Journal of Transport Geography 60 (2017) 47–58

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Multilayer dynamics of complex spatial networks: The case of global maritime flows (1977–2008)

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ARTICLE INFO

Article history:
Received 11 October 2016
Received in revised form 14 February 2017
Accepted 18 February 2017
Available online xxxx

Keywords:
Assortativity
Homophily
Maritime transport
Path-dependency
Port
Spatial network

ABSTRACT

This article investigates the degree of overlap among the different layers of circulation composing global maritime flows in recent decades. Mobilizing several methods originating from complex networks allows us to shed new light on specialization and diversification dynamics affecting the evolution of ports and shipping. The principal confirm the strong and path-dependent influence of multiplexity on traffic volume, range of interaction and centrality from various perspectives, such as matrices correlations, homophily, assortativity, and single linkage analysis. While the network grows and concentrates around large hubs over time, traffic distribution is also place-dependent due to the reinforced position of already established nodes.

1. Introduction

One of the most challenging issues of current network science is to better understand the structure and evolution of multiplex networks, namely complex systems made up of several layers (D'Agostino and Scala, 2014; Garas, 2016). The basic definition of a multiplex network is the possibility for nodes to be connected by two or more links of a different nature. One typical example in transport studies is the multimodal network comprising various combinations of transport modes between terminals or cities (i.e. road, rail, air, sea), such as a corridor, but other examples can be found in other contexts such as in social networks (i.e. friendship and professional ties). Whereas the analysis of multiplex networks had been the focus of numerous studies in past decades and across all scientific disciplines, geographers have long remained focused on single (or uniplex) networks, such as roads and railways, despite early advances in the field back in the 1960s, when Gunnar Törnqvist, for instance, modeled a network made of both physical and information flows (see a review by Peris, 2016).

As seen in Table 1, recent works on multiplex spatial networks in geography predominantly focused on transport flows and networks, notwithstanding the inclusion of more informal or virtual relationships such as Internet or banking linkages among cities. These works widely differ in geographic scope, from national to global, and in methodology, from the use of vector or raster information in a Geographic Information System (GIS) to the application of graph theory, complex networks and simulation techniques to determine the interdependencies at stake among the different layers and nodes. Such diversity echoes the synthetic works by Boccaletti et al. (2014) and Kivelä et al. (2014) which underlined the lack of a comprehensive approach to multiplex networks and the corresponding terminology. Some recent advances about multiplex networks were made in the field of air transport (Cardillo et al., 2013).

This paper proposes to further develop our understanding of the multiplex properties of spatial networks, based on the analysis of maritime flows. It innovates in several ways in the broader field of multiplex and spatial network research. First, it provides a dynamic empirical analysis of 32 consecutive years of network structure, while the majority of existing studies remain theoretical, based on simulation due to lack of data, and rather static. While the vast majority of maritime network analyses focused on container shipping (see Ducruet, 2015 for a review of the field), Table 1 points to a number of earlier studies of maritime networks from a multiplex perspective, but mainly as one of the different layers under consideration (Nelson, 2008; Parshani et al., 2010; Ducruet et al., 2011; Tavasszy et al., 2011). This paper adopts another perspective, namely the decomposition of the global maritime network as a multiplex entity in itself and its disaggregation across several layers, based on the fact that maritime transport relies on the circulation of diverse types of vessels and cargoes linking ports around the world. Maritime transport networks may thus be defined as one single network made of complementary layers or as a multiple networks having their own rationale. Such a perspective is rarely found in earlier studies. Kaluza et al. (2010) compared the network topologies of three different maritime layers created by the movements of tankers, cargo

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http://dx.doi.org/10.1016/j.jtrangeo.2017.02.007
0966-6923/

Table 1
Empirical analyses of multilayered spatial networks in geography.

Author(s) and year	Networks	Area
Choi et al. (2006)	Air, Internet	World
Nelson (2008)	Road, rail, river, maritime	World
Bogart (2009)	Road, canal, port	England
Parshani et al. (2010)	Air, maritime	World
Jin et al. (2010)	Road, rail	China
Devriendt et al. (2010)	Air, Internet	Europe
Ducruet et al. (2011)	Air, maritime	World
Tavasszy et al. (2011)	Maritime, road	World
Tranos (2011)	Air, Internet	Europe
Berroir et al. (2012)	Rail, patents, commuting	France
Liu et al. (2013)	Air, multinational firms	World
Ducruet (2013)	Maritime	World
Scheidel (2013)	Maritime, road	Roman empire
Shen et al. (2013)	Maritime, road	USA/World
Burger et al. (2014)	Commuting	Netherlands
Derudder et al. (2014)	Air, road, rail	South Asia
Ducruet and Itoh (2015)	Maritime	Asia-Pacific
Van Meeteren et al. (2016)	Banks, APS firms	World

ships and containerships respectively but without examining their overlaps and interdependencies. Ducruet and Itoh (2015) confronted the specialization, topology, and complementarity of several maritime transport layers to the socio-economic features of the connected subnational regions in the Asia-Pacific area. The current paper is closer to an earlier article by Ducruet (2013) who investigated the interdependence of the five different layers composing maritime flows, thereby demonstrating the strong influence of multiplexity on port centrality and network topology. However, these works remained static and could not account for a dynamic view on the evolution of multiplexity.

Investigating the dynamics of multiplex networks in the context of shipping and ports raises a number of questions specific to this area that also have the potential to foster progress in other research domains. In terms of layers, maritime transport is often seen as an aggregate of incompatible logics, from passenger flows using cruise or ferry ships to the transport of minerals, oil, containers or automobiles by bulk ships. Such layers serve different trades, use different handling facilities and related technologies, and therefore different ships and terminals, notably since the period of specialization (Mayer, 1973). In addition, these layers behave differently as they are based either on tramp shipping for bulks, with on-demand voyages from origin to destination market, or on regular schedules for containers (liner shipping). These differences are thus reflected in the respective geographic coverage of their network patterns (Kaluza et al., 2010) and reinforced by the geographic scope of their activity; ferries, for instance, travel shorter distances within seas or basins while bulks and containers are more transoceanic and deep-sea. Yet, the ocean-space where ships move remains constrained by the shape of coastlines and the location of ports, which forces maritime flows to converge at certain passages and corridors, such as canals and straits. The global maritime network can thus be defined as one composite system serving trade and mobility through different albeit complementary technological means. This motivates the search for interdependencies among its various layers, notably from an evolutionary perspective, and questions the effects of specialization and technological change on maritime network design. In other words, each layer (bulk, containers) can be seen as a transport system on its own, namely an individual network, from an operational perspective in terms of shipping and cargo handling technologies. Yet, this paper adopts a broader economic geography perspective to the maritime network as one single transport system composed of interdependent and complementary layers serving world trade and mobility, and as one segment only within the broader value chain (Robinson, 2002).

When it comes to ports, the question of research takes another meaning. As in all spatial networks, such nodes cannot grow and multiply their connections ad infinitum due to lack of space for infrastructure expansion, cost, and related congestion issues. Ports went through successive phases of adaptation to changing shipping technologies, resulting in a spatial distribution of separated port functions based on the construction of specialized terminals and new ports. Yet, the limited number of easily accessible port sites (Rodrigue et al., 2013) and the economic gains fostered by economies of scale motivated certain nodes to keep concentrating maritime traffic and become multifunctional, sometimes at the expense of smaller and more specialized ones. Traffic diversity, or the ability of ports to capture a great variety of flows, can thus be seen as an essential component of port competitiveness. However, this dimension has rarely been addressed per se, despite the early recognition that larger ports often exhibit a diversified portfolio as a reflection of their wider overseas linkages and more complex local economic structure (Carter, 1962; Kenyon, 1970). Through attracting diverse maritime flows, ports capture value through jobs and related companies, and reduce their exposure to market and trade fluctuations (Ducruet et al., 2010; Ducruet and Itoh, 2016). In turn, diversification is not the sole strategy of ports; some of them were proactive in adopting containerization, which is considered to be the most valuable traffic, while others strived for specialization in their core function, such as automobile imports (Hall, 2004). Many factors, such as location and hinterland accessibility, influence such strategies as not every port can become a multifunctional hub, a typical case being ports fully dependent on the exploitation of a particular natural resource.

Throughout academic and professional literature, it remains unclear whether port specialization or diversification as *processes* are path-dependent and place-dependent (see Neffke et al., 2011 on the case of regions); in other words, we need to further understand how port nodes are embedded in diverse maritime layers and if so, how this evolves over time. Existing literature on complex networks, which suggests a high probability of new links connecting already established and larger nodes through a preferential attachment process (Barabasi and Albert, 1999), is well reflected in the case of port system evolutionary models, where shipping flows become increasingly concentrated at the main pivotal hub along a given range, which is often the best candidate for adopting technological innovations (Wang and Ducruet, 2013). This recalls in many ways the innovation diffusion processes modeled by Hägerstrand (1952) based on the key factors of proximity and hierarchy. However, diseconomies of scale are likely to appear in such load centers (Hayuth, 1981) for the reasons cited above, encouraging traffic de-concentration and relocation to smaller or new ports, which grow through specialization and may later diversify. The goal of this paper is not to fully explain traffic variety per se, but rather, to observe its distribution and evolution from a network perspective.

This paper continues as follows: the next section introduces the data necessary to analyze global maritime flows and their evolution over 32 years in the form of a graph or network. The subsequent section is the core of the analysis, where we test a number of methods to describe the changing distribution and interdependency of six maritime layers by looking at both nodes and links. The conclusion discusses the outcomes of this study and its contribution to both transport and network studies.

2. Data and methodology of multiplex network construction

The primary source of data on the changing distribution and pattern of global shipping flows is *Lloyd's List Intelligence* (LLI), a world leader in maritime insurance and information. This data consists in daily merchant vessel movements among ports of the world, including arrival and departure dates, vessel capacity in deadweight tons (DWT), and vessel type. The study period of 32 consecutive years (1977–2008) permits the examination of the stability of the results over time and the verification of how traffic variety has evolved alongside major economic, geographic, and technological changes affecting global maritime trade. The year of its commencement preceded the opening up of China and the operation of Hong Kong's first container terminal, as