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Hybrid heuristics for a short sea inventory routing problem

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ABSTRACT

We consider a short sea fuel oil distribution problem where an oil company is responsible for the routing and scheduling of ships between ports such that the demand for various fuel oil products is satisfied during the planning horizon. The inventory management has to be considered at the demand side only, and the consumption rates are given and assumed to be constant within the planning horizon. The objective is to determine distribution policies that minimize the routing and operating costs, while the inventory levels are maintained within their limits. We propose an arc-load flow formulation for the problem which is tightened with valid inequalities. In order to obtain good feasible solutions for planning horizons of several months, we compare different hybridization strategies. Computational results are reported for real small-size instances.

1. Introduction

Maritime transportation is the major mode of transportation of goods worldwide. The importance of this mode of transportation is obvious for the long distance transportation of cargoes but it is also crucial in local economies where the sea is the natural link between the local developed regions, such as countries formed by archipelagoes. When a company has the responsibility of coordinating the transportation of goods with the inventories at the ports, the underlying planning problem is a maritime inventory routing problem. Such problems are very complex. Usually modest improvements in the supply chain planning can translate into significant cost savings.

In this paper we consider a real Short Sea Inventory Routing Problem (SSIRP) occurring in the archipelago of Cape Verde. An oil company is responsible for the inventory management of different oil products in several tanks located in the main islands. Fuel oil products are imported and delivered to specific islands and stored in large supply storage tanks, so the inventory management does not need to be considered in these tanks. From these islands, fuel oil products are distributed among all the inhabited islands using a small heterogeneous fleet of ships with dedicated tanks. These products are stored in consumption storage tanks with limited capacity. Consumption rates are assumed to be given and constant over a time horizon of several months. Some ports have both supply tanks for some products and consumption tanks of other products.

We have witnessed an increased interest in studying optimization problems within maritime transportation (Christiansen, Fagerholt, Nygreen, & Ronen, 2007, 2013; Christiansen, Fagerholt, & Ronen, 2004) and, in particular, in the last fifteen years, problems combining routing and inventory management (Andersson, Hoff, Christiansen, Hasle, & Løkketangen, 2010; Christiansen & Fagerholt, 2009). These problems are often called Maritime Inventory Routing Problems (MIRPs). Most of the published MIRP contributions are based on real cases from the industry, see for the single product case (Christiansen, 1999; Flatberg, Haavardtun, Kloster, & Løkketangen, 2000; Furman, Song, Kocis, McDonald, & Warrick, 2011; Grønhaug, Christiansen, Desaulniers, & Desrosiers, 2010) and for the multiple products case (Al-Khayyal & Hwang, 2007; Christiansen et al., 2011; Rakke et al., 2011; Ronen, 2002; Siswanto, Essam, & Sarker, 2011; Stålhane et al., 2012).

This SSIRP is addressed in a companion paper (Agra, Christiansen, & Delgado, 2013b) where different mathematical formulations are discussed and compared for the SSIRP considering a shorter time horizon. There, two main approaches to model the problem are considered. One uses a continuous time model where an index indicating the visit number to a particular port is added to most of the variables. This approach was used in Al-Khayyal and Hwang (2007), Christiansen (1999) and Siswanto et al. (2011) for MIRPs where the production and/or consumption rates are considered given and fixed during the planning horizon. The other approach consists of using a model that combines a discrete and continuous

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time where the discrete time corresponds to an artificial discretization of the continuous time. Discrete time models have been developed in Agra, Andersson, Christiansen, and Wolsey (2013), Furman et al. (2011), Grønhaug and Christiansen (2009), Grønhaug et al. (2010), Rakke et al. (2011), Ronen (2002), Song and Furman (2013) to overcome the complicating factors with time varying production and consumption rates. In addition, for each approach two new extended formulations are tested in Agra et al. (2013b).

In Agra, Christiansen, and Delgado (2013a), the SSIRP for short-term planning is considered. For the short-term plans demand orders are considered, that is, fixed amounts of oil products that must be delivered at each port within a fixed period of time. These orders are determined from the initial stock levels and the consumption rates and lead to a problem with varying demands (corresponding to the demand orders). Several key issues taken into account in the short-term problem are relaxed here or incorporated indirectly in the data. For instance, port operating time windows that are essential in the short-term plan are ignored here. Otherwise, the problems considered originate from the same company in the same region. These problems are solved using the same commercial solver we use here, considering a formulation which is improved by the strengthening of defining inequalities and the inclusion (through separation) of valid inequalities. In Al-Khayyal and Hwang (2007) a problem similar to the SSIRP is considered with constant consumption rates and dedicated compartments in the ships.

In this paper we develop and compare different hybrid heuristics for the SSIRP. As discussed in Andersson et al. (2010) and Song and Furman (2013), most combined maritime routing and inventory management problems described in the literature have particular features and characteristics, and tailor-made methods are developed to solve the problems (Christiansen & Fagerholt, 2009). These methods are often based on heuristics or decomposition techniques. Recent hybrid heuristics that use MIP solvers as a black-box tool have been proposed. Here we consider and combine three hybrid heuristics: Rolling Horizon (RH), Local Branching (LB) and Feasibility Pump (FP). In RH heuristics the planning horizon is split into smaller sub-horizons. Then, each limited and tractable mixed integer problem is solved to optimality. Within maritime transportation RH heuristics have been used in Hwang (2005), Rakke et al. (2011), Sherali, Al-Yakoob, and Hassan (1999), Siswanto et al. (2011), Song and Furman (2013). Local Branching (LB) was introduced by Fischetti and Lodi (2003) to improve feasible solutions. LB heuristics search for local optimal solutions by restricting the number of binary variables that are allowed to change their value in the current solution. Feasibility Pump (FP) was introduced by Fischetti, Glover, and Lodi (2005) to find initial feasible solutions for MIP problems.

Computational experiments reported in Section 6 show that a combined heuristic using the three approaches outperformed the other tested heuristics and, in particular, outperformed the most used approach within MIRPs, the RH heuristic.

To solve each subproblem we consider the arc-load flow (ALF) formulation introduced in Agra et al. (2013b), since this was the model with the best performance among all the tested models for this problem with short time horizons. The ALF formulation is improved by a pre-computation of estimates for the number of visits to each port, and with the inclusion of valid inequalities. In particular, we introduce a new family of clique inequalities for MIRPs when continuous time models are used.

The main contributions of this paper, the heuristic strategies and the valid inequalities, can easily be used in other MIRPs.

The remainder of this paper is organized as follows. In Section 2, we describe the real problem. The arc-load flow formulation is presented in Section 3 and strategies to tighten the formulation are discussed in Section 4. In Section 5 we describe several hybrid heuristics. The computational experimentations are reported in Section 6. Final conclusions are given in Section 7.

2. Problem description

In Cape Verde, fuel oil products are imported and delivered to specific islands and stored in large supply storage tanks. From these islands, fuel oil products are distributed among all the inhabited islands using a small heterogeneous fleet of ships. The products are stored in consumption storage tanks. Two ports have both supply tanks for some products and consumption tanks for other products, while the remaining ports have only consumption tanks. Not all islands consume all products. The consumptions (which are usually forecasted) are assumed to be constant over the time horizon. It is assumed that each port can receive at most one ship at a time and a minimum interval between the departure of a ship and the arrival of the next one must be considered. Waiting times are allowed.

Each ship has a specified load capacity, fixed speed and cost structure. The cargo hold of each ship is separated into several cargo tanks. The products can not be mixed, so we assume that the ships have dedicated tanks to particular products.

The traveling times between two consecutive ship visits are an estimation based on practical experience. Additionally, we consider set-up times for the coupling and decoupling of pipes, and operating times.

To prevent a ship from delivering small quantities, minimum delivery quantities are considered. The maximum delivered quantity is imposed by the capacity of the consumption storage tank. Safety stocks are considered at consumption tanks. As the capacity of the supply tanks is very large when compared to the total demand over the horizon, we omit the inventory aspects for these tanks.

In each problem instance we are given the initial stock levels at the consumption tanks, initial ship positions (which can be a point at sea) and quantities on board each ship. The inter-island distribution plan consists of designing routes and schedules for the fleet of ships including determining the number of visits to each port and the (un)loading quantity of each product at each port visit. The plan must satisfy the safety stocks of each product at each island and the capacities of the ship tanks. The transportation and operation costs of the distribution plan must be minimized over a finite planning horizon.

3. Mathematical model

In Agra et al. (2013b) a comparison of six different formulations for the SSIRP for a shorter time horizon is given. Three of those formulations consider a time discretization and the other three consider continuous time. For each time option the following formulations are considered: an arc-load formulation, where the model keeps only track of the information of the load on board each ship compartment in each port visit; an arc-load flow formulation, where new variables are used to keep the information about the quantity of each product in each compartment when a ship leaves a port en route to the next one; and a multi-commodity formulation, where the flow on each arc is disaggregated accordingly to its destination. That comparison led to the choice of the continuous time arc-load flow formulation. In this section we present that arc-load flow formulation.

3.1. Routing constraints

Let V denote the set of ships. Each ship $v \in V$ must depart from its initial position in the beginning of the planning horizon. The set