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A MILP model for planning the trips of dynamic positioned tankers with variable travel time

Leonardo Salsano de Assis, Eduardo Camponogara *

Department of Automation and Systems Engineering, Federal University of Santa Catarina, Cx.P. 476, 88040-900 Florianópolis, SC, Brazil

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ABSTRACT

The transportation of the crude oil produced in offshore oilfields to onshore terminals is performed by vessels, known as shuttle tankers. Scheduling shuttle-tanker operations entails solving complex problems to ensure a timely offloading of the platforms, taking into account several logistics and inventory constraints. This work proposes a new MILP formulation that advances previous works by considering variable travel time between platforms and terminals. The combination of the MILP formulation with an optimization solver constitutes a decision-support tool to aid engineers reach optimal decisions for a planning horizon. To handle large-scale instances, rolling-horizon and relax-and-fix strategies are proposed.

1. Introduction

The oil & gas industry is faced with complex logistics networks that encompass operations such as oil exploration (upstream), oil refining (midstream) and product distribution (downstream) (Kazemi and Szmerekovsky, 2015). In a simplified form, crude oil is produced in offshore platforms and then transferred to onshore terminals by sub-sea pipelines or Dynamically Positioned Tankers (DPTs), here simply called shuttle tankers. After being delivered at the onshore terminals, the crudes are sent to refineries and will be processed in distillation columns to produce oil products such as asphalt, diesel, gasoline, and fuel gas, among others. Finally, these products are delivered to chemical, pharmaceutical and energy industries and end consumers.

Because oil pipelines are not available in deep-water offshore oilfields, the upstream part of the oil chain relies on Floating Production Storage and Offloading Units (FPSOs), or simply platforms, to produce and store crude oil. For the large number of platforms, a fleet of shuttle tankers is needed due to high volume of oil that must be transferred from the platforms to onshore terminals. This need gives rise to the problem of scheduling trips of shuttle tankers between the platforms and onshore terminals over a planning horizon, hereafter referred to as the Shuttle Tanker Scheduling Problem (STSP).

Shuttle tanker scheduling is of paramount importance to oilfield operations. First, halting production at a platform due to the lack of storage capacity is not acceptable since it entails shutting off wells. Besides being a complex operation, shutting off a well is a risky procedure that can compromise future production: wells can take a considerable time to be brought back to full operation and production downtime represents a major loss of revenue. Second, the amount of oil left in the platforms incurs a loss of revenue. In other words, the oil company has to pay interests to access the cash equivalent left at the

* Corresponding author.
E-mail address: eduardo.camponogara@ufsc.br (E. Camponogara).

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platforms in the form of oil. On the other hand, there is a cost to bring the oil to the onshore terminals, being related to the rental and operation of shuttle tankers. However, much more important than the costs involved, is the need to keep the platforms with sufficient storage capacity to receive the daily production of its wells, a condition that must be ensured by carefully planned offloading operations.

Logistics decisions are concerned with when and how materials should be acquired, moved and stored. Such decisions are divided in three hierarchical levels: strategic, tactical and operational (Ghiani et al., 2013). Being the highest level in the hierarchy, the strategic decisions are planned considering the long-term (usually over years). They deal with investment decisions such as fleet size and composition, and network design. Tactical decisions consider the medium-term (months) and deal with the assignment of vessels to routes (ship routing and scheduling). Finally, in the lowest level, operational planning is carried out for the short term (weeks or daily) in order to decide the types of products and quantities to be loaded and discharged in each site visit (Christiansen et al., 2004).

This work proposes a discrete-time Mixed-Integer Linear Programming (MILP) formulation to serve as a decision-support tool for tactical and operational planning of shuttle tanker trips, which are scheduled to perform offloading operations in platforms and uploading operations at onshore terminals under inventory constraints. The problem addressed in this paper can be classified as a combined inventory management and routing problem in the maritime context (Andersson et al., 2010).

For the platforms, the STS problem must account for critical constraints on the range of well production rates, storage capacity, minimum volume stored to ensure platform stability, inventory control and material balance, among others. For the shuttle tankers, constraints and parameters like storage capacity, volume of oil to be offloaded from platforms and the inventory balance play a major role.

The remainder of this paper is organized as follows. Section 3 introduces the proposed mathematical model and presents theoretical properties regarding the formulation. A review of the literature on maritime inventory routing is presented in Section 2. Rolling-horizon and relax-and-fix heuristics are discussed in Section 4. The computational results and analysis appear in Section 5. Finally, Section 6 presents conclusions and suggests directions for future research.

2. Literature review

The increasing need of bulk raw materials and industrialized goods worldwide has demanded a growth of fleet capacity for seaborne world trade. This scenario has brought the attention of researchers over the years and a vast literature on ship routing and scheduling has been developed since then.

The literature on ship routing and scheduling can be divided in three major fields regarding the operation of vessels: liner, industrial and tramp. In *liner shipping*, vessels must follow a fixed route with a predefined schedule, trying to maximize the profit (it is similar to a public bus service). The major research segment of this operation mode is on container shipping. In *industrial shipping operation*, vessels and cargoes are owned and controlled by the same agent. This type of operation tries to minimize the cost of deliveries and it is usually performed by vertically integrated companies. In *tramp shipping*, vessels transport available cargoes in order to maximize profit (it is similar to a taxi cab operation). Besides, each of these operation modes deals with strategic, tactical and operational planning problems. Extensive reviews comprising four decades on ship routing and scheduling appear in the works of Christiansen et al. (2013, 2004) and Ronen (1983, 1993).

More recently, transportation companies are seeking to integrate inventory management information, from costumers and producers, with routing and scheduling decisions in order to better manage the fleet while minimizing operation costs. In that sense, a sub-field of ship routing and scheduling called combined inventory management and routing (CIMR), also known as maritime inventory routing (MIR), has emerged.

CIMR problems are usually found in industrial shipping (Andersson et al., 2010) and most of the available literature concerns the transportation of liquid bulk products (Christiansen et al., 2013).

In the context of CIMR, single product problems are studied by Sherali and Al-Yakoob (2006a,b) and Song and Furman (2013) for the transportation of petroleum products, and by Christiansen and Nygreen (2005) for ammonia transportation. A mixed-integer programming model is developed by Furman et al. (2011) for vacuum gas oil (VGO) routing and inventory management between supply points in Europe and refineries in the United States. Works regarding multi-products transportation problems have also attracted the attention of researchers, *e.g.* Li et al. (2010) deal with different types of chemicals and Al-Khayyal and Hwang (2007) study the transportation of petrochemicals.

At the strategic level, Sherali and Al-Yakoob (2006a,b) propose a mixed-integer programming model to determine an optimal fleet mix and schedules for respectively single and mutiple sources and destinations.

A tactical and operational planning model, integrating oil production and maritime transportation from platforms to terminals and refineries, is proposed by Rocha et al. (2009). This work makes the following assumptions: unlimited number of oil tankers; tankers must be fully loaded in each platform-terminal trip; no inventory management for oil vessels; shipments take only a day and are limited to one per day between a platform and a terminal. An extension is presented by Rocha et al. (2011), who propose a reformulation of inventory balance constraints that can be exploited by solvers. Aizemberg et al. (2014) compare mathematical formulations for the problem presented in Rocha et al. (2011) and proposed a column generation-based heuristic approach.

Continuous and discrete time models are also addressed in the CIMR literature. The selection between these two types of models relies on the nature of production and consumption rates. Usually, if these rates are not decision variables (parameters), continuous time models are used (Christiansen and Nygreen, 2005; Al-Khayyal and Hwang, 2007; Li et al.,