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A scenario-based dynamic programming model for multi-period liner ship fleet planning

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ABSTRACT

This paper proposes a more realistic multi-period liner ship fleet planning problem for a liner container shipping company than has been studied in previous literature. The proposed problem is formulated as a scenario-based dynamic programming model consisting of a number of integer linear programming formulations for each single planning period, and the model can be solved efficiently by a shortest path algorithm on an acyclic network. A numerical example is carried out to illustrate the applicability of the proposed model and solution method. The numerical results show that chartering in ships may not always be a better policy for a long-term planning horizon though it is much cheaper than buying ships in the short-term. Purchasing ships seems to be a more profitable investment in the long run.

1. Introduction

The increasing globalization and inter-dependence of various world economies are leading to a significant positive growth in seaborne trade. According to the review of maritime transport reported by the United Nations Conference on Trade and Development (UNCTAD) secretariat, international seaborne trade increased from 2566 million tons in 1970 to 8168 million tons in 2008 (Chapter 1 of UNCTAD (2009)). In particular, containerized trade by liner shipping is the fastest growing sector in global seaborne transportation, as a result of a combination of various factors, including dedicated purpose-built container vessels, larger vessels capable of achieving increased economies of scale, improved handling facilities in ports, and also the increasing amount of raw materials being carried in containers (here a container refers to the 20-foot equivalent unit [TEU]). With the continuous advancement of ship-building technology and the increase in global container traffic, the dominance of liner shipping is expected to continue to strengthen (Chapter 4 of UNCTAD (2009)).

In order to seize market share in an intensely competitive container shipping market, a liner container shipping company has to make a suitable strategic fleet development and management plan. Therefore, it is critical for such a company to project its fleet. The multi-period liner ship fleet planning (MPLSFP) problem aims to determine the optimal joint fleet development and deployment plan, within a multi-period planning horizon, for a liner container shipping company to effectively provide shipping services. A fleet development plan is used to identify the current and future types and quantities of ships required, while a fleet deployment plan is used to determine the assignment and operation of the fleet to transport containers. A joint fleet development and deployment plan thus includes chartering, purchasing, selling, assigning and operating ships. Hence, this paper focuses on model development and algorithm design for the MPLSFP problem with the objective of profit maximization subject to a given container shipment demand.

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1.1. Literature review

Multi-period or long-term fleet planning problems have been studied for the past several decades. Nicholson and Pullen (1971) were the pioneers in developing a dynamic programming model for a fleet management problem aiming to determine the best sale and replacement policy with the objective of maximizing long-term company assets. They proposed a two-stage decision strategy: the first stage determines a priority order for selling ships based on an assessment of the net contribution to the objective function if a ship is sold in a given year, regardless of the rate at which charter ships are taken on; the second stage uses the dynamic programming approach to find the optimal level of chartering for a given priority replacement order. However, this dynamic programming model is inapplicable for the MPLSFP problem addressed by this study because it does not include fleet deployment each year. Cho and Perakis (1996) developed an integer linear programming model for a long-term liner ship fleet planning problem looking to determine the optimal fleet size, mix and ship-to-route allocation. In their model, as long as those decisions are made at the beginning of the long-term planning horizon, they remain static over the whole horizon. Such a period-independent model cannot characterize a realistic dynamic decision strategy: the fleet size, mix and ship-to-route allocation should be adjustable period-by-period, since the container shipment demand is period-dependent. In other words, it is more rational and practical to assume that the fleet size, mix and ship-to-route allocation are period-dependent (dynamic) decisions rather than static ones. Xie et al. (2000) thus reformulated the long-term liner shipping problem proposed by Cho and Perakis (1996) by applying a dynamic programming approach. They first divided the long-term planning horizon into a number of single periods (each single period is one year). For each period, they used integer linear programming to determine the fleet size, mix and ship-to-route assignment incurring minimal cost. However, they assumed that the annual operating cost and transportation capacity of each ship on each route are constant. This assumption is unrealistic because the costs are voyage-dependent. For example, a ship making 20 voyages on a given route over a given year would certainly incur greater annual operating costs and have a greater transportation capacity than a ship making 10 voyages on the same route. Moreover, Xie et al. (2000) did not consider the important decision of the shipping service frequency for each route.

There have been a number of studies on single-period or short-term ship fleet planning problems. These studies focus on two topics: the fleet size and mix problem (FS&MP) and the fleet deployment problem (FDP). The FS&MP aims to determine the fleet size and mix, for a given set of routes with given required route service frequencies, which minimize the total operating cost. Dantzig and Fulkerson (1954) studied the problem of determining the minimum number of tankers required to meet a fixed schedule. They made this into a linear programming problem of transportation type due to the specific structure of the problem. Fagerholt (1999) proposed a three-phase method to determine the optimal fleet and the corresponding weekly liner routes for the FS&MP integrated ship routing problem. Sambracos et al. (2004) investigated a problem of carrying small containers via coastal freight liners and built an integer linear programming model to determine the fleet size which met the container demand for a minimum cost. Recently, Dong and Song (2009) studied a joint container FS&MP and empty container repositioning problem and solved it based on a genetic algorithm and evolutionary strategy combined with an adjustment mechanism. However, these studies all focused on different topics to this paper this paper; therefore, their proposed methodologies are inapplicable here.

The FDP aims to allocate ships to routes so as to minimize total operating cost. The FDP sometimes includes the determination of lay-up days (if any) for a ship. Laderman et al. (1966) developed a linear programming model for the FDP to satisfy customers' commitments. However, the solution method is not mentioned and no experiment is carried out to show the applicability of their model. Benford (1981) used a trial method to select a fleet deployment strategy that would be most profitable to the owner while satisfying his customers' needs of shipping coal between two specific ports. However, this trial method cannot guarantee an exact solution. Additionally, while this method is efficient for a small fleet size, it is cumbersome for a larger fleet size. Later, Perakis (1985) used the Lagrangian multiplier method to solve the same problem and obtained a much better solution, which reduced the total operating cost by 15.1% compared with Benford's (1981) result. Perakis and Papadakis (1987a,b) revisited this FDP by differentiating between ship cruising speed in ballast and full-load situations. They later extended this FDP to the multi-origin and multi-destination problem (Papadakis and Perakis, 1989) and proposed a nonlinear programming model. The decision variables of optimal ballast and full-load cruising speeds of the ships are predetermined and then the nonlinear programming model is linearized into a linear model. However, the performance of the linearization is not evaluated. Finally, some researchers integrated the FDP with ship routing or scheduling problems, such as Rana and Vickson (1988, 1991), Millar and Gunn (1991), Vukadinović and Teodorović (1994), Horn (2002) and Shintani et al. (2007).

For the single-period/short-term ship fleet planning (SFP) problem, which integrates FS&MP and FDP, an early application of the linear programming approach was given by Everett et al. (1972), who aimed to minimize the life-cycle cost of a fleet. However, the number of ships used in the fleet was assumed to be a real number, which is unrealistic. Perakis and Jaramillo (1991) proposed a linear programming model for the SFP problem for liner operators and carried out a real case study of the liner shipping company Flota Mercante Grancolombiana (FMG). It was found that the total operating costs of the fleet deployment solution obtained using the linear programming model were 12.6% lower than those of the real fleet deployment used by FMG at the time (Jaramillo and Perakis, 1991). However, the number of ships allocated to each route was again assumed to be a real number in the study, which is an unrealistic assumption. To remedy the shortcoming, Powell and Perakis (1997) developed an integer linear programming model for the same problem. The operating costs of the fleet deployment solution obtained using their model were 1.4% lower than FMG's costs at the time. Gelareh and Meng (2010), meanwhile