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Hub-and-spoke network design for container shipping along the Yangtze River

Abstract:

Increasingly large, high-tonnage containerships are becoming a common sight on the Yangtze River, and the shipping network is being transformed accordingly. This paper reports the design of a hub-and-spoke network for a shipping company that is consistent with the characteristics of the Yangtze River. We first explore the economies of scale for container shipping by applying empirical data. Next, we propose a mixed-integer linear programming model, factoring in ship-operating and container-handling costs. We then conduct a numerical experiment and test the effectiveness of the model, and finally discuss the implications of hub-and-spoke shipping network design. The findings reported herein support the trends toward cargo concentration and port regionalization along the Yangtze River.

Keywords: Inland river shipping; Hub-and-spoke network design; Mixed-integer linear programming; Cargo concentration and port regionalization

1. Introduction

The shipping industry has experienced surprising growth in the size of its largest containerships in recent years. For example, the average size of ocean containerships increased from 1500 TEUs (twenty-foot equivalent units) in 1996 to almost 3400 TEUs in 2014. The world's largest container shipping company, the Maersk Line, ordered 20 mega containerships (i.e., 18,000-TEU ships) in 2011. This growth in size is the result of pursuing economies of scale, which are rarely investigated in river shipping, as the ships concerned are relatively small. In China, however, since river-ship standardization in 2001, river containerships have grown significantly in size due to economies of scale, although they remain bound by physical limitations such as a constrained draft. Figure 1 presents the change in size from 2001 to 2012, a period in which the average ship size nearly tripled.

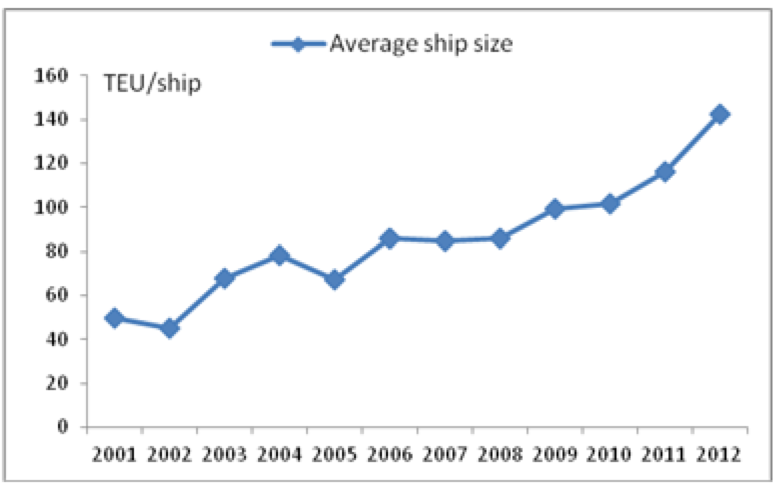

Figure 1 Annual transition in the average size of Chinese river ships

Data source: http://www.jttj.gov.cn/gongbao.asp (in Chinese)

Figure 2 shows the ports along the Yangtze River, which can be divided into three main regions: downstream, from Shanghai to Hukou (near Jiujiang); midstream, from Hukou to Yichang; and upstream, from Yichang to Yibin (near Luzhou). The river depth is more than 12 meters between Shanghai and Nanjing, around 6 meters between Nanjing and Anqing, 4.5 meters between Anqing and Wuhan, 3.7 meters between Wuhan and

Chenglingji, and less than 3 meters between Chongqing and Yibin. Different river depths admit differently sized ships.

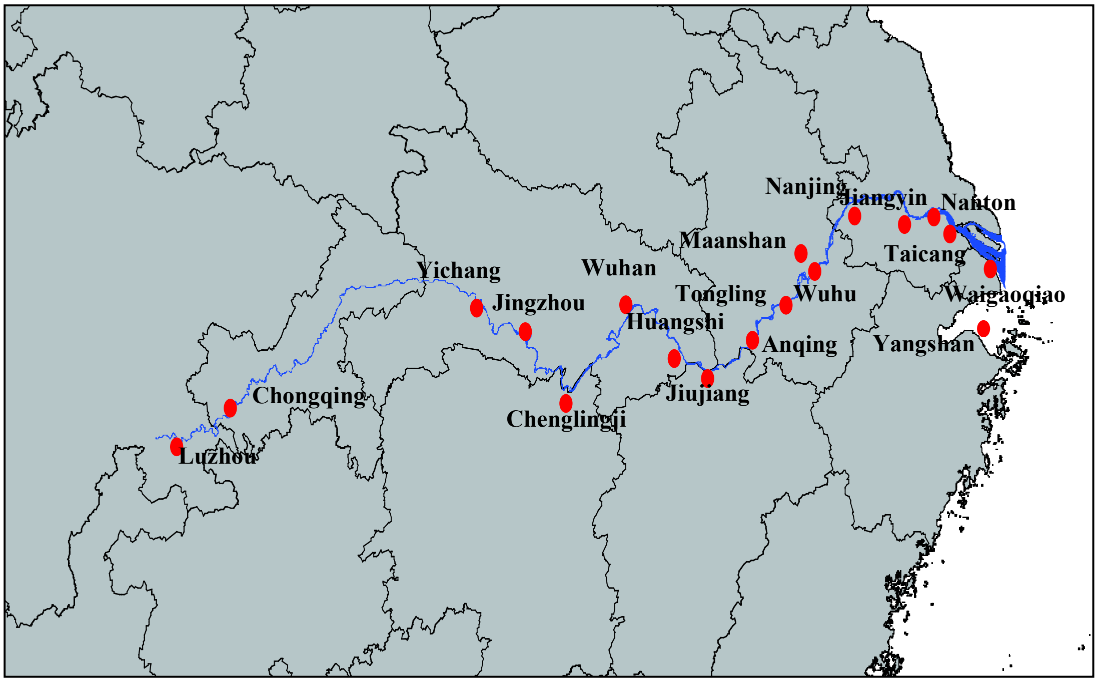

Figure 2 Ports along the Yangtze River

Two classes of ships can sail along the Yangtze River: river ships and river-sea ships. We assume that river ships cannot call at sea ports, whereas river-sea ships can call at both river ports and sea ports. Although the Yangtze River can accommodate both types of ships, river-sea ships rarely sail upstream because of their higher cost. Containers and bulk cargoes are the two most important types of cargo shipped along the river. In this paper, we consider only liner shipping companies. Due to an import-export imbalance, these companies have to transport both laden and empty containers, but we examine the former alone.

The Yangtze River is sufficiently deep downstream, particularly between Nanjing and Shanghai, for sea-going ships to sail directly to certain Asian destinations such as the Korean city of Busan. Shanghai features two port zones, namely, Waigaoqiao and Yangshan, both of which currently serve as regional transshipment hub ports to overseas ports. Waigaoqiao is a river port located at the mouth of the Yangtze River, meaning that river ships can access it directly. Yangshan, in contrast, is a sea port approximately 32 kilometers from the river's mouth. It is the largest transshipment port in China, and connects numerous liner shipping services. River-sea ships can generally deliver containers from such large river ports as Nanjing, Taicang and Waigaoqiao to Yangshan. The port's fourth-stage terminals will be completed in 2017 with the aim of attracting greater container throughput from the Yangtze River. The Shanghai Port Group has invested in several ports along the river, including Taicang, Nanjing and Wuhan, in the expectation that they will become part of the transshipment hub of Yangshan Port.

After 30 years of rapid development, the Chinese economy has entered a "new normal" stage, and is facing multiple challenges. The Chinese government has proposed a structural adjustment process whose aim is to prevent the economic growth rate from potentially falling into decline. In the port industry, external demand has weakened, with the port throughput growth rate along the Yangtze River in Jiangsu province declining from 19.7% in 2010 to 5.6% in 2014 (Statistics Bureau of Jiangsu Province, http://www.jssb.gov.cn/tjxxgk/tjsj/ndsj/). The likely result is ever-fiercer competition among the region's ports. To avoid possible disorder and cut-throat competition among those ports, and to maximize their efficiency and effectiveness, the regional government of is actively seeking solutions for the sustainable development of the port system from think tanks and academia.

This paper is based on a consulting project designed to help the regional government better understand the possible trends in port development along the Yangtze River, particularly in Jiangsu province. The aim of the paper was to answer the government's call for solutions by exploring economies of scale for container shipping on the river and designing an efficient hub-and-spoke shipping network based on a proposed mixed-integer linear programming model. Government policy has played a strong role in shaping the pattern of port development in China. For example, Wang and Ducruet (2012) argued that strong support from the central government for Shanghai's globalization favored Yangshan new port's transformation into a container transshipment center over that of neighboring ports (e.g., Ningbo). Once the outcomes of the paper have been adopted by the regional government, many favorable results are likely to follow, such as investments, preferential policies, subsidies and so on, which will in turn reshape the layout of the port system and influence the pattern of port development along the Yangtze River. Note that this paper does not consider the side effects of possible activities by regional governments.

The paper's primary focus is the domestic shipping service network along the Yangtze River. Following Konings et al. (2013), we construct a hub-and-spoke network to model the river's shipping activities. Different from sea or ocean shipping, in river shipping, (i) river ships cannot call at sea ports, (ii) the shipping cost varies by direction and (iii) inland demand fluctuates so widely that a weekly service may fall short. The first two factors can be easily addressed by choosing realistic parameters. For the third, a decision variable is introduced to the model, assigning a corresponding number of ship fleets with particular service frequencies in accordance with the level of demand during a given shipping service period. In practice, liner shipping companies alter their shipping service network every three to six months to accommodate seasonal container demand fluctuation.

2. Literature Review

Sea/ocean shipping has attracted considerable attention in the past decade, with research topics ranging from scheduling and fleet deployment to route design, empty-container repositioning and speed optimization, among others. Details can be found in the review papers of Ronen (1983, 1993), Christiansen et al. (2004) and Meng et al. (2014). McLellan (1997), Gilman (1999), Cullinane and Khanna (1999, 2000) and Imai et al. (2006) investigated the economies of scale of large containerships, and economies of scale have also been explored in the context of inland shipping. For example, Charles (2008) discussed those of dry bulk cargoes and containers in the Rhône-Saône corridor. More recently, Konings et al. (2013) developed a hub-and-spoke network to benefit from economies of scale and to improve container barge transport in the hinterland of Rotterdam. Racunicam and Wynter (2005) and Meng and Wang (2011b) investigated the economies of scale in inland intermodal transportation. Economies of scale are also often discussed in relation to hub-location problems (Alumur and Kara, 2008), which are a major factor in hub-and-spoke network design. Cargo routing is rarely considered in traditional hub-and-spoke network design, although more recently cargo routing and fleet deployment have been integrated in the formulation of hub-and-spoke network design (Meng and Wang, 2011a; Zheng et al., 2014, 2015).

Compared with sea/ocean shipping, river-shipping research is limited. Marbury (1979) investigated the optimal river speed for minimizing fuel consumption. Rissoan (1994), Konings and Ludema (2000), and Charles (2008) discussed the competitiveness of sea-river shipping. A few studies have investigated river shipping and port networks. For example, Wang and Slack (2000) examined the development of the South China container port system, focusing on the interplay between Hong Kong and other ports in the Pearl River Delta. Notteboom and Konings (2004) explored river ports on the Rhine and built an analogical model showing how a container barge network develops over time. Konings (2007) evaluated the improvement realized from reorganizing the container barge service in the Rotterdam hinterland. Frémont and Franc (2010), Wilmsmeier et al. (2011) and Caris et al. (2014) discussed intermodal freight transportation, including inland shipping. In addition, researchers have investigated emissions (Liao et al., 2011), the effects of climate change (Jonkeren et al., 2011), operational energy efficiency (Sun et al., 2013) and environmental policies (Kaiser et al., 2013) in river shipping.

This paper adds to the literature on river shipping services and port geography. Jia et al. (2006) analyzed upstream container transportation to determine the preference for water or land transportation. Luo and Sun (2006) and Zhong and Cheng (2008) investigated a transportation scheme for certain ports. More recently, Yang et al. (2014) proposed an integer programming model to optimize route selection. Their model incorporates fleet deployment, port-calling frequency and transshipment operations, but their findings rely on several unrealistic assumptions. For example, they assume that ships spend the same amount of time at every port regardless of how many containers are handled and formulate route costs by Bureau of Public Roads-type functions (see Kim, 1990), which hinders the identification of loading, discharging and transshipment costs. With regard to the port-geography literature, Notteboom and Rodrigue (2005) proposed a port-system evolution model that subsequent researchers applied to study the development of the shipping system on the Yangtze River (e.g., Veenstra et al., 2008; Notteboom, 2007; Rimmer and Comtois, 2009; Wang and Ducruet, 2012). Veenstra and Notteboom (2011) also investigated structural changes on the river.

This paper builds on the previous literature and makes three new contributions. First, we apply empirical data to explore economies of scale and provide evidence of a concave cost function on the Yangtze River. Second, we implement mixed-integer linear programming to optimize the river's shipping system as a hub-and-spoke network, taking into account the particular characteristics of river shipping. Third, we make the preliminary attempt to enrich the study of port geography from the perspective of shipping network design in the river shipping arena.

3. Economies of Scale

Because it is difficult to determine the average shipping cost per TEU for different ship sizes, we explore the shuttle shipping services between each port pair to reveal the correlation between the average cost and the number of containers shipped annually (annual containers shipped).

The data presented in Table 1 and plotted in Figure 3 are collected from the *Report on Yangtze River Shipping Development* released by the Yangtze River Aviation Management Bureau (2011, 2012).[1] The inset in Figure 3 is the log-log plot. Let $c(x)$ and x denote the average shipping cost per TEU and annual containers shipped, respectively. As x increases, $c(x)$ decreases. Moreover, it manifests a power-law relation, i.e., $c(x) \sim x^{-\gamma}$, where γ ($0 < \gamma < 1$) is the exponent. γ is approximately 0.9, i.e., the slope of the line. Exponent γ represents economies of scale, implying that scale economies are constant on different segments of the Yangtze River.

[1] Between Yangshan and Huangshi, Jingzhou, Anqing, Tongling, Wuhu, Maanshan, Zhenjiang, Yangzhou, Taizhou, Jiangyin and Nantong.

Table 1 Annual containers shipped between Yangshan and 11 other ports and their average cost

Ports	Annual containers shipped (TEUs)	Average cost per TEU (RMB)
Jingzhou	19411	633
Huangshi	15268	903
Anqing	19567	665
Tongling	21749	581
Wuhu	23265	531
Maanshan	24951	483
Zhenjiang	36159	344
Yangzhou	38907	309
Taizhou	40758	288
Jiangyin	42701	268
Nantong	43550	260

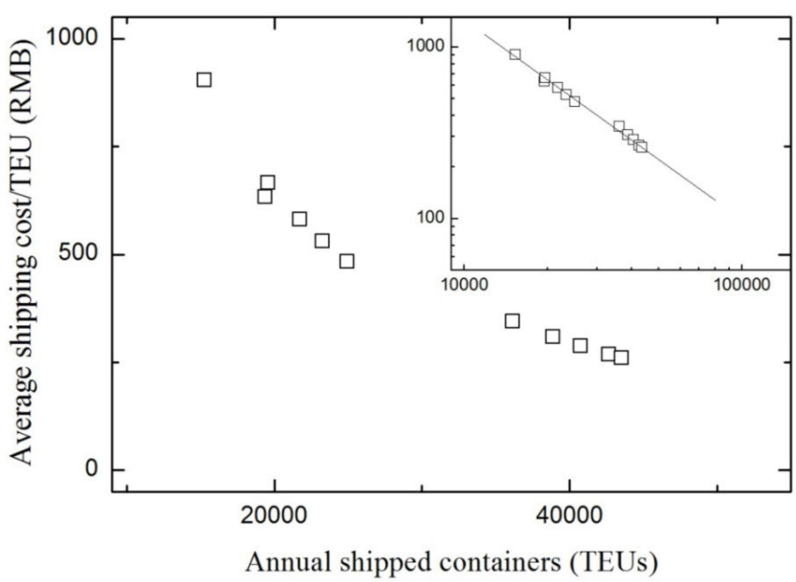

Figure 3 Average shipping cost per TEU versus annual containers shipped (shuttle shipping services)

4. The Model

We propose a mixed-integer linear programming model to optimize the container shipping network on the Yangtze River. Following Konings et al. (2013), we construct a hub-and-spoke network. For the cost structure, we consider the ship-operating cost and container-handling cost. The ship-operating cost is generally the sum of a fixed cost and a variable cost. The fixed cost comprises, for example, the ship-maintenance cost, crew payments and the insurance cost. Note that although the maintenance cost and crew payments are variable in practice, they are seen as fixed in this paper for the sake of simplicity. With regard to the variable cost, we consider only the bunker cost, which is a major component of the ship-operating cost and a function of sailing speed. Here, we assume that the sailing speed is fixed and known in advance. The container-handling cost is the sum of the expenses incurred in loading, discharging and transshipping containers.

The notations are as follows.

$\mathcal{P}$: Set of ports, indexed by i.

$\mathcal{P}_1$: Set of river ports.

$\mathcal{P}_2$: Set of sea ports.

$\mathcal{P}_3$: Set of potential hub ports.

$\mathcal{V}$: Set of ship types, indexed by v.

$\mathcal{V}_1$: Set of river ship types.

$\mathcal{V}_2$: Set of river-sea ship types.

$\mathcal{A}$: Set of arcs, indexed by (i, j).

q_{ij} : Weekly number of containers transported from origin i to destination j, i.e., the OD port pair.

$\mathcal{W}$: Set of OD port pairs, indexed by $\langle o,d \rangle$.

Dis_{ij} : Length of arc (i, j), i.e., the distance between port i and port j.

Cap_v : Capacity of type v ship.

s_v : Sailing speed of type v ship.

c_{ijv}^{bunker} : Hourly bunker cost of type v ship sailing from port i to port j .

t_{iv} : Hourly number of containers handled by type v ship berthed at port i .

c_v^{fix} : Fixed weekly operating cost of type v ship.

c_i^{load} : Cost of loading one TEU at port i .

c_i^{dis} : Cost of discharging one TEU at port i .

c_i^{trans} : Cost of transshipping one TEU at port i .

The decision variables are as follows.

z_{ijv} : A binary variable that is 1 if arc (i, j) is served by ships of type $v \in \mathcal{V}$, and 0 otherwise.

f_{ijv} : Service frequency of ships of type $v \in \mathcal{V}$ on arc (i, j)

m_{ijv} : Weekly number of ships of type $v \in \mathcal{V}$ on arc (i, j) .

x_{ijv} : Weekly number of containers transported by type $v \in \mathcal{V}$ ships on arc (i, j) .

y_{ij}^k : Weekly number of containers transported on the k^{th} path of OD port pair $\langle i, j \rangle$.

The mixed-integer linear programming model is formulated as follows.

$$\begin{aligned} \min \sum_{i\in\mathcal{P}} \sum_{j\in\mathcal{P}} \sum_{v\in\mathcal{V}} & \left[m_{ijv} \cdot c_v^{\text{fix}} + c_{ijv}^{\text{bunker}} \cdot f_{ijv} \cdot \frac{\text{Dis}_{ij}}{s_v} + x_{ijv} \cdot \left(c_i^{\text{trans}} + c_j^{\text{trans}} \right) / 2 \right] \\ & + \sum_{i\in\mathcal{P}} \sum_{j\in\mathcal{P}} q_{ij} \cdot \left[\left(c_i^{\text{load}} + c_j^{\text{dis}} \right) - \left(c_i^{\text{trans}} + c_j^{\text{trans}} \right) / 2 \right] \end{aligned} \tag{1}$$

subject to

$$\sum_{\forall k \in \mathcal{R}_{ij}} y_{ij}^{k} = q_{ij}, \forall \langle i, j \rangle \in \mathcal{W}; \tag{2}$$

$$\sum_{\forall v \in \mathcal{V}} x_{ijv} = \sum_{\langle r,s \rangle \in \mathcal{W}} \sum_{k \in \mathcal{R}_{rs}} y_{rs}^{k} \cdot \delta_{k,ij}^{rs}, \forall (i, j) \in \mathcal{A}; \tag{3}$$

$$x_{ijv}\left(\frac{1}{t_{iv}} + \frac{1}{t_{jv}}\right) + \frac{\text{Dis}_{ij}}{s_{v}} f_{ijv} \le 168 m_{ijv}, \forall (i, j) \in \mathcal{A}, \forall v \in \mathcal{V}; \tag{4}$$

$$x_{ijv} \le f_{ijv} \cdot \text{Cap}_{v}, \forall (i, j) \in \mathcal{A}, \forall v \in \mathcal{V}; \tag{5}$$

$$m_{ijv} \le M \cdot z_{ijv}, \forall (i, j) \in \mathcal{A}, \forall v \in \mathcal{V}; \tag{6}$$

$$z_{ijv} \le f_{ijv}, \forall (i, j) \in \mathcal{A}, \forall v \in \mathcal{V}; \tag{7}$$

$$m_{ijv} \ge f_{ijv}, \forall (i, j) \in \mathcal{A}, \forall v \in \mathcal{V}; \tag{8}$$

$$\sum_{\forall v \in \mathcal{V}} z_{ijv} \le 1, \forall (i, j) \in \mathcal{A}; \tag{9}$$

$$\sum_{\forall v \in \mathcal{V}} \sum_{\forall j \in \mathcal{P}} z_{ijv} \ge 1, \forall i \in \mathcal{P}; \tag{10}$$

$$\sum_{\forall v \in \mathcal{V}} \sum_{\forall i \in \mathcal{P}} z_{ijv} \ge 1, \forall j \in \mathcal{P}; \tag{11}$$

$$f_{ijv} = 0, \forall i \; or \; j \in \mathcal{P}_{2}, \forall v \in \mathcal{V}_{1}; \tag{12}$$

$$y_{ij}^{k} \ge 0, \forall k \in \mathcal{R}_{ij}, \forall \langle i, j \rangle \in \mathcal{W}; \tag{13}$$

$$x_{ijv} \ge 0, \forall (i, j) \in \mathcal{A}, \forall v \in \mathcal{V}; \tag{14}$$

$$f_{ijv} \in \mathrm{Z}^{+} \bigcup \{0\}, \forall (i, j) \in \mathcal{A}, \forall v \in \mathcal{V}; \tag{15}$$

$$m_{ijv} \in \mathrm{Z}^{+} \bigcup \{0\}, \forall (i, j) \in \mathcal{A}, \forall v \in \mathcal{V}; \tag{16}$$

$$z_{ijv} \in \{0,1\}, \forall (i, j) \in \mathcal{A}, \forall v \in \mathcal{V}., \tag{17}$$

where M is a large positive constant; 168 in constraint (4) is the number of hours in a week; $\mathcal{R}_{ij}$ is the set of routes from port i to port j; and $\delta_{k,ij}^{rs}$ is a binary variable that equals 1 if route (i, j) belongs to the k^{th} path of OD port pair $\langle r, s \rangle$, and 0 otherwise. Objective function (1) minimizes the weekly cost, which comprises three terms: (i) the fixed operating cost, (ii) bunker cost and (iii) container-handling cost.

Constraint (2) follows the flow-conservation constraints. Constraint (3) describes the relationship between arc flow x_{ijv} and OD path flow y_{ij}^{k}. Constraint (4) enforces the number of ships deployed to maintain a certain service frequency. Constraint (5) is capacity constraint, and constraints (6)-(8) allow only open arcs. Constraint (9) states that at most one type of ship serves one arc. Constraints (10) and (11) ensure that at least one type of ship serves each port. Constraint (12) prohibits river ships from calling at sea ports, and constraints (13) and (14) guarantee that y_{ij}^{k} and x_{ijv} are non-negative. Constraints (15) and (16) guarantee that f_{ijv} and m_{ijv} are non-negative integers, and constraint (17) keeps z_{ijv} binary.

We adopt the following reasonable assumptions.

(i) Containers cannot be transshipped more than twice.

(ii) Containers are transshipped only at hub ports.

(iii) Potential hub ports are known in advance.

The first two assumptions are common (e.g., Alumur and Kara, 2008; Meng and Wang, 2011a; Zheng et al., 2014, 2015), and the third is made to reduce computational complexity. The rationale for this assumption is further addressed in the next section.

We next analyze the degree of computational complexity. The number of ports is $|\mathcal{P}|$, the number of ship types is $|\mathcal{V}|$, and the number of arcs is $|\mathcal{A}|$. Generally, $|\mathcal{V}| << |\mathcal{P}| < |\mathcal{A}|$ because the types of ships owned by a given company are limited, and each port is visited at least once a week. The number of OD pairs is $|\mathcal{W}|$, which is bounded by $|\mathcal{P}|^2$. Containers mainly travel between Shanghai (i.e., Yangshan and Waigaoqiao) and the other ports on the Yangtze River. As a result, $|\mathcal{W}|$ is further bounded by $4|\mathcal{P}|$ or $O|\mathcal{P}|$. When the potential hubs are given, $|\mathcal{A}|$ is bounded by $O|\mathcal{W}|$ because of the first two assumptions cited above. Hence, our model has at most $O|\mathcal{W}|$ decision variables and $O|\mathcal{W}|$ constraints because both the decision variables and constraints are bounded by the number of OD port pairs. Therefore, we can solve this model using a linear programming solver such as CPLEX.

5. Numerical Example

In this section, we provide a numerical example to demonstrate the effectiveness of our model. The solution is obtained from CPLEX in a Windows 7 environment on a 3.4 GHz Dual Core PC with 4 GB of RAM. The data come from an anonymous shipping company, and prove that scale economies exist in container shipping along the Yangtze River.

5.1 Data Description

We reviewed 21 ports, i.e., Luzhou, Chongqing, Yichang, Jingzhou, Chenglingji, Wuhan, Huangshi, Jiujiang, Anqing, Tongling, Wuhu, Maanshan, Nanjing, Zhenjiang, Yangzhou, Taizhou, Jiangyin, Nantong, Taicang, Waigaoqiao and Yangshan. All data presented herein are derived from realistic data (albeit modified for confidentiality). It should be noted that every port between Nanjing and Shanghai is sufficiently large and deep for use as a hub by sea-going vessels. Assume that eight ports, i.e., Chongqing, Wuhan, Jiujiang, Nanjing, Jiangyin**,** Taicang**,** Waigaoqiao, and Yangshan, can become hubs (i.e., are potential hub ports). Table 2 lists the parameters of the eight ship types considered in this paper. Note that the two bunker cost values correspond to two shipping directions. Because all of the ships considered are small in size, the Nanjing Yangtze Bridge and water draft impose no limitations.

Table 2 Ship type parameters

Ship type	Ship capacity (TEUs)	Ship speed (km/hour)	Bunker cost (RMB per hour)	Fixed cost (RMB per week)
River ships	100	18	400/500	10000
	150	19	450/550	13000
	200	20	500/600	16000
	300	21	550/650	20000
River-sea ships	200	18	500/600	15000
	250	18	500/600	18000
	300	18	500/600	21000
	350	22	600/700	25000

Source: Zhang (2010).

5.2 Results and Analysis

Table 3 displays the results on the hubs and their feeder allocations. Based on our model, Chongqing, Wuhan, Nanjing, Waigaoqiao and Yangshan are chosen as hub ports. Although some feeder ports (e.g., Wuhu) are allocated to more distant hubs, most belong to nearby downstream hubs, as the upstream-to-downstream delivery costs are lower. Waigaoqiao has the most feeder ports; that is, in the absence of transshipment, more containers are transported to/from Waigaoqiao. Most containers to/from Yangshan prefer transshipment at Waigaoqiao, where both river and river-sea ships can call, because of the higher cost associated with river-sea ships, the only ships that can call at Yangshan. According to 2013 Shanghai Port statistics[2], 6.7 million TEU containers, i.e., 41.5% of river port throughput, were transshipped at Waigaoqiao. This percentage is higher than that of any other ports on the Yangtze River. Note that some feeder ports, e.g., Tongling, Wuhu, Zhenjiang, Jiangyin, Nantong and Taicang, are allocated to more than one hub, i.e., multiple allocation.

[2] http://www.statssh.gov.cn/fxbg/201402/267243.html

Table 3 Results of hub location and feeder allocation

Hub ports	Allocated feeder ports
Chongqing	Luzhou
Wuhan	Yichang, Jingzhou, Chenglingji, Huangshi, Jiujiang
Nanjing	Anqing, Tongling, Wuhu, Maanshan, Zhenjiang
Waigaoqiao	Tongling, Wuhu, Maanshan, Zhenjiang, Yangzhou, Taizhou, Jiangyin, Nantong, Taicang
Yangshan	Jiangyin, Nantong, Taicang

Figure 4 shows the hubs and their feeder allocations. As noted in Section 1, the Yangtze River is divided into upstream, midstream and downstream regions. Each region has at least one hub, and each hub and its associated feeder ports are located in the same region. Hence, in river shipping, geographic location determines hub location and feeder allocation.

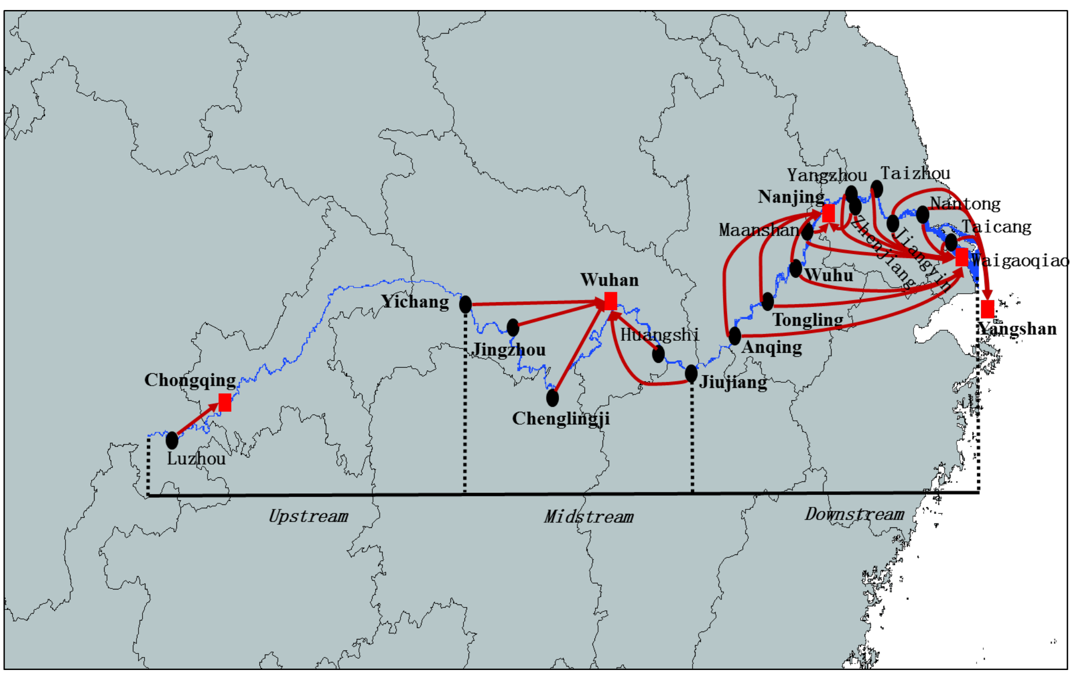

Figure 4 Hubs and their feeder allocations

The number of ships and ship-board capacity in both directions are shown in Table 4. The ship counts are close in both directions, whereas the ship-board capacity varies. Because more containers originate upstream, the ship-board capacity is greater in that direction, i.e., 7850 ($4050+3800=7850$) versus 5350 ($3250+2100=5350$). In both directions, there are twice as many river ships as river-sea ships. The two ship-board capacities are close only in the upstream-to-downstream direction, suggesting that larger river-sea ships travel in that direction.

Table 4 Number of ships and ship-board capacity in two directions

	Weekly number of ships		Ship-board capacity	
	River ships	River-sea ships	River ships	River-sea ships
From upstream	23	14	4050	3800
From downstream	22	9	3250	2100

In Figure 5, we plot the average cost versus annual containers shipped. The correlation between them can be estimated by concave function $c(x)=6249.6x^{-0.572}$; i.e., the scale economies are identical for different shipping segments, which is consistent with Figure 3.

Exponent $\gamma \approx 0.572$ is smaller than the 0.9 in Figure 3, which is obtained from the annual demand of all shipping companies, whereas 0.572 is obtained from weekly demand from one company. As previously noted, cargo shipping is seasonal, with liner companies altering, or even redesigning, their shipping networks every three to six months. Different data samples will result in different exponent estimates.

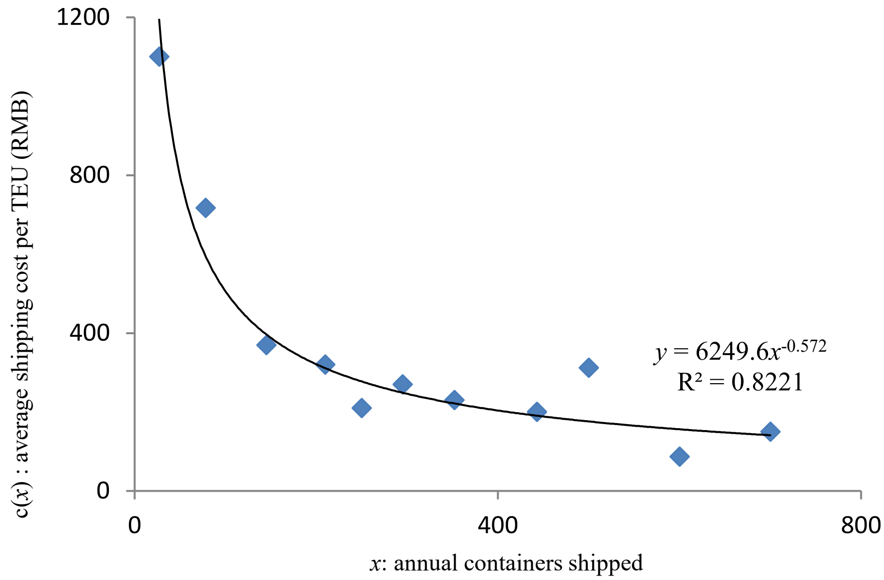

Figure 5 Scale economies of container shipping along the Yangtze River

Table 5 lists the number of containers handled by direct services, one transshipment and two transshipment services, respectively. It can be seen that more than 66% of containers are shipped without any transshipment, and less than 1% of containers experience two transshipments. This is because (i) transshipment incurs extra loading and unloading costs, and (ii) the ships on the Yangtze River are quite small, meaning that it is not always necessary to consolidate containers. Although it is common in sea/ocean shipping for containers to be transshipped twice, it rarely occurs in river shipping.

Table 5 Number of containers by transshipment

	Weekly shipped containers	Ratio
Direct service	5380	66.3%
With one transshipment	2657	32.8%
With two transshipments	75	0.9%
Total OD demand	8112	

5.3 Extension

As noted, the Yangtze River between Nanjing and Shanghai is sufficiently deep to allow short-sea ships to connect the ports in this segment to sea ports in nearby countries such as Japan and Korea. To reflect that reality, we introduce a dummy port, which is assumed to be 1000 kilometers from Waigaoqiao. This dummy can be regarded as representing external demand from either a single sea port or a group of sea ports. For simplicity, container demand between the dummy port and any port along the Yangtze River is assumed to be proportional to container demand between Waigaoqiao and that particular port. Let μ denote the proportional coefficient. Two types of short-sea ships are considered to provide short-sea shipping services, as shown in Table 6.

Table 6 Parameters for short-sea ships

Ship type	Ship capacity (TEUs)	Ship speed (km/hour)	Bunker cost (RMB per hour)	Fixed cost (RMB per week)
Short-sea ships	800	25	2000	35000
	1500	29	3000	50000

We also introduce two additional candidate hub ports, i.e., Yangzhou and Taizhou, to ameliorate the diversity of hub samples in the downstream areas of the Yangtze River, particularly those between Nanjing and Shanghai.

Table 7 presents the results on the downstream transshipment ports selected to reflect differing degrees of external demand. When μ is small (e.g., μ=0.2), external demand from the dummy port is low. It should be noted that external demand is transshipped via the hub ports chosen in the previous section (i.e., Nanjing and Waigaoqiao), and the majority of the transshipment volume (74.3%) goes to Waigaoqiao. When μ is large (e.g., μ=0.5, 1 or 2), external demand becomes larger. Although the majority of transshipment volumes (89.5%, 81.4% and 73.2% when μ=0.5, 1 and 2, respectively) are still handled by the previously chosen hub ports (i.e., Nanjing, Waigaoqiao and Yangshan), Taicang and Taizhou are also now selected as transshipment ports, together handling 10.5%, 18.6% and 26.8% for μ=0.5 , 1 and 2, respectively. The ratio of transshipment volume via Waigaoqiao decreases with an increase in external demand from the sea ports nearby because it is no longer necessary to consolidate containers at Waigaoqiao when the number of containers delivered to and/or from certain river ports (including those transshipped from upstream areas of the Yangtze River) is large enough to sustain short-sea regular shipping services.

Table 7 Transshipment ports in downstream areas of the Yangtze River selected for differing degrees of external demand

μ	Optimal transshipment ports to meet external demand
0.2	Nanjing (25.7%),* Waigaoqiao (74.3%)
0.5	Nanjing (31.6%), Taicang (10.5%), Waigaoqiao (57.9%)
1	Nanjing (25.6%), Taicang (18.6%), Waigaoqiao (41.9%), Yangshan (13.9%)
2	Nanjing (22%), Taizhou (14.6%), Taicang (12.2%), Waigaoqiao (26.8%), Yangshan (24.4%)

** The number in parentheses indicates the ratio of external demand routed via a different port.*

6. Conclusion

This paper explores the scale economies of container shipping along the Yangtze River. It reveals a power-law relationship between the average shipping cost per TEU and the number of containers shipped annually, which implies that scale economies do exist on certain segments of the Yangtze River. We propose a mixed-integer linear programming model to optimize the shipping network by adopting a hub-and-spoke structure. The results of a numerical experiment show that most feeder ports are allocated to their nearby downstream hubs because shipping costs are lower from the upstream to the downstream. We also reveal that containers are rarely transshipped twice in river shipping, although the practice is common in sea/ocean shipping. Because transshipment incurs extra loading and unloading costs, and the ships that sail the Yangtze River are quite small, it is not always necessary to consolidate containers. As it has the most feeder ports, Waigaoqiao appears to be the most important transshipment hub on the Yangtze River, which helps to explain the cargo concentration proposed by Notteboom and Rodrigue (2005) and Wang and Ducruet (2012). In addition, we find that each region of the river (upstream, midstream and downstream) has at least one hub and that each hub is in the same region as its associated feeder ports, which supports the port regionalization trend proposed by Notteboom and Rodrigue (2005) and Veenstra and Notteboom (2011). By considering the short-sea shipping services between the downstream river ports and nearby foreign sea ports, we ascertain that additional river ports will serve as transshipment ports when external demand from the foreign ports increases, thereby weakening the dominant transshipment position of Waigaoqiao.

The work reported herein was part of a consulting project for the regional government. Hence, the findings may bring a side effect to the pattern of port development along the Yangtze River given that the regional government plays a strong role in such development.

This research could be further extended by relaxing some of the assumptions in our hub-and-spoke network design problem. First, the potential hub ports could be randomly selected. Second, the actual container shipment demand from some nearby sea ports could be taken into consideration. Finally, the way in which government investment and competition policies are likely to further affect the pattern of port development along the Yangtze River could be discussed.

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