ITLS

Shipping network design in a growth market: The case of Indonesia

By
Ningwen Tu[1], Dimas Adiputranto[2], Xiaowen Fu[2] and Zhi-Chun Li[1]

[1] School of Management, Huazhong University of Science and Technology, China
[2] Institute of Transport and Logistics Studies (ITLS), The University of Sydney Business School, Sydney, Australia

INSTITUTE of TRANSPORT and LOGISTICS STUDIES

The Australian Key Centre in

Transport and Logistics Management

The University of Sydney

Established under the Australian Research Council's Key Centre Program.

NUMBER:	Working Paper ITLS-WP-17-08

TITLE: **Shipping network design in a growth market: The case of Indonesia**

ABSTRACT: This paper investigates the design issues of a shipping network when cargo demand increases rapidly. A gravity-type model for origin-destination (OD) demand estimation is first presented and calibrated based on the current cargo volumes of the Indonesian maritime market. A model for minimizing total system cost, which is the sum of shippers' and carriers' costs, is then proposed to design the shipping network with cargo demand levels forecasted for future years. The results show that for the Indonesian maritime market, although a hub-and-spoke (HS) network is appropriate for the current low level of shipping demand, a point-to-point (PoP) structure will be needed at higher traffic volumes in the future. Additional domestic hub ports shall be developed as cargo demand increases over time. The results suggest that a progressive policy can be promising for infrastructure investments in developing countries: government planning and regulations may be introduced in early years to enhance infrastructure utilization and economic return. With increased demand the market may be liberalized to promote healthy competition.

AUTHORS: **Tu, Adiputranto, Fu and Li**

CONTACT: INSTITUTE OF TRANSPORT AND LOGISTICS STUDIES (H73)

The Australian Key Centre in Transport and Logistics Management

The University of Sydney   NSW 2006   Australia

Telephone: +612 9114 1813

E-mail: business.itlsinfo@sydney.edu.au

Internet: http://sydney.edu.au/business/itls

DATE: April 2017

1. Introduction

The Republic of Indonesia, which consists approximately 17,500 islands, is an archipelago country in Southeast Asia. According to BPS Statistics Indonesia [1] (2015), Indonesia is divided into 34 administrative provinces over five main islands and four archipelagos. The country shares land borders with Malaysia, East Timor and Papua New Guinea, and marine boundaries with Singapore, Philippines and Australia. As the world's largest archipelago country, marine shipping is a major transportation mode for Indonesia. The Indonesian president, Joko Widodo, has declared twice that he wants to transform the country into a strong maritime nation, confirming the nation's policy priority of developing the maritime sector.

To achieve the vision of an economically strong maritime nation, the Indonesian government has initiated several maritime programs. One program, called Pendulum Nusantara, was proposed by the state corporation PELINDO 2 in 2012. The implementation, which started in January 2016, is expected to be finished by 2018 (Desfika, 2016). This program plans to develop six main hub ports connected with regular shipping services, as depicted in Figure 1 (Lino, 2012). The Pendulum Nusantara program also includes the Sorong-West Pacific Hub Port Development Project, which aims to develop the Port of Sorong into an international gateway in the West Pacific, connecting East Asia to Oceania, as shown in Figure 2. The development of the new Sorong port alone is anticipated to cost approximately IDR3.5 trillion (about US$245 million).[2]
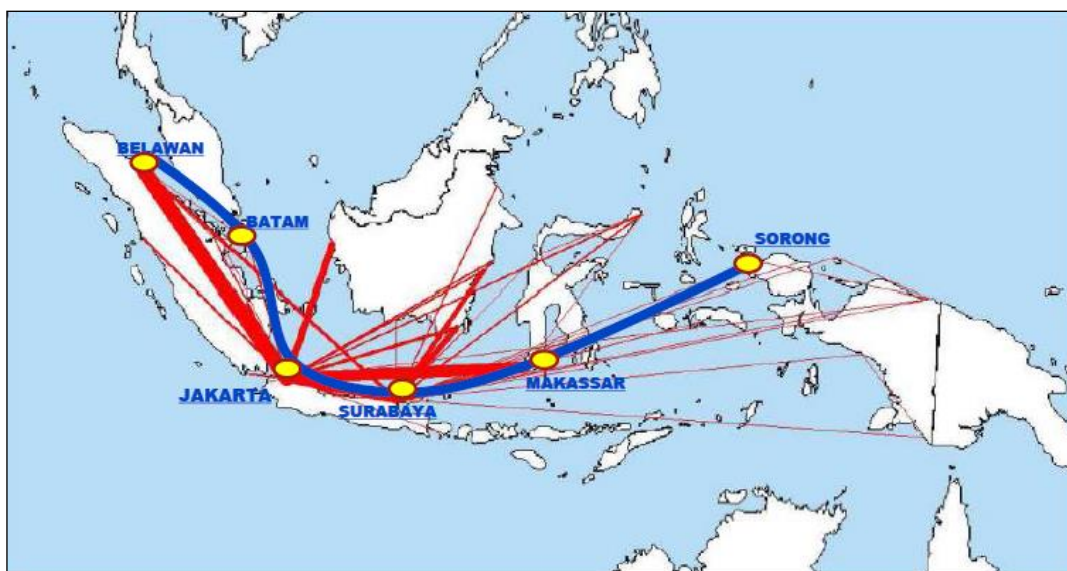

Fig. 1. Proposed main routes for "Pendulum Nusantara".
(Source: Indonesian Ministry of National Development Planning, 2014)

---

[1] BPS Statistics Indonesia (Badan Pusat Statistik Indonesia) is a national statistics office directly under the President of the Republic of Indonesia.

[2] IDR denotes the Indonesian Rupiah. As of 1 Dec 2016, US$1.0 approximates IDR14285.7. This exchange rate will be used for currency conversion hereafter unless specified otherwise.

Fig. 2. Sorong-West Pacific Hub Port Development Project.
(Source: Indonesian Ministry of National Development Planning, 2014)

Another major program is the Maritime Highway Initiative, which is an ambitious plan that consists of the development of 24 strategic ports (5 hubs and 19 feeder ports) throughout the nation, government-backed regular short sea shipping routes and the procurement of new vessels to be used on those routes. The initiative also plans to upgrade regional hubs, Belawan or Bitung, into international hubs that connect Indonesia's domestic network to international network. The Indonesian government has allocated IDR700 trillion (approximately US$49 billion) to the Maritime Highway Initiative over a course of 5 years. Figure 3 depicts the geographic location of the strategic ports and also one possible scheme for how the feeder ports may connect to the proposed hub ports (Indonesian Ministry of National Development Planning, 2014).

With great stakes for such mega-projects, a careful plan and policy assessment is needed before significant investments are made into the related infrastructure. However, the above two programs, if carried out independently, may lead to network and capacity redundancy, which would be very inefficient for a developing country, such as Indonesia. For example, no consensus has been reached with respect to the optimal development strategy for the Sorong port. The port serves as an international gateway hub in the Pendulum Nusantara program, yet it only serves as a feeder port in the Maritime Highway Initiative. Moreover, two separate international hub developments in the country's east could

cause unintended rivalry that might reduce the capacity utilization of both hubs. An inefficient domestic shipping network could also reduce the operational efficiency and economic benefits linked to international commodity trade (Halim et al., 2012). The Indonesian government thus needs to develop a cost-efficient plan for the shipping network improvement at a strategic level.
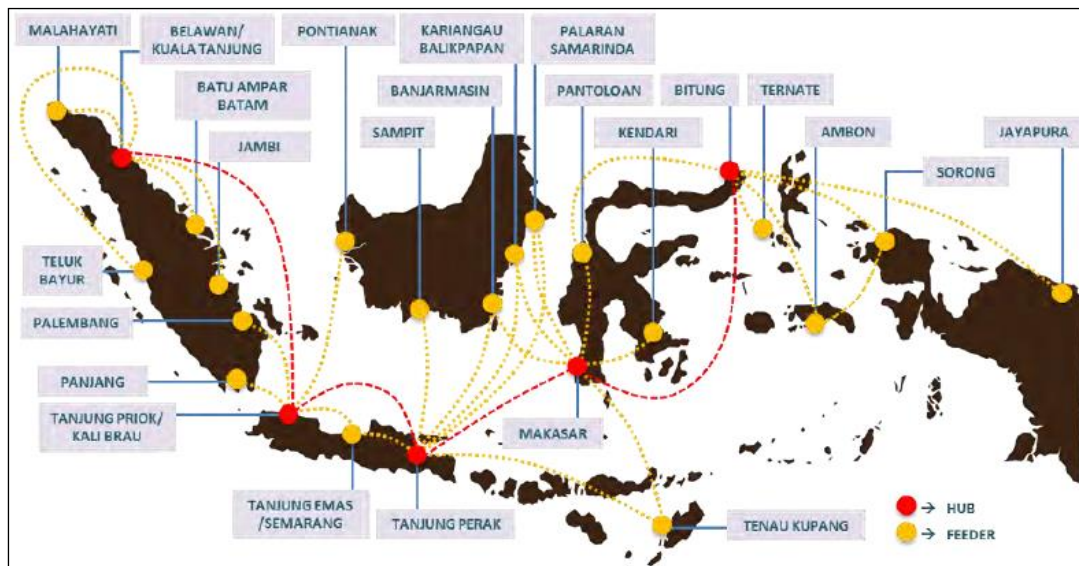

Fig. 3. Geographic locations of 24 strategic ports.
(Source: Indonesian Ministry of National Development Planning, 2014)

Although the literature on shipping network design is well developed, few studies have analyzed the case of Indonesia despite the huge investments involved. Cargo flow between origin-destination (OD) pairs is the most significant input data for network formulation (Bell et al., 2011; Meng and Wang, 2011; Bell et al., 2013; Wang et al., 2015; Zheng and Yang, 2016). Data from different official resources for Indonesia are, however, not entirely consistent. In certain cases, official figures from provincial statistic agencies are inconsistent with national data. For example, the national statistics record "Statistical Yearbook of Indonesia 2015" (BPS, 2016a) reports the amount of unloaded cargo in Maluku province in 2015 to be over 1.7 million gross tons. However, Maluku's own province record, "Maluku Dalam Angka 2015" (BPS, 2016b) states that the amount of unloaded cargo in 2015 was slightly less than 0.8 million gross tons. Such inconsistency in official records poses the challenges of determining actual cargo volumes. Although data on loaded and unloaded cargoes (gross ton) are available at the province level (BPS Statistics Indonesia, 2015), such data are aggregates of OD and transshipment volumes for many destinations at a given port. They may not be directly usable for network design, which requires port-to-port or province-to-province level data. Another challenge is the consideration of shipping network design in a fast-growing market. Although there has been quite some volatility in Indonesia's economic growth over the past decades, it is generally believed that the country can sustain fast expansion in economy and trade. This implies that an optimal design for the

current market may not be the best choice for the future. In addition, as infrastructure investments related to both ports and ships have been quite limited in previous years, a strategic plan for Indonesia needs to take many cost items into consideration instead of focusing on a particular port or on particular shipping companies. Such challenges probably explain why few studies are available in the public domain.

In light of the above, to contribute to the development plan of ports and shipping networks in Indonesia, we first propose an OD demand estimation model to forecast a reliable OD cargo demand matrix for future years. A generalized shipping cost minimization model is then presented to optimize the vessel type and vessel speed for carriers, and to minimize the total system cost (i.e., the sum of shippers' and carriers' costs). This allows us to determine the optimal locations of hub and gateway ports for the creation of an efficient hub-and-spoke (HS) network. The evolution of the optimal network structure is subsequently discussed for different scenarios of cargo demand growth. Our modeling results suggest that the total shipping cost decreases with the cargo handling rate and the scale economy of ship size. At the current low level of cargo demand, an HS network is preferred regardless of the cargo handling rate or the scale economy considered. However, as the cargo demand increases and reaches a threshold, the optimal shipping network will prefer a point-to-point (PoP) structure. Investments in ports and fleets should be planned accordingly in view of this changing network pattern.

The remainder of this paper is organized as follows. Section 2 provides a brief review of the related literature and highlights the contributions of the paper. Section 3 summarizes the market conditions, input data compilations and the method to estimate the OD cargo demand matrix. Section 4 discusses the details of model formulation for HS network design. In Section 5, the proposed models are applied to the Indonesian maritime sector. The last section concludes the paper and provides recommendations for further studies.

2. Literature review

HS networks offer many benefits, such as traffic flow consolidation, large network coverage and simplified operations. They have been widely adopted by airlines, shipping companies, telecommunication systems and logistics operations (Hendricks et al., 1995; Zhang, 1996; Hendricks et al., 1999; Brueckner and Zhang, 2001; Hsu and Hsieh, 2005; Chong et al., 2006; Takano and Arai, 2008; Homsombat et al., 2011; Meng and Wang, 2011; Adler et al., 2014). Hubs serve as transshipment points and replace large quantities of direct connections with fewer indirect connections. O'Kelly (1987), one of the first to study the HS network, developed several heuristics to solve this kind of problems. Several studies have examined waterborne networks based on the HS structure.

Meng and Wang (2011) combined the HS and multiport-calling operations to study the liner shipping service network design problems, but the candidate shipping lines were predetermined. Zheng and Yang (2016) proposed a mixed-integer linear programming model to design an HS network for the Yangtze River and supported the trends of cargo concentration. In Imai et al. (2009), the multiport-calling and the HS network were compared and applied to the problem of the Asia-Europe and Asia-North America trade lanes. Hsu and Hsieh (2005) applied a two-objective model to decide whether to route a shipment through a hub or directly to the destination for a simple network. Chong et al. (2006) proposed a heuristic procedure to solve the problem of scheduling and routing in a hybrid HS network, which included direct delivery. Takano and Arai (2008) applied a new algorithm to solve the p-hub median problem for containerized cargo transport networks. As HS networks have been extensively used and studied, and have been chosen for the Indonesian Maritime Highway program, we model the implications of such a network configuration for the Indonesian market. We consider the 24 "strategic ports" included in the Maritime Highway program and compare alternative hub schemes for the shipping network.

A large number of studies on shipping networks have been conducted. Tran and Haasis (2013) reviewed the relevant literature and concluded that network design can be carried out with alternative objectives, such as cost minimization, sailing and dwelling time minimization, shipping distance minimization, travel and transit time minimization, profit and/or revenue maximization, shipping volume maximization and other alternative objectives adopted in the industry and/or imposed by government agencies in the case of container liner shipping. Network efficiency indicators have also been used, such as Nagurney-Qiang measures, which reflect the weighted average of shipping volume per unit cost (Nagurney and Qiang, 2008). Cost minimization has been widely applied to shipping problems, such as several global-scale simulation models, namely, the World Container Model (Tavasszy et al., 2011), Container World (Sinha-Ray et al., 2003) and GloTram-2 (Smith et al., 2011), and models developed for the regional and national levels (see the multilevel modeling framework developed by Halim et al., 2012). As shipping companies' profits and revenues depend on market dynamics, which are difficult to precisely predict in the long term, we choose the cost minimization as the objective function in this paper to optimize the service quality of carriers and the choice of hub ports. As Indonesia is a developing country with low average income, shippers and carriers are likely to be sensitive to transport costs in the foreseeable future. Therefore, focusing on cost minimization is likely to offer more relevant insights and recommendations to policymakers and the maritime industry in Indonesia.

As an important starting point for any network design, estimation of OD demand is of critical importance for the Indonesian maritime sector. Munizaga and Palma (2012) argued that an OD demand matrix is a fundamental prerequisite in a transport analysis for both research and policy

planning purposes. However, they also emphasized that it is common to have major data gaps for reliable estimation of cargo movements. This is a major challenge in the case of container shipping in Indonesia, as there is no reliable cargo movement data at the province-to-province or port-to-port level. Many studies have tried to estimate an OD matrix or point-to-point trade volumes through using gravity type models or other mathematical solutions. To estimate a full OD matrix with limited data, Levine et al. (2009) formulated an optimization model with which a disaggregated OD demand representation can be generated with aggregated data and a gravity model. They used a case study to identify the movement of containers shipped from international ports to final destinations in the U.S. However, this method cannot be directly applied to the case of Indonesia due to significant differences in data availability and aggregation level. Luo and Grigalunas (2003) developed a gravity model to distribute U.S. containerized imports to states based on population. However, distance factor was not included in the specification. Firdaus and Widyasanti (2010) applied a general gravity model to measure the trade volumes between the domestic regions within Indonesia and found that interregional trade tends to be higher in the Java region, which is the economic center of Indonesia. Banitya (2013) applied a gravity model to identify the variables that affect Indonesia's domestic trade. Because gross domestic regional product (GRDP) and transport distance are important determinants of trade volume, based on the findings of previous studies on network design and Indonesian trade and transport, a gravity function similar to the specification in Silva and Tenreyro (2005) will be adopted in the problem of estimating OD cargo demand matrix. As different port facilities and vessels are needed for different types of cargoes (Zhuang et al., 2014), we focus on container shipping only. Compared to dry bulk and tanker transport, container shipping plays a more important role in trade and economic growth (Lau et al., 2013). In addition, bulk goods shipping mostly uses PoP networks, thus the associated planning is relatively straightforward. The following section first introduces the input data used for the analysis, followed by the specification of the models.

3. OD demand estimation and parameter calibration

3.1. Market definition and ports considered

Both the Pendulum Nusantara and the Maritime Highway programs planned in Indonesia involve a large number of ports. Therefore, we consider shipping networks based on the 24 strategic ports that are to receive funding and development support from the programs. Table 1 provides a list of the strategic ports; their locations are displayed in Figure 3.

Table 1 Strategic ports.

No.	Port Name	Abbrev.	Status	No.	Port Name	Abbrev.	Status
1	Malahayati	P1	Feeder	13	Banjarmasin	P13	Feeder
2	Belawan	P2	Hub	14	Balikpapan	P14	Feeder
3	Batam	P3	Hub	15	Samarinda	P15	Feeder
4	Teluk Bayur	P4	Feeder	16	Pantoloan	P16	Feeder
5	Jambi	P5	Feeder	17	Makassar	P17	Hub
6	Palembang	P6	Feeder	18	Kendari	P18	Feeder
7	Panjang	P7	Feeder	19	Bitung	P19	Hub
8	Tanjung Priok	P8	Hub	20	Tenau Kupang	P20	Feeder
9	Tanjung Emas	P9	Feeder	21	Ternate	P21	Feeder
10	Tanjung Perak	P10	Hub	22	Ambon	P22	Feeder
11	Pontianak	P11	Feeder	23	Sorong	P23	Hub
12	Sampit	P12	Feeder	24	Jayapura	P24	Feeder

To transform the data for loaded and unloaded cargoes from the provincial level to the port level, each province is allocated to one of the 24 strategic ports based on the shortest distance from the province capital to a port, and the ports' loaded and unloaded cargoes are gathered from the provinces they serve. To avoid data inconsistency problems, all of the data used for cargo and container movements should come from the same source. Indonesia's national records are used because they are more detailed and cover all regions. The province-port pairs are shown in Table 2.

Table 2 Indonesian province-port pair.

No.	Province Name	Port	No.	Province Name	Port
1	Aceh	P1	18	Lampung	P7
2	Bali	P10	19	Maluku	P22
3	Banten	P8	20	Maluku Utara	P21
4	Bengkulu	P4	21	Nusa Tenggara Barat	P20
5	Gorontalo	P19	22	Nusa Tenggara Timur	P20
6	Jakarta	P8	23	Papua	P24
7	Jambi	P5	24	Papua Barat	P23
8	Jawa Barat	P8	25	Riau	P2
9	Jawa Tengah	P9	26	Sulawesi Barat	P17
10	Jawa Timur	P10	27	Sulawesi Selatan	P17
11	Kalimantan Barat	P11	28	Sulawesi Tengah	P16
12	Kalimantan Selatan	P13	29	Sulawesi Tenggara	P18

13	Kalimantan Tengah	12	30	Sulawesi Utara	P19
14	Kalimantan Timur	P14	31	Sumatera Barat	P4
15	Kalimantan Utara	P15	32	Sumatera Selatan	P6
16	Kepulauan Bangka Belitung	P6	33	Sumatera Utara	P2
17	Kepulauan Riau	P3	34	Yogyakarta	P9

Both domestic and international shipping demands should be considered in the choice of shipping networks. Currently, approximately 80% of the international trade in Indonesia is routed through the Port of Tanjung Priok before entering or leaving international routes and thus this port is assumed to be the international gateway for the current shipping network. In our model, international shipping to and from other markets are aggregated to six major hub ports, as summarized in Table 3. This assumption is consistent with the reality and allows us to focus on network modeling within Indonesia, which is the main target of government investment plans.

Table 3 International port destination.

No.	Region	Port Name	Abbrev.
1	ASEAN	Singapore	I1
2	North & East Asia	Shanghai	I2
3	The Americas	Los Angeles	I3
4	Oceania	Melbourne	I4
5	Europe	Rotterdam	I5
6	Africa & Rest of Asia	Dubai	I6

3.2. Specifications of cargo volume

Although we focus on container shipping, the available data on cargo movements are mostly in gross tons. This requires a conversion of gross ton cargo to container volume. Statistics Indonesia (2015) reported that in 2014, a total of 1,550,271,403 gross tons of cargos were shipped through the sea and the World Bank (2016) reported that a total of 11,900,763 TEUs (twenty-foot equivalent unit) were shipped in Indonesia. Leonardi and Browne (2010) indicated that 1 TEU carries approximately 10 tons of cargos, which implies that container shipping accounts for approximately 7.7% of Indonesia's sea shipping. However, PELINDO 2 (2015) stated that there were 599,425,593 gross tons of cargos and approximately 5,710,000 TEUs handled in Port of Tanjung Priok in 2015. This implies that container shipping accounts for approximately 9.5% of Tanjung Priok's sea shipping. PELINDO 3 (2015) also reported that there were 463,851,457 gross tons of cargos and approximately 3,100,000 TEUs moving into Port of Tanjung Perak in 2015, which suggests a market share of 6.7% for container shipping in terms of tonnage. Based on these observations, the ratio of 7.7% for the overall Indonesia is between

the ratio of 9.5% for Port of Tanjung Priok and the 6.7% for Port Tanjung Perak, which means that it is feasible to transform the tonnage traffic to the container traffic by 7.7% in the model calibration. Loaded and unloaded cargo tonnage at the strategic ports is gathered from BPS Statistics Indonesia (2015), for which the same conversion rule with ratio 7.7% is used.

Still, detailed information about the shipping network in Indonesia and the operation details, such as vessel size and number, shipping speed and transshipment volume, are not available to us. To make the estimation process tractable, it is assumed that the current shipping network within Indonesia is PoP and the loaded/unloaded cargo volume at ports can be treated as the demand generated at the origin/attracted to the destination. The only exception is the Port of Tanjung Priok, which is the biggest international gateway. It is assumed that the cargos from foreign ports enter Indonesia through specific Indonesian gateways (e.g., Tanjung Priok). Thereby, the transportation of the international cargos involves two networks: an international network and a domestic network. For the international cargo demand, one thus needs to collect the data of the international cargo volume between foreign ports and Indonesian international gateways, and the data of the cargo volume between the gateways and other domestic ports. These data can be gathered directly from BPS Statistics Indonesia (2015). We will discuss the related costs separately for domestic network and the international network later.

3.3. OD demand estimation

When both the total traffic volume generated at origin ports and the total traffic volume attracted to destination ports are known, we can adopt a doubly constrained gravity model and the likelihood estimation of parameters to estimate a reliable OD cargo demand matrix for Indonesian shipping network. A general OD demand matrix pattern is shown in Table 4.

<p align="center">Table 4 OD demand matrix.</p>

Destination / Origin	1	2	$\cdots$	n	$\sum$
1	0	q_{12}	$\cdots$	q_{1n}	O_1
2	q_{21}	0	$\cdots$	q_{2n}	O_2
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
n	q_{n1}	q_{n2}	$\cdots$	0	O_n
$\sum$	D_1	D_2	$\cdots$	D_n	

In Table 4, n is the total number of ports and q_{ij} denotes the cargo demand between OD pair (i, j). The last column represents the total cargo volume originating at each origin port and the last row represents the total cargo volume attracted to each destination port (i.e. the sum of elements in each row/column must equal to the total traffic generation or attraction).

The doubly constrained model has been widely used in transportation demand forecast and trip distribution analysis (see Sheffi, 1985), and is specified as follows:

$$q_{ij} = K_{ij} O_i D_j \exp(-\gamma u_{ij}), \quad \forall i, j, \tag{1}$$

subject to

$$\sum_j q_{ij} = O_i, \quad \forall i, \tag{2}$$

$$\sum_i q_{ij} = D_j, \quad \forall j, \tag{3}$$

where the OD cargo demand q_{ij} is proportional to the total cargo volume originating at the origin port i, O_i and the total cargo volume attracted to the destination port j, D_j. q_{ij} is dependent on the service level between that OD pair, $\exp(-\gamma u_{ij})$, which is a negative exponential function of the OD travel time u_{ij}. K_{ij} is a constant, and γ is an unknown parameter to be estimated. Eqs. (2) and (3) are the conservation constraints.

After some algebraic operations, the doubly constrained model (1)-(3) can further be written as

$$q_{ij} = A_i B_j O_i D_j \exp(-\gamma u_{ij}), \quad \forall i, j, \tag{4}$$

where

$$A_i = \frac{1}{\sum_j B_j D_j \exp(-\gamma u_{ij})}, \quad \forall i, \tag{5}$$

$$B_j = \frac{1}{\sum_i A_i O_i \exp(-\gamma u_{ij})}, \quad \forall j. \tag{6}$$

Substituting Eqs. (5) and (6) into (4), one can indicate that the resultant OD demand q_{ij} satisfies constraints (2) and (3).

In Eq. (4), γ is an unknown parameter and needs to be calibrated. In this paper, the maximum likelihood method can be adopted. To do so, we define the maximum likelihood function L as follows.

$$\max_{\gamma} \ L = \frac{M!}{\prod\limits_{ij} M_{ij}!} \prod_{ij} \left(\frac{q_{ij}(\gamma)}{M} \right)^{M_{ij}}, \tag{7}$$

where M_{ij} is the number of cargos observed to be transported from port i to port j and M is the total number of cargos in the system, i.e., $M = \sum\limits_{i,j} M_{ij}$. After rewriting Eq. (7) as the logarithm function and deleting the constant parts, the calibration for the parameter γ in the OD demand can be stated as follows (Boyce and Zhang, 1998).

$$\max_{\gamma} \ \ln L(\gamma) = \sum_{ij} M_{ij} \ln q_{ij}(\gamma), \tag{8}$$

subject to Eqs. (4)-(6).

Boyce and Zhang (1998) showed that the likelihood function (8) is quite flat and the variation in the value of γ could result in negligible changes in $\ln L(\gamma)$. Therefore, once one finds a value of γ such that the estimated total cargo travel cost $\sum\limits_{i,j} q_{ij}(\gamma) u_{ij}$ approximately equals the actual observed total cargo travel cost $\sum\limits_{i,j} M_{ij} u_{ij}$, then that value of γ can be considered as its calibrated value. The step-by-step procedure for estimating the value of γ in Eq. (8) is shown as below.

Step 1. Choose an initial value for parameter γ, represented as $\gamma^{(1)}$, set the iteration counter to $k = 1$.

Step 2. Determine $\left\{ q_{ij}^{k}(\gamma^{(k)}) \right\}$ in terms of Eqs. (4)-(6) by using furness iteration method (see Sheffi, 1985).

Step 3. If $\left| \left(\sum\limits_{i,j} q_{ij}^{k}(\gamma^{(k)}) u_{ij} \middle/ \sum\limits_{i,j} M_{ij} u_{ij} \right) - 1 \right| < \varepsilon$ (ε is a pre-specified precision), stop; otherwise, update the value of γ as follows and return to Step 2.

$$\gamma^{(k+1)} = \gamma^{(k)} \left(\sum_{i,j} q_{ij}^{k}(\gamma^{(k)}) u_{ij} \middle/ \sum_{i,j} M_{ij} u_{ij} \right). \tag{9}$$

The estimated and observed values are compared to produce a new value of γ for the next iteration.

However, in reality the observed cargo flow moving from origins to destinations is not available for most of OD pairs. Therefore, we adopt a minimization problem together with a exponential function

as used in Silva and Tenreyro (2005) to generate an initial OD cargo flow to replace M_{ij} in model (8), expressed as

$$\min \; \Delta = \sum_i \left| \left(O_i - \sum_j M_{ij} \right) \middle/ O_i \right| + \sum_j \left| \left(D_j - \sum_i M_{ij} \right) \middle/ D_j \right|, \tag{10}$$

subject to

$$M_{ij} = \eta_{ij} \exp \left[a_0 + a_1 \ln(Y_i Y_j) + a_2 \ln(O_i D_j) - a_3 D_{ij} \right], \tag{11}$$

where Y_i and Y_j are the GRDPs of regions i and j, respectively. D_{ij} is the distance between i and j. η_{ij} is the error factor, and $a_0, \cdots, a_3$ are the unknown parameters to be estimated. M_{ij} is determined by the aggregated GRDP of the regions where the ports are serving for, the trade volumes and the transport distance between the two ports. The objective function (10) aims to minimize the total relative error between the observed volume and the volume predicted by the exponential function (11). Inputting initial cargo flow $\{M_{ij}\}$ into model (8), γ can be updated in a subsequent search process to produce an OD cargo demand matrix with minimum error.

3.4. Parameter calibration for the Indonesian maritime market

In order to estimate the OD cargo demand matrix for the Indonesian shipping network, the expressions (10) and (11) are used to obtain an initial OD cargo demand matrix $\{M_{ij}\}$ that minimizes the relative error between the estimated and observed cargo demands. Using 2014 domestic data of Indonesia, the coefficients of the exponential function (11) are estimated as $a_0 = 19.4346$, $a_1 = 0.0107$, $a_2 = 1.0085$, $a_3 = 0.0015$ and $\eta_{ij} = 0.5746$. Inputting the initial cargo volume $\{M_{ij}\}$ into model (8) and adopting the solving procedure introduced above, the parameter γ can be calibrated as a value of 0.3711, with an average error of less than 10^{-7} between the estimated OD cargo demand $\{q_{ij}\}$ and the actual demand data. The future OD cargo demand matrix can then be estimated using the gravity model (4)-(6) with γ value of 0.3711.

4. Shipping network design model

The shipping network design in this paper aims to determine an optimal HS network by locating domestic hub ports and international gateway ports. Domestic hubs have the function to agglomerate the domestic cargos, whereas the international gateways agglomerate the export/import cargos before leaving/entering the domestic network. Without loss of generality, the following basic assumptions are made for simplifying the modeling process:

A1. The feeder ports, candidate domestic hubs and international gateways are pre-determined.

A2. Three stakeholders are considered in the shipping network to be designed, namely the authority (the government), the shippers, and the carriers. The authority aims to determine the optimal locations of hub and gateway ports in the HS network. The carriers seek to optimize the vessel type and vessel speed to minimize its total shipping cost. The shippers choose their routes with minimum travel cost.

A3. Each domestic feeder port could be linked to at least one domestic hub. Domestic hubs are fully connected to each other. Each representative international port of the regions is directly linked to unique gateway(s). Therefore, the whole network can be decomposed into the domestic network and the international network.

A4. Cargo transfers at hub ports en route do not exceed twice. If the sailing distance between the origin and the destination is less than threshold, direct delivery must be used.

For presentation purposes, some notations used in this paper are defined as follows.

N set of all ports, which consists of domestic ports and international ports

N_D set of domestic ports

N_I set of international ports i.e., $N = N_D \cup N_I$

A set of shipping legs

a a shipping leg which is defined as the direct linkage between ports, $a \in A$

R_{ij} set of routes between OD pair (i, j)

H set of all hub ports

G set of all gateways

$\bar{H}$ set of candidate hub ports , $\bar{H} \subseteq N_D$

$\bar{G}$ set of candidate gateways, $\bar{G} \subseteq N_D$

4.1. Shippers' route choices

A shipping network involves three types of participants: ports, carriers and shippers. Ports are the interfaces between ground transportation and waterborne transportation, where many cargo handling activities can be performed. Carriers provide transport services, whereas shippers aim to minimize the generalized transport costs, which include the price paid to carriers and the time cost during cargo transportation (Hsu and Hsieh, 2005, 2007; Talley, 2014). According to assumption A3, the transportation of international cargo includes that in the domestic network and that in the international network. The shippers' route choices on these two networks are thus presented as follows.

4.1.1. Travel cost and route choice in domestic network

The transport time on route $r \in R_{ij}$, represented as T_r, includes the voyage time, TS_r, on the sea and handling time at the transshipment port, TH_r. The voyage time per TEU, TS_r, is determined by the nautical distance and the ship's velocity as follows:

$$TS_r = \sum_{a \in A} \frac{D_a \delta_{ar}}{24 V_a}, \quad \forall r \in R_{ij}, i, j \in N_D, \tag{12}$$

where D_a, measured in nautical mile, is the shipping distance of leg a. V_a is the vessel speed (in knot). $\delta_{ar} = 1$ means route r contains leg a, and $\delta_{ar} = 0$, otherwise.

Port handling time can be separated into two categories, namely the handling time at origin/destination ports and the handling time at hub ports. The handling time at origin/destination ports is composed of the loading or discharging time, while the handling time at transshipment hubs contains both discharging and loading time, which are all proportional to the handling rate and transshipment volume. Let A_i^+ represents the set of legs with port $i \in N$ as a head node and A_i^- represents the set of legs with $i \in N$ as a tail node. Therefore, the total handling time per TEU by using route r is computed as

$$TH_r = \sum_{a \in A_i^-} \frac{S_a \delta_{ar}}{24 \sigma} + \sum_{h \in H} \left(\sum_{a \in A_h^+} \frac{S_a \delta_{ar}}{24 \sigma} + \sum_{a \in A_h^-} \frac{S_a \delta_{ar}}{24 \sigma} \right) + \sum_{a \in A_j^+} \frac{S_a \delta_{ar}}{24 \sigma}, \quad \forall r \in R_{ij}, i, j \in N, \tag{13}$$

where S_a (in TEU) is the vessel size on leg a and σ (TEUs/h) is the number of containers that can be discharged or loaded at the port per hour.

Let U_r be the total time cost for cargo shipping on route r. The minimum time cost between OD pair (i, j) can then be expressed as

$$U_{r*} = \min(U_r, \forall r \in R_{ij}), \quad \forall i, j \in N_D, \tag{14}$$

where

$$U_r = \kappa(TS_r + TH_r), \quad \forall r \in R_{ij}, \tag{15}$$

where κ is the shipper's value of shipping time. r^* denotes the optimal shipping route between OD pair (i, j).

Once the optimal shipping route r^* is determined for each OD pair, the shipping demand is then assigned to that route, i.e.,

$$f_r = \begin{cases} \tilde{q}_{ij}, & r = r^*, \\ 0, & \text{otherwise}, \end{cases} \quad \forall r \in R_{ij}, i, j \in N_D, \tag{16}$$

where f_r is the cargo shipping demand on route r and the shipping demand $\tilde{q}_{ij}$ is the aggregated demand between port pair (i, j). If both ports i and j are not the gateway ports, then $\tilde{q}_{ij}$ represents only the domestic demand (i.e., q_{ij}), which can be obtained by the OD demand estimation model proposed in the previous section. However, if one of the two ports, port i or j, is a gateway, $\tilde{q}_{ij}$ is the sum of the domestic demand and the international demand passing through that gateway.

4.1.2. Travel cost and route choice in international network

The international network adopts the PoP structure, and the international cargos are transported directly between foreign ports and Indonesian gateways. The minimum time cost between origin $i \in N_I$ and the international gateway can be expressed as

$$U_{r*} = \min(U_r, \forall r \in \underset{g \in G}{\cup} R_{ig}), \quad \forall i \in N_I, \tag{17}$$

where

$$U_r = \kappa \sum_{a \in A} \left(\frac{D_a \delta_{ar}}{24 V_a} + 2 \frac{S_a \delta_{ar}}{24 \sigma} \right), \quad \forall r \in \underset{g \in G}{\cup} R_{ig}, i \in N_I, \tag{18}$$

where the bracket in Eq. (18) represents the total time consumption on leg a of route r, in which the first term in the bracket denotes the sailing time and the second term denotes the handling time at origin and destination port. Therefore, the international shipping demand is assigned according to the following shortest-route rule:

$$f_r = \begin{cases} \sum_{j \in N_D} q_{ij}, & r = r^*, \\ 0, & \text{otherwise}, \end{cases} \quad \forall r \in \underset{g \in G}{\cup} R_{ig}, i \in N_I, \tag{19}$$

where $\sum_{j \in N_D} q_{ij}$ is the total export cargo demand leaving international port $i \in N_I$. The import cargo demand entering port $i \in N_I$, $\sum_{j \in N_D} q_{ji}$, can also be assigned to the corresponding routes in the same way.

4.2. Carriers' decisions on vessel size and velocity

Carriers determine the service quality and shipping operations for their operating network, such as vessel type, velocity and frequency, to attract cargos and minimize their shipping costs. The total shipping cost for a carrier contains three categories of costs, namely sailing-related costs, port-related costs and container-related costs. Sailing-related costs include the fuel cost during voyage and the daily charter and operating cost. The daily fuel cost per vessel is estimated to be proportional to the cube of vessel velocity and the fuel efficiency of the vessel, the vessel capacity and the fuel price (Corbett et al., 2009; Wang et al., 2015). The specified expression for daily fuel cost, C_{FC}, (in US\$) is as follows.

$$C_{FC} = \lambda \mu \sqrt{S} V^3, \tag{20}$$

where V (in knot) is the vessel velocity. S (in ton) is the vessel capacity. μ (in ton$^{1/2}$/knot^3) is the fuel efficiency parameter that changes with vessel size (Notteboom and Vernimmen, 2009); and λ is the fuel price, measured in US\$ per ton of fuel.

The daily capital and operating cost per vessel are influenced by several factors, such as crew, ship size, insurance policy and maintenance (Hsu and Hsieh, 2007; Tran, 2011). We can approximate the daily capital and operating cost for each vessel as follows.

$$C_{OP} = \alpha_1 S^{\alpha_2}, \tag{21}$$

where $\alpha_1 > 0$ (in US\$) is the capital cost parameter, S (in ton) is the ship size and $0 < \alpha_2 \leq 1$ is the factor modeling the effect of scale economy due to vessel size.

Port-related charges mainly include each vessel's port dues and the stevedoring costs for containers at ports. Port dues are paid for pilotage, towage and berth occupancy (Hsu and Hsieh, 2007; Tran, 2011), and are determined by the gross tonnage of a vessel (Tran, 2011). Port dues C_{PU} are computed as follows (Wijnolst et al., 2000).

$$C_{PU} = \theta W, \tag{22}$$

$$W = \omega_1 S + \omega_2, \tag{23}$$

where θ is the expense rate per gross ton. The gross tonnage W is converted from the vessel capacity S (in TEU); and ω_1 and ω_2 are relative parameters.

The stevedoring costs are paid for container loaded and unloaded at ports, and increase with the number of transshipment operations during a voyage. In the domestic network, total stevedoring costs per TEU at all ports on route r, represented as $c_{N,r}$, are specified as

$$c_{N,r} = 2\beta\left(\sum_{h \in H} \delta_{hr} + 1\right), \quad \forall r \in R_{ij}, i, j \in N_D, \tag{24}$$

where β is the fee charged per container. $\delta_{hr} = 1$ means hub port $h \in H$ is on route r, and $\delta_{hr} = 0$ otherwise. $\sum_{h \in H} \delta_{hr}$ is the total number of transshipments on route r. For the international network, each route traverses two ports only, namely an international port and a gateway. Thus, the stevedoring costs per TEU at all ports on each route in the international network is 2β. Additionally, container-related costs are the lease costs for the usage of containers during transportation, which are determined by the unit rent cost, the total quantity of containers used by the vessels and the whole transportation duration.

Based on the above specifications, the total shipping cost minimization model for determining optimal vessel size and speed for carriers is as follows.

$$\min_{\mathbf{V},\mathbf{S}} \pi(\mathbf{V},\mathbf{S}) = \sum_{i,j \in N_D} \sum_{r \in R_{ij}} f_r c_{N,r} + \sum_{i \in N_I} \sum_{j \in N_D} 2\beta q_{ij} + \sum_{j \in N_D} \sum_{i \in N_I} 2\beta q_{ji}$$

$$+ \sum_{a \in A} \left[C_{PU}^a F_a + C_{FC}^a F_a \frac{D_a}{24V_a} + \left(c_L q_a + C_{OP}^a F_a\right)\left(\frac{D_a}{24V_a} + 2\frac{S_a}{24\sigma}\right)\right], \tag{25}$$

where $\mathbf{V}$ and $\mathbf{S}$ are the vectors of vessel velocities and ship sizes, respectively. $q_a = \sum_{i,j \in N_D} \sum_{r \in R_{ij}} f_r \delta_{ar} + \sum_{i \in N_D, g \in G} \sum_{r \in R_{ig}} f_r \delta_{ar} + \sum_{g \in G, i \in N_D} \sum_{r \in R_{gi}} f_r \delta_{ar}$ is the total cargo flow on leg a. $F_a = \text{int}\left(q_a / S_a\right)$ represents the round-off value of the annual number of voyages for vessel S_a on leg a. c_L is the lease cost per container. C_{PU}^a, C_{FC}^a, and C_{OP}^a are, respectively, the daily port due, daily fuel cost and daily operating cost for specific leg a. $D_a / 24V_a$ is the sailing time on leg a and $S_a / 24\sigma$ is the discharging/loading time at the head port/the tail port of leg a for vessel S_a. The right hand of the objective function (25) contains four parts: the first part represents the total stevedoring costs at all ports in the domestic network; the second and third parts represent the stevedoring costs at all ports in the international network; the fourth part represents the total cost at all shipping legs, including the total port dues of vessels, the fuel costs, the container rental costs and the capital and operating costs of vessels during the whole year's voyage.

4.3. Total system cost minimization for design of hub ports and gateways for the authority

To design the shipping network, the government determines the optimal locations of hubs and international gateways from given sets of candidate ports to minimize the total maritime system cost. The total system cost is the sum of the carriers' total shipping cost and shippers' total cost in the whole shipping network. The network design problem can be formulated as the following cost minimization model

$$\min_{\mathbf{x},\mathbf{y}} \Phi\big(\mathbf{V}(\mathbf{x},\mathbf{y}),\mathbf{S}(\mathbf{x},\mathbf{y})\big) = \pi\big(\mathbf{V}(\mathbf{x},\mathbf{y}),\mathbf{S}(\mathbf{x},\mathbf{y})\big) + \sum_{i,j \in N_D} \sum_{r \in R_{ij}} U_r\big(\mathbf{V}(\mathbf{x},\mathbf{y}),\mathbf{S}(\mathbf{x},\mathbf{y})\big) \cdot f_r\big(\mathbf{U}(\mathbf{V}(\mathbf{x},\mathbf{y}),\mathbf{S}(\mathbf{x},\mathbf{y}))\big)$$

$$+ \sum_{g \in G, i \in N_I} \sum_{r \in R_{gi} \cup R_{ig}} U_r\big(\mathbf{V}(\mathbf{y}),\mathbf{S}(\mathbf{y})\big) \cdot f_r\big(\mathbf{U}(\mathbf{V}(\mathbf{y}),\mathbf{S}(\mathbf{y}))\big), \tag{26}$$

subject to

$$\sum_{h \in \bar{H}} x_h = P, \tag{27}$$

$$\sum_{g \in \bar{G}} y_g = Q, \tag{28}$$

$$x_h = \begin{cases} 1, & \text{port } h \text{ is set to be a hub,} \\ 0, & \text{otherwise,} \end{cases} \quad \forall h \in \bar{H}, \tag{29}$$

$$y_g = \begin{cases} 1, & \text{port } g \text{ is set to be a gateway,} \\ 0, & \text{otherwise,} \end{cases} \quad \forall g \in \bar{G}, \tag{30}$$

where $\mathbf{x}$ and $\mathbf{y}$ are the decision variables. π, which is a function in $\mathbf{x}$ and $\mathbf{y}$ through $\mathbf{V}$ and $\mathbf{S}$, is determined by the carrier's shipping cost minimization model (20)-(25). $\mathbf{U}$, which is a function in $\mathbf{y}$ and $\mathbf{x}$ through $\mathbf{V}$ and $\mathbf{S}$, is determined by the shipper's route choice model (12)-(19). The objective function (26) includes three kinds of costs, namely the total carriers' shipping cost and the total shippers' time cost in the domestic and international shipping networks. Constraints (27) and (28) state that P new domestic hubs and Q new gateways will be built in the network. Constraints (29) and (30) define 0-1 decision variables.

In order to solve the 0-1 integer programming problem (26)-(30), we develop a heuristic solution algorithm as follows.

Step 1. Initialization. Set $\Phi^* = +\infty$ as the upper bound of the objective function Φ in Eq. (26).

Step 2. First loop operation (determining optimal locations of gateway ports). Given the set of candidate gateways $\bar{G}$, check all possible gateway schemes sequentially with one scheme at a time. Let $G^{(1)}$ denote the initial gateway scheme. Set the scheme counter to $k = 1$.

Step 3. Second loop operation (determining optimal locations of domestic hub ports). Given the set of candidate domestic hubs $\bar{H}$, check all possible hub schemes sequentially with one scheme at a time. Let $H^{(1)}$ denote the initial hub scheme. Set the scheme counter to $l = 1$.

Step 3.1. If all possible gateway schemes are checked, then go to Step 4.

Step 3.2. Solve the carriers' shipping cost minimization model (20)-(25) to obtain the optimal velocity and ship size patterns $\mathbf{V}^{(l)}$ and $\mathbf{S}^{(l)}$ and the shippers' route choice model (12)-(19) to generate the route flow $\mathbf{f}^{(l)} = \left\{ f_r^{(l)} \right\}$ and the transportation time cost $\mathbf{U}^{(l)} = \left\{ U_r^{(l)} \right\}$. Then, compute the objective value $\Phi^{(l)}$ for the current hub scheme $H^{(l)}$ with the fixed gateway scheme $G^{(k)}$.

Step 3.3. Termination check for the second loop operation. If $\Phi^{(l)} < \Phi^*$, then put $\mathbf{V}^* = \mathbf{V}^{(l)}$, $\mathbf{S}^* = \mathbf{S}^{(l)}$, $\mathbf{f}^* = \mathbf{f}^{(l)}$, $\Phi^* = \Phi^{(l)}$, $\left\{ \mathbf{x}^*, \mathbf{y}^* \right\} = \left\{ \mathbf{x}^{(l)}, \mathbf{y}^{(k)} \right\}$, and $l = l + 1$, and go to Step 3.1. Otherwise, set $l = l + 1$ and go to Step 3.1.

Step 4. Termination check for the first loop operation. If all possible hub schemes are checked, then terminate the algorithm and output the optimal solution $\left\{ \mathbf{V}^*, \mathbf{S}^*, \mathbf{x}^*, \mathbf{y}^*, \mathbf{f}^* \right\}$ and the corresponding objective function value Φ^*. Otherwise, set $k = k + 1$, and go to Step 3.

5. Case study for Indonesian maritime market

5.1. Parameter calibrations and specifications

The OD demand estimation model and the cost-minimization model for shipping network design are applied to the Indonesian maritime market. Data for the 2014 GRDPs of provinces and the loaded and unloaded cargos in 2013 are collected for all provinces. We first forecast the GRDPs and the cargo volumes for year 2014, 2019 and 2024 based on the observed data. According to BPS Statistics Indonesia (2015), Indonesia's GDP in 2014 was approximately IDR10,542 trillion (approximately US$737 billion) with an annual growth rate of 5.21%. BPS Statistics Indonesia (2015) forecasted an average annual growth of 5.50% over the next 5 years (i.e., 2014-2019), whereas the Indonesian Ministry of National Development Planning (2014) forecasted an average annual growth of 7.00% over the sequential period of 5 years when the proposed government development initiatives are applied nationwide (i.e., 2019-2024). The GDP forecasts for specific future years are summarized in Table 5.

Table 5 Indonesian GDP forecast (trillion IDR).

Year	2014	2019	2024
GDP	10,542	13,778	19,324

Note: "IDR" stands for Indonesian currency and US$1.0 approximates IDR14285.7 on 1 December 2016

The annual GRDP growth rates of provinces in 2014 are obtained from BPS Statistics Indonesia (2015). With reference to the national annual growth and the regional annual growth in 2014, the growth rate of GRDP for each province from 2014 to 2019 can be predicted to be proportional to the growth rate of the national GDP (BPS Statistics Indonesia, 2016c). The cargo volume at the province level is also predicted to be proportional to the GRDP, as trade volume is significantly influenced by the overall economy. Voyage distance data are compiled for port-pairs from searates.com and Google Earth.

In our analysis, seven candidate ports may serve as domestic hubs, including the ports of Belawan, Batam, Tanjung Priok, Tanjung Perak, Makassar, Bitung and Sorong. Four candidate ports may serve as international gateway ports, including the ports of Belawan, Tanjung Priok, Bitung and Sorong. A port can be a domestic hub and an international gateway at the same time. In a hybrid HS network, cargo may be delivered directly or via transshipment. We first consider scenarios with only one international gateway, although there can be one to seven domestic hubs. If a port is not chosen to be a hub by the total system cost minimization model, it is then set to be a feeder port. Hub ports are fully connected to each other. To make the model tractable, it is assumed that domestic cargo can pass through at most two hubs, whereas direct delivery is used when the sailing distance between an origin and a destination is less than 1,000 nautical miles. Direct delivery has the advantage of short travel time and no transshipment cost. However, direct delivery may lead to legs not well served and cause higher costs for the whole PoP structure when cargo volumes are not very large.

Five types of vessels with capacities of 3,000 TEU, 4,000 TEU, 5,000 TEU, 8,000 TEU and 10,000 TEU are considered for the network. The values of the various relevant parameters are collected from previous studies. With reference to Notteboom and Vernimmen (2009), the approximate values of fuel efficiency of vessel μ for the ship types are $5.434 \times 10^{-5} \sqrt{\text{ton}}/\text{knot}^3$, $5.129 \times 10^{-5} \sqrt{\text{ton}}/\text{knot}^3$, $4.750 \times 10^{-5} \sqrt{\text{ton}}/\text{knot}^3$, $5.809 \times 10^{-5} \sqrt{\text{ton}}/\text{knot}^3$ and $5.643 \times 10^{-5} \sqrt{\text{ton}}/\text{knot}^3$, respectively. The bunker fuel price is set to be $\lambda = 375\text{US\$/ton}$ (Tran, 2011), α_1 is assumed to be $40\text{US\$/day} \cdot \text{ton}^{\alpha_2}$ and $\alpha_2 = 0.6257$ (Tran, 2011). The lease cost per container, c_L, is assumed to be US\$4.5/TEU/day and the rate of depreciation or time cost related to the shipment, κ, for each container is assumed to be US\$20/TEU/day (Bell et al., 2013). Wijnolst et al. (2000) notes that gross tonnage can be calculated as $W = 12.556S + 1087.2$ and $\theta = 0.1884(\text{US\$})$ per gross tonnage. The handling charge per movement of container, β, is assumed to be US\$100/TEU and a port handles 100 TEUs per hour with six cranes (Tran, 2011).

With the above parameters, the routes between each OD pair can be uniquely chosen and the optimal

velocity for the vessel on leg a can be obtained by $V_a^* = \sqrt[3]{(c_L q_a + C_{OP}^a F_a)/2\lambda\mu_a F_a \sqrt{S_a}}$, which increases with container lease rate and operation cost and decreases with fuel price and fuel efficiency. More modeling results are presented as follows.

5.2. Discussions of results

Figure 4 displays how the optimal hub schemes change with different total number of hubs for three cargo demand levels, respectively, for 2014, 2019 and 2024 when only the Indonesian domestic market is considered. In this figure, the numbers in the square brackets represent the corresponding optimal hub schemes for a given number of hubs. It can be noted that there is a big difference in the optimal hub schemes for 2014, 2019, and 2024. Specifically, the optimal hub schemes include four ports for 2014, namely Belawan (port 2), Batam (port 3), Tanjung Priok (port 8), and Tanjung Perak (port 10), and five ports for 2019, namely ports 2, 3, 8, 10 and Makassar (port 17). The corresponding total costs (including both the shippers' cost and the carriers' cost) of the domestic network under the optimal schemes for 2014 and 2019 are US$1.316 billion and US$1.665 billion, respectively. However, in 2024, the optimal network structure is a PoP structure, with a total cost of US$2.232 billion. These results indicate that for the domestic market, the HS network is preferred at the low cargo demand levels (e.g., as of 2014 and forecasted for 2019) because the HS network can save cost due to cargo agglomeration and usage of large-size vessels. However, the PoP network is more efficient at a high cargo demand level (e.g., forecasted for 2024) due to decreased transshipment costs. In addition, it can also be noted that the ports of Belawan, Tanjung Priok and Tanjung Perak are usually chosen as the domestic hubs because the regions served by these ports have large population size, high GRDPs, and large port throughputs.
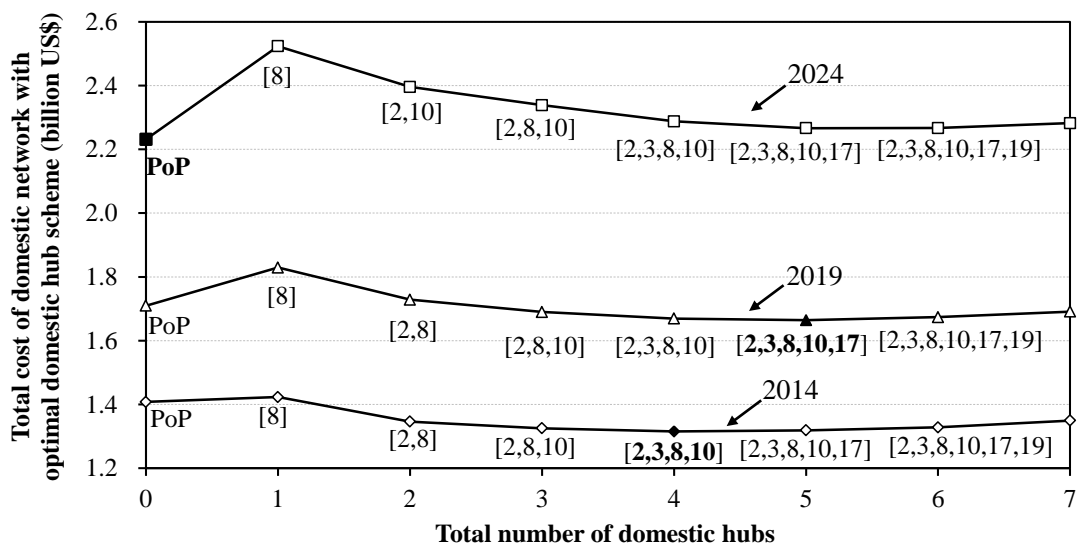

Fig. 4. Changes of optimal domestic hub schemes with total number of domestic hubs.

Table 6 indicates the optimal network configurations and the corresponding total system cost, including those for the domestic market and the international market, for different levels of OD cargo demand in 2014, 2019 and 2024 when only one port is chosen as the international gateway. It can be noted that the Port of Tanjung Priok (port 8) is always the optimal choice. This is consistent with the fact that approximately 80% of the international trades in Indonesia currently pass through the Port of Tanjung Priok. Table 6 also shows that at the demand level of 2014, the scheme with four domestic hubs, which include the ports of Belawan (port 2), Batam (port 3), Tanjung Priok (port 8), and Tanjung Perak (port 10), is the best choice. With growth in cargo demand, the corresponding total number of the optimal hubs is increasing. Specifically, compared to 2014, with an increased GRDP, population and port throughputs, the Port of Makassar (port 17) is added as the fifth domestic hub for 2019. However, in 2024, the optimal domestic network structure changes to a PoP structure which offers lower cost at a high demand level.

Table 6 Optimal scheme for Indonesian shipping network when only one port is chosen as the gateway.

Year	2014	2019	2024
Optimal gateway	Tanjung Priok (Port 8)	Tanjung Priok (Port 8)	Tanjung Priok (Port 8)
Optimal domestic hub scheme	[2,3,8,10]	[2,3,8,10,17]	PoP
Total cost for the domestic network (billion US$)	1.797	2.333	3.182
Total cost for the international network (billion US$)	1.392	1.862	2.654
Total system cost (billion US$)	3.189	4.195	5.836

As mentioned, without a careful plan establishing two independent international gateways in the east area of Indonesia (i.e., the development of the Port of Bitung as planned in the Maritime Highway and the Port of Sorong as planned in the Pendulum Nusantara program) may cause an unintended rivalry that reduces the overall economic benefits. Therefore, we investigate the scenarios in which one of the two candidate ports of Bitung (port 19) and Sorong (port 23) is also chosen as an international gateway in addition to Tanjung Priok (port 8). Table 7 shows the optimal domestic hub schemes and the corresponding cost for different years. It can be seen that the Port of Bitung is always a better candidate than the Port of Sorong in terms of the total system cost for 2014, 2019, and 2024. Specifically, the total system cost with the additional gateway port Bitung are US$0.069 billion, US$0.094 billion, and US$0.123 billion lower than those with the additional gateway port Sorong in the three years, respectively. In addition, in 2024, the optimal shipping network structure for Indonesia becomes the PoP structure regardless of the choices of international gateways.

Comparing Tables 6 and 7, it can be observed that the total cost of the international network decreases with the development of an additional gateway. Specifically, compared to the case with just one gateway (i.e., Port Tanjung Priok (port 8)), adding Port of Bitung (port 19) as a gateway port can lead to a decrease in the total cost of the international network by US$0.079 billion, US$0.086 billion, and US$0.100 billion for 2014, 2019 and 2024, respectively. However, the total cost of the domestic network increases due to an addition of Port of Bitung as a gateway. Specifically, the total cost of the domestic network, respectively, increases by US$0.157 billion, US$0.199 billion, and US$0.284 billion for 2014, 2019 and 2014. As a result of a tradeoff between the international network cost decrease and the domestic network cost increase, the total system cost (i.e., the sum of total international network cost and total domestic network cost) increases. Thereby, developing one international gateway (i.e., Port of Tanjung Priok (port 8)) outperforms developing two international gateways in all the years considered, in terms of the total system cost. That is to say, choosing Port of Tanjung Priok only as the international gateway is enough for the Indonesian maritime market in the next decade.

Table 7 Comparison of different schemes for Indonesian shipping network when Port of Bitung (port 19) or Port of Sorong (port 23) is introduced as an additional gateway (given the existing gateway port of Tanjung Priok (port 8)).

Candidate gateway	Year	2014	2019	2024
Bitung	Optimal domestic hub scheme	[2,3,8,10,19]	[2,3,8,10,19]	PoP
	Total cost for the domestic network (billion US$)	1.954	2.532	3.466
	Total cost for the international network (billion US$)	1.313	1.776	2.554
	Total system cost (billion US$)	3.267	4.308	6.020
Sorong	Optimal domestic hub scheme	[2,3,8,10,23]	[2,3,8,10,23]	PoP
	Total cost for the domestic network (billion US$)	2.007	2.604	3.558
	Total cost for the international network (billion US$)	1.329	1.798	2.585
	Total system cost (billion US$)	3.336	4.402	6.143

As our network configurations are not entirely endogenous, additional tests are carried out to test whether they are robust to other factors. The shipping cost minimization model for carrier is applied

to compute the total shipping cost of domestic network for a PoP network versus an HS network, with the ports of Belawan (port 2), Tanjung Priok (port 8) and Tanjung Perak (port 10) serving as the domestic hubs and the Port of Tanjung Priok serving as the international gateway. Figure 5 reports the total shipping cost for the domestic network with different handling rates σ. Improved handling rates at ports reduce the dwelling time at the origin port, transshipment hubs and destination port, thus reducing the associated operation costs. Reduced transport time also reduces shippers' time cost. These benefits are confirmed as shown in Figure 5, where costs at different cargo volumes decline with the handling rate.

Figure 5 also shows that the total shipping cost of the HS network is lower than that of PoP direct delivery for the demand levels of 2014 and 2019, but exceeds the cost of the PoP network at the 2024 level. The cost differences are presented in Figure 6. Note that in 2014 and 2019, cost differences between PoP network and HS network are positive and increase with handling rate, as higher handling rates are particularly beneficial for HS networks, which involve more transshipment activities. However, when the demand becomes sufficiently high, such as the forecasted 2024 level, a PoP network is more efficient than an HS network, although higher handling rates still reduce the cost gaps of these two types of networks. Therefore, if the handling rate is low, direct delivery via a PoP network may be preferred when shipping demand is high.
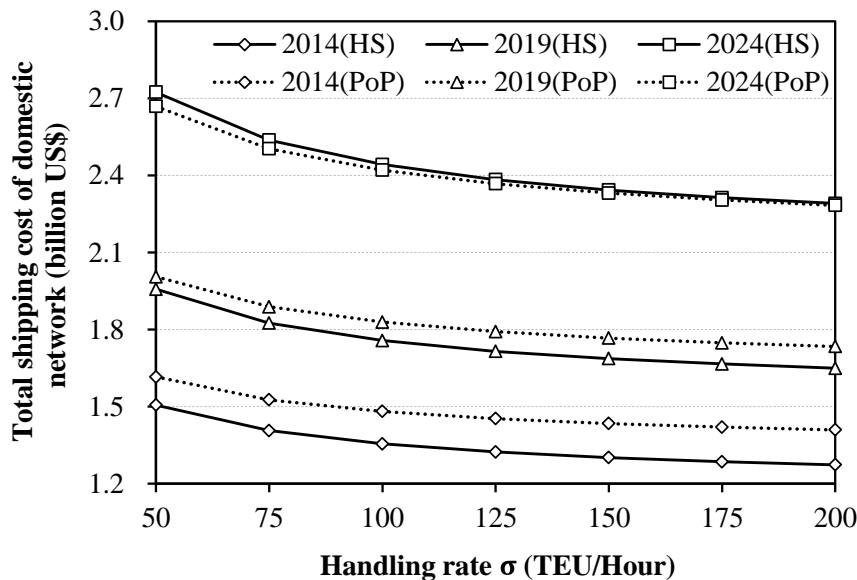

Fig. 5. Effects of handling rate σ on total shipping cost of domestic maritime network: PoP vs. HS networks.
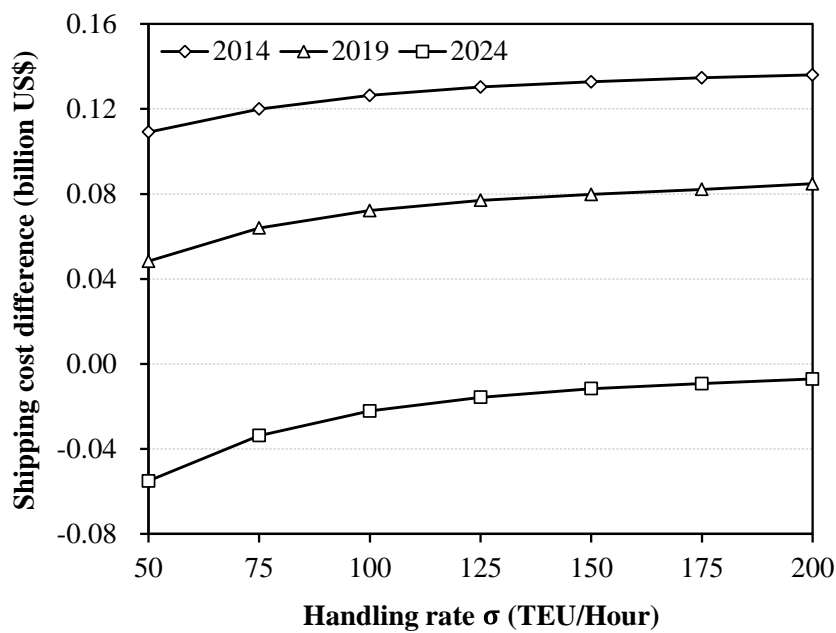
Fig. 6. Effects of handling rate σ on difference in total shipping cost of domestic maritime network: PoP vs. HS networks.

Figure 7 illustrates changes of the total shipping cost of the domestic network with different values of α_2 ($0 < \alpha_2 \leq 1$), which is a factor describing the scale economy associated with vessel size when computing capital and operating costs. Figure 7 shows that as α_2 increases (i.e., equivalently, the scale economy decreases), the total shipping cost marginally increases regardless of the PoP or HS network structures. This implies significant cost saving when large ships replace small ships, but such a benefit diminishes at large vessel sizes.

In order to further identify the difference between PoP and HS networks, Figure 8 displays carriers' shipping cost difference between the two network structures with different values of α_2. It can be seen that at the demand level of 2014, the cost difference increases slowly with α_2. This is because an HS network can save cost through agglomeration of traffic volumes at hubs and thus more large vessels can be used. However, such a cost saving advantage diminishes in future years with growing demand. Therefore, at a high demand level in 2024, a PoP network will be more efficient than an HS network because the cost savings related to fewer transshipments in the PoP network exceeds the cost savings due to the ship scale economy in the HS network.
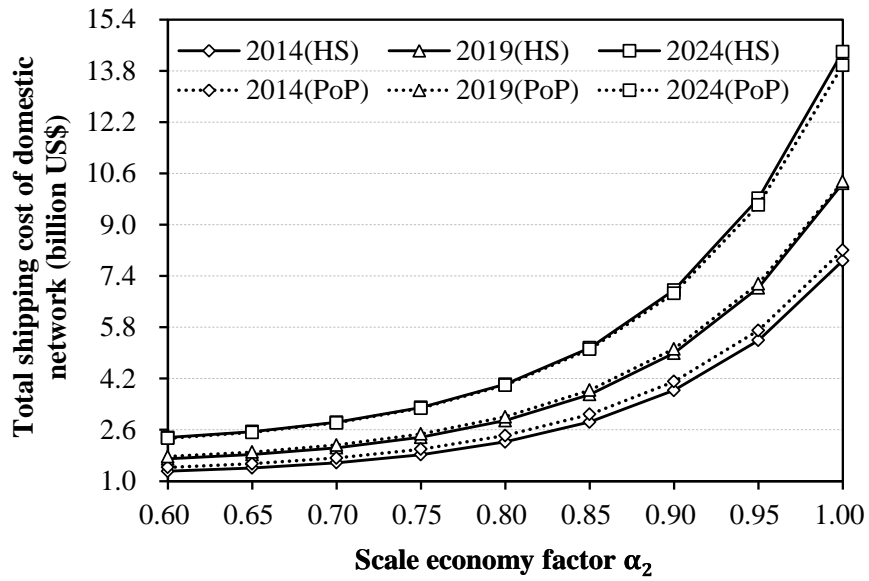
Fig. 7. Effects of scale economy factor α2 on total shipping cost of domestic maritime network: PoP vs. HS networks.
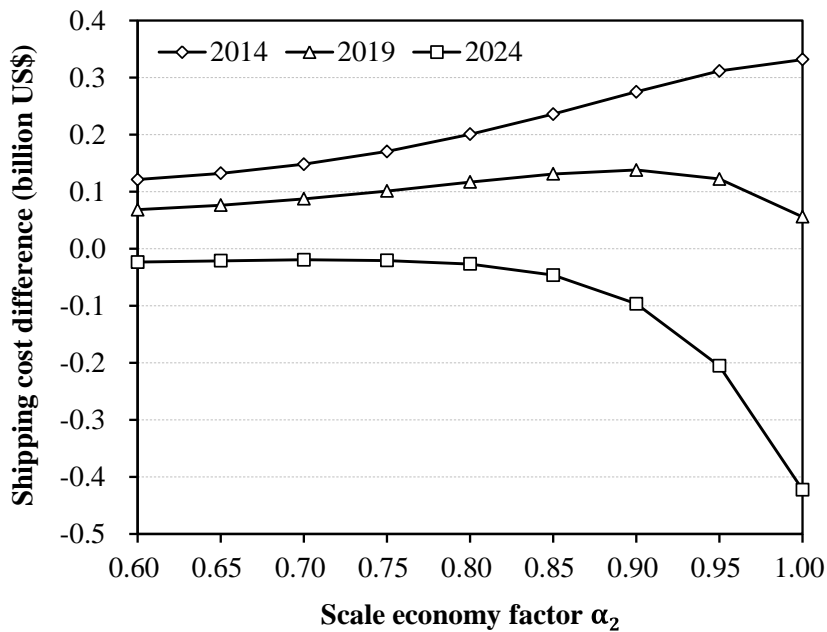

Fig. 8. Effects of scale economy factor α2 on difference in total shipping cost of domestic maritime network: PoP vs. HS networks.

6. Concluding remarks

As a major archipelago country with a huge population, substantial investment in Indonesia's maritime sector is needed to promote the nation's trade and economic growth. Despite the huge stakes involved, there is significant inconsistency between strategic government plans, such as the Pendulum Nusantara and Maritime Highway initiatives. Large investments in the maritime sector usually take a very long time to finish, during which rapid growth in cargo volumes are expected for Indonesia. All of these issues call for careful planning by the country's maritime sector and government policy. However, few studies have investigated the optimal design of the shipping network in Indonesia and even less is known about how government policies and investment plans should adapt to changing demand over time. This paper aims to fill these gaps in research and policy planning by conducting a comprehensive study of shipping network design.

To overcome the severe shortage of detailed cargo flow data, a doubly constrained gravity model combined with the parameter estimation procedure is first applied to the Indonesian markets to calibrate a full OD cargo demand matrix for the current and future markets. A total system cost minimization model is then developed, which consists of carriers' total shipping cost related to port-to-port cargo delivery (such as cargo bunker fuel cost, capital and operating cost, container lease cost, port dues and handling cost), and shippers' time cost which is related to the total delivery time. The proposed model considers both domestic and international cargo flows to determine the optimal domestic hubs and international gateways for the Indonesian maritime market.

Some important findings and new insights have been obtained. First, as a result of the tradeoff between scale economy of large ships and transshipment costs, an HS network is preferred at low cargo demand levels (e.g., in 2014 and 2019), whereas a PoP network is more efficient at high demand levels (e.g., in 2024). Specifically, an HS network configuration is more cost effective for Indonesia at the current traffic volume. With rapid growth in cargo demand, however, a PoP network structure will outperform an HS network structure in 2024. Second, the ports of Belawan, Tanjung Priok and Tanjung Perak have good potential to become the domestic hubs because they serve regions that have large population size, high GRDPs, and large cargo throughputs. Third, only one international gateway (i.e. Tanjung Priok) is needed for the Indonesia maritime market for the next decade.

In addition to these detailed recommendations for shipping network design in Indonesia, our study also reveals the importance of considering market dynamics in strategic planning and government policy. One major policy decision is whether government intervention and planning should be imposed. Government intervention may avoid duplicate investments and thus increase the utilization

and return of infrastructure investment. However, market-based mechanisms tend to be more responsive and efficient, bringing competition and innovations in the long term. Our analysis suggests that the optimal decision may evolve dynamically with market conditions. For the case of the Indonesian maritime sector, when demand is relatively low, only one international gateway and four domestic hubs are needed. With increased traffic volumes, additional domestic hubs should be built. However, when the demand is large enough, the PoP structure will be optimal. These modeling results suggest that a progressive policy may be promising for developing countries that are usually short of capital. In the early stages when demand is relatively low, government intervention and planning can avoid duplicate investments and promote operational efficiency. However, as traffic volume and demand increase over time, it may be optimal to liberalize the maritime sector and promote healthy competition between ports and regions. We also highlight the interactive dynamics between port operations and shipping networks. As shown in our sensitivity tests in Figures 5 to 8, increased port capacity and handling rates influence the optimal network configuration of container carriers (HS vs PoP). However, the scale economy of large ships also affects the network configuration and thus the throughput and transshipment volumes at ports. Therefore, government policy and planning should be both long term and comprehensive. Finally, because the OD cargo flows are one of the key determinants of optimal shipping networks, it is important for governments to compile more detailed data. Compared to advanced economies, statistical agencies in developing countries often compile less detailed data. This can be an expensive mistake, as more infrastructure investment and associated planning are often needed in developing countries.

Although we have tried to conduct a comprehensive study using real market data, some simplifying assumptions and model calibrations have been imposed due to the lack of some critical data. The network configuration is not entirely endogenous and we have not considered more complex hybrid networks. Although our modeling results suggest that a progressive government policy is promising, in reality government interventions often give rise to corruption and bureaucracy, especially in developing countries. These issues, however, are difficult to model in quantitative analysis. Our study is a step toward better planning and policymaking, yet more advanced studies should be carried out when more detailed data are available. Such efforts are particularly important for the maritime sector, in which infrastructure development involves substantial investment over extended periods.

References

Adler, N., Fu, X., Oum, T.H., Yu, C., 2014. Air transport liberalization and airport slot allocation: The case of the Northeast Asian transport market. Transportation Research Part A 62, 3-19.

Banitya, R.R., 2013. Gravity Model of Trade in Indonesian Market. Paper presented at the 6th Conference of Indonesian Students Association in Korea, Daejeon, July 7, 2013.

Bell, M.G.H., Liu, X., Angeloudis, P., Fonzone, A., Hosseinloo, S.H., 2011. A frequency-based maritime container assignment model. Transportation Research Part B 45(8), 1152-1161.

Bell, M.G.H., Liu, X., Rioult, J., Angeloudis, P., 2013. A cost-based maritime container assignment model. Transportation Research Part B 58(3), 58-70.

Boyce, D.E., Zhang, Y., 1998. "Parameter estimation for combined travel choice models," in Lundqvist, L., Mattsson, L.G., Kim, T.J. (eds.), Network Infrastructure and the Urban Environment. Berlin: Springer-Verlag Berlin Heidelberg, pp. 177-193.

Brueckner, J.K., Zhang, Y., 2001. A model of scheduling in airline networks: How a hub-and-spoke system affects flight frequency, fares and welfare. Journal of Transport Economics and Policy 35(2), 195-222.

BPS - Statistics Indonesia, 2015. Statistical Yearbook of Indonesia 2015, catalogue no. 1101001, BPS - Statistics Indonesia, Jakarta.

BPS - Statistics Indonesia, 2016a. Statistical Yearbook of Indonesia 2015, catalogue no. 1101001, BPS - Statistics Indonesia, Jakarta.

BPS - Statistics Indonesia, 2016b. Maluku in Figures 2015, catalogue no. 1102001.81, BPS - Statistics Maluku, Ambon.

BPS - Statistics Indonesia, 2016c. [Seri 2010] Laju Pertumbuhan Produk Domestik Regional Bruto per Kapita Atas Dasar Harga Konstan 2010 Menurut Provinsi, 2011-2014, viewed April 3, 2016, <https://www.bps.go.id/linkTableDinamis/view/id/964>.

Chong, L., Kennedy, D., Chan, W.M., 2006. Direct shipping logistic planning for a hub-and-spoke network with given discrete intershipment times. International Transactions in Operational Research 13(1), 17-32.

Corbett, J.J., Wang, H., Winebrake, J.J., 2009. The effectiveness and costs of speed reductions on emissions from international shipping. Transportation Research Part D 14(8), 593-598.

Desfika, T.S., 2016. Pembangunan Pelabuhan Sorong Dimulai Januari 2016, Berita Satu, November 17, viewed March 15, <http://www.beritasatu.com/ekonomi/322774-pembangunan-pelabuhan-sorong-dimulai-januari-2016.html>.

Firdaus, M., Widyasanti, A.A., 2010. Indonesian Interprovincial Trade: What Can Be Revealed from a Gravity Modeling? Paper presented at the 10th Indonesian Regional Science Association International Conference, Surabaya, July 28-29, 2010.

Halim, R.A., Tavasszy, L.A., Seck, M.D., 2012. Modeling the global freight transportation system: A multi-level modeling perspective. Proceedings of the 2012 Winter Simulation Conference, pp. 1-13.

Hendricks, K., Piccione, M., Tan, G., 1995. The economics of hubs: The case of monopoly. Review of Economic Studies 62(1), 83-99.

Hendricks, K., Piccione, M., Tan, G., 1999. Equilibria in networks. Econometrica 67(6), 1407-1434.

Homsombat, W., Lei, Z., Fu, X., 2011. Development status and prospects for aviation hubs—A

comparative study of the major airports in Southeast Asia. Singapore Economic Review 56(4), 573-591.

Hsu, C.I., Hsieh, Y.P., 2005. Direct versus terminal routing on a maritime hub-and-spoke container network. Journal of Marine Science and Technology 13(3), 209-217.

Hsu, C.I., Hsieh, Y.P., 2007. Routing, ship size, and sailing frequency decision-making for a maritime hub-and-spoke container network. Mathematical and Computer Modelling 45(7/8), 899-916.

Imai, A., Shintani, K., Papadimitriou, S., 2009. Multi-port vs. hub-and-spoke port calls by containerships. Transportation Research Part E 45(5), 740-757.

Indonesian Ministry of National Development Planning, 2014. *Pengembangan Tol Laut Dalam Rpjmn 2015-2019 dan Implementasi 2015*, Directorate of Transportation, Jakarta, viewed February 29, 2016.

Lau, J., Ng, A., Fu, X., Li, K., 2013. The evolution and research trend of container shipping. Maritime Policy & Management 40(7), 654-674.

Lino, R.J., 2012. Transporting Light to the Nation: Indonesia Maritime Infrastructure, World Export Development Forum 2012, at Jakarta, October 15.

Leonardi, J., Browne, M., 2010. A method for assessing the carbon footprint of maritime freight transport: European case study and results. International Journal of Logistics Research & Applications 13(5), 349-358.

Levine, B., Nozick, L., Jones, D., 2009. Estimating an origin-destination table for us exports of waterborne containerised freight. Transportation Research Part E 45(4), 611-626.

Luo, M., Grigalunas, T.A., 2003. A spatial-economic multimodal transportation simulation model for us coastal container ports. Maritime Economics and Logistics 5(2), 158-178.

Meng, Q., Wang, S., 2011. Liner shipping service network design with empty container repositioning. Transportation Research Part E 47(5), 695-708.

Munizaga, M.A., Palma, C., 2012. Estimation of a disaggregate multimodal public transport origin–destination matrix from passive smartcard data from Santiago, Chile. Transportation Research Part C 24(9), 9-18.

Nagurney, A., Qiang, Q., 2008. An efficiency measure for dynamic networks modeled as evolutionary variational inequalities with application to the Internet and vulnerability analysis. Netnomics 9(1), 1-20.

Notteboom, T.E., Vernimmen, B., 2009. The effect of high fuel costs on liner service configuration in container shipping. Journal of Transport Geography 17(5), 325-337.

O'Kelly, M.E., 1987. A quadratic integer program for the location of interacting hub facilities. European Journal of Operational Research 32(3), 393-404.

PELINDO 2 2015, Annual Report 2014, Jakarta.

PELINDO 3 2015, Annual Report 2014, Surabaya.

Sheffi, Y., 1985. Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods. Englewood Cliffs, New Jersey: Prentice-Hall, Inc.

Silva, J.M.C.S., Tenreyro, S., 2005. The log of gravity. Review of Economics and Statistics 88(4), 641-658.

Sinha-Ray, P., Carter, J., Field, T., Marshall, J., Polak, J., Schumacher, K., Song, D., Woods, J., Zhang, J., 2003. Container World: Global agent-based modelling of the container transport

business. In Proceedings of 4th International Workshop on Agent-Based Simulation.

Smith, T., Barrett, M., Parker, S., Eoin, O., 2011. Description of GloTraM-2, a prototype model to calculate the future energy emissions and costs of the global shipping industry. Transport and Logistic Group, Delft University of Technology.

Takano, K., Arai, M., 2008. A genetic algorithm for the hub-and-spoke problem applied to containerized cargo transport. Journal of Marine Science and Technology 14(2), 256-274.

Talley, W.K., 2014. Maritime transport chains: Carrier, port and shipper choice effects. International Journal of Production Economics 151, 174-179.

Tavasszy, L., Minderhoud, M., Perrin, J.F., Notteboom, T., 2011. A strategic network choice model for global container flows: Specification, estimation and application. Journal of Transport Geography 19(6) 1163-1172.

Tran, N.K., 2011. Studying port selection on liner routes: An approach from logistics perspective. Research in Transportation Economics 32(1), 39-53.

Tran, N.K., Haasis, H.D., 2013. Literature survey of network optimization in container liner shipping. Flexible Services and Manufacturing Journal 27(2/3), 139-179.

Wang, K., Fu, X., Luo, M., 2015. Modeling the impacts of alternative emission trading schemes on international shipping. Transportation Research Part A 77, 35-49.

Wijnolst, N., Waals, F., Bello, F., Gendroneau, Y., Kempen, D.V., 2000. Malacca-Max 2: Container Shipping Network Economy. Delft: DUP.

World Bank 2016, Container port traffic (TEU: 20 foot equivalent units), World Bank, viewed 10 March 2016, <http://data.worldbank.org/indicator/IS.SHP.GOOD.TU>

Zhang, A., 1996. An analysis of fortress hubs in network-based markets. Journal of Transport Economics and Policy 30, 293-308.

Zheng, J., Yang, D., 2016. Hub-and-spoke network design for container shipping along the Yangtze River. Journal of Transport Geography 55, 51-57.

Zhuang, W., Fu, X., Luo, M., 2014. A game theory analysis of port specialization—Implications to the Chinese port industry. Maritime Policy and Management 41(3), 268-287.