European Journal of Operational Research 222 (2012) 65–75

Contents lists available at SciVerse ScienceDirect

European Journal of Operational Research

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

Production, Manufacturing and Logistics

The sample average approximation method for empty container repositioning with uncertainties

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ARTICLE INFO

Article history:
Received 13 March 2011
Accepted 17 April 2012
Available online 25 April 2012

Keywords:
Transportation
Empty container repositioning
Sample average approximation
Scenario decomposition
Progressive hedging

ABSTRACT

One of the challenges faced by liner operators today is to effectively operate empty containers in order to meet demand and to reduce inefficiency in an uncertain environment. To incorporate uncertainties in the operations model, we formulate a two-stage stochastic programming model with random demand, supply, ship weight capacity, and ship space capacity. The objective of this model is to minimize the expected operational cost for Empty Container Repositioning (ECR). To solve the stochastic programs with a prohibitively large number of scenarios, the Sample Average Approximation (SAA) method is applied to approximate the expected cost function. To solve the SAA problem, we consider applying the scenario aggregation by combining the approximate solution of the individual scenario problem. Two heuristic algorithms based on the progressive hedging strategy are applied to solve the SAA problem. Numerical experiments are provided to show the good performance of the scenario-based method for the ECR problem with uncertainties.

1. Introduction

Containerization has become more and more important in international freight transportation since 1970. In 2004, over 60% of the world's maritime cargo is transported in containers, while some routes among economically strong countries are containerized up to 100% (Steenken et al., 2005). One main issue in the containerized transportation is the imbalance of container flow, which is the result of global trade imbalance between different regions. It is reported that the imbalance of container has increased these years, e.g., the imbalance between Asia and the USA in 1995 was 0.5 million TEUs, that in 2005 was 8.2 million TEUs, and that in 2007 was 10.5 million TEUs (Moon et al., 2010). Under this situation, empty containers have to be repositioned from import-dominated ports which hold a large number of surplus empty containers to export-dominated ports which need a large number of empty containers. In recent years, the operational cost spent on repositioning empty container increases along with the global containerization. Thus, maintaining higher operational cost efficiencies in repositioning empty containers becomes a crucial issue.

There are increasing studies considering empty container flows in recent years. Generally, these studies could be classified into three levels, i.e., strategic level, tactical level and operational level. At strategic level, Zhou and Lee (2009) studied the price strategy and competition of two transportation companies. Empty container flow was considered in their study. Song and Carter (2009) analyzed the container-sharing and route-coordination strategy among shipping companies. Imai et al. (2009) studied the logistic design problem with empty container flow in consideration. At tactical level, the empty container flow was considered in the formulation of service network design problem (Shintani et al., 2007; Chen and Zeng, 2010), ship deployment problem (Liu et al., 2007) and fleet sizing problem (Lai et al., 1995; Du and Hall, 1997; Dong and Song, 2009). The threshold policies for empty container inventory control problem were also studied (Li et al., 2007; Song and Dong, 2008). From the operational perspective, the importance of ECR for shipping industry has been highlighted by numerous studies recently. One direction focused on the inland empty container flow. Empty container transportation among terminals and several inland depots was analyzed (Crainic et al., 1993; Jula et al., 2006; Wang and Wang, 2007; Chang et al., 2008; Bandeira et al., 2009; Zhang et al., 2009). Another direction was to analyze the empty container flow in maritime transportation network (Cheung and Chen, 1998; Feng and Chang, 2008). Besides, there are some studies developing intermodal models which consider both inland and maritime transportation (Chong et al., 2002; Erera et al., 2005; Olivo et al., 2005).

In the maritime transportation, container operators have to deal with some uncertain factors like the real transportation time between two ports/deports, future demand and supply, the in-transit time of returning empty container from customers, and the available capacity in vessels for empty containers transportation,

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http://dx.doi.org/10.1016/j.ejor.2012.04.018

etc. There are several studies taking into account the uncertain nature of parameters. In an early work of Cheung and Chen (1998), a two-stage stochastic network model was developed to determine the maritime ECR and leasing decisions. The two-stage modeling is highly significant in that it successfully combines the deterministic information and the uncertain information in the ECR. A stochastic quasi-gradient method and a stochastic hybrid approximation procedure were applied to solve their stochastic model. Erera et al. (2009) presented a robust optimization framework based on time–space network for dynamic ECR problems. The robust repositioning plan was developed based on the nominal forecast value and could be adjusted under a set of recovery sections. The advantage of this approach is that it is consistent with the current ECR operation and easy to apply. Francesco et al. (2009) proposed a multi-scenario model to address the ECR problem in a scheduled maritime system. This scenario-based model is promising because deterministic optimization techniques could be applied to solve the stochastic ECR problem. By considering more information on the uncertain parameters, this scenario-based method can provide better ECR decisions than the current approach in shipping industry which only considers the expected value of the uncertain parameters. In their study, opinions of shipping companies were considered to generate scenarios when the distributions of uncertain parameters cannot be estimated through historical data. The multi-scenario model provided by Francesco et al. (2009) is subject to a small number of scenarios. Our study focuses on developing scenario-based model when the distribution of uncertain parameters can be estimated. In shipping industry, ocean liners usually keeps historical data on some uncertain parameters. Based on the data, distributions of these parameters in the future are able to be forecasted. Random scenarios could be generated based on these distributions.

The stochastic ECR problem with a large number of scenarios is usually difficult to solve. One of the most popular techniques for solving dynamic, stochastic programs is Approximate Dynamic Programming (ADP), which has been widely used to solve stochastic fleet management problem. Powell and Topaloglu (2005) used piecewise linear approximations for freight car distribution. Topaloglu and Powell (2006) showed that the ADP-based method works well for multi-commodity problem that arises in the dynamic resource allocation problem. Simao et al. (2009) applied ADP to a large-scale case which involves over 6000 drivers at a high level of detail. ADP also has been applied to solve the ECR problem in maritime shipping network. In Lam et al. (2007)'s study, the ECR problem was formulated as a dynamic stochastic programming with the decision policy optimal in the infinite horizon cost sense. They showed that linear approximation may be insufficient to fully describe the cost function for the multi-port multi-service system. While ADP is a good approach to solve the problem, one of the main challenges in ADP is the identifying a good cost-to-go function to represent the actual future cost. Innovative modeling which is able to exploit the structure of the problem is necessary for the function to have sufficient accuracy.

Interview with a shipping company reveals that weekly container shipping decisions require forecast of future demands, remaining vessels' capacities, and supply. Due to the dynamically changing environment and the low forecasting accuracy in container shipping industry, the forecasting has to be adjusted when new information is updated. Thus, we develop a two-stage stochastic model in rolling horizon policy to deal with the dynamically changing forecasting. As a widely used sampling method, SAA avoids the need to approximate the value function, and it is selected to solve the stochastic ECR problem with multiple scenarios in this study. By using the decomposition methods proposed in this paper, the sub-problem of the large-scale SAA problem could be efficiently solved by commercial software. To our knowledge, no existing study applies the SAA method to the stochastic ECR problem with a large number of scenarios. This study is to fill in this gap.

The main aim of this study is to apply optimization techniques to the real-time maritime ECR problem considering uncertainties. The first specific objective of this study is to propose a stochastic model for ECR which incorporates uncertainties. The SAA method is applied to solve this stochastic model. As the SAA problem usually has a large scale, the second specific objective is to solve the SAA problem.

The results of our study are significant for several reasons:

- The optimization model could be easily applied to the shipping industry as our model considered the actual service schedule and most port requirements.
- The stochastic model which considered some uncertain parameters may provide more robust decisions and thus the operation cost for ECR may be further reduced.
- The SAA method could be applied to solve the stochastic programs with a large number of scenarios, by which good solutions could be provided.
- The algorithms based on the progressive hedging strategy could be applied to deal with the SAA problem with multiple scenarios.

The remainder of this paper is organized as follows. In Section 2 we provide the description of our general problem. Section 3 shows the solving methodologies to solve our proposed model. Section 4 presents the results of computational studies. Finally, we give conclusions and outline directions for future research in Section 5.

2. Problem formulation

The focus of this study is to make operational level maritime ECR decisions for shipping companies. Due to the global trade imbalance, containers in surplus regions like Europe have to be repositioned to deficit regions like Asia. In this case, request for containers have to be placed in advance, so containers in the surplus region could be loaded to vessels and then be transported to the deficit region. However, the lead times of across-region orders are usually long. For example, in the port rotation of the westbound of Atlantic Pacific Express (APX) shown in Table 1, the transit day from New York to the first arrived port in Asia (Tokyo) is more than 30 days. The order for across-region empty containers from North America to Asia should be placed about 4 weeks in advance, so surplus empty containers could be loaded to vessels from New York, Norfolk, Charleston, Manhandle, Balboa, San Pedro and Oakland in turn according to the order. In actual situation, whether

Table 1
The port rotation of service APX (westbound).

Port	City	Transit day	Arrive	Transit day	Depart
F96	New York	–	–	00	Sat
KFK	Norfolk	01	Sun	02	Mon
KCS	Charleston	03	Tue	04	Wed
MIT	Manhandle	07	Sat	08	Sun
OAJ	Balboa	08	Sun	09	Mon
SPQ	San Pedro	16	Mon	17	Tue
OAK	Oakland	19	Thu	20	Fri
TKY	Tokyo	30	Mon	30	Mon
KOB	Kobe	31	Tue	31	Tue
CIW	Chiwan	34	Fri	35	Sat
HKG	Hong Kong	35	Sat	36	Sun
KAO	Kaohsiung	36	Sun	37	Mon
P2H	Busan	39	Wed	–	–