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Network design, fleet deployment and empty repositioning in liner shipping

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ABSTRACT

We present an integrated modelling framework for the joint problems of network design, fleet deployment and empty repositioning in liner shipping. In our problem the number of service routes and their design are an endogenous part of the problem. The cost of a route is a set function mapping a subset of edges, vessel types and quantities to deploy to the set of non-negative real numbers. Since such cost structures cannot be accommodated in a compact formulation, our modelling framework, which is based on the paradigm of the Benders reformulation, integrates separate problems aiming to obtain a solution to the integrated problem. In this work we look at the Benders approach as a tool for integrating separate optimization problems rather than decomposing an integrated holistic optimization problem. Our numerical experiments show that the method is very efficient in solving instances of this problem with respect to both the problem size and the computational time.

1. Introduction

The container trade imbalance on a container flow direction refers to the situation in which the number of export and import containers (even with respect to the type of containers) differs significantly. This occurs for several reasons. While in developing countries the volume and even sometimes the value of import containerized freight is significantly more than the volume and value of export containerized freight, in some developed countries the imbalance is of a different nature. In the second group of economies, often the imbalance occurs because the import containers and the export containers are not of the same type, that is, one is composed of mainly 1-TEU (twenty-foot equivalent unit) containers and the other contains more 2-TEU (1-FEU, forty-foot equivalent unit) containers.

A major part of this imbalance is due to the spatial distribution of production and consumption centres and the nature of imports and exports in different economies around the globe (Wang, 2007). Maritime shippers spend on average $100 billion per year on operating their container assets, of which around $16 billion is spent on repositioning empty containers (Rodrigue, 2016). However, according to the UNCTAD (2015), in 2015 the global ports' throughput was almost 2.2 times the whole containerized trade volume, implying a significant load of repositioning activities.

The East-West trade imbalance is continuing to expand, and the operation is becoming increasingly costly. Among the three major East-West trade routes (i.e., Transpacific, Transatlantic and Europe-Asia), in 2015 carriers operating between Asia and North America had to reposition 1.2 million TEUs more than they did in 2014. This is an indication of the increasing

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imbalance on the corresponding trade routes. On the other hand, the amount of empty repositioning has decreased by around 600,000 TEUs for the trade between Asia and Europe (including the Mediterranean region). However, still on the corresponding route(s), the total number of empty containers repositioned is as high as around 7.8 million TEUs (UNCTAD, 2015).

Drewry concludes that *'The East-West trades were a bad place to be for ocean carriers in 2015. Carrier profitability/losses in 2016 will be heavily influenced by the exposure to hot or cold trades, while carriers should also expect additional associated empty container repositioning costs from the widening East-West services trade gap'* (see Waters (2016) and Container Insight Weekly[1]).

In the literature the problems of network design and empty repositioning in liner shipping are often studied separately. What we refer to as a 'network design problem' is the problem of designing from scratch a network (characterized by a set of nodes and a set of arcs incident to those nodes) and the corresponding service routes composed of those arcs (legs of calls) constituting the ship round trips. Our problem is not to choose routes only from among set of *a priori* existing and known ones.

In liner shipping service networks, three main patterns may be observed on a service route: (1) *pendulum* segments (Fig. 1a), which are in the form of direct calls between two major ports, (2) *butterfly* segments (Fig. 1b), in which certain ports are called at twice, and (3) *cyclic* segments (Fig. 1c), in which every port is visited exactly once on a route and which are composed of more than two ports. In practice, a route can be of a general form, as one can observe in Fig. 2.

Designing a liner shipping network from scratch is a complex process. Here, neither the total number of routes in an optimal design nor the combination and number of segments of each category on every route are known in advance. However, in reality one can exploit the existing knowledge of real practice to preprocess and identify: (1) the ports that must/must not be served by a main route, (2) the ones that must not be served unless by feeder services, (3) the direct links that are unlikely to be established (e.g. a call of a medium/mega-sized vessel to Greenland or Iceland, a normal call to a port in Libya before heading towards a U.S. port or a port call to an Israeli port before calling at Beirut in Lebanon or Tartous in Syria) and (4) the ports that cannot be called at unless using certain vessel classes (e.g. due to the draught limit, port efficiency issues, etc.).

1.1. Context and contribution

This work has been motivated by an industrial project that we carried out for a major (above the mid-size) liner shipping company to design a decision support system for analysing the operation. The results were validated through several months (over two years of CPU time) of computational experiments.

This work contributes in the following ways. It proposes the first integrated modelling framework and scalable algorithmic approach that can fully (with a practically accepted level of details) characterize the structure of an optimal operational network for a liner service provider. It allows liners to analyse their network in different scenarios (entire redesign or incremental and zonal redesign), such as fixing part of their network and analysing the remaining part. From the methodological point of view, it proposes a solution-method-driven modelling framework that can integrate separately designed models into a single optimization problem. More importantly, it extends the Benders decomposition to an exact method that can accommodate experts' knowledge.

1.2. Literature review

Over the past few years, this research area has become very active. However, the connection with the computational operations research is still rather weak. In the following we review some of the closely related work in the literature. We first review the articles dealing purely with the network design and deployment decision followed by those that also take into account empty repositioning feature.

Huang et al. (2015) addressed the problem of fleet deployment and empty repositioning. Although it is said to be a liner service network design problem, they assumed that the routes are precisely known in advance and one only decides on whether or not to deploy a vessel on a given route, thereby identifying whether or not it becomes part of the operational network. Here, no decision is made on the structure of a route. They proposed an MIP model and used CPLEX to solve it. Gelareh and Pisinger (2011) studied the problems of fleet deployment, network design and hub location. They proposed a mathematical model and a Benders decomposition algorithm. Their network structure is based on hub-and-spoke structures. However, no empty repositioning is taken into account, and the network structure is not of a general form. They solved rather small instances to optimality.

Reinhardt and Pisinger (2012) proposed another model for the liner shipping network design, taking into account the cost of transhipment, a heterogeneous fleet, route-dependent capacities and butterfly routes. Again no empty repositioning is taken into account. They proposed a branch-and-cut approach to solve instances of the problem. Shintani et al. (2007) addressed a network design and empty repositioning problems. They dealt with a single route, and the route is identified by solving a knapsack problem in a two-stage modelling framework. Fleet deployment and empty repositioning are considered in this modelling framework, and a genetic algorithm is applied to solve the problem.

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