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(s, S) policy model for liner shipping refueling and sailing speed optimization problem

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A B S T R A C T

This work expounds on implementing an effective dynamic (s, S) policy to solve a liner shipping refueling and speed determination problem under both bunker prices and consumption uncertainties. While solving an optimization model which incorporates a continuous distribution is extremely challenging, we use sample average approximation method to solve it. However, the resulting problem is still a very large-scaled problem. Therefore, we propose two variations of the progressive hedging algorithm to tackle it. Numerical results show that our solution method is efficient and, in addition, our dynamic (s, S) policy model has significant cost reduction potential compared to stationary models.

1. Introduction

The liner shipping industry has long been regarded as the world's economic engine either for its direct economical contribution or for its role as the facilitator of international trades. According to worldshipping.org (2012), using 2007 as the base year, liner shipping industry contributed annually a direct GDP of approximately US$183.3 billion and transported close to 60% of the value of total global trade. As of 31st October 2010, there were approximately 400 liner services and 4800 container ships in operation (marisec.org, 2012). From an environmental point of view, shipping is considered to be a more carbon-efficient mode of transportation than airline or rail industry for instance. Container ships mainly use bunker fuels, which are distillates from the crude oil refinery process, as its energy source. In a comprehensive report done by imo.org (2008), shipping industry accounted for only 2.7% of the global CO_2 emissions in year 2007. As numerous technologies have been invented to improve the engine efficiency of ships and with increasing international regulations on green house gas emissions from shipping operators, the shipping industry will remain a relatively "green" transportation modality for a long time to come.

However, most of the liner shipping companies are currently facing tough market conditions. Sky rocketing bunker prices severely undermine the already marginal profits and the oversupply of shipping capacity accumulated the past few years makes competition especially fierce. Therefore, it is not surprising that many liners have slowed down their vessels. The main reason is that by reducing the vessel speeds, a large amount of bunker is saved which results in a huge cost reduction (Ronen, 1982; Yao et al., 2011). Another reason is that this practice partially mitigates the industry's over capacity problem, as more ships and containers are deployed in order to keep a weekly service under lower sailing speeds. However, there is a trade off between sailing speed and service level. Thus, an optimization approach of determining the vessel speeds in the

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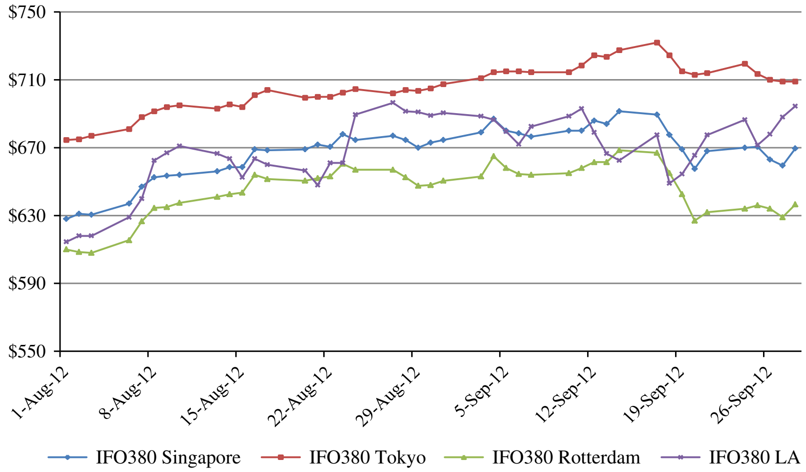

Fig. 1. IFO380 prices at four major bunkering ports around the world from August to September, 2012. (Data source: http://shipandbunker.com.)

operational level, instead of decisions based on experience, is essential when we are talking about thousands of ships and liner service networks.

Another fact about the bunker prices is that they have significant fluctuations on a daily basis and differences across different regions. Therefore, where and how much to bunker is another important decision to reduce cost. Fig. 1 shows the IFO380 prices at four major bunkering ports around the world from August to September, 2012. For example, by bunkering enough fuel under fuel tank capacity limit at those ports with low prices, thousands of dollars can be saved even in a single purchase. Oh and Karimi (2010) presented a mixed-integer linear programming model that optimized the operation of a multiparcel tanker under uncertain bunker prices. However, the stochastic nature of the bunker prices were not fully tackled because price scenarios were given before the solving of the model. More precisely, it is more a deterministic model than a stochastic one. For the "liner" case in Besbes and Savin (2009), they showed that the optimal refueling policy was of the buy-up-to form and the value of buy-up-to level belonged to a small finite set in the presence of random bunker prices. However, vessel sailing speed was given in the problem formulation and bunker consumption uncertainty were not considered. Our previous work, Sheng et al. (2013), studied how to dynamically determine the vessel speed and refueling decisions under uncertain bunker prices and consumptions. The bunkering and speed decisions depended on the actual realization of the bunker prices. Bunker consumption uncertainty was modeled into a chance constraint to control the probability of the ship running out of bunker to be less than a predefined value. Therefore, there was not an effective refueling policy provided which can also determine the bunkering decisions based on the actual bunker consumptions.

We found that our problem nature is very similar with that of the inventory management. Bunker fuel in our case is the "product"; Bunker consumption within each leg is the "product demand" during each period; And inventory holding costs are similar in both cases. In the inventory management literature, many researchers (Scarf, 1993; Karlin, 1960; Zheng and Federgruen, 1991, etc.) have established that, under mild assumptions, a simple (s, S) replenishment policy is optimal. Here s is the re-order point. When the inventory level is less than or equal to s, an order is triggered, which increases the inventory level up to S. In Kalymon (1971), a single-item multi-period inventory problem was studied where the future purchase prices for the item was modeled by a markovian stochastic process and convex holding and shortage costs and a set-up cost for ordering were assumed. It showed that a policy of the form $(s_i(p), S_i(p))$ (i denotes the ith period) was optimal based on the aforementioned assumptions in the finite horizon case. Here, p is the realized item prices at the current time. Thus, very naturally, we want to implement a similar $(s_i(p), S_i(p))$ (i denotes the ith port-call on the route) policy in our bunkering decision to provide a contingent bunkering plan, the execution of which depends on the actual bunker prices and consumption realizations. What is different is that in our problem, p means the historical realized bunker prices up till the current time. At each port, there is a bunker re-order point $s_i(p)$ associated with it. If bunker inventory is below this critical point, a bunkering decision takes place and bunker inventory is increased to the bunker up to level $S_i(p)$. This allows a more flexible operational bunkering plan; the decision of whether to bunker or not depends on the actual bunker price realizations as well as the ship bunker inventory at every port.

However, what further complicates our problem is that our policy parameters are a combination of discrete and continuous variables, which make solving approaches based on dynamic programming practically impossible. Moreover, we need to make the vessel speed decision for each leg. This differentiates our problem from the inventory management problem because, in the latter, "product demand" is usually external and not part of the decision, while vessel speed would determine the bunker consumption in our case. Meanwhile, this poses yet another additional challenge in our problem. Hence, special effort has been dedicated to devise an effective solving scheme which will be discussed later.

The rest of the paper is organized as follows: In the following section, we will give a general description of our problem. In Section 3, a brief introduction of how we tackle the bunker consumption with sample approximation approximation will be