European Journal of Operational Research 235 (2014) 367–377

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Methods for strategic liner shipping network design

Judith Mulder *, Rommert Dekker

Econometric Institute, Erasmus University Rotterdam, The Netherlands

ARTICLE INFO

Article history:
Available online 3 October 2013

Keywords:
Transportation
Liner shipping
Network design
Scheduling

ABSTRACT

In this paper the combined fleet-design, ship-scheduling and cargo-routing problem with limited availability of ships in liner shipping is considered. A composite solution approach is proposed in which the ports are first aggregated into port clusters to reduce the problem size. When the cargo flows are disaggregated, a feeder service network is introduced to ship the cargo within a port cluster. The solution method is tested on a problem instance containing 58 ports on the Asia–Europe trade lane of Maersk. The best obtained profit gives an improvement of more than 10% compared to the reference network based on the Maersk network.

1. Introduction

Seaborne shipping is the most important mode of transport in international trade. More than 80% of the international trade in 2010 is transported over sea (UNCTAD, 2010). In comparison to other modes of freight transport, like truck, aircraft, train and pipeline, ships are preferred for moving large amounts of cargo over long distances.

In the shipping market, three types of operations are distinguished: tramp shipping, industrial shipping and liner shipping (Lawrence, 1972). Tramp ships do not have a fixed schedule and are used for immediate deliveries where the most profitable freight is available. Therefore, the activities in tramp shipping are very irregular. In industrial shipping the cargo owner controls the ship and the objective becomes to minimize the cost of shipping. In liner shipping, ships follow a fixed route within a fixed time schedule; this is most common in the container trade.

The decision making in liner shipping can be distinguished on three different levels: the strategic, tactical and operational planning levels (Agarwal & Ergun, 2008). In the strategic planning level the optimal fleet-design is determined. This means that both the optimal number of ships in a fleet and the optimal ship sizes are determined in this level. This stage is very important, because the capital and operating cost in the (liner) shipping industry are very high. The ship-scheduling problem is solved in the tactical planning level. In this level, the service network is designed by creating ship routes and allocating the available ships to these routes. Finally, in the operational planning stage, it is determined which cargo is transported and which route(s) are used to ship the cargo. This problem is also referred to as the cargo-routing problem. The decisions made in a planning level influence the decision making in the other levels. Therefore, it could be profitable to solve the problems on the different levels simultaneously.

1.1. Literature review

Over the last decades, maritime transport has become a more popular field of research. In 1983 the first survey on ship routing and scheduling was published (Ronen, 1983). This survey gives a detailed overview on the research performed on ship routing and scheduling in the period before 1983. In a sequel, Ronen (1993) provides a detailed summary of published research on ship scheduling and related problem in the period from 1983 to 1993. Next, the survey of Christiansen, Fagerholt, and Ronen (2004) describes the major developments in the ship routing and scheduling problems in the period from 1994 to 2004. Finally, Wang and Meng (2011) give an overview of the most important existing literature on liner shipping studies and propose directions for further research.

Little research is performed on the determination of the optimal fleet design. Fagerholt (1999) develop a 3-phase solution approach to optimize the fleet size in liner shipping networks in which all feasible routes are generated and combined. Thereafter, the optimal fleet size is determined using a set partitioning problem, which is also solved in this phase. Powell and Perakis (1997) use an integer programming model to optimize the fleet deployment for a liner shipping company. They compare the results to the results obtained with a linear programming model. When using a linear programming model, manipulation of the results is needed to guarantee integer solutions. Both solution approaches become time consuming when the problem becomes larger.

Song et al. (2007) discuss a cargo allocation model with two objectives. The first objective is to minimize the unassigned cargo

* Corresponding author. Tel.: +31 10 4088903.
E-mail address: mulder@ese.eur.nl (J. Mulder).

0377-2217/$ - see front matter
http://dx.doi.org/10.1016/j.ejor.2013.09.041

volume. The second objective is to minimize total costs corresponding to a given minimal unassigned cargo volume. Because the model is very difficult to solve by analytical methods, the solution space is first truncated. Thereafter, the authors select priority rules and make use of heuristics to find solutions of the model.

Most research is related to the combined ship-scheduling and cargo-routing problem. First, Fagerholt (2004) and Rana and Vickson (1991) present integer programming problems to solve the combined ship-scheduling and cargo-routing problem. They are able to solve small instances in a reasonable amount of time, but for larger instances their methods become too time consuming.

Next, some research exists in which mathematical programming methods, like Benders decomposition, are used to solve the combined ship-scheduling and cargo-routing problem (see for example Agarwal & Ergun (2008), Álvarez (2009) and Gelareh & Pisinger, 2011). These methods can be used to solve some very small instances to optimality, but for larger instances heuristic methods are still needed.

1.2. Contribution and outline

The objective of this study is to develop a service network in liner shipping. The service network should consist of a set of routes, the allocation of ships to the routes, the sailing speed of the ships on each route and the allocation of cargo over the routes. We assume that the liner shipping company is free to select the ships it needs to cover the routes, but we impose a maximum number of routes to which certain ship sizes can be allocated to prevent that only very large ships will be allocated in the network. In other words, our goal is to solve the fleet-design, ship-scheduling and cargo-routing problems simultaneously, where we consider the case with limited availability of ships.

In comparison to the current literature, our main contribution is to provide a solution approach for the integrated network design problem, in which we incorporate methods for fleet-design, ship-scheduling, speed-selection and cargo-routing. Since large liner shipping companies have to change their networks quite often, this integrated problem is essential in the current economy. In our test set, substantial savings can be obtained by solving the network design problem in an integrated way.

This paper is organized as follows. In Section 2 the problem is defined in more detail. Next, in Section 3 the methods used to solve the combined problem are proposed. Section 4 describes results from a case study and in Section 5 the main conclusions from this research are drawn.

2. Problem formulation

We consider the combined fleet-design, ship-scheduling and cargo-routing problem with limited availability of ships. In this section, first the three individual problems are described. Thereafter, a formulation of the combined problem is given.

2.1. Fleet-design problem

The goal of the fleet-design problem is to determine the optimal composition of the fleet. In this problem, both the number and the size of ships in the fleet have to be determined. For the shipping company it is important to determine the optimal fleet design, because the costs related to the fleet are very high. Costs related to the fleet composition can be distinguished in two types: fixed cost (e.g. Capital Expenditures (CAPEX)) and variable cost (e.g. Operating Expenditures (OPEX)).

In this paper, we investigate the optimal fleet design of a liner shipping company, so we do not consider an initial fleet. Therefore, the company can choose ships freely, although the number of routes that can be performed with ships is limited for each ship size. In this way, we prevent unrealistic outcomes with many large ships in the fleet. Finally, we assume that all ships are available at the beginning of the planning period.

The underlying route network and demand have to be considered when determining the fleet composition of a liner shipping company. However, the fleet design is determined for 10–20 years, because of the high cost incurred by replacing a ship. In such a period, the demand structure can change, which can cause changes in the route network. Therefore, when determining the optimal fleet design, both present and future demand have to be considered.

Economies of scale are another important factor in purchasing new ships. Larger ships usually have lower transportation cost per TEU than smaller ships. However, the fixed cost of larger ships are higher than that of smaller ships. The demand on the route that the ship will serve also influence the decision of the ship size.

2.2. Ship-scheduling problem

In the ship-scheduling problem, the service network has to be designed. A service network consists of a set of ship routes and the allocation of ships to the routes. Furthermore, the optimal sailing speed has to be determined for each ship route. A ship route is a sequence of ports that are visited by a ship. The ship routes are cyclic and consist of a westbound and an eastbound trip. Each port can be visited at most once on the westbound trip and at most once on the eastbound trip. So, ports can be visited twice on a ship route.

The allocation of ships to routes can be restricted, because for example a port on the route cannot handle a certain type of ship. Once a ship is allocated to a certain route, it will serve this route during the whole planning horizon. Most shipping companies operate schedules in which each route is served once a week to maintain a customer base and to provide customers with a regular schedule (Agarwal & Ergun, 2008). Therefore, in general the number of ships needed for one ship route has to be at least equal to the number of weeks needed to complete an entire round tour (rounded above). In this paper we will also require weekly route schedules.

2.3. Cargo-routing problem

In the cargo-routing problem, the shipping company makes two decisions. They decide which demands they accept and which routes are used to transport this cargo from the origin to the destination port. When the cargo-routing problem is solved as an individual problem, the service network is assumed to be known beforehand. Our goal is to maximize the profit for one shipping company, so competition is not investigated. Revenues are obtained by transporting cargo between their origin and destination port. However, costs are also incurred by the transportation of the cargo. For some demand pairs the revenue that can be obtained will not exceed the cost incurred by transporting the cargo. This demand will then be rejected by the shipping company. Furthermore, it is possible that some profitable demands are rejected because other demands are more profitable.

When the demand of a demand pair is (partly) satisfied, the cargo will be picked up in the origin port and delivered at the destination port. When the origin port is visited on several ship routes, it has to be determined to which route the cargo is allocated. The same holds for the destination port. Some origin and destination ports will be visited on the same ship route, while other cargos have to be transhipped to other routes for which costs are incurred. All these decisions are made in the cargo-routing problem.