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# A framework for crude oil scheduling in an integrated terminal-refinery system under supply uncertainty

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ABSTRACT

Operational decisions for crude oil scheduling activities are determined on a daily basis and have a strong impact on the overall supply chain cost. The challenge is to develop a feasible schedule at a low cost that has a high level of confidence. This paper presents a framework to support decision making in terminal-refinery systems under supply uncertainty. The proposed framework comprises a stochastic optimization model based on mixed-integer linear programming for scheduling a crude oil pipeline connecting a marine terminal to an oil refinery and a method for representing oil supply uncertainty. The scenario generation method aims at generating a minimal number of scenarios while preserving as much as possible of the uncertainty characteristics. The proposed framework was evaluated considering real-world data. The numerical results suggest the efficiency of the framework in providing resilient solutions in terms of feasibility in the face of the inherent uncertainty.



## 1. Introduction

The world oil industry increasingly faces new challenges with the trend of globalization. Sudden fluctuations in the prices of oil and its products, new limits for exploration and exploitation of oil reserves, a new global awareness regarding environmental conservation, and partnerships between major players in the market are some of the factors that contribute to an increasingly dynamic and competitive environment in the global oil industry. To cope with this new paradigm, companies are compelled to improve their performance throughout the supply chain from the exploration and production of oil to the order placement and delivery of the final products (Yung-Yu, Wen Long, & Taylor, 2005).

For more than fifty years, the oil industry has made intensive use of mathematical programming to support scheduling decisions in refineries, pipelines, and terminals (Ulstein, Nygreen, & Sagli, 2007). The operational decisions made in the day-to-day scheduling of petroleum handling activities have a strong impact on the total cost of the whole supply chain and must therefore be carefully managed. The challenge is to develop a schedule with low costs and a high level of confidence that is feasible for a given time period.

Classically, petroleum scheduling problems involve the selection of crude flows, the allocation of vessels to tanks, the allocation of tanks to crude distillation units (CDU), and the calculation of crude compositions. In most contexts, they can be closely related to batch process scheduling problems. In fact, many researchers have developed models and solution techniques for the petroleum scheduling problem and most of them are based on mixed-integer linear programming (MILP) and mixed-integer nonlinear programming (MINLP). A general classification of the optimization models for batch processes based on the time representation, mass balances, event representation, and objective functions is presented in the works of Méndez, Cerdá, Grossmann, Harjunkoski, and Fahl (2006) and Floudas and Lin (2004).

In the context of managing wider systems comprising, for example, marine terminals and feeding pipelines, the perspectives have to be extended so that these other elements can be included in the planning process. The pioneering work of Lee, Pinto, Grossmann, and Park (1996) approached the problem of inventory management for a refinery that receives its crude oil supply from vessels by means of a MILP optimization model. Thus, it is crucial that the vessel unloading activities are somehow synchronized with the refinery operations, which is not a simple task given the irregular nature of how these two portions of the system operate. However, the best way to guarantee that the complete system operates in sync is to optimize it as a whole, leading to difficult mathematical formulations. This is the main reason that has led several researchers to address this problem. Depending on the characteristics

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of the system under consideration, it might be necessary to consider aspects such as product quality and time representation that will increase the complexity of the model and thereby jeopardize their applicability to real systems.

Wenkai, Hui, Hua, and Tong (2002) presented an MINLP model for the short-term scheduling of oil unloading, storage, and processing. The authors propose successive reformulations to convert the initial model into an MILP model, which could be solved more efficiently. Más and Pinto (2003) proposed an MILP model to address the problem in a distribution complex containing ports, refineries, and a pipeline infrastructure capable of transferring crude oil between them. Reddy, Karimi, and Srinivasan (2004) proposed an MINLP model considering a multi-CDU refinery and multiple oil suppliers. The authors propose a strategy based on the solution of MILP models considering shorter time periods to avoid nonlinearities. Jia and Ierapetritou (2004) proposed a spatially decomposed approach to the overall problem that considers three portions: the crude oil unloading and blending, production unit operations, and product blending and delivery. Saharidis, Minoux, and Dallery (2009) proposed an MILP model based on a novel event-based time representation for the crude oil unloading and distillation unit charge scheduling in which fewer variables are necessary, thereby enabling the computational performance to be improved. More recently, Chen, Grossmann, and Zheng (2012) presented a wide comparison between alternative formulations for the same problem and proposed improvements for the best-known formulations.

One major difficulty associated with operational planning activities is related to uncertainties inherent in the process, which often compromises the efficiency of the decision support tools that are not able to take uncertainties into consideration. However, despite the potential benefits of considering uncertainty into the scheduling problem, very few works explicitly address this matter. The reason behind this fact is associated with the challenging scale and the computational complexity associated with these models (Escudero, Quintana, & Salmerón, 1999).

Li and Ierapetritou (2008) presented a literature review of different approaches for dealing with uncertainty in process scheduling problems and highlighted that there are still a small number of papers that incorporate uncertainties in their studies. Gupta and Zhang (2009) proposed a model that incorporates the uncertainty issue in the availability of crude oil and provides a solution space instead of a single point solution that may help to minimize the loss due to the late or early arrival of vessels. In Wang and Rong (2009), a two-stage robust model was proposed to solve the crude oil scheduling problem under uncertain conditions, such as ship arrival times and fluctuating product demand. Cao, Gu, and Xin (2010) proposed a stochastic chance constrained MINLP model to solve the refinery short-term crude oil scheduling problem under CDU demand uncertainty.

The objective of this study is to propose a framework for solving the problem of oil supply operational planning in petroleum refineries supplied through marine terminals. This problem covers the scheduling of the berthing and unloading activities in the marine terminal, defining the stock levels of the terminal and refinery tanks, and determining the pumping schedule for the pipeline connecting the terminal to the refinery. In addition, the proposed framework must be able to allow for the consideration of the uncertainty in order to provide robustness to the decision process, in particular regarding the variability related to the arrival of the oil supply.

To solve this problem, we propose a two-stage stochastic MILP model that simultaneously defines the scheduling of oil pumping through a pipeline and the sequencing of ships berthing at a terminal at the lowest possible cost. The model also needs to ensure compliance with the refinery demand while assuming that the arrival of the vessels at the terminal is subject to uncertainty. To adherently represent this uncertainty, we propose a framework for generating scenarios for the stochastic model that is based on statistical analysis of historical data, scenario sampling, and a scenario-tree reduction technique originally proposed Heitsch and Römisch, (2003, 2007). Last, we present numerical results derived from the application of this framework into a real-world case study based on a terminal-refinery system located in southern Brazil. These results indicate the adequacy of the proposed approach for the operational planning of the terminal-refinery system, especially concerning the robustness of the proposed schedule.

This paper provides several contributions to the current literature. First, we propose a novel integrated model that considers both the scheduling of berthing and unloading activities at the terminal and the scheduling of pumping activities through a pipeline. To the best of our knowledge, no other model considers this sort of system taking into consideration both problems at once. Second, we extend the model so that the uncertainty in the oil supply availability is taken into account. The consideration of this uncertainty within the proposed model using stochastic optimization is also a novel feature.

This paper is structured as follows. Section 2 gives a detailed description of the main characteristics of the problem that will be considered in the mathematical model, which is given in Section 3. In Section 4, we provide details on the process to represent the uncertainty regarding the arrival of vessels. Section 5 provides numerical experiments showing the benefits of adopting the proposed approach and in Section 6 we present our conclusions.

## 2. Problem description

Oil is often supplied through marine terminals that are connected to petroleum refineries. These terminal-refinery systems are typically connected by pipelines that are used to transfer the oil that is received in the terminal. This integration implies a highly complex operation because of the necessity to coordinate the decisions made at the terminal, the refinery, and the pipeline.

Most of the transformation processes along the petroleum supply chain have a continuous nature. These particular characteristics impose an additional difficulty on managing the oil flow, especially in geographically wide locations. Transportation is usually performed using vessels for long distance travel or dedicated pipelines, which are more cost effective than any other means of transportation for inland oil transportation. However, these pipelines consist of high energy-demanding hardware so their use must be carefully managed.

The key challenge in this type of supply system is guaranteeing synchronization for efficient operations. Synchronizing these decisions is a difficult task because of the conflicting nature of the objectives of the terminal and the refinery. Although it is crucial for the refinery to receive exactly what it needs for the planned production, the terminal operators seek to unload the vessels as soon as possible to avoid demurrage costs.

The flexibility to control the oil flow between the marine terminal and the refinery is provided by the tanks available at each of these locations. These tanks have a limited storage capacity and are responsible for guaranteeing a continuous flow in the refinery and storing the oil supply arriving in the marine terminal.

Uncertainties are inherent in the process because of the dependence between the oil supply and maritime conditions. Maritime transportation and docking activities are subject to weather and ocean stream conditions, which directly impact the arrival time of the vessels and/or the start of unloading activities. This uncertainty concerning when the oil supply will be available in the terminal jeopardizes the possibility of anticipating decisions concerning pumping activities from the terminal to the refinery, which is