Journal of Transport Geography 55 (2016) 51–57

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

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

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ARTICLE INFO

Article history:
Received 5 January 2015
Received in revised form 1 July 2016
Accepted 4 July 2016
Available online xxxx

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

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.

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. Fig. 1 presents the change in size from 2001 to 2012, a period in which the average ship size nearly tripled.

Fig. 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 m between Shanghai and Nanjing, around 6 m between Nanjing and Anqing, 4.5 m between Anqing and Wuhan, 3.7 m between Wuhan and Chenglingji, and less than 3 m between Chongqing and Yibin. Different river depths admit differently sized ships.

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 km 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

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http://dx.doi.org/10.1016/j.jtrangeo.2016.07.001
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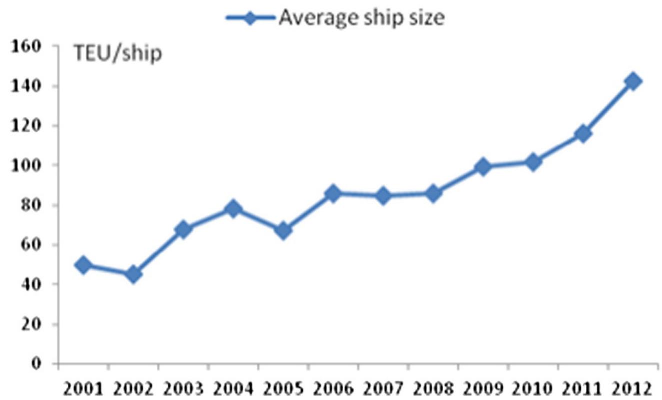

Fig. 1. Annual transition in the average size of Chinese river ships. Data source: http://www.jttj.gov.cn/gongbao.asp (in Chinese).

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. Racunica 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

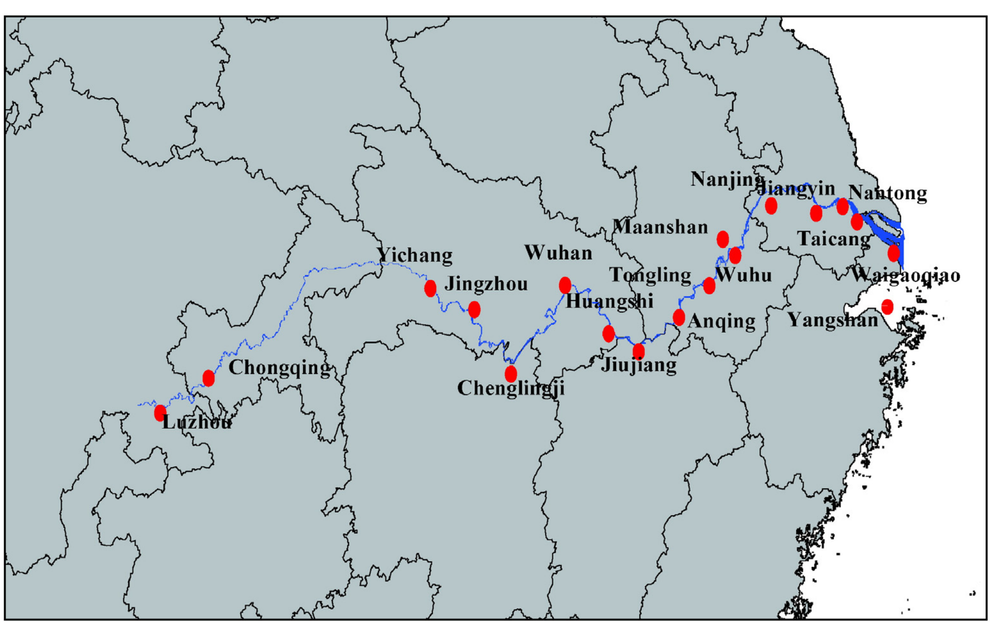

Fig. 2. Ports along the Yangtze River.