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Continuous Optimization

Fundamental properties and pseudo-polynomial-time algorithm for network containership sailing speed optimization

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ABSTRACT

In container liner shipping, bunker cost is an important component of the total operating cost, and bunker consumption increases dramatically when the sailing speed of containerships increases. A higher speed implies higher bunker consumption (higher bunker cost), shorter transit time (lower inventory cost), and larger shipping capacity per ship per year (lower ship cost). Therefore, a container shipping company aims to determine the optimal sailing speed of containerships in a shipping network to minimize the total cost. We derive analytical solutions for sailing speed optimization on a single ship route with a continuous number of ships. The advantage of analytical solutions lies in that it unveils the underlying structure and properties of the problem, from which a number of valuable managerial insights can be obtained. Based on the analytical solution and the properties of the problem, the optimal integer number of ships to deploy on a ship route can be obtained by solving two equations, each in one unknown, using a simple bi-section search method. The properties further enable us to identify an optimality condition for network containership sailing speed optimization. Based on this optimality condition, we propose a pseudo-polynomial-time solution algorithm that can efficiently obtain an epsilon-optimal solution for sailing speed of containerships in a liner shipping network.

1. Introduction

Liner shipping companies deploy containerships on regularly scheduled services to transport containers. Unlike tramp shipping, containerships in liner shipping have to sail according to the planned schedule no matter whether they are fully loaded or not (Christiansen, Fagerholt, & Ronen, 2004, 2013). Once designed, the liner services are operated for a period of three to six months. Therefore, it is important for liner shipping companies to design efficient services as a large proportion of the total operating cost is fixed once the services are designed (Brouer, Alvarez, Plum, Pisinger, & Sigurd, 2014; Mulder & Dekker, 2014; Ng, 2014; Plum, Pisinger, & Sigurd, 2014; Zheng, Sun, & Meng, 2014).

Bunker cost is a significant component in the total operating cost of a liner shipping company. Ronen (2011) estimated that when bunker fuel price is around 500 dollars/ton, the bunker cost constitutes about three quarters of the operating cost of a large containership. In 2011, the bunker price in Singapore reached 647 dollars/ton (UNCTAD, 2012). On 10 March 2015, the bunker price at Rotterdam dropped to 296 dollars/ton (Bunkerworld, 2015), which considerably cut down the costs for liner shipping companies.

The bunker consumption is largely affected by the sailing speed of containerships. When the speed increases, the bunker consumption increases more than linearly. Studies usually assume that daily bunker consumption is approximately proportional to the sailing speed cubed (or bunker consumption per unit of distance is proportional to the sailing speed squared). Wang and Meng (2012) calibrated the exponent to be between 2.7 and 3.3 using historical operating data of containerships, which supports the power of three approximations. Suggested by a ship engine manufacturing company, Du, Chen, Quan, Long, and Fung (2011) adopted the exponent of 3.5 for feeder containerships, 4 for medium-sized containerships, and 4.5 for jumbo containerships. Kontovas and Psaraftis (2011) suggested using an exponent of 4 or greater when the speed of containerships is greater than 20 knots. As a result of the high bunker price and the sensitivity of bunker consumption on sailing speed, slow-steaming is a common technique to curb bunker consumption. After 2007, many liner shipping companies adopted the slow-steaming strategy to reduce bunker expenditure (UNCTAD, 2011). However, shippers are unhappy about slow steaming because it increases the transit time of cargoes from origin to destination.

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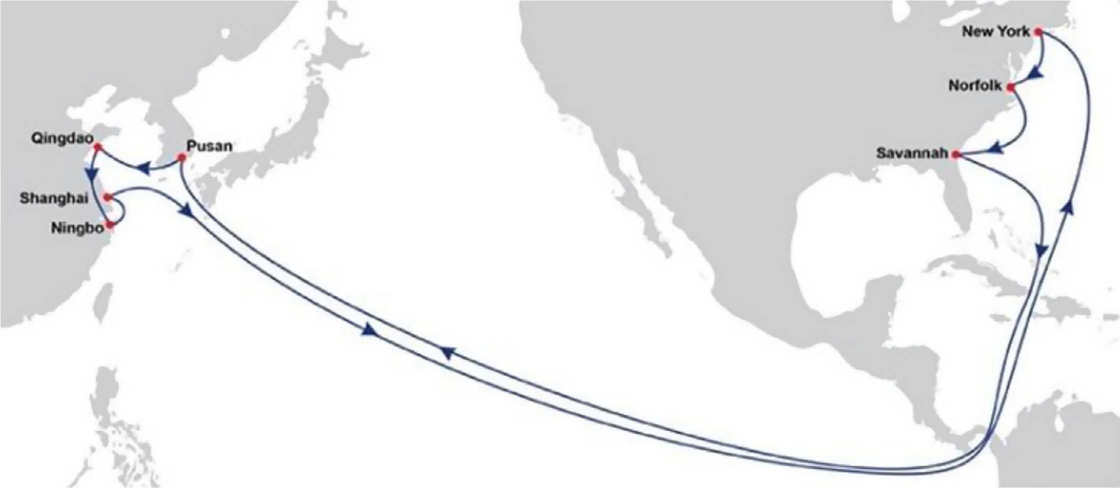

Port Rotation
Eastbound: Pusan - Qingdao - Ningbo - Shanghai - New York - Norfolk - Savannah
Westbound: New York - Norfolk – Savannah - Pusan - Qingdao - Ningbo - Shanghai

Transit Time (Days) Asia to North America (Eastbound) From \ To	New York (Thu)	Norfolk (Sat)	Savannah (Mon)
Shanghai (Sat)	26	28	30
Ningbo (Thu)	28	30	32
Qingdao (Wed)	29	31	33
Pusan (Mon)	31	33	35

Transit Time (Days) North America to Asia (Westbound) From \ To	Pusan (Sun)	Qingdao (Tue)	Ningbo (Thu)	Shanghai (Fri)
Savannah (Tue)	26	28	30	31
Norfolk (Sat)	29	31	33	34
New York (Fri)	30	32	34	35

Fig. 1. NCE service provided by OOCL (2013).

In fact, on one hand, slow-steaming reduces bunker consumption and thereby bunker cost; on the other hand, it also decreases the effective shipping capacity and increases the transit time. Liner shipping companies usually provide a weekly service frequency, which means that each port of call is visited on the same day every week (Bell, Liu, Angeloudis, Fonzone, & Hosseinloo, 2011; Brouer et al., 2011, 2013). For example, Fig. 1 shows the North & Central China East Coast Express (NCE) operated by Orient Overseas Container Line (OOCL, 2013) which has a weekly frequency, meaning that the round-trip journey time (weeks) is equal to the number of ships deployed. For example, the round-trip journey time of NCE is 63 days, and hence 9 ships should be deployed to maintain a weekly service. If, for example, slow-steaming increases the round-trip journey time to 70 days, then 10 ships must be deployed, which leads to higher ship operating costs (manning, maintenance, insurance, consumables, etc.). Moreover, slow-steaming results in a longer transit time of containers. Consequently, the inventory cost for customers will be higher. For instance, Notteboom (2006) estimated that one day delay of a 4000-TEU (20-foot equivalent unit) ship implies a total cost of 57,000 Euros associated with the cargos in the containers. Therefore, liner shipping companies must design the speed to balance the trade-off between ship cost, bunker cost, and inventory cost.

It should be noted that a more straightforward approach for shipping lines is to set a maximum transit time for each port pair. The maximum transit time approach and the inventory costs approach have similarities and differences. On one hand, we could consider the maximum transit time as a “soft” constraint in some cases: a 30 days’ maximum transit time does not mean there are no cargoes when the real transit time is 30.1 days, but means there are fewer cargoes due to customers’ loss. Similarly, a 30 days’ maximum transit time does not mean there is no difference for the customers whether the real transit time is 29 days or 1 day. In the maximum transit time approach, if we penalize transit time longer than the maximum one and reward shorter transit time, the model will be the same as the inventory cost approach where the inventory cost rate is equal to the penalty rate and the reward rate. In fact, both Alvarez (2012) and Kim (2014) have used the inventory costs as a surrogate for level of service provided by shipping lines. On the other hand, if we treat the maximum transit time as a “hard” constraint to account for perishable products, then the shipping line will not provide a very short transit time even when the bunker price is low because nothing is gained by fast steaming. By contrast, when the bunker price is low, in the inventory costs approach the speed will be higher than that in the maximum transit time approach because the inventory cost implicitly assumes that the liner shipping company gains more revenue when the transit time is shorter by charging a higher freight rate or receiving more demand from customers.

There are a number of studies that are devoted to the optimization of sailing speed in different contexts of maritime transportation: shipping network design (Alvarez, 2009), ship fleet deployment (Gelareh & Meng, 2010; Meng & Wang, 2010), ship schedule construction (Bell & Bichou, 2008; Qi & Song, 2012), selection of bunkering port and volume (Kim, 2014; Yao, Ng, & Lee, 2012), emission control (Kim, Chang, Kim, & Kim, 2012, 2013; Kontovas & Psaraftis, 2011; Psaraftis & Kontovas, 2010, 2013), berth allocation (Du et al., 2011; Zhen, Chew, & Lee, 2011a, 2011b), and minimizing bunker cost (Fagerholt, Laporte, & Norstad, 2010; Hvattum, Norstad, Fagerholt, & Laporte, 2013; Kim, 2014; Kim, Kim, & Lee, 2014; Norstad, Fagerholt, & Laporte, 2011; Ronen, 2011; Wang & Meng, 2012). These studies have developed various mathematical models and optimization algorithms. Fagerholt et al. (2010) and Norstad et al. (2011) discretized the possible sailing speed and used dynamic programming to find the optimal speed to adopt in a tramp shipping environment. Du et al. (2011) investigated a joint berth allocation and speed optimization problem. They transformed the power relation between sailing speed and bunker consumption rate to second-order cone programming (SOCP) constraints and took advantage of state-of-the-art solvers to solve the SOCP problem. Wang and Meng (2012) generated