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A joint optimization model for liner container cargo assignment problem using state-augmented shipping network framework

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ABSTRACT

This paper proposes a state-augmented shipping (SAS) network framework to integrate various activities in liner container shipping chain, including container loading/unloading, transshipment, dwelling at visited ports, in-transit waiting and in-sea transport process. Based on the SAS network framework, we develop a chance-constrained optimization model for a joint cargo assignment problem. The model attempts to maximize the carrier's profit by simultaneously determining optimal ship fleet capacity setting, ship route schedules and cargo allocation scheme. With a few disparities from previous studies, we take into account two differentiated container demands: deterministic contracted basis demand received from large manufacturers and uncertain spot demand collected from the spot market. The economies of scale of ship size are incorporated to examine the scaling effect of ship capacity setting in the cargo assignment problem. Meanwhile, the schedule coordination strategy is introduced to measure the in-transit waiting time and resultant storage cost. Through two numerical studies, it is demonstrated that the proposed chance-constrained joint optimization model can characterize the impact of carrier's risk preference on decisions of the container cargo assignment. Moreover, considering the scaling effect of large ships can alleviate the concern of cargo overload rejection and consequently help carriers make more promising ship deployment schemes.

1. Introduction

In past decades, we have witnessed a booming development of global trade and economy, and already realized that maritime freight transportation turns to be more and more important for promoting world trade. Every year, more than 1.5 billion-ton productions are containerized and delivered to worldwide markets. According to the statistical report of maritime transportation review (UNCTAD, 2014), among all the seaborne cargoes, more than 50% by value are transported by the container shipping service, and the global containerized trade grew by 4.6% in 2013 taking total volumes to 160 million Twenty-foot Equivalent Units (TEUs), up from 153 million TEUs in 2012. Allured by a prosperous prospect of the growing shipping market, carriers would like to quickly expand related container shipping business, and consequently bring about intense competition in this active market. In order to enhance their competitiveness, the carriers desire to design more effective and efficient cargo allocation schemes to maximize their profits, particularly combining with other management strategies (e.g., ship schedule optimization and fleet deployment adjustment).

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In recent decades, the container cargo allocation/assignment problem has attracted much attention in the maritime studies, for example, Ronen (1983), Christiansen et al. (2004), Branchini et al. (2015), Brouer et al. (2011), Song and Dong (2012), Christiansen et al. (2013), Bell et al. (2013), Brouer et al. (2014), Norstad et al. (2011), Wang et al. (2014b), Karsten et al. (2015), to name but a few. For instance, Brouer et al. (2011) investigated the cargo allocation problem subject to the availability of empty containers and put forward both arc-flow and path-flow formulations. Bell et al. (2013) developed a cost-based liner container assignment model that minimizes the total shipping cost including container handling costs, container rental and inventory costs. Song and Dong (2012) discussed a joint optimization problem of cargo allocation and empty container repositioning in the operational level planning for a shipping network constituting with multi-route, multiple vessel types and multi-voyage. Though typically regarded as operational-level decision-making, the cargo allocation problem is often considered as a subproblem in many tactical-level decision problems, for example, in the network design problem (e.g., Agarwal and Ergun, 2008; Imai et al., 2009; Meng and Wang, 2011; Brouer et al., 2014), ship route schedule design (e.g., S. Wang et al. (2014)), fleet deployment optimization problem (e.g., Fagerholt, 1999; Branchini et al., 2015), and vessel speed optimization (e.g., Psaraftis and Kontovas, 2014; Fagerholt et al., 2015). Much of the literature has indicated that the decisions made in different planning levels always intertwine together (e.g., Christiansen et al., 2004; Agarwal and Ergun, 2008). For example, a tactical-level setting of ship route schedules invariably affects the results of operational-level cargo allocation.

In addition to deterministic cargo assignment models, a few researchers paid attention to the impact of demand uncertainty, for example, in container routing problem (e.g., Dong et al., 2015), container yard template planning (e.g., Zhen, 2014), and vessel fleet deployment optimization (e.g., Ng, 2014, 2015). For example, Dong et al. (2015) proposed a two-stage stochastic programming model to address the problem of joint service capacity planning and dynamic container routing in liner shipping network with uncertain demands. Interested readers are referred to Ronen (1983, 1993) and Christiansen et al. (2004) for early developments, and Christiansen et al. (2013), Meng et al. (2014) for a comprehensive literature and detailed discussions on recent advances.

Recently, quite a few researchers have pointed out that the container cargo assignment problem refers to a series of container shipment activities, including container loading/unloading, inter-transshipment among different ship routes and/or intra-transshipment of the same ship route at revisiting, dwelling at the visited port, in-transit waiting (transshipment waiting and delivery waiting at the origin port) and in-sea transport, etc. For example, Bell et al. (2013) considered the container handling costs, rental and inventory costs as well as in-sea shipping costs in the design objective function of the cargo assignment problem. Wang et al. (2014b) pointed out the importance of optimizing ship route schedules so as to address extra container storage costs of waiting for delivery. Recently, Karsten et al. (2015) recommended a framework of building dummy links to describe container transshipment operations. However, to the best of our knowledge, no existing network establishment approach is provided to make an explicit integration of various operations of cargo shipments from the viewpoint of container shipping activity chain. An integrated shipping network would help decision-makers precisely estimate the total cost of container cargo shipments and facilitate various applications of shipping network optimization. To bridge this gap, this study aims to propose a state-augmented shipping (SAS) network framework to build the integrated liner container shipping network.

In addition, several important and practical issues have not received sufficient attention in the literature yet, which are elaborated below.

(1) We start with the container cargo demand at current state. Almost all previous studies assumed that the container cargoes were collected from a homogeneous shipping market. Actually, a carrier receives fixed container cargoes subject to long-term contracts from large manufacturers, and meanwhile collects spot container cargoes from the spot market. It is not surprising that two categories of demands would exhibit quite diverse features. The contracted container cargoes are generally shipped with low freight rates; whereas shippers in the spot market need to pay high service charges. Moreover, different from the former deterministic contracted basis demand, the daily spot demand may inherently have high uncertainty. With the above disparities, we need to distinguish these two kinds of cargo demands in the cargo assignment problem, and should notice that the arising uncertain spot demand gives rise to new challenges in model formulation and impact evaluation of the carrier's risk preference.

(2) Another important issue is the economies of scale of large ships. The value of the scaling effect of ship capacity setting has not been sufficiently investigated in the literature of cargo assignment problem. The first quantitative assessment of the scaling effect of container ship size on aggregated shipping costs was carried out by Cullinane and Khanna (1999). Subsequently, Imai et al. (2006) discussed the container mega-ship viability by a comparison analysis between hub-and-spoke network for mega-ship and multi-port calling network for conventional ship size. Song and Dong (2012) took into account multi-vessel in the cargo allocation problem, but the economies of scale of ship size were not addressed. Wang et al. (2014a) stressed the importance of addressing economies of scale of large container ships in decision-making and considered the optimization of ship capacity setting as one of crucial game strategies in the marketing competition analysis.

Considering the scaling effect of different ship fleet capacity settings in the cargo allocation scheme is rewarding to the carrier. First, the differentiated shipping costs with respect to different ship fleet capacity settings generate a more precise estimation of the carrier's profit, which can assist the carrier to make tangible operational schemes. Second, a joint optimization combining ship capacity setting provides a tractable method to resolve the cargo overload