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The polarization of global container flows by interoceanic canals

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Abstract

It is widely acknowledged that the two major interoceanic canals of Panama and Suez play a central role in global trading flows. However, their precise weight for specific commodities such as containers has barely been estimated, as well as the geographical and topological influence of the canals on global freight flows. This study first confirms the high vulnerability of the global maritime network as its connectivity depends on only two major nodes. In reference to existing research on the vulnerability of (transport) networks and based on a global database of containerships movements, this paper proposes measuring the impact of removing the canals on a) the whole network structure and b) on the position of individual ports. Main results point at noticeable changes in the configuration of world flows.

Keywords: maritime transport, networks, ports, vulnerability

1. Introduction

The main goal of the two interoceanic canals is to avoid deviation from the main trading routes connecting the principal economic centers of the world economy, namely Europe, Asia, and North America. It is estimated that Suez and Panama canals together concentrate about 15% of world seaborne trade, thus giving them high strategic importance. Thus, those two canals are considered being critical infrastructures raising issues of transport security (Salter, 2007), notably since many studies have investigated the economic potential of alternative routes due to congestion, cost, time, and piracy problems around the transoceanic canals (Verny and Grigentin, 2009; Fu et al., 2010; Liu and Kronbak, 2010; Notteboom, 2012).

However, rare studies have gone deeper into the measurement and implications of such vulnerability for canals, ports, and shipping networks. For instance, Berle et al. (2011) as well as Angeloudis et al. (2007) provide a rich discussion on the failure modes in the maritime transportation system but without providing empirical evidence about the precise role of canals. Throughout the research field of network vulnerability and critical infrastructures, more likely are studies of the worldwide energy supply including some maritime elements (Rodrigue, 2004; Zavitsas and Bell, 2011), the Internet network (Grubestic et al., 2008), the airline transport network (Derudder et al., 2007), and road networks (Jenelius et al., 2008).

One first attempt to measure the centrality of interoceanic canals in the global maritime network was performed by Kaluza et al. (2010) as well as Ducruet and Notteboom (2012a) in their analysis of worldwide maritime container flows, thus implicitly claiming the overall vulnerability of the network. Other works on maritime networks have eluded vulnerability issues except the one of Guerrero et al. (2008) on supply chain disruption and vessel rerouting and the one of Ducruet et al. (2010) on hub dependence as a measure of vulnerability for ports. Instead, other works on liner shipping networks focus on the overall topological structure of flows (Deng et al., 2009; Hu and Zhu, 2009), the interdependence with airline

networks (Parshani et al., 2010), or the geographic coverage of ocean carriers such as Maersk (Frémont, 2007).

The main goal of this chapter is to offer novel empirical evidence about the respective and combined influences of interoceanic canals in global maritime flows. It takes its inspiration from a wide array of methods and applications in network analysis in general. Its ambition is to measure and map the vulnerability of the global maritime network in relation to interoceanic canals at various geographic levels, from individual nodes to global sea routes. The case of container flows is explored through exploiting a global database of vessel movements in 1996 and 2006. After introducing the data and overall methodology, one first section describes the geographic coverage of the canals' influence on global vessel circulations and an estimation of their traffic weight in total container flows. The second section further discusses the topological importance of the canals and its evolution with regard to optimal network configurations and flow structures. A discussion about the local and global implications of the results is provided in the last section to conclude the chapter and identify further research pathways.

2. Data and methodology

Daily vessel movements are reported by Lloyd's List on a regular basis. Extracting all movements of fully cellular container vessels in 1996 and 2006 allowed to build a port-to-port matrix including both Suez and Panama canals as well as all ports connected by those ship calls. The resulting network is weighted by the sum of vessel capacities in TEUs (Twenty-Foot Equivalent Units) passing through links and nodes during one year of movements, while it is kept undirected for simplicity.

One first method has been to identify the trajectory of vessels passing through each and/or both canals defined by their full voyage within each year of observation. The analysis of freight circulations through trajectories rather than segments provides better results as it catches the overall patterns of moving objects (Guo et al., 2010). Such an approach allows for considering the geographic coverage of canal-related shipping and its weight regarding world shipping in general. The share of canal-related traffic can be calculated at every port, range, and continent depending on the level of observation.

Secondly, we measure the vulnerability of the network through two complementary approaches. On the one hand, average eccentricity and average transitivity are calculated on the level of the entire network before and after removing canals and canal-related circulations. Such measures indicate how much do canals influence the overall fairness and connectedness of the network. We distinguished between links having more than 50% of their traffic being canal-related and all the links carrying canal-related traffics. This allows for comparing differences in link removal since some inter-port links carry both canal-related and other traffics. Eccentricity is a common measure of geodesic distance in graph theory and can be labeled Koenig number, Shimbeld distance, and closeness centrality in the literature (Ducruet and Rodrigue, 2012). It corresponds for each node to the number of links needed to reach the most distant node in the network. Averaging all local measures provides one single measure at network level ranging from 0 (nodes are distant to each other) to 1 (nodes are close to each other). Average eccentricity has been used in network vulnerability studies to measure the global impact of node or link removal (Shimbeld, 1953; Gleyze, 2005). Transitivity is a measure of connectedness proposed by social network analysis (Wasserman and Faust, 1994) and labeled clustering coefficient in the literature on complex networks. It corresponds to the probability that the adjacent neighbors of a given node are also connected to each other: the number of existing triangles (or triplets) is divided by the number of possible triangles (or

triplets), thus ranging from 0 (no triangles) to 1 (all triangles). Low values often correspond to nodes having dominant functions while its adjacent neighbors are poorly connected (cf. hub-and-spoke pattern) while high values depict tightly connected and more homogenous patterns. With reference to studies of cascading failures in networks, we also compare the effects of canal removal on the centrality of individual ports (Albert et al., 2004; Gorman et al., 2004; Wang and Rong, 2009).

On the other hand, the optimal or maximum capacity route is extracted from the original network using the minimum spanning tree algorithm proposed by Kruskal (1956). The latter method belongs to a family of studies on the search for the optimal or shortest path on the level of the entire network (see also Roy, 1959; Warshall, 1962; Floyd, 1962; Johnson, 1977) and/or for a given node or link in the network (Bellman, 1958; Dijkstra, 1959; Ford and Fulkerson, 1962). The Kruskal algorithm is chosen for its simplicity and due to the fact that it remains a widely accepted reference in graph theory. We apply the algorithm to the inverse of traffic weight (TEUs) by link in order to extract the maximal weight spanning tree, i.e. the optimal route connecting all ports and carrying the maximum traffic volume. Based on this simplification of the network, we measure for each node its Strähler stream order (i.e. level of ramification) to reveal the branching property of ports and canals in the optimal route, as well as their degree centrality (i.e. number of adjacent neighbors). The Strähler index is well adapted to tree-like networks and has been used extensively in the case of river networks (see Haggett and Chorley, 1969; Taaffe and Gauthier, 1973).

3. Geographic coverage of canal-related flows

On a world level, the share of canal-related flows in total flows was calculated on the basis of direct and indirect vessel calls between ports (Table 1). Slightly more than half of global

container flows pass through the canals and this share has increased for individual and both canals between 1996 and 2006.

[Insert Table 1 about here]

The combined weight of the two canals is slightly lower than the sum of their individual importance since some vessels have used both canals during their service notably those ensuring line-bundling and round-the-world voyages (Ducruet and Notteboom, 2012b). The weight of the Panama Canal (PC) remains lower than the weight of the Suez Canal (SC) in accordance with the fact that the Europe-Asia route accounted for the majority of world container flows (27.7 million TEUs in 2007), followed by the Asia-USA route (20.3 million TEUs) and the Europe-USA route (7.2 million TEUs) according to other sources (Containerisation International). The relative weight of the canals has increased between 1996 and 2006, and canal-related traffic growth has been higher than total container traffic growth (+216%) over the period. Thus, the polarization exerted by the canals has gained grounds despite the development of trade routes not using the canals, such as intra-regional flows and south-south flows. This aggregate measure of the canals' importance might differ according to the size of vessels and in terms of traffic frequency, but such analyses would have gone beyond the scope and goal of this study. Yet, it is important to recognize that this methodology cannot account for the entire picture regarding the spatial distribution of canal-related flows. In fact, some of the vessels passing through the canals, notably the largest ones, act as mother vessels in their origin and/or destination region by loading/unloading cargoes to/from feeder vessels. A more complete picture of canal-related flows would thus be obtained by capturing the final and first port of call for each container passing through canals.

However, it is impossible to know which vessel has been mother or feeder and how and where has cargo been transferred between them. This lack suggests that while the estimated total traffic weight of the canals might be close to reality, the more precise geographic spread of canal-related traffic is impossible to assess. One may even imagine a wider study looking at inland origins and destinations of canal-related flows but such information is not yet accessible on a large scale.

Another approach is to measure the weight of canal-related flows by geographic entity at various levels such as continents, ranges, and ports. At continent level, the largest economic poles of the world are the most dependent upon the canals, but this dependence varies from one continent to another, according to the canal considered, and over time. Europe and North America are the most dependent on canals. North America has witnessed the fastest growth in canal-related traffic, with a combined share of 68% in 2006, making it the world's most canal-dependent region. Many reasons might explain this trend, such as congestion issues at West Coast ports making land bridge connections less beneficial to shippers than maritime services between East and West coast through Panama (Hall, 2004). Europe as a whole has about 60% of its flows depending on canals, but while the share of Suez Canal has remained stable around 55%, the Panama Canal has decreased from 15% to 9% over the period. Asia's reliance on the canals occupies half of its traffics, but probably due to its higher share of intraregional trade, its reliance on Suez Canal is lower than Europe and has slightly lowered from 44% to 42%, while the Panama canal has increased its share from 11% to 13%. Latin America has reached the same level than Asia, while Oceania and Africa rely much less on canals than other regions, due to their dominant north-south traffic and their reliance on hub-feeder transshipment in many cases such as Maghreb ports polarized by Mediterranean hubs and Australian ports being partly polarized by the Singapore hub for European trades.

[Insert Table 2 about here]

At range level, the weight and share of canal traffic appears clearly circumscribed within certain areas and not in others. In terms of volume, Panama traffic is the highest at the Northeastern seaboard of the United States, followed by Northeast Asian ranges, the U.S. West Coast, and Northwest Europe. China and the U.S. Northeastern seaboard concentrate most of Panama's traffic in 2006 compared with 1996. In terms of relative weight, Panama traffic remains concentrated in the vicinity of the canal itself as it supports an important proportion of North-South trades in the Americas. The weight and share of Panama traffic in Europe and Africa has stagnated and even decreased between 1996 and 2006. For the Suez Canal, a dramatic increase in weight and share occurred at the South European and Black Sea ranges, in accordance with increased trade flows between Europe and Asia as well as the establishment of several transshipment hub ports in the Mediterranean since the mid-1990s. Noticeable decline in traffic share is observed for Japanese, Indian subcontinent, and Gulf states ranges, thereby depicting the combined effects of growing intra-regional trade as well as the reinforcement of hub-and-spoke configurations within the Asia-Pacific region, so that such ports in general transship their containers at neighboring hubs instead of shipping directly through Suez Canal.

[Insert Figure 1 about here]

The analysis at port level allows for a clearer observation of traffic impacts (Figure 2). The combined traffic of the two canals is distributed along the circumterrestrial route linking the three main economic poles. A noticeable number of ports appears to be highly vulnerable in the pattern of flows since a dominant share of their traffic is explained by the canals. The distribution of vulnerability rests upon a subtle combination of distance and scale: on the one hand proximity to the canals foster related traffics, and on the other, larger hubs and gateways, often despite distance to the canals, generate high volumes and shares of canal-related traffic. In general, Asian ports appear to be less dependent on canals than their European and North American counterparts, probably due to higher levels of intra-regional traffics. The vulnerability is thus much localized in certain areas: the U.S. Northeastern seaboard (Panama traffic) and a number of West European ports (Suez traffic) such as Southampton and Gioia Tauro at both years. The Panama Canal that is often seen as a key node for Asia-North America trades has in fact a relatively low importance for Asian ports. The share of Suez traffics at Asian ports has notably decreased for Singapore and a number of Northeast Asian ports. Thus, there is a combination of liner service reconfiguration and trade reorientation in the changing geographic coverage of canal traffics.

[Insert Figure 2 about here]

4. Topological impacts of interoceanic canals

4.1 Canal removal and cascading failures

Average eccentricity and transitivity were calculated at both years on the level of the entire network before and after removing partly and fully each or both canal's related circulations

(Table 3). Results in 1996 confirms the crucial role of canals in bringing world ports closer, as eccentricity decreases after removals compared with the original value (0.765). The combined effects of the two canals is not clearly visible since it is equal to Suez deletion impacts (for largest flows) and inferior than Suez deletion impacts (for all flows). The largest difference in eccentricity is observed for the Suez Canal (0.674) whereas removing Panama Canal's links and flows does not much influence the network's structure. This confirms previous results where the geographic coverage of Panama Canal's flows remained much narrower than the one of the Suez Canal. In 2006, the original eccentricity is significantly lower than in 1996 (0.644), which in itself indicates a dramatic increase in the size and geographic coverage of the liner shipping network (Ducruet and Notteboom, 2012a), thus making ports relatively more distant from each other than previously. One notable difference with 1996 is that removing canal-related circulations, either individually or in combination, increase the eccentricity thus making ports closer to each other. This counterintuitive result can be explained by crucial trends occurring along the period. In 1996, remote regions remain poorly connected so that the role of the canals is central and few bypasses do exist. The progression of South-South flows within the southern hemisphere, namely between Latin America, Africa, and Asia-Pacific as well as the relatively stagnant share of the canals in total flows (from 50 to 56%) have resulted in a less sparse network. Removing canal-related circulations thus reveal the strength of those new transversal linkages among world economies. This is why the Suez Canal has the highest impact on making ports closer: Asia and Europe are closer outside the Suez canal when considering the expanding links between Asia, Africa, and Latin America, the two latter being still well connected with Europe. The role of canals in an era of growing South-South trades appears more as a bottleneck than a facilitator of exchanges.

[Insert Table 3 about here]

In terms of transitivity, one same trend is observed in 1996 and 2006 that is the increasing polarization of the network after removing canal-related circulations. A complementary result is provided in Figure 3 where we map the centrality of ports before and after canal removal. The whole network of direct links (left side) heavily depends on two central nodes (interoceanic canals) being the connectors between an Euromediterranean-Atlantic group and an Asia-Pacific group. Each group at both years is polarized by a few ports. Rotterdam and Singapore are the most central ports of their belonged group, followed by Antwerp, Hamburg, Hong Kong, and Busan respectively. In 2006, Bremerhaven and Shanghai emerge as complementary hubs. The removal of all canal-related circulations, since it does not disconnect the global network, confers a very high centrality to other intermediate nodes. Those are South African ports in 1996 (Durban, Cape Town) and Brazilian ports in 2006 (Santos, Sepetiba). Removing canal-related circulations had the effect of increasing the centrality of established ports within their belonged group, notably Singapore and Rotterdam. In parallel, the multiplication of transshipment ports and hub-and-spoke strategies serving liner shipping operations contributed to this phenomenon. This also explains why the impact of canal removal has been much bigger in 2006 than in 1996 despite comparable transitivity levels in the original network. In addition, the combined removal had stronger impacts than individual removals.

[Insert Figure 3 about here]

4.2 Optimal routes and ramification

After extracting the optimal route from the original matrix, we map the centrality and ramification level of ports and canals using a Gem-Frick visualization algorithm (Figure 4). The design of the optimal route confirms the existence of two large subsystems or sub-trees each polarized by Rotterdam and Singapore, which have the largest number of adjacent neighbours (degree) and a high level of ramification (Strähler). In 1996, the Suez Canal has the highest ramification level as it stands, together with Djibouti, Reunion, and Aden at the source of the global tree. The gravity centre of the global maritime system is thus clearly around the Suez Canal but it has shifted to other locations in 2006. Singapore as well as a number of Latin American ports (i.e. Vitoria, Santos, Paranagua, Port of Spain, Kingston, etc.) took over Suez Canal at the source of the optimal route. This corroborates previous results since Asian traffics have increasingly penetrated the Atlantic through direct calls bypassing the Suez Canal, i.e. around the Cape of Good Hope. Many African ports have shifted under Asian influence due to the fast development of Asian Foreign Direct Investment (FDI) in Africa (Chaponnière, 2010). Asian terminal operators have also multiplied terminal concessions in many African ports such as in the Maghreb (Mohammed-Chérif and Ducruet, 2011) and West African ranges (Debie, 2012) during that period. Emerging economies such as Brazil have generated increasing volumes of flows linking not only Asia but also traditional partners such as Europe and the U.S. (see also Guy, 2003), thus becoming a new gravity centre for global shipping. Notably, the interlining function of Algeciras that appeared clearly in 1996 for connecting East-West and North-South flows considerably reduced in 2006 since Durban in South Africa appears as a new relay hub between West Africa and Asia.

[Insert Figure 4 about here]

Overall, we observe a significant shrink of Rotterdam's influence in the network as an effect of the aforementioned factors. The sub-network including New York, Houston, Casablanca, and a number of Atlantic European ports is in 2006 connected to Hong Kong via Itajai, a Brazilian port. Although the method has removed many links that connect ports in more complex ways, the resulting pattern is by no means revelatory of profound changes in network configurations.

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Conclusion

The application of several network analytical methods to the global matrix of inter-port vessel movements provides many clues about the changing role of canals and ports in liner shipping flows. As such, it informs us better about the way shipping networks both reflect and shape the world economy and its components (Ullman, 1949; Vigarié, 1968). As a complement to studies of network vulnerability, this research provides several evidences about the distribution of canal-related flows and their wider significance for ports and shipping. After providing a novel estimation of the importance of canal traffic in global container flows, the research revealed the uneven geographic coverage of the canal's influence at different levels of analysis. While canal traffic concentrates at the vicinity of those major infrastructures, it reveals the higher vulnerability of the "old Atlantic world" compared with emerging countries such as in the Asia-Pacific and South Atlantic regions. Canal's role in global shipping has thus

shrunk during the period under study (1996-2006) as an effect of growing South-South trades and Asia's expansion across the Cape of Good Hope. Former structures, such as Rotterdam's prominence as the main hub of Europe-Atlantic networks, are thus currently losing grounds, since Latin American ports play a new role in network interlining. Yet, there is a permanency of a bipolarization of the world organized by Singapore and Rotterdam, which remain the main pivotal nodes. Drastic changes are better felt for smaller ports such as Algeciras which interlining function has declined. Further research shall test the continuity of such trends by applying these methods on more recent data, as a means taking into account, too, the likely impacts of the 2008 financial global crisis on network configurations. Untangling the respective influence of carrier decisions and territorial factors will remain a difficult challenge to tackle.

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Table 1: Importance of canal-related flows in global flows (% TEUs)

	Panama Canal	Suez Canal	Panama + Suez Canals
1996	16.41	41.79	50.87
2006	17.31	42.98	56.26
Traffic growth (%)	233.49	225.27	249.76

Source: own calculation based on Lloyd's List

Table 2: Importance of canal-related flows by continent (% TEUs)

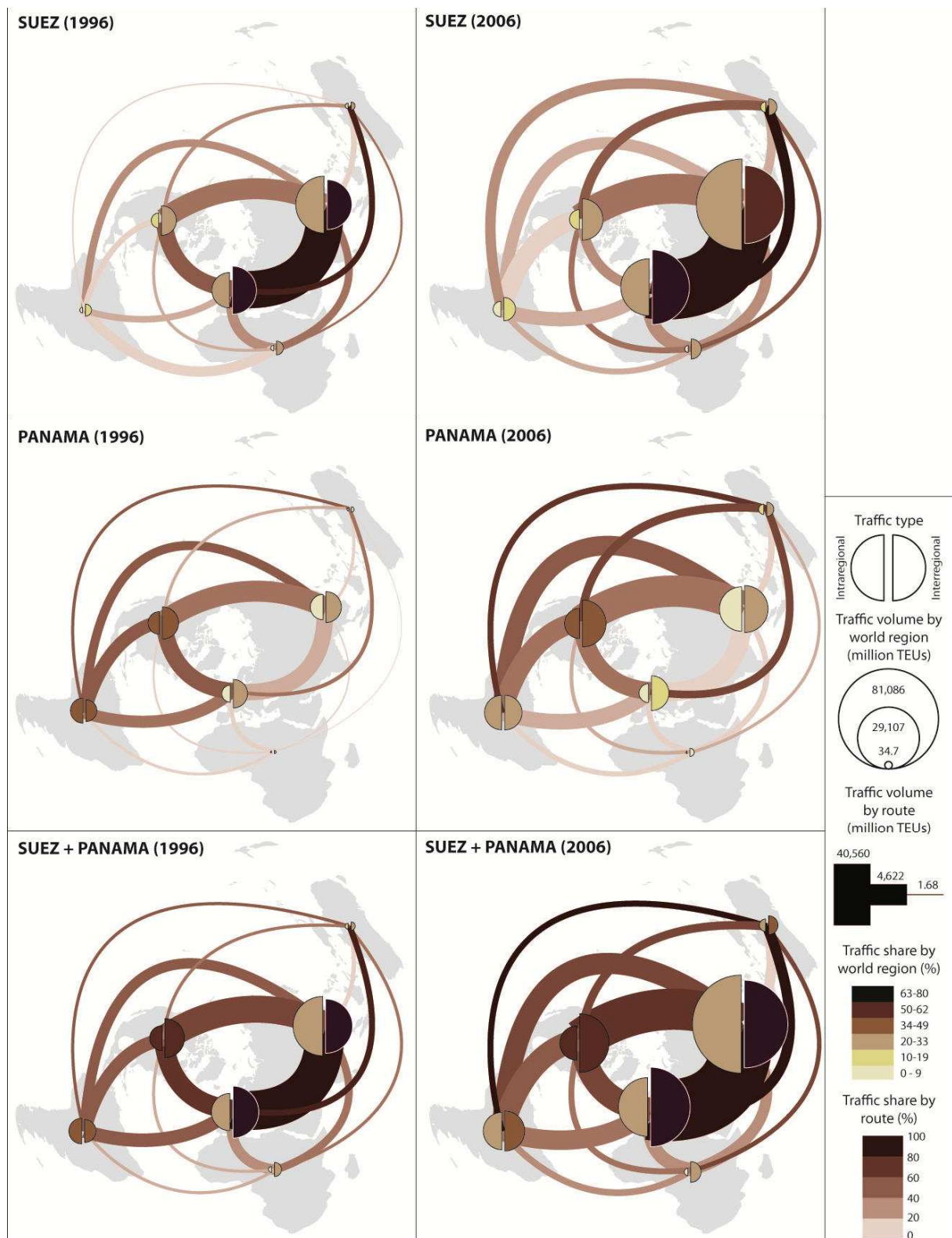
Continent	Panama Canal			Suez Canal			Panama + Suez Canals		
	1996	2006	96/06	1996	2006	96/06	1996	2006	96/06
Africa*	1.55	3.36	+1.81	23.78	19.44	-4.35	25.02	20.50	-4.52
Asia	11.17	13.38	+2.21	44.14	42.12	-2.02	49.05	51.29	+2.24
Europe	15.14	9.04	-6.11	55.02	55.50	+0.48	61.21	60.14	-1.07
Latin America*	40.75	43.17	+2.42	8.04	12.82	+4.78	43.70	51.16	+7.46
North America	35.86	48.36	+12.50	28.37	30.99	+2.62	51.26	68.48	+17.22
Oceania-Pacific	6.94	23.06	+16.12	19.32	26.98	+7.66	20.62	35.25	+14.63

* excluding canal traffic itself

Table 3: Topological effects of removing interoceanic canals in 1996 and 2006

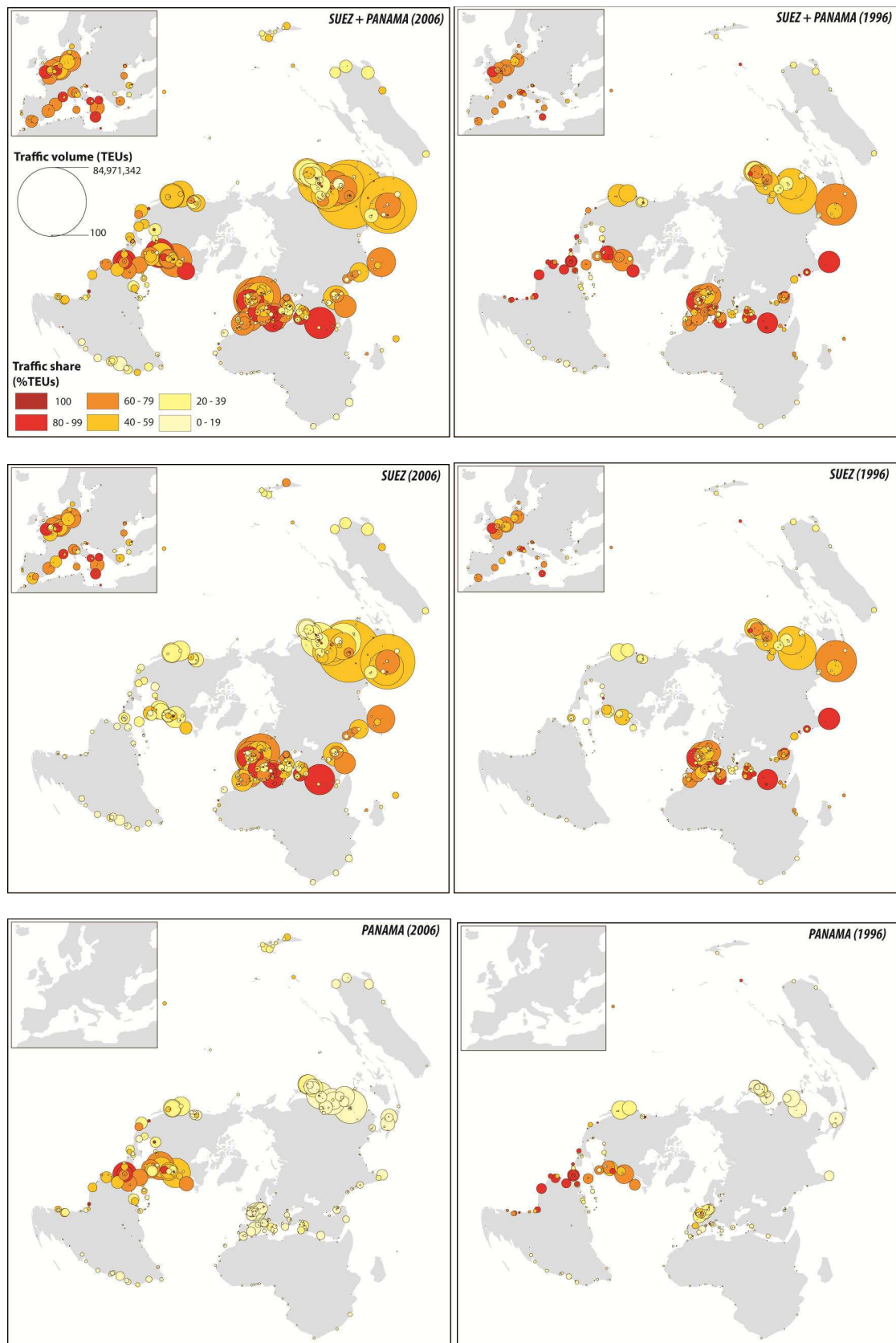
		Eccentricity		Transitivity	
		1996	2006	1996	2006
Original network		0.765	0.644	0.527	0.517
Without links > 50% canal-related traffic	Panama	0.762	0.666	0.489	0.492
	Suez	0.698	0.742	0.444	0.476
	Both	0.698	0.739	0.417	0.436
Without all canal-related links	Panama	0.749	0.707	0.451	0.394
	Suez	0.674	0.731	0.399	0.413
	Both	0.688	0.720	0.349	0.267

Figure 1: Canal-dependent traffic among continents in 1996 and 2006



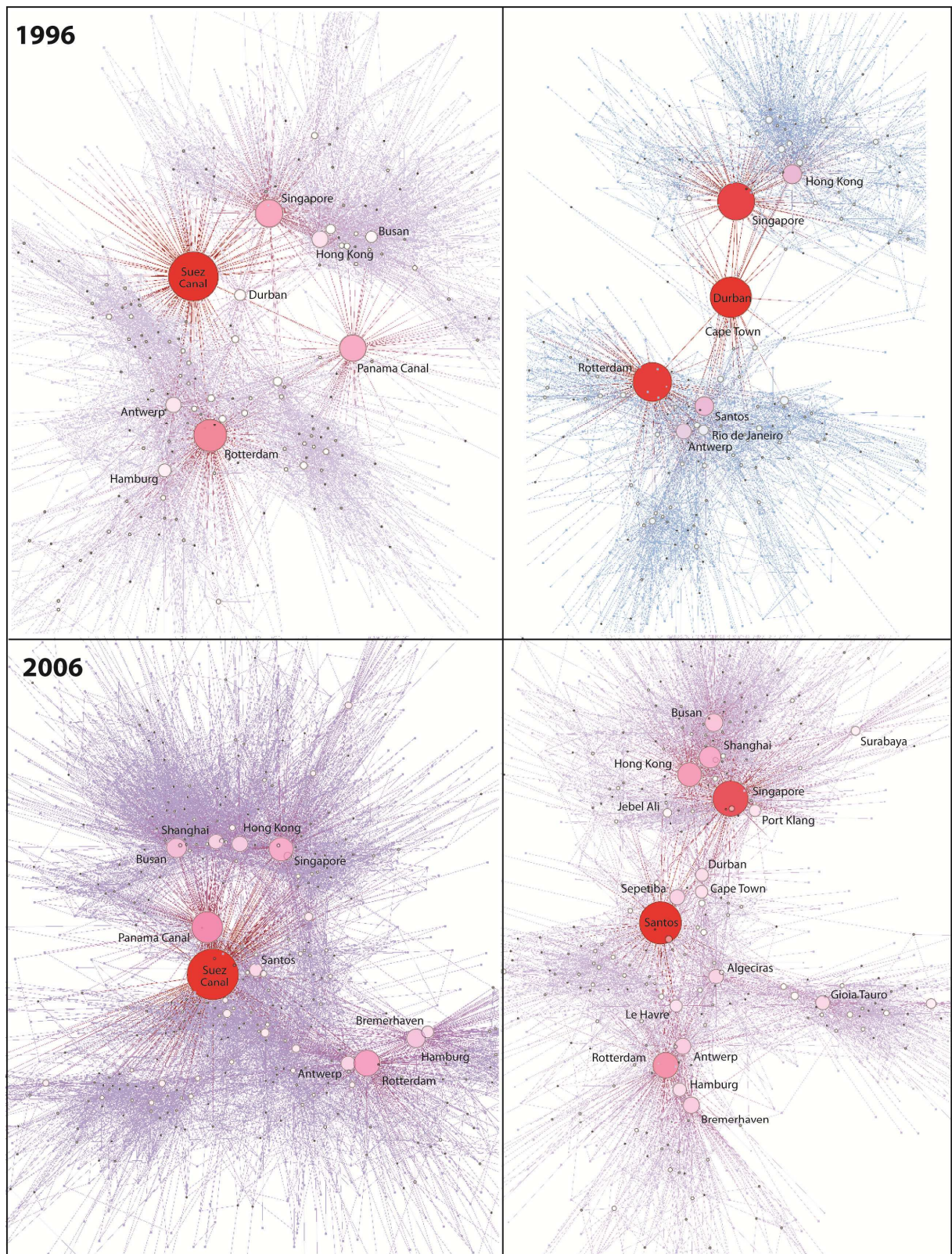
Source: own realization based on Lloyd's maritime data

Figure 2: Canal-dependent traffic at world ports in 1996 and 2006



Source: own realization based on Lloyd's maritime data

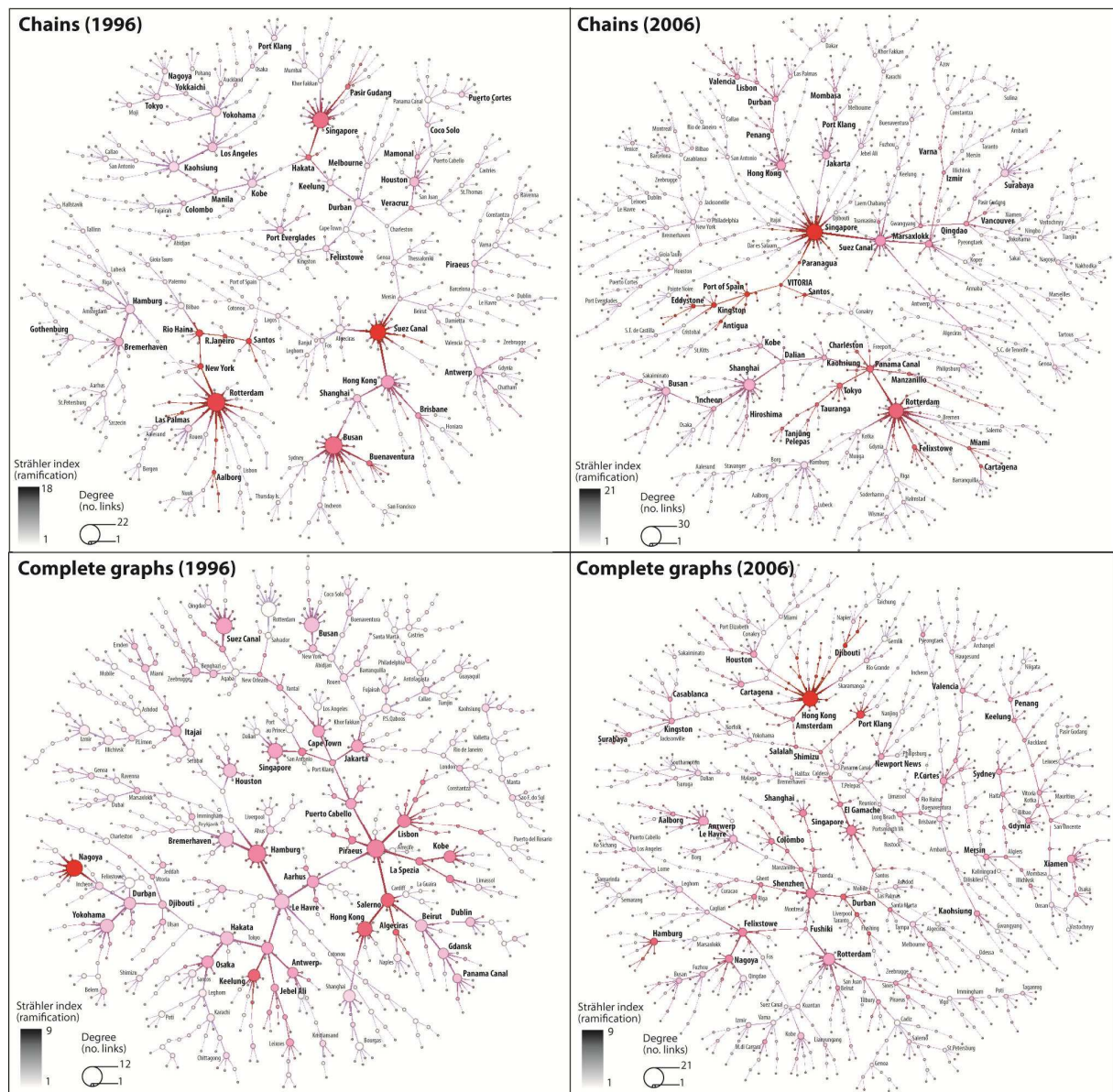
Figure 3: Visualization of canal centrality and impacts in 1996 and 2006



Source: own realization based on Lloyd's maritime data & TULIP software

N.B. left figures show the whole network; right figures show the network without canals and their related links

Figure 4: Situation of ports and canals on the optimal traffic route in 1996 and 2006



Source: own realization based on Lloyd's maritime data & TULIP software