Journal of Transport Geography 99 (2022) 103297

Contents lists available at ScienceDirect

Journal of Transport Geography

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

Sea-land interdependence and delimitation of port hinterland-foreland structures in the international transportation system

Paul H. Jung [a,*], Jean-Claude Thill [a,b]

[a] Department of Geography and Earth Sciences, University of North Carolina at Charlotte, 9201 University City Blvd, Charlotte, NC 28223, USA
[b] School of Data Science, University of North Carolina at Charlotte, 9201 University City Blvd, Charlotte, NC 28223, USA

ARTICLE INFO

Keywords:
Spatial structure
Port system
Hinterland-foreland continuum
Port triptych
Functional regionalization
Stochastic blockmodel
Network analysis

ABSTRACT

Acknowledging that sea-land intermodal integration and transshipment are core transformations of the contemporary international logistic system, we study the spatial and functional structure of a port system across land and sea in this context. Previous port-driven regional development models have focused only on landside port-hinterland spatial structures in the local vicinity of ports, not seaside inter-port connections together. By revisiting the concepts of port triptych and hinterland-foreland continuum, we argue that the spatial structure of a port system should consider both flows to and from ports together when tracing spatial structures of hinterlands and forelands. Incorporating the network-based analytical model of the nonparametric weighted stochastic blockmodel, we study the global-scale structures of hinterlands and forelands under integrated landside-seaside freight flow dynamics. We investigate the network block structures of cargo shipping routes between Europe and the United States based on micro-level shipping flow data. We find a rich and meaningful collection of different network blocks of hinterlands, feeder and hub ports, and forelands that mirror the functional division of logistic processes across space, the interdependent relationships between hinterlands and forelands along a logistical continuum.

1. Introduction

As logistic and supply chains have expanded to multiple points across countries, ports are now perceived as more critical elements in mediating local economic activities to the global market. In the literature, their unique function in the transportation system is well recognized as central places of shipping activities that drive urban agglomeration and regional economic growth mainly in their vicinity (Ducruet, 2010). This notion remains influential today, and many researchers and policymakers are paying attention to how ports can drive economic growth in their surrounding urban region (Hall and Jacobs, 2012). One classical approach is to examine port-hinterland relationships based on flow patterns on the land side and to trace how urban regions are structured with regard to ports and how they interface with nearby territories.

However, this approach may fall short of capturing the spatial dynamics of the modern port system. As the international freight shipping technology has evolved tremendously, transportation flows to and from ports have increased in complexity over time. Indeed, advances in the international logistic system, such as cargo containerization, intermodalism, and inland freight distribution centers, have fundamentally transformed the way ports and hinterlands interact spatially. Inland distribution, feeder and trunk line shipping and transshipping at intermediate hub ports are some of the multiple logistical processes that move international cargo and functionally integrates places in the economic space (Hesse and Rodrigue, 2004; Woxenius, 2012). Intermodal logistic integration has boosted the importance of hinterland-side transportation facilities placed beyond ports' direct vicinity. Also, foreland-side intermediate hub ports have taken on more critical roles in supporting multiple logistic chains across land and water (Rodrigue and Notteboom, 2010). Thus, a port now operates not only as a central place to the surrounding urban region, but as one of multiple nodal points along the entire freight shipping corridor in support of integrated logistics and shipping.

The complexity of the modern port system calls for closer examination of both landside and seaside freight shipping flows as whole and of unfragmented flows across land and sea. It is already a few decades ago that a similar notion was first proposed in the literature as hinterland-foreland continuum (Robinson, 1970) and port triptych (Vigarié, 1979; Charlier, 1992). Both concepts suggested that hinterland and foreland structures can be more meaningful when landward and

* Corresponding author.
E-mail address: pjung1@uncc.edu (P.H. Jung).

https://doi.org/10.1016/j.jtrangeo.2022.103297
Received 12 October 2021; Received in revised form 17 January 2022; Accepted 21 January 2022
Available online 2 February 2022

seaward segments of the freight shipping flows are understood together. However, scan attention has been paid to how to corroborate such structures and empirical validation supporting this concept is rather sparse today. Constrained by the lack of data tracking freight shipping trajectories both on land and on sea, the research designs of recent empirical studies have only analyzed one of either the hinterland or foreland side and have paid lip service to the critical role of ports in interfacing the two sides. In addition, the development of new analytical tools has not been followed by substantive findings on spatial structures that emerge from the contemporary state of the logistic integration across land and sea.

The purpose of this paper is to study if and how the contemporary state of the logistic integration across land and sea shapes spatial structures of the port system. We revisit the concept of hinterland-foreland continuum and port triptych and the issue of spatial organization at the global scale. Based on the observation of the entire freight shipping flow trajectories spanning land and water, we examine how structures of hinterlands and forelands at the global scale emerge with landside-seaside flow dynamics concomitantly in the context of the modern port system. By doing so, we address the following questions: First, do hinterlands and forelands exist interdependently? If so, how can we define and delimit hinterlands and forelands based on their interdependent relationships with each other? What are the characteristics of interdependent relationships between hinterlands and forelands? Second, how are hinterland distributions spatially represented? What is the spatial extent of inland urban regions that are served by a port system? Third, how are functional relationships made between ports via transshipment? If ports do not only compete but also complement each other, does a functional division between hubs and feeders exist in the inter-port network?

To address these questions, we employ a network-based classification model, the nonparametric weighted stochastic block model (npWSBM). The npWSBM classifies network nodes into groups (or blocks) by similar connectivity patterns and structural equivalences from multi-adic connections. It is especially useful to characterize block-to-block relational structures from complex network data to simplify and quantify the whole network structure. We apply the npWSBM to Europe-U.S. containerized cargo shipping data that track trajectories from sources, ports, and finally to the U.S. piers. Since Europe has contestable markets of freight shipping and inter-port transshipment occurs frequently, the network-based views are useful to comprehend the spatial structure of economic territories that emerge from the logistic integration across land and sea. The model can comprehensively trace features that emerge from dyadic, triadic and even multi-adic interdependent structures across hinterlands and forelands. Cartographic representation of the network node blocks identified by npWSBM reveal the spatial structures embedded in the economic relations evidenced by freight shipping flows.

In the next section, we present the relevant background on the spatial structures of port systems and on the functional regionalization research to find their theoretical connections. Then the npWSBM is introduced as the method to empirically trace a network structure of the international freight shipping system. We also provide a general description of the data on U.S.-bound containerized cargo shipping used in the empirical part of this research. The following section discusses the results of the network analysis. The conclusion section discusses potential applications, limitations, and directions for future research.

2. Theoretical background

This paper extends two strands of literature: 1) the spatial structures of port systems and 2) network-based regionalization research. While the former provides the theoretical background of port systems, the latter proposes a methodological foundation for applications of the network-based regionalization model to the context of the port system. In this section, the background of each strand is reviewed to draw the hypothesis that forelands and hinterlands of the port system are structured interdependently.

2.1. The spatial structures of the port system

The port-hinterland relationship has been studied to address how the economic growth of surrounding urban regions occurs in relation to the functioning of a port system. The classical port development model of Bird (1980) and Taaffe et al. (1963) depicts a port system with differentiated spatial structure where locational advantage induces agglomeration of economic activities, urban expansion and economic growth of nearby port areas. The locational advantage of lower freight costs in the vicinity of ports is considered a driving force of the symbiotic relationship between ports and hinterlands, and of business co-location that bolsters urban agglomeration activities near ports (Hesse, 2010; Ng et al., 2014). In line with this notion, spatial structures of the port system have been captured by simply delineating a port's surrounding region as the port's exclusive service area based on physical proximity (e.g., Niérat, 1997).

As the modern international transportation system has advanced, researchers started to question the classical port development model that suggests a simple bilateral landside interaction between ports and hinterlands (see Robinson, 1970; Vigarié, 1979; Charlier, 1992). They argued that spatial dynamics of the port system should be understood in the wider spatial extent framed by shipping flows to and from the ports. In an early study, Robinson (1970) argued that hinterlands and forelands cannot be comprehended separately but are interdependent instead, since shipping flows between hinterlands and ports are part of the whole logistic process spanning across land and water. He observed that destinations of the import flows through Vancouver from Japan were spatially distributed very differently from those from the United Kingdom and those from all other countries. His analysis concluded that the hinterland distribution strongly depends on characteristics and directions of freight flows from forelands.

In the same spirit, Vigarié (1979) proposed the port triptych model to refer to an inseparable relationship between a port, its hinterland and its foreland. The model suggests that depicting the spatial structure of a port system by delimiting a hinterland based on the physical proximity from ports is flawed. Instead, the spatial structure of a port system should regard landside transportation flows to ports as a part of the entire transportation flows across land and water. Charlier (1992) also pointed out that segmenting traffic flows to and from ports may disregard the modern logistic chain, intermodal transport and feedering practices. In sum, ports are no longer viewed as central places connected in simple ways to their hinterlands.

The notion of the port triptych has been further extended in the context of the modern port system as Notteboom and Rodrigue's (2005) conceptual model of port regionalization. Acknowledging the rising importance of inland distribution centers, they argued that port development takes place in a way that port terminals establish integrated network connections with inland ports and distribution services distributed in extensive inland areas. The proposed port regionalization model posits that the spatial extent of the port system goes beyond the vicinity of the ports and can be extended to a wider regional scale. Challenging the hinterland-foreland dichotomy, Rodrigue and Notteboom (2010) extended the port regionalization model to address logistic integration not only on the landside with inland distribution centers but also on the seaside with intermediate hub ports. As hinterlands are structured by regionalization of port terminals and inland distribution centers, they argued that a cluster of ports are also regionalized as a result of the inter-port logistic integration between feeders and hubs on forelands. Considering that containerization and intermodal transportation are strongly linked to the functions of inland distribution centers and hub-and-spoke distribution systems, hinterland-based and foreland-based regionalization are not separate but coupled and interdependent phenomena in effect, as argued by the port triptych thesis

(Rodrigue and Notteboom, 2010). Monios and Wilmsmeier (2012) argued that port regionalization may take difference forms according to the development strategies of governments, port authorities and maritime and land shipping lines, and according to the institutional relationships between them. Raimbault et al. (2016) highlighted the importance of institutional relations of shippers and logistics providers across land and water in creating integrated logistics chain and shaping port regionalization.

There are well grounded theories pointing to port triptych structures as emerging from the contemporary state of the logistic process across sea and land, but empirical validation is still quite limited. For example, Ducruet and Zaidi (2012) suggested that the emergence of port systems and foreland-side spatial structures can be apprehended by the network structure of inter-port flows, but their analysis was focused on capturing the clusters of the maritime network and did not address landside flows and ensuing hinterland-side structures. Guerrero (2014) proposed 4 types of French hinterlands mainly based on the magnitude of how landside transportation flows from hinterlands to ports are diminished by distance, without considering how the shipments forwarded from land are transported on the maritime side. Ducruet et al. (2015) proposed a typology of port regions based on local socioeconomic characteristics and ports' commodity specialization with no regard for patterns of land and maritime transportation flows to and from ports. Santos and Soares (2019) presented a methodology for delimiting hinterlands by calculating the minimum generalized costs from load centers to different container terminals, but comprehensive patterns of both maritime and land shipping flows are not considered in their analysis. Berli et al. (2018, 2020) analyzed the centrality and accessibility of ports and cities that arise in the sea-land intermodal network by taking both landward and seaward shipping flows into account. Thus, even though the port triptych is a well acknowledged concept in international transportation studies, empirical studies have rarely addressed the whole shipping process across land and water.

2.2. Network-based regionalization: methodological and modeling perspective

The functional regionalization research aims to understand how regions are organized around nodal locales based on socioeconomic and functional relationships between areas (Fox and Kumar, 1965; Brown and Holmes, 1971; Cliff et al., 1975; Haggett et al., 1977; Masser and Scheurwater, 1980; Hoover and Giarratani, 1984; Cliff and Haggett, 1998). Spatial structures are captured by discretizing the continuous space into a group of discrete regions and by presenting underlying structures of spatial patterns and socioeconomic relationships, especially highlighting spatial heterogeneity, functional divisions, hierarchies and spatial interactions among the identified regions (Farmer and Fotheringham, 2011).

Recent functional regionalization studies have explicitly incorporated the network science approach to better trace spatial structures based on the multi-adic network structures between areas. For example, Farmer and Fotheringham (2011) introduced the network science concepts of modularity and community structures (Newman, 2004, 2006) to identify functional regions by qualitatively distinguishing intra- or inter-regional commute patterns. De Montis et al. (2013) applied a community detection algorithm to a commute flow network to reveal functional regions that emerge from the human mobility patterns. Community detection algorithms were also adopted to detect functional regional differentiation based on the spatial interaction of mobile phone data (e.g., Gao et al., 2013; Sobolevsky et al., 2013; Chi et al., 2014). Likewise, based on the observation of spatial interactions of social media activities, Shen and Karimi (2016) developed a regionalization method based on multidimensional network measures, and Liu et al. (2014) presented a regionalization pattern of the human mobility in China by employing a community detection algorithm. Bergmann and O'Sullivan (2018) used the stochastic blockmodel to detect functional regions formed by the network structures of both migration outflow and inflow patterns between counties. Adopting the network science approach enables to consider network structural features made by flow relationships among more than two entities in the functional regionalization, such as network clustering, centrality, hierarchies, intermediacy, structural equivalence, structural holes, in contrast to more traditional approaches that simply detect bilateral flows between origin and destination areas.

Even though international transportation has rarely been studied from the functional regionalization perspective, there is increasing research that applies the concepts of network science and geographic information science. Ducruet et al. (2010b) pointed out that new concepts and methods of network science from physics had not been fully adopted in maritime geography despite the network nature of global maritime shipping. The graph visualization and network-based centrality measures were suggested to address hub-and-spoke structures and port hierarchy in the Atlantic (Ducruet et al., 2010b) and Northeast Asian (Ducruet et al., 2010a) maritime transportation systems. Ducruet and Zaidi (2012) applied the topological decomposition method to the international maritime shipping network and reinterpreted results as the foreland-based regionalization of ports in the context of complex network science. Ducruet and Notteboom (2012) also presented clustering maps and spatial distribution of degree centrality measures of ports at the global scale that show how port systems integrate foreland localities and form foreland-based spatial structures through the global maritime transportation network. The long-term evolution of the maritime transportation systems from 1890 to 2010 is also examined through the single linkage analysis (Ducruet et al., 2018). Community detection algorithms were also adopted to explore the hinterland-side regionalization based on the trajectory records of U.S.-bounded export cargo shipping (Jung et al., 2018). Techniques of network-based geographic information science have been applied to reveal sea-land network characteristics of port systems and intermodal shipping flows by integrating spatial data of road and maritime route networks and spatial data of freight shipping flows across land and water (Shen, 2013; Berli et al., 2018, 2020; Shen et al., 2020).

To overcome the design limitations of earlier studies, we use the stochastic blockmodeling (SBM) approach to functional regionalization. The SBM shrinks a complex network into a simplified block-to-block network where sets of nodes are reduced to blocks according to similarity in directions and cohesion of network flows. It has been widely used in various studies examining the relational structures in various contexts such as human migrations (Bergmann and O'Sullivan, 2018), the global city network (Zhang and Thill, 2019) and the brain network (Faskowitz et al., 2018). In the context of international transportation, the SBM approach can detect the embedded network structure among groups of origin localities depending on the same port systems, corresponding forwarding ports and intermediate ports. Due to its flexibility in detecting various types of network structures, it can account for the complex functional connections among landside and seaside networks, simultaneously.

3. Methods and data

3.1. Data

We take the case of maritime shipping from Europe to the U.S. to study the concept of port triptych. The Port Import Export Reporting Service (PIERS) Trade Intelligence database contains individual records of door-to-door containerized shipping from product sources in Europe to the U.S. ports. Due to their detail in shipping trajectories, PIERS data have been used to investigate port choice patterns of inland cargo shipping in Europe (Kashiha and Thill, 2016; Kashiha et al., 2016a; Kashiha et al., 2016b) and in the evaluation of quality of inland transport systems in South America (Tiller and Thill, 2015). Through this database, the path of each bill of lading can be tracked down to 4 nodal locations: source of shipping (O), first forwarding port (P1), intermediate port (P2) and U.S. destination port (PUS). These disaggregated trajectories allow us to trace the spatial interaction relationship between forwarding ports, on the one hand, and corresponding source localities in port service areas and transshipment points on the way to the U.S. port of entry, on the other hand.

The dataset includes a variety of shipments that takes different shipping routes and transshipment patterns, but we exclude outlier shipment cases that occur rarely. The outlier cases tend to occur mostly once but have quite peculiar shipping behaviors. In effect, they are akin to noise over which the network model would struggle to maintain its statistical power. Also, since small ports only have very few shipments, it is difficult to precisely capture connectivity patterns in the network. Hence, we filtered out shipment cases that do not directly cross the Atlantic and are transshipped instead at ports in other regions than Europe, such as Asia, South Africa and South America. Because of the peculiarity of the shipping behavior, we also excluded shipment cases from small islands and only included shipment cases that originated from mainland Europe and from British Isles. Shipment cases were also removed if they were shipped through extremely small ports that were found to process only one or two shipments in our original dataset. We filtered out shipment cases if either forwarding or intermediate port is out of the 99.5th percentile by port throughput.

In this research, we use the containerized shipment cases from Europe to the U.S. in October 2006. From an original dataset comprising 106,602 bills of lading, the removal of outliers leaves 103,359 bills of lading, from 12,501 origin localities, 80 forwarding ports, 27 intermediate ports, to 35 U.S. ports of entry. The total shipment volume is 195,921.8 Twenty-foot Equivalent Units (TEUs).

3.2. Construction of sea-land shipping network data

We compile a shipping network on the containerized shipment data that describes the shipping paths across land and sea (O-P1-P2-PUS). The network data encompass nodes of landside shipping sources and ports links of the landside and maritime shipping flow. The links have three different components[1]: 1) landside shipping flows between source nodes and first forwarding port nodes (O—P1), 2) seaside flows between first forwarding port nodes and intermediate port nodes before cargo departs to U.S. ports (P1-P2) and 3) seaside long-haul trip to a U.S. port (P2-PUS). In case of direct shipping without transshipment, the first forwarding port and the intermediate port are coded identically (P1 = P2).

This leads us to construct two networks based on the respective flow components: the landside shipping network (O-P1) and the maritime shipping network (P1-P2 and P2-PUS). Total cargo shipping is aggregated by origin-destination dyads in these networks. In the hinterland shipping network, we do hexagonal binning of the shipping sources by 25 km radius to standardize their geographical units. Administrative units of each country can be quite varied as they reflect their own socio-political context. Since the geographical scope of this study is that of large economic spaces, using geographically standardized units is an appropriate strategy to avoid the biases associated with the modifiable areal unit problem. The locations of shipping sources are identified by the city names of their shipping addresses, which is prone to deviation from their real production or shipping origins. In addition to standardizing geographical units across the European space, the hexagonal binning approach also enables to reduce spatial uncertainty due to the positional errors of geocoding the shipping addresses.

By way of their interface at the ports, the landside and maritime shipping networks are then integrated as a single sea-land shipping network. While numerous source nodes send their shipping to far fewer forwarding ports, ports send or receive shipping according to whether the shipping is transshipped. By this network construction process, we gain a sea-land shipping network with 2262 nodes and 6483 links, including 2143 source nodes, 119 port nodes, 5569 landside links and 914 maritime links.

[1] Two types of exceptions do not align with the three components described above. A few cases have a Caribbean port as intermediate port (P2). Then, the P1-P2 segment is a long-haul maritime trip across the Atlantic, and the P2-PUS segment is a short maritime trip between the Caribbean and the U.S. Coast.

3.3. Method: nonparametric weighted stochastic blockmodel

The SBM is a statistical network model that estimates embedded network block structures by partitioning nodes based on network flow patterns, structural equivalences (topologically similar positions) and community structures marked by strong cohesion among nodes (Karrer and Newman, 2011). As a data generalization technique, it can be compared to principal components analysis, which reduces the number of variable dimensions into main principal components, and to cluster analysis, which classifies similar observations with similar scores to the same group. Similarly, the SBM assigns nodes and links in the original network to blocks and block-to-block links in the block network. Since we argue in support of the view that maritime shipping is a hinterland-foreland continuum and in support of the concept of port triptych in the port system (Robinson, 1970; Charlier, 1992), the SBM is well suited as it offers the advantage of handling all origin-destination links of the shipping trajectories on both hinterland and foreland sides. It assigns each node into a single block based on similarity in their connectivity patterns, each identified block indicates a group of source or port nodes sharing similar landward or seaward shipping patterns in the sea-land shipping network. Thus, the original network with many nodes and links is simplified and reduced to a shrunk network of a reduced number of blocks and between-block links, and the whole network structure is understood with the block-to-block shrunk network. Examining connectivity between the identified blocks helps us to understand components of the port triptych structures.

We adopt the npWSBM proposed by Peixoto (2018), which finds the embedded network block structures based on the quantified strength of the edge weights without prior setting of the number of network blocks. The npWSBM can detect network structures based on not only community structures but also structural equivalences, through which it is possible to find the hierarchy and functional differentiation of ports and the clustering of hinterlands and ports. The network block structure is estimated nonparametrically by finding the optimal partition from the observed hierarchical structure of the given weighted network, unlike the weighted stochastic block model of Aicher et al. (2015) that requires the prior setting of the number of blocks (Peixoto, 2018). Since shipping from a certain locality may be contested between different ports (Wan et al., 2018), we use the containerized cargo volume (TEUs) as the network weight.

Let us consider a global cargo shipping system. It can be represented by a directed graph $G = G(N, \boldsymbol{A}, \boldsymbol{\Omega}, \boldsymbol{b})$ where N is a set of nodes of sources and all ports, $\boldsymbol{A}$ is a binary adjacency matrix whose element $a_{ij} = 0$ or 1 indicates the dyadic connectivity between i and j; $\boldsymbol{\Omega}$ is an edge weight matrix whose element $\omega_{ij} \in \mathbb{R}$ indicates the continuous real weight of a_{ij}, and $\boldsymbol{b}$ is a vector of embedded block memberships of all nodes which are to be determined. The graph $\boldsymbol{G}$ is assumed to be generated conditionally upon the latent block structure:

$$P(\boldsymbol{A}, \boldsymbol{\Omega} | \boldsymbol{b}, \boldsymbol{\theta}, \boldsymbol{\gamma}) = P(\boldsymbol{\Omega} | \boldsymbol{b}, \boldsymbol{\gamma}) P(\boldsymbol{A} | \boldsymbol{b}, \boldsymbol{\theta}) \quad (1)$$

and

$$P(\boldsymbol{\Omega} | \boldsymbol{b}, \boldsymbol{\gamma}) = \prod_{rs} P(\boldsymbol{\Omega}_{rs} | \boldsymbol{\gamma}_{rs}) \quad (2)$$

where $\boldsymbol{\theta}$ and $\boldsymbol{\gamma}$ are two sets of parameters that characterize the probability distributions of a_{ij} and ω_{ij} for all $i, j \in N$, respectively, $\boldsymbol{\Omega}_{rs}$ is an edge weight matrix among nodes in the blocks $\boldsymbol{r}$ and $\boldsymbol{s}$, γ_{rs} is a set of parameters that characterize the probability distribution of the edge weights between $\boldsymbol{r}$ and $\boldsymbol{s}$. It should be noted that the weight ω_{ij} is sampled conditionally on γ only when the corresponding edge exists. $P(\boldsymbol{A}|\boldsymbol{b},\boldsymbol{\theta})$ indicates the generation of the unweighted graph based on binary graph connectivity only.

The npWSBM is premised on a hierarchical structure in the network blocks (Peixoto, 2014). The hierarchical structure detected by the npWSBM is illustrated in Peixoto (2014), (Fig. 1). In this view, each node i is nested into level-1 blocks, each of which is again nested into level-2 groups until it reaches level L, which has a single block. Thus, all levels of nodes/blocks are mutually exclusive sets that are exhaustively nested into their higher blocks. The lower block is estimated from the estimated upper block, so it does not require a priori setting of the number of blocks. The embedded block structure parameter $\boldsymbol{b}$ can be specified by the following L-level block structure (Peixoto, 2018):

$$\boldsymbol{b} \equiv \{\boldsymbol{b}^l\} = \left\{ \left\{ b_i^{(l)} \right\}_l \mid i \in N, l \in \{1, \cdots, N\} \right\} \tag{3}$$

where $b_i^{(l)}$ is a block membership of node i at level l such that $b_i^{(l)} \in \{1, \cdots, B_l\}$ and $B_L = 1$. A L-level set of parameters characterizes the edge weight distributions in each block of each level, $\boldsymbol{\gamma} = \{\boldsymbol{\gamma}^l\}$ with $\boldsymbol{\gamma}^{L+1} = \{\hat{\boldsymbol{\gamma}}\}$ being a single hyperparameter at the topmost level. Each $\boldsymbol{\gamma}^l$ is generated by the following probability, conditional to the setting of its higher-level block-to-block graph:

$$P(\boldsymbol{\gamma}^l|\boldsymbol{A}, \boldsymbol{b}^{l+1}, \boldsymbol{\gamma}^{l+1}) = \prod\nolimits_{rs} P\left(\boldsymbol{\gamma}^l_{rs}|\boldsymbol{A}, \boldsymbol{b}^{l+1}, \boldsymbol{\gamma}^{l+1}_{b_r^{(l+1)} b_s^{(l+1)}}\right) \tag{4}$$

where $b_r^{(l+1)}$ and $b_s^{(l+1)}$ denote the $(l+1)$-level blocks to which the l-level blocks $\boldsymbol{r}$ and $\boldsymbol{s}$ belong. Using a nonparametric Bayesian inference approach and a priori hierarchical structure, $\boldsymbol{b}^* \equiv \{\boldsymbol{b}^l\}^*$ can be obtained through maximizing the following Bayesian posterior probability (Peixoto, 2018):

$$\{\boldsymbol{b}^l\}^* = \underset{\{b^l\}}{\operatorname{argmax}} P(\{\boldsymbol{b}^l\}|\boldsymbol{A}, \boldsymbol{\Omega}) = \underset{\{b^l\}}{\operatorname{argmax}} \frac{P(\boldsymbol{A}, \boldsymbol{\Omega}|\{\boldsymbol{b}^l\}) P(\{\boldsymbol{b}^l\})}{P(\boldsymbol{A}, \boldsymbol{\Omega})}. \tag{5}$$

Since $P(\boldsymbol{A}, \boldsymbol{\Omega})$ is not computationally feasible, the optimal solution $\{\boldsymbol{b}^l\}^*$ can be obtained through the Metropolis-Hastings algorithm, which compares the likelihood ratio between two stochastically generated solutions. For detail on the algorithm for the optimal solution, see Peixoto (2018).

3.4. Estimation issues and determination of best-fit results

Since the Metropolis-Hastings algorithm uses a random assignment, the npWSBM may generate inconsistent block memberships in each iteration. In order to obtain consistency of the estimation results, we take the block result from the posterior distribution generated from multiple iterations of block results. After running a model 10,000 times to generate the posterior distributions, we obtain a block result by averaging the 10,000 block membership results.

To find the best-fit model that represents the network block structure, we consider six edge weight distributions for the edge weight matrix $\boldsymbol{\Omega}$: normal, log-normal, exponential, Poisson, binomial and geometric distributions. For each weight distribution, we obtain a block result from the 10,000 iterations and measure the goodness-of-fit by the log likelihood scores. Of the six sets of results, we choose the one that gives the highest log-likelihood scores as the best-fit edge weight distribution.

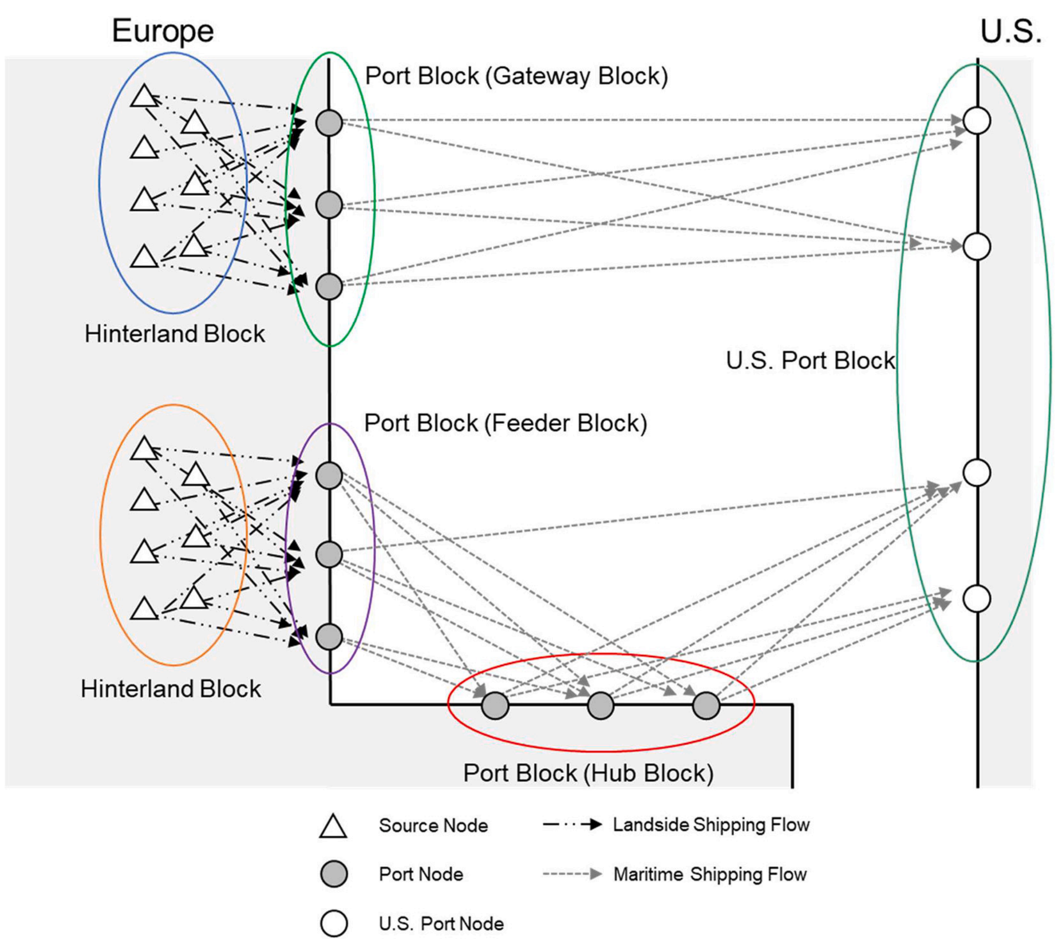

Fig. 1. Schematic hinterland, port and U.S. port blocks in the sea-land shipping network.

Even though the npWSBM can innately and non-parametrically find the optimal number of blocks, we should consider if the result of the optimal block number is externally valid with regard to spatial distributions of ports and sources. Since the npWSBM only considers network connections between nodes and their structural equivalence, not their spatial locations, it is possible that the results are difficult to interpret if geographically distant nodes (ports or sources) are assigned to the same block. To mitigate this issue, we find the most interpretable network block membership by adjusting the number of blocks around the optimal number and then by visually checking the spatial distributions of block memberships. The model estimation was implemented with the Python library *graph-tool* module (Peixoto, 2022).

4. Results

4.1. Contextualization of the network blocks and calibration of the stochastic blockmodel results

Of the six edge weight distributions assessed, the log-normal model is found to have the highest log-likelihood values, indicating the best model fit among all edge weight distributions (Table A1). Hence, we choose this distribution for the rest of the analysis. While the global optimal result includes 18 blocks, we check whether this solution is sufficiently interpretable and presents good external validity. In addition, we generate a series of solutions by externally imposing the number of blocks in the range of 10 to 65, and calculate the associated log-likelihood values. The log-likelihood is highest with 18 blocks (123 links), the global optimum (Fig. A1). The second and third best solutions are obtained with 20 and 24 blocks (136 and 155 links), respectively.

The three sets of npWSBM results present that source nodes, non-U.S. port nodes and U.S. port nodes are completely partitioned into different blocks; all nodes assigned to each block are the same type. This shows that the npWSBM discerns the difference in connectivity patterns of the three types of nodes: 1) a group of source nodes send shipments to port nodes (dubbed 'hinterland block' hereafter); 2) a group of non-U.S. port nodes receive landside inbound shipments from source nodes and seaside inbound shipments from other port nodes simultaneously, and also send seaside outbound shipments to other port nodes ('port block' hereafter); and 3) U.S. ports only receive maritime shipments from non-U.S. ports ('U.S. port block' hereafter). Given that the whole sea-land shipping network can be split into modules of hinterland, port blocks and U.S. port block, the port triptych structure can be understood as a collection of hinterland, port blocks and U.S. port block and connections between them. Based on the npWSBM results, we can further categorize three types of port blocks: *feeder*, *hub* and *gateway* blocks (Detailed characteristics of three types of port blocks are described later). The schematic illustration of hinterland, port and U.S. port blocks consistent with this conceptualization is presented in Fig. 1.

The global optimal log-normal model identifies 18 blocks embedded in the Europe-U.S. freight shipping network, 6 hinterland blocks, 11 port blocks and 1 U.S. port block. The spatial representation of the npWSBM results depicts hinterland and port blocks with their geographical extent and shipping characteristics (Fig. A2). Despite having the highest log-likelihoods, we find that the solutions with 18 and 20 blocks are limited in representing the full reality of the European port system, especially in its eastern part (Fig. A2). Even though these results are the two best from a statistical criterion perspective, they have poor ability to depict that Balkan and Baltic ports are physically separate and that they

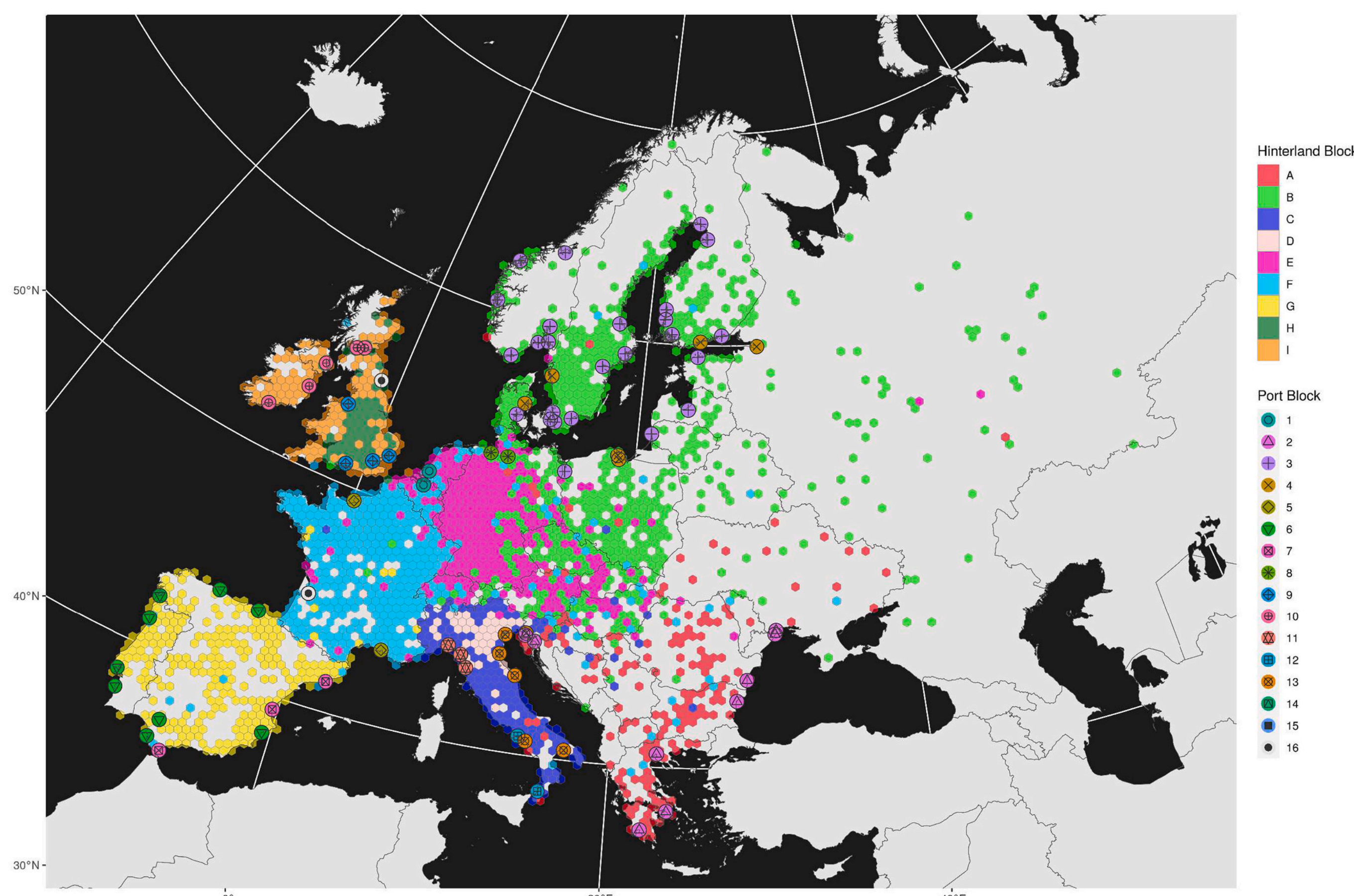

Fig. 2. Spatial representation of the hinterland and port blocks from the final stochastic block modeling results (25 blocks) (Note: Land areas with no color indicate that no shipment is sourced from those areas. Shipments from small islands are excluded from the analysis).

actually constitute different port systems in the East Mediterranean and Baltic seas. It can be argued that Balkan and Baltic ports have in common to serve contiguous but peripheral territories surrounding the economic core of Europe as feeders to other hub ports.

This leads us to turn to the third optimal solution, which encompasses 24 blocks, as the solution worthy of consideration for the rest of our analysis. This solution identifies 9 hinterland blocks (blocks A–I), 14 port blocks (block 1–14) and 1 U.S. port block (block 15) (Fig. 2). Balkan and Baltic ports are assigned to distinct port blocks 2 and 3, respectively, and the eastern landside areas are split into Balkan (block A) and Baltic areas (block B). This provides more interpretable results where we can capture the spatial structure between hinterland, forelands and ports more meaningfully.

As a final step, we check if the detected port blocks have sufficient cohesion without any outlier nodes. We measure the cosine similarity in the block-to-block connection between each port node and their assigned block to see if individual port nodes have significantly different connectivity patterns from those of the block they are assigned to. The cosine similarity is 0 when a port node has a connectivity pattern uncorrelated with that of their assigned block; it is 1 when a port node has a perfectly correlated connectivity pattern. All port nodes, except Bordeaux and Newcastle, have a cosine similarity above 0.5, indicating a high level of cohesiveness to the assigned block. Bordeaux and Newcastle have low cosine similarity scores (0.146 and 0.367, respectively) that indicates that they have a significantly different and peculiar connectivity pattern from the rest of their block. This is probably because these ports serve their localized hinterlands destined to the U.S. by shipping Bordeaux wine and Newcastle brown ale, respectively. Hence, Bordeaux and Newcastle are excluded from their block membership and are left as unassigned isolate nodes (block 16).

4.2. Characteristics of hinterland and port blocks

In the 25-block solution, 9 hinterland blocks each encompass areas that source freight shipments with similar connectivity patterns to ports (Fig. 2). The whole European economic space is partitioned into 9 hinterland areas, including the Balkans (A), Baltic-Scandinavia (B), Italy (C), Northern Italy (D), Netherlands-West Germany (E), Belgium-France (F), Iberia (G) and Inland (H) and Coastal British Isles (I). Table 1 shows each hinterland block's detailed profile, including total freight volume, total transshipment volume and transshipment rate. Many hinterland blocks align with country borders, while blocks A, B and E span multiple neighboring countries. This indicates that freight logistics in countries like France, United Kingdom, Ireland, Portugal, Spain and Italy are processed mostly at the domestic level or within two adjacent countries,

Table 1
Hinterland blocks from the final stochastic block modeling results. (Note: Bold texts indicate that the hinterland block's transshipment rate is more than 50%.)

Hinterland block	Area	Total shipment [TEUs]	Transshipment [TEUs]	Transshipment rate
A	Balkans	3545.19	2551.34	**71.97%**
B	Baltic-Scandinavia	23,347.24	16,416.76	**70.32%**
C	Italy	9803.62	1738.6	17.73%
D	Northern Italy	26,918.34	2672.45	9.93%
E	Netherlands-Western Germany	70,197.74	2901.38	4.13%
F	Belgium-France	28,407.84	3046.31	10.72%
G	Iberia	15,138.99	5308.87	35.07%
H	Inland British Isles	13,878.75	1884.65	13.58%
I	Coastal British Isles	4684.09	2551.64	**54.47%**

but shipments from Balkan, Baltic and Scandinavian countries depend on cross-country inland transportation for freight shipping. The high rates of transshipment for shipments from blocks A and B also indicate that these areas have limited access to direct shipping line services for export shipments to the U.S. but depend on other hub functions in other countries.

Each port block encompasses a group of ports that have similar landward and seaward shipping flow patterns. Hence, the existence of these port blocks points to a systematic order in port nodes at the interface between hinterlands and forelands. These blocks, therefore, empirically corroborates the soundness of the concept of port triptych and demonstrate its staying power in the contemporary international port system. Characterization of these blocks will enable us to better understand the contemporary modalities of the organization of the hinterland-to-foreland continuum. These results (Tables 2 and 3) identify 14 port blocks that serve different coastal areas of Europe: Antwerp-Rotterdam (1), Balkans (2), Baltic-Scandinavia (3, 4), France (5), Iberia (6, 7), Hamburg-Bremerhaven (8), England (9), Scotland-Ireland (10) and Italy (11,12,13). Remotely located offshore ports (14) and U.S. ports of entry (15) are identified as separate blocks that fall outside of the map. Due to their low cosine similarity scores, Bordeaux and Newcastle are classified as isolate ports (16), Table 2 shows each port block's detailed profile, including the total landside inbound shipment volume, landside inbound transshipment volume, total seaside outbound shipment volume, seaside outbound transshipment volume and transshipment rates and the relative rate, which indicates that the ratio of the block's transshipment rate to that of the whole Europe. The block membership is listed in Table 3. Each foreland block is found to have distinct shipping flow patterns, mainly indicated by the proportion of outbound and inbound transshipments.

As shown in Fig. 1, we categorize the port blocks by their role in the whole shipping network based on the preponderance of transshipment activities. The following conventions are used. When a block's ports receive and forward landside freights to other ports for transshipment more frequently than the average (19.94%), they can be considered *feeder* block. If a block's ports receive and transfer maritime freights to U.S. ports of entry more frequently than the average, we define the block as a *hub* block. When a block transfers both landside and maritime freight less frequently than the average, the ports forward shipments directly to U.S. ports of entry, and we call the block a *gateway*. Considering that the ports of Antwerp and Rotterdam (block 1) transfer substantial amounts of maritime shipments from other ports to U.S. ports (15.52% of the total transshipments), and that Hamburg and Bremerhaven (block 8) forward significant amounts of landside freights directly to U.S. ports of entry, blocks 1 and 8 are considered to have characteristics of both gateway and hub, so they are classified as a *gateway-hub* blocks. Because of the geographical remoteness from Europe, we categorize the ports in block 14 as *offshore hubs*.

4.3. The network block structure of the port system

We now examine how hinterland and port blocks are integrated in the sea-land shipping network and constitute the whole port system in Europe. To this end, nodes and links are aggregated by blocks, and the node-level network is reduced to the block-level shrunk network (Fig. 3). The visualization of the block-level shrunk network leads a number of findings about the spatial structure of the port system in Europe.

First, we find that trade shipments are structured via the dominant role of a few large port blocks. In our dataset of U.S.-bound shipments, the U.S. ports receive 69.9% of the total shipment volume from port blocks 1, 8 and 11 as the last port of export, including Antwerp, Rotterdam (block 1); Hamburg, Bremerhaven (block 8); Genoa, La Spezia and Leghorn (block 11). This is not just because these blocks process landward shipments from their own hinterlands, like blocks D, E and F, but also process cargo transshipped through other feeder blocks.

Table 2
Port blocks from the final stochastic block modeling results. (Note: Bold texts indicate that the port block's relative rate is more than 1.)

Port block	Area	Role	Inbound landside shipment				Outbound maritime shipment to U.S. ports			
			Total [TEUs]	Transshipment [TEUs]	Transshipment Rate	Relative Rate	Total [TEUs]	Transshipment [TEUs]	Transshipment Rate	Relative Rate
1	Antwerp-Rotterdam	Gateway Hub	53,194.14	1137.74	2.14%	0.11	58,120.32	6063.92	10.43%	0.52
2	Balkans	Feeder	4233.70	3554.84	83.97%	**4.21**	861.52	182.66	21.20%	**1.06**
3	Baltic-Scandinavia	Feeder	6628.73	6628.73	100.00%	**5.01**	0	0	0.00%	0.00
4	Baltic-Scandinavia	Feeder	11,333.44	9950.13	87.79%	**4.40**	1652.26	268.95	16.28%	0.82
5	France	Gateway	13,837.63	1866.63	13.49%	0.68	13,161.14	1190.14	9.04%	0.45
6	Iberia	Feeder	5894.73	4771.08	80.94%	**4.06**	1920.21	796.56	41.48%	**2.08**
7	Iberia	Hub	9956.79	1120.67	11.26%	0.56	13,271.76	4435.64	33.42%	**1.68**
8	Hamburg-Bremerhaven	Gateway Hub	36,075.31	1547.51	4.29%	0.22	49,335.97	14,808.17	30.01%	**1.51**
9	England	Gateway	14,562.46	825.10	5.67%	0.28	15,422.63	1685.27	10.93%	0.55
10	Scotland-Ireland	Feeder	3609.75	3609.75	100%	**5.01**	0	0	0.00%	0.00
11	Northern Italy	Gateway	30,403.52	2077.07	6.83%	0.34	29,491.15	1164.70	3.95%	0.20
12	Italy	Hub	4797.91	589.06	12.28%	0.62	7671.50	3462.65	45.14%	**2.26**
13	Italy	Feeder	1393.69	1393.69	100.00%	**5.01**	0	0	0.00%	0.00
14	Outside of Europe	Offshore Hub	0	0	0.00%	0.00	5013.34	5013.34	100.00%	**5.01**
All	The whole Europe	–	195,921.8	39,072	19.94%	1.00	195,921.8	39,072	19.94%	1.00

Especially, blocks 8 and 11 are found to be the main intermediate nodes between U.S. ports, feeders and hinterlands, indicating their critical role as hubs in the European port system.

Second, Europe's trade logistics is driven by the hub-and-spoke system where a few hub ports and many feeder ports hold complementary functional division. The node-level shrunk network (Fig. 3) shows a functional division in the trade logistics between a few hubs and many feeders represented by the block-to-block connection. We find hub or gateway blocks (1, 7, 8, 11, 12 and 14) near the center of this network (block 15), which stands for the whole set of U.S. ports of entry to which they have direct shipping lines. We also find feeder blocks (2, 3, 4, 6, 10 and 13) placed at the periphery around the corresponding hub blocks, whose feeder operations are tied to. The hub blocks do not only serve hinterland blocks but they also mediate shipments between U.S. ports and feeder blocks as maritime transshipment points. In contrast, the feeder blocks are positioned between hinterland blocks and hub blocks, indicating a role in providing feeder operations that forward shipments to hub ports. The connection among feeder and hub blocks shows how feeder and hub ports maintain a complementary multi-adic relationship via the logistic integration for the whole shipping process.

Third, while some hinterland areas have direct access to the shipping lines to U.S. ports, others have indirect access through the feeder ports. Hinterland blocks D, E and F maintain a strong tie to hub or gateway blocks directly connected to the U.S. ports (11, 1, 5 and 8); on the other hand, hinterland blocks at the periphery (A, B, G and I) of the shrunk network are mainly connected to feeder blocks, not hub nor gateway blocks. The former hinterlands are the areas where direct shipping line services to the U.S. are provided, but the latter hinterland blocks have limited direct access to the shipping lines to the U.S.; thus, most of their shipments can reach U.S. ports through transshipment via feeder and hub blocks. Hinterland blocks A, B, G and I are direct hinterlands of the feeder blocks 2, 4, 6 and 10, respectively, but at the same time, they also can be considered as indirect hinterlands of hub blocks 12, 8, 7 and 1, respectively, because their shipments to the U.S. should be transshipped through these hub blocks.

4.4. Block-to-block trajectory and hinterland-foreland continuum

Adopting the concepts of hinterland-foreland continuum (Robinson, 1970) and port triptych (Vigarié, 1979), we examine the entire trajectory of all shipments across land and water to comprehend the foreland-hinterland continuum structure of the European port system. On the aggregate, we track the block-level shipment flows departing from each hinterland and their flow patterns throughout the shipping trajectory from sources to U.S. ports of entry. By matching each of the 4 nodal locations (O-P1-P2-PUS) in the shipments' sequence to their assigned block, we produce an alluvial plot that tracks block-to-block shipment flows (Fig. 4). The group of flows departing from each hinterland block is color-coded to trace patterns through *en route* nodal points to the final U.S. ports of entry. Direct and transshipped shipments are separated to better illustrate flow patterns. Based on the block-to-block shipping trajectory patterns, the hinterland-foreland continuum structures in the European economic space are described as follows.

Block A (Balkan area) is the area mainly served by the hub-and-spoke distribution system of Naples-Gioia Tauro, where port blocks 2 and 12 work together in the East Mediterranean area. Since the ports on the Balkan coast lack long-haul shipping lines to the U.S., the shipments exhibit patterns of being first forwarded to the feeder ports in block 2, and then transferred to the hub ports in block 12. Even though Naples and Gioia Tauro (block 12) are located in Italy and are topographically separated from the block A, they are transit points on the maritime routes to the U.S. and have a locational advantage in being hub ports for shipments sourced from block A.

Block B (Baltic-Scandinavia) depends on the hub-and-spoke distribution system of Bremerhaven-Hamburg (block 8) interfaced with port blocks 3 and 4 to serve the Baltic Sea area. Freight flows from block B account for the largest share of the total transshipments handled by the latter two blocks. While very few shipments are directly shipped to the U.S. through ports in blocks 4 and 8 (Fig. 4-(a)), most shipments are shipped by the feeder operations of blocks 3 and 4 and then transshipment at Bremerhaven or Hamburg (block 8). The ports in both blocks 3 and 4 are primarily dedicated to feeder operations exclusively for connecting block A and Bremerhaven-Hamburg. Given that a few shipments are directly shipped through ports in block 8, the latter plays a very limited role as a local hub by providing long-haul shipping lines to the U.S.

Block C (Italy) covers a hinterland area that generates a smaller amount of shipments than block D. This area does not depend on a single shipping channel to the U.S., so the hinterland-foreland structure is quite complex. A small volume of shipments are directly forwarded to the U.S.

Table 3
Port block membership.

Block	Area	Role	Ports
1	Antwerp-Rotterdam	Gateway Hub	Antwerp, Rotterdam
2	Balkans	Feeder	Varna, Rijeka, Kalamata, Piraeus, Thessaloniki, Constanta, Koper, Illyichevsk, Odessa
3	Baltic-Scandinavia	Feeder	Copenhagen, Fredericia, Tallinn, Kemi, Oulu, Mantyluoto, Rauma, Turku, Kotka, Riga, Klaipeda, Trondheim, Aalesund, Bergen, Kristiansand, Larvik, Oslo, Fredrikstad, Szczecin, Helsingborg, Malmo, Ahus, Norrkoping, Stockholm, Gavle
4	Baltic-Scandinavia	Feeder	Aarhus, Helsinki, Gdansk, Gdynia, St Petersburg, Gothenburg
5	France	Gateway	Le Havre, Fos
6	Iberia	Feeder	Leixoes, Lisbon, Sines, Bilbao, Gijon, Vigo, Seville, Cadiz, Alicante
7	Iberia	Hub	Algeciras, Valencia, Barcelona
8	Hamburg-Bremerhaven	Gateway Hub	Hamburg, Bremerhaven
9	England	Gateway	Tilbury, Felixstowe, Liverpool, Southampton
10	Scotland-Ireland	Feeder	Cork, Dublin, Grangemouth, Glasgow, Belfast
11	North Italy	Gateway	Genoa, La Spezia, Leghorn
12	Italy	Hub	Naples, Gioia Tauro
13	Italy	Feeder	Salerno, Taranto, Ancona, Ravenna, Venice, Trieste
14	Outside of Europe	Offshore Hub	Freeport (Bahamas), Caucedo (Dominican Republic), Haifa (Israel), Kingston (Jamaica)
15	U.S. Ports	U.S. Ports of Entry	New Westminster (Canada), Vancouver BC (Canada), Cleveland, Portland, Boston, New York, Perth Amboy, Chester PA, Philadelphia, Baltimore, Norfolk, Newport News, Richmond VA, Wilmington NC, Charleston, Savannah, Jacksonville, Palm Beach, Port Everglades, Miami, Tampa, Mobile, New Orleans, Beaumont, Galveston, Houston, Long Beach, Los Angeles, Port Hueneme, San Francisco, Oakland, Vancouver WA, Seattle, San Juan, Honolulu
16	Isolates	–	Bordeaux, Newcastle

through Genoa-La Spezia-Leghorn (block 11) and Naples-Gioia Tauro (block 12). As for block A, this area also depends on a shipping process through the hub-and-spoke distribution systems of Genoa-La Spezia-Leghorn (block 11), supported by the feeder operations of blocks 12 and 13, and Naples-Gioia Tauro (block 12), supported by block 13.

Italy’s Northern industrial areas (Block D) shows a direct hinterland area exclusively served by Genoa-La Spezia-Leghorn (gateway block 11). While a few shipments are processed through transshipment from block 11 to 14 and from 13 to 12, the dominant volume of shipments are directly shipped through block 11. The port functions of Genoa-La Spezia-Leghorn work as a main gateway for block D by exclusively providing a direct access to shipping lines to the U.S. without the need for transshipment.

The Netherlands and Western Germany (block E) constitute a direct hinterland area of two main gateway-hub blocks, namely Antwerp-Rotterdam (block 1) and Bremerhaven-Hamburg (block 8) (Fig. 4(a)). Placed between the two gateway-hub blocks, this area has a high level of direct access to the two port blocks’ direct shipping lines to the U.S.; very little of its freight is transshipped. Benefitting from this great accessibility advantage, this area is found to generate the largest shipment volume to the U.S. of all hinterland blocks. Given that the shipping flows are bifurcated to two streams into the two gateway-hub blocks, this area is an overlapping hinterland where those gateway-hub ports fiercely compete with each other.

Block F (Belgium-France) marks a direct hinterland area served by Antwerp-Rotterdam (block 1) and Fos-Le Havre (block 5) that provide direct shipping lines to the U.S. A few shipments confined to the Western Mediterranean are observed to be transferred between blocks 5 and 7, where Fos serves as a feeder port towards the three large Spanish hubs, but the amount is not significantly large. This block is the area where four main gateway ports compete and attract shipments from different directions: Le Havre attracts shipments from the North, Fos from the South, and Antwerp-Rotterdam in the Northeast. Despite the small amount of transferring shipments, similarly to block E, this area can be considered an overlapping hinterland of Antwerp-Rotterdam (block 1) and Fos-Le Havre (block 5).

Shipments from block G (Iberia) depend on the complementary operation of port blocks 6 and 7, distributed along Spanish and Portuguese coastline. Similar to the block C, there are multiple shipping channels to the U.S., and the hinterland-foreland structure is complex here too. The shipments are both directly shipped and transferred through feeder-hub connections. While the direct shipments tend to sail through Algeciras-Valencia-Barcelona (block 7), large hub ports in the Western Mediterranean, shipments that are transshipped have a pattern of first being forwarded to feeder ports in block 6 and then transshipped at the hub ports in block 7. Limited cargo is transferred at other port blocks, namely 1, 5 and 14. Thus, block G is integrated with the hub-and-spoke system of Algeciras-Valencia-Barcelona where block 6 offers feeder operations and block 7 provides a hub function.

Similar to block G, the shipments from blocks H and I (Inland and Coastal British Isles) are both directly shipped and transferred through feeder-hub connections. Block H mainly serves as the direct hinterland area of block 9, while block I represents a hinterland area served overwhelmingly by the feeder operation of block 10 and the hub function of Antwerp-Rotterdam (block 1). While block 10 is dedicated to feeder operations in the British Isles (Fig. 4(b)), block 9 assumes the role of local hub by providing long-haul shipping services and processing shipments transferred from block 10. However, a dominant share of the transferring shipments is processed through non-local hub ports, Antwerp-Rotterdam (block 1), rather than domestic local hub ports in block 9. Thus, block H depends on block 9 for direct long-haul shipping service to the U.S., while block I is part of the hub-and-spoke distribution system of Antwerp-Rotterdam, where block 10 provides feeder service.

5. Conclusions

As international freight shipping technologies went through major leaps forward over the past two to three decades, spatial interactions of international freight transportation can no longer be regarded as a simple dyadic relationship between ports and their hinterlands. The multiple logistic processes enabled by cargo containerization and intermodal integration and transshipment have added more complexity in comprehending flow patterns and spatial structures of port systems. This study aimed at studying spatial structures of a port system by addressing integrated landside-seaside freight flow dynamics with micro-level trajectory records of export cargo shipping.

This work makes theoretical and methodological contributions to the domain of international freight transportation research. We addressed complex flow behaviors of modern freight shipping and provided empirical validation to support contemporary discussions on spatial structures of port systems. By adopting the npWSBM model of network science and tracing patterns of the whole trajectory of freight shipping, we substantiated the conceptual frameworks of port triptych (Vigarié, 1979) and hinterland-foreland continuum (Robinson, 1970) on a large dataset of sea-land shipping records. The block structures identified by the npWSBM in the sea-land shipping network have brought to light various hinterland-foreland continuum structures in Europe and the fundamental interdependency between hinterlands and forelands. Ports were classified to the same block by their functions in the whole logistic

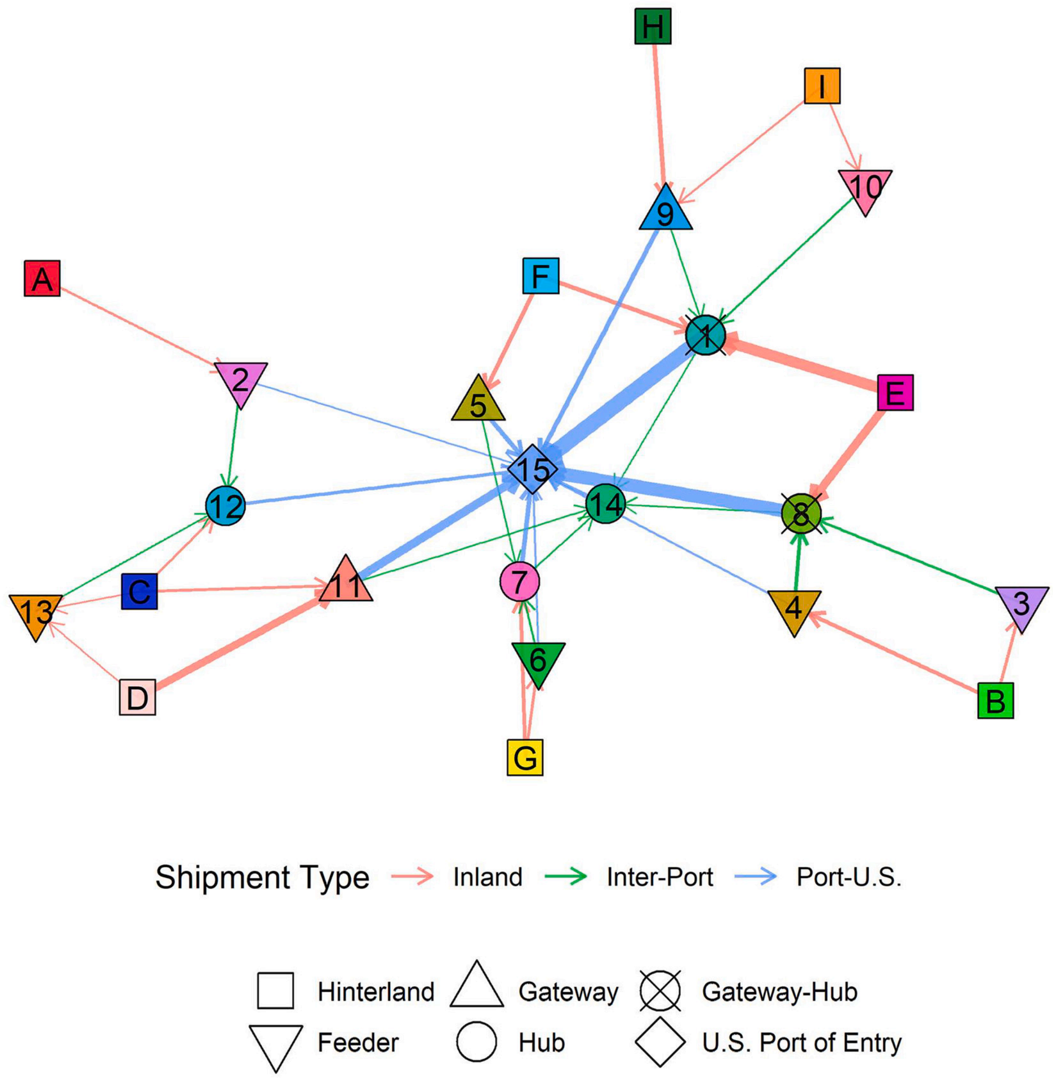

Fig. 3. The block-level shrunk network of the sea-land freight shipping system of Europe. Squares, circles, triangles, and diamonds stands for blocks of diverse types. They are labeled according to the lists in Tables 1 and 2. (Note: The network is visualized with Fruchterman-Reingold layout).

process, such as feeder or hub operations, and their geographic expression was found to align well with logistical practices. Feeder, gateway and hub port blocks complement each other's functions in the whole logistic process and, together, delineate logistically coherent hinterland areas. Thus, the hinterland areas are not just limited by the local vicinity of ports where shipments are first forwarded, but by the range of the hub-and-spoke shipping network of hub ports. The network-based view espoused in this analysis enhances our understanding of hinterland-foreland continuum structures that arise when landward and seaward shipping flows are regarded together.

The network-based analysis sheds new light on port-driven regional development policies by materializing the hinterland-foreland continuum perspective. Still many maritime transportation policies separately regard either landside transportation corridor development or seaside shipping line service. Our analysis can help policymakers to establish a comprehensive transportation development strategy that simultaneously relates inland transportation corridors to good maritime accessibility (Notteboom and Rodrigue, 2005). By capturing closely related hinterland and foreland regions and their hinterland-foreland continuum structures, policymakers can better understand a geographical scope of freight transportation flows, better promote the coordination between inland and maritime transportation development, and foster the building of sea-land transportation governance between local governments, shipping line companies and port authorities across different countries (Notteboom and Rodrigue, 2005; Wilmsmeier et al., 2011; Notteboom et al., 2013). Based on the understanding of the hinterland-foreland continuum structures, entities of local governments and port authorities can pursue extra-local economic cooperation beyond the ports' vicinity to combine inland transportation development and maritime deep-sea service (Hall and Jacobs, 2010).

However, we acknowledge some of the limitations of this research. Due to restricted access to data, our analysis only covers U.S.-bound outgoing freight shipping flows. Accordingly, our results represent only a fraction of Europe's overall freight flows, so the spatial structures identified may not reflect the full substance of Europe's port system and may not show the whole hinterland-foreland continuum structures in Europe. For example, shipments departing from Northern Italy to China are likely to cross the Suez Canal, so their flow patterns across land and sea would be much different from those of the cross-Atlantic shipments depicted here.

Moreover, our dataset only includes shipment records in 2006, so the results may not show the recent landscape of the European port system. In spite of this caveat, we believe our analysis provided an effective validation of the structure of the European maritime shipping systems across the hinterland-ports-foreland continuum as advanced decades ago. Also, because the shipments in our dataset occurred after China

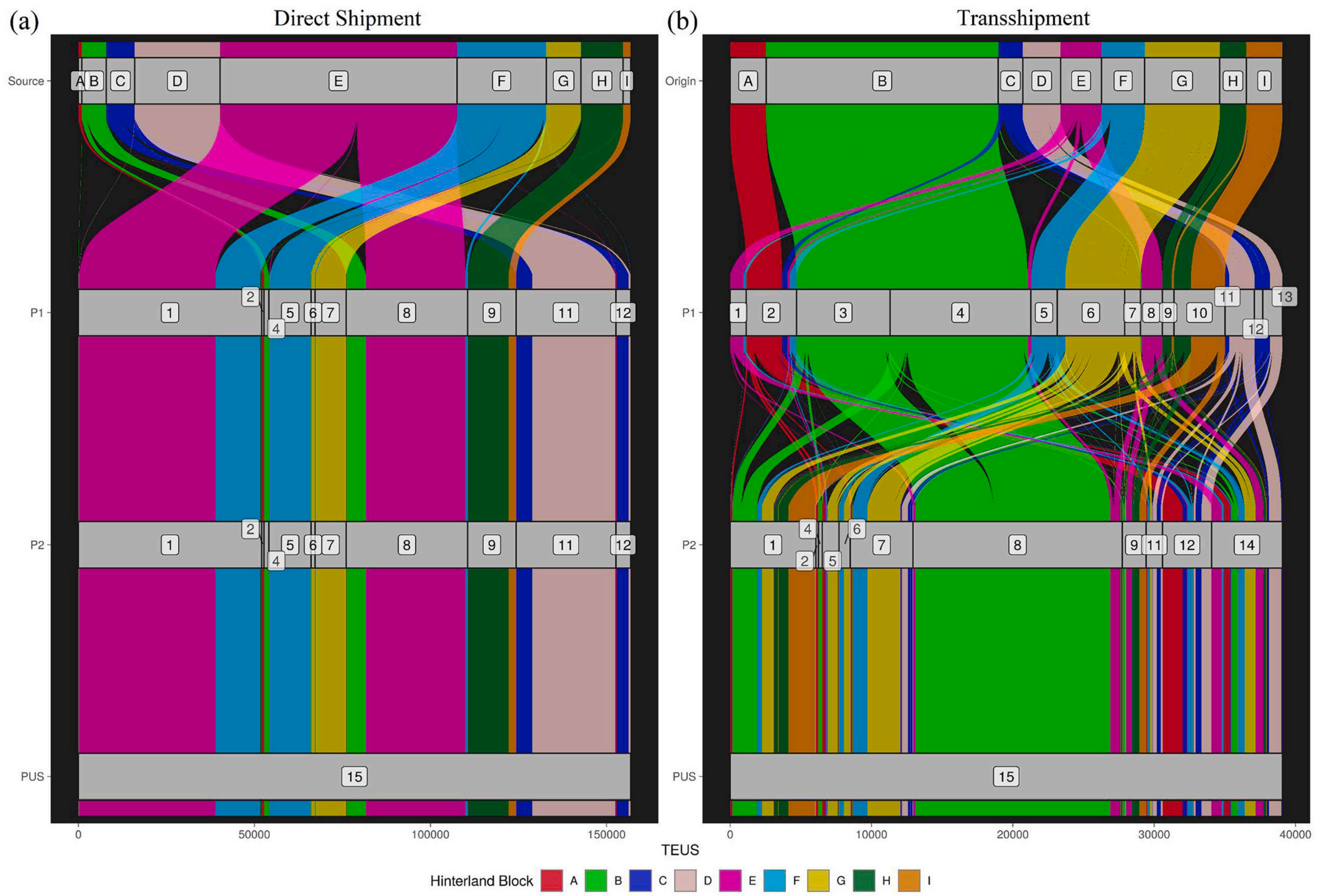

Fig. 4. Alluvial plot of block-to-block shipment flows: (a) Direct Shipment Flow, (b) Transshipment Flow.

joined the World Trade Organization in 2001 and China-U.S. containerized trade shipments increased exponentially, the results are still relevant in representing the European port system as far as trade shipments to the U.S. are concerned. Further research on a more recent time period would help to understand the precise landscape of the European port system in terms of port triptych.

Our dataset does not have the whole shipping trajectory over U.S. ports of entry, so it was not possible to analyze the whole foreland structure on the U.S. side, as a match to the hinterland structure on the Europe. Analysis on a dataset combining with exact receiving locations would promise to reveal more detailed structures of the port triptych both in the U.S. and in Europe.

Also, our analysis does not consider commodity types of shipments. It is true that different hinterland areas have specialized local industries and freight shipping behaviors must be tied to the type of goods for export. This is likely to affect the relationship between hinterlands and ports and resulting hinterland-foreland structures. Since existing stochastic block models only consider connectivity between nodes and the flow intensity (freight volume), it is not yet possible to explicitly treat qualitative characteristics of the flow like commodity types. Future developments in stochastic block modeling in this direction may expand the use of network-based functional regionalization to examine how hinterland-foreland structures depend on the commodity specialization of ports.

Lastly, expanding this analysis to other world regions would allow to scale up to the world's port system as a whole. Important questions such as whether the properties identified here for Europe are universal, or whether other forms of organization may emerge under diverse degrees of freedom of freight movements across borders, diverse levels of economic and logistic integration, and diverse landscapes of economic advancement. Along the same line, a longitudinal analysis would underscore the critical role that long-term changes in the economic, trade, and technology contexts may have on the adaptation of hinterland-foreland continuum structures.

Authors statement

Paul H. Jung: Conceptualization, Methodology, Analysis, Visualization, Draft writing, editing and review. Jean-Claude Thill: Conceptualization, Data acquisition, Methodology, editing and review.

Declaration of Competing Interest

None.

Acknowledgements

We wish to acknowledge the valuable comments made by the anonymous reviewers on an earlier version of the manuscript. We deeply thank Behnam Nikparvar and Mona Kashiha for their painstaking help in data management of the shipping records used in this paper. An earlier version of this manuscript was presented at 2019 North American Meetings of the Regional Science Association International, Pittsburgh, PA, USA.

Appendix A. Supplementary figures and tables

Supplementary figures and tables to this article can be found online at https://doi.org/10.1016/j.jtrangeo.2022.103297.

References

Aicher, C., Jacobs, A.Z., Clauset, A., 2015. Learning latent block structure in weighted networks. J. Complex Netw. 3 (2), 221–248.
Bergmann, L., O'Sullivan, D., 2018. Reimagining GIScience for relational spaces. Can. Geogr. 62 (1), 7–14.
Berli, J., Bunel, M., Ducruet, C., 2018. Sea-land lnterdependence in the global maritime network: the case of Australian port cities. Netw. Spat. Econ. 18 (3), 447–471.
Berli, J., Ducruet, C., Martin, R., Seten, S., 2020. The changing interplay between European cities and intermodal transport networks (1970s–2010s). In: Lozano, R., Carpenter, A. (Eds.), European Port Cities in Transition. Springer, pp. 241–263.
Bird, J., 1980. Seaports and Seaport Terminals. Hutchinson University Library, London.
Brown, L.A., Holmes, J., 1971. The delimitation of functional regions, nodal regions, and hierarchies by functional distance approaches. J. Reg. Sci. 11 (1), 57–72.
Charlier, J., 1992. Ports and hinterland connections. In: Dolman, A.J., Van Ettinger, J. (Eds.), Ports as Nodal Points in a Global Transport System. Pergamon, Oxford, UK, pp. 105–121.
Chi, G., Thill, J.-C., Tong, D., Shi, L., Liu, Y., 2014. Uncovering regional characteristics from mobile phone data: a network science approach. Pap. Reg. Sci. 95 (3), 613–631.
Cliff, A.D., Haggett, P., 1998. On complex geographic space: computing frameworks for spatial diffusion processes. In: Longley, P.A., Brooks, S.M., McDonnell, R., MacMillan, B. (Eds.), Geocomputation: A Primer. Wiley, New York, NY, pp. 231–256.
Cliff, A.D., Haggett, P., Ord, J.K., Bassett, K.A., Davies, R.B., 1975. Elements of Spatial Structure: A Quantitative Approach. Cambridge University Press, New York, NY.
De Montis, A., Caschili, S., Chessa, A., 2013. Commuter networks and community detection: a method for planning sub regional areas. Eur. Phys. J. 215 (1), 75–91.
Ducruet, C., 2010. Port regions and globalization. In: Notteboom, T.E., Ducruet, C., De Langen, P.W. (Eds.), Ports in Proximity: Competition and Coordination Among Adjacent Seaports. Ashgate, pp. 41–53.
Ducruet, C., Notteboom, T., 2012. The worldwide maritime network of container shipping: spatial structure and regional dynamics. Global Netw. 12 (3), 395–423.
Ducruet, C., Zaidi, F., 2012. Maritime constellations: a complex network approach to shipping and ports. Marit. Policy Manag. 39 (2), 151–168.
Ducruet, C., Lee, S.-W., Ng, A.K.Y., 2010a. Centrality and vulnerability in liner shipping networks: revisiting the Northeast Asian port hierarchy. Marit. Policy Manag. 37 (1), 17–36.
Ducruet, C., Rozenblat, C., Zaidi, F., 2010b. Ports in multi-level maritime networks: evidence from the Atlantic (1996–2006). J. Transp. Geogr. 18 (4), 508–518.
Ducruet, C., Itoh, H., Joly, O., 2015. Ports and the local embedding of commodity flows. Pap. Reg. Sci. 94 (3), 607–627.
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). J. Transp. Geogr. 66, 340–355.
Farmer, C.J.Q., Fotheringham, A.S., 2011. Network-based functional regions. Environ. Plan. A 43 (11), 2723–2741.
Faskowitz, J., Yan, X., Zuo, X.-N., Sporns, O., 2018. Weighted stochastic block models of the human connectome across the life span. Sci. Rep. 8 (1), 12997.
Fox, K.A., Kumar, T.K., 1965. The functional economic area: delineation and implications for economic analysis and policy. Pap. Reg. Sci. 15 (1), 57–85.
Gao, S., Liu, Y., Wang, Y., Ma, X., 2013. Discovering spatial interaction communities from mobile phone data. Trans. GIS 17 (3), 463–481.
Guerrero, D., 2014. Deep-sea hinterlands: some empirical evidence of the spatial impact of containerization. J. Transp. Geogr. 35, 84–94.
Haggett, P., Cliff, A.D., Frey, A., 1977. Locational Analysis in Human Geography. Edward Arnold Ltd, London, UK.
Hall, P.V., Jacobs, W., 2010. Shifting proximities: the maritime ports sector in an era of global supply chains. Reg. Stud. 44 (9), 1103–1115.
Hall, P.V., Jacobs, W., 2012. Why are maritime ports (still) urban, and why should policy-makers care? Marit. Policy Manag. 39 (2), 189–206.
Hesse, M., 2010. Cities, material flows and the geography of spatial interaction: urban places in the system of chains. Global Netw. 10 (1), 75–91.
Hesse, M., Rodrigue, J.-P., 2004. The transport geography of logistics and freight distribution. J. Transp. Geogr. 12 (3), 171–184.
Hoover, E.M., Giarratani, F., 1984. Introduction to Regional Economics. Knopf, New York, NY.
Jung, P.H., Kashiha, M., Thill, J.-C., 2018. Community structures in networks of disaggregated cargo flows to maritime ports. In: Popovich, V., Schrenk, M., Thill, J.-C., Claramunt, C., Wang, T. (Eds.), Information Fusion and Intelligent Geographic Information Systems (IF&IGIS'17). Springer International Publishing, pp. 167–185.
Karrer, B., Newman, M.E.J., 2011. Stochastic blockmodels and community structure in networks. Phys. Rev. E 83 (1), 1–10.
Kashiha, M., Thill, J.-C., 2016. Spatial competition and contestability based on choice histories of consumers. Pap. Reg. Sci. 95 (4), 877–894.
Kashiha, M., Depken, C., Thill, J.-C., 2016a. Border effects in a free-trade zone: evidence from European wine shipments. J. Econ. Geogr. 16 (6), 1–23.
Kashiha, M., Thill, J.-C., Depken II, C.A., 2016b. Shipping route choice across geographies: coastal vs. landlocked countries. Transp. Res. E 91, 1–14.
Liu, Y., Sui, Z., Kang, C., Gao, Y., 2014. Uncovering patterns of inter-urban trip and spatial interaction from social media check-in data. PLoS One 9 (1).
Masser, I., Scheurwater, J., 1980. Functional regionalisation of spatial interaction data: an evalution of some suggested strategies. Environ. Plan. A 12 (12), 1357–1382.
Monios, J., Wilmsmeier, G., 2012. Giving a direction to port regionalisation. Transp. Res. A Policy Pract. 46 (10), 1551–1561.
Newman, M.E.J., 2004. Fast algorithm for detecting community structure in networks. Phys. Rev. E 69 (6), 066133.
Newman, M.E.J., 2006. Modularity and community structure in networks. Proc. Natl. Acad. Sci. 103 (23), 8573–8574.
Ng, A.K.Y., Ducruet, C., Jacobs, W., Monios, J., Notteboom, T., Rodrigue, J.P., Slack, B., Tam, K., Wilmsmeier, G., 2014. Port geography at the crossroads with human geography: between flows and spaces. J. Transp. Geogr. 41, 84–96.
Niérat, P., 1997. Market area of rail-truck terminals: pertinence of the spatial theory. Transp. Res. A Policy Pract. 31 (2), 109–127.
Notteboom, T.E., Rodrigue, J.-P., 2005. Port regionalization: towards a new phase in port development. Marit. Policy Manag. 32 (3), 297–313.
Notteboom, T., De Langen, P., Jacobs, W., 2013. Institutional plasticity and path dependence in seaports: interactions between institutions, port governance reforms and port authority routines. J. Transp. Geogr. 27, 26–35.
Peixoto, T.P., 2014. Hierarchical block structures and high-resolution model selection in large networks. Phys. Rev. X 4 (1), 1–18.
Peixoto, T.P., 2018. Nonparametric weighted stochastic block models. Phys. Rev. E 97 (1), 1–17.
Peixoto, T.P., 2022. Graph-tool: Efficient Network Analysis [online]. Available from: https://graph-tool.skewed.de/ (Accessed 7 Jan 2022).
Raimbault, N., Jacobs, W., van Dongen, F., 2016. Port regionalisation from a relational perspective: the rise of Venlo as Dutch international logistics hub. Tijdschr. Econ. Soc. Geogr. 107 (1), 16–32.
Robinson, R., 1970. The hinterland-foreland continuum: concept and methodology. Prof. Geogr. 22 (6), 307–310.
Rodrigue, J.P., Notteboom, T., 2010. Foreland-based regionalization: integrating intermediate hubs with port hinterlands. Res. Transp. Econ. 27 (1), 19–29.
Santos, T.A., Soares, C.G., 2019. Container terminal potential hinterland delimitation in a multi-port system subject to a regionalization process. J. Transp. Geogr. 75, 132–146.
Shen, G., 2013. 10 GIS-based Analysis of US International Seaborne Trade Flows.
Shen, Y., Karimi, K., 2016. Urban function connectivity: characterisation of functional urban streets with social media check-in data. Cities 55, 9–21.
Shen, G., Yan, X., Zhou, L., Wang, Z., 2020. Visualizing the USA's maritime freight flows using DM, LP, and AON in GIS. ISPRS Int. J. Geo Inf. 9 (5).
Sobolevsky, S., Szell, M., Campari, R., Couronné, T., Smoreda, Z., Ratti, C., 2013. Delineating geographical regions with networks of human interactions in an extensive set of countries. PLoS One 8 (12).
Taaffe, E.J., Morrill, R.L., Gould, P.R., 1963. Transport expansion in underdeveloped countries: a comparative analysis. Geogr. Rev. 53 (4), 503–529.
Tiller, K.C., Thill, J.-C., 2015. Spatial patterns of landside trade impedance in containerized South American exports. J. Transp. Geogr. 58, 272–285.
Vigarié, A., 1979. Ports de commerce et vie littorale. Hachette, Paris, France.
Wan, Y., Zhang, A., Li, K.X., 2018. Port competition with accessibility and congestion: a theoretical framework and literature review on empirical studies. Marit. Policy Manag. 45 (2), 239–259.
Wilmsmeier, G., Monios, J., Lambert, B., 2011. The directional development of intermodal freight corridors in relation to inland terminals. J. Transp. Geogr. 19 (6), 1379–1386.
Woxenius, J., 2012. Directness as a key performance indicator for freight transport chains. Res. Transp. Econ. 36 (1), 63–72.
Zhang, W., Thill, J.C., 2019. Mesoscale structures in world city networks. Ann. Am. Assoc. Geogr. 109 (3), 887–908.