



Dynamic programming for optimal ship refueling decision



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ABSTRACT

This study investigates an optimal control policy for a liner ship to decide at which ports and how much fuel the liner ship should be refueled under stochastic fuel consumption in each leg and stochastic fuel price at each port. Based on some properties proved in this study, a dynamic programming algorithm is then designed to obtain some important threshold values, which are used in the optimal control policy for ship refueling decision. Extensive experiments show that the proposed method can obtain the optimal decision within a reasonable time (about 170 s) for various scales of problem instances (up to 30 ports) as well as various settings of probability distributions. In addition, some comparative experiments also show that the proposed optimal decision policy can save at least 8% fuel consumption cost by comparing with some relatively simple rules and save about 1% cost on average by comparing with some brilliantly-designed rules.

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1. Introduction

The fluctuating world oil price and world maritime transportation market bring a lot of uncertainties to operations management of shipping liners. This study investigates an optimal control policy for a liner ship to decide at which ports and how much fuel the liner ship should be refueled. This paper studies this refueling decision problem for a liner ship. Suppose a ship visits a given sequence of ports. Due to the limitation of its tank volume, the fuel in the tank usually cannot support the ship to fulfill the whole sailing process without refueling at some ports in the voyage. Then where the ship should be refueled during its voyage as well as how much fuel the ship should be refueled at a port becomes an important decision for shipping companies as the bunker fuel expenditure is a main part of the total operation cost of a liner ship (or cruise ship).

If all the fuel consumption during each leg in the voyage can be exactly estimated and the fuel price at each port in the voyage is fixed, this decision problem is trivial. In reality, the fuel price is usually different at each port and also fluctuates frequently. But the voyage time is usually a relatively long time, which implies the fuel price may have a significant dynamic nature during a ship's voyage.

The fluctuation of fuel price is common in reality. The fuel price may sharply decline (or increase) at the same port in one month. Moreover, the fuel price at different ports may be quite different even on the same day. For example, the fuel price gap between Singapore and Vancouver was \$54/ton on 15 December 2015. In addition, a liner ship's voyage usually covers a relatively long period. There are usually significant changes of fuel price during liner ships' voyages in reality. Therefore, the ship refueling decision policy should also consider the stochastic feature of the fuel price at each port.

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If the fuel price at each port can be exactly predicted, it is also not difficult to solve the optimal refuel decision for the ship in order to minimize the total fuel cost. However, both the fuel consumption during each leg and the fuel price at each port during the voyage are stochastic. Although the route length of each leg from one port to another port is deterministic, the fuel consumption in the leg is uncertain because it is influenced by many factors such as sailing speed, draft, trim, weather/sea conditions (e.g., wind, waves, sea currents and sea water temperature) and the consumption of power for all types of facilities on the ship. Since the number of containers is unpredictable and the ship needs to unload or load at each port, the ship's dwell time at ports becomes uncertain. Then the ship must adjust its sailing speed so as to meet its scheduled arrival time for its next port; otherwise the ship may be punished by waiting a long time at the anchorage of ports. The sailing speed significantly affects the fuel consumption of a leg. In addition, the uncertain weight of cargos or passengers (mainly for cruise ships) during each leg will influence the ship's draft, which also further incurs the uncertain fuel consumption for each leg. Moreover, the weather/sea conditions are difficult to capture. All of these factors make the fuel consumption during each leg become uncertain.

Based on the above analysis, if both the fuel consumption during each leg and the fuel price at each port during the voyage are stochastic, how to obtain the optimal policy for refueling a liner ship is an interesting problem for the shipping liner. This paper makes an explorative study on this problem. Several properties are proved in this study. On the basis of these properties, a dynamic programming algorithm is then proposed to obtain some important threshold values, which are used in the optimal control policy for ship refueling decision. Numerical experiments are conducted on the basis of a real world example of a cruise ship. The numerical results validate the effectiveness of the proposed method.

2. Literature review

The refueling decision is similar to the inventory replenishment problem to some extent if the fuel in a ship's tanker is regarded as the parts in a warehouse. The optimal refueling decision can also be investigated by borrowing the idea of the optimal inventory control (Lee et al., 2006), for which the methodology of dynamic programming is widely used (Meng and Wang, 2011; Chen et al., 2004). Different from the optimal inventory control, the study on the optimal refueling decision policy for a liner ship needs to consider special features originating from the maritime shipping backgrounds. This study concerns two factors: one is the fuel consumption of ships, the other is the fuel prices. Related works are discussed mainly through these two aspects.

The fuel consumption is mainly influenced by the speed, draft, trim, and weather/sea conditions. Qi and Song (2012) and Wang and Meng (2012) studied ship schedule design problems with considering the speed of a ship; uncertain port time is taken into account in these two studies. Lindstad et al. (2013) considered the factor of ship draft to design a new bulk ship for decreasing fuel cost. Yang et al. (2014) identified the optimal trim configuration to improve ship energy efficiency. Zhen et al. (2016, 2017) examined port operations considering vessels' fuel consumption. Plenty of recent studies considered weather conditions and optimized ship routes to minimize the bunker fuel consumption (Lin et al., 2013; Zhang et al., 2013; Fang and Lin, 2015). Besikci et al. (2016) developed an artificial neural network model to predict fuel consumption for various operational conditions, which can be used on a real time basis for energy efficient ship operations. By using the shipping log data available in practice, Meng et al. (2016) put forward a practical method to combine the fuel consumption rate with a lot of determinants such as sailing speed, draft, sea, and weather conditions.

Few of the fuel consumption related works have mentioned the refueling decisions. Kim et al. (2012) considered the optimum ship speed, refueling ports and amounts of fuel for a given ship's route, and developed an epsilon-optimal algorithm to solve the problem. Its main contribution lies in considering a lot of realistic factors such as bunker prices, carbon taxes, and greenhouse gas emissions. Yao et al. (2012) designed a bunker fuel management strategy for a single shipping liner service, which includes refueling ports selection, refueling amounts determination and ship speeds adjustment; the complexity of this problem mainly lies in the fact that these three decisions are highly interrelated. Although the above studies considered a lot of complex factors, the fuel price at each port is given as deterministic parameters in their problems, which is different from the setting of uncertain fuel price in this study. In reality, contracts are often used for bunker purchasing, ensuring supply and often giving a discounted price (Pedrielli et al., 2015). Plum et al. (2014) proposed a mixed-integer programming model for bunker purchasing with contract and designed a column generation algorithm to solve the model. Ghosh et al. (2015) studied a refueling decision problem, which considered some special issues. For example, the ship has a contract with fuel supplier; ship can choose to refuel at the contract price or the spot price at a port; there is a penalty if the ship does not use up a certain amount of fuel stated in the contract. For the above two contract related studies, the second one considered more complex (realistic) factors in contract design, but is mainly oriented for one ship route; while the first one is oriented for a shipping network. Considering the real sailing speed may deviate from the planned one, Wang and Meng (2015) examined the ship speed and refueling decision in a liner shipping network, and developed a mixed-integer nonlinear optimization model under the worst-case bunker consumption scenario. One of its main contributions lies in proposing a close-form expression for the worst-case bunker consumption. Sheng et al. (2015) proposed a dynamic (s,S) policy for a liner shipping refueling and speed determination problem. Two variations of the progressive hedging algorithm were designed to tackle large-scale problem instances. Meng et al. (2015) considered different bunker prices at different ports for a tramp ship routing decision problem. The main contribution is the design of a branch-and-price based exact solution method for maximizing the total profit by routing ships to carry the given cargoes as well as determining the amount of bunker refueled at each port.

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