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Liner shipping network design with deadlines

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ABSTRACT

It is crucial for a liner shipping company to design its container shipping network. Given a set of port-to-port container shipment demands with delivery deadlines, the liner shipping company aims to design itineraries of portcalls, deploy ships on these itineraries and determine how to transport containers with the deployed ships in order to maximize its total profit. In this paper we first demonstrate NP-hardness of this problem and subsequently formulate it as a mixed-integer non-linear non-convex programming model. A column generation based heuristic method is proposed for solving this problem. Numerical experiments for container shipping on the Asia–Europe trade lane show that the proposed solution algorithm is efficient to find good quality solutions.

1. Introduction

Liner container shipping is characterized by high operating cost as a liner shipping company has to maintain its published services on a regular basis even when a full payload of container is not available. A large proportion of the operating cost is determined at the stage of shipping network design. Liner shipping network design is a medium-term planning decision made by a liner shipping company every 3 to 6 months. Since the financial crisis in 2008, liner shipping companies have to cut down their operating costs in order to survive in the competitive container shipping market with low freight rate. Predictably, they can benefit from designing/altering their liner shipping networks. With a small ship fleet, it is possible to design the network from a limited number of candidate ship routes (or services) based on experience of liner service designers. However, global liner shipping companies own a much larger ship fleet due to acquisition, merger and collaboration. Without the aid of the systematic optimization techniques, it is almost impossible to design an efficient liner shipping network.

In the near-homogeneous liner shipping market, offering short transit time from an origin port to a destination port is an important factor, especially when the goods involved are time sensitive. Typical examples are perishable goods and consumer goods such as fashion and computers [16]. Transit time also has implications for port operators. The first portcall in an area usually means shorter transit time than other ports in the area, and hence shippers prefer to choose it as the discharge port. Therefore, port operators (for example, West European ports due to their geographical proximity) are striving to be the first portcall in the area. In fact, liner shipping companies have a target transit time or "market level" transit time for each pair of ports. The market level transit time has to be maintained in the shipping network design. This market level transit time can be considered as the delivery deadline, that is, a liner shipping company must warrant a level of service such that the real transit time from an origin port to a destination port does not exceed the delivery deadline. Therefore, to design an efficient liner shipping network while satisfying the market level transit time requirement is a practical decision issue faced by liner shipping companies. This issue is referred to as liner shipping network design problem with deadlines (LSNDPD) hereafter.

1.1. Literature review

Compared to the tramp shipping network design [20,21,6–9,4,11,13], liner shipping network design has attracted much fewer research efforts [15]. Rana and Vickson [17] contributed a seminal work by proposing a mixed-integer linear programming model for a single liner route design. Rana and Vickson [18] later extended this model to design multiple liner routes. They employed Lagrangian relaxation method for solving the mixed-integer linear programming models. Shintani et al. [22] used a genetic algorithm to design a single liner route while taking into account empty container repositioning. Agarwal and Ergun [1] proposed a multi-commodity based space–time network model for the liner shipping network design with cargo routing. This model covers heterogeneous ship fleet, weekly service frequency, multiple liner routes and cargo transshipment operations. Agarwal and Ergun [1] proved that the general network design problem is weakly NP-hard as it can be reduced to a knapsack problem.

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Alvarez [2] developed heuristic solution methods to design liner shipping networks while considering different sailing speeds. Gelareh et al. [12] examined the design of a hub-and-spoke network for a liner shipping company. Blander Reinhardt and Pisinger [19] presented a branch-and-cut approach for designing butterfly ship routes. Song and Dong [23] designed a ship route with multiple cycles. Brouer et al. [5] provided a benchmark suite for liner shipping network design problems. They further proved that the general network design problem is strongly NP-hard as it can be reduced to a traveling salesman problem. Moreover, the general network design problem with a set of candidate port rotations is strongly NP-hard as it can be reduced to a set covering problem.

The liner shipping network design models mentioned above basically have the following two assumptions. First, they implicitly assume that the time spent by a ship at a particular port, which is called port time, is constant. Nevertheless, port time actually depends on many port related factors such as number of quay cranes deployed, availability of prime movers, efficiency of yard operations, and stowage plan for container ships. In fact, about 21% of the scheduled round-trip time is port time [16] and most of the port time is used for container handling. Thus, two parameters are the most essential to reflect port time in network design: number of containers handled and productivity (average handling time for one container) of a port. When designing a liner shipping network, we do not know the number of containers handled at a particular port on a certain liner route beforehand. It is thus more reasonable and practical to formulate the port time as a function of the number of containers handled. Second, and more important, no transit time requirement from an origin port to a destination port is considered in the above studies. Since shippers will turn to other shipping companies if the transit time is too long, shipping network designers always keep in mind the market level transit time when designing a service.

1.2. Objectives and contributions

The objective of this study is to develop an optimization model and design a tangible solution algorithm for the liner shipping network design problem with deadlines (LSNDPD). The aforementioned literature review clearly shows that the LSNDPD is a new research issue with practical significances. For each origin–destination (O–D) port pair, there is a potential container shipment demand and to fulfill the demand (or part of the demand) the real transit time must not be longer than the market level transit time or deadline. The LSNDPD aims to design itineraries of portcalls (port rotations), deploy ships on these itineraries and determine how to transport containers with the deployed ships in order to maximize total profit.

The LSNDPD is quite different from vehicle routing problem with pickup and delivery and time windows (VRPPDTW). First, the number of calls at a port is unknown since the LSNDPD allows split delivery of containers among different ships. As a result, the load/discharge volume when a ship visits a port is also unknown. Second, in the LSNDPD, each port serves as the origin port (pickup port) and destination port (delivery port) for many other ports. Third, the port time is a function of the number of containers handled at the port. Fourth, a fixed weekly service frequency has to be maintained because weekly service is the convention in liner shipping. The inclusion of deadlines and variable port time brings a great challenge to the problem in that design of a service route (itinerary and ship deployment) and determination of its container delivery pattern (volume of containers delivered for each O–D port pair) have to be investigated simultaneously. As a result of the fixed service frequency and variable port time, the number of ships required on a geographical route (itinerary of portcalls) also needs to be determined on the basis of the container delivery pattern. The LSNDPD is also different from vehicle routing problem with split delivery (VRPSD). Besides the container handling time, deadlines, and weekly service requirement that are different from VRPSD, two liner routes may have more than one split customer in common. Nevertheless, in VRPSDs, there exists an optimal solution in which no two routes have more than one split customer in common [10]. These characteristics make the LSNDPD inherently different from the VRPs, and hence new models and algorithms have to be developed.

In this paper, we first demonstrate that the LSNDPD is NP-hard, and the LSNDPD can be formulated as a mixed-integer non-linear non-convex programming model. We subsequently propose a column generation based heuristic method where a column corresponds to a service route together with its container delivery pattern. Extensive numerical experiments of container shipping on the Asia–Europe trade lane show that the proposed solution algorithm is efficient to find good quality solutions.

The remainder of this paper is organized as follows. Section 2 elaborates liner shipping network design problem with deadlines. Section 3 shows NP-hardness of the problem NP-hard and formulates it as a mixed-integer non-linear non-convex programming model. Section 4 develops a column generation based heuristic method for solving the model. Section 5 carries out numerical experiments on the Asia–Europe shipping service operations of a global liner shipping company to assess computational performance and practical significance of the proposed model and algorithm. Conclusions and future works are presented in Section 6.

2. Notation, assumptions and problem description

Consider a liner shipping company that designs its shipping network consisting of ship routes to transport containers over a set of ports denoted by $P = \{1, 2, \ldots, n\}$ where n is the number of ports in the network. These ports are usually visited according to a natural sequence such as their geographical locations. A typical example is the Asia–Europe trade lane shown in Fig. 1 and a ship operated by a liner shipping company sailing from west to east (eastbound) visits the ports in the following way: Southampton → Sokhna → Jeddah → Salalah → Colombo → Singapore → Hong Kong → Xiamen → Ningbo → Shanghai → Qingdao → Dalian. Ports are visited in the opposite sequence on the westbound voyage.

A ship route comprises a rotation of ports with inbound and outbound directions. The outbound and inbound voyages of a ship route may be asymmetrical in practice, that is, some ports are called by ships in either the outbound or inbound direction but not both, as shown in Fig. 2. Moreover, the two end ports where a ship reverses its direction are also to be determined in ship route design. Each ship route is deployed with a string of homogeneous ships to maintain the weekly service frequency. Let V denote the set of ship types available and lowercase letter v stand for a particular ship type. Ships in the same type are homogeneous in terms of load capacity, average sailing speed, cost structure and other ship-specific properties. Represent by Cap_v the container capacity (20-foot equivalent units or TEUs) of a ship in type v.

For the sake of presentation, a ship route is further classified as follows. A sequence of portcalls that forms an outbound and an inbound voyage is termed as a *geographical ship route*. A geographical ship route together with its deployed type and number of ships is called a *service ship route*. A service ship route together with its container delivery pattern, that is, the number of containers for each O–D port pair to transport, is referred to as a *full ship route*.