ARTICLE IN PRESS

Transportation Research Part E xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Time constrained liner shipping network design

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ARTICLE INFO

Article history:
Received 4 December 2015
Received in revised form 4 February 2016
Accepted 2 March 2016
Available online xxxx

Keywords:
Liner shipping
Network design
Transit time
Transshipments

ABSTRACT

We present a mathematical model and a solution method for the liner shipping network design problem. The model takes into account coordination between vessels and transit time restrictions on the cargo flow. The solution method is an improvement heuristic, where an integer program is solved iteratively to perform moves in a large neighborhood search. Our improvement heuristic is applicable as a real-time decision support tool for a liner shipping company. It can be used to find improvements to the network when evaluating changes in operating conditions or testing different scenarios. Computational results on the benchmark suite *LINER-LIB* are reported.

1. Introduction

The *time constrained liner shipping network design problem*, TCLSNDP, is a core planning problem faced by container carriers. The problem is to design a set of cyclic routes, *services*, for container vessels to provide transport for goods while respecting cargo travel time restrictions. The objective of the problem is to maximize the profit of the liner shipping company through the revenues gained from container transport taking into account the fixed cost of deploying vessels and the variable cost related to the operation of the routes and the handling cost of cargo transport. As a consequence of maximizing profits the liner shipping network design problem generally allows rejection of some commodities if deemed unprofitable.

Liner shipping companies offer a range of services that are operated according to a published schedule with a fixed frequency to make it easier for customers to plan ahead. *Scheduling* decisions refer to the temporal aspect of the vessel routings and include the timing of events along the entire round trip. A *fleet* of vessels is deployed to the services such that the capacity and speed is in accordance with the demand maintaining the desired frequency. Global carriers generally deploy vessels with similar characteristics to a service to reduce the complexity of the network design and corresponding schedules (Notteboom and Vernimmen, 2009; Stopford, 2009). The services give rise to a network of related ports. Containers, or more generally commodities, are transported through the network from port A to port B, and a transport may include the use of several services to connect between the origin and destination ports. The transits between services are referred to as *transshipments* and the *transit time* is the time used to transport a container from origin to destination. Each transport must respect a maximal transit time restriction of each individual commodity. In practice transit times vary from one day to several months and most containers are transshipped no more than twice corresponding to a feeder – main line – feeder connection. However, some containers can be subject to more transshipments increasing the risk of delays and total handling time. Generally, customers prefer transports with no or few transshipments. The number of transshipments can vary

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http://dx.doi.org/10.1016/j.tre.2016.03.010
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Please cite this article in press as: Karsten, C.V., et al. Time constrained liner shipping network design. Transport. Res. Part E (2016), http://dx.doi.org/10.1016/j.tre.2016.03.010

based on the origin and destination regions. A network with direct connections between all serviced ports would offer low transit times and no transshipments, but at the same time it would be very expensive to operate for the carrier as most pairs of ports do not have enough container demand to fill a vessel. This illustrates the trade-off faced by liner shipping companies between the cost of networks versus transit time and/or number of transshipments offered to the customers. Providing low freight rates by minimizing the cost of the network is likely to result in prolonged transit times as exemplified in Karsten et al. (2015). Likewise designing a network to minimize transit times is likely to result in a very costly network since speed increases.

The main costs associated with the fleet include fuel cost, port and canal charges, and financing of vessels (this includes capital costs of acquiring or financing a vessel and the operational cost (OPEX) which includes crew, maintenance, and insurance). Stopford (2009) estimated the fuel cost to be 35–50% of a vessel's operational cost, capital cost to be 30–45%, OPEX to be 6–17%, and port cost to be 9–14%. This obviously depends on the fuel price and general economic environment. The cargo handling cost is calculated from the load and unload cost at the origin and destination ports and the cost associated with transshipments at intermediate ports. In addition to this, there are costs for the customer associated with owning or leasing containers. The load and unload costs do not depend on the routing of the container, whereas the transshipment cost does. Revenues are obtained by transporting cargo through the network and varies based on the type of cargo and the level of service offered.

Recent literature on the liner shipping network design problem, LSNDP, allows arbitrary transit times for all commodities (Brouer et al., 2014b,a; Liu et al., 2014; Wang and Meng, 2014; Mulder and Dekker, 2014; Plum et al., 2014; Reinhardt and Pisinger, 2012; Gelareh et al., 2010; Agarwal and Ergun, 2008) although it is generally acknowledged that transit times are decisive for the competitiveness of the network design, e.g. Brouer et al. (2014a). Initial work to construct a multi-criteria objective function is presented in Alvarez (2012) that considers a bi-linear expression for the inventory cost of the cargo on board vessels, but the level of service calculations are not computationally tractable in the already very complex liner shipping network design models. However, the inventory cost of commodities on board vessels is only indirectly a concern to the carrier, when excessive transit times result in the customers switching to a different carrier. Hence, the carriers concern is to ensure a maximal transit time corresponding to the market level of service. Wang and Meng (2014) introduce deadlines on commodities in a non-linear, non-convex mixed-integer programming (MIP) formulation of liner shipping network design with transit time restrictions. As a consequence the model does not allow transshipment of cargo, which is another common trait of the liner shipping network design problem.

Brouer et al. (2014b) develop a matheuristic for the LSNDP. The matheuristic is an *improvement* heuristic according to the categorization in the survey on matheuristics by Archetti and Speranza (2014) meaning that an integer program is used as a move operator. The present paper extends the method of Brouer et al. (2014b) to include transit times. Alvarez (2012) presents mathematical expressions for the inventory cost of containers during transport. No computational results are reported as the mathematical expressions are not easily incorporated into existing models of the LSNDP. In Wang et al. (2013) an integer program for deciding minimum cost container paths for a single OD pair respecting transit time and cabotage restrictions is considered. Karsten et al. (2015) present a column generation algorithm for a time constrained multicommodity flow (MCF) problem applied to a liner shipping network. A resource constrained shortest path problem is solved for each origin using a specialized label setting algorithm. Different topologies of graphs for liner shipping networks are presented. Computational results for solving the MCF problem with and without transit times on global-sized liner shipping networks are reported. The solution times for the time constrained MCF problem is comparable to solving the MCF problem without transit time restrictions. The algorithm of Karsten et al. (2015) is used in the matheuristic presented in this paper for evaluating a given network during the search. A liner shipping network design problem considering transit time restrictions is presented in Wang and Meng (2014). The model excludes transshipments between services. The problem is proven to be NP-hard and is formulated as a non-linear, non-convex mixed integer program. A column-generation-based heuristic is developed and a case study is presented for a network of 12 main ports on the Asia–Europe trade lane with three different vessel classes. The model is suggested as an aid to planners in a liner shipping company and the case study provides high-quality network suggestions and important insights to assist the planners. The authors suggest incorporation of transshipments along with transit time restrictions as an area of future research.

Meng et al. (2014) and Christiansen et al. (2013) provide broader reviews of recent research on routing and scheduling problems within liner shipping.

In this paper we present a capacitated multicommodity network design formulation for the TCLSNDP allowing for an arbitrary number of transshipments and enabling restrictions on transit time of individual commodities. This paper is an extension of a conference paper (Brouer et al., 2015) presented at ICCL'15 that proposed an adaptation of the matheuristic of Brouer et al. (2014b) to show that it is possible to incorporate the transit time restrictions in a heuristic context. Here, we introduce additional discussions on level of service requirements and show that it is tractable to incorporate a limit on the number of transshipments for each commodity. We present new computational results for incorporating transit time as well as limiting the number of transshipments. The benchmark instances presented in Brouer et al. (2014a), *LINER-LIB*, are used for the computational results of this paper. The benchmark instances contain maximum transit time for all OD pairs.

The rest of this paper is organized as follows: Section 2 introduces our mathematical model. Section 3 extends the integer program (IP) used as a move operator in Brouer et al. (2014b) to also consider transit times. Section 4 reports computational results for the benchmark instances. Section 5 shows the sensitivity to the provided transit times and Section 6 extends the algorithm and results with a limit on the number of transshipments. We end the paper by drawing conclusions and discussing extensions in Section 7.

Please cite this article in press as: Karsten, C.V., et al. Time constrained liner shipping network design. Transport. Res. Part E (2016), http://dx.doi.org/10.1016/j.tre.2016.03.010