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Profit-based maritime container assignment models for liner shipping networks

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ABSTRACT

We propose the problem of profit-based container assignment (P-CA), in which the container shipment demand is dependent on the freight rate, similar to the “elastic demand” in the literature on urban transportation networks. The problem involves determining the optimal freight rates, the number of containers to transport and how to transport the containers in a liner shipping network to maximize the total profit. We first consider a tactical-level P-CA with known demand functions that are estimated based on historical data and formulate it as a nonlinear optimization model. The tactical-level P-CA can be used for evaluating and improving the container liner shipping network. We then address the operational-level P-CA with unknown demand functions, which aims to design a mechanism that adjusts the freight rates to maximize the profit. A theoretically convergent trial-and-error approach, and a practical trial-and-error approach, are developed. A numerical example is reported to illustrate the application of the models and approaches.

1. Introduction

Maritime transportation is vital to the world trade and economy. As reported by UNCTAD (2012), over 70% of global trade by value is carried by sea. A large proportion of general cargoes transported by ship are containerized. Containers are transported on liner shipping services with fixed sequences of ports of call and fixed schedules at a regular frequency. Liner container shipping networks operated by global liner shipping companies are complex. A liner shipping network may consist of several dozens of ship routes and several hundreds of ports. Containers can be transported between two ports on one ship route, or more than one ship route connected by transshipment. Therefore, it is a challenging task for a liner container shipping company to plan and operate an efficient shipping network.

As a consequence of the ever-increasing global container trade and the downturn of the shipping market, more and more research has been carried out to assist liner shipping companies to improve their shipping services (Christiansen et al., 2004, 2013; Meng et al., 2014). Liner container shipping planning problems can be classified into three categories: strategic, tactical, and operational. Examples of strategic problems are fleet planning and alliance formation. Container distribution at the strategic level, for example, for determining the fleet size in the future 20 years, is usually largely simplified. In fact, at the

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strategic level, the container shipment demand is generally aggregated to be from one continent to another without transshipment. As a result, container distribution is easy to formulate.

Tactical-level problems involve decisions that affect the operations in the next 3–6 months, such as designing ship routes or whether a ship route should be operated (Alvarez, 2009; Reinhardt and Pisinger, 2012; Mulder and Dekker, 2014), which type of ship should be deployed (Fagerholt, 1999, 2004; Fagerholt et al., 2009), and determining the sailing speeds and emissions of ships (Psaraftis and Kontovas, 2010, 2013, 2014; Qi and Song, 2012; Psaraftis, 2012). Container assignment, also called container routing, that is, how to transport containers from their origins to their destinations, is often incorporated in models for making tactical-level decisions. Nevertheless, at the time of making tactical-level decisions, the container shipment demand can only be estimated. Therefore, the purpose of container assignment in tactical-level models is to evaluate the quality of the tactical-level decisions, for example, which candidate liner shipping network is more profitable. The container assignment decisions will not be implemented because the real demand may be different from the estimated one used for evaluating tactical-level decisions.

Agarwal and Ergun (2008) designed a liner container shipping network to maximize the profit. They assumed that the container shipment demand and the revenue for shipping one container between two ports in each day of a week was known and constant over the planning horizon. The liner shipping company could freely choose which containers to transport. Container storage cost at ports and the marginal shipping cost for transporting one more 20-foot equivalent unit (TEU) on a voyage leg were formulated. However, to simplify the problem, the container transshipment cost was not considered at the network design stage. Brouer et al. (2014) also examined network design problems and they further provided a rich database of benchmark problem instances for researchers to compare different network design algorithms. In contrast to Agarwal and Ergun (2008), Brouer et al. (2014) considered the aggregated demand between ports in each week rather than in each day of a week. Wang and Meng (2013) developed a network alteration approach that also incorporated a fixed weekly demand. Shintani et al. (2007), Meng and Wang (2011), and Song and Dong (2013) have considered both laden and empty containers in network design.

Brouer et al. (2011) developed a tactical planning tool including a delayed column generation approach that could efficiently find the optimal container assignment. In their model, the container shipment demand and the revenue for shipping one container between two ports in each period of the planning horizon were known. The liner shipping company chose only the most profitable containers to transport. Bell et al. (2011) proposed a frequency-based container assignment model to minimize the sailing and dwell time of containers. Based on this work, Bell et al. (2013) proposed a cost-based container assignment model to minimize the sum of container handling costs, inventory costs of laden containers and both laden and empty container leasing costs. Both studies belong to the category of tactical-level container assignment models. Similar to Brouer et al. (2014), in Bell et al. (2011, 2013) the container shipment demand between ports in a week was known and fixed over the planning horizon. Unlike Agarwal and Ergun (2008) and Brouer et al. (2014) in which the liner shipping company could choose which containers to transport, the container shipment demand in Bell et al. (2011, 2013) must be fulfilled by the whole liner shipping network consisting of shipping services from all liner shipping companies in the world. Moreover, in contrast to Agarwal and Ergun (2008) and Brouer et al. (2014) that have aimed to design better shipping services for a single liner shipping company, the main purpose of Bell et al. (2011, 2013) was to predict the future (3–6 months) container flow pattern all over the world, which could be used by shipping lines, port authorities, terminal operators, shippers, national and regional planning authorities as well as marine insurers. Wang (2014) reviewed three link-based formulations for container flow optimization—origin–destination-based, origin-based, and destination-based—and proposed a new compact hybrid-link-based formulation.

Operational-level container assignment aims to come up with implementable decisions on the detailed routing of containers. Song and Dong (2012) assumed a known container shipment demand between any two ports in each period in the planning horizon. They captured a detailed cost structure and minimized the total costs while requiring that all container shipment demand must be fulfilled and empty containers must be repositioned.

Some studies have considered uncertain container shipment demand. Meng et al. (2012) examined a container ship fleet deployment problem taking into account uncertain container shipment demand with known probability distribution. Ng (2014) developed a robust fleet deployment model with limited information on the probability distribution of demand. Meng and Wang (2012) investigated the fleet deployment problem considering different demands in different weeks of a planning horizon. Wang et al. (2013a) analyzed the worse-case outcome out of all of the demand scenarios that formed a polyhedron.

It can be seen that all of the above-mentioned laden container assignment studies have assumed that the container shipment demand is exogenous. Wang et al. (2013b) developed a branch-and-bound approach for ship scheduling assuming that the demand is a decreasing function of the transit time, called transit-time-sensitive demand. Hence, the demand in Wang et al. (2013b) is endogenous.

There is also a stream of literature that is solely dedicated to the transportation of empty containers. The studies in this stream usually assume that laden containers have the priority and laden container routing is a given input. Empty container repositioning and the fleet size of containers are two topics that are addressed in models. Some works have taken a deterministic approach, such as Choong et al. (2002) and Erera et al. (2005). Most investigations, especially recent ones, have focused on stochastic/uncertainty factors of the problem. Crainic et al. (1993) examined the inland transportation of empty containers between ports, depots and customers. Cheung and Chen (1998) proposed a two-stage stochastic network model to capture the stochastic and dynamic nature of the empty container repositioning problem. Lam et al. (2007) presented an