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Location of regional and international hub ports in liner shipping

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Abstract

Purpose – This paper aims to investigate the location of regional and international hub ports in liner shipping by proposing a hierarchical hub location problem.

Design/methodology/approach – This paper develops a mixed-integer linear programming model for the authors' proposed problem. Numerical experiments based on a realistic Asia-Europe-Oceania liner shipping network are carried out to account for the effectiveness of this model.

Findings – The results show that one international hub port (i.e. Rotterdam) and one regional hub port (i.e. Zeebrugge) are opened in Europe. Two international hub ports (i.e. Sokhna and Salalah) are located in Western Asia, where no regional hub port is established. One international hub port (i.e. Colombo) and one regional hub port (i.e. Cochin) are opened in Southern Asia. One international hub port (i.e. Singapore) and one regional hub port (i.e. Jakarta) are opened in Southeastern Asia and Australia. Three international hub ports (i.e. Hong Kong, Shanghai and Yokohama) and two regional hub ports (i.e. Qingdao and Kwangyang) are opened in Eastern Asia.

Originality/value – This paper proposes a hierarchical hub location problem, in which the authors distinguish between regional and international hub ports in liner shipping. Moreover, scale economies in ship size are considered. Furthermore, the proposed problem introduces the main ports.

Keywords Liner shipping, Hierarchical hub location, Mixed-integer linear programming

Paper type Research paper

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1. Introduction

In liner shipping, containers are shipped by the liner shipping company on the regularly scheduled shipping service routes, i.e. liner shipping network. At the strategic decision level, the liner shipping network design problem has attracted much interest (Christiansen *et al.*, 2013; Meng *et al.*, 2014). The location of hub ports is a key problem that significantly impacts decision making in liner shipping network design. This is because large ships or mega-ships are usually deployed to serve hub ports, and small ships are used to serve feeder ports. Generally, any transshipment port can be regarded as a hub port. Globally, there are a great number of hub ports. Although transporting containers from feeder ports, there are some hub ports where the consolidated containers are not high enough to necessitate a mega-ship serving these hub ports. From the liner shipping company point of view, hub ports can be classified into different categories. This motivates us to investigate a hierarchical hub location problem, in which we distinguish between regional and international hub ports in liner shipping. Generally, the regional hub ports are used to consolidate containers from their associated feeder ports, and then these containers are transported to the nearby international hub ports called by large ships or mega-ships.

Furthermore, this paper introduces another port type, main port. In practice, there are some major ports, each of which has a high import or export container shipment demand. Although served by large ships (or mega-ships), these major ports cannot be used to transship containers for certain liner shipping companies, due to maritime cabotage legislations. For example, as the biggest port with respect to container throughput, Shanghai port is not a hub port of Maersk Line. Such a port is regarded as a main port in this paper. In addition, assuming that Shanghai port is a hub port of a liner shipping company, it is not suitable for this liner shipping company to set up another hub port (e.g. Ningbo port) close to Shanghai port, to benefit from scale economies. If the container demand associated with Ningbo port is quite high, it is an economical way for a large ship to call at both Shanghai port and Ningbo port. In this case, Ningbo port is regarded as a main port.

The conventional hub location problem is initiated by Goldman (1969), followed by O'Kelly (1986a, 1986b, 1987). In the conventional hub location problem, economies of scale are usually characterized by a fixed discount factor of transportation cost between two hub nodes (Alumur and Kara, 2008). A few traffic flow-based cost functions reflecting economies of scale are also suggested and investigated in O'Kelly and Bryan (1998), Horner and O'Kelly (2001), Racunicam and Wynter (2005), Sun and Zheng (2016). Moreover, in the conventional hub location problem (Alumur and Kara, 2008), all hub nodes are connected with each other, and the feeder nodes are connected to the hub nodes by direct links. All the traffic that any feeder node wants to send and/or receive travels on these links. These assumptions are later relaxed (O'Kelly and Miller, 1994; Campbell *et al.*, 2005a, 2005b; Alumur *et al.*, 2009).

Related to the hub location problem, many studies have been done on liner shipping network design, especially for hub-and-spoke (H&S) shipping network design. Fagerholt (1999, 2004), Sambracos *et al.* (2004) and Karlaftis *et al.* (2009) investigated a feeder shipping service route design problem with one hub port and many feeder ports. Imai *et al.* (2006, 2009) compared H&S strategy with multi-port-calling (MPC) strategy. Gelareh *et al.* (2010) proposed a competitive hub location problem for designing liner shipping networks. Meng and Wang (2011) presented a combined H&S and MPC shipping network design problem, as well as considering empty container repositioning. Zheng *et al.* (2014, 2015) discussed liner H&S shipping network design by proposing different multi-stage decomposition approaches. Later, Zheng and Yang (2016) investigated H&S network design for container shipping along the Yangtze River. For more studies on liner shipping network design, please refer to the review papers (Christiansen *et al.*, 2013; Meng *et al.*, 2014).

Yaman (2009) relaxed the conventional hub location problem by introducing two types of hub nodes, and proposed a hierarchical hub location model (denoted by Yaman's model). Later, Alumur *et al.* (2012) extended Yaman's model by considering multimodal transportation, as well as time-definite deliveries. Our study is a straightforward extension of Yaman (2009) by considering ship fleet deployment. In Yaman's model, two given transportation discount factors are used to describe scale economies for two different arc types (i.e. hub-central hub arc and central hub-central hub arc) in the hub level network. In liner shipping, the liner shipping company benefits from scale economies in ship size. Hence, economies of scale are determined by ship fleet deployment. It means that the transportation discount factors for different arcs cannot be given in advance. Moreover, we assume that scale economies can occur at any shipping service arc. In practice, ships with different sizes are deployed on different feeder shipping services. Hence, we consider ship fleet deployment in our hub location problem, and the transportation discount factor depends on the size of the deployed ships, similar to Gelareh and Pisinger (2011). In Gelareh and Pisinger (2011), each port is either a hub port or a feeder port. Moreover, the transportation discount factor is only considered in the hub-level network, and the ship size-dependent transportation discount factor is given between 0.6 and 0.8 in Gelareh and Pisinger (2011). In this paper, the ship operating costs for different ship types are used to calibrate the ship size-dependent transportation discount factors, which are considered for all shipping service arcs in our hierarchical hub location problem.

The rest of this paper is organized as follows. Section 2 gives notation, assumptions and problem description. Section 3 develops a mixed-integer linear programming model for our hierarchical hub location problem. Section 4 carries out the numerical experiments based on an Asia-Europe-Oceania liner shipping network. Finally, a summary is given in Section 5.

2. Notation, assumptions and problem description

2.1 Hub ports, main ports and feeder ports

Let $\mathcal{P}$ denote a set of ports. These ports are further classified into four subsets: international hub ports denoted by $\mathcal{P}^1$, regional hub ports denoted by $\mathcal{P}^2$, main ports denoted by $\mathcal{P}^3$ and feeder ports denoted by $\mathcal{P}^4$. This paper aims to distinguish among these four subsets. To simplify our problem, we assume that the regional hub ports are only used to consolidate containers from their associated feeder ports, and then these containers are transported to the nearby international hub ports. Let h_1 denote the number of international hub ports and h_2 denote the number of regional hub ports to be opened. As mentioned before, the container shipment demands are quite high at main ports. Different from international hub ports, main ports do not serve any regional hub port and feeder port. To determine the set of main ports, we assume that the import or export container demand associated with any main port is larger than a critical value, denoted by m_c. Figure 1 shows a simple hierarchical hub location network with four port types.

Let $\mathcal{W} = \{(o,d) | o \in \mathcal{P}, d \in \mathcal{P}\}$ be a set of origin-destination (OD) port pairs, and let D_{od} represent the weekly number of containers to be transported for the OD port pair $(o,d) \in \mathcal{W}$ over a seasonal planning horizon. Following Yaman's model, container routing can be determined when our hierarchical hub location problem is solved.

2.2 Cost structure

Different from Yaman's model, we do not consider the fixed transportation discount factors for describing scale economies. Evidently, the liner shipping company can benefit from scale economies in ship size. As shown in Sun and Zheng (2016), scale economies in liner shipping can be mainly described by the ship chartering cost and bunker cost with respect to ship size. Let V denote a set of ship types available for the liner shipping company. For cost structure in our

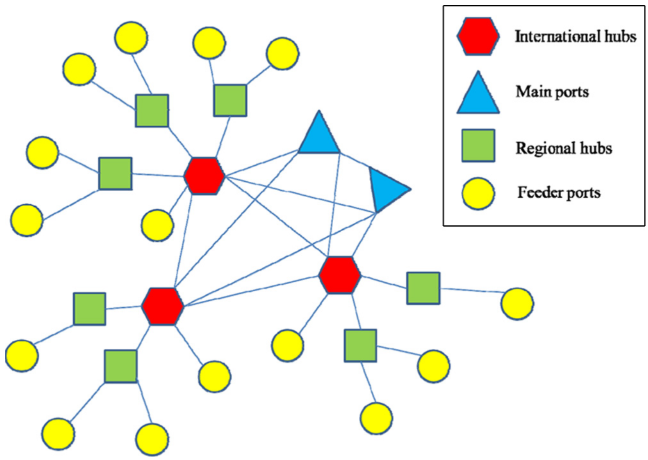


Figure 1.
A simple hierarchical hub location network with four port types

hierarchical hub location problem, this paper considers container handling cost at each port and the transportation cost at sea, where ship type-dependent transportation discount factor is considered. Let c_i^{handle} denote the cost for loading or discharging one container at port i. Let α_v denote the average transportation cost for ship type $v \in \mathcal{V}$ when transporting one twenty-foot equivalent unit (TEU) container for one nautical mile. Let Dis_{ij} represent the distance between port i and port j.

3. Model

The decision variables for our hierarchical hub location problem can be defined as follows:

z_{ijl} = A binary variable which takes value 1 if feeder port i ($\forall i \in \mathcal{P}$) is allocated to regional hub j ($\forall j \in \mathcal{P}^2 \cup \mathcal{P}^3$) allocated to international hub port l ($\forall l \in \mathcal{P}^1 \cup \mathcal{P}^3$), and 0 otherwise;

z_{jjl} = A binary variable which takes value 1 if regional hub j ($\forall j \in \mathcal{P}^2 \cup \mathcal{P}^3$) is allocated to international hub port l ($\forall l \in \mathcal{P}^1 \cup \mathcal{P}^3$), and 0 otherwise;

z_{lll} = A binary variable which takes value 1 if port l ($\forall l \in \mathcal{P}^1 \cup \mathcal{P}^3$) is an international hub port, and 0 otherwise;

y_{ij}^v = A binary variable which takes value 1 if shipping service arc (i, j) is served by type v ship, and 0 otherwise;

$\bar{x}_{ij}^1$ = Number of weekly containers transported on shipping service arc (i, j), where port i is a feeder port and port j is a regional or international hub port;

$\hat{x}_{ij}^1$ = Number of weekly containers transported on shipping service arc (j, i), where port i is a feeder port and port j is a regional or international hub port;

$\bar{x}_{ij}^2$ = Number of weekly containers transported on shipping service arc (i, j), where port i is a regional hub port and port j is an international hub port;

$\hat{x}_{ij}^2$ = Number of weekly containers transported on shipping service arc (j, i), where port i is a regional hub port and port j is an international hub port;

x_{ij}^3 = Number of weekly containers transported on shipping service arc (i, j), where port i and port j are either international hub ports or main ports;

g_{kl}^i = Number of weekly containers originated from i and transported from international hub port (or main port) k to international hub port (or main port) l;

$\bar{f}_{jl}^i$ = Number of weekly containers originated from i and transported from regional hub port j to international hub port l; and

$\hat{f}^i_{jl}$ = Number of weekly containers destined to i and transported from international hub port l to regional hub port j.

For any particular arc (i, j), its associated container flow x_{ij} can be described as follows:

$$x_{ij} = \bar{x}^1_{ij} + \hat{x}^1_{ji} + \bar{x}^2_{ij} + \hat{x}^2_{ji} + x^3_{ij} \tag{1}$$

Let $c_{ij}(\cdot)$ denote the cost for transporting x_{ij} containers between port i and port j , served by type v ship, then:

$$c_{ij}(x_{ij}, y^v_{ij}) = (c^{\text{handle}}_i + c^{\text{handle}}_j) \times x_{ij} + \alpha_v \times Dis_{ij} \times \text{Cap}_v \times y^v_{ij} \tag{2}$$

where Cap_v is the capacity of a ship with type v. The transportation discount factors for different ship types (i.e. α_v) can be calibrated by using the cost function in Sun and Zheng (2016). Similar to a piece-wise linear function approximating nonlinear cost function in O'Kelly and Bryan (1998), our transportation discount factor-based cost function is equivalent to traffic flow-based nonlinear cost function for describing scale economies.

Based on sets of candidate international and regional hub ports (denoted by $\mathcal{P}^1$ and $\mathcal{P}^2$), we assume $\mathcal{P}^1 \subset \mathcal{P}^2$ to simplify our model formulation. Moreover, any candidate regional hub port, whose associated container demand is larger than m_c, is not regarded as a main port in this paper. Namely, $\mathcal{P}^2 \cap \mathcal{P}^3 = \Phi$. The proposed hierarchical hub location problem can be formulated by the following mixed-integer linear programming model:

$$\begin{aligned} \min \sum_{v \in V} \sum_{i \in \mathcal{P} \backslash \mathcal{P}^3} \sum_{j \in \mathcal{P}^2} \left[c_{ij}(\bar{x}^1_{ij}, y^v_{ij}) + c_{ij}(\hat{x}^1_{ij}, y^v_{ij}) \right] + \sum_{v \in V} \sum_{i \in \mathcal{P}^2} \sum_{j \in \mathcal{P}^1} \left[c_{ij}(\bar{x}^2_{ij}, y^v_{ij}) + c_{ij}(\hat{x}^2_{ij}, y^v_{ji}) \right] \\ + \sum_{v \in V} \sum_{i \in \mathcal{P}^1 \cup \mathcal{P}^3} \sum_{j \in \mathcal{P}^1 \cup \mathcal{P}^3} c_{ij}(x^3_{ij}, y^v_{ij}) \end{aligned} \tag{3}$$

subject to:

$$\sum_{j \in \mathcal{P}^2} \sum_{l \in \mathcal{P}^1} z_{ijl} = 1, \forall i \in \mathcal{P} \backslash \mathcal{P}^3; \tag{4}$$

$$z_{ijl} \leq z_{jjl}, \forall i \in \mathcal{P} \backslash \mathcal{P}^3, j \in \mathcal{P}^2 \backslash \{i\}, l \in \mathcal{P}^1; \tag{5}$$

$$\sum_{j \in \mathcal{P}^2} z_{ijl} \leq z_{lll}, \forall i \in \mathcal{P}^2, l \in \mathcal{P}^1 \backslash \{i\}; \tag{6}$$

$$\sum_{l \in \mathcal{P}^1} z_{lll} = h_1; \tag{7}$$

$$\sum_{j \in \mathcal{P}^2} \sum_{l \in \mathcal{P}^1} z_{jjl} = h_1 + h_2; \tag{8}$$

$$\bar{f}^i_{jl} \geq \sum_{m \in \mathcal{P} \backslash \{j\}} D_{im} \times (z_{ijl} - z_{mjl}), \forall i \in \mathcal{P} \backslash \mathcal{P}^3, j \in \mathcal{P}^2, l \in \mathcal{P}^1 \backslash \{j\}; \tag{9}$$

$$\hat{f}^i_{jl} \geq \sum_{m \in \mathcal{P} \backslash \{j\}} D_{mi} \times (z_{ijl} - z_{mjl}), \forall i \in \mathcal{P} \backslash \mathcal{P}^3, j \in \mathcal{P}^2, l \in \mathcal{P}^1 \backslash \{j\}; \tag{10}$$

$$\sum_{k\in\mathcal{P}^1\cup\mathcal{P}^3\backslash\{l\}} g^i_{lk} - \sum_{k\in\mathcal{P}^1\cup\mathcal{P}^3\backslash\{l\}} g^i_{kl} = \sum_{(i,m)\in W} D_{im} \sum_{j\in\mathcal{P}^2\cup\mathcal{P}^3} (z_{ijl} - z_{mjl}), \forall i \in \mathcal{P}, l \in \mathcal{P}^1 \cup \mathcal{P}^3; \quad (11)$$

$$z_{ljl} = 0, \forall j \in \mathcal{P}^2, l \in \mathcal{P}^1\backslash\{j\}; \quad (12)$$

$$z_{lll} = 1, \forall l \in \mathcal{P}^3; \quad (13)$$

$$z_{ijl} = 0, \forall i,j \in \mathcal{P}, l \in \mathcal{P}^3\backslash\{i\}; \quad (14)$$

$$z_{jil} = 0, \forall i,j \in \mathcal{P}, l \in \mathcal{P}^3\backslash\{i\}; \quad (15)$$

$$z_{jli} = 0, \forall i,j \in \mathcal{P}, l \in \mathcal{P}^3\backslash\{i\}; \quad (16)$$

$$z_{ilj} = 0, \forall i,j \in \mathcal{P}, l \in \mathcal{P}^3\backslash\{i\}; \quad (17)$$

$$z_{lji} = 0, \forall i,j \in \mathcal{P}, l \in \mathcal{P}^3\backslash\{i\}; \quad (18)$$

$$z_{lij} = 0, \forall i,j \in \mathcal{P}, l \in \mathcal{P}^3\backslash\{i\}; \quad (19)$$

$$\sum_{v\in V} y^v_{ij} \leq 1, \forall i \neq j \in \mathcal{P}; \quad (20)$$

$$\sum_{j\in\mathcal{P}\backslash\{i\}} \sum_{v\in V} (y^v_{ij} + y^v_{ji}) \geq 1, \forall i \in \mathcal{P}; \quad (21)$$

$$\bar{x}^1_{ij} \leq \sum_{v\in V} \mathrm{Cap}_v \times y^v_{ij}, \forall i \in \mathcal{P}\backslash\mathcal{P}^3, j \in \mathcal{P}^2; \quad (22)$$

$$\hat{x}^1_{ji} \leq \sum_{v\in V} \mathrm{Cap}_v \times y^v_{ji}, \forall i \in \mathcal{P}\backslash\mathcal{P}^3, j \in \mathcal{P}^2; \quad (23)$$

$$\bar{x}^2_{ij} \leq \sum_{v\in V} \mathrm{Cap}_v \times y^v_{ij}, \forall i \in \mathcal{P}^2, j \in \mathcal{P}^1; \quad (24)$$

$$\hat{x}^2_{ij} \leq \sum_{v\in V} \mathrm{Cap}_v \times y^v_{ji}, \forall i \in \mathcal{P}^2, j \in \mathcal{P}^1; \quad (25)$$

$$x^3_{ij} \leq \sum_{v\in V} \mathrm{Cap}_v \times y^v_{ij}, \forall i \neq j \in \mathcal{P}^1 \cup \mathcal{P}^3; \quad (26)$$

$$\bar{x}^1_{ij} - \sum_{(i,m)\in W} D_{im} \sum_{l\in\mathcal{P}^1} z_{ijl} = 0, \forall i \in \mathcal{P}\backslash\mathcal{P}^3, j \in \mathcal{P}^2\backslash\{i\}; \quad (27)$$

$$\hat{x}^1_{ij} - \sum_{(m,i)\in W} D_{mi} \sum_{l\in\mathcal{P}^1} z_{ijl} = 0, \forall i \in \mathcal{P}\backslash\mathcal{P}^3, j \in \mathcal{P}^2\backslash\{i\}; \quad (28)$$

$$x^3_{kl} - \sum_{i\in\mathcal{P}} g^i_{kl} = 0, \forall k \neq l \in \mathcal{P}^1 \cup \mathcal{P}^3; \quad (29)$$

$$\bar{x}^2_{jl} - \sum_{i \in \mathcal{P} \setminus \mathcal{P}^3} \bar{f}^i_{jl} = 0, \forall j \in \mathcal{P}^2, l \in \mathcal{P}^1 \setminus \{j\}; \tag{30}$$

$$\hat{x}^2_{jl} - \sum_{i \in \mathcal{P} \setminus \mathcal{P}^3} \hat{f}^i_{jl} = 0, \forall j \in \mathcal{P}^2, l \in \mathcal{P}^1 \setminus \{j\}; \tag{31}$$

$$z_{ijl} \in \{0, 1\}, \forall i \in \mathcal{P}, j \in \mathcal{P}^2 \cup \mathcal{P}^3, l \in \mathcal{P}^1 \cup \mathcal{P}^3; \tag{32}$$

$$\hat{f}^i_{jl} \geq 0, \forall i \in \mathcal{P}, j \in \mathcal{P}^2, l \in \mathcal{P}^1; \tag{33}$$

$$\bar{f}^i_{jl} \geq 0, \forall i \in \mathcal{P}, j \in \mathcal{P}^2, l \in \mathcal{P}^1; \tag{34}$$

$$g^i_{kl} \geq 0, \forall i \in \mathcal{P}, k, l \in \mathcal{P}^1 \cup \mathcal{P}^3; \tag{35}$$

$$y^v_{ij} \in \{0, 1\}, \forall i, j \in \mathcal{P}, v \in \mathcal{V}; \tag{36}$$

$$\bar{x}^1_{ij}, \hat{x}^1_{ij}, \bar{x}^2_{ij}, \hat{x}^2_{ij}, x^3_{ij} \geq 0, \forall i, j \in \mathcal{P}. \tag{37}$$

The objective function (3) aims to minimize the total cost, including the costs on three different types of shipping service arcs. Constraints (4) show that each port is allocated to a regional hub port and an international hub port. It means that single allocation is considered in this paper. Constraints (5) describe that if port i is allocated to regional hub port j and international hub port l, then regional hub port j should be allocated to international hub port l. Constraints (6) enforce that port i is allocated to international hub port l, then port $l$must be an international hub port. Constraints (7) and (8) show that the number of international hub ports and regional hub ports to be opened is fixed to h_1 and h_2, respectively. Constraints (9) and (10) are used to calculate the container flows between the regional hub port and its associated international hub port. Constraints (11) are flow conservation constraints for transporting containers among the international hub ports. Constraints (12) are redundant, but they can strengthen our model. Constraints (13)-(19) are used to define main ports, which do not serve any port. Constraints (20) show that any shipping service arc cannot be served by ships with different types. Constraints (21) enforce that each port is served by at least one ship type. Constraints (22)-(26) are capacity constraints for different arc types. Constraints (27)-(31) are used to calculate the container flows on different shipping service arcs. Constraints (32)-(37) define the domain of decision variables.

4. Numerical experiments

In this section, we provide the numerical results for a realistic Asia-Europe-Oceania shipping service network with 46 ports. The OD container demand is derived from one liner shipping company with some modifications due to commercial confidentiality. For heterogeneous ships, we consider four different ship types, and the ship type-related parameters are shown in Table I. To describe scale economies in ship size, Sun and Zheng (2016) calibrated the ship

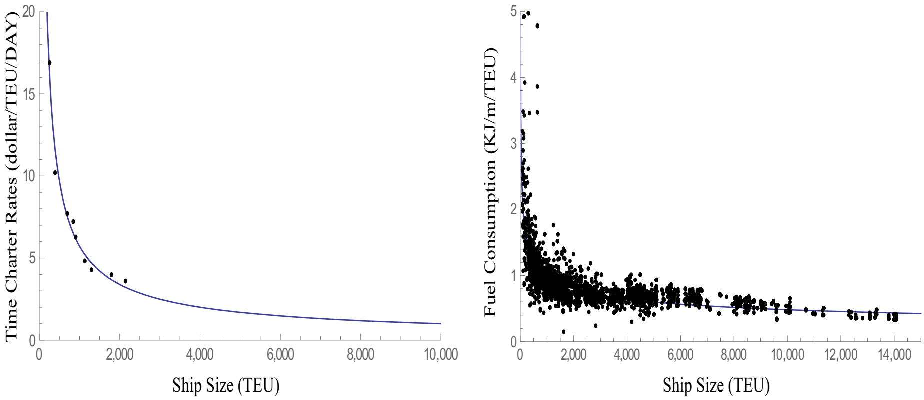
Table I.
Ship type-related parameters

Ship type	0	1	2	3
Ship capacity (TEUs)	1,500	3,000	5,000	10,000
α_v (USD per n mile)	0.1375	0.1105	0.0941	0.0757

chartering cost and bunker cost with respect to ship capacity, as shown in Figure 2. This paper mainly considers bunker cost, which is a major component of ship operating cost. By making use of the bunker cost function in Figure 2, the ship type-dependent transportation discount factor is calibrated, as shown in Table I. The proposed model is solved by using CPLEX.

According to the geographic location, 11 ports, i.e. Rotterdam, Thamesport, Sokhna, Salalah, Colombo, Singapore, Hong Kong, Kaohsiung, Shanghai, Pusan and Yokohama, are selected as candidate international hub ports, all of which are regarded as a portion of candidate regional hub ports. At each region, we select extra one or more ports as candidate regional hub ports. Including the 11 candidate international hub ports, Bremerhaven, Zeebrugge, Karachi, Cochin, Chennai, Jakarta, Yantian, Qingdao, Kwangyang, Dalian, Tokyo and Nagoya are selected as candidate regional hub ports. In our case study, the number of international hub ports and regional hub ports to be opened is fixed to $h_1 = 8$ and $h_2 = 5$, respectively. As mentioned before, the set of main ports depends on the value of m_c. Evidently, there are too many main ports in the international hub level network if m_c is small, and the benefit of scale economies can be reduced. If m_c is very large, the number of main ports is limited. This paper investigates the impacts of different values of m_c on our problem.

Table II reports the location of regional and international hub ports, as well as feeder allocation, for $m_c = 500$. Eleven main ports are also listed in Table II. As shown in Table II, Rotterdam, Sokhna, Salalah, Colombo, Singapore, Hong Kong, Shanghai and Yokohama are finally opened as international hub ports. Zeebrugge, Cochin, Jakarta, Qingdao and Kwangyang are opened as regional hub ports. Sydney, Antwerp, Hamburg, Aqabah, Port Klang, Ningbo, Jeddah, Xiamen, Chiwan, Jebel Ali and Southampton are regarded as main ports. All the rest of the ports are feeder ports. Generally, feeder ports are allocated to their nearby regional (or international) hub ports, which are further allocated to their nearby international hub ports. There is one international hub port (i.e. Rotterdam) and one regional hub port (i.e. Zeebrugge) to be opened in Europe. Two international hub ports (i.e. Sokhna and Salalah) are located in Western Asia, where no regional hub port is established. One international hub port (i.e. Colombo) and one regional hub port (i.e. Cochin) are opened in Southern Asia. One international hub port (i.e. Singapore) and one regional hub port (i.e. Jakarta) are opened in Southeastern Asia and Australia. Three international hub ports



Source: Sun and Zheng (2016)

Figure 2. Economies of scale for charter rates (left) and fuel consumption (right)

Table II.
Location of regional and international hub ports and feeder allocation for $m_c = 500$

International hubs	Regional hubs	Feeder ports
Rotterdam	Zeebrugge	Le Havre, Thamesport
	–	Bremerhaven
Sokhna	–	–
Salalah	–	Nhava Sheva
Colombo	Cochin	Chennai, Karachi
	–	Chittagong
Singapore	Jakarta	Brisbane, Fremantle, Adelaide
	–	Melbourne, Laem Chabang, Ho Chi Minh
Hong Kong	–	Manila, Yantian, Kaohsiung
Shanghai	Qingdao	Dalian, Xingang
	Kwangyang	Pusan
Yokohama	–	Tokyo, Nagoya, Kobe
Main ports	Sydeny, Antwerp, Hamburg, Aqabah, Port Klang, Ningbo, Jeddah, Xiamen, Chiwan, Jebel Ali, Southampton	

(i.e. Hong Kong, Shanghai and Yokohama) and two regional hub ports (i.e. Qingdao and Kwangyang) are opened in Eastern Asia.

As an international hub port, Sokhna does not serve any regional hub port and feeder port, similar to a main port. This is because there are only two other ports (i.e. Aqabah and Jeddah) near Sokhna, and both of these two ports are main ports in our case study. As regional hub ports, Zeebrugge, Cochin and Jakarta are allocated to Rotterdam, Colombo and Singapore, respectively. The other two regional hub ports (i.e. Qingdao and Kwangyang) are allocated to Shanghai. Some feeder ports (e.g. Bremerhaven, Nhava Sheva and Chittagong) are directly allocated to the international hub ports, without connecting with any regional hub port. Any other feeder port (e.g. Le Havre, Thamesport, Chennai and Karachi) is allocated to a single regional hub port, which is further allocated to an international hub port.

Next, we consider different values of m_c by changing from 100 to 900. Table III shows the frequency of ports to be opened as regional and international hub ports. Evidently, Rotterdam, Sokhna, Salalah, Colombo, Singapore, Hong Kong, Shanghai and Yokohama are always chosen as international hub ports for different values of m_c. It seems that m_c does not have an impact on the location of international hub ports. From Table III, we can find that the location of regional hub ports can be slightly impacted by m_c. All opened regional hub ports and their chosen frequency are listed in Table III. In Tables IV and V, we typically show the location of ports with different types for $m_c = 200$ and $m_c = 900$, respectively. We can find that it has an obvious impact on our problem, especially for feeder allocation, by introducing

Table III.
Frequency of ports to be opened as regional and international hub ports

International hubs	Frequency	Regional hubs	Frequency
Rotterdam	1	Kwangyang	1
Sokhna	1	Cochin	1
Salalah	1	Jakarta	0.888888889
Colombo	1	Zeebrugge	0.777777778
Singapore	1	Qingdao	0.666666667
Hong Kong	1	Yantian	0.444444444
Shanghai	1	Chennai	0.111111111
Yokohama	1	Tokyo	0.111111111

International hubs	Regional hubs	Feeder ports
Rotterdam	Zeebrugge	Le Havre, Thamesport
	–	Bremerhaven
Sokhna	–	–
Salalah	–	–
Colombo	Cochin	Chennai, Karachi
Singapore	Jakarta	Brisbane, Fremantle
	–	Ho Chi Minh
Hong Kong	–	Manila, Yantian, Kaohsiung
Shanghai	Qingdao	Dalian, Xingang
	Kwangyang	Pusan
Yokohama	–	Tokyo, Nagoya, Kobe
Main ports	Adelaide, Melbourne, Sydeny, Chittagong, Antwerp, Hamburg, Nhava Sheva, Aqabah, Port Klang, Ningbo, Jeddah, Xiamen, Chiwan, Leam Chabang, Jebel Ali, Southampton	

Table IV. Location of regional and international hub ports and feeder allocation for $m_c = 200$

International hubs	Regional hubs	Feeder ports
Rotterdam	–	Zeebrugge, Le Havre, Thamesport, Bremerhaven, Antwerp, Hamburg
Sokhna	–	Aqabah
Salalah	–	Jebel Ali
Colombo	Cochin	Chennai, Karachi, Nhava Sheva
	–	Chittagong
Singapore	Jakarta	Brisbane, Fremantle, Adelaide, Melbourne, Sydeny
	–	Port Klang, Laem Chabang, Ho Chi Minh
Hong Kong	Yantian	Kaohsiung
	–	Manila
Shanghai	Qingdao	Dalian, Xingang
	Kwangyang	Pusan
Yokohama	–	Tokyo, Nagoya, Kobe
Main ports	Ningbo, Jeddah, Xiamen, Chiwan, Southampton	

Table V. Location of regional and international hub ports and feeder allocation for $m_c = 900$

main ports. This is mainly because container routing process can be impacted by introducing main ports.

5. Summary

This paper has proposed a hierarchical hub location problem in liner shipping by considering four types of ports, i.e. international hub ports, regional hub ports, main ports and feeder ports. It develops a mixed-integer linear programming model for the proposed problem. Different from the previous hierarchical hub location problem, we consider that the ship size dependent transportation discount factors for describing scale economies. Moreover, main ports are introduced in our hierarchical hub location problem. According to Table III, one can find that it has a slight impact on location of regional hubs, by introducing main ports, which has an obvious impact on feeder allocation, as shown in Tables II-V.

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