Developing a Probabilistic Model for Constructing Seaport Hinterland Boundaries

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Abstract. Seaport competitiveness has been attracting a great deal of attention. It is shaped not only by a port’s performance and shipping liner calls but also by its hinterland. However, planners face a number of difficulties for identifying the boundaries of the hinterland, as these are determined by several factors, such as commodity types and final destinations, hinterland connections, inland transport costs, travel costs, and sea shipping costs. Hence, hinterland analysis is often simplified by relating it to the administrative boundaries, which do not correctly represent the actual condition of seaport demand behaviour. Furthermore, the boundaries do not behave deterministically in response to changing factors, which creates a challenge when estimating hinterland boundaries. This paper presents a deterministic model for constructing seaport hinterland boundaries, which considers hinterland connections, generalised transport cost from any point related to the transportation network. Thus, the boundaries do not necessarily coincide with the administrative region. Moreover, a model is proposed for reflecting the stochastic decisions of shippers to select a seaport, which may be utilised for approximating port demand variation. A case study is also presented for exploring the applicability of the proposed model.

1. Introduction

The rising uncertainty of global trade and sustainable infrastructural investment are placing massive competitive pressure on modern ports, especially those in mature markets in well-developed regions [1]. Against this background, managing the seaport hinterland has been shown to be an influencing factor in the sustainable development of seaports. For example, Tan [2] analyses the evolution of the port city of Singapore, which has elevated the port of Singapore to one of the two leading container hub ports in the world.

The theoretical meaning of the port hinterland is a fuzzy concept, since many definitions can be found in the literature and it can be adjusted with respect to different variables as well (e.g. type of cargo). A port’s hinterland is the inland area where it acquires the majority of its business [3]. Concretely, the catchment area of a specific port is the scatter of inland cargo origin/destination points generating traffic flow passing through it. In abstract terms, the traditional concept of the hinterland represents it as an area whose contour is a continuous line bounding the port’s economic influence on the shore.

Recent research states that the port hinterland is of particular importance to port managers for several reasons [4]. Firstly, port managers can obtain knowledge on hinterland accessibility and hence improve their port’s market share by analysing how the transportation network affects the extent and size of the hinterland. Secondly, port managers can identify potential customers (i.e. shippers) located in the hinterland.

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hinterland and negotiate long-term contracts with them to build customer loyalty and retain more customers. Thirdly, on top of game-theoretic analysis methods, the port hinterland concept offers a new way of looking into a port’s competitiveness. Port managers can understand a port’s standing compared to its major rivals through hinterland analysis and identify ports they might collaborate with in order to enjoy a coalition surplus.

Several studies have been published to discuss the issue of seaport hinterland. Wan et al. discussed how hinterland accessibility can affect a port’s efficiency using the case of U.S. container ports [5]. Nazemzadeh and Vanelslander applied the analytical hierarchy process method to obtain port selection criteria in descending order of importance: port cost, geographical location, quality of hinterland connections, and so on [6]. Zhuang and Yu used the breakpoint model and Huff’s model (a gravity model) embedded in ArcGIS to derive the hinterlands of two ports, but neither of the models incorporates the uncertainty in transportation cost or time [7]. Kramberger et al. proposed an interesting mixed linear integer model to identify port hinterlands from a shippers’ point of view [8].

This paper discusses a deterministic and a probabilistic model for delimiting the boundaries of the seaport hinterland. The models were developed based on the generalised cost incurred for sending goods to the port and the utility value for reflecting the seaport competitiveness. In the case of the deterministic model, the boundaries are constructed by connecting transport nodes according to generalised cost. Since the transport nodes are possibly denoted not only at the macro level of a zone (e.g. the administrative region) but also at the micro level (e.g. intersections of links), the analysis hence promisingly provides more precise boundaries of the seaport hinterland. In addition, as shippers do not behave deterministically, also a probabilistic model is proposed for reflecting the stochastic way of decision-making of shippers to select a seaport. The model may be used for estimating the demand range of a seaport considering randomness in shipper decision-making.

Knowledge about hinterland boundaries can have great benefits. It can help local governments to design an efficient and accessible transport network for attracting more cargo flow. In addition, port managers can identify key factors that affect the size and extent of the port’s market area. Furthermore, it also allows shippers to better choose the proper port to handle their goods after gaining knowledge about seaport accessibility.

The rest of this paper is arranged as follows. In the following section, the modelling framework is described. In the third section, a case study is elaborated for investigating the applicability of the model. Finally, in the fourth section, the methodologies, results and analyses in the paper are summarized.

2. Modelling Framework

2.1. Deterministic-based Model

The deterministic-based model was formed by considering the unit transport cost, where a particular point, \( i \), is determined as belonging to the hinterland of a port, \( j \), only if the transportation cost is smaller compared to the transportation cost between \( i \) and other ports (elements of \( J \)). The transportation cost to be considered is the unit transportation cost of the shortest path between \( i \) and \( j \). In the transportation network, with \((N, A)\), set of nodes \( n \in N \), arc \( a(s,t) \in A \) and cost in arc \( c_{at} \), the common shortest path formulation is:

\[
\begin{align*}
\text{minimize} & \quad \sum_{(s,t) \in A} c_{st} x_{st} \\
\text{subject to:} & \quad \sum_{s} x_{ts} - \sum_{t} x_{st} = 1 \\
& \quad \sum_{t} x_{ti} - \sum_{i} x_{it} = 1 - n
\end{align*}
\]
\[ D_{ij} = \begin{cases} 1 & \text{if } u_{ij} = \min\{u_{i1}, u_{i2}, \ldots, u_{ij}\} \\ 0 & \text{otherwise} \end{cases} \]  

(2)

where,
\( u_{ij} \): shortest-path cost from node-\( i \) to seaport-\( j \).
\( D_{ij} \): binary variable with value 1 if node-\( i \) is part of the hinterland of seaport-\( j \) and 0 otherwise,
\( J \): total number of available seaports.

The shortest-path cost is fixed for a certain condition of the network. Therefore, the seaport has a permanent hinterland as long as there are no changes in the network, which is formulated based on the binary variable in Eq. (2). The hinterland boundaries of seaport-\( j \) are then determined by connecting the nodes or interpolations between the locations that have the same transportation cost for accessing adjacent ports. A node can be defined as an administrative region (i.e. subdistrict), a freight terminal, an link intersection or any point in the land area as long as it can be related to the network. Since a node may represent a smaller area than an administrative zone, seaport hinterlands do not necessarily coincide with administrative regions, as is commonly implemented.

2.2. Probabilistic-based Model

Different from the deterministic-based model, the probabilistic model is based on the assumption that nodes are not fixed as hinterland members of a certain seaport but possess the possibility to be hinterland member of more than one seaport. The probability is influenced by the shortest-path cost to access the available ports. Lower cost will give a seaport a higher possibility of being chosen by a region for distributing goods. The equation below illustrates the probability-based model.

\[ p_{ij} = \frac{e^{-\alpha u_{ij}}}{\sum_j e^{-\alpha u_{ij}}} \]  

(3)

where,
\( p_{ij} \): probability of node-\( i \) to be part of the hinterland of seaport-\( j \) or proportion of demand for node-\( i \) using port-\( j \)
\( \alpha \): coefficient

As inferred from Eq. (3), the node probability is calculated by dividing the utility value for transporting goods from node-\( i \) to seaport-\( j \) with the total utility value for sending goods from node-\( i \) to other seaports. By considering the other seaport utility values, this model is expected to provide a more realistic representation for capturing the decision-making of shippers and to be better at making port demand predictions.
3. Case Study

For a better illustration of the proposed model of seaport hinterland identification, it was implemented for a hinterland analysis for container transportation in Java Island (Indonesia), being the island with the highest container traffic (comprising more than 60% of total Indonesian container traffic). There are 5 provinces with three existing main container ports (Tanjung Priok Port in Jakarta, Tanjung Emas in Semarang, Central Java Province, Tanjung Perak Port, Surabaya, East Java Province) servicing both domestic and international container traffic. There is also a container port still under construction, the Patimban Port, in Subang, West Java (see the figure below).

![Transportation network and container ports in Java Island.](image)

**Figure 1.** Transportation network and container ports in Java Island.

By the location, the three ports seem designated to service each province it is situated in and its surroundings. In other words, the hinterland for container traffic of Tanjung Priok Port includes the provinces of Jakarta, Banten and West Java. The hinterland of Tanjung Emas Port includes the provinces of Central Java and Yogyakarta, while the hinterland of Tanjung Perak Port would be the province of East Java.

3.1. Deterministic Port Hinterland by Shortest-path cost

Referring to Eq. (1) shortest-path cost (from any point to access a port) may be based on distance, travel time and generalised cost (through the network). To calculate these costs, the transportation network of Java Island was modelled with 962 links and 573 nodes, as shown in Figure 2. Each link is attributed with end nodes, length and average speed of trailer (container truck), taking into account the width or capacity and existing traffic. Meanwhile, the unit cost was derived from the trucking unit fare, which is set by the Trucking Company Associations (see Figure 3) and time value for converting travel time to monetary value using the Container Storage Tariff, which is Rp. 60,000/day.

![Transport network model of Java Island.](image)

**Figure 2.** Transport network model of Java Island.
The least cost by distance, travel time and generalised cost from each node to the three available container ports in Java Island was then plotted (with interpolation between adjacent nodes) as in Figures 4, 5 and 6 with the particular hinterland boundaries.

**Figure 3.** Unit fare by distance.

**Figure 4.** Distribution of least distance to container ports in Java Island.

**Figure 5.** Distribution of least travel time to container ports in Java Island.

**Figure 6.** Distribution of least generalised cost to container ports in Java Island.
It can be seen that the hinterland boundaries by generalised cost are very close to those by distance, since the trucking fare unit is almost linear to the distance and the time cost value that was used is very low compared to the other costs. For commodities that are considered time-sensitive, the hinterland boundaries will be closer to the hinterland boundaries by travel time.

By this approach, the connectivity level of points or areas to the ports can also be identified (in this case container ports). The areas with a red colour have the worst connectivity to the main container ports. If in those areas there are some industrial estates or other activities that require accessing a main container port, then some measures need to be taken to reduce land transportation costs.

The operation of a new port will surely reduce the areas with the worst port connectivity, but for the case of Patimban Port, which is currently in the construction stage, its close location to Tanjung Priok Port makes the hinterland boundary hazier.

**Figure 7.** Distribution of least generalised cost to the container port in Java Island with Pantimban Port in operation.

### 3.2. Probabilistic Hinterland for Port Demand Prediction

The probabilistic approach in Eq. (3) is not meant for distinguishing the boundaries of the hinterland but is more useful for port demand prediction. The result of this approach can also be plotted to indicate the probability of areas to use a particular port. Furthermore, if the demand originating from or attracted to an area is known, the number of shippers that will use a particular port can be predicted by multiplying the demand with the probability value.

For the Java Island case, the model was applied for predicting the probability of using the Tanjung Priok Port without and with Patimban Port in operation, as can be seen in Figures 8 and 9.

**Figure 8.** Probability distribution for using Tanjung Priok Container Port by area.
It can be seen that with the new Patimban port in operation there will be no more ‘almost-certain’ area as the Tanjung Priok Port hinterland. Regardless of the capacity and port performance of Patimban Port, considering the location of the port and the industrial estates around its hinterland, its introduction may influence traffic flow in Tanjung Priok Port significantly.

4. Conclusions
The hinterland of a seaport should be determined based on a number of factors. One of the most important ones is the transportation network, which greatly influences the transportation (land access) cost, which determines the competition between ports. Depending on the commodity, the cost may be time-sensitive or not. The proposed deterministic approach for identifying the port hinterland is useful for prediction, not only regarding the seaports but also regarding port access and the surrounding transport networks. In particular, it can also be applied for measuring the connectivity level of any area to a seaport. Meanwhile, the probabilistic approach is more useful for predicting port demand, taking into consideration that the port user is not limited by certain boundaries. However, by determining the probability limits it can also be used for identification of the boundaries of the seaport hinterland.

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