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Liner shipping service network design with empty container repositioning

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ABSTRACT

This paper proposes a liner shipping service network design problem with combined hub-and-spoke and multi-port-calling operations and empty container repositioning. It first introduces a novel concept – segment – defined as a pair of ordered ports served by one shipping line and subsequently develops a mixed-integer linear programming model for the proposed problem. Extensive numerical experiments based on realistic Asia–Europe–Oceania shipping operations show that the proposed model can be efficiently solved by CPLEX for real-case problems. They also demonstrate the potential for large cost-savings over pure hub-and-spoke or pure multi-port-calling network, or network without considering empty container repositioning.

1. Introduction

A liner container shipping company operates a fleet of ships deployed on its shipping lines comprising a series of ports to transport containers from one port to another at a regular service frequency. Liner container shipping companies are transporting more containers than before due to the ever-increasing container shipment demand, as well as acquisition, consolidation and merging within the liner container shipping industry. As a result, they deploy large ships sailing among hub ports to benefit the economies of scale. The increase in ship size and shipment demand also leads to a shift of the ship deployment strategy from multi-port-calling (MPC) to combined hub-and-spoke (H&S) and MPC especially for global liner container shipping companies such as Maersk (2010). The combined H&S and MPC operations have some common characteristics as the conventional H&S operations used in airline and telecommunication networks: large ships are deployed on main shipping lines serving hub ports, feeder shipping lines with small ships are provided to serve feeder ports whose container volumes are not large enough to justify a direct call and some containers have to be transshipped at hub ports. However, the combined H&S and MPC operations in liner shipping have two unique features as follows: (a) container transshipment cost and handling time cannot be negligible because they constitute a substantial portion of the operating cost and the round-trip time, respectively; (b) direct container shipment between any two ports including feeder ports is allowed. These two unique features make the combined H&S and MPC operations significantly different from the conventional H&S operations assumed by existing studies on the conventional hub-and-spoke network design in which the transfer cost at hub nodes are not accounted for and all shipment between two spoke nodes must be transferred at the corresponding hub(s) (see Alumur and Kara (2008), for a review).

In addition to transporting laden containers from shippers, liner container shipping companies have to reposition their empty containers caused by the imbalance of import and export trade. Take the trans-Pacific trade lane for example: container flow from Asia to North America is estimated at 15.4 million twenty-foot equivalent units (TEUs) in 2007, while in the opposite westbound direction, the flow is only 4.9 million TEUs (UNCTAD, 2008). This imbalance leads to the empty

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container accumulation in import-dominant areas (North America) and shortage in export-dominant ones (Asia). Hence, these empty containers have to be repositioned from the former to the latter.

The volume of laden containers transported by a particular liner container shipping company between two ports varies after a period of 3–6 months. For example, the laden container volume from Asia to Europe often increases significantly in the fourth quarter of a year due to the Christmas Day. Thus, every 3–6 months, the liner container shipping company has to alter its current liner shipping service network and redeploy ships according to the port-to-port container shipment demand forecasted for the next 3–6 months. This alteration aims to determine which shipping lines among many candidate shipping lines should be chosen to operate, what type of ship and how many ships should be deployed on each chosen shipping line, how to route laden containers and reposition empty containers subject to the combined H&S and MPC operations with the objective of minimizing the total operating cost. This decision problem within a medium-term planning horizon, i.e., 3–6 months, is referred to as the liner shipping service network design problem with combined H&S and MPC operations and empty container repositioning. The purpose of this study is to develop a proper mathematical model for this problem that can be efficiently solved by widely used optimization solvers such as CPLEX.

1.1. Literature review

There are mainly two types of studies on the shipping service network design problem: tramp shipping service network design and liner shipping service network design (see Ronen (1983, 1993), Christiansen et al. (2004); for reviews). The former type deals with ship routing and/or fleet deployment for transporting bulk cargo such as coal and iron ore without taking into consideration of the H&S shipping operations. This is because in tramp shipping the cargo volume between each origin–destination (O–D) port pair is very large and hence cargo consolidation at hubs is unnecessary. The existing studies on the liner shipping service network design problem can be classified into two categories – with and without H&S operations – which are reviewed below.

For the liner shipping service network design with the conventional H&S operations, in a pioneering study, Fagerholt (1999) investigated a feeder shipping service line design problem for a special H&S shipping network with one hub port and many feeder ports. He proposed a set-partitioning model by enumerating all the possible shipping service lines and combining these single shipping service lines into multiple shipping service lines if possible. This model is reliant on the assumption that all ships have the same sailing speed. Fagerholt (2004) extended this set-partitioning model to address a heterogeneous ship fleet with a given cost structure, capacity and in particular, sailing speed, for each type of ship. Sambracos et al. (2004) carried out a case study on the feeder shipping service line design to dispatch small containers in the Aegean Sea, from one depot port (Piraeus) to 12 other ports (islands). They assumed a homogeneous ship fleet to meet container shipment demand with minimum operating cost including fuel consumption and port charges. This problem is later generalized by Karlaftis et al. (2009) to account for container pick-up and delivery operations as well as time deadlines. They formulated this extended problem as a vehicle routing problem (VRP) with pick-up and delivery and time windows. The feeder service network design issue raised by these four papers has specific features that distinguish the feeder network from global liner shipping network. The foremost distinction is that liner shipping companies adopt the conventional H&S operations in a feeder service network with a single hub port. The hub port can be treated as the depot in conventional VRPs. Therefore no transshipment exists in these feeder shipping service networks.

For the liner shipping network design without H&S operations, Rana and Vickson (1988) contributed a seminal work by building a mixed-integer linear programming model for a single shipping line design problem. Rana and Vickson (1991) later extended this model to design multiple shipping lines. They employed the Lagrangian relaxation method for solving their mixed-integer linear programming model. In both models, the port-calling sequence by a ship is predetermined and cargo transshipment operation is not allowed. Shintani et al. (2007) relaxed the assumption of port calling precedence and also considered empty container repositioning to design a single shipping line. They employed the genetic algorithm to solve their problem. Still, transshipment is excluded. To incorporate cargo transshipment, Agarwal and Ergun (2008) proposed a multi-commodity based space-time network model for the liner shipping service network design problem with cargo routing. This model covers heterogeneous ship fleet, weekly service frequency, multiple shipping lines and cargo transshipment operations. In order to simplify the space-time network and algorithm design, transshipment cost at ports is not taken into account at the network design stage, and the time spent by a ship at a port is considered as constant no matter how many containers are handled.

There are some academic studies on the cost-effectiveness comparison between the conventional H&S operations and MPC operations. Hsu and Hsieh (2007) formulated a two-objective optimization model by separately minimizing shipping cost and inventory cost to decide whether to route a shipment through a hub or directly to its discharge port. Their model also incorporates ship deployment including ship size and mix, and service frequency determination for a given shipping service network. Imai et al. (2006) studied the economic viability of mega-containerships by means of a game-theory model. Based on this model, Imai et al. (2009) compared the efficiency of two shipping network topological structures with empty container repositioning: conventional H&S network and MPC network. The networks investigated in these studies are either pure H&S network or pure MPC network, but not the combined H&S and MPC network.

The empty container repositioning issue has received more attention recently (e.g., Cheung and Chen, 1998; Li et al., 2007; Lam et al., 2007; Dong and Song, 2009; Francesco et al., 2009). These studies investigate empty container repositioning at the *operational* level, thereby requiring a higher priority for loaded containers, whereas empty containers are hauled with