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Scheduling of loading and unloading of crude oil in a refinery using event-based discrete time formulation

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ABSTRACT

One of the most critical activities in a refinery is the scheduling of loading and unloading of crude oil. Better analysis of this activity gives rise to better use of a system's resources, as well as control of the entire supply chain. It is important that the crude oil is loaded and unloaded contiguously, primarily for security reasons (e.g. possibility of system failures) but also to reduce the setup costs incurred when flow between a dock and a tank or between a tank and a crude distillation unit is reinitialized. The aim of the present paper is to develop an exact solution approach, widely applicable to most refineries where several modes of blending and several recipe preparation alternatives are used. A novel time formulation is proposed for the scheduling of the system under study called event-based time representation where the intervals are now based on events instead of hours.

1. Introduction

Production scheduling defines which products should be produced and which products should be consumed in each time instant over a given period (typically 30 days); hence, it defines which run-mode to use and when to perform changeovers in order to meet the market needs and to satisfy the demand. The study presented in this paper focuses on the scheduling of loading and unloading of crude oil in intermediate storage tanks, between docks and Crude Distillation Units (CDUs) and/or Vacuum Distillation Units (VDUs). A refinery is a system composed of docks, pipelines, a series of tanks to store the crude oil (and prepare the different blends), CDUs, VDUs, production units (such as reforming, cracking, alkylating and hydrotreating), blenders and tanks to store the raw materials and the final products. Once the quantities and the types of crude oil required are known, schedulers must schedule the loading and unloading of tanks. The problem that arises then is how to schedule the transfer of crude oil from the docks to the tanks and from the tanks to the CDUs/VDUs, minimizing the setup cost of the system.

There are several different ways that a refinery can receive crude oil: (a) through the use of a pipeline, (b) through the use of tankers or (c) through a combination of both pipelines and tankers. In a typical refinery system, after crude oil is loaded into the tanks it must remain there for a few hours in order to be separated from the seawater. Tanks typically have the capacity to hold hundreds of thousands of cubic meters of crude oil. The crude oil must be stored there before being sent to a CDU/VDU. It is very important that the crude oil is loaded and unloaded contiguously, both for security reasons and to reduce the setup cost incurred when flow between a dock and a tank or between a tank and a CDU/VDU is reconfigured.

The system under study in this paper is composed of a series of tanks to store crude oil, docks to accommodate the boats delivering the crude oil, blenders and CDUs/VDUs. Moreover, this system is also composed of pipelines, which connect the docks with the tanks and the tanks with the CDUs and VDUs (see Fig. 1). Finally, electric pumps for loading and unloading the crude oil, as well as mixers for the preparation of the blends required by the CDUs and VDUs, are two other important components of the system. The objective is to schedule the loading and unloading of crude oil in the tanks to minimize the setup cost. Scheduling must take into account operational constraints and constraints relating to the use and the availability of resources (see Section 3.2). It must also take into account dimensions of the system and the capacity of each resource, as well as the selected recipe preparation alternative and mode of blending.

There are several modes of blending and various recipe preparation alternatives, which make the problem of loading and unloading of crude oil more complicated. The modeling of these two aspects requires the introduction of a high number of decision variables and constraints into the problem. In a typical refinery there are 1–10 tanks for the storage of the crude oil. The storage capacity of each tank can range from 80,000 m^3 to 150,000 m^3. Crude oil flows from the docks to the tanks, and its flow depends on the unloading capacity of the boats, ranging from 1000 m^3/h to 5000 m^3/h.

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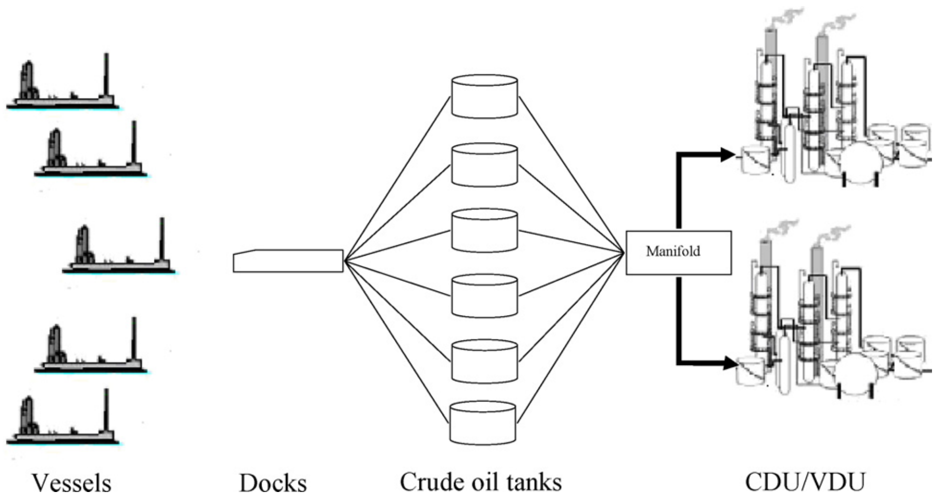

Fig. 1. System under study.

Duration of a boat's unloading is typically defined a priori by contract. After the loading of tanks from the boats, crude oil flows from the tanks towards the CDU/VDU. This flow corresponds to the distillation capacity of each unit. Each CDU/VDU has a distillation capacity that can range from 200 m^3/h to 2000 m^3/h. A typical refinery is composed of 2–4 CDUs/VDUs and 1 or 2 docks, which can accommodate 4–5 vessels per month.

The data and the parameters of the system are dimensions of the refinery, arrival dates of vessels based on medium-term planning, demand of crude oil by the CDU/VDU, initial conditions (quantity and composition in each tank) and the system's capabilities (operational times, tanks capacity and flow limits). Moreover, the number of tanks available for storage and their storage capacity are known. The production rates are determined prior to the selection of the recipe preparation alternative and the blending mode, which are known as well.

The modeling of this problem involves both continuous and binary decision variables. The continuous variables correspond to flows from docks to tanks, flows from tanks to CDUs/VDUs, and quantities stored in the tanks. Binary variables are used to specify connections between docks and tanks, connections between tanks and CDUs/VDUs, and also the availability and setup for loading and unloading of the tanks. The constraints necessary to describe the system include: (a) satisfying operations rules; (b) satisfying material balances; (c) meeting storage capacity constraints; (d) satisfying blend properties; (e) establishing a connection between docks and tanks; (f) establishing connections between tanks and CDUs/VDUs; and (g) setup of tanks for loading or unloading.

The paper is organized as follows. Section 2 gives a literature overview for the scheduling of crude oil and the various types of models and solution methods developed in this area. Section 3 presents the objective of our research and describes the system under study. For a better understanding, a real numerical example (derived from a refinery in Greece) will serve as an illustration. Section 4 presents a general model that takes into account the various modes of mix preparation and the multiple distillation options. After the presentation of the models and the solutions they provide, we will draw a comparison between the solution obtained by the proposed modeling and the sub-optimal solution obtained by the implementation of the method currently used by the refinery decision-makers. In Section 5, we will develop a reformulation of the problem based on the partitioning of the time horizon according to events intervals. Section 6 presents several valid inequalities for the scheduling of crude oil that accelerate the convergence of the model and can be applied in a general system. Section 7 draws conclusions indicating prospective for future research.

2. Literature review of production scheduling in petroleum companies

The problem of scheduling and planning in petroleum companies has appeared since the introduction of linear programming (Floudas, 1995; Grossmann & Floudas, 1987; Manne, 1956; Pardalos, 2002; Symonds, 1955). The developed methods for the resolution of this problem are classified into three general groups: the exact methods that use either discrete or continuous time representation and the heuristic methods. A very interesting and complete overview of the developments in the scheduling of multiproduct/multipurpose batch and continuous processes is presented by Floudas and Lin (2004). The authors present all continuous as well as discrete time formulations existing in the literature before 2004 and discuss and examine their strengths and limitations through computational studies. In the following section a detailed and updated overview of scheduling of crude oil is presented.

2.1. Methods based on discrete time representation

Chronologically, the first approach for the problem of scheduling in a refinery uses a discrete time formulation. The principle of discrete time representation is to split the scheduling time horizon into intervals of equal size and use binary variables to specify whether an action starts or finishes during an interval. One of the first published approaches was presented by Shah (1996). The author presents a model based on discrete time representation for the scheduling of crude oil (SCO) leading to the resolution of a mixed integer linear program (MILP). In this formulation, due to nonlinearity issues the problem was broken up into two sub-problems: the upstream, which considers the loading of crude oil from docks to the storage tanks, and the downstream, which refers to the unloading from the tanks to the CDUs. This approach guarantees a feasible, but not optimal, solution for the system. The objective is to minimize the heel of crude oil left in a tank after its content has been transformed to CDU. In Shah (1996), the author proposes a model that solves the problem of SCO for a system where the available tanks can feed only one CDU at a time and where a CDU can be fed by only one tank at a time. Moreover, the author subdivides the scheduling time horizon into intervals of equal duration. Each activity must start and finish within the boundaries of these intervals. We notice that the system under study considers one dock but the model could be easily