between ports, we show a decrease in the global maritime connectivity and significant differences between ports and inter-port links. Furthermore, we find that Covid-19 mitigation measures implemented by governments affected regional port hierarchies differently, with a reduction in port concentration in Europe and Africa and an increase in Asia and North America. Globally, very large ports and small but densely inter-connected ones resisted better to the crisis than the others, while small transshipment hubs and bridges appear to have been more negatively impacted. These findings have implications for the design of more resilient port strategies and transport policies by states and firms.

Keywords: Maritime transportation, Covid-19, pandemic, complex networks, disruption

Highlights

- Global container transport is analyzed as a complex network of ports
- A net decrease in connectivity is observed between 2019 and 2020
- Emerging inter-port links are identified
- Covid-19 mitigation measures have impacted regional port hierarchies differently
- Large ports and small but densely inter-connected ports resisted better

Introduction

Unprecedented in its intensity and geographical scope, the current outbreak of the Covid-19 pandemic impacted maritime supply chains heavily. It led to a slowdown in maritime trade, reducing demand and port throughput. The reaction of container shipping companies, i.e. stopping certain services or cancelling port calls, made the maritime transport supply more unstable. At the same time, the Covid-19 related restrictions such as lockdowns, also caused port congestion and delays in cargo handling, weakening maritime supply chains and connectivity. The rebound of the Chinese economy on one side and the measures taken by OECD countries to restart their economies on the other side, have had an important impact on demand, helping households to buy essential goods (Ashraf, 2020). The second half of 2020 was marked by a dramatic rise in container freight rates, which was the strongest since the 2003's Chinese export boom (Yeng, 2021). Although the impacts of the Covid-19s crisis on maritime transportation are unprecedented, it isn't the first global shock on the containerized network and shares some important features with the 2008/2009 crisis (Notteboom et al., 2021). Thus, it can be interesting for the maritime industry to capitalize on the knowledge gained from this new crisis so as to be better equipped for the next one, whenever it happens.

As a first step in this direction, this research provides an overview of the ways in which a global shock such as the Covid-19 crisis affected the global port network. It examines the changes in the container port network before and after the Covid-19 outbreak, and analyzes the extent to which the hierarchical position of ports changed within the network. The paper also attempts to assess how the Covid-19 mitigation measures implemented by governments have affected ports.

We measure the evolution of maritime connectivity using two main network indicators: weighted degree and clustering coefficient. Our analysis also includes a description of the most dynamic links. We use a rich AIS dataset provided by VesselFinder which describes container vessel movements between ports for three lunar seasons (spring, summer, autumn).

As compared to port-centered analyses, the current work adopts a relational perspective, paying attention to the links between ports and the overall structure of the network. In that respect, our work is more focused on the perspective of shippers and on how the characteristics of containerized services at ports have been affected by a global shock. Furthermore, as suggested by Rousset and Ducruet (2020), the maritime network and its response to shocks depend on many different actors and the knowledge regarding how their individual decisions are made is limited. It is thus interesting to complement network approaches with empirical ones.

We test whether there are different effects of the national Covid-19 mitigation policies on port systems. Our findings show that large ports and small but densely inter-connected ports resisted better to the crisis than the others, while small ports playing hub or bridge functions

have been more severely hit. The impact of the crisis on the concentration of port throughput at the regional level is less straightforward and depends on the region considered. Thus, in Asia and North America, Covid-19 mitigation policies have led to the concentration of vessel calls in the largest ports of each country whereas, in Europe and Africa, they led to a de-concentration of vessel calls.

These findings quantify how measures taken by national governments affected port systems. They provide insights on the ways in which regional hierarchies and inter-port maritime links were impacted by the Covid-19 pandemics, allowing governments to better evaluate the effects of their health policies on port activities and maritime trade. Furthermore, the development of risk metrics and indices, which can help firms to assess network nodes in terms of risks, has recently been recognized as an area which could benefit from further research (Sheffi, 2018).

The rest of the paper is organized as follows. The next section reviews the literature on maritime networks as well as the recent works on Covid-19. We then present the database and the structure of the maritime network before the Covid-19 outbreak. The following section analyses the main changes on inter-port links and an exploratory empirical analysis of the effects of Covid-19 mitigation policies. The last section concludes the paper.

Background

The importance of ports as critical nodes in global transport networks and supply chains has been researched in multiple disciplines (Wendler-Bosco and Nicholson, 2020, Ducruet 2020). Our approach is more in line with transportation studies that empirically analyze the vulnerability of transport networks and hubs. Also of relevance to the study of shocks is the study of risks in supply chains, which shares a common context. This section reviews transport network studies dealing with shocks and then provides brief background on the studies specifically analyzing effects of Covid-19.

Vulnerability of maritime networks and hubs

Research assessing the vulnerability of transport networks uses a variety of approaches and spatial scales, depending on the types of shocks analyzed. There are two strands of research that are particularly connected to the topic of this paper: regional/local studies and global investigations. The first approach analyzes the relationship between the magnitude of an event and the effects on neighboring ports as such port substitution. In a port-centered analysis, Xu and Itoh (2018) showed how Hanshin's earthquake in the mid-1990s accelerated a change in the hierarchy of Japanese ports, with Busan (South Korea) replacing Kobe as a regional hub for many of the Japanese secondary ports in the North of Japan.

The role of geography has been recognized by Rousset and Ducruet (2020), who studied the effects of Hanshin's earthquake, together with the 9/11 World Trade Center attack and hurricane Katerina, on a network perspective. They measured how shocks strongly localized on ports simultaneously affected other ports in the network. One of their findings is that

ports that are geographically close need more time to return to pre-shock connectivity levels than further ones. Another relevant finding is that the three disruptions resulted in an increase of the average clustering coefficient, meaning that the network became more meshed after the shock.

In an econometric approach, Vershuur et al. (2020) analyzed short-term disruptions across 74 ports and 27 natural disasters, using Automatic Identification System (AIS) data. They showed that the duration of the disruption appears to be connected with the severity of event, measured by parameters such as wind speed and storm surge. They also showed that, during short-term disruptions, port substitution is rarely observed, going against an assumption of several theoretical models (e.g. Achurra-Gonzalez et al., 2019). One explanation for this lack of substitution capacity is that maritime companies are often engaged in long term relationships with ports and terminal handling operators, with the former often choosing to wait or implement strategies such as port skipping or port swapping (Li et al, 2015).

Global investigations have attempted to assess how the global maritime network changed after a global shock such as the 2008/2009 crisis. Gonzalez-Laxe et al. (2012) used an AIS dataset to study changes in the containerized transport network. They found that, within a context of global decrease of maritime connectivity, large hubs evolve differently. While centrally-located ports in East-West trade lane such Singapore and Hong-Kong resisted well, others, such as Busan and Rotterdam, at both ends of the route, showed a substantial decrease in connectivity. Furthermore, in a subsequent study (Pais-Montes et al. (2012) the same authors highlighted positive dynamics in small container ports of emerging regions Brazil, Turkey, East Africa and the Indian subcontinent. In short, the 2008/2009 crises resulted in contrasted evolutions of ports regardless of their size and function (hub/gateway).

The effects of Covid-19 on freight transport

Recent global studies, not necessarily focused on network analyses, studied changes in the maritime sector during the Covid-19 crisis, which is still ongoing at the time of writing this paper. One of the most complete qualitative analysis was carried out by Notteboom et al. (2021), who compared it with the 2008/2019 crisis, from the perspective of carriers, stevedores and ports. One of their key findings is that the impacts of the Covid-19 shock on ports and the shipping industry were smoothed by the strategic behavior of shipping companies, who responded quickly to the drop in demand by implementing capacity control measures. These measures were particularly important between April and June 2020, with carriers withdrawing up to 20% of their capacity on the main trade lanes, through blank sailings and service cancellation. These measures, amongst others, favored a better utilization of the deployed vessel capacity, increasing in many cases the number of container movements per port call.

In a more quantitative vein, Vershuur et al. (2020) estimated the trade losses during the first eight months of the pandemic, using AIS vessel data and international trade database

and the Oxford Covid-19 Government Response Tracker (OxCGRT). They estimated the distribution of international trade at the level of ports, distinguishing between imports and exports. They found that a number of developing countries increased their imports during the crisis, likely due to an increased need for food and medical supplies¹. They also found that exports grew in many ports in Brazil, the Gulf of Mexico. Other countries, such as India, Myanmar, Vietnam and the Philippines, increased their exports of manufactured goods maybe as substitutes for Chinese exports during the lockdown. At the end, the authors found that the Covid-19 mitigation measures negatively affected the maritime exports of countries, but the relationship was not significant for imports. Although this paper shed light on the ways Covid-19 affected trade it does not tell us much about how it affected the connectivity of ports. To help to fill this void this research focuses on the connectivity of ports. Furthermore, we use the same datasets (AIS data and OxCGRT) in order to measure how the Covid-19 mitigation policies impacted port hierarchies at regional and global levels.

Data and Method

The global maritime network is characterized by a graph in which nodes are ports and links are vessel movements, using Automatic Identification System (AIS) data provided by VesselFinder. In total, our dataset covers container services during the period Spring-Summer-Autumn (“spsuau” henceforth) of 2019 and 2020 (Table 1).

A glimpse on the main and simpler sample indicators for both networks computed shows around 1.1M of positions (ports), ordered and grouped by ascending timestamp and IMO number, using PostgreSQL database, in order to obtain a set of consecutive ordered positions for each vessel, which, thereafter, will define the pairs of nodes able to consider a network structure (Pais-Montes et al., 2012).

Some vessels have not travelled in spsuau2020 with respect spsuau2019 (5,673 and 5,744, respectively). Taking account that the vessels designated for end of service or scratch must not be a significant percentage, maybe some kind of idle fleet behavior could be glimpsed in these evolution.

With an average size of 1,875 TEUs, it deserves attention the fact that the accumulative account is (except for the smallest classes) always smaller in spsuau2020 than in spsuau2019. Should an evidence of slowdown in active fleet’s size be searched here?

Our analysis is mostly based on operational indicators and complex network indicators, taking two distinct views: First, the global maritime system is seen as a port network, with nodes being ports and links representing the vessel connections between ports. We also investigate the regional port hierarchies.

¹ The restrictions on workplace procedures also limited production capabilities and increased the need for imports, as kindly suggested by one of the anonymous referees.

For the network part, our analysis relies on the main indicators that graph theory provides, in line with the wide academic literature developed during the last ten years (Ducruet, 2020), focused in applying this methodology to the problem of the seaborne trade. We focus on four different well-known dimensions (Pais-Montes et al.2012): port degree (number of direct connections between nodes); weighted degree (total amount of cargo arriving or departing to/from one port at a given moment); betweenness centrality of a position (total number of shortest paths connecting two random edges and passing through this given node); and clustering coefficient (measure of neighborhood interconnection).

All the ‘Anchorage’ positions (close to call but not mooring events) have been erased in the very first step of sample cleaning. After that, terminals have been aggregated when they belonged to the same port authority. For example, we have grouped Hongqiao, Shanghai, Yangshan and Taicang under the same ID ‘Shanghai’. But this is not the case for Long Beach and Los Angeles, geographically close but not under the same port authority.

The differences between the two time intervals considered are small, but they point to a slight increase in the degree, a reduction of the total amount of cargo operated at terminals, a clear loss of influence (betweenness centrality) for the average or median port, and also a slow decrease of the capacity for the mean port to connect itself with neighbor terminals. Of course these are generic considerations of the two network computed and an in depth analysis of what lies beneath should follow this brief exposition.

		Spring-Summer-Autumn 2019 ¹		Spring-Summer-Autumn 2020 ¹		
		value	count(*)	value	count(*)	
AIS positions		572.713		549.968		
#		5.744		5.673		
Vessels	size (TEUs)	min	43	1	43	1
		percentile 10	700	517	707	539
		median	1.875	2.376	1.875	2.307
		average	3.552	3.321	3.592	3.259
		percentile 90	8.800	4.969	8.800	4.861
		max	21.413	5.744	21.569	5.673
Ports	avg size (TEUs)	#	1.001		1.010	
		min	901	818		
		percentile 10	1.144	1.082		
		median	1.938	1.862		
		average	2.114	2.056		
		percentile 90	3.353	3.346		
	max	4.587	4.710			
nodes		1.001		1.010		
edges		8567		8752		
Network parameters	degree	min	1		1	
		percentile 10	9		9	
		median	20		21	
		average	28		30	
		percentile 90	57		63	
	max	198		191		
weighthed	min	26		44		

degree (kTEUs)	percentile 10	148	143
	median	886	802
	average	3.952	3.755
	percentile 90	9.409	9.357
	max	101.490	92.227
betweenness centrality	min	0	0
	percentile 10	9	9
	median	328	315
	average	2.107	2.061
	percentile 90	4.852	5.347
max	63.002	74.030	
μ (clustering coefficient)		0.601	0.597

¹no data available from the 10th of November to the 20th of December

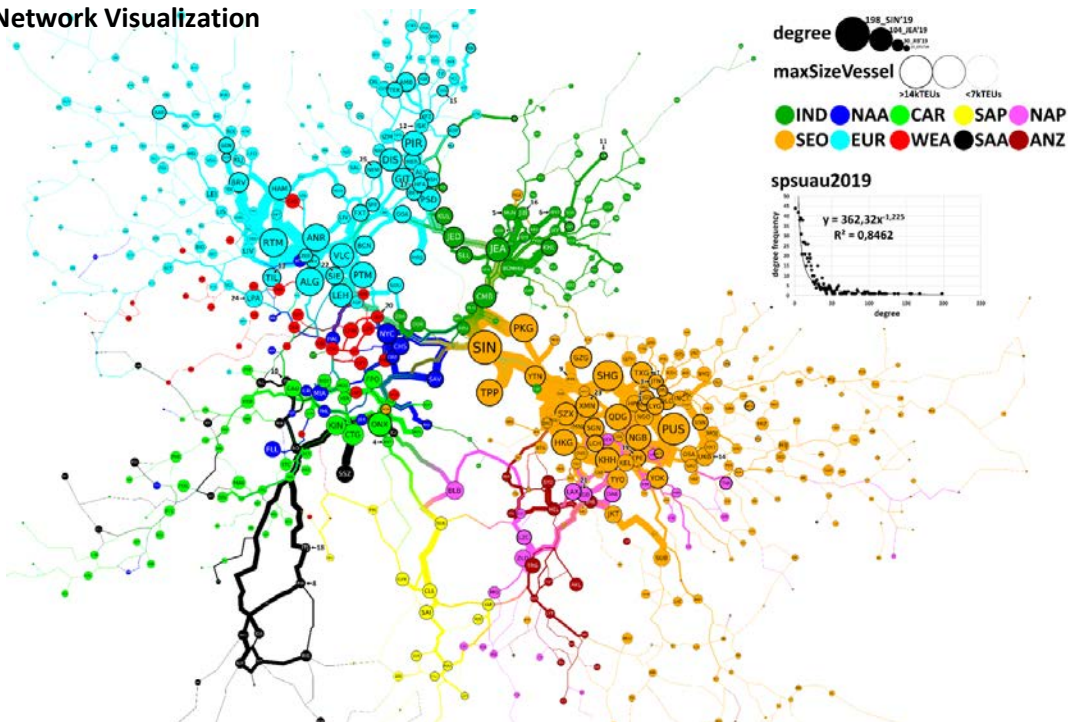
TABLE 1. SAMPLE COMPOSITION.

The network before and after Covid-19 outbreak

The network structure in 2019

FIGURE 1. GLOBAL CONTAINER NETWORK, SPRING-AUTUMN, 2019

Yi-Fan Hu Network Visualization



Geographical location

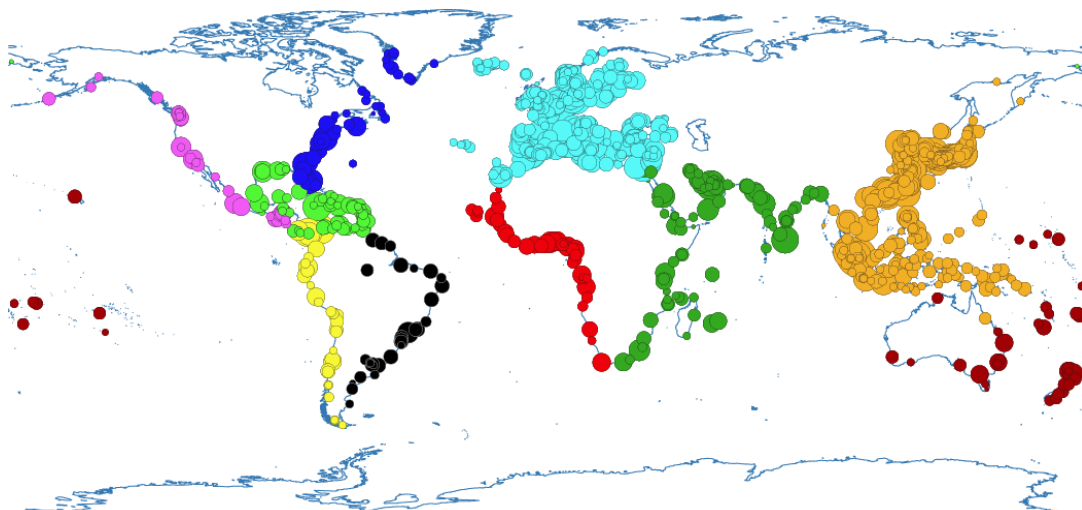


Figure 1 displays the global container network in spsuau2019, with a visualization obtained using the Yifan Hu force-directed algorithm, when starting with the same boundary conditions. This algorithm is particularly relevant for drawing large graphs, reducing edge-crossing (Hu, 2005). It provides a good trade-off to approximate short and long range relationships between container ports. The Yifan Hu layout method converges to a unique solution, which is obtained when the iterations threshold $\epsilon < 1.0E-4$ is reached. Hence, by establishing a negative exponential distribution for the degree frequency (Cohen and Havlin, 2010) with enough statistical significance (R^2 of 0.8462 and 0.8474 for 2019 and 2020 periods, respectively), the Yifan Hu methodology appears as a robust procedure for adding a valid topological distance function, based on the node's direct connectivity.

In the graph, the size of nodes reflects their degree and the thickness of links reflect the number of vessels transiting through them. Each color represents a port region (see Appendix 6), the main ones being the Far East (dark yellow) and the Euromed (light blue). These two areas concentrate most of the largest nodes, and generate many of the thickest links. Other highly connected regions are organized around the Indian Ocean (dark green) the Caribbean (light green) and, to a lesser extent, the Atlantic Coast of North America (dark blue).

There are important differences between regions. The Atlantic Coast of South America (black) and Oceania (dark red) have an elongated shape. Others, such as the Indian Ocean (dark green) and the Far East (dark yellow) combine a relatively compact structure around the main nodes, and a more scattered tail of related small nodes. Each region is more or less polarized around one or several large nodes. Thus, some regions, such as Euromed (light blue), Africa (red), the Caribbean (light green), the Atlantic coasts of North America (dark blue) and South America (black), have largely intertwined port links, while it is not the case of others. Port links in the Pacific Ocean are also intertwined, albeit to a lesser extent.

The main ports at the center of the graph are mostly from East Asia (dark yellow): Singapore (SIN) Tanjung Pelepas (TPP) and Port Kelang (PKG), yellow). The Indian Ocean region (green), West Africa (red) and the Atlantic Coast of North America (dark blue) are also relatively close to the center of the graph. At the margins of the graph most of the nodes are small, and the ties with rest of the network are few and small. Between the core and the margins there is a large zone with nodes of very different size, such Busan (PUS) in East Asia (dark yellow), Colon (ZLO) in the Pacific (pink) ,Cartagena (CTG) in the Caribbean (light green), Hamburg (HAM) and (PIR) in Euromed (light blue).

We find in Figure 3 (2019) that the main links take place between East Asia and Euromed. Strongly mediated by Singapore (SIN), the shipping services appear to follow two well-separated tracks: one making strong intermediate calls in Middle East positions (Jeddah - JED- and Jebel Ali -JEA-) and in the Mediterranean range line formed by Port Said (PSD)- Piraeus (PIR)-Malta Freeport (DIS); and the other one directly supplying from Singapore (SIN) to Valencia (VLC)-Algeciras (ALG)-Tanger MED (PTM)-Le Havre (LEH) line.

Adjacent to this East Asia - Euromed axis, the different World regions appear in different pre-Covid configurations. Starting or arriving from Euromed ports: the West Coast of Africa, tangent to the European subnetwork of services (with some merging like Casablanca -CAS- or Abidjan -ABJ-); the Northern America Atlantic (NAA) positions, strongly mixed with Caribbean (CAR) services; and the South American Atlantic Positions, which tend to be mainly mediated by CAR hubs.

The North America Pacific (NAP) region (especially for the northern port group of Seattle (SEA) - Vancouver (VAN), and for Oakland (OAK)) appears to be tightly with several Asian hubs. The Australia-New Zealand (ANZ) region appears to play a subsidiary role and is more connected with the North America Pacific than with East Asia. Special mention must be made of the Colon (ONX) - Balboa (BLB) line, which represents an alternative route through Panama. The South America Pacific Coast (SAP) seems to be weakly connected with the rest of the network, mainly through Buenaventura (BUN), which links the South America Pacific Region with North America Pacific.

All in all, the graph highlights a core/periphery structure with the most important nodes and routes and the core over which largest vessels are deployed.

Changes in inter-port links before and after the Covid-19 outbreak

Largest positive variations

Port 1	Port 2	Weighted degree variation rate
Gwangyang, KR	Shanghai, CN	453%
Port Qasim, PK	Mundra, IN	432%
Yokohama, JP	Manzanillo, MX	196%
Qingdao, CN	Gwangyang, KR	192%
Yantian, CN	Los Angeles, US	158%
Gwangyang, KR	Ningbo, CN	139%
Singapore, SG	Rotterdam, NL	132%
Tema, GH	Lome, TG	112%
Incheon, KR	Dalian, CN	109%
Piraeus, GR	Port Said, EG	85%
Gioia Tauro, IT	Kulayyah, SA	55%
Tanger Med, MA	Algeciras, ES	55%
Rotterdam, NL	Southampton, UK	50%
Singapore, SG	Kobe, JP	50%
Valencia, ES	Gioia Tauro, IT	48%
Port Klang, MY	Qingdao, CN	47%
Brisbane, AU	Singapore, SG	40%
Sines, PT	Antwerpen, BE	39%
Shanghai, CN	Long Beach, US	39%
Port Said, EG	Kulayyah, SA	37%
Buenaventura, CO	Guayaquil, EC	36%
Jebel Ali, AE	Mundra, IN	34%

Largest negative variations

Port 1	Port 2	Weighted degree variation rate
Buenaventura, CO	Callao, PE	-55%
Jebel Ali, AE	Mumbai, IN	-48%
San Antonio, CL	Callao, PE	-46%
Busan, KR	Hong Kong, HK	-44%
Rotterdam, NL	Colombo, LK	-41%
Felixstowe, GB	Singapore, SG	-39%
Kaohsiung, TW	Busan, KR	-39%
Ningbo, CN	Taipei, TW	-38%
Jebel Ali, AE	Port Klang, MY	-34%
Port Klang, MY	Mumbai, IN	-34%
Rotterdam, NL	Felixstowe, GB	-34%
Genova, IT	Barcelona, ES	-34%
Le Havre, FR	Rotterdam, NL	-34%
Buenos Aires, AR	Rio Grande, BR	-33%
Lazaro Cardenas, MX	Balboa, PA	-32%
Jebel Ali, AE	Karachi, PK	-31%
Kaohsiung, TW	Qingdao, CN	-30%
Colon, PA	New York, US	-30%
Balboa, PA	Buenaventura, CO	-28%
Kaohsiung, TW	Shenzhen, CN	-28%
Felixstowe, GB	Antwerpen, BE	-27%
Valencia, ES	Tanger Med, MA	-27%

Yantian, CN	Singapore, SG	34%	Southampton, GB	Le Havre, FR	-27%
Felixstowe, GB	Hamburg, DE	33%	Marseille, FR	Valencia, ES	-26%
Mundra, IN	Karachi, PK	31%	Long Beach, US	Busan, KR	-26%

TABLE 2. MAIN INTERNATIONAL EDGES. TOP 25 LARGEST VARIATIONS. IN BOLD: SHORT DISTANCE.

Table 2 shows the largest variations in international port links between the spring-autumn period in 2019 and 2020. The short distance links appear in bold, and represent 60% of the top-50 largest variations (both positive and negative).²

In the case of positive variations, the share of short distance links is slightly lower, at 56%. Many of the short links seem to be “hierarchical”, in the sense that they involve a large and a secondary port within Asia. It is the case, for example, between large Chinese gateways (Shanghai, Dalian and Qingdao) and South Korean secondary ports (Gwangyang, Incheon). A similar pattern occurs in the Indian subcontinent between Mundra, which is the top Indian gateway, with much smaller ports in Pakistan (Port Qasim, Karachi). Outside of Asia, positive variations are not systematically associated to hierarchical links. In the Mediterranean, they concern inter-hub ties (Port Said, Piraeus, Tanger Med, Algeciras, Valencia, Gioia Tauro). In Northern Europe, they concern cross-channel connections between the top gateways (Rotterdam, Hamburg) and British ports (Southampton, Felixstowe)³. It is worthwhile to mention two short distance links in emerging regions outside Asia: between Lome and Tema in West Africa, and between Buenaventura and Guayaquil in the West Coast of South America. Many of the above-mentioned ports also appear in the top-25 list of increasingly connected ports (Appendix 5).

Some of the most dynamic links connect distant ports mainly on East-West trade lanes: three are Transpacific, one connects Europe to Asia. The port of Singapore is involved in four of the eleven most dynamic long distance links.

When it comes to the negative variations, the share of short distance links is slightly higher, at 64%. Seven of the sixteen short distance declining links involve European ports. Three of them concern the cross-channel trade (Felixstowe is linked with Antwerpen and Rotterdam, Southampton-Le Havre). The rest concerns Mediterranean ports, such as for example Valencia-Marseille or Genoa-Barcelona.

In Asia negative variations on short distance links notably affect top ports in South Korea (Busan) and Taiwan (Kaohsiung, Taipei) in their relationships with each other and with

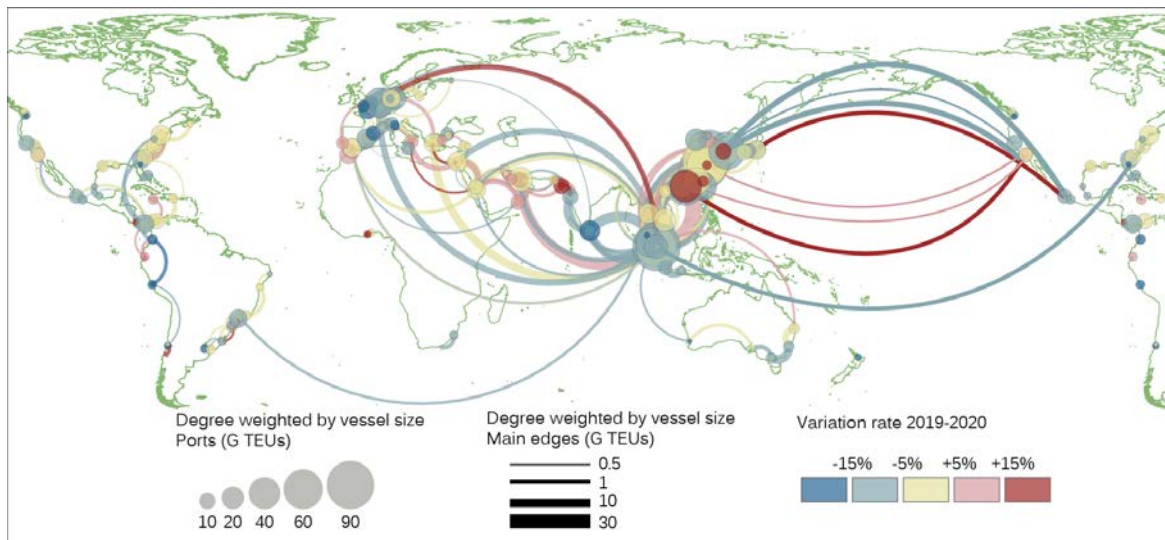
² We consider short distance the inter-port links within a 48 hours navigation range, using the website sea-distances.org as a reference, with a vessel speed of 18 knots.

³ The confluence of Covid and Brexit placed extra pressure on UK ports. In 2020, British importers ordered more goods as a preventive strategy against the risk of a hard Brexit. In a context of capacity shortage, carriers were reluctant to take bookings from the UK because of the congestion at English ports (KBB Review, 2021).

(Mainland) Chinese ports. A number of declining links can also be found in the West Coast of South America, involving ports such as Balboa, Buenaventura and Callao.

In the top main negative variations, there are some long distance links. Three of them concern the links of Jebel Ali with other ports in the Indian Ocean and Malacca strait. There are two Europe-Asia links and one Transpacific.

FIGURE 2. MAIN EDGES (95 PERCENTILE)



The map in Figure 2 provides a geographical visualization of the main variations at the level of ports and links. It shows that only few ports, mostly in East Asia, saw their positions improved between 2019 and 2020. Many of the World largest ports declined, particularly in the Malacca Strait (Singapore, Tanjung Pelepas, Port Kelang), Colombo and Europe. In the Middle East and North America, changes were less dramatic. When it comes to variations on the links, the map confirms the importance of East Asia and Malacca strait.

Many of the negative variations concern the relationships between ports in the Malacca strait with their counterparts in Europe, Sri Lanka and in the East Coast of America. Another port which lost momentum is Busan in many of its Transpacific links.

The links exhibiting the greatest positive variations connect Asian ports with each other and with the rest of the world. It is the case for example of Malacca strait ports' links with China, Transpacific trade from China to North America, and shorter distance links around the Suez Canal.

All in all, the main positive variations concern links between Asian ports and links between Asia and the rest of the world. However, there are some important hubs around China that have lost momentum such as Busan, Kaohsiung and Port Klang. Another major change relates to the connections of the Indian subcontinent, which are increasingly channeled through Mundra to the detriment of hubs such as Colombo or Jebel Ali. The situation in the rest of the world is overall negative, especially in Europe with only few hubs improving their

weighted degree (Tanger Med, Sines, Gioia Tauro). There is a reorganization of the cross-channel links, with negative consequences for several ports such as Le Havre and Felixstowe.

Some ports from emerging have seen their inter-port links increasing more than expected. This is for example the case of a number of ports in Brazil and Turkey (see list of 4 increasingly connected ports in Appendix 5). Brazil has seen in 2020 an increase in the capacity deployed to Asia (Gomez Paz & Sanchez, 2021) and even an increase of its food exports. Turkey was one of the few countries to avoid an economic contraction in 2020, and has been able to repurpose clothing manufacturing to the production of personal protective equipment during the Covid-19 crisis (Barlow et al., 2021). Both countries were prominent in some of the most resilient sectors, which were textiles and food. They appear as relevant candidates for near-shoring part of the supply chains of essential goods, which have been proven to be particularly vulnerable during the Covid-19 crisis (Van Hassel et al., 2021).

Exploratory analysis of the correlation between lockdowns and the geographical concentration of port calls

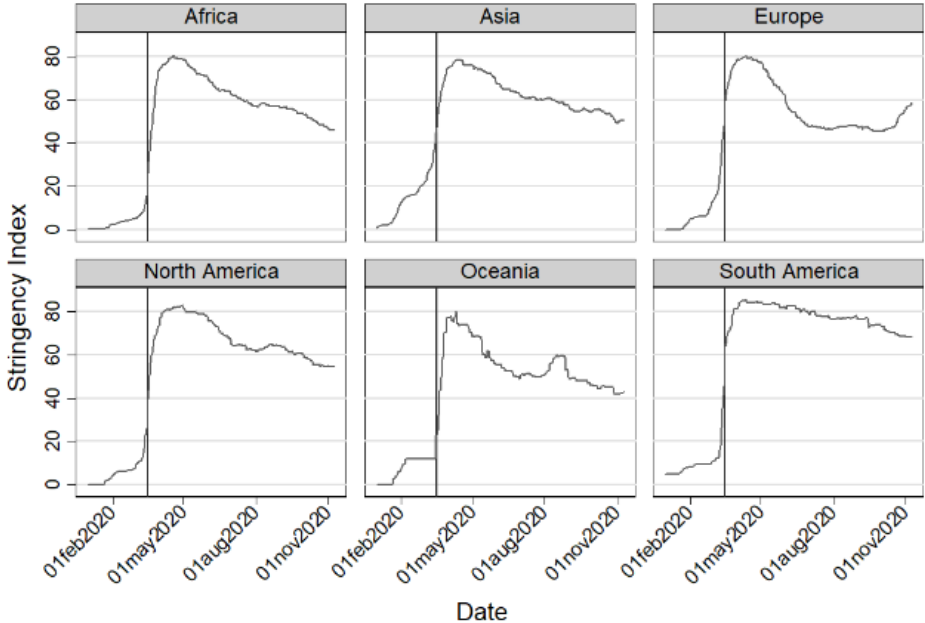


FIGURE 3. EVOLUTION OF THE COVID-19 STRINGENCY INDEX IN THE FIRST NINE MONTHS OF 2020 (SOURCE: THOMAS ET AL., 2021)

We empirically investigated how the Covid-19 outbreak affected port activity. First, we examined how the crisis affected regional port hierarchies, by measuring changes in the concentration of ports’ throughput (more precisely of ports’ weighted degree which is the sum of the capacities of the vessels calling at a port [measured in number of TEUs]) in each region. Then, we analyzed the unequal impacts of the crisis on ports’ throughput, depending on ports’ network characteristics. For the sake of simplicity, we considered that the governmental measures against the spread of Covid-19 were simultaneously launched in mid-March 2020 throughout the world and were kept in place until the end of the period

under study (i.e. autumn 2020), so that our analyses basically compared the periods before and after mid-March 2020. The OxCGRT database built by Thomas et al. (2021) confirms this simultaneity, as shown in Figure 3, where the time evolution of the average Stringency Index of Covid-19 measures taken by governments in each region is depicted. This Stringency Index is an aggregated indicator built by Thomas et al. (2021), which takes into account school closing, workplace closing, cancellation of public events, restrictions on gatherings, closing of public transport, stay at home requirements, restrictions on internal movements, international travel controls and public information campaigns. This figure clearly shows that mid-March 2020 (represented by the black vertical line) was indeed a turning point for governmental measures taken to contain the Covid-19 epidemics.

Impact of Covid-19 on regional port hierarchies

The concentration (i.e. inequality) of throughput at ports has been widely used in port geography to measure spatial change in port systems (see Ducruet et al, 2009 for a compelling literature review). A port system generally evolves from an initial pattern of scattered ports with similar throughput levels, to a hierarchical pattern dominated by the most competitive ports. Port concentration may favor economies of scale both on sea and land transport legs, but may also reduce international trade's resilience by making it dependent on a handful of ports. Beyond a certain level, concentration may also lead to congestion and high levels of pollution.

Several mechanisms can be expected to play a role in the determination of the evolution of the port concentration linked with the Covid-19 crisis, depending on the preexisting structure of international flows of "essential" and "non-essential" goods and on the distribution of these flows across ports. First, during economic crises, maritime trade of essential goods tends to be more resilient than the trade of non-essential goods (Notteboom et al, 2021). Therefore, if "non-essential" goods are more concentrated in large ports than "essential" goods, the crisis would lead to a de-concentration of flows. If, on the opposite, "essential" goods are more concentrated in large ports, the opposite phenomenon would take place. Second, the closure of country borders and the ensuing delays at border crossings may reduce the ability of the largest ports to attract hinterland flows from neighboring countries, also leading to de-concentration. Third, port delays due to the introduction of additional sanitary protocols could have played either way, depending on whether small or large ports were the most subject to delays during this period.

The Gini coefficient is used to evaluate the concentration of ports' throughput (measured in terms of weighted degrees where the weight corresponds to the vessel capacity measured in TEUs) at the regional level. Its evolution is depicted in Figure 4, where the vertical line corresponds to mid-March 2020 (the date at which most governmental measures were implemented).⁴ We can observe on this figure that the weekly variations of the Gini

⁴ Note that we chose to focus on weekly observations of Gini coefficients, rather than monthly, seasonal or yearly ones, in order to ensure a sufficient number of observations for the subsequent statistical analysis. The volatility of this weekly data is quite moderate, as the computation of the Gini coefficient at the continental level allows to (spatially) average out port level volatility of weekly throughput.

coefficient are larger in peripheral regions (Africa, Oceania, South America), due to a lower volume of overall port throughput. In the regions that are the most central in the maritime network (Asia, Europe), the Gini coefficients are significantly higher and rather stable over time. In Africa, there is a clear upward trend of the Gini coefficient before the Covid-19 outbreak, which appears to have been stopped by the crisis. There are no clear upward or downward trends in the other regions. However, a closer look at the figure shows a slight de-concentration in Europe after mid-March 2020, and a slight concentration in North America. A simple difference-in-differences methodology, comparing the before- and after-Covid-19 periods, is applied to study the evolution of five inequality indicators of port throughput in order to confirm these observations. The following specification is used:

$$\text{Ln}(\text{Ineq}_{Cw}) = \sum \alpha_C 1_{w,cov} \times 1_C + \sum \beta_{Cm} 1_C \times 1_m + \gamma_{CW} \times 1_C + \epsilon_{Cw}$$

Where $\text{Ln}(\text{Ineq}_{Cw})$ is the logarithm of one of the five indicators measuring inequality in port throughput within region C during week w, $1_{w,cov}$ is a dummy equal to 1 if week w is after the start of Covid-19 governmental measures, i.e. after mid-March, 1_C is a dummy for region C, 1_m is a dummy for month m and ϵ_{Cw} is an error term. The first sum therefore allows to measure an estimation of the effect of Covid-19 on each region, the effect on region C being measured by α_C . The second sum corresponds to region*month fixed effects and the third term controls for the time trend of inequalities between port throughputs at the regional level.

The five indicators measuring inequality in port throughput are the following: the Gini coefficient, Atkinson’s index with a parameter of 1 and 2, and the Generalized Entropy coefficient with a parameter of 0 and 1.

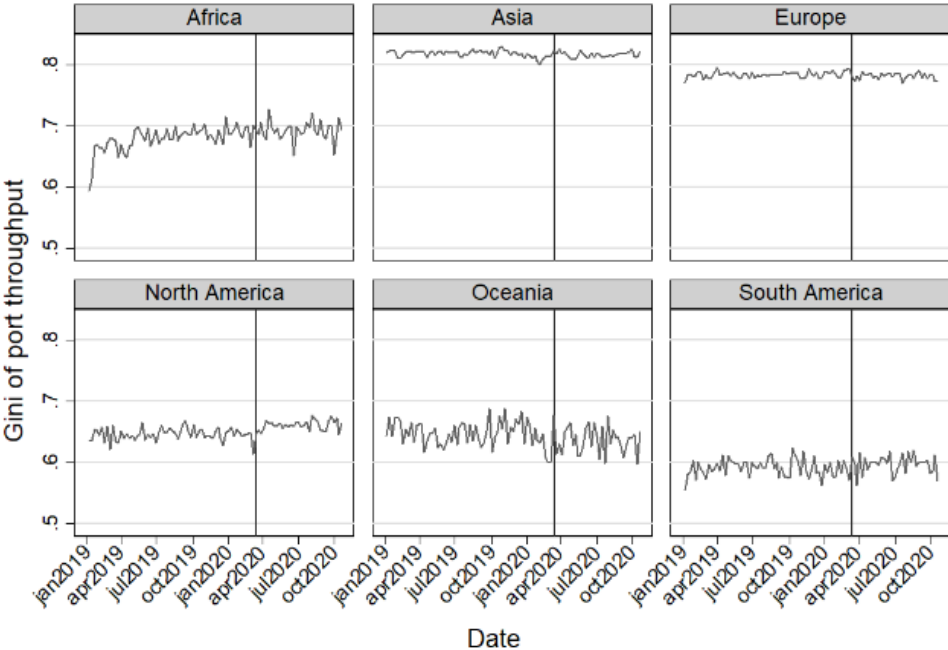


FIG. 4. GINI COEFFICIENT MEASURING INEQUALITIES IN PORTS' THROUGHPUTS (I.E. PORTS' WEIGHTED DEGREES MEASURED IN NUMBER OF TEUS) AT THE REGIONAL LEVEL.

The regressions' results are depicted in Table 3, where each column corresponds to a different inequality index and each line to the effect of Covid-19 measures on a specific region. The results suggest that Covid-19 measures were associated with a de-concentration of port throughputs in Europe and Africa, and a concentration in Asia and North America.⁵ It is not evident to interpret these contrasted effects. However, we may formulate the following hypothesis. In Europe, the level of port throughput concentration was particularly high before the Covid-19 crisis (the concentration of port throughput was only higher in Asia as can be seen in Figure 4). One of the conditions enabling this high concentration of port throughput is the free flow of goods between the many well-connected small European countries. In this context, the sanitary measures introduced at the borders of European countries may have led to diversion effects, reorienting trade to national ports instead of larger ports located in neighboring countries. The same kind of border effect may have been at play in Africa, while it is possible that Asia and North America, where cross-border hinterlands are less important, were less affected by border effects. It is also possible that the largest ports in Europe and Africa handled a larger proportion of "non-necessary" goods as compared to their Asian and North American counterparts.⁶

Variables	(1) Gini	(2) Gen. Ent. 0	(3) Gen. Ent. 1	(4) Atkin. 1	(5) Atkin. 2
Covid*Europe	-0.011*** (0.003)	-0.034*** (0.012)	-0.033*** (0.011)	-0.014*** (0.005)	-0.004 (0.002)
Covid*Africa	-0.032** (0.016)	-0.084** (0.036)	-0.090** (0.043)	-0.051** (0.022)	-0.023** (0.010)
Covid*Asia	0.006*** (0.002)	0.064*** (0.010)	0.008 (0.008)	0.022*** (0.003)	0.012*** (0.003)
Covid*North America	0.021** (0.009)	0.039* (0.021)	0.048** (0.022)	0.022* (0.012)	0.009* (0.005)
Covid*South America	0.000 (0.012)	0.011 (0.030)	0.007 (0.027)	0.006 (0.020)	0.001 (0.013)
Covid*Oceania	0.027* (0.015)	0.074 (0.047)	0.069* (0.035)	0.045 (0.028)	0.021 (0.018)
Observations	570	570	570	570	570
R-squared	0.973	0.967	0.977	0.953	0.898

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

TABLE 3. DIFFERENCE-IN-DIFFERENCES ESTIMATION OF COVID'S IMPACT ON INEQUALITIES IN PORTS' THROUGHPUTS AT THE REGIONAL LEVEL

⁵ To be more precise, the first coefficient of Column (1) means, for example, that the Covid-19 crisis is estimated to have led to a 1.1% decrease in port concentration in Europe, as measured by the Gini coefficient.

⁶ The same analysis has been led with a monthly time unit. The results obtained are consistent with the weekly ones in the sense that all point estimates have the same sign. However, with monthly data, the statistical power of the analysis is much reduced, so that fewer point estimates are statistically different from zero.

Impact of the governmental measures against the spread of Covid-19 on ports' throughput, depending on ports' position in the maritime network

To understand how Covid-19 affected ports, we now turn to the assessment of the impact of governmental measures on ports' weighted degree (i.e. weighted by vessel capacity measured in TEUs), depending on ports' position in the maritime network, focusing on two key indicators: the weighted degree and the clustering coefficient.⁷⁸ The clustering coefficient of a port corresponds to the ratio of the number of links between its neighboring ports (i.e. the ports it is linked with) divided by the number of links that could possibly exist between these ports. In other words, it is the ratio of the number of observed triangles (or triplets, cliques) as compared to the maximum numbers of possible triangles (or triplets, cliques) in the neighborhood of node i . This coefficient is low for ports playing the role of hubs or bridges (i.e. ports that are strategic pivots between different world regions and which neighboring ports are poorly connected with each other) within the network and high for ports that are well-integrated in densely interconnected parts of the network (Ducruet et al., 2016).

The link between these two indicators is non-trivial, as evidenced by the graph in Appendix 2: very small ports may have very high or very low clustering coefficients, but very large ports logically do not have very high clustering coefficients (as they are linked with many ports, which cannot all be linked with each other). The Appendix 3 shows that the geographical distribution of ports, depending on their clustering coefficient, is quite balanced.⁹ To get a first flavor of how network indicators can lead to different effects of the Covid-19 crisis, we subdivide the sample of 647 ports into 4 categories:

- (1) low clustering coefficient and low weighted degree
- (2) low clustering coefficient and high weighted degree
- (3) high clustering coefficient and low weighted degree
- (4) high clustering coefficient and high weighted degree

where low (resp. high) clustering coefficient means “below the median clustering coefficient” (resp. above) and idem for the weighted degree. The average evolution of the logarithm of the throughput of ports belonging to each category is depicted in Figure 5. We can observe in this figure that the throughput seems to have decreased after the start of Covid-19 governmental measures in all categories of ports except the fourth, which is associated with both a high clustering coefficient and a high weighted degree.

⁷ The weighted degree of a port corresponds to the number of vessel calls, weighted by vessel capacity (measured in TEUs).

⁸ The impact of other centrality measures such as betweenness centrality has also been investigated, but found to be insignificant.

⁹ The table of Appendix 5 depicts, for each continent, the proportion of ports belonging to each quintile of clustering coefficient.

In order to evaluate more precisely the effect of Covid-19 depending of ports' network characteristics, we apply, once more, a difference-in-differences methodology, using the following specification:

$$\text{Ln}(F_{p,c,m}) = \alpha \times 1_{m,cov} + \sum \alpha_n 1_{m,cov} \times B_{pn} + \sum \beta_{cm} 1_c \times 1_m + 1_p + \epsilon_{pcm}$$

where $\text{Ln}(F_{p,c,m})$ is the logarithm of the throughput of port p located in country c during month m , $1_{m,cov}$ is a dummy variable equal to 1 if month m is equal to or after March 2020, B_{pn} is a measure of port p 's level of centrality in the maritime network according to index n (n can be the clustering coefficient or the weighted degree),¹⁰ 1_c is a dummy equal to 1 if the country is c , 1_m is a dummy equal to 1 if the month is m , 1_p is a dummy equal to 1 if the port is p and ϵ_{pcm} is an error term.

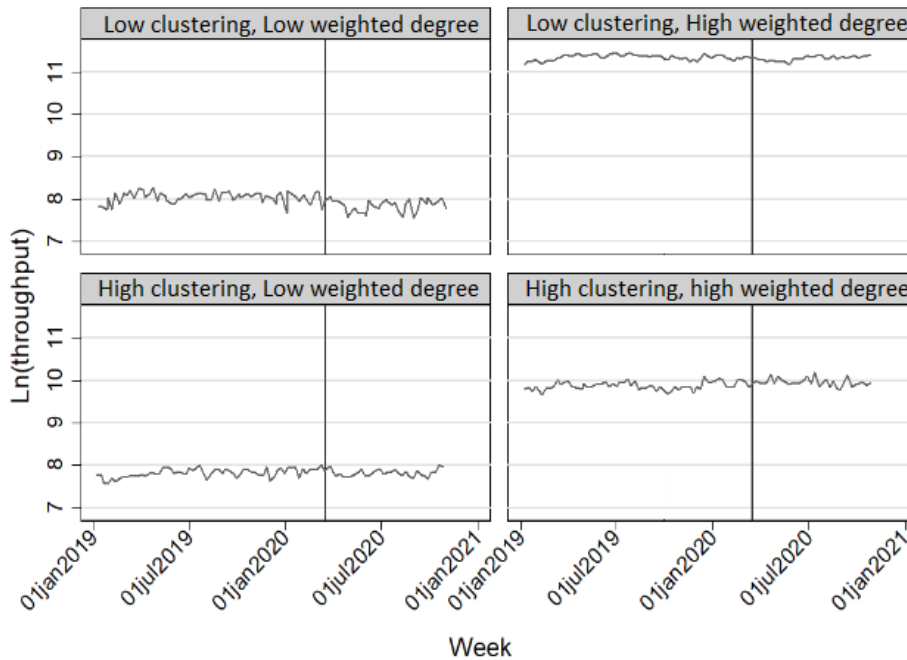


FIG. 5. EVOLUTION OF THE LOGARITHM OF PORT THROUGHPUT (MEASURED IN NUMBER OF TEUS)

Alternative specifications are also tested with, instead of country*month fixed effects, (1) season fixed effects, (2) season*region fixed effects, (3) season*country fixed effects, (4) year*port and season*country fixed effects. The results of the regressions, run at the world scale, are depicted in Table 7, where our preferred specification corresponds to Column (5) and the four preceding columns correspond to the four alternative specifications just described. We can observe that Covid-19 governmental measures had a negative effect on ports' throughput (first line of the table), and that high clustering coefficients and high weighted degrees seem to have mitigated this negative effect of Covid-19.¹¹¹² Thus, it

¹⁰ Note that the weighted degree has been normalized so that it is never larger than 1.

¹¹ In this table, the first coefficient of Column (1) means that the Covid-19 outbreak is estimated to have led to a 19% decrease in port throughput on average. The second coefficient means that a port with a clustering level

appears that two profiles of ports seem to have well resisted to the crisis: large ports (i.e. with high weighted degrees) and small ports inserted in dense local maritime networks (i.e. with high clustering coefficients). Indeed, while the formers' crucial role in the structure of the maritime transport network ensured them continued traffic, the latter's' key location within dense parts of the network seems to have protected them against a drop of activity. On the contrary, ports playing the roles of hubs or bridges in the network have been more severely affected by Covid-19 mitigation measures.¹³

	Whole world				
	Spec. 1 (1)	Spec. 2 (2)	Spec. 3 (3)	Spec. 4 (4)	Spec. 5 (5)
Covid	-0.191*** (0.045)	-0.193*** (0.045)	-0.191*** (0.045)	-0.196*** (0.047)	
Covid*Clustering	0.237*** (0.077)	0.240*** (0.077)	0.238*** (0.078)	0.238*** (0.078)	0.271*** (0.094)
Covid*Weighted Deg.	0.337*** (0.105)	0.346*** (0.106)	0.328*** (0.106)	0.327*** (0.107)	0.232 (0.199)
Observations	13,932	13,932	13,932	13,932	13,932
R-squared	0.013	0.015	0.055	0.055	0.282
Number of ports	647	647	647	647	647
Controls					
FE port	X	X	X	X	X
FE year*port				X	
FE season	X				
FE season*continent		X			
FE season*country			X	X	
FE month*country					X

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

TABLE 7. DIFF-IN-DIFF ESTIMATION OF THE IMPACT OF COVID-19 CRISIS ON PORT THROUGHPUT, DEPENDING ON THE NETWORK CHARACTERISTICS OF PORTS (CLUSTERING COEFFICIENT AND WEIGHTED DEGREE)

of 1 (the maximum clustering coefficient possible) experienced a 24% larger increase in port throughput due to the Covid-19 than a port with a clustering level of 0 (the minimum clustering coefficient possible). The third coefficient means that a port with a normalized weighted degree of 1 (the maximum normalized weighted degree possible) experienced a 33.7% larger increase in port throughput due to the Covid-19 than a port with a weighted degree of 0 (the minimum weighted degree that is theoretically possible).

¹² The impact of the average size of ships coming to ports has also been investigated, but found to be insignificant.

¹³ These results also hold when considering only European or only Asian ports (Europe and Asia being the regions with the highest number of ports), as can be seen in Table "Appendix 2".

Conclusions

This research considered the container transport system as a complex network of ports. It showed a neat decrease in port connectivity between 2019 and 2020 in terms of weighted degree. Most ports have lost connectivity. However, some ports and inter-port links have better resisted than the others and, in some cases, have even been able to progress. The positive variations concern links between Asian ports and links between Asia and the rest of the world. Yet, some important hubs around China have lost momentum, such as Busan, Kaohsiung and Port Klang. The evolution in the rest of the world is, on the overall, negative, especially in Europe where only a few hubs improved their weighted degree (Tanger Med, Sines, Gioia Tauro). A reorganization of the cross-channel links is observed, with negative consequences for several ports such as Le Havre and Felixstowe. Some ports in emerging countries have seen their inter-port links increase more than expected. This is, for example, the case of a number of ports in Brazil and Turkey, which appear to be relevant candidates for near-shoring part of the production that is currently located in East Asia.

We also analyzed the effects of Covid-19 mitigation measures on port activity at regional and global levels. We found that Covid-19 mitigation measures impacted regional port hierarchies. These effects, however, differ depending on the regions, with an increase in port concentration in Asia and North America and a decrease in Europe and Africa. The sanitary measures introduced at the borders of European and African countries may have led to diversion effects, reorienting trade to national ports instead of larger ports located in neighboring countries. It is possible that in Asia and North America, where cross-border hinterlands are less important, these border effects were less important.

At the global level, Covid-19 mitigation measures had uneven impacts on ports, depending on their weighted degree and on their clustering coefficient. Large ports seem to have resisted better than smaller ports. And, when highly interconnected with their neighbors (high clustering coefficient), small ports have resisted better than the rest. Conversely, ports playing hub or bridge functions have been more severely hit. This result is in line with former works highlighting the higher volatility of hub traffic as compared to hinterland traffic. It calls for carefully examining port projects that focus exclusively on transshipment, as it may increase ports' vulnerability to global shocks such as the Covid-19 crisis.

This research contributes to the extant literature on maritime networks by evaluating the impact of a global external shock, thereby allowing for a closer view on how maritime networks are affected by rapid changes in the macroeconomic environment. The results of our research are also important both for governments and practitioners, as they shed light on how the transportation system reacts to crisis periods. Identifying system vulnerabilities may help to reconsider the organization of global sourcing and supply chain strategies.

Concerning the impact of global crises on the containerized network, some questions remain open. In our view, the issue of blank sailings and delays is central to understanding how the crisis impacted the geography of containerized transport. However, the computation of

these two indicators raises a number of methodological issues, such as the relevant way to identify regular shipping services in a context where a same vessel can be deployed on several distinct services during a same year. Consequently, the present paper abstracted from these questions, focusing on the evolution of the structure of the maritime network and leaving the analysis of blank sailings and delays for future research. Eventually, this article on vessel movements tells only one part of the story. A subsequent study on port throughputs could provide a useful complement for a better understanding of the impacts of Covid-19 on port activity.

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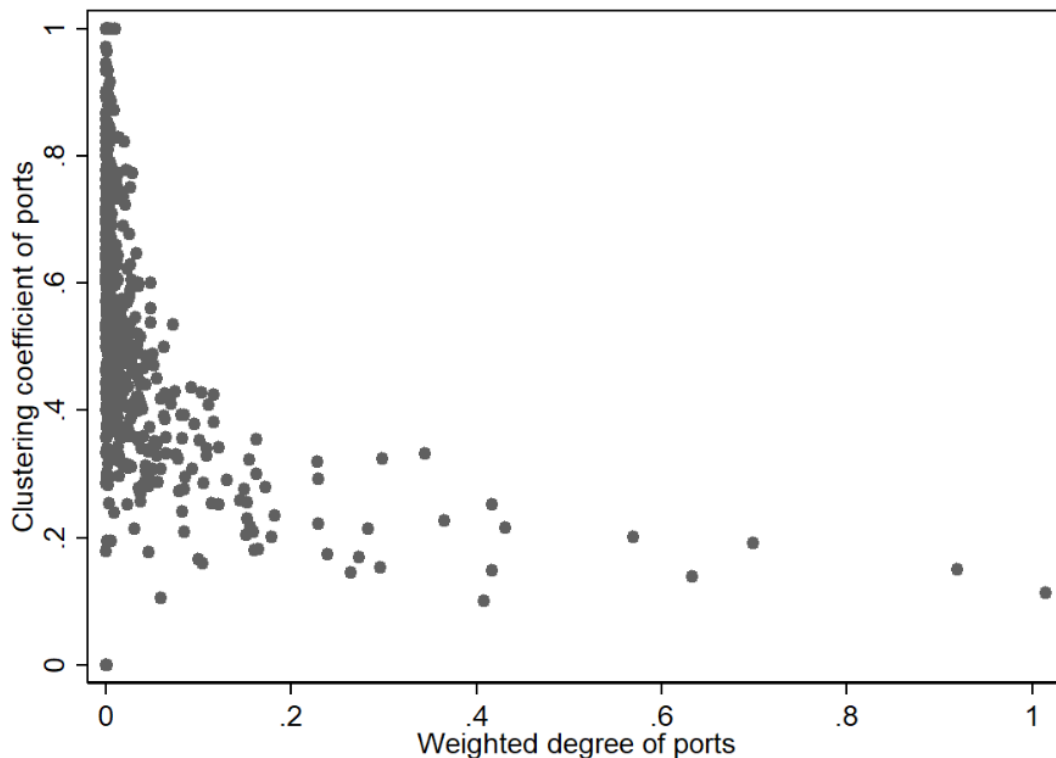
Appendices

Selecting the specifications of Columns (4) and (5) of Table 5 and running them on European, Asian and other regions' ports separately, we obtain Table 6. In this table, we can observe that, even though the lesser number of observations increases standard errors, a high clustering coefficient seems to have protected ports against the negative impact of Covid-19 on other ports' degree.

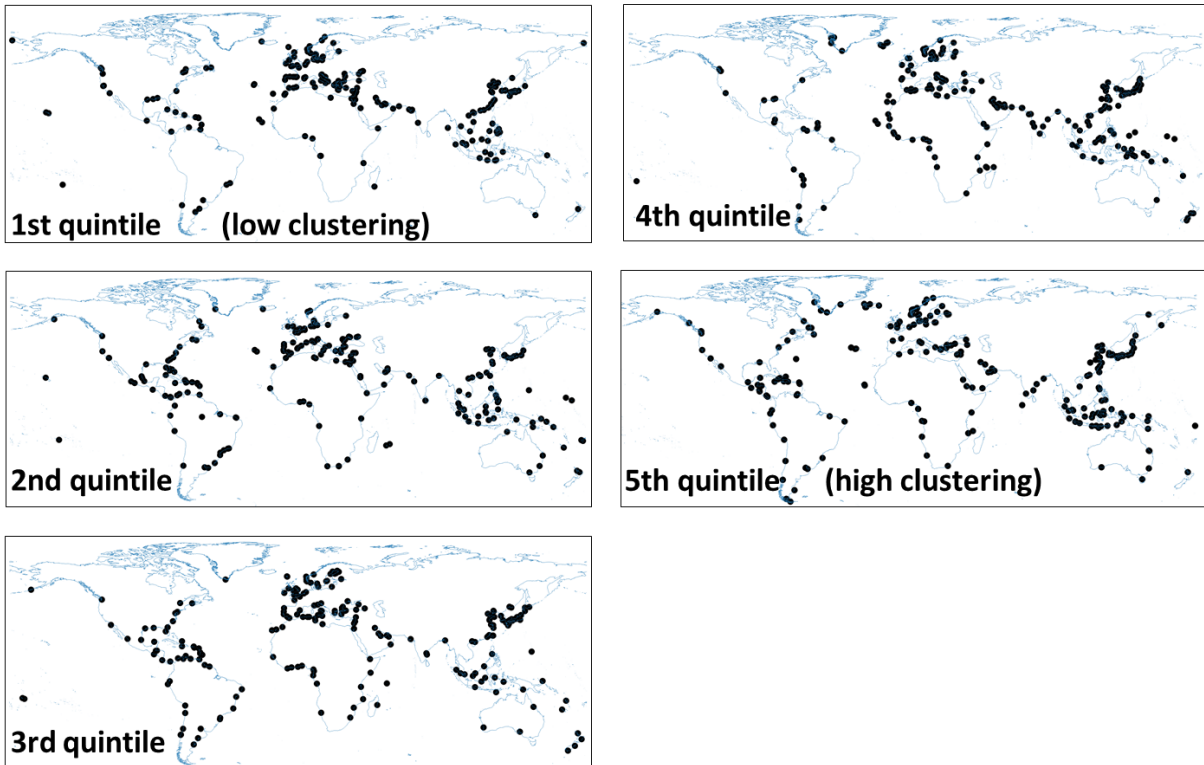
Geographic zone	Europe		Asia		Other continents	
	Spec. 4 (1)	Spec. 5 (2)	Spec. 4 (3)	Spec. 5 (4)	Spec. 4 (5)	Spec. 5 (6)
Covid	-0.266*** (0.089)		-0.265*** (0.101)		-0.103 (0.072)	
Covid*Clustering	0.348*** (0.127)	0.354*** (0.132)	0.384** (0.152)	0.424** (0.178)	0.041 (0.129)	0.088 (0.160)
Covid*Weighted Deg.	0.801** (0.353)	0.967** (0.381)	0.343** (0.148)	0.255 (0.237)	0.372 (0.504)	0.382 (0.747)
Observations	3,799	3,799	4,959	4,959	5,174	5,174
R-squared	0.049	0.202	0.047	0.252	0.087	0.412
Number of ports	174	174	233	233	240	240

Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

APPENDIX 1. DIFF-IN-DIFF ESTIMATION OF THE IMPACT OF COVID'S CRISIS ON PORT THROUGHPUT, DEPENDING ON THE NETWORK CHARACTERISTICS OF PORTS (CLUSTERING COEFFICIENT AND WEIGHTED DEGREE) IN EUROPE, ASIA AND THE OTHER REGIONS



APPENDIX 2. DISTRIBUTION OF PORTS DEPENDING ON THEIR CLUSTERING COEFFICIENT AND WEIGHTED DEGREE



APPENDIX 3. GEOGRAPHICAL DISTRIBUTION OF PORTS DEPENDING ON THEIR CLUSTERING COEFFICIENTS (GROUPED BY QUINTILES)

Clustering coefficient		Africa	Asia	Europe	North A..	Oceania	South A..	World
(Low)	1st quintile	12%	19%	20%	30%	28%	15%	20%
	2nd quintile	21%	16%	20%	25%	16%	31%	20%
	3rd quintile	25%	19%	23%	17%	28%	25%	22%
	4th quintile	25%	19%	23%	7%	13%	13%	18%
(High)	5th quintile	16%	26%	14%	22%	16%	15%	20%
	Total	100%	100%	100%	100%	100%	100%	100%

APPENDIX 4. GEOGRAPHICAL DISTRIBUTION OF PORTS DEPENDING ON THEIR CLUSTERING COEFFICIENTS (GROUPED BY QUINTILES)

Betweenness centrality variation ranking position	Port, Country	Vessel size 3rd quartile (k TEUS)	Vessel size 3rd quartile variation rate	Degree	Degree variation rate	Weighted degree (G TEUS)	Betweenness centrality (normalized)	Betweenness centrality (normalized) variation rate
1	Taichung, TW	2.6	4.4%	41	355.8%	5.9	0.004	93.2%
2	Gwangyang, KR	6.8	-20.1%	65	339.9%	11.3	0.051	89.3%
3	Jintang, CN	8.2	51.9%	64	30.1%	4.4	0.034	82.1%
4	Houston BC, US	8.0	23.1%	27	3.3%	2.8	0.007	77.3%
5	Mundra, IN	9.6	-4.3%	64	49.0%	11.3	0.072	74.7%
6	Hamad, QA	9.2	-2.1%	31	11.4%	5.7	0.009	68.6%
7	Port Qasim, PK	9.4	2.2%	23	28.7%	3.7	0.002	66.9%
8	Paranagua, BR	10.5	5.0%	23	2.8%	7.1	0.007	61.8%
9	Bangkok, TH	1.8	0.0%	25	12.5%	4.0	0.005	52.2%
10	Salvador, BR	9.0	0.0%	19	-4.9%	3.6	0.005	51.6%
11	Jubail, SA	13.0	-2.2%	12	4.7%	2.8	0.000	49.3%
12	Iskenderun, TR	7.1	-15.5%	47	-0.9%	3.1	0.053	48.4%
13	Tilbury, GB	9.4	-1.8%	71	-2.7%	11.1	0.081	48.3%
14	Kobe, JP	4.6	0.0%	71	-2.4%	10.6	0.065	47.9%
15	Trieste, IT	15.2	8.9%	23	-4.2%	2.5	0.003	47.7%
16	Djibouti, DJ	10.4	0.4%	32	-8.3%	2.7	0.027	44.3%
17	Haifa, IL	6.7	-16.2%	51	-0.6%	3.8	0.063	44.1%
18	Itajai, BR	8.7	0.0%	16	2.7%	2.4	0.006	42.0%
19	Taipei, TW	5.7	0.0%	53	-2.5%	7.1	0.036	41.6%
20	Tema, GH	5.8	16.2%	36	49.5%	3.4	0.010	40.9%
21	Long Beach, US	13.1	9.8%	46	5.4%	8.9	0.033	40.3%
22	Sines, PT	11.6	23.1%	55	10.4%	7.0	0.042	39.7%
23	Xiamen, CN	11.4	-13.0%	98	-0.4%	29.7	0.108	38.5%
24	Las Palmas, ES	8.5	25.5%	70	0.2%	3.8	0.101	38.5%
25	Nemrut, TR	6.2	-0.1%	75	13.1%	5.2	0.079	35.6%

APPENDIX 5. TOP 25 RANKING OF INCREASINGLY CONNECTED PORTS, SPRING-AUTUMN 2019/2020

VARIATION

NAP	North America Pacific
SAP	South America Pacific
NAA	North America Atlantic
CAR	Caribbean
SAA	South America Atlantic
EUM	Europe - Mediterranean
WEA	West Coast of Africa
IND	Indian Ocean + Persian Gulf
SEO	South East Asia
ANZ	Australia – New Zealand

APPENDIX 6. WORLD PORT AREAS SPLITTING