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Delimiting port hinterlands based on intermodal network flows: Model and algorithm

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ABSTRACT

This study aims to propose a tangible approach to delimiting the probabilistic hinterland of a port of interest. We first build a geometric model for the probabilistic port hinterland based on intermodal network flows jointly using discrete choice analysis and geographical information of shippers. We further design an algorithm that can efficiently determine the hinterland boundaries using the sample approximation of shippers' choice probabilities. We provide theoretical results that characterize the minimum computational effort required to achieve a certain degree of accuracy in the sample approximation. We also offer two numerical case studies to justify the proposed approach.

1. Introduction

The recent changes in the world economy due to market globalization have triggered a substantial increase in international seaborne trade and intermodal freight transportation. The seaborne trade accounts for a major proportion of the world trade. A seaport, providing infrastructure facilities for cargo movements between inland and sea, serves as a critical logistics hub in intermodal transportation (Rodrigue and Notteboom, 2009). Mega ports such as Shanghai, Singapore, and Yantian (at Shenzhen) have been playing an important role in maintaining the economic well-being of the areas that they serve. The area served by a port of interest, over which shippers desire their goods to be delivered to a specific destination via the port, is referred to as the port's hinterland (with respect to the destination). We herein use "shippers" to represent all types of customers of seaports, e.g., the third-party logistics companies, manufacturers or transporters, who coordinate and oversee the entire intermodal transportation processes of goods between origin–destination (O–D) pairs, and we consider the origins where shippers send goods from as the geographical locations of the shippers.

Port hinterland is of particular importance to port managers for several reasons. First, a port manager can obtain the knowledge of how hinterland accessibility alters the port's market share by analyzing how the hinterland transportation network affects the extent and size of the port's hinterland. In fact, there have been quite a deal of studies (Wang and Yun, 2013; Wan et al., 2014) pointing out that dedicated port hinterlands are deemed crucial in facilitating smooth goods movements and ensuring goods to reach their final destinations in a quicker and cheaper fashion. Second, a port manager could identify the potential customers (i.e., shippers) located in the hinterland and negotiate a long-term contract with them to build

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customer loyalty and retain more customers. Third, on top of game-theoretic analysis methods (e.g., Ishii et al. (2013)), port hinterland offers a new way to look into a port's competitiveness. A port manager can understand the port's standing in the competition with its major rivals through hinterland analysis and identify possible ports to be collaborated with to enjoy a coalition surplus.

A port's hinterland depends on the port selection of shippers – the shippers who opt to use the port are considered to be located within the hinterland and those who do not are outside the hinterland. It has been known that whether or not a shipper is willing to choose a port does not depend solely on the characteristics of the port itself, e.g., port charges and goods handling time; it is inherently affected by the overall performance of the entire transportation process with the port as a mid-way transfer hub connecting land and sea (Lam and Gu, 2013). Shippers use *intermodal routes* to transport goods. An intermodal route is a path between an O–D pair, which involves multiple modes of transportation and several transfer nodes. A transfer node functions as an interacting point that switches goods between multiple modes. Examples of transfer nodes include dry ports (e.g., rail-truck terminals), seaports, and border crossing terminals between two adjacent countries. All the available intermodal routes and possible direct links between all O–D pairs constitute an *intermodal transportation network*. We consider that the primary goal of shippers is to choose an intermodal route in the intermodal network to transport her goods. As a port could only be a component (a very critical component though) of intermodal routes, it will be selected if shippers are interested in choosing a route including it. Thus, port selection is a companion result of the route choice of shippers. The flow distribution over the intermodal network resulting from the route choice determines the flow through the port, providing a result about the port's share of the total network flow. Thus, we study port hinterland based on the allocation of intermodal transportation flows across the intermodal transportation network.

As reasoned above, port hinterland is a result of port selection, which in turn results from the intermodal route choice of shippers. Consider a shipper with a specific geographical location (i.e., the origin) who can access a port of interest and desires her goods to be delivered to a specific destination. There often exists a set of intermodal routes between the origin and the destination which are available to her. We use the classical discrete choice theory (Ben-Akiva and Lerman, 1985) to model the route choice of shippers. In discrete choice modeling, a shipper's route choice is considered to be dependent on her preferences towards the available routes, which are measured by the *utilities* of the routes. A route's utility is often described as a function of many attributes, such as transportation cost, time and the level of service along the route. Within the framework of discrete choice modeling, route utilities are often considered to be random over the population of decision makers (i.e., shippers in our study) (Train, 2003), and as it will soon become clearer in Section 3, utilities can reasonably be formulated as random variables.

We now adopt a widely used assumption on the rationality of shippers that a shipper would choose the route with the maximum utility to transport her goods (Ben-Akiva and Lerman, 1985). The randomness in route utilities causes that shippers will choose an intermodal route as well as the ports on the route with certain probability. Thus, the hinterland of a port, over which shippers transport goods through the port, is also of a probabilistic nature. This notion is important enough to warrant a formal definition: the (destination based) probabilistic hinterland of a port is an area, over which shippers transport goods to a specific destination through the port with probability in range $[\alpha, 1]$, where $\alpha \in [0, 1]$. The boundary of the probabilistic port hinterland, on which all shippers will choose the port with the same probability α, is called the α-boundary.

Delimiting port hinterland and determining its α-boundary can benefit a broad range of communities. For local governments who have ports as the main engines of their economic developments, port hinterland analysis can help design an efficient and accessible hinterland network to attract more cargo flows. By analyzing port hinterland, a port manager can identify key factors that affect the size and extent of the port's market area. Besides, a shipper can choose a proper port to handle her goods after gaining the knowledge of the hinterlands of the ports available to her.

1.1. Positioning and objective

The probabilistic port hinterland was first defined by Wang et al. (2009) which provided a scenario analysis on how landbridge operations impact the hinterland of Shanghai port using a simple two-route network. Meng and Wang (2010) developed an approach to determine the hinterland area with Gaussian distributed route utilities. Their work used a sampling approximation method to estimate the choice probabilities of shippers but did not offer any analytical results on the computational effort required in the sampling process. In addition, the work did not propose a method to determine hinterland boundaries.

Though it has been long since the work of Meng and Wang (2010), to the best of our knowledge, there is no result existing for determining a port's hinterland and its α-boundaries with distribution-free route utilities or for offering any analytical results on the hinterland estimation. Our study is aimed at filling the void by extending the work of Meng and Wang (2010). In this study, we move forward to develop a generalized model of probabilistic port hinterland with free distributions of route utilities, estimating the α-boundaries of a port of interest with network effects, and proving theoretical results about the quality of the sample approximation of shippers' choice probabilities.

To be precise and concise, the objective of our study is to develop an application-friendly model and algorithm that can be applied in the real world to delimit the probabilistic hinterland of a port of interest through determining its α-boundaries.