

A Study of Refiner's Price Risk Management using Financial Engineering

You-Tay Lee^{*}
Chang-Kyu Yi^{**}

〈요약〉

본 연구의 목적은 파생금융상품의 가격결정이론을 이용하여 정유회사가 활용할 수 있는 재무적 위험헤지기법을 제공하는 데 있다. 일반적으로 정유회사는 원유가격의 변동에서 비롯되는 가격위험을 단순히 생산관리 차원에서 관리하고 있으나 이러한 관리기법은 높은 비용을 초래한다. 본 연구는 가격위험을 관리하고자 하는 정유회사에게 재무관리 차원에서 효율적인 헤지기법을 제공한다.

본 연구에서 적용되는 옵션상품의 기초자산은 크랙스프레드(crack Spread)이다. 크랙스프레드는 난방용 기름(heating oil)과 무연휘발유(unleaded gasoline)의 가격과 원유(crude oil)가격의 차이를 나타내며 정유회사의 정유순익(gross refining margin)을 대표한다. 따라서 본 연구는 원유가격의 변동에서 발생하는 가격위험을 생산원가(production cost)를 행사 가격으로 하는 풋옵션을 이용하여 효율적으로 관리하는 기법을 제공한다.

만약 정유회사가 위에서 설명된 풋옵션을 자본시장이나 금융기관을 통해서 구할 수 없을 경우 정유회사는 풋옵션을 합성전략에 의해 창출할 수 있다. 다시 말해서 정유회사는 풋옵션의 가격과 기초자산의 매도 및 매수포지션을 분석하여 풋옵션에 의한 헤지결과와 동일한 헤지결과를 얻을 수 있다. 이러한 헤지기법을 다이나믹헤지라고 한다.

마지막으로 이항분포 옵션가격결정모델을 이용하여 풋옵션의 가격을 제시하였다. 풋옵션의 가격은 기초자산의 변동성과는 정(+)의 관계를 나타내고 반대로 평균회귀요인(mean reversion factor)과는 부(-)의 관계를 나타내고 있다.

* Associate Professor, Department of Business Administration, PuKyong National University

** Full-time Instructor, Department of Business Administration, Dong-A University

I. Introduction

Financial innovations implemented by financial engineering allow investors, corporations, and financial services firms to enjoy reduced costs of raising funds, enhanced investment returns, and more precise management of risk exposures. Mason, Merton, Perold, and Tufano (1995) describe financial innovation as the dynamic force that allows the financial system to provide more efficient allocation of resources in the economy.

Financial engineering is also a systematic approach that investors, corporations, and financial services firms use to produce better solutions to specific financial problems. For example, financial engineering enables technical advances in pricing and hedging that support more comprehensive derivative securities markets and risk management systems.

In this study we apply financial engineering concepts to provide financial hedging strategy for refinery companies.

The process of financial engineering for refiners involves three steps: 1) Identification of the Problem; 2) Analysis of the Problem; and 3) Valuation.

Identification of the Problem

Most refiners rely on mechanical or operational hedging methods such as balancing throughput, changing output mix, or adjusting maintenance shutdown schedules in order to protect gross refining margins against the price risk. All these hedging methods involve huge costs. The futures and options ideas of financial engineering allow a refiner to implement a more efficient hedging strategy, which is created using financial contracts.

Analysis of the Problem

How do we find the best solution to the refiner's problem, given the current state of financial markets and finance theory? First, refiners have the hypothetical asset of the "crack spread," which is defined as the cash price difference between refinery input (crude oil) and major refinery products (unleaded gasoline and heating oil). Crack spread represents the refiner's gross margin, as the price of crude oil constitutes more than 85 percent of total refining costs, and the prices of unleaded gasoline and heating oil contribute, on average, more than 80 percent of the gross refining margin.

We know that the underlying asset (the crack spread) follows a mean-reverting process. Therefore we can create a put option on the crack spread with production cost as an exercise price, in order to hedge downside crack spread risk. The put price can be thought of as an insurance premium.

Alternatively, if the refiner cannot obtain a put option from a financial market or a customized contract with a financial intermediary, it can create a put synthetically. The procedure of creating a synthetic put requires taking a position in the underlying asset (the crack spread) so that the sensitivity of the position to changes in the crack spread is kept equal to that of the put option. This financial engineering procedure enables refiners to lock in their, gross refining margin at a predetermined profit level (e.g., a break-even value of the crack spread).

Valuation

We adapt the well-known binomial option pricing model and apply it to obtain put prices on crack spreads. Put prices represent hedging costs for refiners and premiums for financial intermediaries that offer this kind of insurance plan for customers (refiners). We are directly linking capital markets theory (option pricing theory) and corporate management. Our work not only provides new financial tools for refinery companies, but it also tests the applicability of financial engineering procedures in new research settings.

Section II provides basic information about actual refinery technology. First we describe the mechanics of the refinery process and discuss the refining ratio which is a key term in calculating out hypothetical asset of the crack spread. Second, we describe the crack spread, which constitutes the refiner's gross refining margin.

In Section III, we analyze the financial meaning of crack spreads, with particular attention to their value movements, as we treat the crack spread as an underlying asset (state variable) in the option pricing model. To analyze the value process of crack spreads, we assume the no-arbitrage cost-of-carry principle developed in the futures markets.

In Section IV, we analyze the risk exposures that refiners should consider in operating a refining business, and then provide an optimal hedging strategy.

In Section V and VI, we apply a binomial option pricing model to calculate the put option prices and deltas that play a key role in contractual hedging, and present the results for put prices including deltas. We also show results for various sensitivity analyses in order to see how

the changes of major parameters in the model can affect the changes of put prices and deltas.

A summary and conclusions appear in Section VII.

II. An Overview of the Refinery Industry

The refinery industry is one of the largest industries in the world. Its economic scale and values are so huge that it behooves refinery managers to pay attention to refinery operations and petroleum price movements.

There are more than three hundred refineries in the United States alone, with a total operable capacity exceeding fourteen million barrels per day. U.S. refineries are the technology leaders worldwide, and their facilities are safe, modern, and efficient.¹⁾ However, environmental, health, and safety regulations are rapidly increasing the cost of refining in the U.S. Table 2-1 shows integrated operations for the U.S. refinery industry.

Table2-1 U.S. Refinery Operations

(000 barrels/ day avg.)

	Year		% Change
	1994	1993	
U.S Refinery Operation	1994	1993	% Change
Input to Crude Distillation Units	14,045	13,851	1.4
operable Capacity	15,144	15,143	(0.0)
Refinery Utilization (%)	92.7%	91.55%	

Source: American Petroleum Institute. Monthly Statistical Reports for June. Sept. Dec. 1994

NPN-"National Petroleum News." Mid-June 1995.

1. Refining Technology

Refining is the process of converting crude oil into salable products. Crude oil is not useful

1) U.S refiners' utilization of crude throughput is 94.8%, a percentage that is much higher than in Japan(70%), U.K(87.9%), Italy(68.0%), and France(82.9%). See "Refinery Throughputs: Heavy autumn Turnarounds in U.S ." Petroleum Argus, Aug.22,1994.2.

in its raw state. The maximum value of a barrel of crude oil is attained after it is refined. The refiner's task is made easier by the fact that petroleum consists of only hydrocarbons (molecules composed of atoms of carbon and hydrogen). The relative simplicity of the petroleum mixture allows refiners to separate one group of hydrocarbons from another by simple means such as distillation. Depending on refinery set-up, refiners can change their output mixture to correspond to market demands, within certain limits.

The refinery processes include distillation, alkylation, thermal cracking, catalytic cracking, reforming, isomerization, and hydrocracking, as well as catalytic desulfurization and hydrotreating. Distillation begins by heating crude oil in a furnace that is in an atmospheric distillation tower. As the crude is heated, the lighter portions of the crude are given off as gases. The more heat applied, the greater the proportion of the crude vaporized. The tower is arrayed vertically with many trays, each designed to capture (through condensation) only a selected portion of the rising gas. Lighter forms of the crude continue to rise until they reach a tray that can convert them into a liquid state. Each liquid state in different trays is considered a separate product.

This description is only a brief introduction to refinery operations. Actual operations are naturally far more complex and involve many additional processes (such as alkylation and polymerization). Each refinery has its own unique processing scheme that is determined by the equipment available, operating costs, and production demand. The optimum refinery now for any refiner depends on economic considerations, and no two refiners are identical in their operations.

2. Refining Ratio

The refinery process yields products range from unleaded gasoline, heating oil, kerosene, and jet fuel to solvents, lubricating oils, greases, waxes, petrochemicals, asphalt, and coke. All are derived from crude oil.

Normally, one barrel of crude oil yields gasoline (43.0%), heating oil (21.5%), residual (11.5%), and so on as in Table 2-2. We call this ratio the "refining ratio." The refining ratio depends not only on the processing technology that a refinery applies but also on the type of crude oil.

Table2-3 shows that 43 percent of U.S. total domestic petroleum demand is gasoline, and 18 percent is heating oil. These two major components represent more than 60 percent of the total domestic demand. These percentages approximately match the refining ratios.

Table2-2 Average Refining Ratio

type	percentage (%)	type	percentage(%)
Gasoline	43.0	Asphalt	3.1
Heating Oil	21.5	Coke	2.6
Residual	11.5	LPG	2.3
Jet Fuel	6.9	Kerosene	1.3
Feed Stocks	4.7	Lubricants	1.3
Still Gas	3.8	Miscellaneous	0.7

Source: Anderson (1984).

Table2-3 U.S. Petroleum Demand, 1995 Forecast

(000 barrels/ day)

	1st Quarter	2nd Quarter	3rd Quarter	4th Quarter	1994 Average and(%)of total	1994-95 %Change
Domestic Products						
Gasoline	7,356	7,780	7,920	7,744	7,702 (43.18)	1.4%
Aviation Fuels	1,550	1,545	1,566	1,567	1,557 (8.73)	1.7
Heating Oil	3,538	3,085	3,001	3,293	3,228 (18.10)	1.5
Residual Fuels	1,025	870	809	900	897 (5.04)	(8.8)
All Other	4,338	4,347	4,537	4,571	4,449 (24.95)	1.3
Total Domestic Demand	17,807	17,627	17,833	18,072	17,835 (100.00)	0.9
Total Exports	951	916	909	985	940	2.4
Total Demand	18,758	18,543	18,742	19,057	18,775	0.9

Source: Independent Petroleum Association of America Supply and Demand Committee. Short-Run Report.

Table 7. April 1995.

NPN-"National Petroleum News." Mid-June 1995.

3. Crack Spreads

The crack spread is a unique form of cash spread. We define the crack spread as the difference between cash prices of refinery input and cash prices of refinery outputs. We limit the refinery input to crude oil that is likely supplied through futures trading on the New York Mercantile Exchange (NYMEX). We also concentrate on refinery outputs of two major petroleum products, unleaded gasoline and heating oil, futures contracts on which trade on the NYMEX. Hence, the magnitude of the hypothetical asset, the crack spread, represents a refiner's gross refining margin.

Crack spreads are obtained by the simultaneous purchase of crude oil and sale of petroleum products, i.e., unleaded gasoline and heating oil in the predetermined quantities for each asset as calculated by the refining ratio. Crack spread ratios reflect the approximate amounts of heating oil and unleaded gasoline that are converted or produced from a barrel of crude oil. Refining ratios are flexible over the course of a year, depending on the technology of the refinery and of the demand for and supply of petroleum products.

The traditional refining ratio is 3 : 2 : 1, implying that three barrels of crude oil are assumed to yield two barrels of gasoline and one barrel of heating oil.²⁾ Recently however, many refiners and spread traders have recognized that a 5 : 3 : 2 ratio more correctly reflects reality because of current high dependence on heavier imported crudes, increased demand for high-octane unleaded gasoline, and rapid changes in refining technology.³⁾

In this study, we only consider the 5 : 3 : 2 ratio is an achievable refining ratio, i.e., five barrels of crude oil yield three barrels of gasoline and two barrels of heating oil,

The crack spreads (Φ) are calculated as follows:

$$\Phi = (0.6 \times P^{HU}) + (0.4 \times P^{HO}) - P^{CL} \quad (2-1)$$

where P^{HU} is an unleaded gasoline price for one barrel;

P^{HO} is a heating oil price for one barrel; and

P^{CL} is a crude oil price for one barrel.

2) Most quoted crack futures spreads on the NYMEX are 2 : 1 : 1 for ease of calculation.

3) Edwards and Ma (1992), and interview with oil industry experts Moon-Ki Han and Ki-Wook Lee (Yukong Ltd.) and Robert I. Hassler (Conoco Refinery Co.).

The magnitude of this spread reflects the refiner's gross refining margin. Since the crude oil price contributes 85 percent of the refiner's total operating costs, unleaded gasoline and heating oil prices provide 80 percent of total refining revenues.⁴⁾ Additionally, these prices tend to move together because the prices of heating oil and unleaded gasoline are strongly influenced by the price of crude oil.

Because crack spreads are a function of three energy assets, each asset's price process plays an important role in determining the crack spread price process. For example unleaded gasoline prices and heating oil prices display opposing seasonal trends over the year, depending on seasonal demand and supply (see Table 2-4). This fact may imply that if crude oil prices move constantly over a year, crack spreads may also move constantly despite dampening effect caused by opposite seasonality effects for unleaded gasoline and heating oil.

Table2-4 Petroleum Products Supplied. 1994

(000,000 barrels/day)

Products	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
Unleaded Gasoline	6.9	7.3	7.4	7.5	7.6	7.9	7.8	8.0	7.6	7.5	7.5	7.9
Heating Oil	3.7	3.6	3.3	3.1	2.9	3.1	2.7	3.1	3.1	3.1	3.2	3.2
Total	10.6	10.9	10.7	10.6	10.5	11.0	10.5	11.1	10.7	10.6	10.7	11.1

Source: Energy Information Administration, Weekly Petroleum Status Report Table 9. Mar. 3. 1995.

NPN- "National Petroleum News." Mid-June 1995.

III. Behavior of Crack Spreads

Our objective in this section is to study the dynamics of crack spreads, because we treat crack spreads as underlying assets (state variables) in our option pricing model. To analyze

4) See NYMEX Energy Hedging Manual (1986).

the process of crack spreads, we apply the no-arbitrage cost-of-carry principle developed in the futures markets. The cost-of-carry model allows us to figure out the relationship between cash prices and futures prices.

1. Cost-of-Carry Model

Cost-of-carry is defined as the costs that are associated with holding (or carrying) an asset (such as a commodity). These include interest costs (financing costs), storage costs, and insurance costs. The cost-of-carry model is used to investigate the relation between futures price and cash price. In equilibrium the futures price is equal to the cash price plus the cost of carry.

Fama and French (1987) formulate a no-arbitrage cost-of-carry model for commodity markets including interest rates, storage costs, and convenience value. The price of a futures contract at time t that matures at time T , $F(t,T)$, and the current cash price of a commodity $S(t)$ are related as follows:

$$F(t,T) = S(t)e^{(r+u+c)\gamma} \tag{3-1}$$

- where r is the rate of interest between time t and T ;
- u is the marginal storage cost expressed as a percentage;
- c is the marginal convenience yield; and
- γ is a commodity holding period. $T - t$.

Equation(3-1) generally assumes that:

- 1) No transaction costs are associated in trading assets.
- 2) There are no restrictions in lending or borrowing money.
- 3) No credit risk is associated in trading either futures or the physical commodity.
- 4) Commodities can be stored indefinitely.
- 5) There are no taxes.

The cost-of-carry is positive if storage creates a net cash outflow, and negative if convenience yield is large enough to offset the cost of storage and the interest rate.

Convenience yield is the implied yield or non-pecuniary return from holding a commodity. This convenience yield reflects the market's expectations concerning the

future availability of the commodity. The greater the possibility that shortages will occur during the life of the futures contract, the higher the convenience yield. If users of the commodity have high inventories, there is very little chance of shortages in the near future, and the convenience yield tends to be low. Low inventories conversely tend to lead to high convenience yields.

Fama and French (1988) test these contentions with industrial commodities such as steel and copper. They find that when inventory levels are low, futures prices are less volatile than cash prices, and the convenience yield rises faster than the inventory. When inventory levels are high, the cash and futures prices have approximately the same variability and the convenience yield curve becomes flatter.

According to Equation (3-1), when holding a commodity has a convenience yield the futures price will be below full carry. In an extreme case, the market can be so far below full carry that the cash price can exceed the futures price. When the cash price exceeds the futures price, or when the nearby futures price exceeds the distant futures price, the market is in normal "backwardation." Hence, convenience yield is a measure of the degree of backwardation in a market.

In other words, high demand for a commodity results in a high convenience yield for that commodity. A decline in the convenience yield implies that the market expects the shortage to subside over time so that the commodity price would increase."

For example, the crude market is normally in backwardation, expressing high demand for crude in the immediate future. The main reason is that refiners are reluctant to have unexpected supply interruptions (e.g., local shortages) because it is very costly to shut down an operation process for temporary shortages. This indicates that the convenience yield, c , is high enough to cover other costs, $r + u$, in Equation (3-1). We can also say that a commodity has a convenience yield when traders are willing to pay a premium to hold the physical commodity at a certain time. As we will see later, heating oil (unleaded gasoline) futures prices are high in the winter (summer)-just when people need heat (gas for cars).

5) For more detail, see Siegel and Siegel(15)90). pp. 367-371.

2. Crack Spread Components

The cash markets for crude oil and petroleum products are among the most complex cash markets. There is an active market for and trading in crude oil still in the ground or extracted from the ground, for example. Oil companies, refiners, and end-users are all participants in the cash markets for crude oil. Investment banks have also started to arbitrage and speculate in the oil markets just as they do in many financial markets. In addition, there are very competitive cash markets in the derivative products that are refined from crude oil, such as unleaded gasoline and heating oil.

In the past two decades, the petroleum markets have undergone a major transformation. Until the early 1970s, the oil market was characterized by stable prices; there were long-term contracts between major petroleum firms and government price controls. The market system of stable prices disappeared with the Middle East oil embargo of 1973, which gave rise to the increased pricing power of the Organization of Petroleum Exporting Countries (OPEC). Petroleum prices then became the most volatile of all commodity prices.

Since then the deregulation of the U.S. oil markets, the political crisis in Iran in the late 1970s, the growth of the petroleum cash markets, and conflicts within OPEC have all contributed to ongoing volatility of petroleum prices. The increased volatility of petroleum prices ultimately led to the development of futures trading in crude oil and its products.

The major petroleum futures exchange in the United States is the NYMEX, which trades contracts on crude oil, unleaded gasoline, heating oil, and propane. In our study, we limit oil markets to the NYMEX and hence prices of crude oil, unleaded gasoline, and heating oil are obtained from NYMEX.

A. Crude Oil

There are three major variables in the grading of crude oil: field of origin, API gravity, and sulfur. The field of origin is a reference point for physical characteristics of crude oil. These characteristics include pour point, viscosity, color, flash and fire points, percentage of water, distillation yields, and metallic contaminants.

The par grade of crudes traded on the NYMEX is West Texas Intermediate (WTI) with 40 degrees API gravity and 0.4% sulfur.

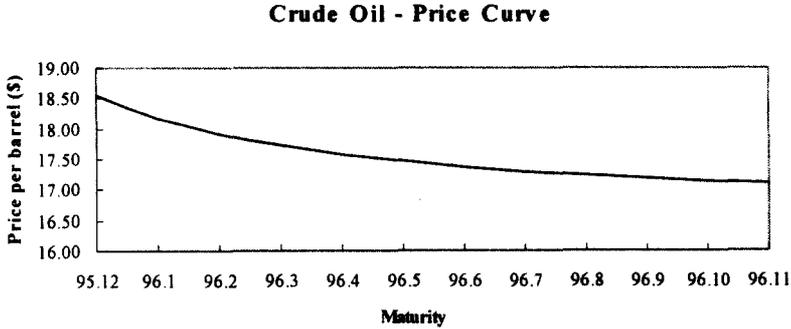
Figure 3-1 Crude Oil Futures Price Curve (1995. 12)

Figure 3-1 shows the typical futures price movement for crudes.³⁻²⁶⁾ It is clear that crudes have convenience values and that the futures market experiences normal backwardation. Actually many refiners purchase and store crude oil instead of using the futures market. The main reason is to protect crude users from unexpected supply interruptions. It is very costly for refiners to shut down in temporary shortages.

Interruptions can also occur due to political reasons. Political turmoil in the Middle East, for instance, has led to huge oil shortages. Thus, refiners may store crudes for convenience values.

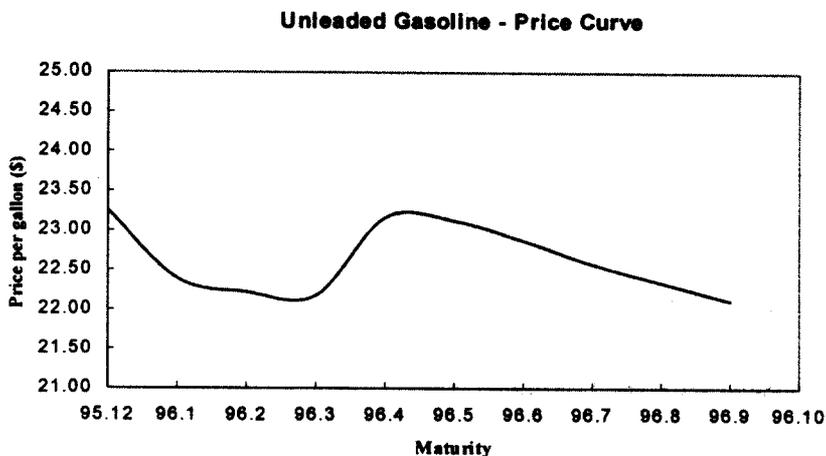
B. Unleaded Gasoline

The development of unleaded gasoline is a result of government restrictions on automobile emissions. These restrictions require the use of catalytic converters and force all automobiles to use only unleaded gasoline. Originally, refiners added lead to enhance octane ratings of gasoline. To produce high-octane unleaded gasoline without adding lead, refiners have developed advanced reformulation techniques.

Figure 3-2 illustrates the significant seasonal trends in unleaded gasoline price movements. The most important issue in the pricing of unleaded gasoline futures is the convenience value of unleaded gasoline, which is determined primarily by seasonal factors. Demand for gasoline is high in the summer months (the driving season) and lower in the winter months.

6) We examined one-year futures prices movements for three energy commodities (crude oil, unleaded gasoline, and heating oil) on the last trading day of November 1995.

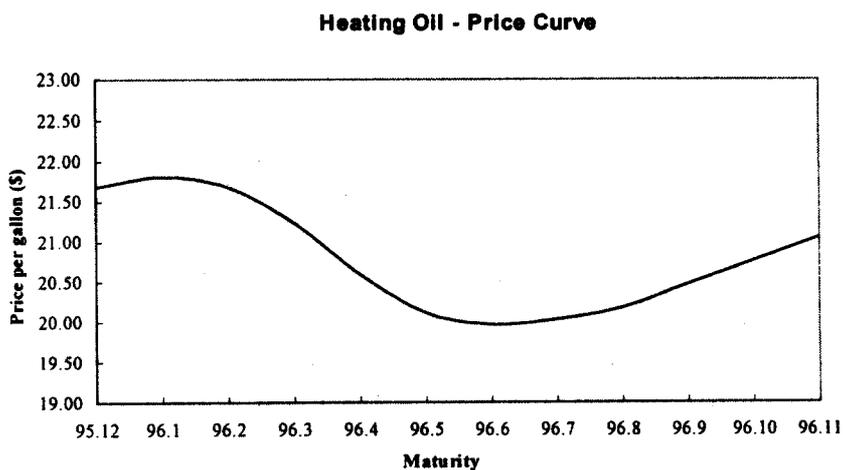
Figure 3-2 Unleaded Gasoline Futures Price Curve (1995. 12)



C. Heating Oil

Heating oil that is traded in NYMEX is No. 2 fuel oil or as gas oil.

Figure3-3 Heating Oil Futures Price Curve(1995. 12)



The seasonal consumption and production patterns of heating oil are the mirror opposite of unleaded gasoline, as should be clear in Figure 3-3. The months of greatest demand are in winter, the time of lowest demand for gasoline. This phenomenon is desirable for refiners, because they can adjust their output to produce relatively more heating oil for the winter months and relatively more gasoline for the summer months.

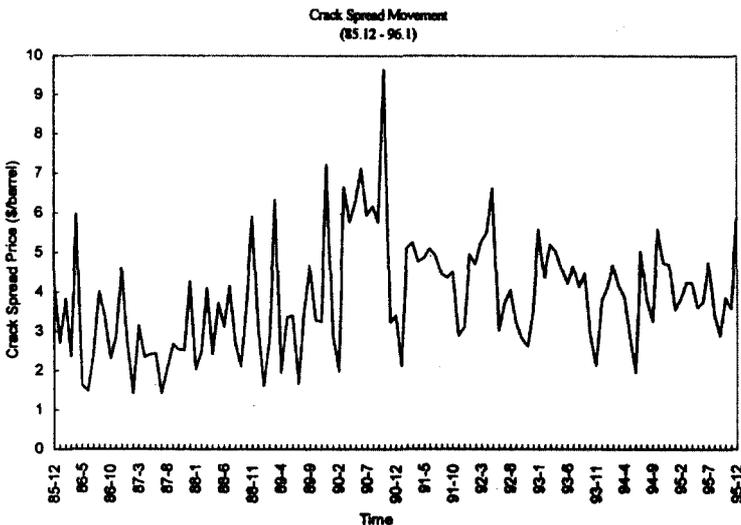
In late summer and early fall, refiners begin to produce more heating oil than is consumed in order to match the large demand in the winter. At the end of the winter, they start producing less heating oil and more gasoline in anticipation of the driving season.

Thus, we expect heating oil to have a convenience value from the end of winter to the beginning of summer.

3. Crack Spreads Movement

We use monthly settlement prices of crude oil, heating oil, and unleaded gasoline futures contracts from NYMEX. The set of data obtained from Knight-Ridder Financial includes futures prices on three commodities markets between December 1985 and January 1996.⁷⁾

Figure 3-4 Crack Spread Movements (1985.12-1996. 1)



7) To calculate crack spreads, data sets start in January 1986 because unleaded gasoline has been traded since 1986 and is the newest of the three commodities.

Figure 3-4 shows the movement of crack spreads between December 1985 and January 1996 calculated according to Equation (2-1). Futures prices that are the nearest to maturity are taken as a proxy for cash prices (Fama and French, 1987).

There is a considerable variation in the crack spread. In 1990, for example, it ranged from a low of about \$1.00/barrel to a high of almost \$10.00/barrel. Changes of this magnitude obviously reflect the relative volatility of the prices of crude oil, unleaded gasoline, and heating oil. Usually, crack spreads move up and down within a band between a high of \$6.00/barrel and a low of \$2.00/barrel. If petroleum product prices fall relative to crude oil price, the crack spreads narrow; if prices rise, the spreads widen.

IV. Contractual Hedging Strategy for Refiners

The major issue in this Section is to analyze the risk exposures that refiners should consider in operating a refining business, and provide an optimal hedging strategy.

1. Crack Spread Risk

Refiners convert crude oil into a portfolio of refined products at a marginal refining cost or production cost. The gross refining margin covaries with the change in the crack spreads since 85 percent of refining costs are represented by the price of crude oil. It is therefore important for refiners to cope with unexpected changes (decreases) in crack spreads; in brief, they must manage crack spread risk.

For the moment, we assume that a refining firm makes operating decisions at discrete time points. It purchases crude oil, converts crude oil, and sells a mixture of products including heating oil and unleaded gasoline simultaneously. There refining firm always faces the risk that the gross refining margin (i.e., the crack spread) will be less than the production cost.

In that case, most refiners try to find a solution using physical or traditional methods such as balancing throughput, changing output mix, or adjusting maintenance shutdown

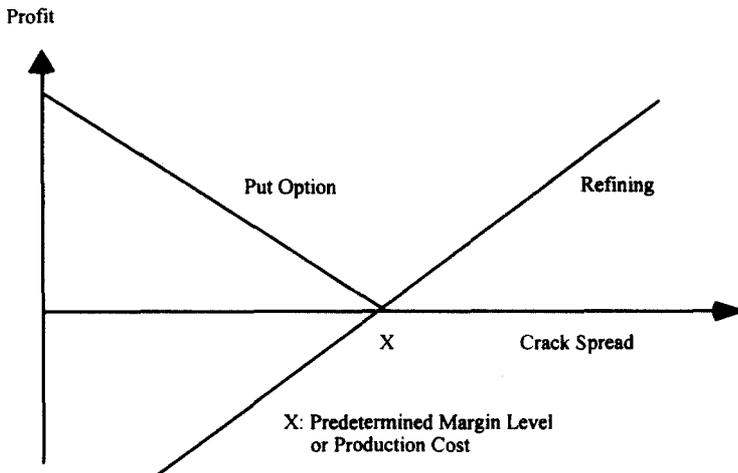
schedules.⁸⁾ These choices not only involve huge costs but also cause interruptions in production management. The use of financial engineering strategies such as protective puts or synthetic puts allows refiners to hedge crack spread risk at a lower cost while continuing to operate the refinery in the most efficient manner.

2. Managing: Crack Spread Risk with Put Options

Crack spread risk has been defined as an unexpected decrease in crack spreads to the level of production cost or lower. If the crack spread exceeds production costs, outputs are produced at refinery capacity and only the put premium is at risk, otherwise, the loss from the crack spread risk is hedged by exercising a put option.

In other words, refiners operate their production lines continuously, and a long position of put options takes care of downside crack spread risk. Figure 4-1 shows the refiners' payoff diagram with a put option in place.

Figure 4-1 Contractual Hedging Strategy for Refiners

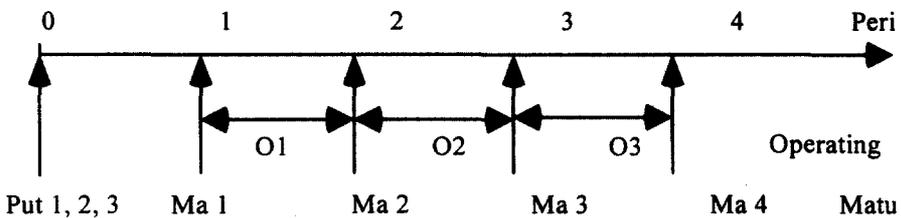


8) These are the choices cited in an interview with oil experts. The interviewees include Moon-Ki Han and Ki-Wook Lee (Yukong), Woo-Sang Yoo (Daewoo), and Robert J. Hassler (Conoco). Hereafter, references to "oil experts" mean these interviewees.

We assume that a refiner operates the production process in a discrete time period and can shutdown the production process temporarily. In addition, the refiner must make the operating decision for the next period at the end of the current period. If the refiner decides to implement a particular refinery process, the operation will continue for that period without any interruptions.

Suppose a refiner is interested in hedging crack spread risk over three production periods (three months), i.e., the refiner builds a hedging strategy once each quarter of the year⁹⁾. Since a shutdown involves huge costs, the refiner may consider a contractual hedging method to protect its operating margin against the crack spread risk. Figure 4-2 illustrates the refiner's hedging strategy more formally. The sum of the values of Put 1, 2, and 3 indicates the refiners hedging costs over the three periods, 01, 02, and 03.

Figure 4-2 Hedging Time Horizon



At time 0, the refiner owns three European put options (Put 1, 2, and 3) that have maturities Ma 1, Ma 2, and Ma 3. At the end of period 0, or, the beginning of period 1 (Ma 1), the refiner must make a decision as to whether it will continue to refine or whether it will shut down for a specified period of O1. Conceptually, if the crack spread at time 1 is greater than the exercise price (production cost) of the put option, the refiner will produce outputs at capacity for period 1, which is the period between time 1 and time 2. If the crack spread at time 1 is lower than the production cost, the refiner will temporarily shut down the refinery process for the period O1. In fact, the operational hedging techniques using shutdown option involve huge costs.¹⁰⁾

9) We recognize from interviews with oil experts that refineries are accustomed to controlling the monthly quantity of crude oil quarterly using a linear programming method to deal with crack spread risk. Hence, we infer that a refiner makes hedging decisions in each quarter of a calendar year.

From the point of view of a contractual hedging strategy (ie.. continuous refining + protective put), when the crack spread is lower than the exercise price, the refiner is able to compensate for a negative profit by exercising the put option. For periods of 02 and 03, Put 2 and Put 3 play the same role as Put 1.

A. Protective Put Strategy

The idea of the protective put strategy, the simplest form of portfolio insurance, derives from the stock market; see Pozen (1978). A stockholder who wants protection against a falling stock price may buy a protective put to guarantee the minimum price of the stock. This transaction involves simply buying a put option on a stock and buying the stock itself.

The protective put works like an insurance policy. When you purchase insurance (a European put option) for any private asset (operation of a refinery), you pay a premium (the option price) which assures you that in the event of a loss (when the crack spread is less than product-on costs), the insurance will cover at least some of the loss (downside crack spread risk). The insured (the refinery) determines the deductible level (the strike price) according to its risk preferences. If a loss does not occur during the policy life (the European option maturity), the insured (the refinery) simply loses the premium.

B. Synthetic Put Strategy

An alternative hedging method for refiners involves creating put options synthetically. A synthetic put hedging strategy that involves adjustments of underlying assets with changes of put option delta is also known as a dynamic hedging strategy.

In theory, refiners can achieve insurance by buying a protective put on crack spreads. The trouble with this approach is that put options on the crack spread are not always available in the market. Even if there were put options, options markets do not always have the liquidity to absorb the transactions that refineries that are used to handling large amount of funds might like to make. Refiners might also like strike prices (production cost or levels of the gross refining margin to be protected) and exercise dates (when the refiner makes

10) Recently, the most significant developments in the petroleum product markets have been a required substantial reduction in the sulfur content of heating oil, and the introduction of reformulated unleaded gasoline. Refiners have had to spend a tremendous amount of money to upgrade their production processes to meet these specifications. Because of these large capital investments, refiners hardly execute the shutdown option when the crack spreads become weak.

the operating decision) that are different from those available in traded options markets.

The synthetic put can be created by both a financial intermediary and a refiner. First, we consider the synthetic put strategy for a financial intermediary. The financial intermediary (an investment banker, for example) is defined as a refinery investor who does not actually possess the refinery production process, but can replicate the refinery process by holding securities of crack spreads. Suppose the financial intermediary or the refinery investor realize that put options on crack spreads that properly match the strike price and the maturity are not available in the markets. In this case, the investor can create a synthetic put from trading the crack spreads. This involves taking a position in the underlying asset of the crack spread so that the delta of the position is kept equal to the delta of the required put option. This strategy is exactly the same as portfolio insurance for stocks.

O'Brien (1988) and Singleton and Grieves (1984) discuss the mechanics and strategies of portfolio insurance based on synthetic puts. O'Brien (1988) illustrates the way the principle of dynamic portfolio insurance works in detail, including the use of index futures. He also provides ideas regarding determination of portfolio insurance costs.

Singleton and Grieves (1984) show that synthetic put strategies clearly succeed in reducing risk. but that they do so only at a fair price for the portfolio.

Assume that a financial intermediary, a refinery investor, would like to replicate refinery production, benchmarking to a refiner whose refinery capacity is one million barrels per month. We also assume a crack spread is a single security and obtained by using a 5: 3 :2 refining ratio. Suppose the refinery investor wishes to purchase a European put on the crack spread with a strike price of production costs or guaranteed refining margin and an exercise date in one month. The refinery investor's portfolio is the replicated refinery capacity times the crack spread, which we call the refinery portfolio.

The delta of the European put on the crack spread is given by

$$\Delta = \frac{\partial f}{\partial \Phi} \tag{4-1}$$

In a binomial model, we have the delta as:

$$\Delta_0 = \frac{f_1^1 - f_1^0}{u\Phi(0) - d\Phi(0)} \tag{4-2}$$

where f and Φ represent the European option price and the crack spread, respectively.

At a given time Δt , f_u^1 denotes the option value when the crack spread is $u\Phi(0)$, and f_d^1 denotes the option value when the crack spread is $d\Phi(0)$.

Equations (4-1) and (4-2) imply that the delta is the rate of change in option price with respect to the price of the underlying asset of the crack spreads. The delta of the put option is negative. Accordingly, in order to create a synthetic put, the refinery investor should ensure that at any given time, i.e., at the option maturity date, a proportion Δ_0 of the refinery portfolio has been sold and the proceeds invested in riskless assets.

More formally, a synthetic put strategy can be described as

$$P = -\Delta\Phi + RF \quad (4-3)$$

where P stands for the synthetic put and RF for the amount of investment in the risk-free asset.

If the refinery investor sells off the proportion of the portfolio equal to the put option's delta, and places the proceeds in risk-free assets, the resulting exposure to the crack spread market will equal that of the protective put position. As the prices of petroleum products decrease, or the price of crude oil increases (i.e., the crack spreads decrease), the delta of the put becomes more negative, and the proportion of the refinery portfolio sold must be increased. As the crack spreads increase, the delta of the put becomes less negative, and the proportion of the refinery portfolio sold should decrease (i.e., some of the original refinery portfolio must be repurchased).

The synthetic put strategy means that, at any given time, the refinery investor's funds are allocated to both a refinery portfolio and risk-free assets. As the value of the refinery portfolio increases, risk-free assets are sold, and the position in the refinery portfolio is increased. As the value of the refinery portfolio declines, the position in the refinery portfolio is decreased, and riskless assets are purchased.

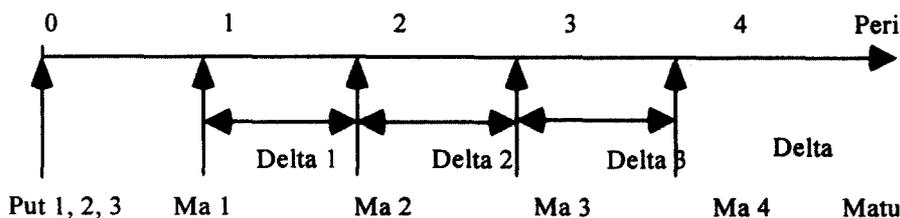
The cost of the insurance arises because the refinery portfolio manager is always selling after a decline in the crack spread market and buying after a rise in the crack spread market. The synthetic put strategy also requires that the refinery portfolio manager continually rebalance the portfolio according to the delta of the put option, which also incurs the transaction costs of running a trading operation system.

Second, a refiner can also create a synthetic put the same way the refinery investor does. One difference is that the refiner's underlying asset is the real refining process instead of

the marketable crack spreads for the financial intermediary. Another difference is that the refiner rebalances the positions of underlying assets once before maturity of the put options. In other words, the refiner controls the refinery capacity (the underlying asset), depending on the magnitude of the put option delta at each maturity of a put option. If the delta of the put becomes less negative (i.e., crack spreads increase), the refinery capacity (the actual quantity of throughput) should be increased. Or, if the put option delta becomes more negative (i.e., crack spreads decrease), the refinery capacity should be decreased.

Figure4-3 describes the refiner's synthetic put strategy or dynamic delta hedging strategy in more detail.

Figure4-3 A Refiner's Dynamic Hedging Scheme



The refiner initially uses the synthetic put strategy to protect the refining operating margin against crack spread risk, and hence is interested in the deltas of three hypothetical puts that mature in one month, two months, and three months. Each hypothetical put has a delta: Delta 1 (Δ_1) for Put 1, Delta 2 (Δ_2) for Put 2, and Delta 3 (Δ_3) for Put 3. At each maturity of the put option, the refiner must rebalance the underlying asset (quantity of the throughput), depending on the magnitude of the sum of the deltas. More formally, at time 0 when a refiner sets up the hedging plan for next three periods, Δ_p , indicates the proportion of the refinery capacity that is supposed to be rebalanced:

$$\Delta_p = \sum_{i=1}^3 \Delta_i \tag{4-4}$$

where Δ_p , is the delta of a portfolio put option.

The delta of a portfolio put option, Δ_ρ , changes as time passes. In our hedging scheme, at time 1, the maturity of Put 1, Δ_ρ , consists of Δ_2 , and Δ_3 . Thus, at time 1, the refiner must rebalance the operation capacity based on the new Δ_ρ . At time 2, Δ_ρ , becomes Δ_3 , since put 1 and 2 are expired. However, at time 3, a refiner has a new Δ_ρ , to perform hedging for the next three months. Δ_ρ , is a function of volatility of crack spreads, so a refiner needs to calculate new Δ_ρ , based on new estimations of volatility (see Section VI).

V. Model for Valuing Put Option and Delta

In this Section, We develop the theoretical procedure of pricing put options on the crack spread according to the binomial option pricing model. Black and Scholes (1973) were the first to develop an option pricing model based on the risk-neutral valuation principle, which means that the risk preference of an option investor does not affect option valuation. Cox, Ross, and Rubinstein (1979) propose a discrete-time option pricing model that assumes that 1) movements of underlying assets are binomial in a short period of time, and 2) the world is risk-neutral.

We apply the Cox-Ross-Rubinstein discrete-time binomial option pricing model in order to compute the prices of put options on crack spreads and the deltas of those options.

1. Mean-Reverting of Crack Spreads

We can intuitively recognize the fact that the crack spread follows a mean-reverting process through the crack spread market mechanism. The crack spread is derived from the workings of a combination of three energy markets, such as crude oil unleaded gasoline and heating oil. On the demand side of the markets, crude oil is stable, but unleaded gasoline and heating oil are seasonal over the year. Opposite seasonality effects for unleaded gasoline (high demand in the summer season) and heating oil (high demand in the winter season) are dampening, and consequently make the demand for a combination of these two markets stable over a year. From this fact, we can infer that the distribution of crack spreads for a year is relatively constant and fluctuates only slightly around its long-term mean value because of temporary shocks in each energy market.

The other factor to consider is government regulations or government intervention in oil prices. The ultimate purpose of government regulations is to protect both refiners and final consumers of petroleum products. Suppose crude oil prices rise too far because of a temporary shortage of supply from OPEC. Refiners will suffer from low gross refining margin in the short run. In the long run, consumers for refined products may also suffer from high oil prices, since refiners will increase the prices of refined products to guarantee some minimum level of gross refining margin. Therefore, to protect both refiners and final users, the government can relax regulations for local or non-OPEC suppliers in the event of shortages. Such an action to balance the supply of and demand for crude moderates its price, hence increasing gross refining margin for refiners and protecting consumers against higher prices.

As the process followed by the underlying asset plays an important role in the option pricing model, many researchers have studied the mean-reverting(Ornstein-Uhlenbeck) process, especially in the fixed-income security and stock markets. For example, Chiang, Liu, and Okunev (1995) develop a model with mean reversion of asset prices. They assume that the long-term mean value follows a Geometric Brownian Motion (GBM) and derive a closed-form solution for the underlying asset.

We specify a discrete-time diffusion process for crack spreads reverting to the long-term equilibrium value of the crack spread:

$$\Delta\Phi(t) = \lambda_{\phi}[\bar{\Phi} - \Phi(t)]\Delta t + \sigma_{\phi}\Delta Z_{\phi}(t) \tag{5-1}$$

- where
- $\Delta\Phi(t)$ is change in the crack spread;
 - λ_{ϕ} is the speed of mean reversion coefficient;
 - $\bar{\Phi}$ is the long-term mean value of the crack spread;
 - $\Phi(t)$ is the value of the crack spread at time t ;
 - σ_{ϕ} is the standard deviation of $\Delta\Phi(t)$ per unit of time; and
 - $\Delta Z_{\phi}(t)$ is a Wiener process with mean zero and unit variance,

The λ_{ϕ} is an adjustment parameter or mean reversion factor that pulls the crack spreads toward the long-term mean value. In other words, λ_{ϕ} measures how quickly the crack spread reverts to its long-term mean value. For mean reversion to exist, λ_{ϕ} should be positive. If λ_{ϕ} is negative, the process will not be mean-reverting. When λ_{ϕ} is equal to zero, Equation (5-1) reduces to a random walk.

Moreover, we can infer from Equation (5-1) that if $[\bar{\Phi} - \Phi(t)] < 0$ (ie., the crack spread is above its long-term mean value), the expected change in the crack spread will be negative, and hence the crack spread will regress toward its long-term mean value in the next period. The magnitude of $[\bar{\Phi} - \Phi(t)]$ is a measure of the force of reversion.

To obtain the monthly return of $\Phi(t)$, we divide both sides of Equation (5-1) by $\Phi(t)$ and we have:

$$\begin{aligned} \frac{\Delta\Phi(t)}{\Phi(t)} &= \frac{\lambda_{\Phi}[\bar{\Phi} - \Phi(t)]}{\Phi(t)} \Delta t + \frac{\sigma_{\Phi}}{\Phi(t)} \Delta Z_{\Phi}(t) \\ &= \frac{\lambda_{\Phi}[\bar{\Phi} - \Phi(t)]}{\Phi(t)} \Delta t + \varepsilon, \text{ with error term} \\ &= \frac{\lambda_{\Phi}[\bar{\Phi} - \Phi(t)]}{\Phi(t)} + \varepsilon, \text{ with } \Delta t = 1 \text{ month} \\ &= -\lambda_{\Phi} \left(1 - \frac{\bar{\Phi}}{\Phi(t)}\right) + \varepsilon \end{aligned} \quad (5-2)$$

where $-\lambda_{\Phi} \left(1 - \frac{\bar{\Phi}}{\Phi(t)}\right) = \mu$, the actual drift rate; and

$\sqrt{E(\varepsilon^2)} = \sigma_{\varepsilon}$, the volatility.

We run ordinary least squares (OLS) regression with Equation (5-2) to estimate parameters (λ_{Φ} and $\bar{\Phi}$) and volatility of crack spreads (σ) using monthly crack spreads for the sample period January 1986 through January 1996. The OLS regression results yield the parameter values:¹¹⁾

$$\frac{\Delta\Phi(t)}{\Phi(t)} = -0.5521 \left(1 - 4.217 \frac{1}{\Phi(t)}\right) + \varepsilon \quad (5-3)$$

where $\sigma_{\varepsilon} = 0.4402$.

11) A more advanced econometric analysis could use non-linear estimation techniques to jointly estimate parameters and volatility.

Table 5-1 reports the estimation values and other statistics. Results indicate that the mean-reversion factor is 55.21%, and the volatility is 44.02% on a monthly basis.

Table 5-1 Summary of OLS Results

Mean reversion factor ($\lambda \phi$)	0.5521 per month
Long-term mean value ($\bar{\Phi}$)	4.217 \$ per barrel;
Volatility($\sigma \epsilon$)	0.4402per month
t-statistic	7.813*
DW test	2.03

* p < 0.05

2. Valuation Process

There are three major parameters involved in analyzing the binomial option pricing model (u, d, and p). Basic algebra and statistics allow us to calculate values for these three parameters

We can describe the expected value of the crack spread at the end of an initial time interval Δt as:

$$\Phi(0)e^{-\lambda_{\phi}(1-\frac{\bar{\Phi}}{\Phi(t)})\Delta t} = p_1^{\Phi(0)}u\Phi(0) + (1 - p_1^{\Phi(0)})d\Phi(0) \tag{5-4}$$

In addition, from Equation (5-1), we can develop a specification for the expected change in crack Spreads:

$$E(\Delta\Phi) = \lambda_{\phi}[\bar{\Phi} - \Phi(t)]\Delta t \quad , \text{ and}$$

$$Var(\Delta\Phi) = \sigma^2\Phi(t)^2\Delta t \tag{5-5}$$

Equation(5-5) specifies that the variance of the change in crack spreads in a small time interval Δt is $\sigma^2\Phi(t)^2\Delta t$. Applying the statistics rule of $Var(X) = E(X^2) - [E(X)]^2$, we have:

$$\sigma^2 \Phi(t)^2 \Delta t = p_{t+1}^{\Phi(t)} u^2 \Phi(t)^2 + (1 - p_{t+1}^{\Phi(t)}) d^2 \Phi(t)^2 - \Phi(t)^2 [p_{t+1}^{\Phi(t)} u + (1 - p_{t+1}^{\Phi(t)}) d]^2 \quad (5-6)$$

Finally, With a condition of $u = (1/d)$, Equations (5-4) and (5-6) yield estimations for u , d , and p as follows;

$$u = e^{\sigma \sqrt{\Delta t}} \quad (5-7)$$

$$d = \frac{1}{u} \quad (5-8)$$

$$p_1^{\Phi(0)} = \frac{e^{-\lambda_0 [1 - \Phi(0)] \Delta t} - d}{u - d} \quad (5-9)$$

where σ is the volatility of the underlying asset's rate of return.

Alternatively, suppose we are able to estimate δ_ϕ , directly using the relationship between δ_{CL} , and δ_{HU} and δ_{HO} , where δ_ϕ is both time- and state-dependent. We will have a new pseudo probability instead of Equation (5-9) as:

$$p_1^{\Phi(0)} = \frac{e^{[r - \delta(\Phi(0))] \Delta t} - d}{u - d} \quad (5-10)$$

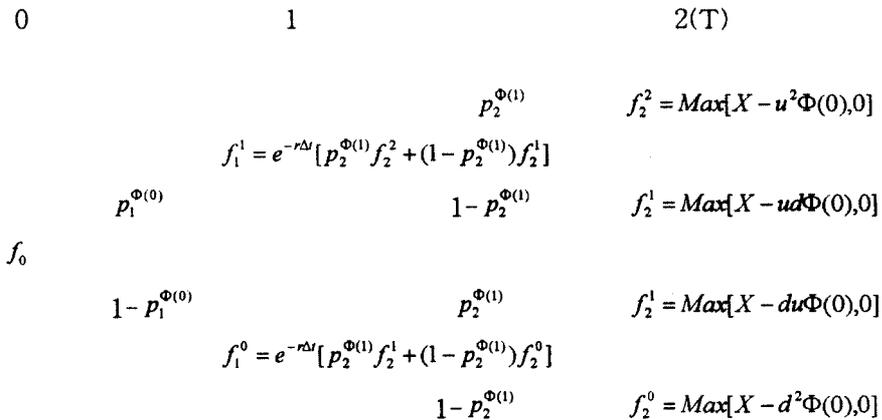
Based on Equation (5-10), the next procedure to calculate option values is to construct the term structure of δ_ϕ , using the futures markets for the crack spread components and build the structure into a binomial framework. For example, assume that δ_ϕ is only a function of time, and Δt is a month, i.e., the δ_ϕ of January is different from that of February. In each month, we apply the proper δ_ϕ that is derived from the term structure of δ_ϕ to calculate a pseudo-probability. If δ_ϕ is a function of both time and crack spread, the pseudo-probability will also change according to the changes in crack spreads.

With all values of parameters estimated, a put option on crack spreads can be obtained numerically by working backward through the binomial tree. Figure 5-1 describes the two-period binomial tree for a European put option process. Options are evaluated by starting at the end of the tree (here, time 2) and working backward.

The value of this put option is known at time 2 (T) maturity, as $\text{Max}[X - \Phi(2)]$, where $\Phi(2)$ is the crack spread value at time 2 (maturity), and X is the strike price. Since we assume a risk-neutral world, the value at each node at time 1 can be calculated by taking the

expected value at time1 and discounting it using the risk-free rate for Δt . Eventually, by discounting the expected values back through all the nodes, the option value at time0 is obtained (eg, $f_0 = e^{-r\Delta t} [p_1^{\Phi(0)} f_1^1 + (1 - p_1^{\Phi(0)}) f_1^0]$).

Figure 5-3 Binomial Tree for European Put on Crack Spread



We can generalize the two-period revised binomial model as an N-period model. Suppose that the life of a European put option on a crack spread is divided into N subintervals of length Δt . Let f_i^j be the value of a European option at time $i\Delta t$ when the crack spread is $u^j d^{i-j}\Phi(0)$ for $0 \leq i \leq N$, $0 \leq j \leq i$. Hence, we know that;

$$f_N^j = \text{Max}[X - u^j d^{N-j}\Phi(0), 0] \tag{5-11}$$

for $j = 0, 1, 2, \dots, N$

There is a probability, $P_{i+1}^{\Phi(i)}$, of moving from (i, j) node at time $i\Delta t$ to the (i+1, j+1) node at time $(i+1)\Delta t$, and a probability $(1 - P_{i+1}^{\Phi(i)})$ of moving from the (i, j) node at time $i\Delta t$ to the (i+1, j) node at time $(i+1)\Delta t$. In other words, the probabilities depend on the state of the crack spread. As the option is a European put option, no early exercise is allowed. The risk-neutral valuation suggests that the option value is

$$f_i^j = e^{-r\Delta t} [P_{i+1}^{\Phi(i)} f_{i+1}^{j+1} + (1 - P_{i+1}^{\Phi(i)}) f_{i+1}^j] \tag{5-12}$$

for $0 \leq i \leq N-1$ and $0 \leq j \leq i$.

VI. Results and Simulation

In this section, we show the results for put prices and deltas calculated using the binomial option pricing model. We also present sensitivity analyses that show the changes of put prices and deltas in response to the changes of major parameters.

To obtain put option prices, we use parameters estimated from real oil price data. The base-case parameters are as follows. The current crack spread, $\Phi(0)$, ranges from \$2.00/barrel to \$6.00/barrel;¹²⁾ the exercise price, X , is \$4/barrel;¹³⁾ the annual risk-free rate, r , is 5.00%;¹⁴⁾ times to maturity, T , are one month, two months, and three months; the volatility of the crack spread rate of return, σ , is 0.4402/month; the mean reversion factor of the crack spread, λ_{ϕ} , is 0.5221/month; the long-term mean of the crack spread, Φ , is \$4.217/barrel.

We apply the binomial model to 144 discrete time periods to calculate put prices (i.e., $\Delta t=1/144$). Figures 6-1 through 6-13 indicate put prices and put deltas for various changes in parameter, assuming that the contract size of the option is 1,000 barrels.

For example, the base-case put prices (deltas) at the current crack spread of \$4.25/barrel are \$0.454/barrel (-20.42%) for one month maturity, \$0.529/barrel (-10.45%) for two months' maturity, and \$0.622/barrel (-6.07%) for three months' maturity. These base-case put prices and deltas at $\Phi(0)=\$4.25$ have important meaning for refiners. Since crack spreads follow a mean-reverting process with a relatively strong forces ($\lambda_{\phi}=0.5521$ /month) toward Φ (that is, \$4.217/barrel), refiners can consider base-case put option prices as a proxy for their average expected insurance expenses.

Suppose a refiner's production capacity is one million barrels per month, and that put options are available in the market. The refiner owning put options can operate its refinery processes constantly, regardless of the changes in crack spreads; this represents a protective

12) From Figure 3-4, crack spreads have ranged between approximately \$6.00/barrel and \$2.00/barrel except during the middle of 1990 (the Gulf War).

13) Exercise prices come from through two sources, published accounting information and interviews with refinery experts. The published source is Value Line's Composite Statistics for Petroleum (Integrated) Industry (December 29, 1995). It notes that refiners' operating margin is 13.5% for 1995. It also estimates that operating margins for 1996 and 1998-2000 are 13.5% and 16.0%, respectively.¹³

14) This is the approximate average of the 3-month T-bill rate from 1975 to 1995

put strategy. Of course, this hedging strategy involves costs. At the initial time of the hedging plan for a quarter of a year (at time0 in Figure 4-2), the refiner purchases one million one-month puts that cost \$454,000, one million two-month puts that cost \$529,000, and finally one million three-month puts that cost \$622,000. The sum of these three put prices, \$1,605,000, is the refiner's hedging cost (insurance expense) for three months. In addition, if a financial intermediary offers a customized insurance plan that covers the same refining loss, the refiner can get some indication of the proper amount of the insurance premium.

The other hedging method available to the refiner is to develop a synthetic put using put deltas. In this case, the refiner needs to reduce refinery capacity by approximately 37% ($20.42\% + 10.45\% + 6.07\%$) at time0 in Figure 4-3 to achieve the same results as would be obtained through a protective put strategy. One month later (at time1), the refiner needs to adjust the amount of crude oil produced, depending on the new portfolio delta ($\Delta_2 + \Delta_3$). In other words, the refiner needs to "rebalance" (reduce or increase) production capacity at each time according to the new put deltas.

On the other hand, suppose a financial intermediary replicates the refinery operation in the form of crack spread securities, and put options on the crack spread are not available in the markets.¹⁵⁾ The financial intermediary immediately must rebalance its crack spread position according to the deltas. The intermediary should sell off 37% of its crack spread portfolio.

At-the-money put prices ($\Phi(0) = \$4.00/\text{barrel}$) for one month, two months, and three months are \$0.477/barrel, \$0.530/barrel, and \$0.628/barrel. Deep in-the-money put prices are sometimes lower than their intrinsic values since the options are European puts and hence cannot be exercised before the maturity date. Another way to explain this phenomenon is that, because the mean reversion factor forces the relatively low crack spread (e.g., $\Phi(t) < \Phi$) to regress to its long-term mean, there is a high probability that the low crack spread will rise to its long-term mean in the next period. Consequently, in the put option payoff function ($\text{Max} [X - \Phi(T), 0]$), a deep in-the-money put price on a mean-reverting underlying asset is likely lower than its intrinsic value.

What if the mean reversion factor is zero; in other words, the net convenience yield for

15) If the put options on the crack spread are buyable in the markets, the hedging strategy is identical with the protective put.

the crack spread is zero? Put prices are never lower than their intrinsic values at any points of current crack spreads in Figure 6-3. The only difference between Figures 6-1 and 6-3 is the degree of the mean reversion factor, Figure 6-1; $\lambda_{\phi}=0.5521$, and Figure 6-3; $\lambda_{\phi}=0$.

At-the-money option prices and deltas are functions of major parameters such as volatility, mean reversion factor, and time-to-maturity. Table 6-1 displays the sensitivity of the at-the-money put prices to changes in these major parameters. The interesting finding is that the changes in volatility and mean reversion factor inversely affect the put prices. Suppose the Long-term mean level of crack spreads, Φ , is equal to the exercise price, X , and $\Phi(0)$ is much lower than its long-term mean. As we saw earlier, in the put option's payoff function of $\text{Max}[X-\Phi(T),0]$, the mean reversion characteristics of Φ make put prices decrease by pulling Φ back to its long-term mean level. On the other hand the degree of volatility affects put prices positively, which is a well-known phenomenon in option pricing models.

Table 6-1 Sensitivity of At-the-Money Put and Deltas to Changes in the Parameters.

Increase in	At-the-Money Put Prices	At-the-Money Deltas
Volatility	Increase	Decrease*
Mean reversion factor	Decrease	Decrease
Time-to-maturity	Increase	Decrease

* This relationship is variable with changes in levels of the exercise prices and the current crack spreads,

Figures 6-1 through 6-3 illustrate the relationship between a put option's time value and an underlying asset's mean reversion characteristics. Figure 6-1 shows the put prices calculated using the base-case reversion factor, $\lambda_{\phi}=0.5521$. Figures 6-2 and 6-3 show the put prices obtained using different mean reversion factors such as $\lambda_{\phi}=0.25$, and $\lambda_{\phi}=0$

In the case of Figure 6-3, when crack spreads follow a random walk instead of mean reversion (i.e., $\lambda_{\phi}=0$), we can see that time value increases with a put option's maturity. If crack spread movements are characterized by mean reversion (i.e., $\lambda_{\phi}\neq 0$) the put price reduction due to mean reversion would exceed the time value, especially at low values of crack spreads. When the crack spread is beneath the exercise price, the increments in time value are not enough to compensate for price reductions caused by movement of the crack spread toward its mean value.

If the crack spread process follows a mean-reverting process, the slope of put prices (i.e., delta of the put) is negatively related to the length of maturities. From Figure 6-4, the shorter the maturity, the steeper the slope (the greater the delta).¹⁶⁾

Figures 6-5 through 6-7 show the relationship between mean reversion factors and put prices for various maturities. For each maturity, the magnitude of the mean reversion factor negatively affects the put prices. The more strongly the crack spread reverts toward its long-term mean, the lower the put price is.

The base-case put price with one-month maturity when the current crack spread is \$4.25/barrel is \$0.454/barrel. The change of mean reversion factor to 0.25 and 0 changes put prices to \$0.529/barrel and \$0.604/barrel. In two-month maturities, the base-case put price of \$0.529/barrel becomes \$0.688/barrel ($\lambda_\phi=0.25$) and \$0.885/barrel ($\lambda_\phi=0$). The put price for the three-month maturity varies from \$0.628/barrel ($\lambda_\phi=0.5521$) to \$0.812/barrel ($\lambda_\phi=0.25$) and \$1.093/barrel ($\lambda_\phi=0$).

In addition, the strength of the reversion power expressed by the magnitude of the mean reversion factor negatively affects the value of the put delta. For the base-case with a current crack spread piece of \$4.25/barrel and one-month maturity, the value of the put delta varies from -35.90% ($\lambda_\phi=0$) to -20.42% ($\lambda_\phi=0.5521$). For the two-month maturity, the variation of the put delta is more volatile, i.e., -33.85% for $\lambda_\phi=0$, -20.02% for $\lambda_\phi=0.25$, and -10.45% for $\lambda_\phi=0.5521$. For the three-month maturity put delta, the values are -31.84%, -14.94%, and -6.07% for $\lambda_\phi=0$, $\lambda_\phi=0.25$, and $\lambda_\phi=0.5521$, respectively.

Figures 6-8 to 6-10 show the effect of the volatility of the crack spread rate of return on put prices of different maturities. Besides the base-case volatility, 20% and 30% volatilities are examined. When the current crack spread is \$4.25/barrel, the base-case put value with one-month maturity is \$0.454/barrel, which is higher than any other put value and with less volatility (\$0.285/barrel for 30% volatility and \$0.162/barrel for 20% volatility). This phenomenon is consistent with that observed for other maturities. Base-case put prices with two-month maturities are \$0.198/barrel, \$0.338/barrel, and \$0.529/barrel for $\sigma=20\%$, $\sigma=30\%$, and $\sigma=44.02\%$. Three-month put prices are \$0.251/barrel ($\sigma=20\%$), \$0.413/barrel ($\sigma=30\%$), and \$0.622/barrel ($\sigma=44.02\%$).

The base-case volatility of 44.02% has been estimated using real monthly data for ten

16) We consider the absolute values of put deltas.

years (1985.12-1996.1). Those periods include significant political events such as the Gulf War, which can cause high volatility in oil prices. The evidence implies that crack spread volatility will depend on selection of the examination period. Thus, to obtain the most accurate put prices and deltas, refiners need to estimate volatility continually, considering the occurrence of oil price-related events.

The underlying asset's volatility is positively related to the put prices, even though there is no clear relationship between crack spread volatilities and put deltas in the base-case. The one-month put deltas are -19.00% ($\sigma=20\%$), -20.44% ($\sigma=30\%$), and -20.42% ($\sigma=44.02\%$) : Two-month put deltas are -10.85% ($\sigma=20\%$), -11.08% ($\sigma=30\%$), and -10.45% ($\sigma=44.02\%$): Three-month put deltas are 6.94% ($\sigma=20\%$), -6.78% ($\sigma=30\%$), and -6.07% ($\sigma=44.02\%$).

When the current crack spread is less than the exercise price (i.e., the put option is in-the-money), however, there is a negative relation between volatility and put delta. If the put option is out-of-the-money, changes in volatility will positively affect changes in the put deltas. The one-month put deltas when the current crack spread is \$2.50/barrel are -54.97% ($\sigma=20\%$), -46.37% ($\sigma=30\%$), and -39.03% ($\sigma=44.02\%$). Two-month put deltas are -21.18% ($\sigma=20\%$), -17.71% ($\sigma=30\%$), and -14.85% ($\sigma=44.02\%$). Three-month put deltas are -9.49% ($\sigma=20\%$), -8.97% ($\sigma=30\%$), and -7.55% ($\sigma=44.02\%$). The results show that in all maturities the deep in-the-money put deltas decrease with increases in volatility.

The one-month deltas when the current crack spread is say \$5.50/barrel (i.e., the put option is out-of-the-money) are -4.27% ($\sigma=20\%$), -8.47% ($\sigma=30\%$), and -11.94% ($\sigma=44.02\%$). Two-month put deltas are -6.36% ($\sigma=20\%$), -7.67% ($\sigma=30\%$), and -8.18% ($\sigma=44.02\%$). Three-month put deltas are -4.95% ($\sigma=20\%$), -5.41% ($\sigma=30\%$), and -5.50% ($\sigma=44.02\%$). The deep out-of-the-money put deltas are positively related to changes in volatility.

Finally, we can see the sensitivity of put price changes with regard to exercise price changes. The exercise price represents a refiner's operating margin level, which covers at least the production costs of refining. Alternatively, the exercise price may be thought of as a deductible in the insurance plan. Risk-averse refiners would probably set exercise prices high enough to cover all costs involved in the refinery process. They are willing to accept the relatively high insurance premiums (put prices). Generally, however, refiners should consider the trade-off between the insurance premium (put price) and the deductible level (exercise

price) before planning to hedge their gross refining margin. If refiners set a high refining margin level which is supposed to be hedged, they will pay a high refining margin level to hedge, they will pay high put prices. Figures 6-11 to 6-13 illustrate the way that put prices change with various levels of exercise price.

Put deltas increase with an increase in exercise price. For the base-case, one-month put deltas are -45.51%(X=6), -34.95%(X=5), -20.42%(X=4) -6.27%(X=3), and -0.21%(X=2) ; two-month put deltas are -23.02%(X=6), -17.2% (X=5), -10.45%(X=4), -3.57%(X=3), and -0.20%(X=2); three-month put deltas are -12.69%(X=6), -9.82%(X=5), -6.07%(X=4), -2.21%(X=3), and -0.15%(X=2). It is important for a refiner or a refinery investor (a financial intermediary) to consider the relationship between exercise prices and put delta values when they design hedging strategies. For instance, put delta values are closely related to the transaction costs involved in the dynamic hedging. And, high exercise prices or high operating margin levels to be insured will entail a high transaction costs.

Figure 6-1 Put Prices with Different Maturities (Base-Case)

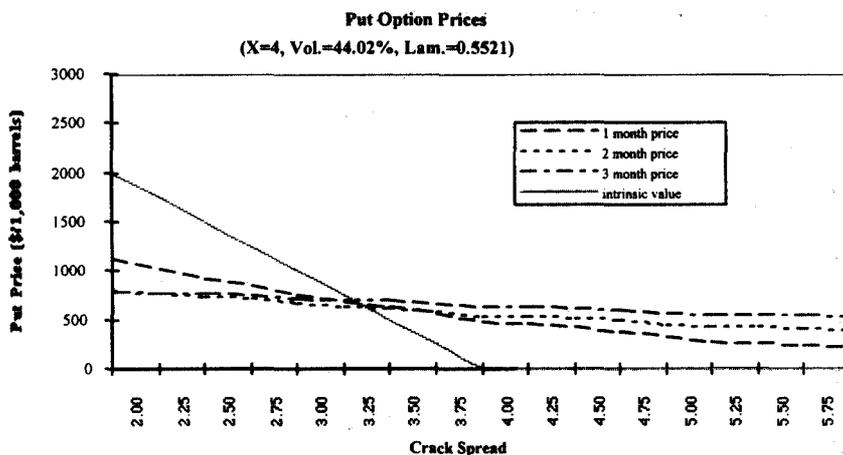


Figure 6-2 Put Prices with Different Maturities ($\lambda_0 = 0.25$)

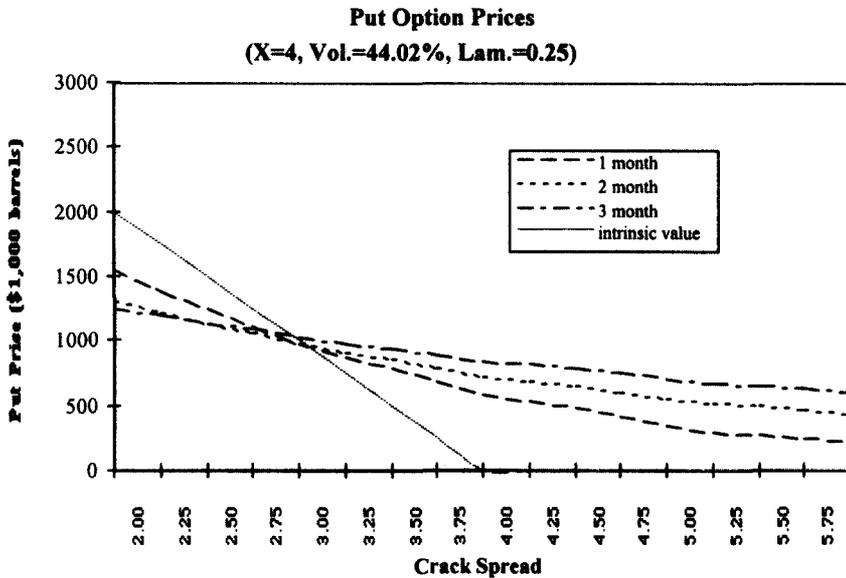


Figure 6-3 Put Prices with Different Maturities ($\lambda_0 = 0$)

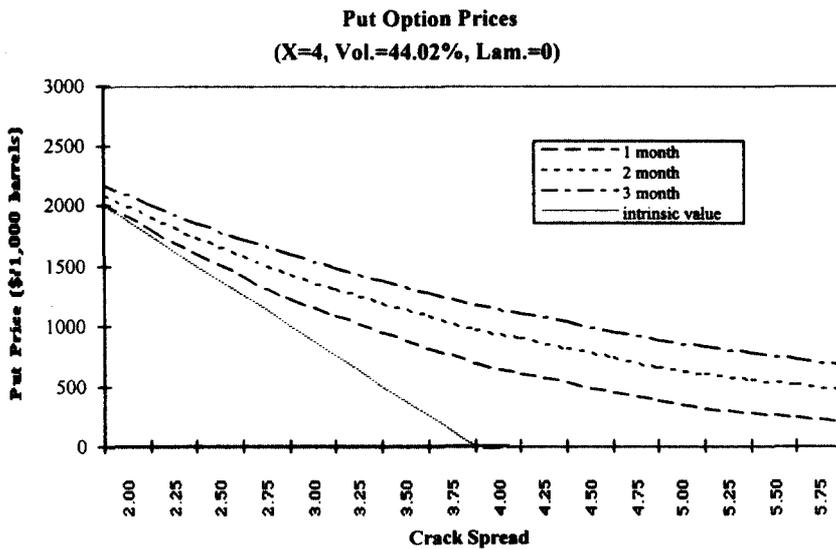


Figure 6-4 Put Deltas with Different Maturities (Base-Case)

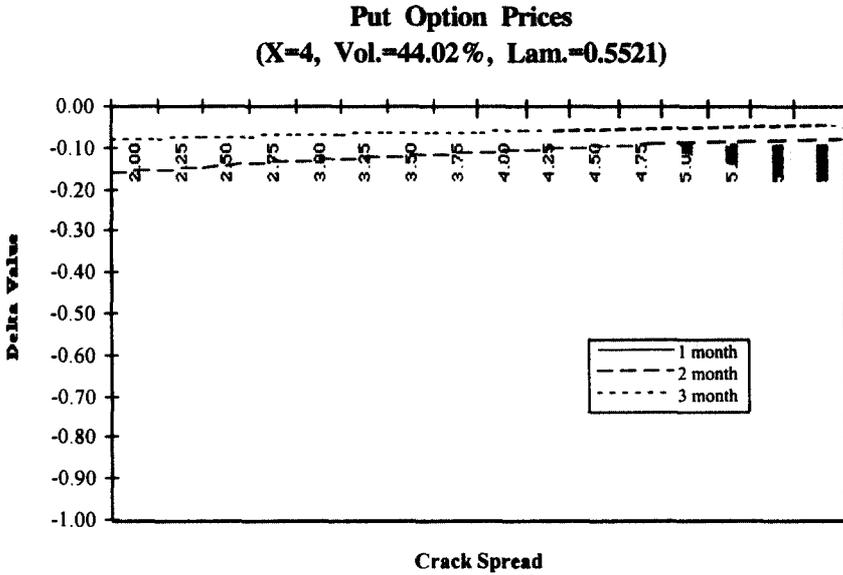


Figure 6-5 Put Prices with Different Mean Reversion Factors (T = 1)

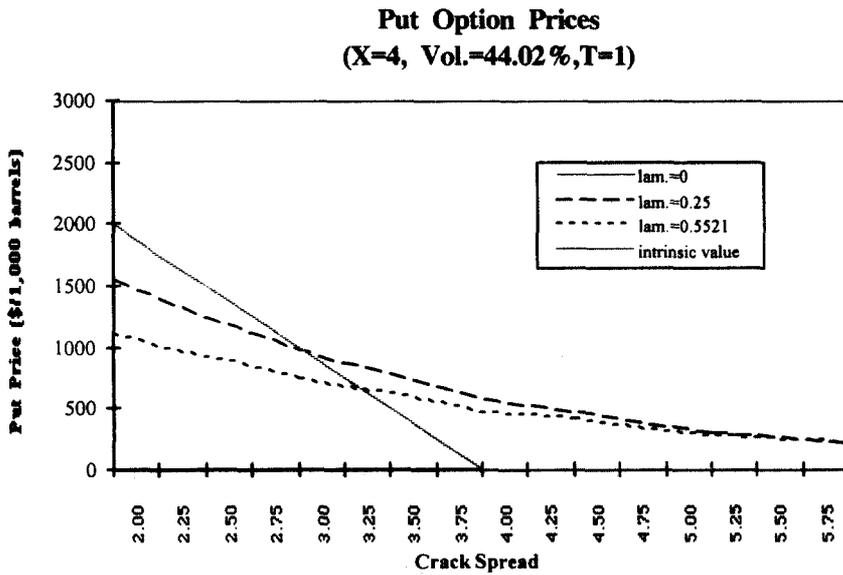


Figure 6-6 Put Prices with Different Mean Reversion Factors (T = 2)

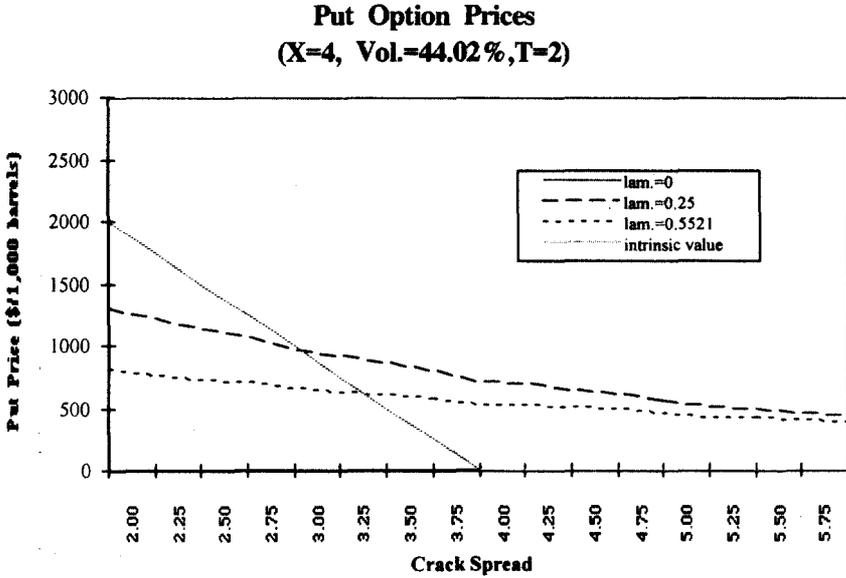


Figure 6-7 Put Prices with Different Mean Reversion Factors (T = 3)

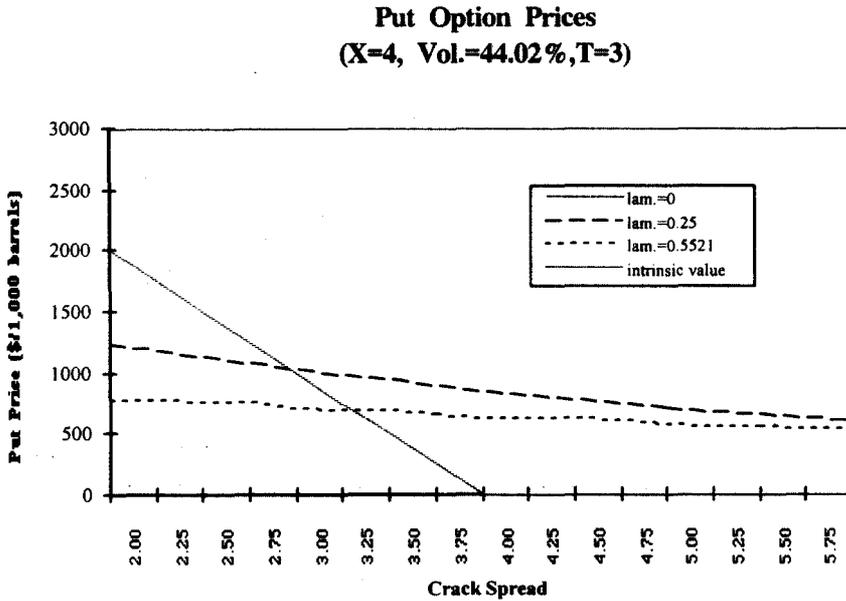


Figure 6-8 Put Prices with Different Volatilities (T = 1)

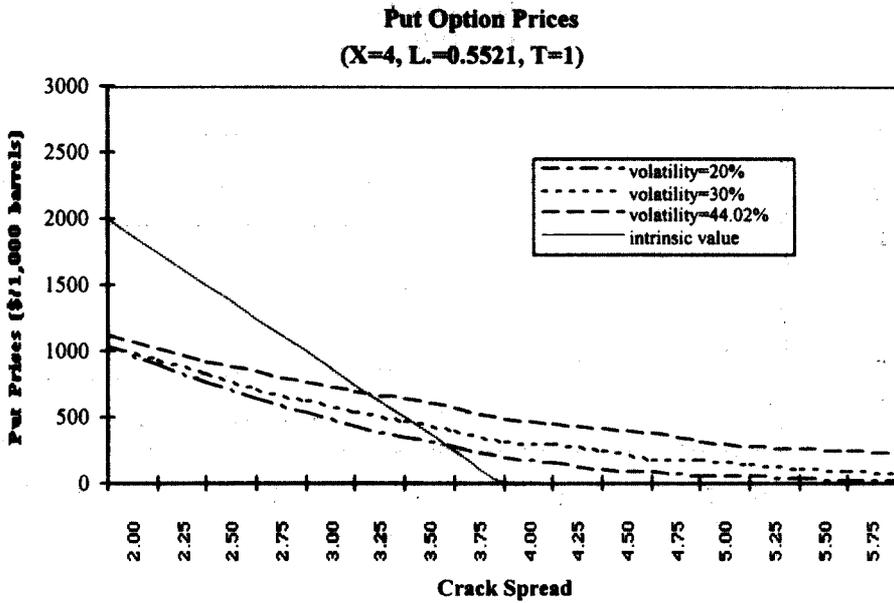


Figure 6-9 Put Prices with Different Volatilities (T = 2)

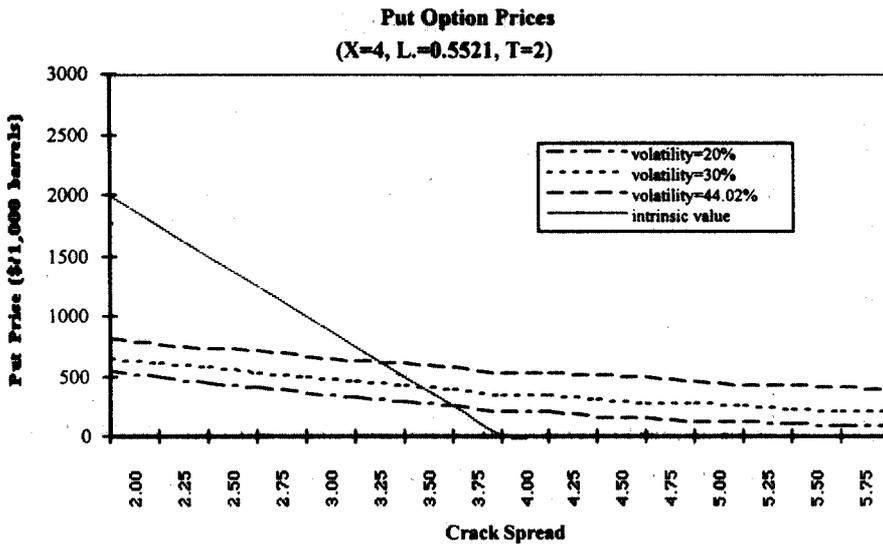


Figure 6-10 Put Prices with Different Volatilities (T = 3)

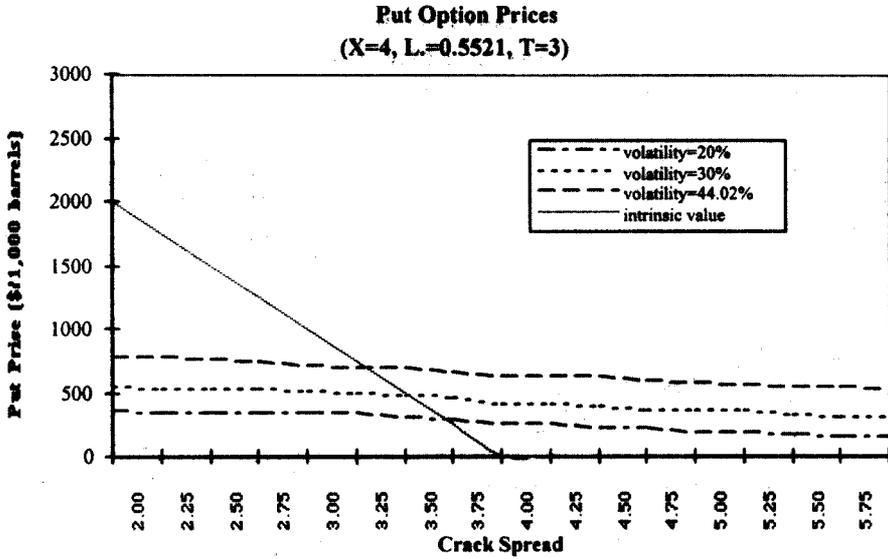


Figure 6-11 Put Prices with Different Exercise Prices (T = 1)

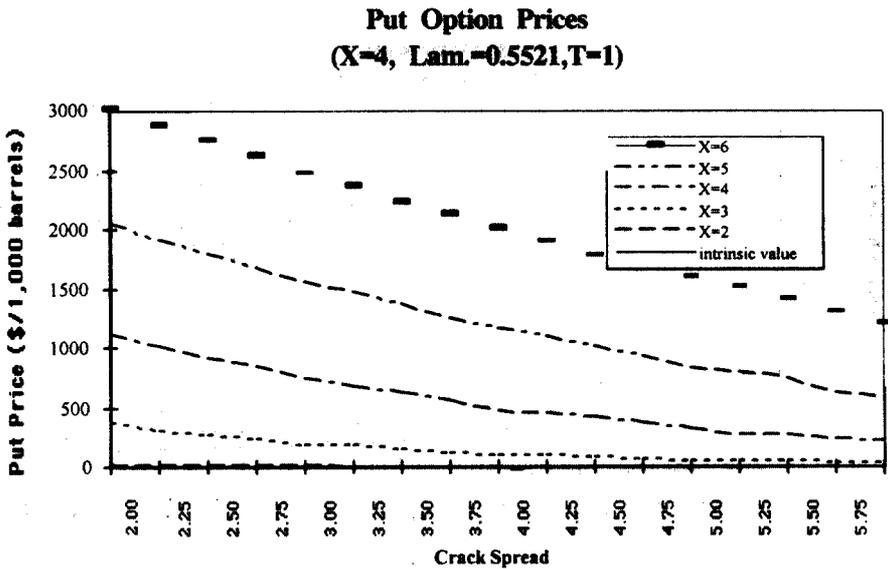


Figure 6-12 Put Prices with Different Exercise Prices (T = 2)

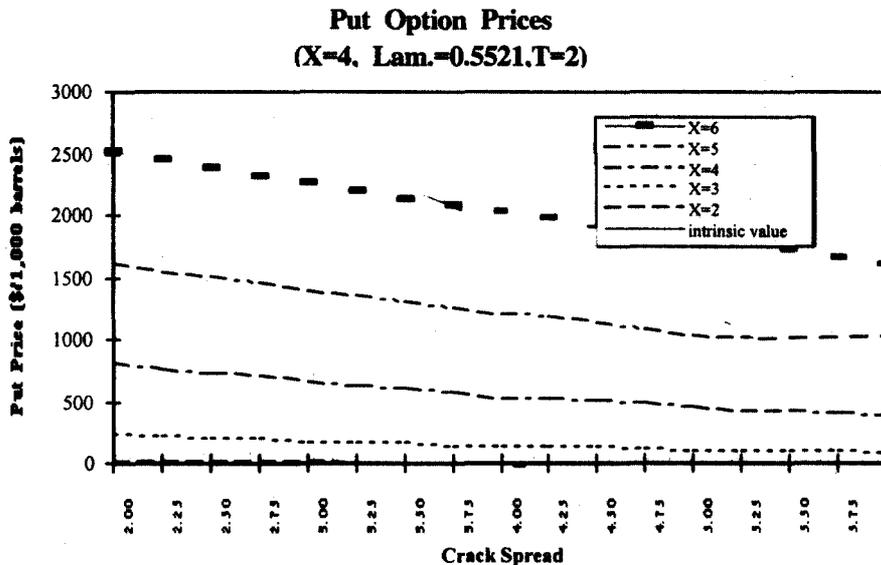
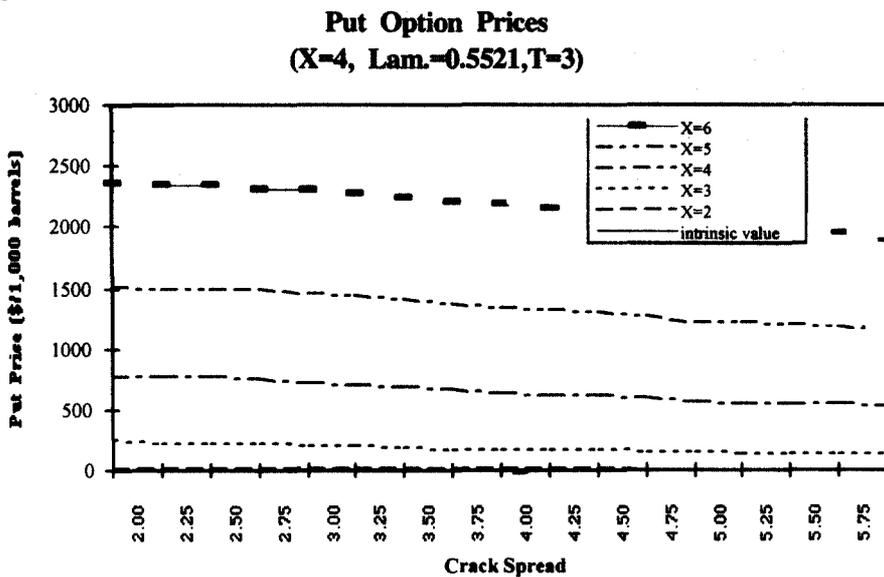


Figure 6-13 Put Prices with Different Exercise Prices (T = 3)



VII. Conclusions

The main purpose of this study has been to explore new applications of finance theory (e.g., financial engineering) developed in the capital markets in order to solve the problems that arise managing corporations. Our analysis of refinery choices is a realistic example.

We posit put options on crack spreads that follow a mean-reverting process, examine their uses, and derive their prices using a binomial option pricing model. Put options can be used as hedging instruments for refiners that convert crude oil into unleaded gasoline and heating oil at a cost. Running their production process continuously, refiners long put options with an exercise price equal to production costs. If the crack spread is low enough not to cover production costs, the refiner will exercise the put options.

Put price represents an insurance premium for the refiners. They can estimate the amount of insurance costs by calculating the put prices. We also suggest a synthetic put strategy (delta hedging strategy) as a method to replicate put options when such options are not available in the market. The results of the binomial model show that, as expected, put prices increase with increasing volatility, but decrease with increasing mean reversion factors, indicating the dampening effect of mean reversion.

Our work is a good example of the links between finance theory (i.e., options pricing theory) developed in the capital markets and corporate management decisions. It not only provides new financial tools for refinery companies but also allows us to test the application of financial engineering procedures in a new research setting. The methodologies and the problem analysis approach may also be applicable to other energy-related industries such as mining or natural gas.

REFERENCES

- American Petroleum Institute, Monthly Statistical Reports, Jun., Sept. and Dec. 1994.
- Anderson, R.O.,1984, Fundamentals of the Petroleum Industry. Norman: University of Oklahoma Press.
- Black, F., and M. Scholes, 1973, "The Pricing of Options and Corporate Liabilities," *Journal of Political Economy*, 637-654.
- Brennan, M.,and E. Schwartz, 1985, "Evaluating Natural Resource Investments," *Journal of Business* 58, 135-157.
- Carr, P. P. and R.A. Jarrow, 1995, "A Discrete Time Synthesis of Derivative Security Valuation Using a Term Structure of Futures Prices," *Handbooks in Operations Research and Management Science* 9, Section 7, *North-Holland*, 225-249,
- Chiang, R, P. Liu, and J. Okunev, 1995, "Modelling Mean Reversion of Asset Prices towards their Fundamental Value," *Journal of Banking and Finance* 19, 1327-1340.
- Cox, J, S. Ross, and M. Rubinstein. 1979,"Option Pricing: A Simplified Approach," *Journal of Financial Economics*, 229-263.
- Edwards. F. R., and C. W. Ma. 1992, *Futures and Options*, New York: McGraw-Hill, Inc.
- Energy Information Administration, Weekly Petroleum Status Report, Mar. 3, 1995.
- Fama, E., and K. French. 1987, "Commodity Futures Prices: Some Evidence on Forecast Power. Premiums, and the Theory of Storage." *Journal of Business* 60, 55-73.
- Fama, E., and K. French, 1988, "Business Cycles and the Behavior of Metals Prices," *Journal of Finance* 43, 1075-1093.
- Hayes, R., and W. Abernathy, 1980, "Managing Our Way to Economic Decline.", *Harvard Business Review* 58, 66-77.
- Hayes, R. and D. Garvin, 1982, "Managing as if Tomorrow Mattered," *Harvard Business Review* 60, 71-79.
- Independent Petroleum Association of America Supply and Demand Committee, Short-Run Report, Apr.1995.
- Laughton, D., and H. Jacoby, 1993, "Reversion, Timing Options and Long-Term Decision Making," *Financial Management* 22, 225-240.
- Leffler. W. L.. 1979, *Petroleum Refining for the Non-Technical Person*, Tulsa: PennWell

Publishing CO.

- Mason, S., R. Merton, A. Perold, and P. Tufano, 1995, *Cases in Financial Engineering: Applied Studies of Financial Innovation*. Englewood Cliffs, New Jersey: Prentice-Hall.
- Myers, S. C., 1987, "Finance Theory and Finance Strategy," *Midland Corporate Finance Journal* 5, 6-13.
- New York Mercantile Exchange, 1986, *NYMEX Energy Hedging Manual*.
- NPN-National Petroleum News, mid-June 1995.
- O'Brien, T. J., 1988, "The Mechanics of Portfolio Insurance," *Journal of Portfolio Management*, 40-47.
- Pozen, R., 1978, "The Purchase of Protective Puts by Financial Institutions," *Financial Analysts Journal* 34, 47-60.
- "Refinery Throughputs: Heavy Autumn Turnarounds in US," *Petroleum Argus*, Aug. 22, 1994. 2.
- Shimko, D. C., 1994. "Options on Futures Spreads: Hedging, Speculation, and Valuation," *Journal of Futures Markets* 14, 183-213.
- Siegel, D. R., and D. F. Siegel, 1990, *The Futures Markets*, Chicago, Illinois: Probus Publishing Company.
- Singleton, C., and R. Grieves, 1984. "Synthetic Puts and Portfolio Insurance Strategies," *Journal of Portfolio Management* 10, 63-69.
- Value Line's Composite Statistics for Petroleum Industry. December 1995.