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New approach for scheduling crude oil operations

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ABSTRACT

Scheduling of crude oil operations is crucial to petroleum refining, which includes determining the times and sequences of crude oil unloading, blending, and CDU feeding. In the last decades, many approaches have been proposed for solving this problem, but they either suffered from composition discrepancy [Lee et al. 1996. Mixed-integer linear programming model for refinery short-term scheduling of crude oil unloading with inventory management. Industrial and Engineering Chemistry Research 35, 1630–1641; Jia et al., 2003. Refinery short-term scheduling using continuous time formulation: crude-oil operations. Industrial and Engineering Chemistry Research 42, 3085–3097; Jia and Ierapetritou, 2004. Efficient short-term scheduling of refinery operations based on a continuous time formulation. Computer and Chemical Engineering 28, 1001–1019] or led to infeasible solutions for some cases [Reddy et al., 2004a. Novel solution approach for optimizing crude oil operations. A.I.Ch.E. Journal 50(6), 1177–1197; 2004b. A new continuous-time formulation for scheduling crude oil operations. Chemical Engineering Science 59, 1325–1341]. In this paper, coastal and marine-access refineries with simplified workflow are considered. Unlike existing approaches, the new approach can avoid composition discrepancy without using iterative algorithm and find better solution effectively. In this approach, a new mixed integer non-linear programming (MINLP) formulation is set up for crude oil scheduling firstly, and then some heuristic rules collected from expert experience are proposed to linearize bilinear terms and prefix some binary variables in the MINLP model. Thus, crude oil scheduling can be expressed as a complete mixed integer linear programming (MILP) model with fewer binary variables. To illustrate the advantage of the new approach, four typical examples are solved with three models. The new model is compared with the most effective models (RKS(a) and RKS(b) models) presented by Reddy et al. [2004a. Novel solution approach for optimizing crude oil operations. A.I.Ch.E. Journal 50(6), 1177–1197; 2004b. A new continuous-time formulation for scheduling crude oil operations. Chemical Engineering Science 59, 1325–1341], which proves that the new approach is valid and feasible in most small-size and medium-size problems.

1. Introduction

Nowadays, oil refining is an operationally complex, low-margin, and extremely competitive industry. There are four areas in the operation management of refinery: planning, tanker-lightering operations, sales and scheduling. In practical operation process, scheduling is core of all operation managements, reconciling actual operations with unexpected situations. At the beginning of each production periods, planners devise monthly plans based on market demand forecasting, and then decide product amounts and material requirements. Tanker-lightering operations involve determining tanker arrival times and crude amounts. Sales offer information about shipping time and product distribution. Based on above procedures, refinery personnel must watch crude oil movements and operations, and match them to varying market demands.

Ordinarily, scheduling of refinery operations can be divided into three parts: crude oil scheduling, production unit scheduling and finished product blending (Jia et al., 2003; Jia and Ierapetritou, 2004). These sub-problems are characteristic of different time horizon, operation procedures and bound constraints, which makes the whole problem complex. Crude oil scheduling includes crude oil unloading, blending and crude distillation unit (CDU) feeding. It is a crucial part in the overall operations and affects the second and the third sub-problems significantly. For this reason, many researchers have focused on the scheduling of crude oil operations.

During the past couple of decades, scheduling of crude oil operations has been investigated in many papers. Based on time representation, all existing formulations can be classified into two categories: discrete-time representations and continuous-time representations.

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Most of works were on discrete-time approaches, where a great deal of uniform time intervals are obtained by decomposing the time horizon and each refinery activity is executed during one or more intervals (Coxhead, 1994; Shah, 1996). Lee et al. (1996) developed a mixed integer optimization model relying on time discretization. They replaced bilinear terms for blending operations with individual component flows, applied an LP-based branch and bound method to solve their model. But their linearizing approach would lead to composition discrepancy as identified by Li et al. (2002) and Reddy et al. (2004a). Pinto et al. (2000) formulated scheduling problems of refinery operations based on both continuous and discrete time representations. They claimed that although continuous time formulations provided substantial reductions on the combinatorial feature of a model, the use of a discrete time representation might still be attractive. To eliminate composition discrepancy, Li et al. (2002) proposed a solution algorithm that iteratively solved two mixed integer linear programming (MILP) models and a non-linear programming (NLP) model. However, as noted by Reddy et al. (2004a), with the limit of solving NLP model, this iterative MILP–NLP combination algorithm could not find a solution in all cases. To solve above problems, Reddy et al. (2004a) presented a new mixed integer nonlinear programming (MINLP) formulation and a novel MILP-based solution approach for optimizing crude oil unloading, storing, and processing in multi-CDU. In their approach, time continuity was approximated and an iterative algorithm was used to avoid composition discrepancy and NLP infeasible solutions. Chryssolouris et al. (2005) proposed an integrated simulation-based approach to solve the scheduling problems of refinery operations which involves the unloading of crude oil to storage tanks, the transfer and blending from storage tanks to charging tanks and crude oil distillation units, and the arrangement of the temperature cut-points for each distillation unit.

Continuous-time representation is another important approach for optimizing crude oil scheduling, where refinery activities can start and finish at any point in the continuous domain of time, and the time intervals are not uniform (Jia et al., 2003; Jia and Ierapetritou, 2004). Jia et al. (2003) addressed the short-term scheduling of refinery operations based on a continuous-time formulation. They solved the problems without considering some operational features, such as the changeover costs arising from the component changes of CDU feeds, multiple tanks feeding one CDU, one tank feeding multiple CDUs, and settling time for brine removal. Moreover, they linearized the bilinear terms of crude oil blending the same as Lee et al. (1996) did, which still led to composition discrepancy. Moro and Pinto (2004) presented mixed-integer programming models relying on a continuous-time formulation. To linearize non-linear terms originating from the product between property and volume, they utilized the discretization approach defined by Voudouris and Grossmann (1992). Finally, they found that their discretization approach would increase the number of binary variable and cannot guarantee feasible results in all cases. Reddy et al. (2004b) presented a new continuous-time formulation of MILP for the short-term scheduling of refinery operations. Two types of time events, namely arrival times of tankers and their latest expected departure times, were used to divide the scheduling horizon into several periods with different lengths. Similar to their predecessor work (Reddy et al., 2004a), the same iterative algorithm was used to eliminate the crude composition discrepancy that proven to be the Achilles heel for existing formulations. More recently, Adhitya et al. (2007) also used this iterative algorithm to avoid composition discrepancy in rescheduling crude oil operations under abnormal supply chain events. In their approach, any schedule can be broken into operation blocks, and then rescheduling is performed by modifying these blocks in the original schedule using simple heuristics to generate a new schedule that is feasible for the new problem data. Mendez et al. (2006) presented a novel MILP-based method that addressed the simultaneous optimization of the off-line blending and the short-term scheduling problem in oil-refinery applications. To preserve the model's linearity, an iterative procedure was proposed to effectively deal with non-linear gasoline properties and variable recipes for different product grades.

As to the above discussion, bilinear term is the most difficult problem for optimizing crude oil scheduling. With this feature, the scheduling problem has to be described as an MINLP model both in discrete and continuous time representation, and thus making a hard procedure for finding feasible solution. Some researchers (Lee et al., 1996; Jia et al., 2003; Jia and Ierapetritou, 2004) neglected the rule that amounts of individual crude that a charging tank feeds must be in proportion to its composition. So, their linearizing approaches suffered from composition discrepancy. Some researchers (Li et al., 2002) divided the whole MINLP model into MILP and NLP model. But their NLP model cannot guarantee feasible solution in all cases. Other researchers (Reddy et al., 2004a,b) proposed an iterative algorithm, where the scheduling problem is expressed as a set of MILP models. However, when time horizon became longer, they needed to solve more MILP models, increasing overall computational time and affecting the final objective value. Unlike existing approaches, our new approach can avoid composition discrepancy without using iterative algorithm and find better solution effectively. In this approach, a new MINLP formulation is set up for crude oil scheduling firstly, and then some heuristic rules collected from expert experience are proposed to linearize the bilinear constraints and selectively prefix some binary variables. Finally, crude oil scheduling problem can be expressed as a complete MILP model with fewer binary variables. In addition, real-world coastal and marine-access refineries with simplified workflow are considered, such as single buoy mooring (SBM), multiple tanks feeding one CDU, one tank feeding multiple CDUs, settling time for brine removal, changeover cost, crude oil netbacks, safety stock penalties and demurrage cost.

The rest of this paper is structured as follows: a detailed problem description is introduced in Section 2. A new MINLP formulation and some heuristic rules for crude oil scheduling are proposed in Sections 3 and 4, respectively. In Section 5, four typical examples are solved by using three distinct models, and the performances of these models are compared.

2. Problem description

Crude oil scheduling is a decision making process to determine the times and sequences of crude oil unloading, storing, blending and CDU feeding to achieve certain objective. In this paper, we focus on coastal and marine-access refineries with simplified workflow that were considered by Reddy et al. (2004b). Fig. 1 is the schematic of crude oil scheduling in this refinery, involving very large crude carriers (VLCCs) carrying several large parcels of different crude oil, crude oil unloading facilities such as SBM station, storage facilities such as storage tanks, and processing facilities such as CDUs. Crude oil scheduling can be depicted as following procedure: at the beginning of production period, some information is known based on tanker-lightering operations, for instance, arrival times of VLCCs, the types and volumes of crude oil carried in each VLCC; when VLCCs arrive at dock, these VLCCs and the crude storage tanks are connected via one SBM pipeline, and then each crude oil parcel is unloaded to storage tanks in a certain sequence. Usually, there is only one SBM, so VLCCs can dock only one at a time. Similarly, there is only one pipeline, so only one crude parcel can be unloaded at any time. As a continuous process, CDUs must be fed continuously in the whole scheduling horizon, and the key components of blended oil have to match the limits of CDU operations. The objective is to satisfy all production demands and maximize total profit.