PLANT-WIDE SCHEDULING AND MARGINAL VALUE ANALYSIS FOR A REFINERY

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Abstract

This paper presents an integrated refinery scheduling model and its applications for a refinery located in Jiujiang, Jiangxi, P.R.China. The model integrates a crude oil unloading and storage area, a refining area, a blending area and a product storage area of the refinery. The scheduling model can be applied for optimizing the operation, configuration and production schedule of the refinery. The new modeling technique and solution strategy were developed to schedule crude oil unloading and storage. This method avoids solving an MINLP problem directly and shortens significantly the solution time. In the refining area, processing units such as CDU (crude distillation unit) and FCC (fluidized-bed catalytic cracking) were included and modeled. Yield models for CDU and FCC were used to optimize the CDU cut points and the FCC conversion level. This allows the refinery model to produce much more reliable and cost-effective solutions. A new analytical method called "marginal value analysis" is proposed to provide additional economic information for all stream flows inside the refinery. Important insights are generated using the analysis to find production bottlenecks, assist in decision making and price intermediate materials, etc. A real industrial example is used to illustrate the plant-wide scheduling model and corresponding marginal value analysis.

Keywords

Refinery, Scheduling, Planning, Optimization, Marginal Value Analysis.

Introduction

A refinery process can be defined as a chain that includes crude oil unloading and storage, refining, product blending and storage. To improve the efficiency of refinery management, mathematical models of all these elements in the chain would be helpful. All these models should be coordinated and integrated to maximize overall profits. Compared with long-term planning, short-term operation scheduling technologies are much less mature. However, intense competition requires that plants promptly respond to market requirements. The scheduling of continuous processes has received more and more attention (Pinto et al., 2000). Lee et al. (1996) addressed the problem of inventory management for a refinery that included an unloading schedule, transferring schedule and charging schedule for crude oils. Pinto et al. (2000) presented a superstructure for refinery planning and proposed several scheduling models for refinery operations. Li Wenkai et al (2002) developed a model and algorithm for the

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scheduling of crude oil unloading and storage. This paper presents an integrated model of a refinery used for short-term scheduling and the strategies for solving this model.

Rigorous models and empirical models are available for CDU. Because of their complexity, rigorous models are not commonly used for production planning. Empirical models use empirical correlations to establish material and energy balances for crude distillation units (CDU). These models were described in great detail by Watkins (1979). Besides the CDU, fluidized-bed catalytic cracking (FCC) is another important unit that strongly influences the profitability of a refinery. Some correlations (Gary et al., 2001) have been developed to estimate the yield of FCC from simple feed properties and known conversion.

The research work on marginal value analysis is still immature. Hui (2000) proposed two novel definitions of marginal costs, MC_F and MC_P, which have important significance in understanding the economic structure of a system.

Plant-wide scheduling

A scheduling model for the whole refinery is developed and described area by area as follows.

Scheduling of Crude Oil Unloading and Storage

The crude oil unloading and storage area consists of a few unloading berths, storage tanks, charging tanks with pipelines among them. The crude oil shipped in vessels is stored in storage tanks and further mixed in charging tanks according to composition constraints. The scheduling model minimizes the operating cost involved in this area, which includes vessel-unloading costs, sea-waiting costs, tank inventory costs, and CDU transition costs. The scheduling model determines the allocation of berths to vessels; the sea-waiting time and unloading duration for each vessel; all stream flow rates; inventory levels in the storage tanks and charging tanks and the distribution of crude oils from the vessels to the charging tanks or storage tanks to meet the concentration requirements of each tank.

For calculating crude oil composition in the storage/charge tanks, non-convex bilinear constraints will be generated. It is found that reformulating the bilinear constraints into linear ones to avoid solving an MINLP problem often results in inconsistent solutions. Instead of linearizing the constraints, the problem is modeled as a combination of an NLP and an MIP. A solution algorithm is proposed that provides optimum and consistent solutions by iteratively solving the NLP and MIP models

Scheduling of Refining Area

The refining area consists of many units such as CDU, FCC, reformer, coker, etc. To model the refining area, the scheduling model should perform material balances of each processing unit to determine the optimal loading and flow rates among the units. Li et al. (2002) developed models for the determination of CDU weight transfer ratio range (WTR) and of FCC fractions transfer ratio correlations.

Determination of the CDU WTR

The procedure for CDU WTR determination uses ASTM boiling ranges of CDU fractions and TBP (True Boiling Point) data of crude oil that can be directly obtained in most refineries. The procedure consists of three major steps as follows.

Step 1. Determination of cutpoints. The boiling ranges of CDU fractions given by Watkins (1979) are used in this paper. These ASTM boiling ranges are converted to TBP boiling ranges using the correlations developed by Watkins (1979). With these TBP boiling ranges, three extreme cases (Max. Naphtha, Max. Light Dist., Max. Heavy Dist.) are then defined and the cutpoints for three extreme cases are calculated.

Step 2. Calculation of the volume and weight transfer ratios of CDU fractions. The crude oil TBP data and CDU fractions API data from crude assay are correlated to form the crude oil TBP equation and CDU fractions API equations. The calculated cutpoints for three extreme cases obtained in step 1 are then sent to crude oil TBP equation to calculate the volume transfer ratios of CDU fractions. Using the calculated API gravity of CDU fractions, the volume transfer ratio of a CDU fraction is then converted to weight transfer ratio. The above procedure is performed for each extreme case to obtain the weight transfer ratios of CDU fractions in each case.

Step 3. After weight transfer ratios corresponding to the three extreme cases are obtained in step 2, the maximum and minimum weight transfer ratios are calculated from the three cases for each CDU fraction. These maximum and minimum weight transfer ratios are then sent to the scheduling model as WTR to optimize the cut points of CDU fractions.

Model for FCC fraction transfer ratios

A procedure for the determination of FCC fraction transfer ratios as a function of FCC conversion is proposed.

Firstly, the yield correlations (when zeolite catalyst is used in FCC) of FCC fractions were obtained from figures provided by Gary et al. (2001). Then, the feed properties, API gravity and Watson characterization factor, were read. The lower limit and upper limit of FCC conversion are determined according to FCC operation conditions such as the regenerator coke burning ability. The conversion range used in this paper is (60%, 85%). The FCC material balance according to the procedure described by Gary et al. (2001) is performed and the weight transfer ratios of FCC fractions are calculated for different conversion levels. Finally, using the data obtained above, correlation of FCC fraction weight transfer ratios vs. FCC conversion is obtained. An equation of each FCC fraction weight transfer ratio vs. FCC conversion is obtained and used in the refinery scheduling model to optimize the FCC conversion level.

Main flow diagram for the refining area model

The main flow diagram for solving the refining area model is illustrated in Figure 1. The whole procedure consists of the following steps:

- Call CDU weight transfer ratio range determination model to calculate the maximum and minimum weight transfer ratios of CDU fractions.
- Call FCC yield model to obtain equations of FCC fraction weight transfer ratio vs. FCC conversion. These equations are used in the refinery model.
- Read initial data, which include the data of unit capacities, unit operation costs, initial octane numbers and pour points and CDU weight transfer ratio ranges.
- Solve the main NLP refining area model.

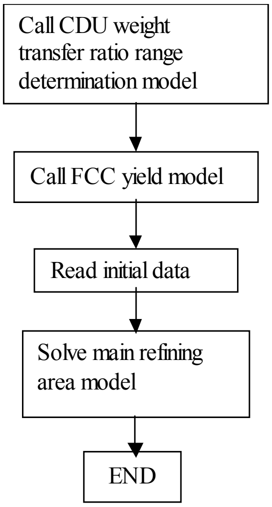

Figure 1. Flow diagram for solving the refining area model

Scheduling of Product Blending

The intermediate products from the refining area are pumped to the blending area. To model the blending area, the scheduling model needs to determine the production rate and the specification of each product. The data needed to start the scheduling of this area include: the octane number of each intermediate stream for gasoline blending; the pour point of each intermediate stream for diesel oil blending and product quality requirements. The widely used linear blending rule for gasoline blending is applied. For diesel blending, improved nonlinear correlation proposed by Semwal et al. (1995) is used in this paper.

For gasoline blending, the octane number of each product should equal or be greater than the required octane number of that product. For diesel oil blending, the pour point of each product should equal or be less than the required pour point of that product.

Scheduling of Product Storage

The product storage area consists of many storage tanks. It can be used as a buffer for products. When the market demand for a product decreases, the product can be stored in the tanks as inventory and sold when the market demand increases. Furthermore, a refinery can adjust its product production rate distribution using these product storage tanks. In modeling the product storage area, the scheduling model needs to determine a material balance for each tank and then determine the suitable inventory level in each tank and the optimal production rate of each product for each day to meet market demands.

Integration Solution Strategy

The scheduling models for all areas were integrated into one model and an algorithm is developed to solve the model. Figure 2 illustrates the developed algorithm.

In Figure 2, the scheduling model for the crude oil unloading and storage area is solved first. Then, the crude oil composition data in storage/charging tanks and the CDU feed flow rates are sent to the refining model. New WTRs are calculated using the new composition data. The refining model is solved using the procedure described in Figure 1. The linear scheduling models for the blending area and the product storage area can either be integrated into one model and solved subsequently or integrated with the refining model and solved in the previous step. Then the "Converge Condition" checks whether the total profits (profits from all four areas) in the current iteration is greater than previous profits. If yes, then the procedure continues to iterate. Otherwise, the algorithm is terminated.

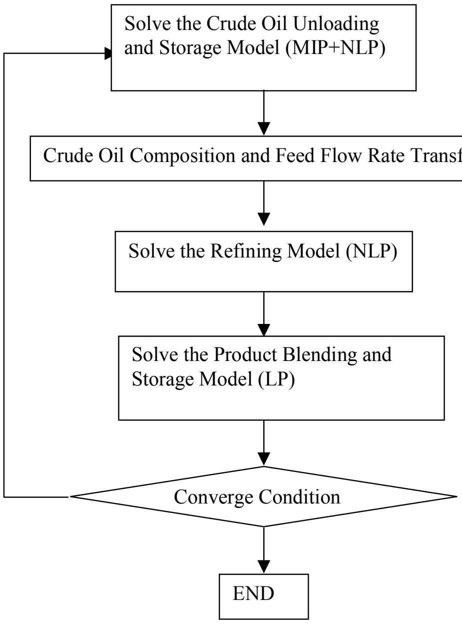

Figure 2. Integrated solution procedure

New Definitions of Marginal Values

Besides direct information such as maximized profit, the crude oil charging schedule and the overall refinery material balance, the optimal solution of the plant-wide refinery scheduling model can also report additional economic information such as marginal values of the crude oil, intermediate products and final products. These marginal values are useful for debottlenecking the refinery, pricing intermediate materials and assisting investment decision.

New definitions of marginal value are defined as the variation in overall profits by adding or taking away a small amount of a stream (Hui, 2000). Adding or taking away a small amount of a stream has different effects on overall profits. For example, in most cases, taking away a small amount of material from CDU fractions will decrease the total profits. But, in some cases, taking away a small amount of material from a CDU fraction will increase the total profits. This indicates that a bottleneck occurred in the process restricting the usage of CDU fractions. The solution to this problem could be to remove the bottleneck so that additional profits can be realized from increasing the CDU fractions or finding a user to export the CDU fractions

Case Study

A real industrial example was provided by Juijiang refinery in China with some modifications in the data to protect the company secrets. In the example, 17 vessels are expected to moor at the docking station during the scheduling horizon of 7 days. The amount and type of crude oil in each vessel is different. The refinery docking station has 4 berths. Every day, at most four vessels can arrive at the docking station. One of the four berths needs to be allocated to each vessel. A vessel can feed at most one storage tank. A storage tank can be charged simultaneously by a maximum of 4 vessels. The company has 7 storage tanks. Unlike some other refineries, the refinery has no charging tank. The number of crude oil types allowed in the vessels and storage tanks during the scheduling horizon is 6 (C1-C6). The crude oil types that are allowed to mix in each storage tank are different. In this example, only tank 6 is used to mix crude oils C2, C4 and C6. All the other tanks can store only one specific type of crude oil. Instead of calculating the sulfur concentration of the feed oil, the concentrations of crude oils are calculated directly by their material balance, so that refinery operators know the exact volume of crude oils in each tank. This example consists of two CDUs that can be charged simultaneously from a maximum of two storage tanks.

An MIP and NLP model was built for the crude oil unloading and storage area and an NLP model was built for the refining area, blending area and product storage area. The whole refinery scheduling model was solved using the algorithm proposed in this paper and the corresponding marginal value analysis was performed. Interesting and useful results were obtained that assisted the company in further improving profitability.

Conclusions

In this paper, plant-wide scheduling of a refinery was studied. Models were developed for scheduling the crude oil unloading and storage area, refining area and product blending and storage area. These models were then integrated and solved using a proposed solution algorithm. By including proper models of CDU and FCC, the model precisely optimized the yield of the units taking into account the properties changes due to the variations of product yields. Marginal costs of the material flows inside the refinery were calculated directly from the optimum solution generated from the models. This cost information provide additional means for improving the profitability of a refinery.

Acknowledgments

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