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A maritime scheduling transportation-inventory problem with normally distributed demands and fully loaded/unloaded vessels

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ABSTRACT

Uncertainties in oil demands have significant effects on the routing and scheduling of oil tankers and inevitably influence the pertinent fleet operational expenses, shortage and excess inventory penalties, and chartering costs. In this paper, we study a stochastic maritime scheduling transportation-inventory problem to transport crude oil from a source using a set of fully loaded heterogeneous vessels to be fully unloaded at a destination over a finite time horizon. Daily demands at the destination are normally distributed random variables and different penalties are imposed on the shortages/excesses in daily storage levels at the destination. The expected total cost of such a fleet operation, consists of the total vessels' operational expenses, expected total penalties resulting from violating specified lower and upper bounds at the destination storage facility, and chartering expenses. We aim to simultaneously optimize the fleet schedules and maintain desirable daily storage levels to meet the stochastic demand requirements at the destination with acceptable reliability levels. We formulate the problem as a stochastic optimization model and then use chance constrained programming to convert it to an exact mixed-integer nonlinear program with a convex objective function and linear constraints. Solutions obtained via the proposed stochastic model and its deterministic counterpart are compared and analyzed to gain insights into the impact of the variations in demands and the probabilities of meeting demands on the overall operation and cost structure.

1. Introduction

1.1. An overview

Maritime transportation plays an essential role in international trade, being responsible for the majority of long-distance shipments in terms of volume [1]. Oil is the world's number one transported product in terms of tonnage, accounting to about 4.8% of the global value of all exported products. Total transported shipments of crude oil amounted to $786.3 billion during 2015, the bulk of which exported from the Gulf Countries amounting to $325 billion or 41.3% of the global crude oil exports [2]. Oil tankers usually costs tens of millions of US dollars with daily operational costs typically exceeding tens

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of thousands of US dollars in addition to the excessive costs associated with chartering. Therefore, efficient routing and scheduling of vessels within large-scale maritime transportation systems presents serious challenges to decision makers due the complexity, uncertainty, dynamic and combinatorial nature of vessel operation (see, e.g., Christiansen et al. [3,4], Hoff et al. [5], and Pantuso et al. [6]). This is particularly true for major oil producing countries, especially during the recent years due to the noticeable depreciation in oil prices, from $120 per barrel (in 2012) to a current price of about $48 per barrel. Hence, it is imperative to employ efficient transportation paradigms and to analyze short-term and long-term demand trends in order to reduce the overall cost associated with such operations.

1.2. Problem specifics

In this paper, we study an oil-related vessel scheduling transportation-inventory problem faced by the Kuwait Petroleum Corporation (KPC), among a host of other transportation problems. The problem is to transport substantial quantities of crude oil from Shuaiba Port in Kuwait (source) to the storage facility at Dalian Xingang Port in China (destination). Even though KPC exports crude oil to many destinations in the world with different demand structures, we focus in this research effort on a single-source and single-destination operational scenario, which is a typical operation that many large-scale oil companies encounter, such as KPC and the Saudi Aramco. This focus stems from the fact that for a destination with considerable long-term demand requirements, KPC is inclined to adopt a long-lasting practice of designating a separate fleet of vessels to satisfy such demand requirements without having any interactions with the demands at the other destinations. In this particular studied case, KPC aims to satisfy contract requirements signed with the Chinese government in cooperation with the major oil companies (such as China Petroleum and Chemical Corporation or China National Petroleum Corporation) to deliver large quantities of crude oil from Shuaiba Port to the storage facility at Dalian Xingang Port. Such a practice is advantageous from both administrative and operational perspectives, and KPC is very much interested in assessing the stochastic aspects of this particular single-source and single-destination scenario. (To ease presentation, we will hereafter use the terms "product, source, and destination" instead of "crude oil, Shuaiba Port, and Dalian Xingang Port", respectively.) Due the nature of the demand in term of the overall required quantity in this particular KPC problem scenario, vessels are assumed to be fully loaded at the source and to be fully unloaded at the destination. A heterogeneous fleet of self-owned and chartered vessels of different types is available, where each vessel type is characterized by its size, speed, loading and unloading times, etc.

The demand structure for the product at the destination is determined based on historical, current, and expected daily consumption rates. Recent studies on some relevant stochastic problems (see Section 2.3) indicate that the nature of demand probability distributions can affect the expected total costs and overall operations (e.g., Bertazzi et al. [7] and Zhang et al. [8]). Thus, it is important to incorporate the precise knowledge of demand probability distributions into modeling considerations. For the proposed vessel scheduling transportation-inventory problem, our statistical analysis of the KPC simulated demands for a six-year period demonstrates that the daily demands for the product at the destination are normally distributed random variables (see Section A1 of the Appendix). Note that, unlike this study in which the demands have been shown to be normally distributed, the literature on some relevent stochastic problems simply assumes that demands have normal distributions (e.g., Aghezzaf [9], Coelho et al. [10], Meng and Wang [11], and Soysal et al. [12]). The rationale for this assumption is that the deviation between the forecasted demand and the actual demand is often approximately normally distributed.

KPC desires to maintain a daily safety stock level, with some specified lower and upper bounds, at the destination storage facility. Daily violations of such permitted stock levels are undesirable to avoid the costs associated with (i) the disruption of operation when the daily shortage levels fall below the allowable lower bound, and (ii) the daily excess inventory levels when the storage level exceed the allowable upper bound. The destination has a limited known storage capacity for the product, and the product daily storage levels are desired to lie within certain lower and upper bounds. Since different shortage and excess daily storage levels may incur different penalty structures in practice, we have proposed and implemented for KPC a penalty structure involving two penalty types for the shortages and two penalty types for the excesses in storage levels. Typically, the first penalty type associated with daily shortages (Type I) and the first penalty type associated with daily excess inventory (Type III) impose relatively light penalties for moderate amounts of shortages and excess inventories, respectively. The other two types of penalties associated with the daily shortage and excess inventory levels (Types II and IV) involve high penalty costs reflecting the utmost undesirability of such storage levels. As mandated by KPC, the high cost of Type II penalty is imposed to prevent a stock-out, while Type IV penalty is enforced to avoid the high cost of leasing temporary storage facilities at the destination. A scenario of this problem with the deterministic daily demands was studied by Sherali and Al-Yakoob [13].

1.3. Contribution and organization

The expected total cost associated with the above described vessel operation, consists of the total vessels' operational expenses, expected total penalties resulting from violating specified lower and upper bounds of the destination storage facility, and expenses associated with time chartering. We aim in this research effort to simultaneously optimize the fleet schedules and maintain desirable daily storage levels to meet the stochastic demand requirements at the destination with acceptable