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Container vessel fleet deployment for liner shipping with stochastic dependencies in shipping demand

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ABSTRACT

The problem of optimal container vessels deployment is one of great significance for the liner shipping industry. Although the pioneering work on this problem dates back to the early 1990s, only until recently have researchers started to acknowledge and account for the significant amount of uncertainty present in shipping demand in real world container shipping. In this paper, new analytical results are presented to further relax the input requirements for this problem. Specifically, only the mean and variance of the maximum shipping demand are required to be known. An optional symmetry assumption is shown to further reduce the feasible region and deployment cost for typical confidence levels. Moreover, unlike previous work that tends to ignore stochastic dependencies between the shipping demands on the various routes (that are known to exist in the real world), our models account for such dependencies in the most general setting to date. A salient feature of our modeling approach is that the exact dependence structure does not need to be specified, something that is hard, if not simply impossible, to determine in practice. A numerical case study is provided to illustrate the proposed models.

1. Introduction

Maritime transportation forms the backbone of international trade (Talley and Ng, 2013). Indeed, estimates of the volume transported in world trade by sea are as high as 80% (UNCTAD, 2013). One important sector within the shipping industry is liner shipping. A liner shipping company transports containerized cargo, following a published sailing schedule on the routes it serves, typically with a weekly sailing frequency (Bell et al., 2013) although new operational models are emerging (Lin and Tsai, 2014). Competition among ocean carriers is known to be especially fierce in liner shipping (Talley, 2012; Lin and Huang, 2013).

One decision of critical importance faced by shipping lines is the fleet deployment problem in which the number and types of ships to be assigned to the shipping routes need to be determined, in order to maximize profits. (In the fleet deployment problem, it is typically assumed that the fleet size and mix is given, e.g. see Meng et al., 2013.) This fleet deployment problem has been first addressed in the literature by Perakis and Jaramillo (1991) and Jaramillo and Perakis (1991) who

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formulated (integer) linear programming models for this planning problem. In these early and subsequent studies (such as Liu et al., 2011; Gelareh and Meng, 2010), it was customary to assume that the container shipping demand was known with complete certainty. Only until recently has this assumption been relaxed, and has shipping demand been more realistically modeled as random variables (e.g. see Meng and Wang, 2010; Meng et al., 2012; Wang et al., 2013; Ng, 2014). Note that others, assuming deterministic demand, have embedded the fleet deployment problem within the liner shipping network design problem (e.g. see Brouer et al., 2013 and Plum et al., 2013). For an overview of these related problems, the reader is referred to the recent review paper by Meng et al. (2013).

Recently, Ng (2014) relaxed the then state-of-the-art assumption that probability distributions are readily available to characterize uncertain container shipping demand by introducing a distribution-free framework in which only a subset of the traditional information needs to be specified, i.e. the mean, standard deviation and a finite upper bound on the maximum shipping demand. (For brevity, in the remainder of this paper, we shall simply refer to a *finite* upper bound as upper bound.) In this paper, new contributions are presented that further advance modeling realism and improve the ease of use of the stochastic vessel fleet deployment problem: First, new models are presented that provide probabilistic guarantees on capacity/demand violations with even less assumptions, i.e. our models no longer require the specification of an upper bound. Instead, they only require knowledge of the mean and variance of the maximum shipping demand, with an optional symmetry assumption that can further reduce the size of the feasible region (and fleet deployment cost) for typical confidence levels. Second, contrary to Ng (2014), the results in this paper are fully analytical, which facilitates their implementation in practice. Third, the provided bounds are shown to be *sharp* under certain conditions (a detailed discussion of the issue of sharpness is deferred until Section 2). Fourth, the distribution-free framework is extended to incorporate the possibility of stochastic dependencies between the shipping demands among the various port pairs. As the specification of marginal probability distributions is already hard, if not impossible (cf. Ng, 2014), specifying stochastic dependence is even harder. Hence, rather than assuming specific dependence forms, with a very high risk of misspecification, we present models that are insensitive to the actual, unknown dependence structure.

The remainder of this paper is organized as follows. In Section 2, a brief review of a variation of a currently available stochastic demand fleet deployment model is presented. New, fully analytical results are then derived that do no longer require the specification of an upper bound on the maximum demand. Whereas Section 2 assumes stochastic independence, Section 3 examines the possibility of (unknown) stochastic dependencies among the shipping demands. A case study illustrates the proposed models in Section 4. Finally, Section 5 concludes the paper.

2. Model review and new analytical results: The case of stochastic independence

Consider the following liner fleet deployment model (e.g. see Meng and Wang, 2010 and Ng, 2014).

Sets

R	set of routes
K	set of ship types

Parameters

c^v_{kr}	the operating cost of a voyage for a ship of type $k \in K$ on route $r \in R$
c^i_k	the cost of chartering in a ship of type $k \in K$
c^o_k	the revenue of chartering out a ship of type $k \in K$
l_k	the number of ships of type $k \in K$ available in the liner company's own fleet
m_k	the maximum number of ships of type $k \in K$ that can be chartered from other ship owners
n_r	the number of voyages required on route $r \in R$ to maintain the liner's desired minimum sailing frequency
p	the planning horizon under consideration (in days)
t_{kr}	the transit time of a ship of type $k \in K$ to traverse route $r \in R$ (in days)
q_k	the capacity of a ship of type $k \in K$ (in TEU)
D_r	the maximum (random) shipping demand among all legs of the voyage on route $r \in R$
α_r	the maximum allowed probability to not meet the demand D_r on route $r \in R$

Decision variables

u_{kr}	the total number of ships of type $k \in K$ to be deployed on route $r \in R$
v_k	the number of ships of type $k \in K$ to be chartered from other ship owners
w_k	the number of ships of type $k \in K$ to be chartered out
x_{kr}	the number of voyages ships of type $k \in K$ completes on route $r \in R$