The spatial determinants of innovation diffusion: evidence from global shipping networks

César Ducruet
Hidekazu Itoh

2022-27 Document de Travail/ Working Paper

EconomiX - UMR 7235 Bâtiment Maurice Allais
Université Paris Nanterre 200, Avenue de la République
92001 Nanterre Cedex

Site Web : economix.fr
Contact : secreteriat@economix.fr
Twitter : @EconomixU

The spatial determinants of innovation diffusion: evidence from global shipping networks[1]

César DUCRUET

French National Center for Scientific Research (CNRS)

UMR 7235 EconomiX, Nanterre, France

cesar.ducruet@economix.fr

Hidekazu ITOH

Kwansei Gakuin University, Nishinomiya, Japan

hito@kwansei.ac.jp

Abstract

Based on untapped shipping and urban data, this article compares the diffusion of steam and container shipping at the port city level and at the global scale between 1880 and 2008. A temporal and multi-layered network is constructed, including the pre-existing technologies of sailing and breakbulk. The goal is to check the differences a) between innovations and their predecessors and b) between innovations, from an urban network perspective. Main results show that despite certain differences, such as historical context, voyage length, speed of diffusion, and geographical spread, the two innovations share a large quantity of similarities. They both fostered port concentration, were boosted by city size and port connectivity, bypassed upstream port sites, and diverged gradually from older technologies. This research thus contributes to the literature on cities, networks, innovation, and maritime transport.

Keywords: containerization; maritime transport; port cities; regional disparity; spatial networks; steam shipping; technological change

Acknowledgement

An earlier version of this research was presented at the World Conference on Transport Research (WCTR) SIG-A2 Conference in Antwerp, Belgium, 5-7 May 2021. The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. [313847] "World Seastems". The authors also acknowledge support from Japan Society for the Promotion of Science (JSPS) projects No. 17KK0058 and 18KK0051, and warmly thank Kenmei Tsubota for his encouragements.

---

[1] This work is the previous version of the article published in Journal of Transport Geography (2022), 101, 103358, https://doi.org/10.1016/j.jtrangeo.2022.103358

1. Introduction

A post from the Harvard Business School underlined that Malcolm P. McLean, the father of containerization, "*made a contribution to maritime trade so phenomenal that he has been compared to the father of the steam engine, Robert Fulton*" (Mayo and Nohria, 2005). The transitions from sail to steam and from breakbulk to containers are unanimously considered to be technological revolutions, with enormous impacts far beyond shipping itself, namely on international trade and economic development. As recalled by Novy et al. (2008), those innovations boosted international trade during the first (1870-1914) and second (1944-1971) waves of globalization by 400% and 471%, respectively, while lowering trade costs by 23% for steam and 16% for containerization. Yet a debate still lingers on about the direction of the influence between trade growth and technological change (see Jacks and Pendakur, 2010; Bernhofen et al., 2016), but this is not the purpose of the present article, which focuses on the factors behind the spread of the technologies.

While they differ in terms of historical context, geographic origin, and technical nature, the two innovations both boosted port productivity (ship turnaround times), enhanced voyage regularity and safety through liner shipping schedules, and fostered hinterland expansion through intermodal connectivity (Palmer, 1999; Stopford, 2008; Kaukiainen, 2012). Another commonality had been to transform port-city relationships, as the escalation of ship size motivated the development of deep-water port facilities away from large urban centers. However, a systematic comparison between those two transitions remains to be done. In their review about maritime innovations, Koukaki and Tei (2020) rightly underlined the fact that "academic studies are quite scattered, often focusing on case studies" so that it is difficult "to generalise research outcomes".

The goal of this paper is to undertake such an analysis at the global level, based on untapped shipping and urban data over the period 1880-2008. It wishes to shed new light on the spatial diffusion mechanisms in terms of network effects, distance effects, and urban effects. Besides its contribution to maritime studies, our work engages in the field of complexity sciences, where innovation diffusion is investigated from both a network theory and an urban theory perspective. Mostly researched at the level of organizations and individuals, innovation diffusion usually refers to the adoption of a new technology over time by members of a social system, identifying the characteristics of innovation and defining categories of adopters (Rogers, 2010). In complex networks research, innovation diffusion is conditioned by the compatibility with earlier technologies and the structure of pre-existing relations (Bohlmann et al., 2010). In geography (Morrill et al., 2020), "*diffusion can be modified by costs and quality of the paths over which the phenomenon moves, by the attractiveness of the phenomenon, and by the ability of the surrounding territory or its people to absorb the phenomenon*". Diffusion may occur by proximity contacts, as distance is crucial in spatial networks (Barthelemy, 2015), or hierarchically through the urban system (Hägerstrand, 1967; Saint-Julien, 2004). Large cities exhibit a higher level of complexity or sophistication because "*the most advanced technologies concentrate in the largest cities*" (Pumain, 2006), as "*largest cities became larger because they were successful in adopting many successive innovations*" (Pumain et al., 2009).

The principal objective of this article is thus to compare the changing shipping network structure during the diffusion phase, based on the analysis of traffic distribution and graph topology. Three main aspects guide our analysis based on the reviewed literature: network connectivity, port system concentration, and urban influence. In the field of port connectivity analyses, such an approach is innovative by its temporal, long-term character, and by the consideration of node and link attributes, unlike most existing studies that remain rather static and purely topological – namely studies of maritime networks in an abstract space (Ducruet, 2020). We will test the hypothesis that both technologies diffused in similar ways despite inherent historical and geographical differences. Steam and containerization will be compared with each other with the same variables and methods, but also with the pre-existing technologies, sail and breakbulk. Both study periods, 1880-1925 and 1977-2008, start well after the introduction of each technology, since the first crossing of the Atlantic occurred in 1819 for steamships and in 1956 for containerships. Therefore, our analysis focuses on the diffusion rather than on the emergence of technologies, namely after reaching a certain state of maturity. This choice is partly conditioned by data constraints. *Lloyd's List* database, the world's most representative source of maritime traffic information, with a global and long-term coverage, only started to report the type of ship and propulsion at those dates.

The remainders of this article are organized as follows. Section 2 reviews the state of the art about the diffusion mechanisms of steam and containers, in terms of port selection, hinterland expansion, shipping network structure, and urban development. It serves as a basis for Section 3 in which we present the data and methodology to run a quantitative comparison of the two transitions, and provide preliminary results based on *Lloyd's List* data. The core of the analysis lies in Sections 4 and 5 where we compare respective characteristics of old and new technologies and search for the spatial determinants of innovation diffusion. Section 6 discusses such results in light of previous literatures and suggest further research pathways.

2. Literature review

The present study takes its roots in previous analyses of the respective transitions. The one from sail to steam, the focus of so many scholarly works (Kaukiainen, 2008), had been particularly well discussed in the synthetic work of Williams and Armstrong (2012), who stated that « *The invention and subsequent development of the steamship represents a great watershed in maritime transport and humankind's relationship with the sea* » (p. 43). Steam as a whole, including railways, created a 'new world of shipping' (Williams, 1997) alongside changes in construction materials, communications and transport technology. What has been described by Kaukiainen (2008) as a massive scholarly interest for the transition from sail to steam also applies to the literature on containerization and its impacts on ports, maritime transport, and supply chains. Kaukiainen (2012) later highlighted that maritime transport efficiency never ceased to progress between the mid-nineteenth century and the late 2000s. As such, the global merchant tonnage, the volume of cargo carried, and the average size of merchant ships grew by 60, 120, and 34 times, respectively. A view of this evolution is provided in Figure 1 based on Miramar Ship Index data (Haworth, 2021).

We present a selection of key works on the effects of shipping innovations as observed by geographers and historians. It is restrained to studies having a wide focus spatially and/or temporally, and to models, which summarize historical phases of port development separated by technological breakthroughs. We refer to Ng and Ducruet (2014) and Ducruet et al. (2009) for more detailed reviews of the field since the 1950s.

2.1 From sail to steam

2.1.1 Network effects

Freed from winds and tide, steamers essentially permitted to launch scheduled services and facilitated intra-port movements. Williams and Armstrong (2010) particularly showed how steam navigation modified voyage patterns between 1835 and 1885. Sailing vessels tended to travel over longer distances than steam, operating through direct calls, and avoiding intermediate stops along their tramp voyage. Steamers were deployed through liner services over shorter distances, while calling at several intermediary ports, partly for refueling at coal stations. Direct calls were therefore gradually replaced by multi-port calls, except for certain routes such as the North Atlantic. Another difference between sail and steam had been the trade focus. Sailing vessels long kept an advantage over steamers for carrying low value and bulky goods, while steamships, especially in the early days of their existence, remained limited by the necessity to carry their own fuel and the engine power, forcing them to specialize on high value, lighter goods (general cargo, perishables, mails and passengers) for which they increasingly became competitive on freight rates.

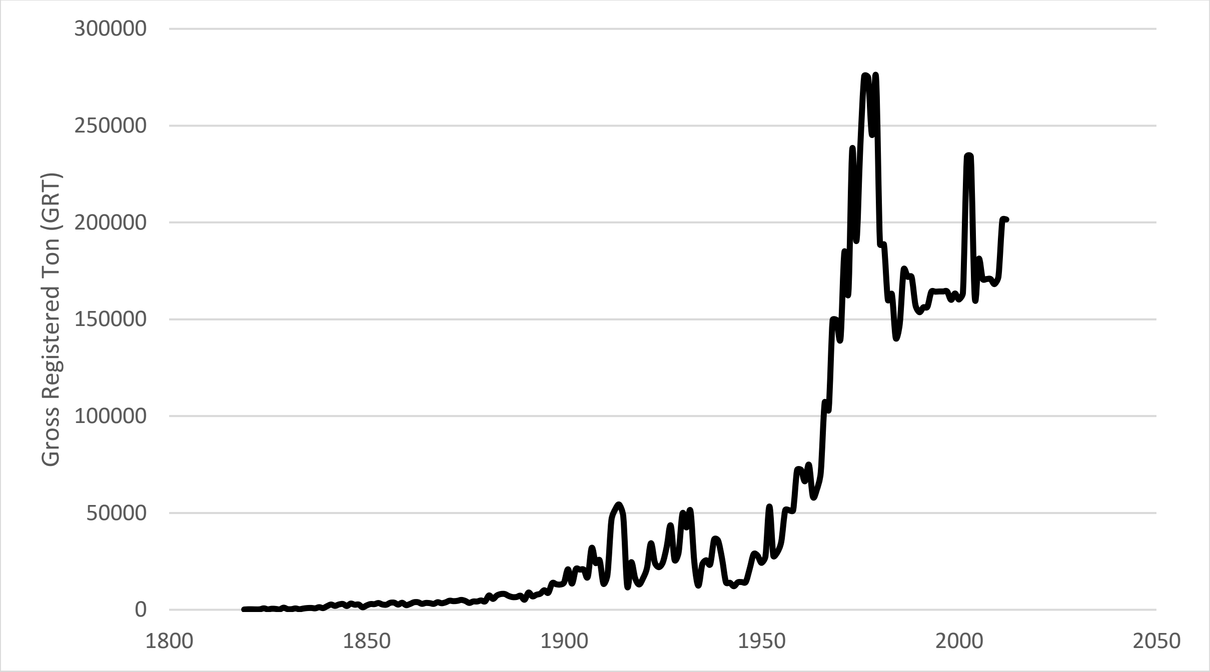

Figure 1: Evolution of maximum vessel size, 1819-2012 (Unit: Gross Registered Tons)

Source: own elaboration based on Miramar data

Further technological progress allowed steamers to absorb market shares in bulk trades through tramp shipping over longer distances. Such transformations created "*a complex web of routes that meshed [whereby] each port now became a link in a chain or chains*" (Williams and Armstrong, 2010, p. 167). Together with the creation of the Suez Canal (1869), "*steamers were now able to make two to three trips per year as opposed to a single round trip so common under sail*" between Europe and Asia (Airriess, 1995), with the effect of increasing competition and reducing freight rates.

Shipping networks in the age of steam remain poorly studied, as the strongest emphasis is put on economic factors and trade growth in economic history. There are exceptions but those do not directly discuss the impact of steam diffusion. For instance, changes in South Asian shipping patterns between 1890-2000 are better explained by territorial changes (i.e. independence) and the construction of new ports (Tsubota et al., 2017). In Northwest Africa, the changing shape of the maritime network between 1900 and 1970 reflects an increasing regional integration following colonial extraversion (Castillo and Ducruet, 2017). To explain differences in the spatial distribution of British and Japanese shipping networks in China in 1920, Wang et al. (2015) refer to geographical factors, competitive forces, and governance, but did not include technology.

2.1.2 Intermodalism and port concentration

In the 19th century, increased port competition in advanced economies fostered a *"logic of permanent adaptation"* (Marnot, 2005) by which port infrastructures had to be constantly modernized and expanded to welcome larger and faster ships. Their connection with land transport, and notably waterways and railways, had become vital especially for bulk trades but also for passengers. This new environment forced ports to focus on speed, quality, security, and cost to remain competitive, fostering traffic concentration at a smaller number of intermodal gateways, which could in turn accommodate further industrial development and warehousing facilities.

Such processes were even more acute in the rest of the world. In East Africa for instance, a process of port system concentration occurred, "*closely associated with maritime technology (in the form of steamships) and with the building of railways linking ports with inland destinations*" (Hoyle and Charlier, 1995, p. 89). In Asia, the spread of the new technology made a great majority of earlier ports physically inadequate, motivating the shift of exports towards the best situated ones to exploit the economies of scale permitted by the larger ships (Murphey, 1969).

Port system evolutionary models well depicted spatial concentration dynamics favoring one leading gateway at the expense of smaller ports, in a context of trade growth, hinterland expansion, and corridor development (Taaffe et al., 1963). Originally based on the developing world, such models were also applicable to developed economies, like for the process of "port piracy" observed by Rimmer (1967) in Australia (1861-1962). The long-term analysis of the Chinese port system by Wang and Ducruet (2013) highlighted the regional resilience of the port hierarchy over time (1868-2010). Thus, successive innovation waves tended to overlap across space by accentuating concentration in the port hierarchy.

2.1.2 Urban effects

Port-city evolutionary models commonly consider technological change as a factor of port-city physical and functional separation. In Hoyle's (1989) model, city and port were in a close synergy since ancient and medieval times, until rapid commercial/industrial growth in the 19th and early 20th centuries forced ports to develop "*beyond city confines*", with linear quays and breakbulk industries. While this model is mainly dedicated to Western port cities, its successive phases are well echoed by contemporary works on Asia (Murphey, 1989). However, specialists of the late 19th and early 20th centuries were more in favor of a sustained association.

For instance, Abrams et al. (2008) found that "*the port cities most subject to large immigration flows were magnets for Corliss steam engine*", based on their analysis of industrial development in U.S. counties over the period 1870-1900. For Konvitz (1994), Atlantic port cities between 1880 and 1920 "*concentrated such a large proportion of the world's commerce*", based on a significant manufacturing sector (including shipbuilding), the reduction of freight rates and the expansion of shipping capacity and services, which altogether favored urban economic growth, while he notes that contemporaries "*frequently compared the dimensions and features of the largest ships with those of the largest buildings in cities*".

Konvitz (1994) also recognized that modern port facilities required deep water access and increased land space, forcing them to develop at distance from traditional urban centers. This spatial separation did not erode the functional relationship between port and city in the age of steam, as port work remained labor-intensive, and shipping "*contributed to the growth of the city center as a business district and to the expansion of financial and communication sectors within the urban economy*". Thus, the separation mentioned by Hoyle (1989) remained a minor shift compared with the ulterior changes brought by the massive port expansions of the 1960s (Bird, 1963).

2.2 From breakbulk to containers

2.2.1 Network effects

While the strongest impact of containerization was on cargo handling and turnaround times (Ducruet et al., 2014) in ports, mixed vessels (such as general cargo ships embarking some containers), and later fully cellular containerships, gradually became faster and larger than conventional cargo liners. The late 1980s, mid-1990s, and mid-2000s constitute turning points in the escalation of ship size, backed by the liberalization of the sector and the absorption of general cargoes and even bulks, in a context of growing demand (Cullinane and Khanna, 2000; Ducruet and Itoh, 2021). Containerization also "*had a tremendous impact on the geography of production and distribution*" (Notteboom and Rodrigue, 2008) and on maritime network design. Multi-port services had been gradually reorganized into a hub structure (Robinson, 1998). Transshipment hubs became pivots along line-bundling services to redistribute containers between main lines (relay/interlining) and between main lines and feeder lines (hub-and-spokes) (Ducruet and Notteboom, 2012).

An extant literature discussed the factors behind the emergence of transshipment (see Fleming and Hayuth, 1994; Rodrigue and Notteboom, 2010) as well as the hub allocation problem in liner shipping network design (see a recent review by Tran and Haasis, 2015). Yet, empirical attempts to detect centralization processes in shipping network design remained unsuccessful (Helmick 1994; McCalla, 2004). The comparison between breakbulk and containers from a network perspective has been proposed (Montes et al., 2012), but in a static way and in recent years, like studies of container shipping networks (Ducruet, 2020).

2.2.2 Port concentration

Containerization has been studied extensively with regard to concentration dynamics, as it fostered port competition at sea and on land. Numerous studies measured container traffic inequality across port systems in the U.S. (Hayuth, 1988; Kuby and Reid, 1992), Europe (Notteboom, 2010), and Asia (Itoh, 2012). Port system evolutionary models, initially designed to depict pre-containerization dynamics, were updated based on both developed (Hayuth, 1981) and developing economies (Airriess, 1989). The port regionalization model of Notteboom and Rodrigue (2005) offers a useful compromise, adding a phase of offshore hub development (maritime space) and the regionalization phase itself (land side) consisting in the deployment of logistics hubs across the hinterland of main ports.

The key factor behind concentration has been the pursuit of economies of scale to save time and cost, by launching evermore larger ships on major trunk lines. Such a process inevitably resulted in a drastic selection of ports capable of welcoming such sea giants, up to the so-called current era of mega-ships. Figure 2 well depicts the escalation of containership size between 1960 and 2014. The mid-1990s period particularly witnessed the emergence of transshipment hubs along major routes and within specific regions (i.e. Caribbean, North Europe, Mediterranean, Persian Gulf, East Asia). While intermodal transport and port selection processes partially reconfigured the pattern of port systems in certain regions, such as North America and Western Europe (Slack, 1990), containerization somewhat reinforced the inherited port city hierarchy in Asia (Lee et al., 2008). Nevertheless, "several peripheral ports (…) are mounting challenges to the major hubs" in Asia as well, based on new management and operational strategies of public and private actors (Slack and Wang, 2002).

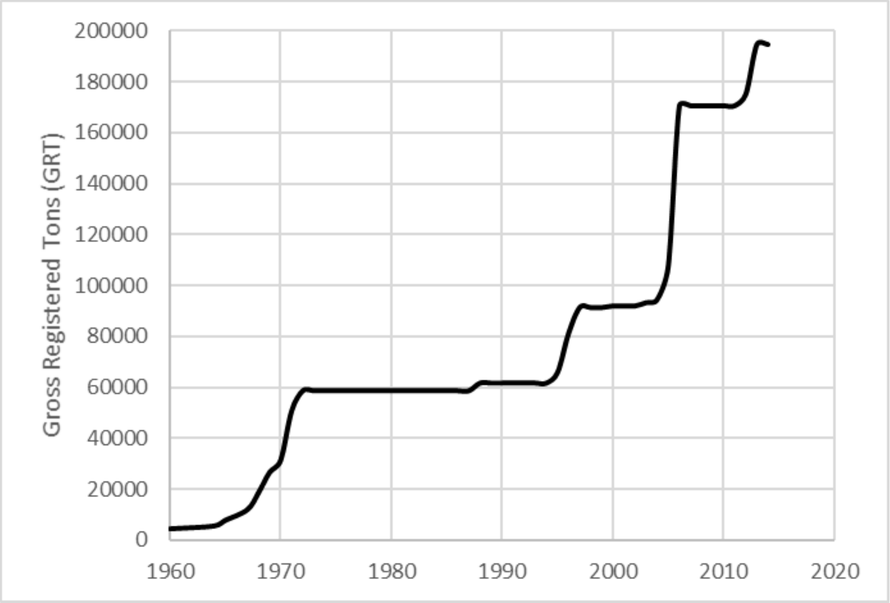

Figure 2: Evolution of maximum containership size, 1960-2014 (Unit: Gross Registered Tons)

Source: own elaboration based on Miramar data

2.2.3 Urban effects

Although a generic model of load center development depicted port system concentration at sites with "a large-scale local market", or large cities (Hayuth, 1981), containerization is commonly believed to have reinforced, if not provoked, port-city separation due to the growing mechanization of port labor and the migration of terminals outside urban cores (Levinson, 2016; Ducruet et al., 2020), followed by waterfront redevelopment in traditional port cities. High port costs, lack of space, and congestion in large, densely populated gateways were observed decades ago by geographers (Bird, 1963). More recently, it was found that container transshipment does not foster urban development (Slack and Gouvernal, 2016; Jacobs et al., 2011), so that the initially high correlation between container traffic and urban population rapidly declined between 1970 and 2005 (Ducruet and Lee, 2006).

A bunch of other empirical studies demonstrated, however, that container traffic kept strong ties with the port region. Regions specialized in container traffic tend to be richer, more densely populated, and specialized in the tertiary sector (Ducruet et al., 2015; Ducruet and Itoh, 2016). While the correlation between vessel traffic and urban population has declined since the 1930s for port cities, it increased for city-regions over the same period (Ducruet et al., 2018). This result confirmed the fading relevance of the port city itself as the relevant spatial unit and local determinant of shipping flows, compared with the enlarged unit of the city-region, should it be port or non-port.

2.3 Synthesis

The respective transitions from sail to steam and from breakbulk to containers thus share numerous commonalities. They triggered new intermodal arrangements, led to hinterland expansion, and port development for larger vessels. New forms of port competition and concentration emerged across port systems, with spatial discrepancies in terms of regional diffusion. However, as summarized in Table 1, our review shows discrepancies among scholarly observations. Works on sail and steam shipping networks remain scarce, so that their topology is ill-defined compared with container shipping, but empirical works on the latter did not find concrete evidence of a rationalization process. While port system concentration is widely recognized for steam, there is a debate for containerization between concentration and de-concentration studies. For urban effects, the physical and functional separation between port and city is well documented and supported by models for both innovations, but at the same time, cities and urban regions continue to attract and boost innovation. Such different views about the same phenomena may come from variations in space and time, or methodologies as underlined by Kuby and Reid (1992) about the right use of concentration coefficients. Other works pointed to a continuity of dynamics in the long term. As remarked by Castillo and Valdaliso (2017) about Spanish ports, "*high concentration levels [...] were driven by the expansion of steam shipping and railways in the first period, and containerization in more recent times*". According to Marnot (2005), 19th century port dynamics resembled those of the twenty-first century "*by nature more than scale*", especially with regards to the impacts of containerization. In China between 1868 and 2010, the port system has always been concentrated, but the increasing number of ports provoked a continuous decline of the share of the top ports in total traffic (Wang and Ducruet, 2013). Such differences strongly motivate a more systematic analysis across port cities of the world.

3. Data and methodology

3.1 The Lloyd's List database

Lloyd's List has long been the world's prime maritime insurer. Less familiar is its early role in printing vessel voyage information since its first publication in 1734. However, no more than three publications cited this data in the 20th century academic literature (for a review, and detailed description of the source see Ducruet et al., 2015). From 1880 onwards, publications detail the daily vessel movements of most of the world fleet, including vessels insured by other companies, making it highly representative of global maritime trade. We thus chose 1880 as the starting year for our research. Table 2 below compares the share of steam between the work of Williams and Armstrong (2012) using data on British ports and our own calculation for world ports based on the *Lloyd's List*. It shows that historians working on the transition from sail to steam with British port data have been too enthusiastic about the speed and completeness of the phenomenon. The world fleet was still very much dominated by sailing vessels in 1880 (87.0%), compared with vessels calling at British ports (53.0%). It is only in 1925 that steamers came to constitute the vast majority (more than 90%) of fleet and traffic, a 15-year gap with the commonly believed figure. This may be because there are large differences between countries and regions, for example, Britain, which transformed itself into a shipping nation with steamships. For containers, our study period corresponds to the "*diffusion wave*", following the "*pioneers*" and the "*early adopters*" (Guerrero and Rodrigue, 2014).

	Sail-to-steam	**Breakbulk-to-containers**
Shipping network topology	Short distance, meshed pattern, multi-port services (Williams and Armsrong, 2010)	Hub-feeder structure in Asia (Robinson, 1998), emergence of transshipment regions (Fleming and Hayuth, 1994; Rodrigue and Notteboom, 2010)
		No clear effects on network topology in North Atlantic (Helmick, 1994) and Caribbean (McCalla, 2004) regions
Port system pattern	Port concentration through corridor development in West Africa (Taaffe et al., 1963); resilience of port primacy in East Africa (Hoyle and Charlier, 1995) and China (Wang and Ducruet, 2013); high concentration through railway development in Spain (Castillo and Valdaliso, 2017) and France (Marnot, 2005); port piracy in Australia (Rimmer, 1967)	Port concentration at load centers (Hayuth, 1981); rationalization and concentration through larger ships, trains, intermodalism, digitization (Kuby and Reid, 1992)
	De-concentration through new port development in Asia (Murphey, 1969)	De-concentration by the challenge of secondary ports (Hayuth, 1988) and new routing patterns (Slack, 1990) in North America and Asia (Slack and Wang, 2002); container throughput de-concentration in Europe (Notteboom, 2010); offshore hub development (Notteboom and Rodrigue, 2005)
Port-city relationship	High port-city correlation at port city level before 1950 (Ducruet et al., 2018); strong impetus given by shipping to urban growth (Konvitz, 1994)	Densely populated regions concentrate containers (Ducruet et al., 2015; Ducruet and Itoh, 2016) ; increasing port-city correlation at city-region level (Ducruet et al., 2018)
	Spatial development of ports beyond city confines (Hoyle, 1989; Konvitz, 1994); functional evolution of port cities into ‘general cities’ (Murphey, 1989)	Large transshipment hubs with no urbanization effects (Slack and Gouvernal, 2016); port location not attractive for maritime services (Jacobs et al., 2011); declining port-city correlation (Ducruet and Lee, 2006); crowding out of port activities (Ducruet et al., 2020)

Table 1: Literature classification on the effects of shipping innovations

Year	British ports*		World ports**	
	Entrances with cargo and in ballast (% tonnage)	Entrances with cargo and in ballast (% vessels)	Number of vessels (% vessels)	Number of calls (% calls)
1855	15.8	12.4	-	-
1860	20.9	15.5	-	-
1870	33.8	22.8	-	-
1880	63.0	47.0	13.0	13.9
1890	82.8	69.8	34.7	38.2
1900	91.8	81.4	57.7	61.6
1910	97.1	90.5	80.8	84.6
1920	-	-	88.2	90.4
1925	-	-	96.5	98.3

Table 2: Share of steam traffic and fleet by data source, 1855-1925

Source: own elaboration based on Williams and Armstrong (2012)* and Lloyd's List data**

Sail and steam traffic are measured by the number of calls. We extracted 272,450 vessel movements for the period between 1880 and 1925 and 3,760,823 ones between 1977 and 2008. For containerization, we use the product between the number of calls and deadweight tonnage (DWT), differentiating vessels amongst fully cellular containerships, general cargo ships, and general cargo ships with container capacity (mixed vessels). We do not consider the rest of the fleet, such as bulk, passengers, and ro-ro, although such ships may also carry containers. This is because the focus of this paper is on the transition from breakbulk to containers. For steam, although *Lloyd's* printed data also details whether sailing ships utilized an auxiliary engine with the number of propellers, the bad quality results of the Optical Character Recognition (OCR) did not allow for the identification of a mixed sail/steam ship category.

3.2 Statistical methods and indicators

The spatial analysis of innovation diffusion does not rely on a specific methodology. In this research, we use a descriptive approach combining network analysis and statistical analysis. Network analysis serves to characterize the topology of each layer (sail, steam; container, general cargo, mixed cargo), with the hypothesis that economies of scale have made the network sparser and more optimal (see Appendix 1 for the formulas of network indices). The Gamma Index, which is the proportion of existing links in the total maximum possible number of links among existing nodes, is a measure oscillating between density / meshedness (0.1) and centralization / sparsity (0). The average clustering coefficient and the power-law slope exponent also depict the extent to which the network is centralized around hubs, with reference to small-world networks for the first and scale-free networks for the second (Newman, 2010). The Gini coefficient, a measure of inequality, serves to depict the level of traffic concentration among world ports, based on the hypothesis that new technologies will be more concentrated than former ones. It is a widely used indicator in port system analyses in geography, combined with the Herfindhal-Hirschman index, another measure of concentration (see Notteboom, 2006).

Based on the reviewed literature, we retain the following independent variables for the multiple regressions on nodes. City size (natural logarithm of population, proxy of economic weight) is seen as both a constraint to and a facilitator of diffusion. Cities are densely populated places where available land for port expansion is scarce and where nautical conditions are limited by the historical site, so that new ports handling new technologies are crowed out to better suited locations (Ducruet et al., 2020). At the same time, cities are prime consumption and production centers, and they provide ports with jobs and other externalities (Hall and Jacobs, 2012). Population data was collected and harmonized from three global urban databases[2]. The year dummy is crucial as it represents the speed of diffusion. World regions dummies express regional heterogeneity. The location type (downstream, inland, upstream, and island) demonstrates connectivity to the sea, as certain situations may be more or less favored. For instance, the upstream site is seen as constraining port growth in the *Anyport* model (Bird, 1963), although certain port cities such as Antwerp and Hamburg have managed to avoid port-city separation (Notteboom, 2016).

Five different centralities of port cities in the global maritime network were calculated due to their complementarity: betweenness centrality (global accessibility), clustering coefficient (fraction of common neighbors; low values for central nodes, high values for meshed nodes), degree centrality (local connectivity; number of connected neighbors), average link clustering coefficient (fraction of common neighbors of a connected pair; low values for bridge nodes, high values for meshed nodes), and inverse clustering coefficient[3] (hub power). The average kilometric length of maritime links (natural logarithm) of port cities represents their interaction range.

In the multiple regression on links, population (city size) is the natural logarithm of the product of the populations of the connected port cities on each pair. The maritime distance of links (interaction range) is the natural logarithm of the kilometer length between port cities. Centrality variables are the differential indices between new and old technologies, weighted and standardized by port traffic to reduce the number of independent variables. Such variables show the relative shipping network advantage of new technologies over former ones at and between port cities.

4. The diffusion process of new technology and network analysis

4.1 General trends and geographic spread

The respective evolution of steam and containers is shown in Figure 3. A similar trend occurred, namely the shift towards a domination of respective innovations. The share of container traffic increased from 20% to 80% over the period, and general cargo traffic nearly disappeared, while mixed vessel traffic, which is also carrying containers, remained around 10% in 2008. It underlines the fact that a growing proportion of general cargo had become containerized.

---

[2] The three databases are Geopolis (1950-1990), Population Statistics (1880-2005), and World Gazetteer (2010). They consider the spatial extent of urbanization (morphological area) to define cities.

[3] This measure is the inverse of the clustering coefficient except zero values. Zero values in the clustering coefficient are often related with sinks or sources, i.e. vulnerable nodes at the extremity of a link (edge), while values close to zero usually depict hubs. The inverse clustering coefficient is more likely to catch hub effects by keeping zero values unchanged and transforming low values into high values, providing a more plausible hierarchy from the least central to the most central ports.

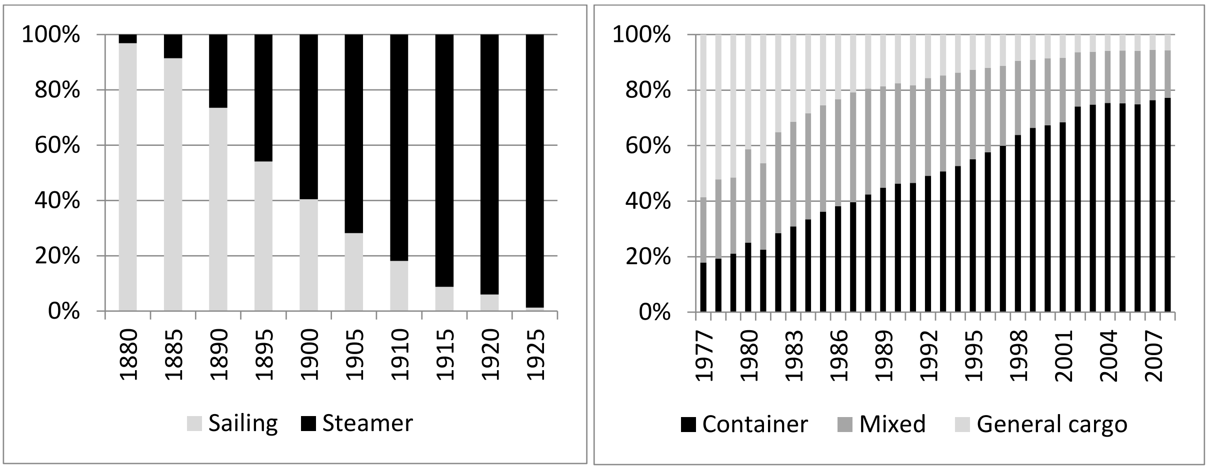

Figure 3: Steam (% calls) and container* (% DWT) traffic share in total shipping traffic

Source: own elaboration based on Lloyd's List data

** total vessel traffic includes only general cargo, mixed general cargo/container, and fully cellular container*

The geographic spread of both innovations is another way to validate the accuracy of data and to make comparisons (Figures 4 and 5). The diffusion of steam is well in line with the findings of Williams and Armstrong (2012) based on shipping movement data at United Kingdom ports (1855-1910). Black sea, the Mediterranean and Asia have been faster in adopting and completing steam, compared with the Americas, especially on the Pacific side, and Australasia, the opposite profile. Such discrepancies can be explained by the resilience of sailing vessels for bulk cargo, long-distance, and wind-favored routes. For containerization, North America stands out as the cradle of the innovation, with the highest rates along the period for the West and East coasts. It is followed by Oceania, Northeast Asia (cf. Japan), and Southeast Asia. Containerization had been well developed initially in Northwest Europe (19.9% in 1977), but the ulterior spread remained rather slow, mainly due to the persistence of general cargo, so that this region is the fourth least containerized in 2008 (69.4%).

At port city level (Figures 6 and 7), maps show in more detail the traffic hierarchy and which places have adopted innovations earlier than others. Steam primarily developed at closed seas (Mediterranean and Black Sea) and along an East-West corridor between Europe and Asia, through the Suez Canal, concerning small and medium-sized ports. The largest traffic, mainly by sail, concentrated in the Atlantic Ocean with New York, Buenos Aires, and London/Liverpool being the leading ports. This pattern persisted in 1900, together with the emergence of large ports with a noticeable share of steam (Rotterdam, Antwerp, Genoa). In 1920, only Buenos Aires and a number of North Atlantic port cities remain below world average for steam traffic share, together with Melbourne and Sydney through wheat trade ensured by windjammers on secondary routes (Bunel et al., 2017). Favorable wind conditions have been a crucial factor to maintain certain sailing routes in the late period. For containerization, the evolution has been mainly hierarchical, as the most advanced ports were also the largest, and this mechanism has dominated up to 2008. The diffusion clearly shows a North-South division of the world, followed by a major shift towards East Asia and in more limited ways to the rest of the world.

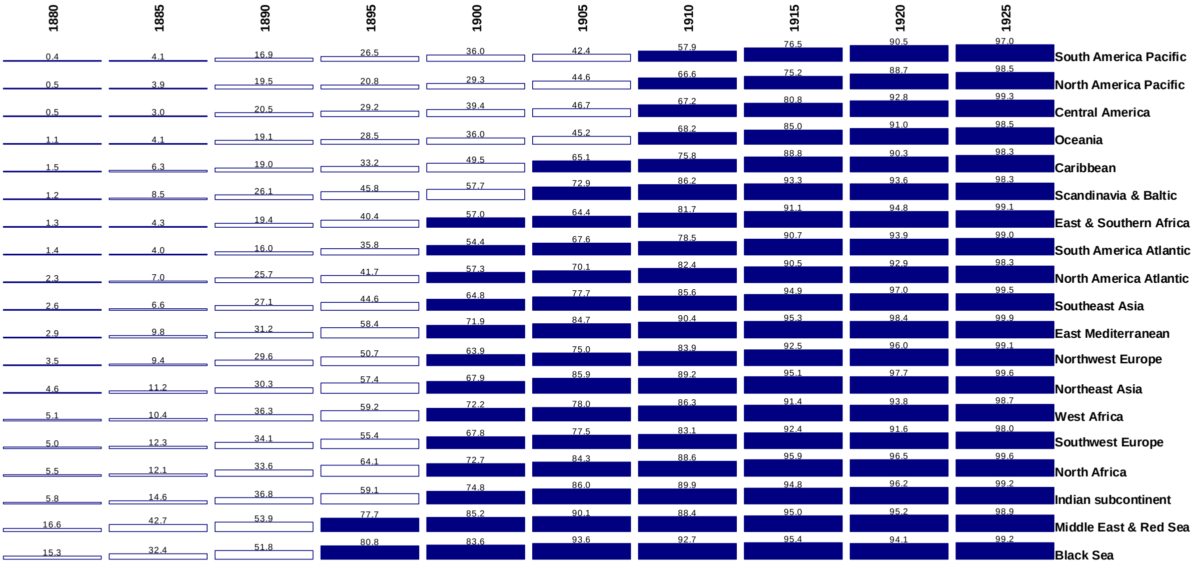

Figure 4: Share of steamer traffic in total vessel traffic by world region, 1880-1925 (% calls)

Source: own elaboration based on Lloyd's List data

4.1 Network interdependency

One first step into the direct comparison of innovation diffusion is the analysis of network overlap (Figure 8). The correlation coefficient between the respective traffics shows to what extent old and new technologies are topologically and geographically combined over the same nodes (port cities) and links (inter-cities), and how this co-occurrence has evolved. In other words, this coefficient will be higher if the technology diffuses on the same port (node) or the same route (link). Figure 6 shows that both innovations are very close to their predecessors (higher values) in the early period, and diverge afterwards. This is even truer at the link level, characterized by lower correlation and faster divergence. The divergence is rather late and abrupt for sail and steam, as the correlation remained highly significant and stable, then declined from 0.7 to slightly above 0.3 between 1915 and 1925.

For container shipping networks, the correlation evolution with general cargo was gradual; it only declined by about -0.2 over the period, notwithstanding oscillations in between. The correlation with mixed ships, initially lower than with general cargo in 1977, increased until the early 1990s and declined quite rapidly afterwards. A similar evolution occurred slowly for nodes, probably because the mid-1990s mark a turning point in the evolution of containerization, namely the introduction of larger vessels and the emergence of transshipment hubs. For sail and steam at node level, respective traffic remained highly correlated over the period, with a slight drop in the late period, or after 1915. This analysis confirms that the topological and geographic structure of shipping innovation much depended on pre-existing relations in the diffusion phase, before developing its own pattern. The new technology began to spread in areas where transportation was originally active, and then it spread to each port, resulting in a division of transportation methods, along with the nearly disappearance of former technologies (lower values).

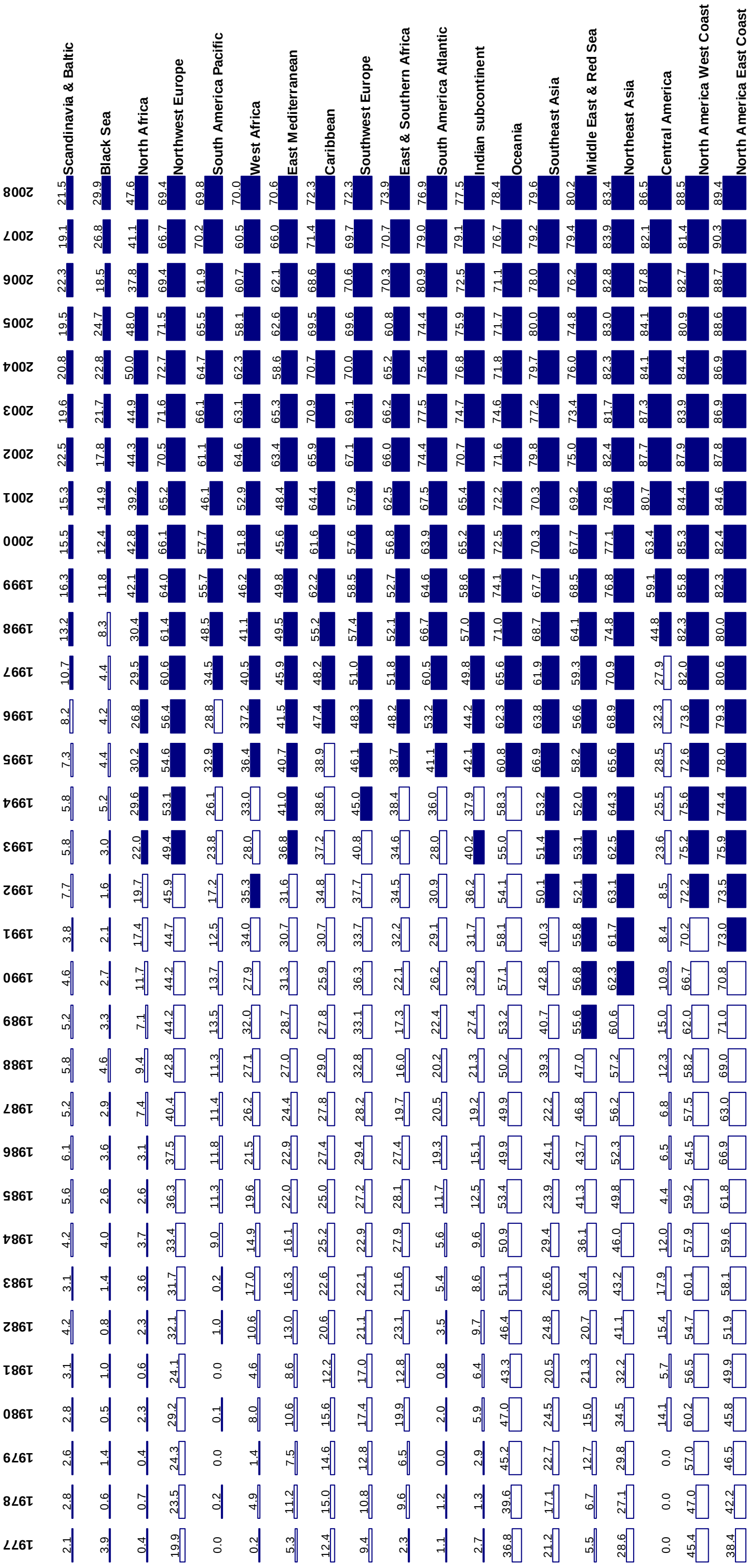

Figure 5: Share of container traffic in total vessel traffic by world region, 1977-2008 (% DWT)

Source: own elaboration based on Lloyd's List data

N.B. total vessel traffic includes only general cargo, mixed general cargo/container, and fully cellular container

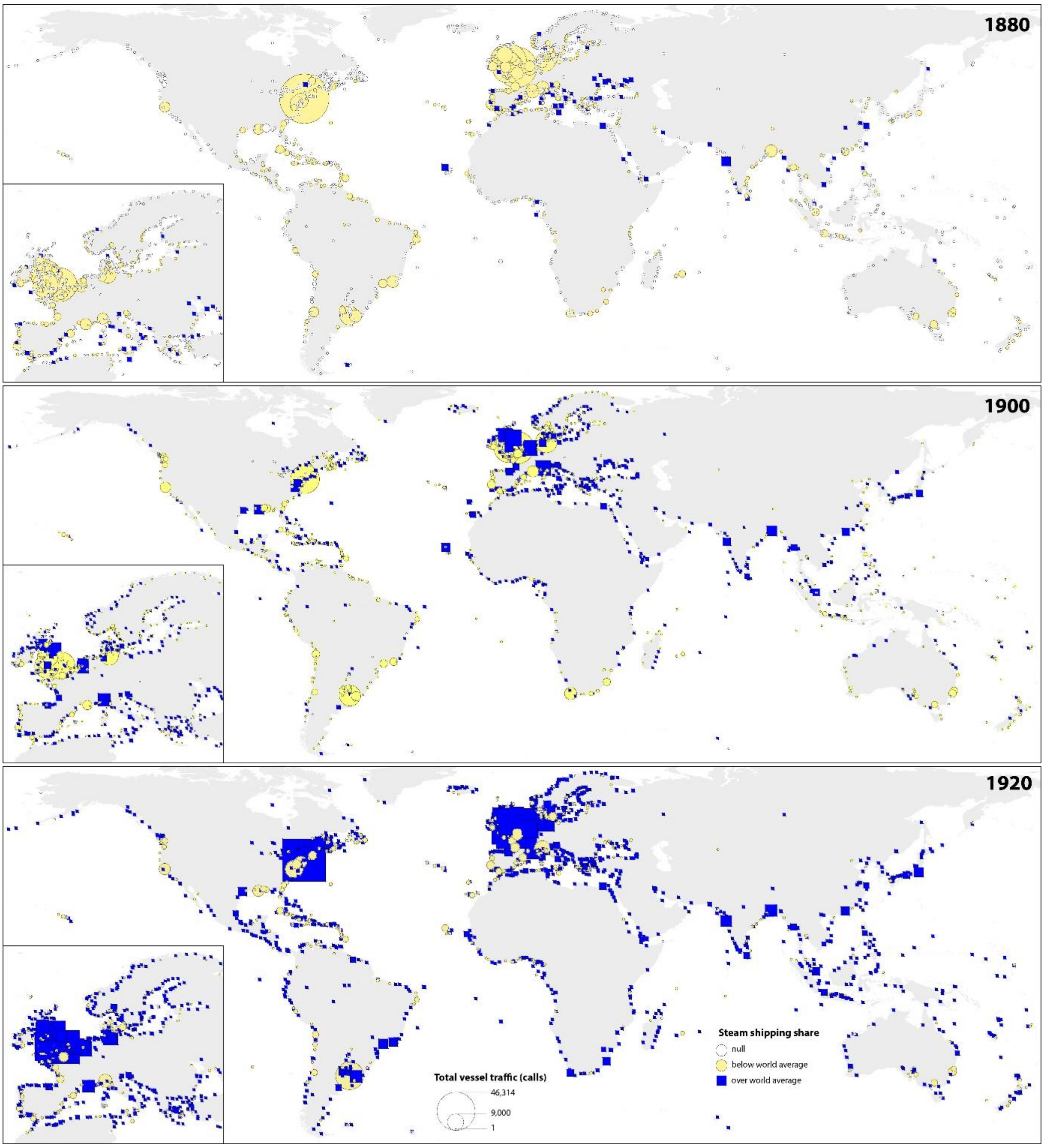

Figure 6: World distribution of vessel traffic and steam specialization at selected years

Source: own elaboration based on Lloyd's List data

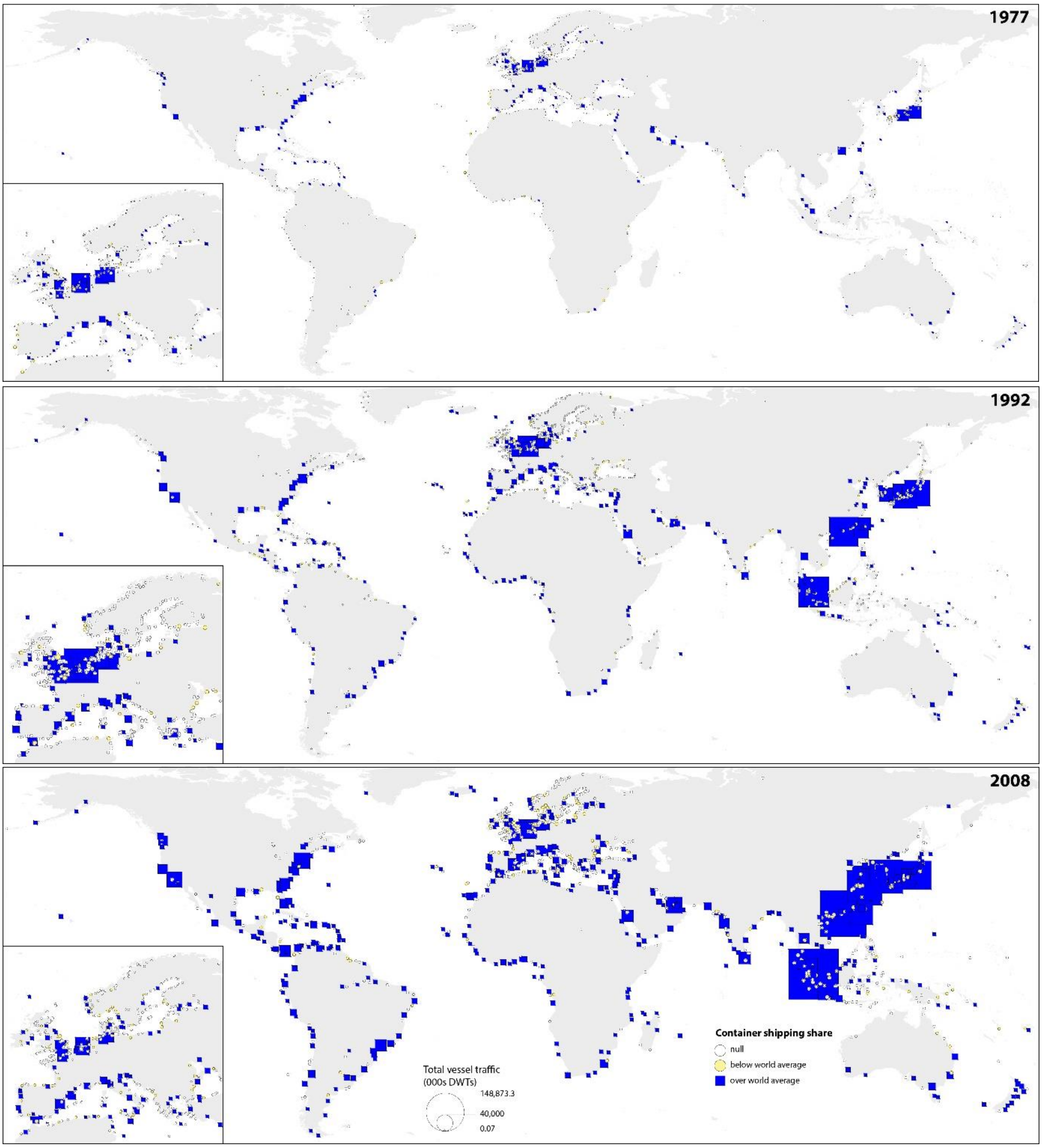

Figure 7: World distribution of vessel traffic and container specialization at selected years

Source: own elaboration based on Lloyd’s List data

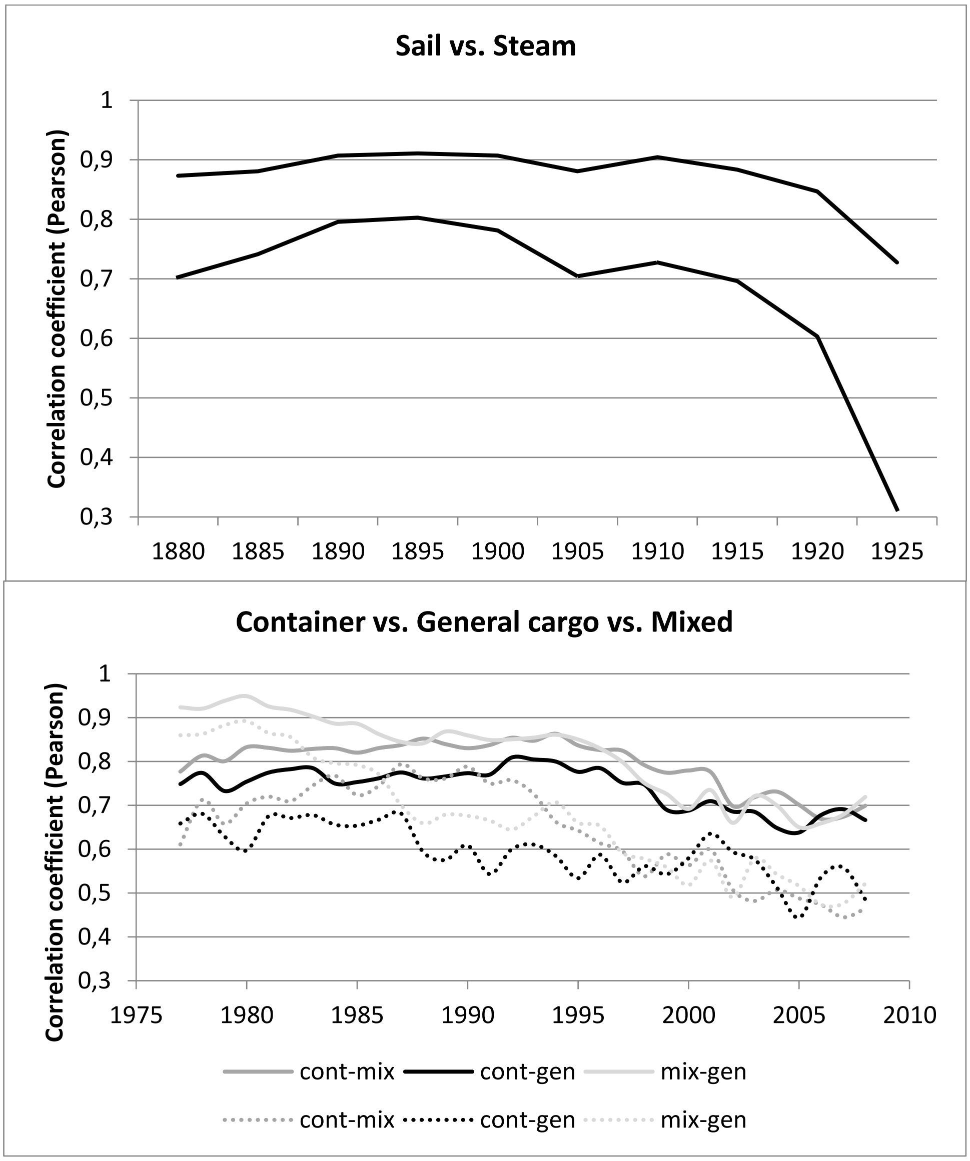

Figure 8: Level of network overlap

Source: own elaboration based on Lloyd's List data

N.B. dotted lines refer to links, full lines to nodes

4.2 Port concentration

Gini coefficients show that both steam and container traffic witnessed an increase in concentration, followed by stability. The rapid increase in the first half of the 1980s is thought to be due to the spread of containerization in regions where it had lagged behind (for example, Middle East & Red Sea, East and Southern Africa, and West Africa, see Figure 5). Container traffic is specific by its slight decline of concentration since the mid-1990s, due to the emergence of large hubs competing with traditional port cities, making the port system more balanced but still highly concentrated, and the continued spread of containerization across the world. Sailing and general cargo traffic, on the contrary, experienced de-concentration, as well as mixed ship traffic (especially after the mid-1990s), as these segments remain organized through multi-port calls and lost market share. The latter process suggests a spatial dispersion and absolute decline of such traffics, which are not anymore the engines of port development. Technology substitution occurred at major ports, and older technologies remained geographically dispersed as auxiliary functions. The Herfindhal-Hirschman index shows that container shipping is the most concentrated segment, but all traffics went through de-concentration, either through dispersion and decline (sail, general cargo, mixed) or the increasing number of large ports (steam, container).

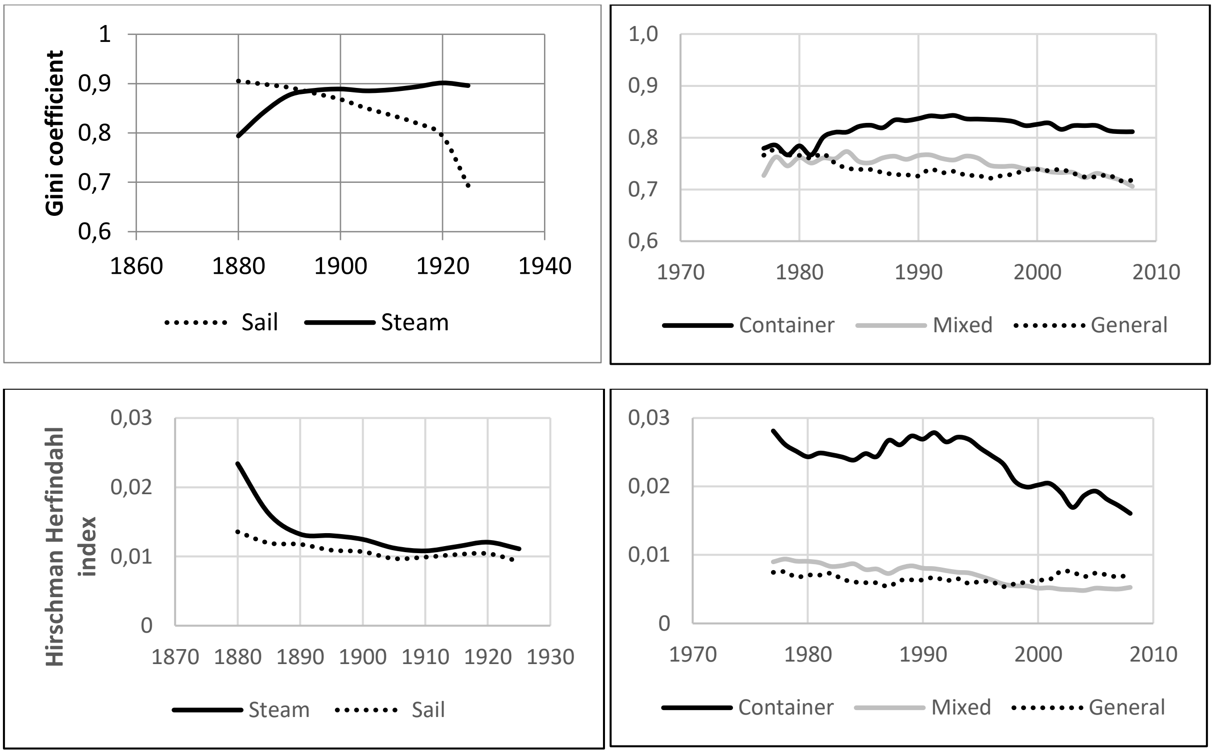

Figure 9: Traffic concentration at node level by fleet type

Source: own elaboration based on Lloyd's List data

4.3 Network centralization and meshedness

Following the aforementioned literature, it is important to characterize the topology of the new shipping networks compared with their existing counterparts. In our results (Figure 10), the two innovations have in common to exhibit, overall, a denser structure (higher Gamma index) than the other fleet types. For steam, it confirms that this innovation mainly developed through short-distance shipping while creating a dense network of multi-port calls. For containers, there is a slow but regular centralization of the network from the 1970s to the 2000s, followed by stability about 0.02 (i.e. 2% of the maximal network is connected). However, one could have expected the centralization process to be more acute. It is probable that such a process is counterbalanced by the development of shortsea and coastal shipping as well as regional integration logics that make the network denser, or multilayered. The centralization of flows upon fewer large hubs is thus attenuated by a growing connectivity among smaller ports.

The average clustering coefficient and power-law slope exponent provide converging results. They both indicate that the network of former technologies (sail, general cargo) became sparser and more centralized along their decline. Like for density, the innovative networks (steam, container) became increasingly connected and clustered. The emergence of transshipment hubs thus did not affect network structure for container shipping, as these nodes remain few compared with the high number of smaller ports ensuring other service types, such as shortsea and coastal shipping.

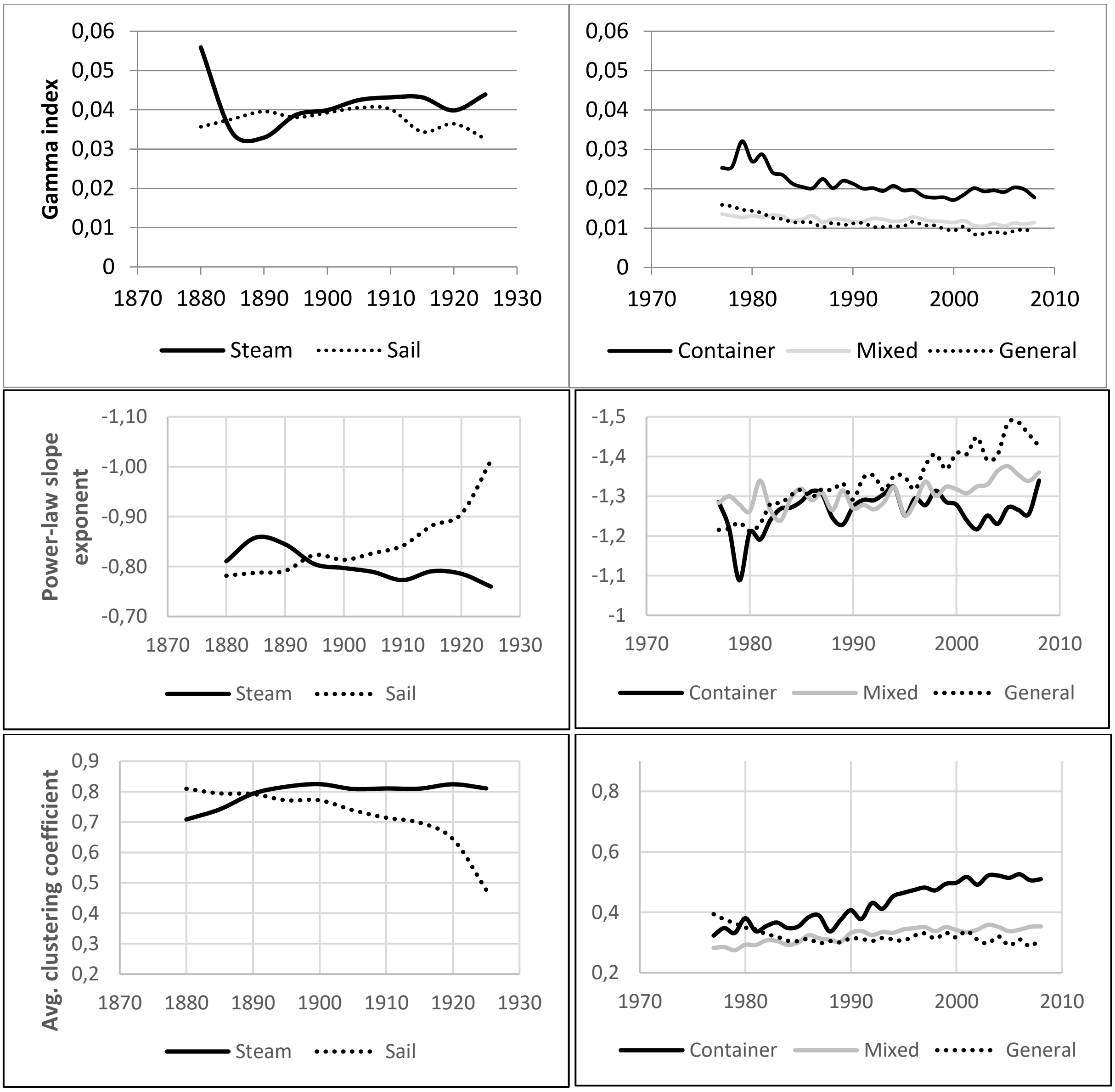

Figure 10: Network centralization by fleet type

Source: own elaboration based on Lloyd’s List data

4.4 Port-city linkages

The urban affinity of different shipping technologies is another fundamental element of their understanding and comparison. The correlation between urban population and vessel calls (Figure 11) goes through a gradual decline of the correlation all over the period, from around 0.65 up to the 1930s to about 0.4 in 2008. This confirms the transition from ‘port-city symbiosis’ to separation, due to the combination of multiple phenomena of which hinterland expansion, port migration, terminal mechanization, and transshipment development. Numerous traditional port cities had lost their port function, while new ports were created away from urban centers. Nevertheless, fleet types share different affinities with cities. Our results for the early period confirm the observations made by Konvitz (1994) about the close association between steam shipping development and urban development in the late 19th and early 20th centuries, as steam traffic is more correlated with city size than sailing traffic. The overall higher number of steamships than sailing ships (calculated by the number of port calls) is due to the shift from sailing ships, which are more geographically constrained like wind, to steamships, which can make regular port calls and are more closely tied to major cities, or economic activities.

Containerization offers a drastically different picture, based on DWT. While the three traffic types start in 1977 with a comparably higher correlation, each of them evolves differently. General cargo, despite its absolute and relative traffic drop, maintained a close association with city size up to 2008. It echoes the work of Charlier (1994) stating that general cargo is the most employment-generative traffic. It is followed by mixed ship traffic, with intermediary correlation values which declined from the mid-1990s onward. Although containerization started with the highest correlation in 1977, it continuously declined over the period. This confirms the widely accepted fact that containerization reinforced port-city separation, its traffic growth being often incompatible with urban development.

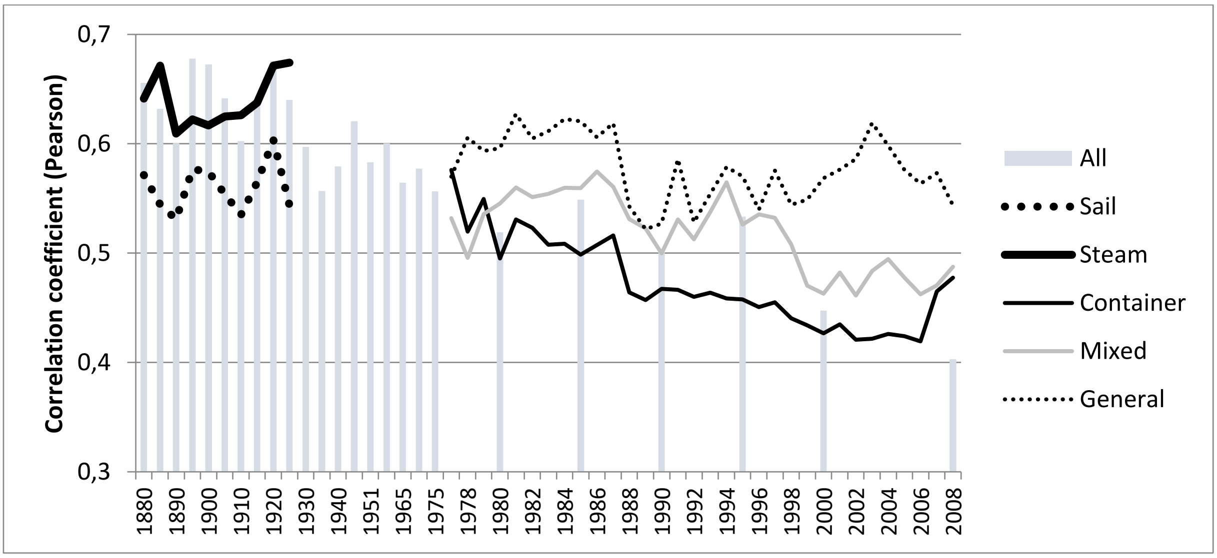

Figure 11: Correlation between urban population and vessel traffic by fleet type, 1880-2008

Source: own elaboration based on Lloyd's List and urban data

5. The determinants of shipping innovation diffusion

This part of the analysis offers a more comprehensive approach to the diffusion of shipping innovations. It considers the traffic share (ship calls for steam revolution, DWTs for containerization) of the innovative technology in the total traffic of port cities (nodes) on the one hand, and inter-city linkages (links) on the other as dependent variables[4]. Those are two distinct albeit complementary spatial units, nodes and links, to look at to provide a full-fledged overview of the determinants of innovation diffusion. Estimated equations are provided in Appendix 2.

5.1 Diffusion from a node perspective

Table 3 highlights interesting differences between the two transitions. In this empirical analysis, the standardized coefficients (Stand.) as well as the coefficients obtained from the functional form are included in order to compare directly the magnitude of the coefficients. While demographic size had a positive influence on innovation diffusion in both cases, this was remarkably of a lower impact for steam. The high correlation between steam traffic and population seen in Figure 9 does not contradict the fact that steam 'specialization' increased at less-populated places than did containerization. This is probably due to the fact that the dispersion of the population was relatively smaller at that time than on containerization age. Comparing the year dummies, we can understand that steamships were larger and spread at a faster rate than container ships (other things being equal). The logic had been more geographic, as seen with the friction of distance (negative sign but statistically insignificant, or maritime distance on steamships will be shorter as in previous study (Williams and Armstrong, 2010)) and the particular role of the Black Sea, a major grain exporter towards the Western world in a period of declining freight rates (North, 1958; Kaukiainen, 1992).

Steam specialization particularly increased in the vicinity of the Suez Canal, as seen with the positive signs (against the baseline region of Scandinavia and Baltic) of Middle East & Red Sea (ARA), East Mediterranean (EMD), and Indian subcontinent (IND), on the way to Northeast Asia (CHI). This occurred somewhat regardless of city size, more through the logic of a powerful East-West maritime corridor. In comparison, containerization was much more dependent on city size to spread, as it evolved through path-dependence (Ducruet, 2013) at existing bulk and general cargo ports which were themselves grown up gateway cities such as New York, Yokohama, Oakland, and Hamburg (i.e. the 'pioneers' according to Guerrero and Rodrigue, 2014), soon followed by Antwerp, Rotterdam, and Hong Kong, to name but a few. Another major difference with steam is the positive influence of distance (statistically significant), as regular transatlantic and transpacific services were established in the 1970s already to serve the economic cores of the Triade, with North American regions (USA – East Coast, USP – West Coast, CAR – U.S. Gulf & Caribbean) and Oceania (AUS) taking the lead (e.g. Sydney, Melbourne). Like for airline networks (Guimera et al., 2005), connectivity is function of distance for large gateways involved in long haul markets.

Steam and containerization share also similarities. In terms of location, upstream port cities have been the least desirable places to develop the new technology (against the baseline of coastal), which implied an increase in vessel size, causing navigation constraints along estuaries and deltas. Containerization was also favored by island sites, especially from the 1980s with the growth of traffic in the Caribbean, the Mediterranean, and East Asia (e.g. Singapore, Japan). Last but not least, degree centrality (DC) has the strongest explanation power for both transitions, followed by average link clustering coefficient (LCC). It means that better connected port cities – in the total network – were

---

[4] An empirical analysis was also conducted considering not only fully cellular container ships but also container capacity (estimated DWTs for container boxes) in mixed ships, but no significant difference was found in the regression analysis results. The difference is, in both the node and link analyses, that the effect of population was smaller, while the effects of distance and year dummies were larger, with same signs on container diffusion. There are also some characteristic differences, such as the generally small effect of regional dummies, and more detailed analysis will be expected in further research.

more likely to develop innovations. The positive sign for LCC suggests that port cities in a meshed neighborhood adopted steam or containerization faster, which is confirmed by the (node) clustering coefficient (CC) for steam. As such, the bridge function (BC) and the hub power (ICC) did not play a strong role for diffusion. As a matter of fact, bridges and hubs emerged after the diffusion phase. The "global standard" phase described by Guerrero and Rodrigue (2014), for containerization, coincides with the launch of sea giants in the mid-1990s.

	Sail to steam (% steam calls)				**Breakbulk to containers (% DWT container)**			
	Adj R2	**S.E.**			**Adj R2**	**S.E.**		
	0.766	0.168			0.460	0.258		
	Beta	**S.E.**	**Stand.**		**Beta**	**S.E.**	**Stand.**	
Const.	0.110	0.072			-0.439	0.008		***
Population	0.014	0.002	0.059	***	0.072	0.001	0.350	***
Distance	-0.006	0.009	-0.008		0.013	0.001	0.065	***
Year dummy	0.019	0.000	0.690	***	0.010	0.000	0.268	***
Regional dummy (at port)								
Middle East & Red Sea	0.013	0.029	0.003		0.168	0.011	0.074	***
Oceania	-0.059	0.016	-0.035	***	0.211	0.009	0.122	***
Black Sea	0.084	0.014	0.045	***	-0.029	0.009	-0.015	***
Central America	-0.032	0.021	-0.011		0.117	0.014	0.040	***
Caribbean	-0.029	0.011	-0.026	***	0.107	0.007	0.082	***
Northeast Asia	0.009	0.015	0.006		0.036	0.007	0.033	***
East & Southern Africa	-0.012	0.017	-0.006		0.104	0.011	0.044	***
East Mediterranean	0.013	0.021	0.005		0.084	0.011	0.037	***
Indian subcontinent	0.019	0.016	0.010		-0.026	0.010	-0.012	**
North Africa	-0.009	0.017	-0.004		-0.096	0.010	-0.048	***
Northwest Europe	-0.036	0.010	-0.036	***	-0.002	0.007	-0.002	
South America Atlantic	-0.038	0.012	-0.025	***	0.025	0.010	0.013	**
South America Pacific	-0.061	0.016	-0.030	***	0.043	0.012	0.018	***
Southeast Asia	-0.052	0.017	-0.027	***	-0.017	0.008	-0.013	**
Southwest Europe	-0.008	0.009	-0.008		0.028	0.006	0.025	***
North America Atlantic	-0.069	0.013	-0.045	***	0.174	0.011	0.081	***
North America Pacific	-0.088	0.020	-0.034	***	0.190	0.015	0.060	***
West Africa	0.034	0.016	0.016	**	0.114	0.009	0.064	***
Location dummy (at port)								
Downstream	-0.006	0.007	-0.007		-0.011	0.005	-0.012	**
Inland	0.002	0.010	0.001		-0.105	0.007	-0.076	***
Upstream	-0.018	0.007	-0.020	**	-0.082	0.005	-0.080	***
Island	-0.003	0.006	-0.004		0.043	0.004	0.058	***
Centralities (at port)								
Betweenness centrality	-0.003	0.005	-0.008		0.019	0.004	0.027	***
Clustering coefficient	0.011	0.004	0.021	**	-0.002	0.002	-0.003	
Degree centrality	0.143	0.007	0.233	***	0.269	0.005	0.313	***
Link clustering coefficient	0.056	0.004	0.120	***	0.024	0.003	0.050	***
Inverse clustering coefficient	0.001	0.007	0.002		-0.005	0.002	-0.012	**

Table 3: Regression results at node (port city) level

N.B. Standardized by 'Scandinavia & Baltic' and 'Coastal'

*** 1%, ** 5%, * 10% significant.

5.2 Diffusion from a link perspective

Compared with nodes, the speed of diffusion had been slower on links (Stand.), for both steam and containerization (Table 4). This can be explained by the friction of space, whereby distance between ports has a negative effect on both innovations' diffusion (negative signs, but statistically insignificant for steam). This friction less impeded steam, which mainly developed through short-distance linkages (multi-port calls), and gradually deployed longer ones with noticeable amounts of cargo and high frequency[5]. As shown in complementary Figure 12, steam was deployed on shorter distances than sail, and containerization on longer distances than breakbulk. Nevertheless, such a figure also highlights that shipping in the age of steam was much more 'global' in scope than nowadays, with the direct connection between faraway ports through a colonial logic. Breakbulk and also ro-ro ships had been better adapted than containerships to short distances. As in the node analysis (5.1), the yearly dummies are larger for steamships than for containerships, suggesting that (other things being equal) steamships spread faster. However, the yearly dummies are smaller in the link analysis than in the node analysis, and it can be understood that even for shipping links, there is a large difference (deviation) between those that spread early and those that spread late.

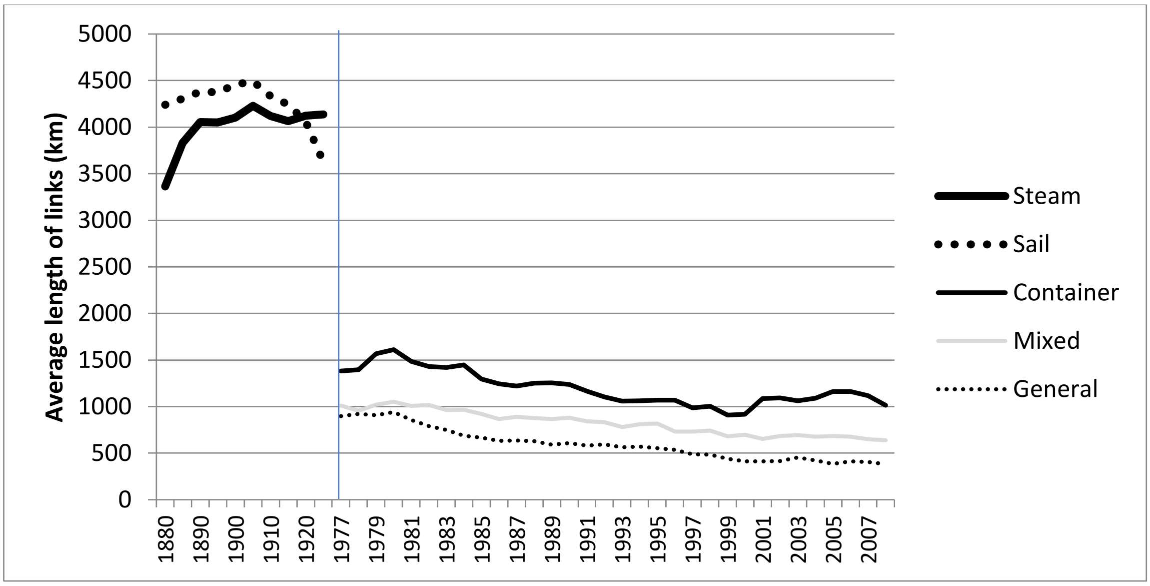

Figure 12: Link distance by fleet type

Source: own elaboration based on Lloyd's List data

In terms of routes for steam development, within West Asia, Europe-West Asia, East Asia-West Asia, and Africa-West Asia (without considering directionality) are the four only lines with a positive sign for links (against the baseline route intra-Europe). In descending order, the most reluctant routes to deploy steam shipping were Latin America-Oceania, North America-Oceania, Latin-North America, followed by the connections of intra-Oceania and intra-Latin and intra-North America, respectively. For containerization, North America-Oceania, East Asia-North America, intra-Oceania, and Europe-Oceania connections are the most salient routes.

---

[5] Steam traffic (share) is based in this paper on the number of ship calls, without considering vessel tonnage, due to the bad quality of OCR results.

	Sail to steam (% steam calls)				**Breakbulk to containers (% DWT container)**			
	Adj R2	**S.E.**			**Adj R2**	**S.E.**		
	0.511	0.295			0.208	0.291		
	Beta	**S.E.**	**Stand.**		**Beta**	**S.E.**	**Stand.**	
Const.	0.097	0.004		***	-0.283	0.003		***
Population	0.009	0.000	0.043	***	0.033	0.000	0.270	***
Distance	-0.001	0.001	-0.003		-0.013	0.000	-0.095	***
Year dummy	0.020	0.000	0.589	***	0.006	0.000	0.158	***
Regional dummy (at ports' pair)								
Africa_Africa	-0.018	0.008	-0.003	**	0.038	0.003	0.020	***
Africa_East_Asia	-0.026	0.006	-0.006	***	0.018	0.008	0.004	**
Africa_Europe	-0.014	0.003	-0.008	***	-0.035	0.002	-0.029	***
Africa_Latin_America	-0.065	0.004	-0.023	***	-0.096	0.006	-0.026	***
Africa_North_America	-0.050	0.004	-0.016	***	-0.078	0.008	-0.016	***
Africa_Oceania	-0.087	0.007	-0.016	***	0.060	0.025	0.004	**
Africa_West_Asia	0.013	0.007	0.003	**	-0.015	0.005	-0.005	***
East_Asia_East_Asia	-0.023	0.007	-0.004	***	0.026	0.002	0.027	***
East_Asia_Europe	-0.012	0.003	-0.007	***	0.187	0.008	0.038	***
East_Asia_Latin_America	-0.063	0.004	-0.023	***	0.051	0.008	0.010	***
East_Asia_North_America	-0.055	0.004	-0.018	***	0.258	0.006	0.072	***
East_Asia_Oceania	-0.072	0.007	-0.014	***	0.082	0.006	0.025	***
East_Asia_West_Asia	0.014	0.006	0.003	**	0.027	0.004	0.011	***
Europe_Latin_America	-0.052	0.002	-0.045	***	0.021	0.004	0.010	***
Europe_North_America	-0.047	0.003	-0.036	***	0.176	0.004	0.072	***
Europe_Oceania	-0.078	0.003	-0.038	***	0.234	0.015	0.026	***
Europe_West_Asia	0.030	0.003	0.015	***	0.091	0.003	0.045	***
Latin_America_Latin_America	-0.097	0.003	-0.037	***	0.069	0.003	0.046	***
Latin_America_North_America	-0.098	0.003	-0.047	***	0.038	0.003	0.020	***
Latin_America_Oceania	-0.130	0.005	-0.038	***	0.053	0.018	0.005	***
Latin_America_West_Asia	-0.024	0.005	-0.007	***	-0.151	0.015	-0.016	***
North_America_North_America	-0.095	0.004	-0.028	***	0.151	0.004	0.062	***
North_America_Oceania	-0.119	0.005	-0.031	***	0.354	0.011	0.051	***
North_America_West_Asia	-0.007	0.005	-0.002		-0.015	0.018	-0.001	
Oceania_Oceania	-0.121	0.011	-0.014	***	0.250	0.006	0.076	***
Oceania_West_Asia	-0.034	0.008	-0.005	***	0.064	0.017	0.006	***
West_Asia_West_Asia	0.078	0.011	0.009	***	0.028	0.004	0.012	***
Location dummy (at ports' pair)								
Coastal_Downstream	-0.012	0.001	-0.012	***	-0.035	0.002	-0.044	***
Coastal_Inland	0.003	0.003	0.001		-0.042	0.003	-0.027	***
Coastal_Upstream	-0.010	0.002	-0.010	***	-0.068	0.002	-0.079	***
Downstream_Downstream	-0.030	0.002	-0.017	***	-0.039	0.002	-0.028	***
Downstream_Inland	-0.013	0.004	-0.004	***	-0.073	0.005	-0.026	***
Downstream_Upstream	-0.030	0.002	-0.021	***	-0.104	0.002	-0.094	***
Inland_Inland	-0.017	0.017	-0.001		-0.113	0.009	-0.020	***
Inland_Upstream	-0.005	0.004	-0.002		-0.119	0.005	-0.040	***
Upstream_Upstream	-0.029	0.003	-0.014	***	-0.100	0.003	-0.064	***
Island_no_yes	-0.011	0.001	-0.013	***	0.021	0.001	0.029	***
Island_yes_yes	-0.019	0.002	-0.013	***	0.004	0.002	0.004	**
Centralities (at ports' pair)								
Betweenness centrality	0.000	0.001	0.000		0.016	0.001	0.026	***
Clustering coefficient	-0.026	0.001	-0.049	***	-0.008	0.001	-0.024	***
Degree centrality	0.131	0.002	0.179	***	0.123	0.001	0.194	***
Link clustering coefficient	0.020	0.000	0.059	***	0.014	0.001	0.056	***
Inverse clustering coefficient	0.012	0.002	0.019	***	0.009	0.001	0.030	***

Table 4: Regression results at link (inter-city) level

N.B. Standardized by 'Europe-Europe (regional)', 'Coastal_Coastal (location)' and 'no_no (island)'

*** 1%, ** 5%, * 10% significant.

It is closely followed by the trunk lines connecting the main economic poles of the Northern hemisphere (Triade), namely East Asia-Europe and Europe-North America. Other important connections having played an important role in the spread of containerization are intra-North America and intra-Latin America, followed by Europe-West Asia, East Asia-Oceania. This geography of containerization spread is well in line with global economic geography.

Like for nodes, city size – the product of population between connected cities on each pair – played a positive role in the diffusion of each innovation, albeit much more for containerization than for steam. The type of location at both ends of links does not show any particular trend, except for the couple “upstream-downstream”, suggesting that flows occurring within river sites (estuaries, deltas) remained dominated by old technologies (against the baseline of “coastal-coastal”). This also applies, for both innovations, to “upstream-upstream”, reflecting upon the inconveniences of such sites to welcome vessels of expanding size. For containerization in particular, the “coastal-upstream” configuration is not in favor of its development in addition to “upstream-downstream”. While the island location has a negative effect for the development of steam, it is positive for containerization, but mainly for “no_yes” (mainland-island, against the baseline of “no_no”). This implies that mainland-island connections gave a stronger impetus than inter-island (yes_yes) connections to containerization, probably because many transshipment hubs situate on islands and serve mainland (gateway/feeder) ports, as seen in the Caribbean, Mediterranean, Southeast Asia, and North Europe (e.g. Rotterdam as a hub for UK).

When it comes to link connectivity, steam and containerization follow the same logic. Link values refer to the relative importance of centralities between new and old technology at both ends of each link. Degree centrality (DC) has the strongest effect on innovation, so that connections between well-connected nodes tend to facilitate diffusion. It is followed by link clustering coefficient (LCC), suggesting that links within dense neighborhoods (local clusters) are more likely to spread innovations. The same applies to links connecting hubs with each other (cf. inverse clustering coefficient (ICC)), a feature which was observed in the global container shipping network by Hu and Zhu (2009). Compared with their work, which remained static, we underline that “rich-club” effects (i.e. higher connectivity among hubs) contribute to innovation diffusion and therefore network transformation.

6. Conclusion

This article is the first comparative analysis of two major shipping innovations, sail-steam and breakbulk-container. Untapped shipping and urban data permitted to construct two spatial networks according to the same methodology. Our main results confirmed strong comparability and added new knowledge, with regard to the debates that characterize both the determinants and the effects of innovation diffusion. The diffusion of containerization had been slower than the diffusion of steam, certainly due to the fact that it implied a major technical adaptation of all the supply chain to the “box”, including not only onboard fixations but also cargo handling equipment at port terminals and intermodal facilities toward the hinterland. With the industrial revolution, steam was also adopted elsewhere than shipping, but steam shipping itself did not impose radical changes to cargo handling and land transport, except in the case of larger ships. Both innovations fostered port concentration worldwide. They also diffused from a stage of convergence with earlier technologies (sailing and breakbulk) to a state of divergence in comparable, gradual ways. They both were favored by city size, especially containerization, although container traffic witnessed a rapidly declining correlation with urban population due to the emergence of transshipment hubs. Another common feature, also shared with various spatial networks, is the friction of distance on innovation diffusion. Upstream port sites have been the least attractive for welcoming steamships and containerships. In terms of connectivity, degree centrality had the strongest positive effect among other centralities on both diffusions. It well reflects the ability of the best-connected nodes to support the transmission of innovations across the network.

As such, this research contributes to the literature on networks, cities, and innovation diffusion that interest economists, geographers, regional scientists but also natural sciences. Our research, however, also comes with certain limitations. The absence of hinterland data hampers a better classification of ports as to the weight of their inland influence and connectivity. *Lloyd's* data only covers the maritime leg of transport chains, without disclosing the true origins and destinations of flows. Sail and steam traffic were measured by the number of ship calls rather than tonnage due to the technical limitations of the OCR used. Urban population only remains a proxy of cities' economic weight. Further research may continue extracting additional publications from *Lloyd's* to cover the emergence and diffusion of diesel-run shipping from the 1920s. The evolution of containerization itself may be approached with more scrutiny by differentiating the different technological waves of innovation in terms of ship size. Furthermore, the same analysis could be envisaged for specific regions or port systems, to confront quantitative results to local variations of the phenomena. The global approach is only a first step into the discovery of main trends and structures, but the current findings motivate a deeper analysis of particular cities and regions.

Further research may consider the transition from steam to diesel and the emergence of containerization, although Lloyd's List archives do not document the precise nature of vessels at the early stages of the latter innovation. Updating the database shall enable the analysis of mega vessels and their impact on shipping network structure. Additional control variables should be added to the analysis, such as trade and GDP, which are drivers of maritime transport on the demand side, such as from the CEPII database[6], as well as more socio-economic indicators for cities and regions for the recent period.

References

Abrams B.A., Li J., Mulligan J.G. (2008) Did Corliss steam engines fuel urban growth in the late nineteenth century? Less sanguine results. *The Journal of Economic History*, 68(4): 1172-1176.

Airriess C. (1989) The spatial spread of container transport in a developing regional economy: North Sumatra, Indonesia. *Transportation Research Part A*, 23(6): 454-461.

Airriess C. (1995) Port-centered transport development in colonial North Sumatra. *Indonesia*, 59: 69-91.

Barthelemy M. (2015) Spatial networks: tools and perspectives. In: Ducruet C. (Ed.), *Maritime Networks: Spatial Structures and Time Dynamics*, London and New York: Routledge, pp. 50-60.

Bernhofen D.M., El-Sahli Z., Kneller M. (2016) Estimating the effects of the container revolution on world trade. *Journal of International Economics*. 98: 26-50.

Bird J. (1963) *The Major Seaports of the United Kingdom*. London: Hutchinson.

---

[6] http://www.cepii.fr/CEPII/fr/bdd_modele/bdd_modele_item.asp?id=32

Bohlmann J.D., Calantone R.J., Zhao M. (2010) The effects of market network heterogeneity on innovation diffusion: An agent-based modeling approach. *The Journal of Product Innovation Management*, 27(5): 741-760.

Bunel M., Bahoken F., Ducruet C., Lagesse C., Marnot B., Mermet E., Petit S. (2017) Geovisualizing the sail-to-steam transition through vessel movement data. In: Ducruet C. (Ed.), *Advances in Shipping Data Analysis and Modeling. Tracking and Mapping Maritime Flows in the Age of Big Data*, Routledge, pp. 189-205.

Castillo D., Ducruet C. (2017) Northwest Africa from colonial to global shipping. In: Ducruet C. (Ed.), *Advances in Shipping Data Analysis and Modeling. Tracking and Mapping Maritime Flows in the Age of Big Data*, Routledge, pp. 397-413.

Castillo D., Valdaliso J.M. (2017) Path dependence and change in the Spanish port system in the long run (1880–2014): An historical perspective. *International Journal of Maritime History*, 29(3): 569-596.

Charlier J. (1994) Sur le concept de tonnages pondérés et économie portuaire. L'exemple du Northern Range. *Les Cahiers Scientifiques du Transport*, 29: 75-84.

Cullinane K.P.B., Khanna M. (2000) Economies of scale in large containerships: optimal size and geographical implications. *Journal of Transport Geography*, 8(3): 181-195.

Ducruet C. (2013) Network diversity and maritime flows. *Journal of Transport Geography*, 30: 77-88.

Ducruet C. (2020) The geography of maritime networks: a critical review. *Journal of Transport Geography*, 88: 102824.

Ducruet C., Cuyala S., El Hosni A. (2018) Maritime networks as systems of cities: the long-term interdependencies between global shipping flows and urban development (1890-2010). *Journal of Transport Geography*, 66: 340-355.

Ducruet C., Haule S., Ait-Mohand K., Marnot B., Kosowska-Stamirowska S., Didier L., Coche M.A. (2015) Maritime shifts in the contemporary world economy. Evidence from the Lloyd’s List corpus, eighteenth to twenty-first centuries. In: Ducruet C. (Ed.), *Maritime Networks: Spatial Structures and Time Dynamics*, London and New York: Routledge, pp. 134-160.

Ducruet C., Itoh H. (2016) Regions and material flows: Investigating the regional branching and industry relatedness of port traffic in a global perspective. *Journal of Economic Geography*, 16(4): 805-830.

Ducruet C., Itoh H. (2021) Introduction to global container shipping market. In: Shibasaki R., Kato H., Ducruet C. (Eds.), *Global Logistics Network Modelling and Policy. Quantification and Analysis for International Freight*, Elsevier, pp. 3-30.

Ducruet C., Itoh H., Joly O. (2015) Ports and the local embedding of commodity flows. *Papers in Regional Science*, 94(3): 607-627.

Ducruet C., Itoh H., Merk O. (2014) *Time Efficiency at World Container Ports*. OECD & International Transport Forum Discussion Papers No. 2014/08, https://doi.org/10.1787/5jrw2z46t56l-en

Ducruet C., Juhasz R., Nagy D.K., Steinwender C. (2020) All aboard: the effects of port development. National Bureau of Economic Research Working Paper 28148, https://www.nber.org/papers/w28148

Ducruet C., Lee S.W. (2006) Frontline soldiers of globalisation: Port-city evolution and regional competition. *Geojournal*, 67(2): 107-122.

Ducruet C., Notteboom T.E. (2012) The worldwide maritime network of container shipping: Spatial structure and regional dynamics. *Global Networks*, 12(3): 395-423.

Ducruet C., Notteboom T.E., de Langen P.W. (2009) Revisiting inter-port relationships under the New Economic Geography research framework. In: Notteboom T.E., Ducruet C., de Langen P.W. (Eds.), *Ports in Proximity: Competition and Coordination among Adjacent Seaports*, Ashgate, pp.11-27.

Fleming D.K., Hayuth Y. (1994) Spatial characteristics of transportation hubs: centrality and intermediacy. *Journal of Transport Geography*, 2(1): 3-18.

Guerrero D., Rodrigue J.P. (2014) The waves of containerization: shifts in global maritime transportation. *Journal of Transport Geography*, 35: 151-164.

Guimera R., Mossa S., Turtschi A., Amaral L.A. (2005) The worldwide air transportation network: Anomalous centrality, community structure, and cities' global roles. *Proceedings of the National Academy of Sciences USA*, 102(22): 7794-7799.

Hägerstrand T. (1967) *Innovation Diffusion as a Spatial Process*. Translated by A. Pred. Chicago: University of Chicago Press.

Hall P.V., Jacobs W. (2012) Why are maritime ports (still) urban, and why should policy-makers care? *Maritime Policy and Management*, 39(2): 189-206.

Haworth R.B. (2021) *Miramar Ship Index*. https://www.miramarshipindex.nz/

Hayuth Y. (1981) Containerization and the load center concept. *Economic Geography*, 57(2): 160-176.

Hayuth Y. (1988) Rationalization and deconcentration of the U.S. container port system. *The Professional Geographer*, 40: 279-288.

Helmick J.S. (1994) *Concentration and Connectivity in the North Atlantic Liner Port Network, 1970–1990*. Unpublished PhD Dissertation. University of Miami, Miami.

Hoyle B.S. (1989) The port-city interface: trends, problems, and examples. *Geoforum*, 20(4): 429-435.

Hoyle B.S., Charlier J. (1995) Inter-port competition in developing countries: an East African case study. *Journal of Transport Geography*, 3(2): 87-103.

Itoh H. (2012) Structural changes in port cargo flow distribution in Asian container port systems. The conference proceedings at the International Association of Maritime Economists (IAME), Taipei, Taiwan, 1-27.

Jacks D.S., Pendakur K. (2010) Global trade and the maritime transport revolution. *The Review of Economics and Statistics*, 92(4): 745-755.

Jacobs W., Koster H.R.A., Hall P.V. (2011) The location and global network structure of maritime advanced producer services. *Urban Studies*, 48(13): 2749-2769.

Kaukiainen Y. (1992) Coal and canvas: Aspects of the competition between steam and sail, c. 1870–1914. *International Journal of Maritime History*,

Kaukiainen Y. (2008) The transition from sail to steam – Growth and crisis during a technological change. In: Scholl L.U., Williams D.M. (Eds.), *Crisis and Transition: Maritime Sectors in the North Sea Region, 1790-1914*, Bremen: H.M. Hauchshild, pp. 62-74.

Kaukiainen Y. (2012) The advantages of water carriage: scale economies and shipping technology, c. 1870-2000. In: Harlaftis G., Tenold S., Valdaliso J.M. (Eds.), *The World's Key Industry. History and Economics of International Shipping*, Palgrave Macmillan, pp. 64-87.

Konvitz J.W. (1994) The crises of Atlantic port cities, 1880 to 1920. *Comparative Studies in Society and History*, 36(2): 293-318.

Koukaki T., Tei A. (2020) Innovation and maritime transport: A systematic review. *Case Studies on Transport Policy*, 8(3): 700-710.

Kuby M., Reid N. (1992) Technological change and the concentration of the U.S. general cargo port system: 1970-88. *Economic Geography*, 68(3): 272-289.

Lee S.W., Song D.W., Ducruet C. (2008) A tale of Asia's world ports: The spatial evolution in global hub port cities. *Geoforum*, 39(1): 372-385.

Levinson M. (2016) *The Box*. Princeton University Press.

Marnot B. (2005) Interconnexion et reclassements : l'insertion des ports français dans la chaîne multimodale au XIXe siècle. *Flux*, 59(1): 10-21.

Mayo A.J., Nohria N. (2005) The truck driver who reinvented shipping. Working Knowledge, Harvard Business School, October 3rd, https://hbswk.hbs.edu/item/the-truck-driver-who-reinvented-shipping

McCalla R.J. (2004) Hierarchical network structure as seen in container shipping liner services in the Caribbean Basin. *Belgeo*, 4: 407-418.

Montes C.P., Freire Seoane M.J., Gonzalez-Laxe F. (2012) General cargo and containership emergent routes: a complex networks description. Transport Policy, 24: 126-140.

Morrill R., Gaile G.L., Thrall G.I. (2020) Spatial diffusion. In: Jackson R. (Ed.), *Web Book of Regional Science*. Regional Research Institute, West Virginia University.

Murphey R. (1969) Traditionalism and colonialism: Changing urban roles in Asia. *The Journal of Asian Studies*, 29(1): 67-84.

Murphey R. (1989) On the evolution of the port city. In: Broeze F. (Ed.), *Brides of the Sea: Port Cities of Asia from the 16th-20th Centuries*, Honolulu: University of Hawaii Press, pp. 223-245.

Newman M. (2010) *Networks: An Introduction*. Oxford University Press.

Ng A.K.Y., Ducruet C. (2014) The changing tides of port geography (1950–2012). *Progress in Human Geography*, 38(6): 785-823.

North D. (1958) Ocean freight rates and economic development 1730-1913. *The Journal of Economic History*, 18(4): 537-555.

Notteboom T.E. (2006) Traffic inequality in seaport systems revisited. *Journal of Transport Geography*, 14(2): 95-108.

Notteboom T.E. (2010) Concentration and the formation of multi-port gateway regions in the European container port system: An update. *Journal of Transport Geography*, 18(4): 567-583.

Notteboom T.E. (2016) The adaptive capacity of container ports in an era of mega vessels: The case of upstream seaports Antwerp and Hamburg. *Journal of Transport Geography*, 54: 295-309.

Notteboom T.E., Rodrigue J.P. (2005) Port regionalization: towards a new phase in port development. *Maritime Policy and Management*, 32(3): 297-313.

Notteboom T.E., Rodrigue J.P. (2008) Containerisation, box logistics and global supply chains: The integration of ports and liner shipping networks. *Maritime Economics and Logistics*, 10: 152-174.

Novy D., Meissner C., Jacks D. (2008) Globalisation and the costs of international trade from 1870 to the present. *VOX^{EU} CEPR*, 16 August, https://voxeu.org/article/globalisation-and-trade-costs-1870-present

Palmer S. (1999) Current port trends in an historical perspective. *Journal for Maritime Research*, 1(1): 99-111.

Pumain D. (2006) *Hierarchy in Natural and Social Sciences*. Dordrecht: Springer.

Pumain D., Paulus F., Vacchiani-Marcuzzo C. (2009) Innovation cycles and urban dynamics. In: Lane D., Pumain D., van der Leeuw S., West G. (Eds.), *Complexity Perspectives on Innovation and Social Change*, Dordrecht: Springer, pp. 237-260.

Rimmer P.J. (1967) The search for spatial regularities in the development of Australian seaports 1861-1961/2. *Geografiska Annaler Series B*, 49(1): 42-54.

Robinson R. (1998) Asian hub/feeder nets: the dynamics of restructuring. *Maritime Policy and Management*, 25(1): 21-40.

Rodrigue J.P., Notteboom T.E. (2010) Foreland-based regionalization: integrating intermediate hubs with port hinterlands. *Research in Transportation Economics*, 27(1): 19-29.

Rogers E.M. (2010) *Diffusion of Innovations*. Simon and Schuster.

Saint-Julien T. (2004) Spatial diffusion. *Hypergeo*, https://www.hypergeo.eu/spip.php?article187

Slack B. (1990) Containerization, inter-port competition, and port selection. *Maritime Policy and Management*, 12(4): 293-303.

Slack B., Gouvernal E. (2016) Container transshipment and logistics in the context of urban economic development. *Growth and Change*, 47(3): 406-415.

Stopford M. (2008) *Maritime Economics*. Routledge.

Taaffe E.J., Morrill R.L., Gould P.R. (1963) Transport expansion in underdevelopped countries: a comparative analysis. *Geographical Review*, 53: 503-529.

Tran N.K., Haasis H.D. (2015) Literature survey of network optimization in container liner shipping. *Flexible Services Manufacturing Journal*, 27: 139-179.

Tsubota K., Kidwai A.H., Ducruet C. (2017) Partition, independence and maritime networks in South Asia. In: Ducruet C. (Ed.), *Advances in Shipping Data Analysis and Modeling. Tracking and Mapping Maritime Flows in the Age of Big Data*, Routledge, pp. 415-431.

Wang C., Ducruet C. (2013) Regional resilience and spatial cycles: Long-term evolution of the Chinese port system (221BC–2010AD). *Tijdschrift voor Economische en Sociale Geografie*, 104(5): 521-538.

Wang L., Notteboom T.E., Yang L. (2015) British and Japanese maritime networks in China in the 1920s. In: Ducruet C. (Ed.), *Maritime Networks: Spatial Structures and Time Dynamics*, London and New York: Routledge, pp. 112-133.

Williams D.M. (1997) *The World of Shipping*. Aldershot: Ashgate.

Williams D.M., Armstrong J. (2010) Changing voyage patterns in the nineteenth century: the impact of the steamship. *International Journal of Maritime History*, 12(2): 151-170.

Williams D.M., Armstrong J. (2012) An appraisal of the progress of the steamship in the nineteenth century. In: Harlaftis G., Tenold S., Valdaliso J.M. (Eds.), *The World's Key Industry. History and Economics of International Shipping*, Palgrave Macmillan, pp. 43-63.

Appendix 1: Network indices

Level	Formula	Description
Whole network	$\gamma = \frac{e}{\frac{v(v-1)}{2}}$	Gamma index; where *e* is the number of edges in the graph and *v* the number of nodes (or vertices)
	$y = ax^b$	Scale-freeness; where *b* is the exponent of the power-law line in a bi-log degree plot
	$\overline{C} = \frac{1}{n}\sum_{i=1}^{n} C_i$	Average clustering coefficient; average value of all local clustering coefficients
Individual nodes	$k_i = C_D(i) = \sum_{j}^{N} x_{ij}$	Degree centrality; for a given node, number of adjacently connected nodes
	$C_B(i) = \frac{g_{jk}(i)}{g_{jk}}$	Betweenness centrality; number of shortest paths on which the node is situated
	$C_i = \frac{2\,n_i}{k_i\,(k_i - 1)}$	Clustering coefficient; share of connected pairs of neighbors in the total maximum possible number of connected pairs

Source:

Ducruet C. (2010) Les mesures locales d’un réseau. Groupe fmr. Document de travail. https://shs.hal.science/file/index/docid/546973/filename/fmr3_mesures_locales.pdf

Ducruet C. (2010) Les mesures globales d’un réseau. Groupe fmr. Document de travail. https://shs.hal.science/halshs-00541902/document

Appendix 2: Functions estimated

(1) Table 3: Regression results at node (port city) level

$$\begin{aligned} share\ (ship\ calls, dwt)_{i}^{t} \\ &= \alpha + \beta \cdot \ln\left(pop_{i}^{t}\right) + \gamma \cdot \ln\left(ave\_dist_{i}^{t}\right) + \delta \cdot year\_dummy^{t} \\ &+ \sum \theta_{k} \cdot regional\_dummmy_{i,k} + \sum \vartheta_{l} \cdot location\_dummy_{i,l} \\ &+ \mu \cdot betw_{i}^{t} + \pi \cdot cluster_{i}^{t} + \rho \cdot degree_{i}^{t} + \sigma \cdot link_{i}^{t} + \tau \cdot invers_{i}^{t} + \varepsilon_{it} \end{aligned}$$

Here, *share*$^{t}_{i}$ is the share of steam ship calls for all calls (*or* of container deadweight tons for all DWTs) at the port(s) in a port city *i* at time *t*, *pop*$^{t}_{i}$ is the number of inhabitants of port city *i* at time *t*, for the samples. And, *ave_dist*$^{t}_{i}$ is the "average" distance of maritime links[7] at the port(s) in a port city *i* at time *t*. *year_dummy*^{t} is linear variable for the samples. In addition, *regional_dummy*$_{i,k}$ and *location_dummy*$_{i,l}$ are binary variables for region or for location at the port(s) in a port city *i*. Centralities or *betw*$^{t}_{i}$, *cluster*$^{t}_{i}$, *degree*$^{t}_{i}$, *link*$^{t}_{i}$ and *invers*$^{t}_{i}$ are centrality variables at the port(s) in a port city *i* at time *t*.

(2) Table 4: Regression results at link (inter-city) level

$$\begin{aligned} share\ (ship\ calls, dwt)_{ij}^{t} \\ &= \alpha + \beta \cdot \ln\left(pop_{i}^{t} \cdot pop_{j}^{t}\right) + \gamma \cdot \ln\left(dist_{ij}\right) + \delta \cdot year\_dummy^{t} \\ &+ \sum \theta_{k} \cdot regional\_dummmy_{ij,k} + \sum \vartheta_{l} \cdot location\_dummy_{ij,l} \\ &+ \mu \cdot betw_{ij}^{t} + \pi \cdot cluster_{ij}^{t} + \rho \cdot degree_{ij}^{t} + \sigma \cdot link_{ij}^{t} + \tau \cdot invers_{ij}^{t} + \varepsilon_{ijt} \end{aligned}$$

Here, *share*$^{t}_{ij}$ is the share of steamship calls for all calls (*or* of container deadweight tons for all DWTs) at the link between the port(s) in a port city *i* and a port city *j* at time *t*, *pop*$^{t}_{i}$ is the number of inhabitants at port city *i* at time *t*, for the samples. And, *dist*$_{ij}$ is the distance between a port city *i* and port city *j* (maritime linkage). *year_dummy*^{t} is linear variable for the samples. In addition, *regional_dummy*$_{ij,k}$ and *location_dummy*$_{ij,l}$ are binary variables for a regional (locational) pair *k* (*l*) between the port(s) in a port city *i* and a port city *j*. Centralities or *betw*$^{t}_{ij}$, *cluster*$^{t}_{ij}$, *degree*$^{t}_{ij}$, *link*$^{t}_{ij}$ and *invers*$^{t}_{ij}$ are centrality variables at the link between the port(s) in a port city *i* and a port city *j* at time *t*.

---

[7] Based on orthodromic distance