Transportation Research Part E 46 (2010) 76–89

Contents lists available at ScienceDirect

Transportation Research Part E

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

A novel modeling approach for the fleet deployment problem within a short-term planning horizon

Shahin Gelareh *, Qiang Meng

Department of Civil Engineering, National University of Singapore, Singapore 117576, Singapore

A R T I C L E   I N F O

Article history:
Received 23 February 2009
Received in revised form 3 June 2009
Accepted 7 June 2009

Keywords:
Liner shipping
Containership
Fleet deployment
Mixed integer programming
Linearization

A B S T R A C T

This paper is concerned with model development for a short-term fleet deployment problem of liner shipping operations. We first present a mixed integer nonlinear programming model in which the optimal vessel speeds for different vessel types on different routes are interpreted as their realistic optimal travel times. We then linearize the proposed nonlinear model and obtain a mixed integer linear programming (MILP) model that can be efficiently solved by a standard mixed integer programming solver such as CPLEX. The MILP model determines the optimal route service frequency pattern and take into account the time window constraints of shipping services. Finally, we report our numerical results and performance of CPLEX on randomly generated instances.

1. Introduction

Over the last decade, due to strong and rapid growth in world economy, shipping services have played an important role in international trades. For example, global container trade in 20-foot equivalent units (TEUs) is estimated to have increased by a factor of five since 1990, which is equivalent to an average annual growth rate of 9.8%. By May 2008, world containership fleet has reached about 13.3 million TEUs while 11.3 million TEUs are on fully cellular containerships.

There are three types of shipping services: (a) liner shipping, (b) industrial shipping and (c) tramp shipping (Christiansen et al., 2004). The liner shipping is specialized in proving reliable and regular services among ports along known sailing routes, and it is mostly used in the long haul maritime transport. Within a planning horizon, a liner shipping operator (company) has to make a decision on its fleet size, mix, allocation of vessel to routes, etc., in order to minimize the total fleet operating cost and keep a satisfactory service level for customers. For the sake of presentation, this decision problem is referred by fleet deployment problem (FDP).

It is well-known that fuel consumption cost normally accounts for more than 50% of the total operating cost of a merchant vessel (Papadakis and Perakis, 1989). The fuel consumption cost of a vessel is a nonlinear convex function with respect to its (sailing) speed. The vessel speed will affect the route service frequency provided by a liner shipping operator. Given a short-term planning horizon, it is interesting to formulate and solve a FDP with the decision variables – fleet size, mix, vessel speed, route service frequency, allocation of vessels to routes and Chartering-in/out strategy – for a liner shipping operator. This paper thus focuses on this short-term FDP. It should be pointed out that a long-term FDP usually does not need to consider the sailing speed and service frequency issue.

* Corresponding author. Tel.: +65 6516 5035; fax: +65 6779 1635.
E-mail address: cvegs@nus.edu.sg (S. Gelareh).

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doi:10.1016/j.tre.2009.06.004

1.1. Literature review

Regarding the bulk cargo shipping operations, (Nicholson and Pullen, 1971) is the pioneering work to model a long-term FDP for a bulk carrier who aims to determine fleet size, mix and allocation of vessels to routes with objective of minimizing life-cycle cost of a fleet. Their linear programming model does not include vessel speed and route service frequency because it deals with a long-term optimal decision problem. Benford (1981) found that vessel speed has significant impact on a fleet's annual operating cost for a bulk carrier providing shipping service between two ports (i.e., one origin–destination pair) although his solution approach to obtain the optimal speed was incorrect. Perakis (1985) resolved the deficiency in solution method of Benford (1981). Perakis and Papadakis (1987a,b) continued to investigate the optimal vessel speed problem by assuming two types of speed variables for each round trip between two ports: full load speed for the departure trip and ballast speed for the return trip. Papadakis and Perakis (1989) proposed a mixed integer nonlinear programming model for a FDP with multiple origin–destination, in which decision variables are fleet size, mix, vessel speed and allocation of vessels to routes. Again the full load and ballast speed variables are separated. In their model each vessel can be loaded at any origin, unloaded at a destination and return to the same origin. After relaxing the integer requirement for some decision variables, they applied a projected Lagrangian method developed for the nonlinear programming problem to solve their FDP. By exploiting especial property of the model, under certain conditions they decouple speed selection problem from the vessel allocation and use a linear programming approach to achieve optimal solution.

Perakis and Jaramillo (1991) and Jaramillo and Perakis (1991a) paved the way for further studies on FDP for liner shipping operators as this problem was received the least attention by researchers at that time. They proposed a realistic model with extensive details for estimating the operating costs of liner vessels on various routes. In their approach, the optimal vessel speed is determined independently and is used as a parameter in the resulting linear programming (LP) model. Additionally, they proposed two mixed integer (MIP) formulations which shown to be promising. Their work was later extended by Powell and Perakis (1997) who proposed an integer programming (IP) model to optimize fleet deployment of the liner shipping company *Flota Mercante Grancolombiana* (*FMG*). Xie et al. (2000) developed a dynamic programming model for a long-term FDP for liner shipping operators. Note that Perakis (2002) has surveyed the literature of the FDP until 2002.

Apparently, Perakis and his research collaborators have significantly contributed in developing mathematical programming models for various FDPs (Perakis and Jaramillo, 1991; Jaramillo and Perakis, 1991a; Powell and Perakis, 1997) and over more than one decade they have proposed a complete set of models and solutions to a series of problem in this area. A slightly different version of the FDP is also examined by Shintani et al. (2007) and Karlaftis et al. (2009), which, respectively, takes into account the empty container repositioning issue and pick-up and deliveries with respect to the deadlines.

So far in all these models (which are mostly related to bulk cargo) the optimal speeds are obtained independently and exogenously[1] (even some authors do not incorporate the speed issues in the liner shipping, e.g., Cho and Perakis (1996)). As a result, travel time of each vessel on each route (if operates on) will become known. This is in fact not realistic. Another drawback of such myopic approaches is that they prohibit the models from finding the optimal travel time of each vessel type which depends on the routes (laws, environmental barriers) and their characteristics (physical attributes of vessels) so that the optimal number of voyages of each vessel and lay-up times as well as the number of charter-in/out vessels can be determined. If the vessel speed is fixed at a myopic optimum, then there will not be sufficient flexibility for considering additional speed-related issues that implies different speeds on different legs. It is believed that the overall optimal solution for the FDP for liner shipping should be achieved by simultaneously considering all such factors.

1.2. Objectives and contributions

The FDPs comprise a wide scope of applications where each particular real-world application imposes specific features and constraints. Therefore, it requires developing a generalized approach so that most of the real-world applications can be easily derived from such a model. On the other hand, models of real-life applications should be easily solvable by the standard mixed-integer programming (MIP) solvers even in the absence of sophisticated solution algorithms.

In this paper, we propose a novel generalized mixed integer nonlinear programming model that works as a basis for FDPs within short-term planning horizon. This model is then linearized to make it effective for general-purpose MIP solvers to solve instances of FDP. A major superiority of this work to other existing work in literature is in the way that the speed is treated. Almost, in all the relevant works in literature, the travel time on routes are imposed by determining the optimal speeds of vessels. Our model finds the optimal travel times of vessels on different routes by taking into account the demand on route, the number of voyages of each vessel over planning horizon, lay-up costs, charter-in/out rates and the availability of charter services. Moreover, our modeling approach allows the model to decide on the optimal frequency of service.

This paper is organized as follow. Section 2 presents a complete and clear description of the FDP addressed by this study. In Section 3, we propose a mixed integer nonlinear formulation and its equivalent linearization along with addressing the flexibility of the proposed model. In Section 4, we present some computational improvements made on the formulations. Numerical results are reported in Section 5. Section 6 concludes our work.

[1] In fact this is mostly because the speed variables come into denominator and result in intractable models.