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Global intermodal liner shipping network design

Zhiyuan Liu [a,*], Qiang Meng [b], Shuaian Wang [c], Zhuo Sun [d,e]

[a] Institute of Transport Studies, Department of Civil Engineering, Monash University, Clayton, Victoria 3800, Australia
[b] Department of Civil and Environmental Engineering, National University of Singapore, 117576 Singapore, Singapore
[c] School of Mathematics and Applied Statistics, University of Wollongong, Wollongong, NSW 2522, Australia
[d] Transportation Management College, Dalian Maritime University, Dalian 116000, China
[e] Centre for Maritime Studies, National University of Singapore, 118425 Singapore, Singapore

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ABSTRACT

This paper presents a holistic analysis for the network design problem of the intermodal liner shipping system. Existing methods for liner shipping network design mainly deal with port-to-port demand. However, most of the demand has inland origins and/or destinations. Thus, it is necessary to cope with inland origin–destination (OD) pairs involving a change in transport mode from inland transportation to maritime shipping. A method is first proposed to convert inland OD demand to port-to-port demand. Then, a framework for global intermodal liner shipping network design is proposed. Finally, the proposed methodology is applied to and numerically verified by a large-scale network example.

1. Introduction

Container trade, which is the fastest-growing cargo segment in world seaborne trade, expanded at an average annual rate of 8.2% between 1990 and 2010. In 2010, container trade volumes reached 140 million twenty-foot equivalent units (TEUs), or over 1.3 billion tons (UNCTAD, 2011). Containers are generally transported by liner shipping companies on regularly serviced ship routes, which also involve container handling operations at loading, discharge or transshipment ports. A liner shipping company (the carrier) announces the schedules and itinerary for its liner shipping service to the customers (the shippers). The customers then decide which liner shipping service to use to transport their containers. Therefore, liner shipping services can be equated with bus services on a road network (Christiansen et al., 2004; Meng et al., 2013). Compared with other transportation modes, liner shipping is more secure, cost-efficient and eco-friendly. Rapid globalization has provided great impetus to the growth of container cargo demand in the liner shipping industry. Thus, to cope with the increased demand, liner shipping companies tend to redesign their liner shipping services approximately every three to six months to minimize operating costs and seek higher profits.

For the sake of presentation, a single liner shipping service is termed a *ship route*, and is uniquely decided by (a) the sequence and schedule of sea ports visited, and (b) the type and number of ships deployed on it. Most of the existing studies on liner shipping network design studies deal with port-to-port origin-to-destination (OD) pairs, meaning that both the origin and the destination of each OD pair are sea ports. Yet, in practice, most of the cargo demand originates from inland locations. For example, Chicago is not a sea port. If the origin and/or destination of a given OD pair is located inland, then it is termed an inland OD pair. For each inland OD pair, an *intermodal transportation* is required to, first, transport a container from its inland

* Corresponding author. Tel.: +61 3 99054951; fax:+61 3 99054944.
E-mail addresses: zhiyuan.liu@monash.edu (Z. Liu), ceemq@nus.edu.sg (Q. Meng), wangshuaian@gmail.com (S. Wang), mixwind@gmail.com (Z. Sun).

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origin to a sea port (by truck, train or barge) and, then, load it onto a liner ship. Thus a mode change is required at the sea port. Herein, any possible location for an origin or destination is termed an *equipment supply point* (EQSP) for the liner shipping company (the company calls it an EQSP because at the origin, the company needs to supply an empty container to the customer, and at the destination, the company needs to collect an empty container or an empty container is supplied to the company). Thus, apart from operating regular maritime liner shipping services between sea ports, a shipping company should also account for transporting inland cargo from its origin to a corresponding export port and then from an import port to an inland destination, using what is known as the *inland network*. Such transportation network design, taking into consideration both maritime liner shipping and the inland network, is termed global intermodal shipping network design.

Compared with designing seaborne liner services alone based on port-to-port demand, intermodal shipping network design is a more practical issue for the liner shipping companies. To better reflect the practical conditions, the transshipment is taken into account in this paper. In addition, the unfulfilled demand issue is also considered; for example, if the weekly demand at one port is 3001 TEUs, it is more profitable for the company to give up one container rather than using a larger container ship, and this one redundant container is termed as unfulfilled demand. These practical features have made it more challenging to solve the global intermodal shipping network design problem. This problem can be reduced to a general network design problem. Agarwal and Ergun (2008) proved that the general network design problem is weakly NP-hard as it can be reduced to a knapsack problem. Brouer et al. (in press, 2013) strengthened the result by proving that the general network design problem is strongly NP-hard as it can be reduced to a traveling salesman problem. Brouer et al. (in press, 2013) further proved that 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. Thus, the global intermodal shipping network design problem is also strongly NP-hard.

To the best of our knowledge, how to comprehensively solve the global intermodal liner shipping network design problem is still an open question in the literature due to its strong NP-hardness. Thus, this topic makes considerable theoretical contributions with practical significance, which is addressed in this paper.

1.1. Literature review

Due to its practical significance, the network design of liner shipping routes has attracted much attention from academic researchers. Rana and Vickson (1988, 1991), Shintani et al. (2007) and Song and Dong (2013) designed a single liner ship route without transshipment. Wang and Meng (2014) designed multiple ship routes without transshipment. Reinhardt and Pisinger (2012) investigated a butterfly ship route design problem where containers can be transshipped from one ship to another. Fagerholt (1999, 2004), Sambracos et al. (2004), and Karlaftis et al. (2009) examined feeder network design problems with one hub port and many feeder ports. Imai et al. (2009) and Gelareh et al. (2010) worked on a hub and spoke liner shipping network design problem with many hubs and many feeder ports. Agarwal and Ergun (2008), Álvarez (2009), Jepsen et al. (2011) and Meng and Wang (2011) studied more general network design problems where the transshipment of containers can occur at virtually any port. Wang and Meng (2013) proposed a novel liner shipping network alteration problem by reversing the port rotation directions. As a result, the designed network is more practical and easily acceptable by liner shipping companies. These studies, however, only deal with the port-to-port container demand, without considering the inland transportation and inland OD pair. There are also studies on container routing with given liner shipping network (Bell et al., 2011; Brouer et al., 2011; Song and Dong, 2012), which is actually a sub-problem of the addressed topic in this study.

Intermodal transportation is an important focus of the inland freight transportation. Intermodal freight transport is defined as the movement of goods in the same loading unit without handling of the goods when transported by different modes, see an in-depth review by Bontekoning et al. (2004) as well as the monographs by McKenzie et al. (1989) and Muller (1995) among many others. Macharis and Bontekoning (2004) have also reviewed the use of operations research in intermodal freight research. Most of these studies, however, only focus on the inland intermodalism; for example, rail-truck and barge-truck. Even when international cargo transportation is considered, seaborne container shipping is not taken as an available transport model. Meng et al. (2012a) considered both the inland and maritime network. However, the set of candidate ship routes are given a priori and no new ship routes are generated. Thus, the existing methodology is thus not available for the global intermodal shipping network design addressed in this paper.

1.2. Objectives and contributions

This paper addresses the network design problem for global intermodal shipping systems by providing a holistic methodology that covers both inland transport expenses and seaborne shipping costs/time. The container cargos are assigned to the best itinerary from their origin EQSP to their destination EQSP, considering the overall transport costs/time, which include (a) inland transportation costs/time, (b) container handling costs/time at loading and discharge ports, and (c) seaborne shipping costs/time. Moreover, to better reflect the real-life conditions, cargos from the same OD pair are allowed to be transported on different itineraries/routes, implying that these cargos would be handled at different ports and shipped via different ship routes. It should be noted that, for the inland transportation, the shipping companies do not usually operate the inland transport services themselves but purchase them from local transport companies (e.g., trucking companies).