

The worldwide maritime network of container shipping: spatial structure and regional dynamics

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Abstract Port and maritime studies dealing with containerization have observed traffic concentration and dispersion throughout the world. Globalization, intermodal transportation, and technological revolutions in the shipping industry have resulted in both network extension and rationalization. However, lack of precise data on inter-port relations prevent the application of wider network theories to global maritime container networks, which are often examined through case studies of specific firms or regions. In this article, we present an analysis of the global liner shipping network in 1996 and 2006, a period of rapid change in port hierarchies and liner service configurations. While we refer to literature on port system development, shipping networks, and port selection, the article is one of the only analyses of the properties of the global container shipping network. We analyse the relative position of ports in the global network through indicators of centrality. The results reveal a certain level of robustness in the global shipping network. While transhipment hub flows and gateway flows might slightly shift among nodes in the network, the network properties remain rather stable in terms of the main nodes polarizing the network and the overall structure of the system. In addition, mapping the changing centrality of ports confirms the impacts of global trade and logistics shifts on the port hierarchy and indicates that changes are predominantly geographic.

Keywords LINER SHIPPING, NETWORK ANALYSIS, NODAL REGIONS, PORT HIERARCHY, SPATIAL CHANGE

Maritime networks are among the oldest forms of spatial interaction. Port hierarchies and the spatial pattern of maritime linkages can be considered as illustrations of wider ongoing processes, such as the regionalization and globalization of trade patterns and

business cycles, thus revealing a certain political economy of the world (Vigarié 1995). Lewis and Wigen (1999) argue that the meta-geography of the world system would be better understood from the maritime looking glass of basins, seas and oceans. Following decades of adaptation and diffusion since the emergence of containerization, the global maritime container shipping network has become a reality (Frémont 2007; Rodrigue and Notteboom 2010). The technological revolution of containerization has gradually produced new forms of relationships among countries, regions and port cities, backed by a continuous pressure on transport costs (Limao and Venables 2001) and an increasing power of shipping alliances and large carriers (Slack and Frémont 2009; Sys 2009). Investigating such changes would complement the lack of evidence about the spatial patterns of commodity chains (Leslie and Reimer 1999) because ports compete not as individual places that handle ships but as crucial links within global supply chains (Hall and Jacobs 2010; Notteboom and Winkelmans 2001).

While the main shipping routes and ports are well described in a number of studies, the structure and evolution of the global maritime network itself has not been fully documented. More extensive is the research on global airline networks due to their closer overlap with systems of cities (Choi et al. 2006; Derudder and Witlox 2009; Guimerà et al. 2005). Despite the local dereliction of port-city linkages in recent decades, maritime transport remains absolutely necessary for globalization. Its crucial weight in world trade volumes (90 per cent) makes it a useful looking glass for analysing the global economy and its geographic architecture. In parallel, the spatial design of maritime transport not only follows trade demand but also possesses its own practical arrangements and network configurations, which also evolve over time. The concentration and regional polarization of flows by load centres and intermediate hubs toward other secondary ports are typical examples of such configurations. It is thus important to evaluate the respective influence of technological factors (for example, carriers and infrastructures, industry changes) and territorial factors (for example geographic and trade proximities, socio-economic developments) in the formation of shipping networks, port hierarchies and maritime regions.

We organize the remainder of this article as follows. Section 2 introduces the concept of port system and reviews the mechanisms shaping port competition, port selection and port concentration, while describing the specificity and complexity of liner service networks. In section 3, we present data on vessel movements (1996 and 2006) and the methodology for analysing the global liner service network, together with some results on the structure and geographic coverage of this network. Section 4 provides a closer look at the port hierarchy based on centrality measures and the geographic pattern of nodal maritime regions. The article ends with a discussion of the research outcomes for further analysis of the global economy and its networks.

Port systems and maritime networks

Port choice and the hierarchy in port systems

Traffic flows through ports are a physical outcome of route and port selection by the relevant actors in the chain. The most relevant service-related and cost factors

explaining port selection by the main players of the transport chain (for example shippers, ocean carriers and forwarders) are identified in the scientific literature on port choice.¹ Port choice becomes a function of the overall network cost and performance. Notteboom (2009b) groups the factors together in the demand profile of the port, the supply profile of the port and the market profile of the port. Typical port choice criteria include factors such as:

- (a) physical and technical port infrastructure, including nautical accessibility (for example draft);
- (b) terminal infrastructure and equipment, hinterland accessibility and intermodal offer;
- (c) geographical location *vis-à-vis* the main shipping lanes and the hinterland;
- (d) port efficiency expressed as port turnaround time, terminal productivity and cost efficiency;
- (e) interconnectivity of the port (sailing frequency of deep-sea and feeder shipping services);
- (f) reliability, capacity, frequency and cost of inland transport services;
- (g) quality and cost of auxiliary services such as pilotage, towage and customs;
- (h) efficiency and cost of port management and administration (for example port dues);
- (i) availability, quality and cost of logistic value-added activities (for example warehousing) and port community systems;
- (j) port security/safety and environmental profile; and
- (k) port reputation.

The aggregate outcome of port choice and supply chain decisions leads to a specific distribution of cargo flows in port systems. The search for regularities in the development of port hierarchies has mostly been done from a continental perspective considering ports as heads of land-based transport corridors willing to extend their hinterland coverage. Early work provided spatial models (Ogundana 1970; Rimmer 1967; Taaffe et al. 1963) suggesting a trend towards an increasing level of cargo concentration in port systems. The concepts of maritime range (Vigarié 1964) and port system (Robinson 1976) originally comprised a set of adjacent seaports in close proximity that were interdependent through land and sea freight flows. However, most scholars have continued focusing primarily on hinterlands, due to the development of intermodalism and logistic chains around ports (Robinson 2002; van Klink 1998) and the higher cost of land transport versus sea transport (Notteboom 2004). The nature and performance of traffics is often explained by the situation of ports within land-based transport and urban systems (Ducruet et al. 2010c).

Although the development of peripheral ports (Hayuth 1981) and offshore hubs has a maritime purpose for cargo distribution toward secondary ports (Notteboom 2005; Slack and Wang 2002), their emergence has been interpreted from the hinterland perspective of a port regionalization process leading to the formation of a

regional load centre network (Notteboom and Rodrigue 2005). There remain important local deviations from general models of port system development due to path dependency and contingency (Notteboom 2006a, 2009a).

The definition of port systems has often been limited to coastal morphology, geographic proximity and administrative boundaries (Ducruet et al. 2009a; Ducruet et al. 2009b). Never have port systems been defined and delineated from the maritime perspective of inter-port linkages. This raises the question of whether physical factors and geographic proximity still play a role in the current spatial patterns of container shipping circulations. The concepts of maritime region and port region, which remain rather descriptive and vague in the literature (Ducruet 2009), may benefit from the application of similar methods used by studies of other global networks (see Derudder and Taylor 2005), allowing for the definition of coherent groups of ports as well as the identification of leader ports. A close look at the current organization of liner shipping networks is necessary before applying specific network analytical tools.

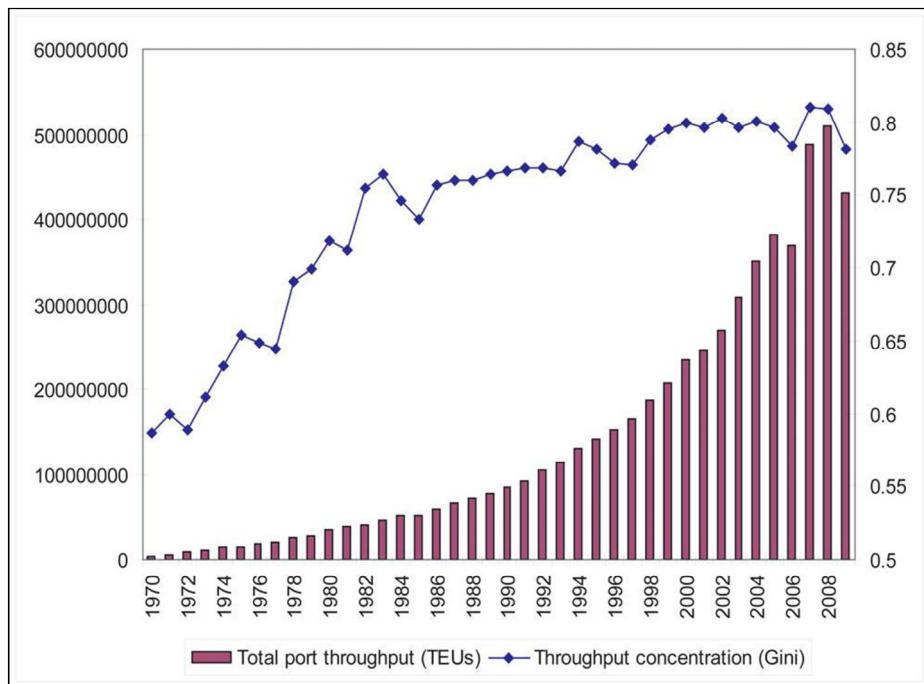
Design and operation of liner service networks

The development of liner shipping in the last 30 years has exceeded the growth of world trade volumes. The activity of this very dynamic branch of maritime transport is measured in Figure 1 based on annual container port throughputs. Besides continuous growth in throughput volumes, we also observe a parallel increase in the concentration in the global port system, notwithstanding slight decreases in recent years, notably after the 2008 financial crisis that directly affected traffic volumes and distributions. Despite those cyclical changes, liner shipping is still built on a series of specific network configurations.

Container shipping features a complex combination of end-to-end services, line-bundling services and pendulum services, which are connected to form extensive shipping networks. Port hierarchy in the container business is intrinsically linked to shipping lines' design of these liner service networks in terms of service variables such as service frequency, vessel capacity, fleet mix, vessel speed and the number and order of port calls (Fagerholt 2004; Notteboom 2006b). Liner service design is a function not only of carrier-specific operational factors (namely lower costs) but also of shippers' needs (for example transit time) and willingness to pay for a better service.

In the last two decades, increased cargo availability has led carriers and strategic alliances among them to reshape their liner shipping networks through the introduction of new types of liner services on the main east–west trade lanes (see Figure 2). The largest ships operate on multi-port itineraries calling at a limited number of ports. The Europe–Far East trade provides a good example. Most mainline operators and alliances running services from the Far East to northern Europe stick to line bundling itineraries with direct calls scheduled in each of the main markets. Notwithstanding diversity in calling patterns on the observed routes, carriers select up to five regional ports of call per loop. Shipping lines have significantly increased average vessel sizes deployed on the route from around 4500 TEU in 2000 to over 7500 TEU in early 2010.² These scale increases in vessel size have put a downward pressure on

Figure 1: World port throughput and concentration, 1970–2009



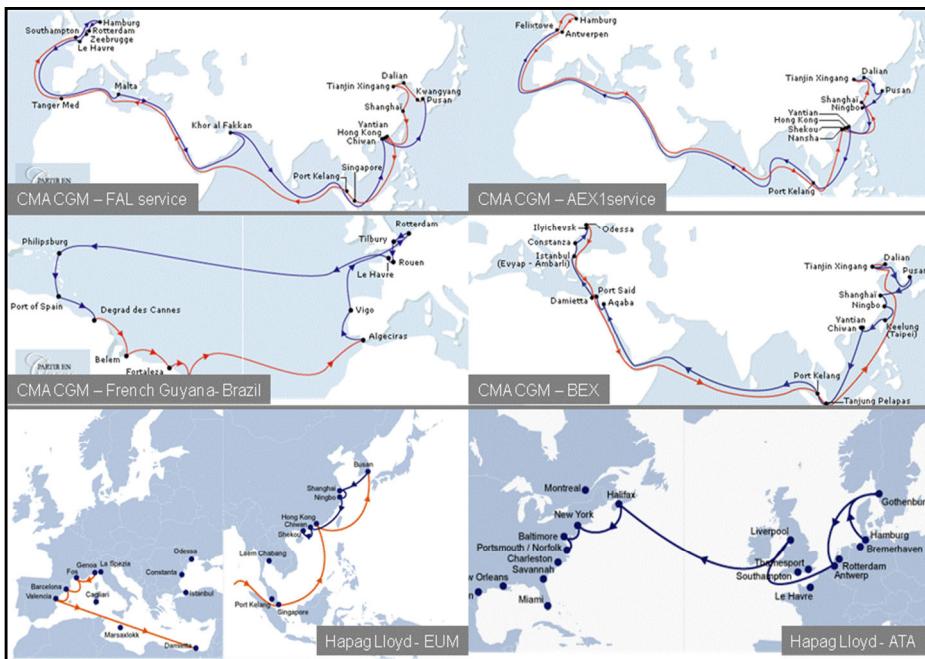
Source: authors' elaboration based on Containerisation International data.

the average number of port calls per loop on the Far East–North Europe trade: 4.9 ports of call in 1989, 3.84 in 1998, 3.77 in October 2000, 3.68 in February 2006 and 3.35 in December 2009.

Maersk Line, MSC and CMA-CGM are among the truly global liner operators with a strong presence in secondary routes. Their networks are based on traffic circulation through specific hubs. Productivity has been improved through the use of larger ships,³ new operational patterns and cooperation between shipping lines. Container shipping lines have been very active in securing (semi)dedicated terminal capacity in the strategic locations within their liner service networks. Figure 3 gives an overview of the strategic ports in the worldwide liner network of Maersk Line. Shipping lines also rely on horizontal integration through operating agreements (for example vessel sharing agreements, slot chartering agreements, consortia and strategic alliances) and mergers and acquisitions. Alliance structures (cf. Grand Alliance, New World Alliance, and CYKH) provide its members easy access to more loops or services with relatively low-cost implications and allow them to share terminals.

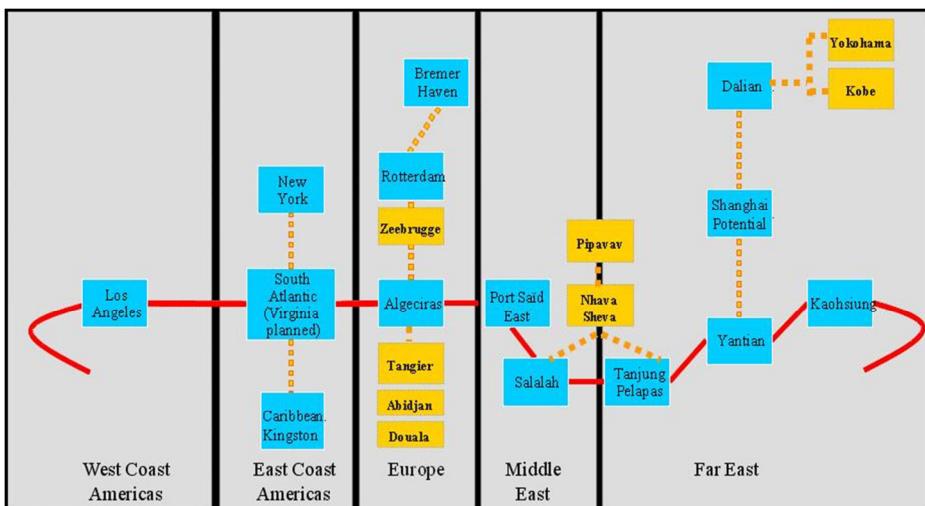
In the last few decades, extensive hub-feeder container systems and short-sea shipping networks have emerged to cope with increasing volumes and to connect to other port ranges (Rodrigue and Notteboom 2010). The economics of transhipment and relay/interlining have resulted in the establishment of intermediate hubs with terminals owned, in whole or in part, by carriers or port operators. In some cases,

Figure 2: Typical examples of liner services on trade routes in relation to Europe



Source: shipping lines' websites.

Figure 3: The main strategic ports in the liner service network of Maersk Line



Note: Relay/interlining involves trade route based transhipment at key network ports between deep-sea vessel strings. The aim is to transfer containers between mainline services, thereby adding new service options.

Source: based on liner service data from Maersk Line.

intermediate hubs were developed within offshore locations often on small islands with an implicit local cargo base (Rodrigue and Notteboom 2010). The development of offshore hubs did not exclude transhipment activities at traditional gateway ports such as in the western Mediterranean port system, where the distinction between hub ports and gateway ports has become blurred (Gouvernal et al. 2005). The position of pure transhipment hubs is generally more unstable than that of pure gateway ports: once traffic volumes for the gateway ports are sufficient, hubs are bypassed and might even become redundant (Wilmsmeier and Notteboom 2010). The location of transhipment hubs remains important, because they lower the deviation distance to/from main trunk lines (Zohil and Prijon 1999). There remains a subtle combination between *centrality* (proximity to origin/destination markets) and *intermediacy* (insertion in carrier networks) in nearly every port (Fleming and Hayuth 1994).

Methodology and liner shipping network characteristics

In their recent review of the scientific literature on maritime network analysis, Ducruet et al. (2010a) stress the scarcity and fragmentation of empirical studies, which are categorized by four main approaches:

- *geographic coverage of carrier networks*: regional or global distribution of the port networks for individual shipping companies based on service data (for example Coscon, Maersk) revealing their strategic choices (Bergantino and Veenstra 2002; Frémont 2007; Rimmer and Comtois 2005);
- *network connectivity*: characteristics of a given network based on its topology, with reference to spatial analysis and graph theory, such as the pioneering study of Joly (1999) showing the tripolar organization of the global maritime system based on Reeds zones, and other works on a regional level (Ducruet et al. 2010b; McCalla 2004);
- *network efficiency*: modelling of port selection processes and search for the optimal location, for instance, of a transhipment hub lowering overall shipping costs (Song et al. 2005; Tai and Hwang 2005; Zeng and Yang 2002); and
- *complex networks*: description of the network's hierarchical structure on a global level comparing its properties with general models of small-world and scale-free networks (Deng et al. 2009; Hu and Zhu 2009; Kaluza et al. 2010).

In this article, we wish to further the interpretation of network structure, port hierarchy and the dynamics influencing them. We give paramount importance to the visualization of the network as a whole and of emerging regional patterns. We base this on a rarely used data source on daily vessel movements, which is more precise than service data and therefore more representative of the reality and complexity of liner shipping.

Data overview

The methodology used for building the global liner network defines an inter-port connection by the circulation of vessels between the ports through a 365-day

sequence of port calls. Thus, nodes (vertices) in the network are the ports and links (edges) in the network are the connections realized by vessel movements (Table 1). We chose the years 1996 and 2006 because 1996 marked the emergence of post-panamax vessels (for example the 6140 TEU *Regina Maersk* was introduced in 1996) and the start of strategic alliances among shipping lines. The year 2006 saw the introduction of the first 10,000+ TEU vessels in a period of rapid container growth mainly triggered by the China effect on the world economy. Data were obtained from Lloyd's Marine Intelligence Unit (LMIU),⁴ which insures most of the world fleet for all types of vessels. The obtained database covers approximately 92 per cent and 98 per cent of the world's fleet of container vessels in 1996 and 2006, respectively. Interestingly, the capacity and size of the fleet as well as the number of vessel movements have grown faster than the number of ports and operators, while the average vessel capacity has grown from 1906 to 2413 TEU. Such evidence confirms the observed limitations for ports accommodating ever-growing vessels and traffic, which remain in the hands of horizontally and vertically integrated companies.

Table 1: Overview of the database on vessel movements, 1996–2006

	1996	2006	2006/1996
No. Ports	975	1,240	1.27
No. Vessel movements	176,439	390,740	2.21
No. Vessels	1,759	3,973	2.26
No. Operators	497	720	1.46
Total slot capacity (TEUs)	3,352,849	9,590,309	2.86
Share world fleet (%) TEUs)	92.15	97.91	+7.75

Source: authors' elaboration based on LMIU data.

The global network was built based on vessel characteristics, ports of call and vessel movements. The first result is a global network composed of weighted and non-directed links between ports, which can be analysed in two different ways. On the one hand, vessel circulations create a graph of direct linkages (GDL) based on the successive ports of call (namely from port A to port B and from port B to port C). On the other hand, it can be argued that two ports are also connected if they belong to the same liner service or loop, although they are not adjacent calls; a graph of all linkages (GAL) thus adds indirect linkages (that is from port A to port C). In the GDL, a direct link never connects Le Havre and Tokyo, whereas, in the GAL, this connection might occur inside a pendulum or round-the-world services. The GAL is the overlap of all individual complete graphs created by the circulation of each vessel. These two dimensions of the same reality (GDL and GAL) may exhibit distinct features in terms of network structure and port hierarchy. To reveal the structural properties of the two graphs for each year of observation, we apply conventional measures derived from

graph theory, which were originally applied to transport networks by Kansky (1963) and from complex systems theory, referring to the works of Barabasi and Albert (1999) and Watts and Strogatz (1998). This set of measures provides clear evidence about the nature of the network based on topological properties (see Ducruet and Rodrigue 2011 for a review of network measures).

One limitation of the data is that they ignore how many full or empty containers ships and ports truly handle. In reality, some vessels may not be fully loaded, since their passage in a port does not always include stevedoring activities (for example a port visit in the framework of bunkering activities). However, with reference to the observation made by Joly (1999), the linear correlation in our data between vessel traffic and port throughput⁵ is very significant: about 88 per cent and 87 per cent of total variance is explained by the regression in 1996 and 2006 respectively. This verifies the good fit and quality of the LMIU data source with official port statistics for analysing container ports and their position in liner shipping networks.

Network structure

Table 2 highlights important differences between the GDL and GAL approaches and between the two years of observation. In terms of network size, the GDL has fewer links than the GAL, which include numerous indirect connections among ports, thus making it about five times larger (edges) and 12 to 13 times longer than the GDL for the same number of ports (vertices). In the GDL, the most central port in terms of maximum degree value connects about 18 to 19 per cent of all ports; in the GAL, it connects 48 to 51 per cent. Such differences in size have a strong influence on other network properties. Indeed, the GAL has about five to six times more density, connectivity and lattice degree compared with the GDL.

More robust measures proposed by physics complement such findings by revealing the polarized or scale-free structure of the GDL with power-law exponents higher than one (-1.35 in 1996 and -1.29 in 2006): few ports concentrate a large number of links (high degree centrality), while most ports have a limited number of links with other ports. Due to its higher density, the GAL is more likely to be a small-world network. Higher average clustering coefficients (0.74 and 0.73), higher transitivity (0.40 and 0.43), lower power-law exponents (-0.62 and -0.65) and smaller diameters (4 and 5) than the GDL indicate the tendency for a given port to have its direct neighbours connected to each other, thus forming tightly connected communities. Thus, the GDL is more representative of hub ports dominating secondary ports, whereas the GAL represents densely connected maritime regions. Consequently, the GAL is more efficient than the GDL because the inclusion of indirect links facilitates the circulation of flows in the graph, as reflected by its shorter average path length. Our results are similar to those of Hu and Zhu (2009) based on 2006 service data, both for the GDL (power-law exponent of -1.7 , average clustering coefficient of 0.4) and the GAL (average clustering coefficient of 0.7). Finally we observe that the network exhibits positive assortative mixing (correlation between the degree centrality of ports and the average degree centrality of their direct neighbours),

Table 2: Topological properties of the global maritime network

Index	Measure	Graph of direct linkages (GDL)		Graph of all linkages (GAL)		
		1996	2006	1996	2006	
Network size	No. vertices	910	1205	910	1205	
	No. edges	5,666	9,829	28,510	51,057	
	Max. degree	165	226	437	610	
	Average degree	12.787	17.027	64.178	87.521	
	Total length (000s km)	5,159	10,813	71,835	130,927	
	Traffic density (TEU/km)	331	407	125	183	
	Max. edge length (km)	10,012	10,018	10,018	10,018	
	Average edge length (km)	1,008	1,227	2,900	2,997	
	Diameter	9	8	4	5	
	Cycles	Cyclomatic number	4,757	8,625	27,601	49,853
Lattice degree	Alpha		0.005	0.012	0.033	0.069
Complexity	Beta		6.226	8.156	31.329	42.370
Connectivity	Gamma		0.014	0.014	0.069	0.070
Scale-free	Power-law coefficient		1.351	1.293	0.624	0.647
Small-world	Average clustering coefficient (local)		0.540	0.545	0.744	0.734
	Transitivity (global)		0.266	0.266	0.404	0.435
Efficiency	Average path length		3.253	3.189	2.230	2.219
Assortativity	Average nearest neighbours degree		0.419	0.430	0.376	0.277
Rich-club*	Topological rich-club coefficient		1.920	2.159	1.820	1.929
	Weighted rich-club coefficient		0.948	0.954	0.946	0.920

*larger ports correspond to the third (upper) quartile of degree centrality distribution

Source: realized by authors based on LMIU data.

which confirms that high degree ports tend to connect to high degree ports. This is corroborated by the rich-club coefficients: the density of links per node among higher degree ports is two times higher than the same density (Beta index) among all ports. Similarly, the proportion of traffic among higher degree ports in their total traffic is very strong (about 95 per cent).

Despite their fundamental differences in size and structure, the two networks share similar evolutionary paths. Network structure has remained somewhat resilient to the aforementioned industry changes (and their spatial consequences), as seen with the stable connectivity (gamma index) and clustering coefficients. However, both networks have become more complex (cf. higher values for alpha and beta indices) due to the multiplication of nodes and edges, resulting in better efficiency as illustrated by the decreased average path length. One important trend that is only visible in the GDL is the decrease of the power-law coefficient, which seems to contradict the higher polarization of shipping networks for individual shipping companies as a result of service rationalization and a reduction of port calls per liner service.

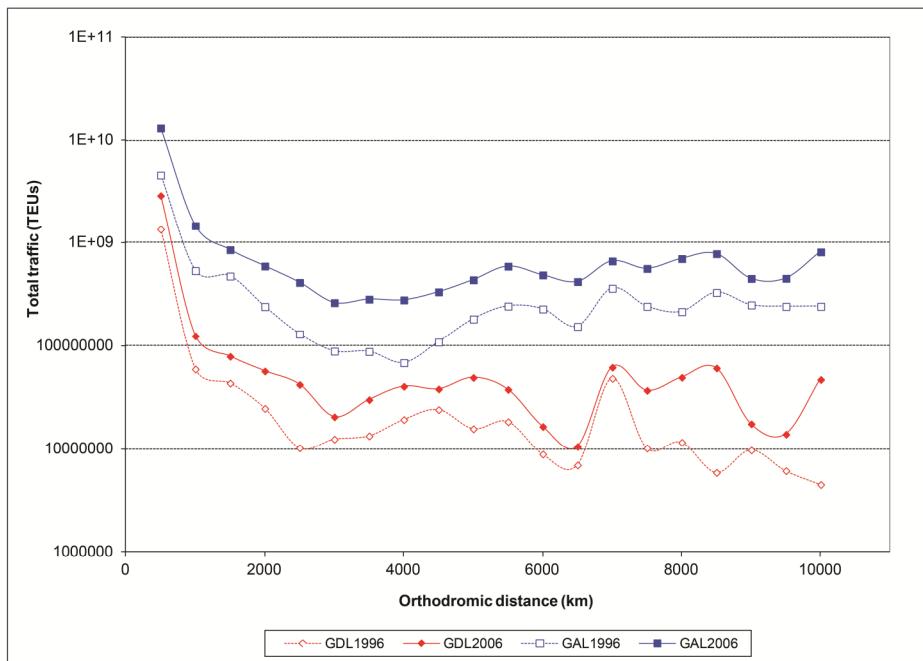
This decrease may be interpreted as the combined influence of bottom-up and top-down retroactions. Bottom-up phenomena include congestion issues at the port-urban interface and regional integration processes. On a local level, large ports face important limitations in terms of lack and cost of available land for further expansion as well as congestion and bottleneck effects at terminals situated within dense urban environments. Port-city separation and the shift of modern terminals outside urban areas may be avoided in some cases through efficient planning policies (Lee et al. 2008). On a regional level, trade growth has multiplied the number of intra-regional shipping connections, thus making the network denser and more evenly distributed. This is particularly true in emerging economies where maritime transport plays a crucial role (for example China, India, Brazil and the Middle East).

Top-down retroactions are found at the level of competition among shipping lines. A number of shipping lines seek differentiation and competitive advantage by fully or partially controlling (semi)dedicated terminal facilities. However, this spatial concentration at the company level does not necessarily result in higher cargo concentration at port system level since individual shipping lines often opt for different locations to set up their hub ports (Cullinane and Khanna 1999; Frémont and Soppé 2007). Traffic thus becomes relatively more balanced among several hubs rather than one mega-hub. Even when dedicated hubs are developed, shipping lines can still follow a risk-spreading strategy over different ports by offering more routing options to shippers. However, there are important variations in the position of individual routes and ports, as demonstrated in the next sections.

Geographic coverage of the network

Figure 4 depicts the interplay between distance and flow intensity, where most traffic occurs across relatively short distances. This trend is more obvious in the GDL approach, where 78 to 79 per cent of worldwide vessel traffic occurs over links of up to 500 kilometres. Links of 100 kilometres or less supported more than half the

Figure 4: Edge and traffic distribution over distance in 1996 and 2006



Source: authors' elaboration based on LMIU data.

worldwide traffic in both years. Strong traffic links are likely to occur among adjacent seaports serving shared hinterlands (for example Antwerp/Rotterdam in the Benelux area) or acting as dual hubs (for example Busan/Gwangyang in South Korea), which often receive multiple calls for the same vessels or liner services. The share of links shorter than 500 kilometres is much lower in the GAL, because it includes many long-distance and high-density indirect maritime links between world ports such as Le Havre–Tokyo and New York–Singapore. There is a noticeable increase in the traffic share of the 3000 to 5000 kilometre edges, caused mainly by the growing importance of trans-Pacific relations. Continued globalization and technological progress in the maritime industry are likely to be responsible for the increased share of the longest links (over 5000 kilometres) from 7 per cent in 1996 to almost 10 per cent in 2006. The increased share of shortest links (from 51 per cent in 1996 to 55 per cent in 2006) illustrate that long-distance links remain inferior to the number and weight of intra-regional linkages (that is short-sea shipping or hub-and-feeder services with a high sailing frequency).

Table 3 illustrates the application of the gravity model for estimating traffic flows by links and by ports.⁶ At the link level, the gravity model is able to estimate a non-negligible proportion of observed flows, although a majority of them cannot be explained by simple kilometric distance and port size. This result indicates that maritime networks are not completely disconnected from spatial matters, despite their low transport cost and high geographic flexibility. Obviously, important

distortions, ranging from the aforementioned port selection factors to wider issues of geopolitics and natural barriers, remain important. More interestingly, results differ according to the type of graph and to the variable used to measure port traffic. The GAL always provides better results, with 35 to 40 per cent of actual flows being explained by the model, compared with 28 to 31 per cent for the GDL. Port throughputs are less relevant than vessel traffic for explaining the flows between ports. Still, almost one-third of the variance is explained by port throughputs in 2006 for the GAL.

At the port level, we summed the estimated traffic of the links for every port, thus generating a third measure of port traffic (that is estimated weighted degree). Higher coefficients are observed in line with the aforementioned high correlation between weighted degree (vessel traffic) and port throughput. The results for port throughput are closer to the estimated traffics than the results for weighted degree (62 per cent in 2006 in GDL and GAL), meaning that estimates of a large proportion of port activity may be based on available port statistics and Euclidean distances between ports.

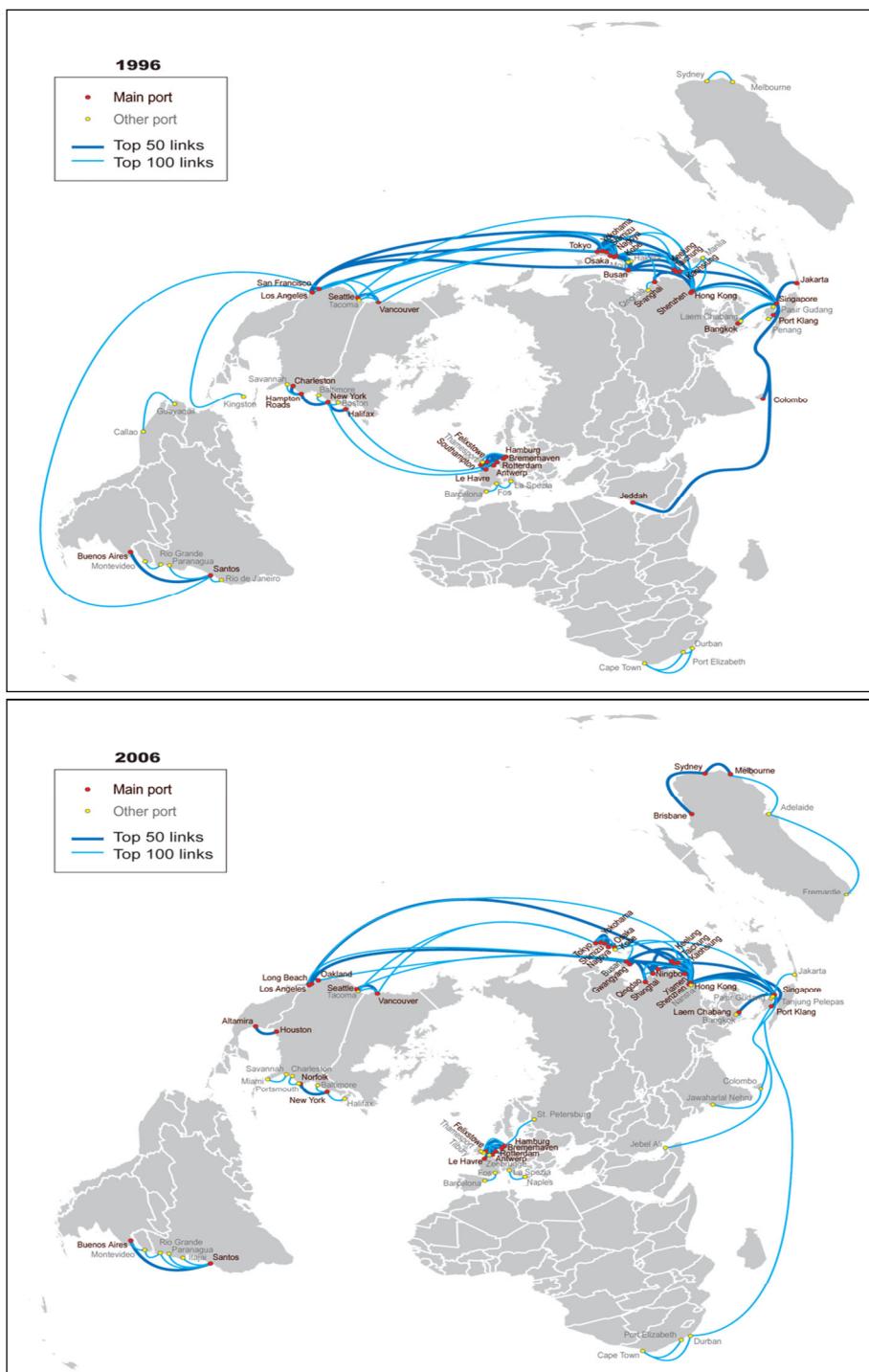
Table 3: Estimated maritime traffic flows based on gravity model

Unit	Type of observed traffic	Direct linkages		All linkages	
		(GDL)	1996	(GAL)	1996
Links	Port throughput		0.145	0.259	0.308
	Weighted degree		0.285	0.309	0.354
Ports	Port throughput		0.533	0.570	0.615
	Weighted degree		0.458	0.414	0.687

Note: values represent determination coefficients (%) of the power-law lines.

A look at the spatial distribution of the heaviest direct links provides interesting findings regarding the network's geographic coverage (Figure 5). The top 100 links represent 52 per cent and 39 per cent of total worldwide vessel traffic in 1996 and 2006 respectively. They connect primarily neighbouring ports and remain intra-regional rather than interregional.⁸ There is a clear dominance of three main poles – Asia, Europe and North America. In each pole, a small number of ports constitute the backbone (that is East Asian corridor, North European range, and US east and west coasts). In 1996, only Buenos Aires, Santos, Jeddah and Colombo stand out as main ports outside these poles. The strongest inter-regional links run between Asia and the two other large poles, with Japan (namely Tokyo) and Singapore acting as turntables across the Pacific and the Indian Ocean respectively. Most other inter-regional links generate less traffic, while some regions remain isolated (for example South Africa and Australia). The pattern in 2006 is similar, but there is an intensification of intra-regional links at the expense of inter-regional links. Busan has

Figure 5: Top hundred direct maritime links in 1996 and 2006



Source: authors' elaboration based on LMIU data and Philcarto⁷ software.

taken over as the key bridge between East Asia and North America, and transatlantic links have disappeared from the top 100 list. Such changes in the network structure and geographic coverage should also be analysed from the perspective of port hierarchies.

Changing port hierarchies

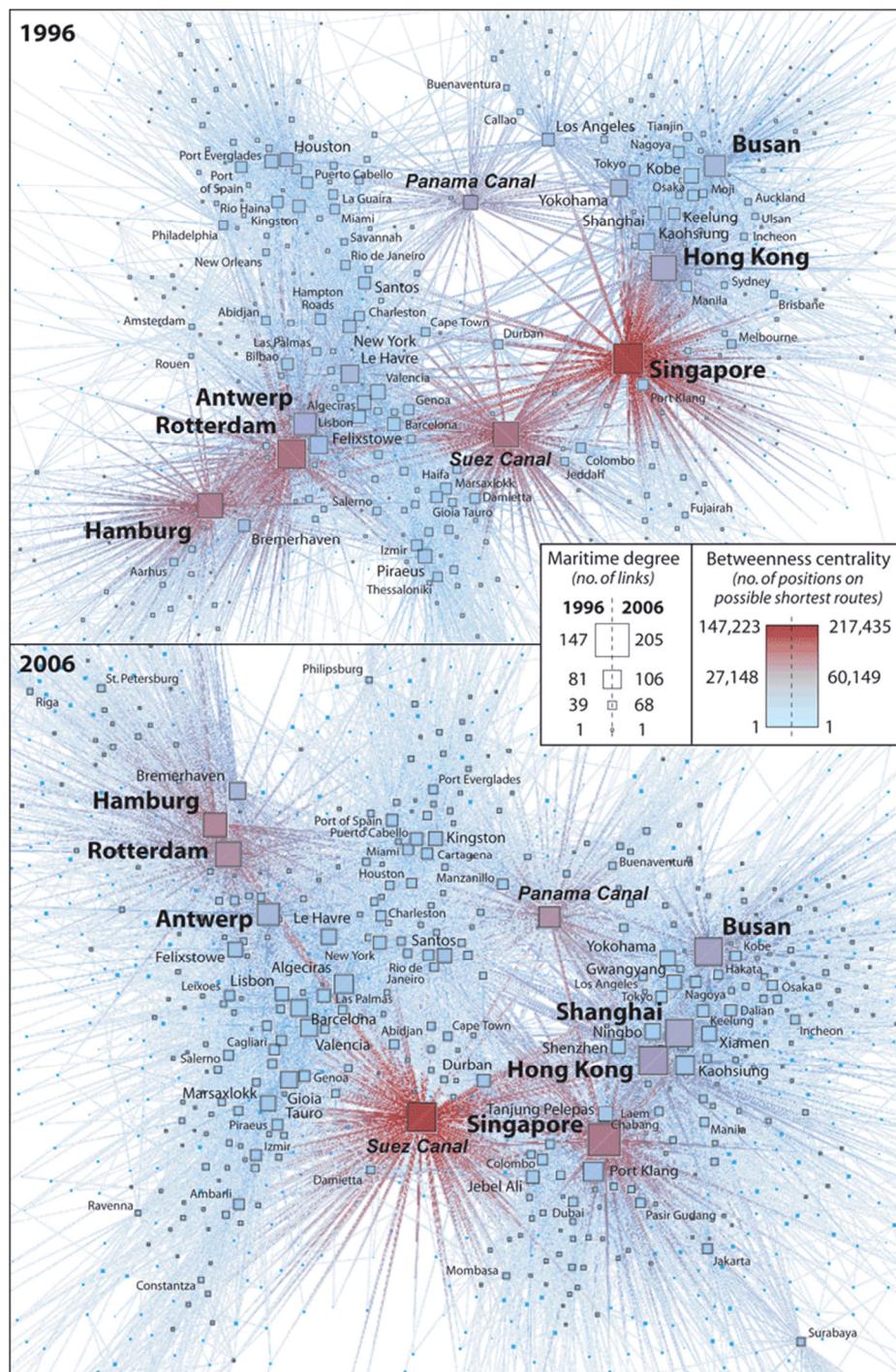
Centrality of ports in the network

The centrality of ports in the network can be approached at the local and global levels. Degree centrality is a local level measure counting for each port the number of connections to other ports. Betweenness centrality is a global level measure summing for each port the number of its positions on the shortest possible paths within the entire network. Degree centrality is a measure of connectivity, while betweenness centrality can be regarded as a measure of accessibility. The hypothesis is that hub ports will have both a high degree centrality and a high betweenness centrality, due to their role as inter-regional pivots in the global network. As defined by Fleming and Hayuth (1994), hub ports are those that welcome mother vessels for redistributing cargoes to satellite (and often secondary) ports via feeder vessel services.

Figure 6 visualizes the GDL and the port hierarchy. At first sight, the geography of the network appears similar over time, with Asia-Pacific centred on the Singapore–Busan axis and Europe–Atlantic with the Le Havre–Hamburg range. Surprisingly, due to their lack of hub/feeder activities, large North American and Japanese ports are poorly represented despite their traffic volume. Inherent to the data, gateway (hinterland) functions of seaports are not included in the analysis. Results indicate that Singapore is the most central port of the global system, which echoes its rank at the top of throughput hierarchy in official statistics.⁹ The very high centrality of the Suez and Panama canals underlines the strong vulnerability of the global network, but they are not taken into account in the following analyses.

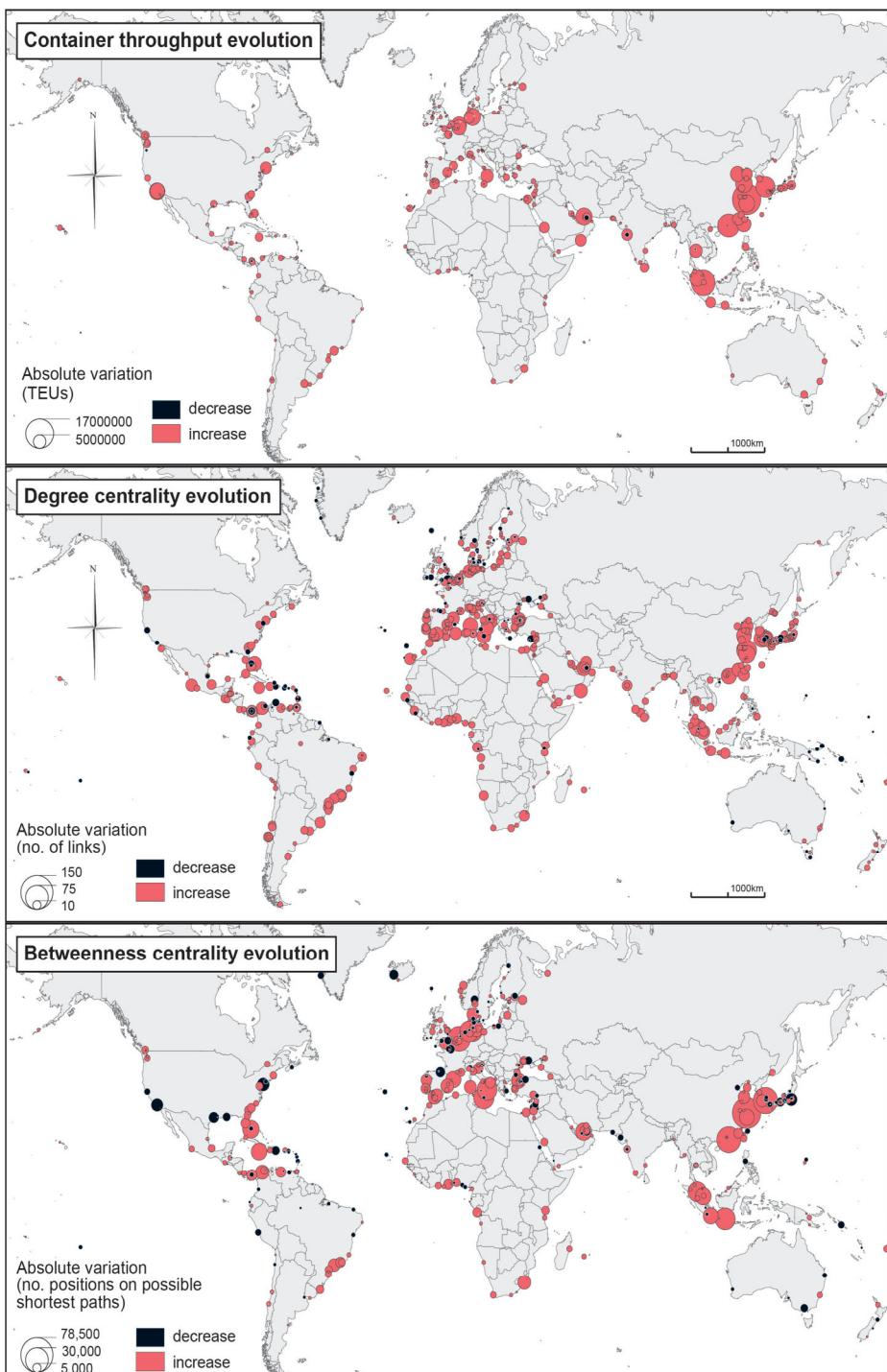
Figure 7 reveals noticeable changes between 1996 and 2006. The lowered centrality of Houston and Port Everglades to Kingston, Jamaica in the Caribbean is a good example of the impact of hub-and-spoke strategies. Several ports have strengthened their positions based on their gateway functions, such as Santos, Brazil and Shanghai, China. In East Asia and the Mediterranean, an increasing number of ports have high connectivity (for example Gwangyang, Port Klang, Xiamen, Shenzhen in Asia; Marsaxlokk, Gioia Tauro in the Mediterranean), but this growth has not altered the established position of established pivotal hubs (for example Singapore, Busan, Algeciras, Gioia Tauro) and gateway ports (for example Barcelona, Valencia in Spain). Conversely, the position of some formerly central ports has lowered significantly, as in the cases of Los Angeles, Houston, New York, Melbourne, Bilbao, North European range ports, Tokyo–Yokohama, Kaohsiung and even Singapore. In contrast with recent literature (Yap 2010), Hong Kong has maintained and even increased its position in the network. This trend is thus a good illustration of the globalization process with the shift of production from mature to emerging economies. Changes in betweenness centrality scores follow a similar geographic pattern

Figure 6: Visualization of the global liner shipping network in 1996 and 2006



Source: authors' elaboration based on LMIU data and TULIP¹⁰ software.

Figure 7: Changes in throughput and centrality, 1996–2006



Source: authors' elaboration based on LMIU data, TULIP and Philcarto software.

with more drastic gaps among ports. We clearly see the strong effects of hub strategies at Kingston, Gioia Tauro, Dubai and Busan, as well as the emergence of large load centres in south Brazil and China. There is a clear North–South divide illustrating emerging economies and differentiating ports according to local and global changes in trade routes and port selection.

Polarization and nodal regions

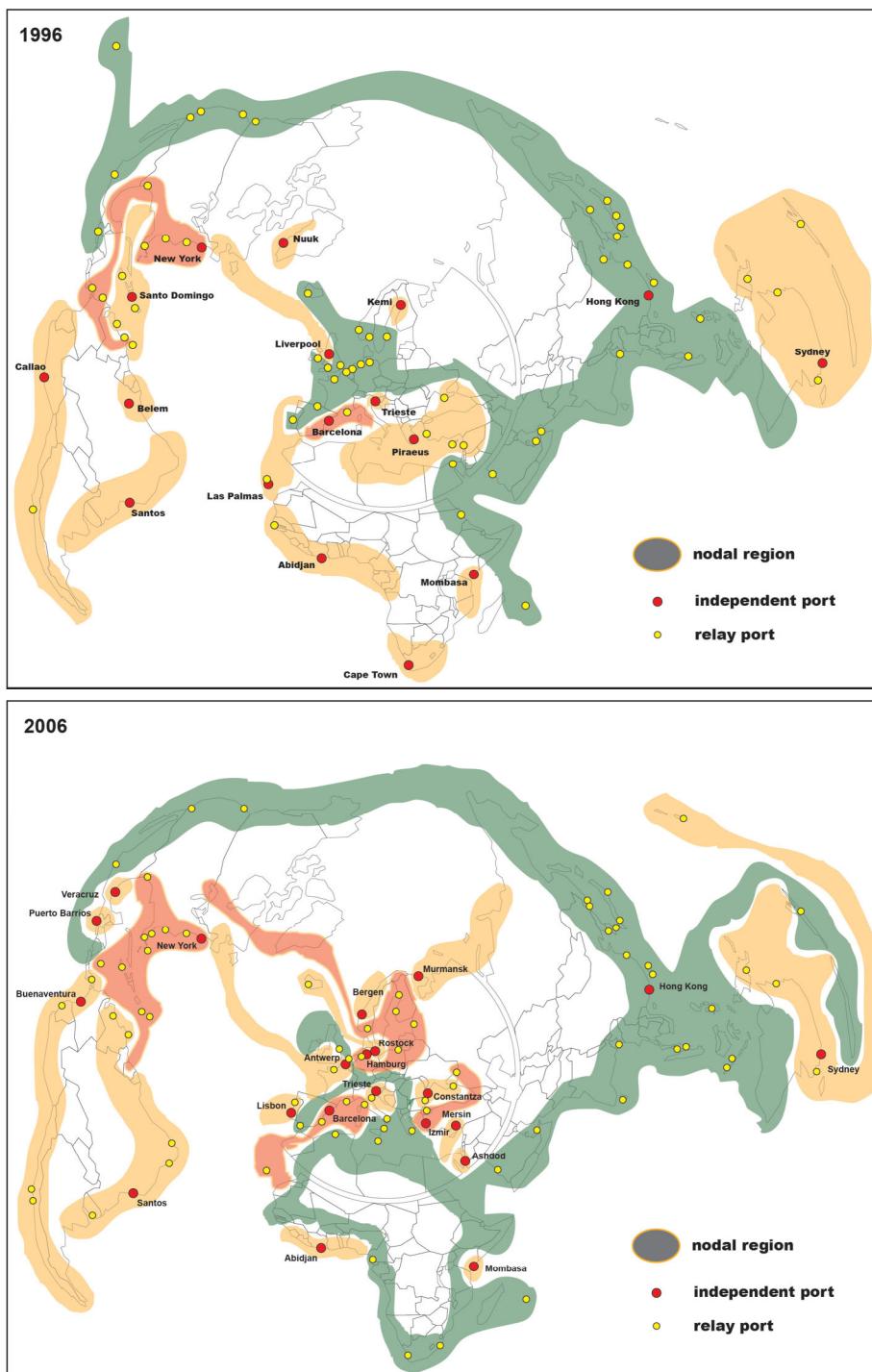
The method applied originally by Nystuen and Dacey (1961) to telephone flows among Washington State cities in the USA has been extensively applied to many transport networks (Cattan 1995; Grubesic et al. 2008; Van Nuffel et al. 2010), but this is the first time that it has been applied to maritime transport. The method allows for delimiting so-called *nodal regions* by focusing on the strongest associations between city pairs, which are believed to reflect the hierarchy of central places in which *subordinate* nodes (satellites) are under the influence of *independent* (dominant) nodes through a transitive principle: an independent city also dominates the satellites of its satellites. Due to its higher average clustering coefficient (see Table 2), this algorithm is applied to the GAL to reduce the likelihood of geographic proximity being the main explanatory factor behind the delimitation of nodal regions.

A small number of nodal regions form the world maritime system and tend to merge or split with each other over time (see Figure 8). Indeed, the global network is highly polarized by a few large entities concentrating 58 per cent and 69 per cent of all ports in 1996 and 2006 respectively. Singapore and Hong Kong's combined nodal regions include 39 per cent in 1996 and 50 per cent in 2006 of all ports, while Hamburg and Rotterdam maintain their 19 per cent share. This complements the sole indicators of centrality and better highlights the increasing influence of Asia on the world economy.

Hong Kong is the independent port of the largest region centred on Asia due to its role as a gateway for South China and centrally located hub in East Asia. Hong Kong's ramifications¹¹ remain focused on East Asia in 1996, except the link with Los Angeles, but they extend much further in 2006 with the inclusion of important Caribbean and Mediterranean ports. Despite their traffic size, other large Northeast Asian ports remain under Hong Kong's influence due to double calls and hub dependence (Yap 2010). Some of them have also extended their influence, such as Busan and Shanghai, while Taiwanese and Japanese ports have seen a significant reduction in their influence.

Comparatively, Singapore possessed a widely diversified tributary area in 1996 due to its pivotal role between Europe and Asia, as reflected by its ramifications covering Southeast Asia, South Asia, the Middle East and large parts of the Mediterranean. This pattern did not change in 2006, notwithstanding the increase in the number of ports under its influence. In fact, a number of large subordinate ports such as Incheon, Surabaya and Port Klang extended their own tributary areas in response to the overwhelming dominance of Singapore and Hong Kong. The extensions of the

Figure 8: Nodal maritime regions of the world in 1996 and 2006



Source: authors' elaboration based on LMIU data and Philcarto software.

latter two ports towards the Mediterranean reflect the importance of the Europe–Asia trade link with a continuous and regular alignment of transhipment hubs during the last two decades. Due to the dominant gateway function of some ports compared with their limited transhipment activities (for example Antwerp, Bremerhaven, Le Havre, Shenzhen, and Tokyo), the port hierarchy does not always overlap traffic volumes.

Although European ports appeared as subordinates of Asian ports in 1996, this was no longer the case in 2006, as the core region has split in two between Europe and Asia. This change can be interpreted in two ways. On the one hand, each region has reinforced its internal connectivity, making it a distinct entity stemming from regional integration forces. On the other hand, the so-called global shift (especially in the manufacturing sector) has placed Asia at the forefront of the global scene, thus relegating Europe and the rest of the world to the periphery.

A closer look at the geographic coverage of Rotterdam and Hamburg, the two main ports of the European nodal region, reveals their respective specialization. In 1996, Rotterdam primarily covered the British Isles, Iceland, the Iberian Peninsula and the Canary Islands, while Hamburg turned towards Scandinavia and the Baltic regions, with Antwerp as a large subordinate. Despite the stability in the number of subordinates and geographic coverage in 2006, Rotterdam extended to Africa and the Black Sea, while Hamburg and Antwerp reached across the Atlantic.

Geographic proximity and regional integration seem to explain the delineation of most nodal regions, except for the giant Asian region, and despite the absence of a comparable transatlantic region. Physical geography that reinforces the internal connectivity of basins may also be responsible for the limited North–South linkages across Europe. Several secondary nodal regions remained in 2006, such as the one centred on New York, which integrated the region comprising Kingston and Rio Haina. Another important region expanded in 2006, the one from Santos primarily bound to Brazilian ports but embracing Venezuela and some Caribbean ports. One may interpret such changes under the context of NAFTA and MERCOSUR arrangements due to growing North–South trade among the Americas.

Some nodal regions have become detached from large ones, such as the region of Lisbon, with strong links to the Azores, the region of Constantza in the Black Sea, the regions of Izmir and Ambarli in Turkey, as well as Puerto Barrios and Veracruz in Central America. Others have remained rather stable in their size and geographic distribution, such as the west Mediterranean range polarized by Barcelona, Trieste in the Adriatic and the West African range polarized by Abidjan, despite a drop in the number of its subordinates that were caught by Algeciras on one side and the Asian region on the other. The independent port has shifted in some regions: Buenaventura has replaced Callao as the head of the Latin American west coast. Conversely, some formerly detached regions have been integrated within a larger one, such as most of Africa and the Mediterranean basin shifting to the Asian region as well as the Belem and Puerto Cabello regions shifting under the influence of Santos (Brazil). Such phenomena depict the expansion of ocean carrier networks, making the world system increasingly interconnected.

Conclusion

This article provides an analysis of the global liner shipping network in 1996 and 2006, a period of rapid change in port hierarchies and liner service configurations. While it refers to a wide literature on port system development, shipping networks and port selection, it is one of the only analyses of the properties of the global container shipping network. It examines the network structure and the relative position of ports based on daily vessel movement data covering all of the world's container fleets. The application of graph theory and complex network analysis provide a number of important and rather novel results about ports and liner shipping networks.

Although market players' changes in port and hub selection and the changing geography of container demand make such networks highly dynamic, we observe a certain robustness in the network structure. While transhipment hub flows and gateway flows might slightly shift among nodes, topological properties remain rather stable. The increasing size and complexity of the network occur in parallel with its decreasing spikiness caused by simultaneous bottom-up and top-down retroactions.

The analysis confirms the strong influence of geography and distance on the distribution of traffic, showing the dominance of intraregional links and demonstrating good applicability of the gravity model for estimating inter-port traffic. As in previous analyses of other global inter-city networks, maritime linkages retain an important regional dimension (Derudder and Taylor 2005), but there is a striking absence and decline of transatlantic linkages as already verified in the global pattern of airline networks (Cattan 2004). The overarching importance of the Asia-Pacific area in the maritime network is best illustrated by delineating the ramifications of nodal regions. This was also made evident when mapping the changing centrality of ports. While the Old World (Atlantic, northern hemisphere) versus the New World (Asia-Pacific, southern hemisphere) would be a too simplistic interpretation of our results, the role of a changing world geography cannot be ignored. As such, analysing the global liner shipping network provides a useful and necessary complement to the study of globalization and regionalization processes, which are often approached through other types of global networks.

Further research in this field may benefit from the inclusion of land-based networks (for example road and rail) as a means of considering hinterland accessibility. Currently, a worldwide database of vessel movements over the contemporary period (1890–2010) for all types of vessels is being built to expand the analysis of the global maritime network's dynamics.

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Notes

1. See Barros and Athanassiou (2004); Chou et al. (2003); Guy and Urli (2006); Malchow and Kanafani (2001); Murphy and Daley (1994); Murphy et al. (1992); Nir et al. (2003); Song and Yeo (2004); Tiwari et al. (2003); and Wiegmans et al. (2008).
2. A TEU (or 20-foot equivalent unit) is a load unit often used to describe the capacity of container ships and container terminals. It is based on the volume of a 20-foot-long intermodal container.
3. The average vessel size increased from 1155 TEU in 1987 to 1581 TEU ten years later, 2417 TEU in 2007 and 2618 TEU in 2009 (UNCTAD 2009). In 2006, Maersk Line introduced the Emma Maersk of around 13,500 TEU capacity, the first vessel to move far beyond the 10,000 TEU mark. The total fleet in late 2009 counted 39 vessels in the range of 10,000–15,500 TEU, and another 168 vessels of above 10,000 TEU unit capacity were on order (source: Alphaliner, www.alphaliner.com).
4. <http://www.seasearcher.com/lmiu/index.htm> (accessed October 2010).
5. Source: Containerisation International.
6. The distance parameter of the gravity model is the orthodromic distance in kilometres (that is taking into account the sphericity of Earth) between ports.
7. We have calculated the share of intra-regional traffic versus total traffic at the level of 25 maritime LMIU regions, which increased from 53 per cent to 55 per cent in the GDL and from 27 per cent to 31 per cent in the GAL.
8. <http://philcarto.free.fr/> (accessed October 2010).
9. Appendix 1 provides detailed centrality scores for the top 25 ports.
10. <http://tulip.labri.fr/TulipDrupal/> (accessed October 2010).
11. Appendix 2 provides a graphic visualization of the largest regions.

**Appendix 1:
Top 25 most central ports in 1996 and 2006**

Graph of direct links (GDL)

Port	1996		Port	2006	
	BC	DC		BC	DC
Singapore	150,240	165	Singapore	174,516	226
Rotterdam	97,875	140	Rotterdam	146,454	167
Hamburg	90,978	124	Hamburg	127,733	150
Hong Kong	61,839	126	Hong Kong	117,675	203
Antwerp	50,513	112	Busan	96,257	190
Busan	39,943	105	Shanghai	92,838	193
Le Havre	34,593	90	Bremerhaven	56,219	105
Houston	32,841	71	Antwerp	53,766	137
New York	32,536	70	Port Klang	52,191	148
Yokohama	31,090	83	Gioia Tauro	47,971	120
Los Angeles	30,726	66	Marsaxlokk	45,183	120
Felixstowe	27,606	88	Surabaya	39,030	50
Kaohsiung	27,551	82	Kingston(JAM)	37,495	104
Piraeus	24,827	71	Algeciras	36,846	130
Melbourne	22,516	44	Valencia	33,688	120
Philadelphia	21,867	44	Miami	32,963	83
Bremerhaven	21,661	56	Barcelona	32,462	118
Algeciras	20,373	72	Le Havre	31,623	98
Port Klang	19,782	58	Kaohsiung	31,419	125
Bilbao	19,549	60	New York	30,607	93
Valencia	17,380	78	Jebel Ali	28,785	97
Port Everglades	16,176	67	Felixstowe	28,216	92
Colombo	16,043	62	Durban	27,708	82
Izmir	14,854	55	Santos	26,306	92
Shanghai	14,719	59	Shenzhen	25,582	107

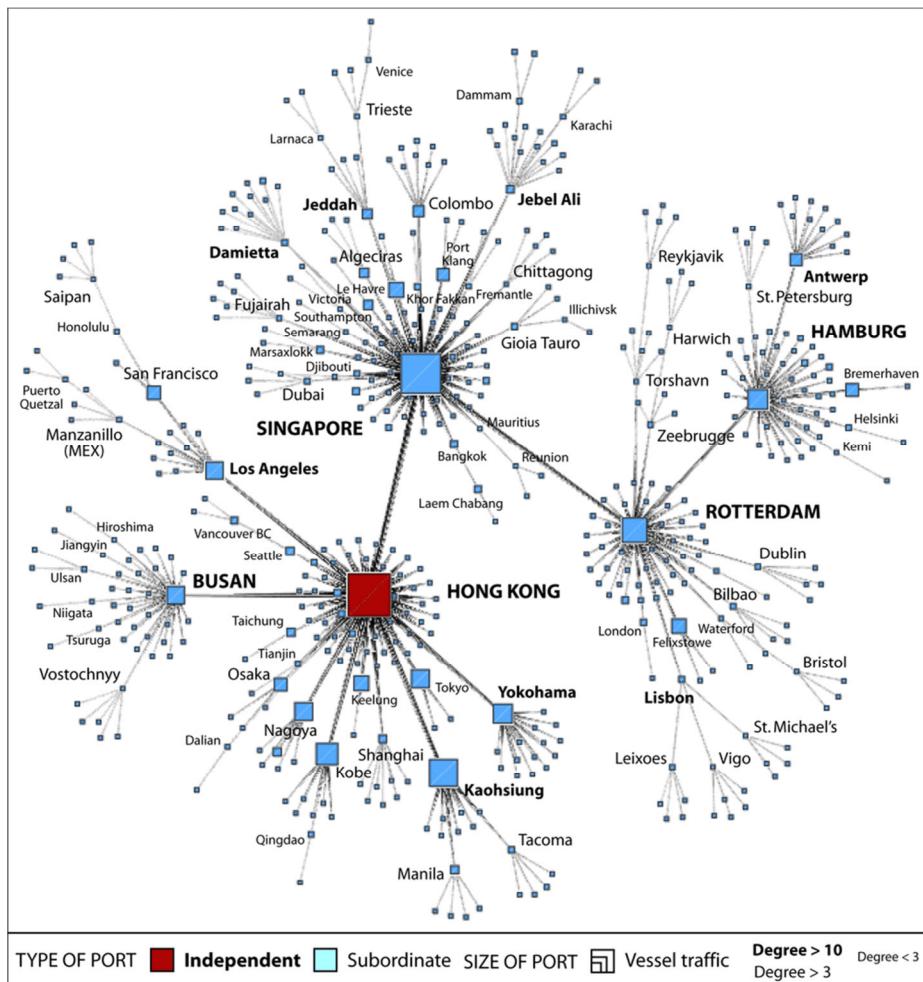
Graph of all links (GAL)

Port	1996		Port	2006	
	BC	DC		BC	DC
Hamburg	45,925	439	Rotterdam	83,246	610
Rotterdam	35,935	427	Shanghai	41,642	556
Antwerp	29,876	414	Antwerp	37,526	536
Busan	18,977	327	Busan	32,718	492
Bremerhaven	17,156	320	Bremerhaven	28,364	424
Yokohama	16,365	316	Port Klang	25,248	464
Felixstowe	15,944	366	Jakarta	22,876	325
Le Havre	13,190	334	Qingdao	19,312	436
Kaohsiung	12,551	291	Shenzhen	16,664	449
Aalborg	12,299	53	Ningbo	15,238	426
Kobe	11,448	277	Ambarli	14,526	347
Port Klang	9,959	264	Felixstowe	14,228	407
Shanghai	9,526	235	Leghorn	13,663	378
Kingston(JAM)	9,152	229	Barcelona	13,137	399
Los Angeles	8,543	241	Colombo	12,347	372
Houston	8,458	238	Durban	11,778	368
Izmir	8,225	270	Xiamen	11,442	383
New York	8,128	298	Bilbao	11,187	304
Fos	7,825	245	Le Havre	9,789	397
Aarhus	7,693	207	Genoa	9,547	371
Port Everglades	7,623	187	Osaka	9,437	330
Genoa	7,372	288	Wismar	9,249	117
Osaka	6,649	226	Kobe	8,998	345
Jeddah	6,465	254	Port Everglades	8,947	279
Bilbao	6,234	227	Leixoes	8,836	288

Note: BC = betweenness centrality (no. of positions on possible shortest paths); DC = degree centrality (no. of ports connected).

Appendix 2: Graph visualization of the largest nodal maritime regions, 1996–2006

Figures are drawn using a GEM-Frick algorithm in TULIP software that positions most central nodes in the centre of the figure and least central nodes to its periphery.





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