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Discrete Optimization

Robust bunker management for liner shipping networks

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ABSTRACT

This paper examines the sailing speed of containerships and refueling of bunker in a liner shipping network while considering that the real speed may deviate from the planned one. It develops a mixed-integer nonlinear optimization model to minimize the total cost consisting of ship cost, bunker cost, and inventory cost, under the worst-case bunker consumption scenario. A close-form expression for the worst-case bunker consumption is derived and three linearization techniques are proposed to transform the nonlinear model to a mixed-integer linear programming formulation. A case study based on the Asia–Europe–Oceania network of a global liner shipping company demonstrates the applicability of the proposed model and interesting managerial insights are obtained.

1. Introduction

Liner shipping mainly involves the transportation of containerized cargo (containers) such as manufactured products, food, and garment (Meng, Wang, Andersson, & Thun, 2014). The unit value of the containers is generally much higher than bulk cargo. Hence, the speed of containerships is higher (e.g., 20–25 knots) to deliver the containers to their destinations in a shorter time. In fact, short transit time is important especially for consumer goods with a short life cycle such as fashion and computers (Notteboom, 2006). At the same time, the daily fuel consumption of ships increases approximately proportional to the sailing speed cubed (Ronen, 2011). Therefore, containerships burn more fuel (bunker) than other types of ships in general and hence it is vital for liner shipping companies to efficiently manage the bunker. For example, Ronen (2011) estimated that when bunker fuel price is around 500 USD per ton the bunker cost constitutes about three quarters of the operating cost of a large containership.

Bunker management has two aspects. The first one is optimizing the sailing speed. A higher speed implies a larger amount of bunker consumed; whereas it also leads to a shorter transit time and a smaller number of ships required to maintain a weekly service frequency. Hence, when the bunker price is high or when there is overcapacity of ships, liner shipping companies tend to deploy more ships to lower down the speed of all the ships plying to a service. Since 2007, many liner shipping companies have adopted the slow-steaming strategy to reduce bunker expenditure and curb the oversupply of shipping capacity (UNCTAD, 2011). It should be mentioned that containerships may not sail at a constant speed on a ship route. On legs with more containers to transport and legs where the bunker consumption is less sensitive to the speed, the sailing speed should be higher (Wang & Meng, 2012a).

The second aspect is the choice of refill port. Containerships load bunker at the ports on their itinerary to avoid detour. Some ports do not provide bunkering services. At the ports where a ship could load bunker (refill ports), the prices may also vary (Kim & Kim, 2012). Moreover, the quality and availability of bunker will be better guaranteed if a shipping company purchases a large amount of bunker at the same port. Consequently, a natural problem faced by a liner shipping company is: how much bunker a ship should load at each refill port?

1.1. Literature review

There are some studies that focus on sailing speed optimization. Notteboom and Vernimmen (2009) and Ronen (2011) investigated the optimal uniform speed on a single ship route. Du, Chen, Quan, Long, and Fung (2011) and Wang, Meng, and Liu (2013c) have examined the possibility of slow steaming via collaboration between port operators and shipping lines. Qi and Song (2012), Wang and Meng (2012c), and Wang and Meng (2012b) have incorporated the choice of speed in a schedule design problem. Wang and Meng (2012a) studied the optimal speed on each voyage leg in a liner shipping network. Wang, Meng, and Liu (2013b) designed the speed while assuming that the container shipment demand depends on the sailing speed. Fagerholt, Laporte, and Norstad (2010), Norstad, Fagerholt, and Laporte (2011) and Hvattum, Norstad, Fagerholt, and Laporte (2013)

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investigated the optimization of sailing speed for tramp ships. Psaraftis and Kontovas (2013, 2014) and Wang, Meng, and Liu (2013a) have provided excellent reviews on studies related to sailing speed optimization models.

Little research has been devoted to the choice of refill port. Both Kim and Kim (2012) and Yao, Ng, and Lee (2012) worked on the speed optimization and the bunkering decisions based on a single liner ship route. Kim and Kim (2012) assumed that the bunker price at each port is independent of the bunkering amount whereas Yao et al. (2012) assumed a lower bunker price when the bunkering amount is larger. Plum, Jensen, and Pisinger (2014a) developed a mixed integer programme for bunker purchasing with contract that is solved by column generation.

The above literature review clearly shows that few studies have addressed the problem of joint speed and bunkering optimization for a liner shipping network. Moreover, all the aforementioned works have assumed that ships sail exactly at the optimal speed derived from mathematical models. However, as a consequence of factors such as wind and sea current, it is impossible for ship captains to guarantee that the real speed perfectly matches the optimal one. Therefore, the predicted total cost may be different from the real total cost and the planned "optimal" speed may no longer be optimal under the uncertainties of the real speed.

1.2. Objectives and contributions

The objective of this paper is to address the practical problem of joint speed and bunkering optimization at the network level considering the uncertainties of real speed. We assume that the real speed may vary within a given range relative to the planned speed. For example, if the planned speed is 18 knots, the real speed may be any value between 17 and 19 knots. The captain will speed up (slow down) if the ship is behind (ahead of) schedule during the voyage to make sure that the ship arrives at the next port of call at the planned time. The bunker prices at different ports are different, and it is advantageous to refill at fewer ports to as the ports will guarantee better quality and availability of bunker. The liner shipping company designs the optimal (planned) speed and chooses the bunkering ports and the amount of bunker to load at each refill port, so as to minimize the worst-case total cost (ship cost, bunker cost, inventory cost) in view of the variability of sailing speed in reality. This problem is referred to as the robust bunker management (RBM) problem in the sequel. The contributions of the paper are three-folds: first, it takes the initiative to address the joint speed and bunkering optimization problem for a liner shipping network; second, it contributes the seminal mathematical model that considers the difference between the planned sailing speed and the real sailing speed. To the best of our knowledge, this practical consideration has not been mentioned in previous studies. Third, a number of interesting managerial insights from case studies are obtained and these managerial insights provide guidelines for shipping companies and refill port operators.

The rest of the paper is organized as follows. Section 2 describes the problem. Section 3 formulates models for worst-case bunker consumption and the robust bunker management problem. Section 4 derives a close-form expression for the worst-case bunker consumption and proposes three linearization techniques for the robust bunker management model. Section 5 reports a case study based on the Asia–Europe–Oceania network of a global liner shipping company. Section 6 concludes.

2. Problem description

Consider a liner container shipping company that operates a number of ship routes, denoted by the set $\mathcal{R}$, regularly serving a group of ports denoted by the set $\mathcal{P}$. The port rotation of a ship route $r \in \mathcal{R}$ can be expressed as:

$$p_{r1} \to p_{r2} \to \cdots \to p_{rN_r} \to p_{r1} \tag{1}$$

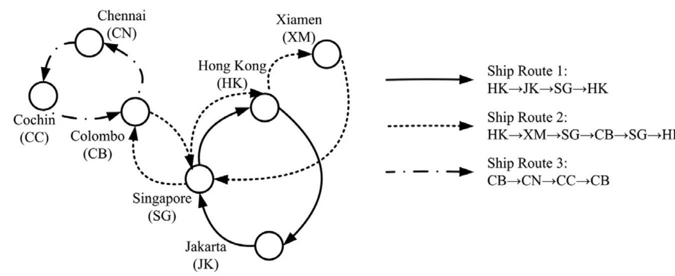

Fig. 1. A liner shipping network with three ship routes.

where N_r is the number of ports of call on the ship route and p_{ri} is the ith port of call. Let $\mathcal{I}_r$ be the set of ports of call of ship route $r \in \mathcal{R}$, i.e., $\mathcal{I}_r = \{1, 2, \ldots, N_r\}$. Defining $p_{r,N_r+1} = p_{r1}$, the voyage from p_{ri} to $p_{r,i+1}$ is called leg i, $i \in \mathcal{I}_r$. Fig. 1 shows a liner shipping network with three ship routes elaborated as follows:

$$\begin{aligned}
&r = 1,\ \ N_r = 3: && p_{r1}(\text{HK}) \to p_{r2}(\text{JK}) \to p_{r3}(\text{SG}) \to p_{r1}(\text{HK})\\
&r = 2,\ \ N_r = 5: && p_{r1}(\text{HK}) \to p_{r2}(\text{XM}) \to p_{r3}(\text{SG}) \to p_{r4}(\text{CB})\\
& && \to p_{r5}(\text{SG}) \to p_{r1}(\text{HK})\\
&r = 3,\ \ N_r = 3: && p_{r1}(\text{CB}) \to p_{r2}(\text{CN}) \to p_{r3}(\text{CC}) \to p_{r1}(\text{CB})
\end{aligned}$$

2.1. Weekly service and ship operating cost

A string of homogeneous ships are deployed on each ship route $r \in \mathcal{R}$ to maintain a weekly service frequency (Bell, Liu, Angeloudis, Fonzone, & Hosseinloo, 2011; Bell, Liu, Rioult, & Angeloudis, 2013; Brouer, Dirksen, Pisinger, Plum, & Vaaben, 2013; Fransoo & Lee, 2013; Plum, Pisinger, & Sigurd, 2014b). Let L_{ri} (n mile) be the voyage distance of the ith leg of route $r \in \mathcal{R}$, t_{ri}^{port} be the fixed time (h) a ship spends at port i on route $r \in \mathcal{R}$ for container handling, m_r be the number of ships deployed on shipping route $r \in \mathcal{R}$, and $\bar{v}_{ri}$ be the average speed (knot) of a ship on the ith leg of route $r \in \mathcal{R}$. We then have the relation:

$$\sum_{i \in \mathcal{I}_r} \left(\frac{L_{ri}}{\bar{v}_{ri}} + t_{ri}^{\text{port}} \right) = 168 m_r, \quad \forall r \in \mathcal{R} \tag{2}$$

where 168 is the number of hours in a week. The left-hand side of Eq. (2) is the rotation time, which is the total time required by one ship to complete a loop. The rotation time consists of the sailing times at sea and the port times. If, for example, the rotation time is 3 weeks, then a ship can re-visit the same port every 3 weeks. To ensure a weekly frequency, we will need to deploy three ships. Therefore, the rotation time (in hours) must be equal to 168 hours multiplied by the number of ships deployed.

Represent by C_r^{ship} the fixed operating cost (USD/week) associated with a ship on route $r \in \mathcal{R}$. The total cost associated with the ships is:

$$\sum_{r \in \mathcal{R}} C_r^{\text{ship}} m_r$$

2.2. Cargo inventory cost

A higher sailing speed implies a shorter transit time of containers, which leads to a lower inventory cost. Therefore we let β be the unit inventory cost of containers (USD per TEU per hour), and W_{ri} be the volume of containers (TEUs) transported on leg i of ship route r. Since the inventory cost of containers at ports is constant, we are only concerned about the inventory cost at sea, the sum of which can be calculated as:

$$\sum_{r \in \mathcal{R}} \sum_{i \in \mathcal{I}_r} \beta W_{ri} \frac{L_{ri}}{\bar{v}_{ri}}$$