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Full-shipload tramp ship routing and scheduling with variable speeds

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ABSTRACT

This paper investigates the simultaneous optimization problem of routing and sailing speed in the context of full-shipload tramp shipping. In this problem, a set of cargoes can be transported from their load to discharge ports by a fleet of heterogeneous ships of different speed ranges and load-dependent fuel consumption. The objective is to determine which orders to serve and to find the optimal route for each ship and the optimal sailing speed on each leg of the route so that the total profit is maximized. The problem originated from a real-life challenge faced by a Danish tramp shipping company in the tanker business. To solve the problem, a three-index mixed integer linear programming formulation as well as a set packing formulation is presented. A novel Branch-and-Price algorithm with efficient data pre-processing and heuristic column generation is proposed. The computational results on the test instances generated from real-life data show that the heuristic provides optimal solutions for small test instances and near-optimal solutions for larger test instances in a short running time. The effects of speed optimization and the sensitivity of the solutions to the fuel price change are analyzed. It is shown that speed optimization can improve the total profit by 16% on average and the fuel price has a significant effect on the average sailing speed and total profit.

1. Introduction

Sea shipping is one of the most important transportation modes especially for large-volume goods between continents. It is estimated that sea cargo is responsible for around 80% of global trade by volume and over 70% by value, and these percentages are even higher in most developing countries [33]. Among the various operational costs of sea shipping, fuel cost accounts for a large proportion. For example, in a liner shipping company, bunker cost can be around 50% [25] or even above 60% [14] of the total operational cost. In addition, the large consumption of fuel results in significant CO_2 and NO_x emissions, which have recently attracted media attention for their negative impacts on climate change and air pollution. According to the International Maritime Organization [5], CO_2 emissions from the maritime sector in 2007 has increased by 86% compared to 1990 and accounted for 3.3% of the world's total emissions. These emissions are expected to continue to increase by 150–250% in 2050 if no action is taken.

The fuel cost, and consequently CO_2 emissions, are strongly dependent on the sailing speed. Ryder and Chappell [31] and Ronen [28] showed that a cubic function can describe the relationship between fuel consumption and speed. The ocean conservation group OCEANA states: “Reducing commercial ship speeds, by only a few knots, yields salutary results for both shipping companies and the environment.” [26]. Therefore optimizing sailing speed in order to reduce fuel cost and CO_2 emissions is an important issue to investigate.

Speed optimization for shipping routes has attracted some attention recently. For liner shipping, most of the previous work focuses on optimizing the speed for one or several fixed route(s) [8,29,23,34]. In these studies, the sailing speed is treated as a variable, which not only determines the fuel consumption but also determines the required ship and/or fleet size to maintain the given service frequency. The yearly profit is expressed as a function of sailing speed, and the optimal sailing speed is obtained when the marginal profit equals zero. Both Ronen [29] and Corbett et al. [8] concluded that when the fuel price is increased, the optimal speed is likely to be reduced when maximizing the profit. This reduction of speed also leads to a reduction of CO_2 emissions. Wang and Meng [34] dealt with the problem of finding the optimal route for containers and the optimal speed for the ships given fixed shipping routes and origin-destination pair of each container. They proposed an outer-approximation method, which uses piecewise-linear functions to approximate the fuel consumption as a function of speed within a predetermined tolerance level.

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In contrast to liner shipping, tramp shipping does not consider service frequency. A ship can sail at different speeds on different sailing legs of a route. The objective of tramp shipping is to minimize the total cost or maximize the total profit for transporting cargoes. Fagerholt et al. [12] considered the problem of optimizing the speed on each leg of a single fixed route. Gatica and Miranda [13] Norstad [24], studied simultaneous routing and speed optimization for a full-shipload problem and a less-than-shipload problem respectively. In [12], the sequence of ports and the time window of visiting each port on a given route are fixed. Three models were presented for solving the problem. The first two models are non-linear models, where the speed is a continuous variable between a minimum and a maximum, and the fuel consumption per distance unit is expressed as a quadratic function of speed. The third model discretizes the time window and converts the problem into a shortest path problem on an acyclic graph. These models were tested on data with up to 16 ports and 10-day time window. It was shown that, compared to the continuous model, the discrete model is able to provide quality solution within short computational time. Gatica and Miranda [13] applied the same idea of discretized time window to the solution of a full-shipload routing and speed optimization problem. They tested their method on generated data instances with up to 15 discretized time-window points, 50 cargoes and 9 ships. Fagerholt et al. [24] formulated the less-than-shipload routing and speed optimization problem as a pickup and delivery problem with an extra continuous decision variable for the speed on each leg. They proposed a recursive smoothing algorithm for determining the optimal speed for a given route, which is shown to be superior to the discretization of arrival time presented in [12]. To solve the routing and speed optimization simultaneously, they proposed a multi-start local search heuristic and tested it on data with up to 10-day time windows.

The problem of routing and scheduling for tramp shipping is very similar to the well-know vehicle routing problem [11,20], which has been studied intensively in the literature. Christiansen et al. [6] and Christiansen et al. [7], gave a good overview of maritime transportation and present different models for routing and scheduling of both tramp and liner ships. A few variations of tramp shipping problems have also been addressed in the previous work. Gatica and Miranda [13] studied a full-shipload problem, where each cargo corresponds to a full-shipload and a ship can only carry one cargo at a time as mentioned above. Brønmo et al. [3], Korsvik et al. [18], Lin and Liu [21], Norstad et al. [24] studied the less-than-shipload problem, in which several cargoes are allowed to be onboard at the same time. The cargo size is fixed in their studies. Brønmo et al. [4], Korsvik and Fagerholt [17], Brønmo et al. [2] allowed the shipping company to choose the quantity of each cargo to be transported, and therefore the delivery quantity becomes a variable between given upper and lower bounds. In [15,19,32], a single cargo can be split between multiple ships.

The work described in this paper originated from a routing and scheduling problem encountered by a large Danish product tanker shipping operator, who transports oil products in full-shipload mode. The shipping operator has a fleet of heterogeneous ships with different sizes and fuel consumptions. It receives cargo orders from the customers, each of which has a specific pickup port, a delivery port and a time window within which the cargo should be picked up. The operator needs to decide whether to accept the cargo, which ship should pickup the cargo at what time, and at which speed each ship should sail on each leg in order to maximize the overall profit. This problem is similar to the full-shipload routing and speed optimization problem considered in [13]. The difference is that, in our problem, the fuel consumption of each ship depends individually on the sailing speed and the load of the ship, i.e., whether the ship is loaded (laden) or empty (ballast); whereas, in [13], the fuel consumption only depends on the speed. To the best of the authors' knowledge, the load dependent fuel consumption has not been considered in the literature. In addition, [13] did not propose any tailored solution method but relied on solving the models using an IP solver. We have formulated two mathematical models for the problem, developed a Branch-and-Price (B&P) algorithm with heuristic column generation, and tested the proposed algorithm on instances generated from real-life data. The computational results show that the branch-and-price heuristic produces optimal or near-optimal solutions in relatively short time.

The main contribution of this paper is the proposed heuristic. The heuristic is able to find high quality solutions in short computation time. It clearly outperforms a commercial IP solver when it comes to computation time and size of the instances that can be handled. In terms of modeling, the present paper is one of the first to consider variable speeds in a tramp shipping planning context and it is the first to consider a load dependent fuel consumption. Although the modeling is greatly simplified by the assumption of full-vessel loads, the assumption itself is realistic. The company used as a case in this project does not carry multiple orders simultaneously on a single ship.

The remainder of the paper is organized as follows. Two mathematical formulations are presented in Section 2 and the heuristic B&P algorithm is described in Section 3. The computational results are given in Section 4, followed by conclusions in Section 5.

2. Mathematical model

Our problem can be defined on the graph $G=(N,A)$, where N is the set of all the nodes and A is the set of feasible arcs in the graph. Let S denote the set of ships. Each ship $s \in S$ starts from node $o(s)$ and ends at dummy node $d(s)$. Let O and D denote the set of all origins and destinations of the ships. Let N_0 denote the set of cargoes. As this is a full-shipload problem, each node $i \in N_0$ corresponds to a cargo, which is transported directly from its load port to discharge port, and is associated with a sailing distance g_i from the load port to the discharge port, a port service time t_i for loading and unloading the cargo and a time window $[a_i, b_i]$, within which the cargo should start being loaded. For $i \in O \cup D$, we set $g_i = 0$, $t_i = 0$, $a_i = 0$ and $b_i = \max_{j \in N_0}\{b_j\}$. The set of all the nodes is $N = N_0 \cup O \cup D$. Let $N_i^+ = \{j : (i,j) \in A\}$ and $N_i^- = \{j : (j,i) \in A\}$ be the set of nodes that can be reached from node i and can reach node i respectively. The distance between two nodes i and j is denoted as d_{ij}, which is the distance from the discharge port of cargo i, or the location of i if $i \in O$, to the load port of cargo j. For the dummy nodes $j \in D$, we set $d_{ij} = 0$, since we do not decide in advance where the ship should end its journey. The ships can sail at different speeds. Let V denote the set of speeds and l^v the time of sailing one distance unit at speed $v \in V$. The fuel consumption depends on the ship, the sailing speed and the load of the ship. Let ${e_s}^v$ denote the ballast fuel cost of ship s sailing one distance unit at speed v. Let ${c_{is}}^v$ be the cost of ship s sailing one distance unit at speed v with cargo i. It should be noted that ${c_{is}}^v$ is determined by the light weight of the ship s, the weight of cargo i and the speed. Examples of approximation functions of ${c_{is}}^v$ can be found in [27]. Due to the fact that the ships are different, not all the ships can serve all the cargoes. For example, a small ship cannot carry a large cargo, and a large ship with deep draft cannot serve a cargo with a shallow load or discharge port. Let binary variable p_{is} be 1 if is feasible for ship s to serve cargo i and 0 otherwise. Let ${r_i}^v$ be the reward of cargo i when served at speed v.