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Optimal crude oil procurement under fluctuating price in an oil refinery

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ABSTRACT

In this paper, we study the optimal procurement and operation of an oil refinery. The crude oil prices follow geometric Brownian motion processes with correlation. We build a multiperiod inventory problem where each period involves an operation problem such as separation or blending. The decisions are the amount of crude oils to purchase and the amount of oil products to produce. We employ approximate dynamic programming methods to solve this multiperiod multiproduct optimization problem. Numerical results reveal that this complex problem can be approximately solved with little loss of optimality. Further, we find that the approximate solution significantly outperforms a set of myopic policies that are currently used.

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1. Introduction

The economics of a refinery mainly depends on the interaction between two key elements: the crude oil operations management and procurement management. Traditionally, the focus of the refineries literature is on the operations management, such as crude oil scheduling and blending, refinery design/configuration, product blending control, etc. Studies on the procurement management with uncertain prices were scarce as crude oil prices were relatively stable. Since the new millennium, however, crude oil prices have become extremely volatile. As the crude oil procurement cost is about 90 percent of the total operation cost, ignoring uncertainties in the crude oil prices may result in significant losses.

Typical refinery operations involve a wide spectrum of activities, which are extremely complex and heavily linked. In this paper, we investigate optimal crude-oil procurement problem with consideration of the interaction between the price dynamics and the refinery operational decisions. This problem is extremely complex for three reasons.

First, crude oil prices are highly volatile. Fig. 1 plots two oils' weekly average spot prices from January 2004 to November 2013. We observe that the prices fluctuate significantly in short periods. It is interesting to see that the path of a crude oil price resembles the path of a stock value. This similarity is not surprising as many financial institutes and funds play in the oil's future market. According to Brennan and Schwartz (1985), Paddock, Siegel, and Smith (1988), and Mostafaei, Sani, and Askari (2013), oil prices approximately follow geometric Brownian motion (GBM) processes. The analysis on high-dimensional GBM can be very complex, and optimal solutions may be extremely hard to obtain.

Second, the procurement of crude oil is a multiperiod decision. For a Chinese state-owned oil refinery, purchase decisions are made every month or every two months. Managers frequently need to decide whether to purchase now or to wait. The purchase quantity of crude oil is also very hard to decide. No managers would like to purchase a lot of crude oil at very high prices. This multiperiod decision is very challenging and important. A bad decision hurts a manager's reputation and performance.

Third, oil refineries produce or consume multiple products at the same time. For instance, operations such as separation or blending involve multiple products at a given mix. As a result, different crude oils' purchases are correlated. This correlation turns the problem into a high-dimensional optimization problem. In our project with a regional Chinese state-owned oil refinery, the dimension goes up to 26. This curse of dimensionality prohibits the search of optimal solutions.

The contribution of the paper is threefold. First, we approximate the dynamic programming problem using orthogonal array (OA) sampling method and multivariate adaptive regression splines (MARS) algorithm. Numerical results reveal that the optimal solution of the approximate problem is a near-optimal solution of the original problem. Second, we find that this optimal solution significantly

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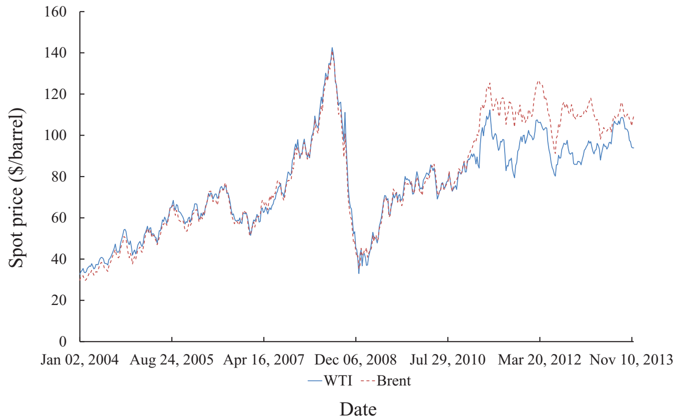

Fig. 1. Weekly average spot prices from January 2004 to November 2013 (based on the data from EIA).

outperforms a set of myopic policies, which first set a minimum inventory requirement at the end of each period and then solve each period independently. Third, numerical results suggest that the superiority is robust to the estimation of oil price drift rate, but not very robust to the volatility of oil price.

The remainder of the paper proceeds as follows: Section 2 briefly reviews the related literature. Sections 3 and 4 describe the single-period and multiperiod setup, respectively. Section 5 presents an approximate solution approach. We test this approximate solution approach in Section 6. Finally, Section 7 offers some concluding remarks. We conclude this introduction with some notational conventions. Vectors will be in boldface. All vectors are column vectors by default, and primes denote transposes. A bar (for example, $\bar{V}$) placed above a variable represents the average value of observations on this variable. A hat (for example, $\widehat{V}$) placed above a function represents an approximation of that function. $\mathbb{E}$ denotes the expectation. Indicator function $1_{\{x\}}$ equals 1 if event x is true and 0 otherwise. Throughout this paper, "increasing" and "decreasing" mean "nondecreasing" and "nonincreasing," respectively.

2. Literature review

Production process in an oil refinery is complicated, with multiple facilities, materials, and production constraints. Many researchers have worked to model and optimize the production process for oil refineries. Bodington and Baker (1990) summarize the use of mathematical programming in the petroleum industry before 1990. Linear programming models were used in the early times (Charnes, Cooper, & Mellon, 1952). With the growth of computer technology, nonlinear programming (NLP) models were introduced to formulate the process more accurately (Adhya, Tawarmalani, & Sahinidis, 1999; Amos, Rönnqvist, & Gill, 1997; Baker & Lasdon, 1985; Chryssolouris, Papakostas, & Mourtzis, 2005; Floudas & Aggarwal, 1990; Golovin, 1979; Lee, Pinto, Grossmann, & Park, 1996; Rigby, Lasdon, & Waren, 1995). Researchers have developed many different approaches to deal with nonlinear parts in refining processes, such as simulation approach (Chryssolouris et al., 2005; Golovin, 1979), successive linear programming (SLP) (Baker & Lasdon, 1985; Griffith & Stewart, 1961), Benders' decomposition (Floudas & Aggarwal, 1990), mixed integer programming (Lee et al., 1996), least square programming (Amos et al., 1997), Lagrangian relaxation (Adhya et al., 1999), etc.

The literatures mentioned above concentrate on the modeling of the refining process. Recently, with the financialization of the oil market, fluctuations of crude oil prices have increased significantly (NA, 2010). As a result, refineries are facing larger risks in crude oil prices nowadays than 10 years ago. Many researchers have developed different models to describe price behaviors, such as geometric Brownian motion (GBM) (Brennan & Schwartz, 1985; Paddock et al., 1988), mean reversion (MR) (Schwartz, 1997), etc. Ederington, Fernando, Lee, Linn, and May (2011) gave a survey on the factors influencing oil prices and the stochastic models describing price behaviors. It is hard to argue which price model is the best for modeling crude oil prices. Al-Harthy (2007) explored the impact of three oil price models—GBM, MR, and MR with jumps—on the uncertainty output of a project's NPV and concluded that the GBM model is a good approximation if the decision is based on the mean value rather than the standard deviation, and if the current oil price is close to the long-term price. Meade (2010) argued that both GBM and MR are not supportable as a long-term model and suggested a mixture of two Gaussian models. Aspen (2011) compared four price models—fixed price, GBM, MR, and a system thinking approach—and concluded that these four models would favor different projects, in which GBM would favor projects with high production at a later stage. Liu, Wang, Zhao, Pan, and Xiao (2012) argued that MR is more appropriate for cases with low future oil price volatility, and GBM is better for high future oil price volatility. Mostafaei et al. (2013) tried to select the best stochastic model for Russian crude oil price, and illustrated that GBM is the best model for the Russian crude oil price. In this paper, we chose GBM to describe crude oil prices.

Although there are many stochastic crude oil price models, few researchers applied those models into refinery operations. In fact, a stream of literatures studied the optimization of refinery operations under uncertainty (see the review by Leiras, Ribas, Hamacher, and Elkamel, 2011). The most popular approach to handle the uncertainty is two-stage stochastic programming (SP) with recourse models (Al-Othman, Lababidi, Alatiqi, & Al-Shayji, 2008; Aseeri & Bagajewicz, 2004; Carneiro, Ribas, & Hamacher, 2010; Escudero, Quintana, & Salmerón, 1999; Khor, Elkamel, Ponnambalam, & Douglas, 2008; Lababidi, Ahmed, Alatiqi, & Al-Enzi, 2004; Pongsakdi, Rangsunvigit, Siemanond, & Bagajewicz, 2006; Ribas, Hamacher, & Street, 2010), in which the first stage decided the crude supply and/or production rate under uncertainty, while the second stage decided detailed refinery operations. Dempster, Pedrón, Medova, Scott, and Sembos (2000) developed a multiperiod model that modeled stochastic prices as scenario trees. Besides the SP formulation, Ribas et al. (2010) proposed a robust min–max regret model and a max–min model. Dong, Kouvelis, and Wu (2013) proposed a different two-stage SP model to study the value of refinery operational flexibility, in which the first stage decided the crude supply under given crude prices and uncertain end-product prices. In conclusion, approaches in refinery operation literatures used two methods to model the crude oil prices: (1) stochastic variables which were independent through time periods and (2) scenario-based approach. In contrast, our GBM oil price model captures oil price fluctuations over time.

3. Single-period model with fixed prices

In this section, we assume that crude oil purchasing prices and selling prices are known and fixed. We discuss the optimal refinery operation in a single period.

3.1. Three refinery processes

We consider three typical and representative refinery processes: (1) separation, (2) mix, and (3) blend. In a separation process, several products are produced from a single input product according to a given formula. For example, a distillation plant can distillate crude oil into refinery gas, liquified gas, light naphtha, kerosine, etc. A mix process is the reverse of a separation process—that is, several input products can be mixed into an output product according to a specific formula. For example, mixing 5 portions of light naphtha,

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