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Discrete Optimization

Formulations for a problem of petroleum transportation

Luiz Aizemberg *, Hugo Harry Kramer, Artur Alves Pessoa, Eduardo Uchoa

Production Engineering Department, Fluminense Federal University, Rua Passo da Pátria 156, 24210-240 Niterói, RJ, Brazil

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ABSTRACT

Oil tankers play a fundamental role in every offshore petroleum supply chain and due to its high price, it is essential to optimize its use. Since this optimization requires handling detailed operational aspects, complete optimization models are typically intractable. Thus, a usual approach is to solve a tactical level model prior to optimize the operational details. In this case, it is desirable that tactical models are as precise as possible to avoid too severe adjustments in the next optimization level. In this paper, we study tactical models for a crude oil transportation problem by tankers. We did our work on the top of a previous paper found in the literature. The previous model considers inventory capacities and discrete lot sizes to be transported, aiming to meet given demands over a finite time horizon. We compare several formulations for this model using 50 instances from the literature and proposing 25 new harder ones. A column generation-based heuristic is also proposed to find good feasible solutions with less computational burden than the heuristics of the commercial solver used.

1. Introduction

Oil tankers play a fundamental role in every offshore petroleum supply chain. Its optimization is usually divided in three levels: strategic, tactical and operational. Strategic decisions deal with fleet sizing, facility location and capacity sizing. Tactical decisions deal with production and distribution planning, transportation mode selection, storage allocation and order picking strategies. Finally, operational decisions deal with shipment and vehicle dispatching (Ghiani, Laporte, & Musmanno, 2004). When dealing with a planning level, all decisions made in the previous levels are assumed to be known. Since each level considers more details than the previous ones, past decisions usually have to be adjusted. Hence, it is important to make both the strategic and tactical models as detailed as possible to guarantee low adjustments in the operational level.

In this paper, we study a tactical optimization model for crude oil distribution by tankers. The problem consists of scheduling the shipments through routes linking platforms (offshore production sites) and terminals (onshore consumer sites). The objective is to ship the products from the platforms to supply the terminals with minimum transportation cost for a finite planning horizon. For each site, the inventory levels must lie between a lower and an upper bound to avoid the lack or excess of product. Also, for each site, the demand or the production is given for the whole planning horizon. The products are shipped only by oil tankers and we assume that the global capacity of the fleet is unlimited. For each transportation, one has to decide the route, the lot size and the delivery day. This problem has already been addressed in Rocha (2010) and Rocha, Grossmann, and Poggi de Aragão (2011).

This paper has two aims. The first aim is to compare mathematical formulations for the transportation problem proposed in Rocha et al. (2011). Firstly, a basic formulation is given, where the inventory level for each day in each site is represented by a continuous variable and the shipments are represented by binary variables. This formulation is similar to many others found in the literature. We refer to Sawik (2011) for an overview of such papers. We also test several variations of the formulation proposed in Rocha et al. (2011), referred to as *Knapsack Cascading*. Lastly, we devise a new formulation that outperforms all previous ones when given to a Mixed Integer Programming (MIP) solver.

The second aim of this paper is to propose a column generation-based heuristic approach. We note that, for difficult instances, the commercial solver used is not capable of finding good feasible solutions at the beginning of the branch-and-bound algorithm tree. Finding a good feasible solution at the very beginning of the tree is crucial to reduce the search by cutting off nodes of such tree, increasing the probability of proving the optimality in a reasonable computational time.

We did our work on the top of a previous paper found in the literature (Rocha et al., 2011). The instances used to test the formulations are those proposed by Rocha et al. Our paper shows a clear evolution concerning the results as the formulations are improved, leading to the generation of new and harder instances (based on the existent ones) to evaluate the potential of such formulations.

* Corresponding author. Tel.: +55 2126295708.
E-mail addresses: luizaizemberg@gmail.com (L. Aizemberg), hugoharry@gmail.com (H.H. Kramer), artur@producao.uff.br (A.A. Pessoa), uchoa@producao.uff.br (E. Uchoa).

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1.1. Literature review

Several models for optimizing the transportation of petroleum products are found in literature, considering different characteristics. In Colvin and Maravelias (2011), the authors consider task selection, scheduling, and resource planning decisions, exploring risk management methods, and develop a multi-stage stochastic programming model. To optimize such models, Mixed Integer Programming is the most used technique. In Magatão, Arruda, and Neves (2004) and Boschetto et al., 2010, MIP is applied to schedule the activities in a real oil pipeline network. The former uses illustrative instances with four products, while the latter uses large instances, where more than 14 oil derivatives and ethanol are transported. In Moro and Pinto (2004), MIP is used to optimize the short-term crude oil scheduling. The authors deal with the separation of brine from the oil, interface separation between different types of oil, and energy consumption in the crude distillation units. MIP is also used in a real-time approach to dispatch petroleum tank trucks (Brown & Graves, 1981) and to optimize the long-term oil derivative scheduling under uncertainty (MirHassani, 2008). Finally, in Banaszewski, Tacla, Pereira, Arruda, and Enembreck (2010) and Aizemberg et al. (2011), the authors deal with the medium-term planning of oil derivatives transportation in the Brazilian oil industry multimodal supply chain network. The former applied an auction based multiagent algorithm, while the latter applied MIP.

Column generation based heuristics (CGH) are found in literature to deal with many different problems: multi-item scheduling (Bahl, 1983), vehicle routing (Mourgaya & Vanderbeck, 2007), cutting stock (Furini, Malaguti, Durain, Persiani, & Toth, 2012), sensor placement (Yavuz, Aras, Kuban, & Ersoy, 2010), generalized assignment (Moccia, Cordeau, Monaco, & Sammarra, 2009) and many others. In general, such approaches share similar main characteristics. First, the linear programming relaxation is solved by column generation. Then, a feasible solution is constructed for the original problem using the obtained columns. For example, in Choi and Tcha (2007) the authors apply a column generation heuristic for the heterogeneous fleet vehicle routing problem which consists of three steps: (i) solve the continuous relaxation; (ii) set the variables of the final restricted master as binaries; and (iii) solve the resulting MIP problem. In Joncour, Michel, Sadykov, Sverdlov, and Vanderbeck (2010), the authors review generic classes of column generation-based heuristics.

1.2. Paper organization

The remainder of the paper is organized as follows. Section 2 presents the problem definitions and the mathematical formulations, including the Dantzig–Wolfe decomposition formulation used by the proposed heuristic. Section 3 shows the column generation-based heuristic procedure, including dynamic programming algorithm for the pricing subproblem. Section 4 discusses the obtained results. At last, Section 5 contains the conclusions of this work.

2. Mathematical formulations

This section presents the mathematical formulations considered for the problem in study.

The optimization problem defined in Rocha et al. (2011) is the following. Let P be the set of platforms and T the set of terminals. The planning horizon consists of D days. A unique product should be shipped from platforms to terminals to satisfy given demands. The inventory levels of platforms and terminals are limited by a lower and an upper bound, i.e., the lack or surplus of the product is not allowed at any point of the network. Oil tankers are grouped in classes according to their capacities. Let C be the set of all tanker classes. It is assumed that only oil tankers with fulfilled capacities are used in the transportation. The objective is to minimize the total transportation costs.

The formulations described in the next subsections consider the following notation:

Indices:

- p: Platform, $p \in P$;
- t: Terminal, $t \in T$;
- c: Class of tanker, $c \in C$;
- d: day, $d \in \{1, \ldots, D\}$.

Subsets:

- $T(p) \subseteq T$: Terminals allowed to send tankers to a platform $p \in P$;
- $P(t) \subseteq P$: Platforms allowed to receive tankers from a terminal $t \in T$;
- $C(p) \subseteq C$: Classes of tankers allowed to pick up oil from platform $p \in P$.

Input data:

- $e_{p,0}$: Initial inventory at platform $p \in P$;
- $e_{t,0}$: Initial inventory at terminal $t \in T$;
- $P_{p,d} \geqslant 0$: Production at platform $p \in P$, in day d;
- $C_{t,d} \geqslant 0$: Consumption at terminal $t \in T$, in day d;
- $CAP_{p,d}$: Maximum inventory capacity at platform $p \in P$, in day d;
- $CAP_{t,d}$: Maximum inventory capacity at terminal $t \in T$, in day d;
- V_c: Capacity of a tanker of class $c \in C$;
- F_c: Transportation cost per day for a tanker of class $c \in C$ (tankers must travel back from the platform to the terminal after each transportation);
- $D_{p,t}$: Transportation time between a platform $p \in P$ and a terminal $t \in T$ in days.

Other definitions will be added as needed by each formulation.

2.1. Natural formulation

For this model the decision variables are defined as follows. $z_{p,t}^{c,d} \in \{0,1\}$ is a binary variable indicating if a tanker of class $c \in C$ is assigned to ship the product from platform $p \in P$ to terminal $t \in T$ at day d. The variables $e_{p,d} \in \mathbb{R}_+$ and $e_{t,d} \in \mathbb{R}_+$ represent the inventory levels at platform $p \in P$ and terminal $t \in T$ at day d, respectively. Thus, the natural formulation ($\mathcal{NF}$) is given by the following:

$$(\mathcal{NF}) \ \min \sum_{p \in P} \sum_{t \in T(p)} \sum_{c \in C(p)} \sum_{d=1}^{D} 2F_c D_{p,t} z_{p,t}^{c,d}, \tag{1}$$

subject to

$$e_{p,d} = e_{p,d-1} + P_{p,d} - \sum_{t \in T(p)} \sum_{c \in C(p)} V_c z_{p,t}^{c,d} \quad \forall p \in P, \ d \in \{1, \ldots, D\}, \tag{2}$$

$$e_{t,d} = e_{t,d-1} - C_{t,d} + \sum_{p \in P(t)} \sum_{c \in C(p)} V_c z_{p,t}^{c,d-D_{p,t}} \quad \forall t \in T, \ d \in \{1, \ldots, D\}, \tag{3}$$

$$0 \leqslant e_{p,d} \leqslant CAP_{p,d} \quad \forall p \in P, \ d \in \{1, \ldots, D\}, \tag{4}$$

$$0 \leqslant e_{t,d} \leqslant CAP_{t,d} \quad \forall t \in T, \ d \in \{1, \ldots, D\}, \tag{5}$$

$$z_{p,t}^{c,d} \in \{0,1\} \quad \forall p \in P, \ t \in T(p), \ c \in C(p), \ d \in \{1, \ldots, D\}. \tag{6}$$

The objective function (1) aims to minimize the total transportation costs. Constraints (2) calculate the inventory balance at each platform, while constraints (3) calculate the inventory balance at each terminal. Constraints (4) and (5) assure that inventory levels