Real Option Valuation in the Refinery Industry

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요 약

본 연구의 목적은 실물옵션이론을 바탕으로 정유회사의 가치평가기법을 제공하는 것이다. 정유회사는 가치평가를 위해서 회계적 가치외에 관리적 유연성(managerial flexibility)을 고려해야 하기 때문에 기존의 DCF방법을 적용하기 보다는 실물옵션방법을 이용하여야 한다.

관리적 유연성은 회사관리자가 적용가능한 생산관리적 기법으로서 회사의 미래 현금흐름에 영향을 주고 따라서 회사의 가치에 영향을 미친다. DCF방법은 이러한 관리적 유연성을 적절히 고려하지 못하여 회사의 가치를 저평가하는 오류를 발생시킨다. 반면 실물옵션방법은 관리적 유연성을 가치평가에 있어서 주요 변수로 인식하기 때문에 정확한 가치평가의 수단이 된다.

옵션가격결정을 위한 기초자산은 크랙스프레드(crack Spread)이다. 크랙스프레드는 경유(heating oil)와 무연휘발유(unleaded gasoline)의 가격과 원유(crude oil) 가격의 차이를 나타내며 정유회사의 정유순익(gross refining margin)을 대표한다. 실물옵션방법에 의한 정유회사의 가치는 DCF방법에 의한 가치보다 두 배가 크다는 결론을 제시한다. 즉 관리적 유연성이 존재하는 회사의 경우는 가치평가에 있어서 실물옵션방법을 이용하여 가치를 저평가하는 오류를 범하지 않아야 한다.

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Ⅰ. Introduction

In this study we apply real options approaches to value refinery companies' managerial flexibilities (e.g., shutdown flexibility). "Real option" in this context describes managerial flexibility, which has an impact on a corporation's general decision making process. Refinery managers should realize that their managerial flexibility (e.g., a shutdown option) can affect the company's future cashflow and thereby its value. The well-known discounted cash now (DCF) approach cannot adequately capture managerial flexibilities, so it undervalues firms with real options. A real options approach takes into consideration the flexibility management has to revise future decisions to meet unexpected future market conditions.

By using dynamic programming techniques, we can calculate a refiner's value that takes account of its managerial flexibility (its real options) such as the decision to shut down. Using the revised binomial option pricing model and dynamic programming methods, we obtain value for refineries with operational flexibilities that are much higher than values produced by traditional discounted cash flow (DCF) approaches.

In Section Ⅱ, we analyze the 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 Ⅲ, we develop a dynamic programming frame work to calculate the refiner's value assuming managerial flexibility or the presence of real options. We apply the model to obtain the refiner's value with a financial flexibility. We demonstrate the impact of the presence of a single real option (the shutdown option) on the refiner's value. We also summarize arguments regarding the conflict between traditional valuation DCF approaches and real options valuation methods, and note relevant studies these areas. In addition, we explain the formal dynamic programming model that becomes a generalized valuation model when the project entails real options. We apply the model to our case and show the results in Section Ⅳ. A summary and conclusions appear in Section Ⅴ.

Ⅱ. 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.

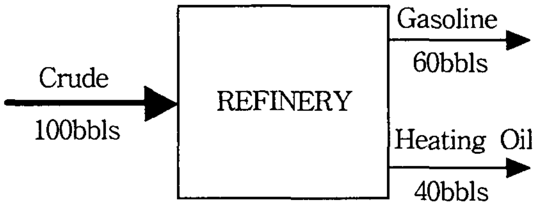
Crack spreads are obtained by the simultaneous purchase of crude oil and sale of petroleum products, i.e.. unleaded gasoline and heating oil in the predetermined quantities for each asset as calculated by the refining ratio. Crack spread ratios reflect the approximate amounts of heating oil and unleaded 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.[1] Recently however, many refiners and spread traders have recognized that a 5 : 3 : 2 ratio more correctly reflects reality because of current high dependence

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

on heavier imported crudes, increased demand for high-octane unleaded gasoline, and rapid changes in refining technology.[2)]

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,



In other words, the hypothetical asset of the refiner's crack spread that is a state variable in the option pricing model is derived based on the 5 : 3 : 2 refining ratio.

The crack spreads (Φ)are calculated as follows :

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

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.

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.[3)] 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

2) 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.).
3) See NYMEX Energy Hedging Manual (1986).

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. 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.

Ⅲ. Valuing a Refinery with a Shutdown Option

This chapter develops a dynamic programming framework to calculate the refiner's value for three months under a naive producing strategy and a real operating strategy. First, we discuss conflicts between traditional valuation methods of discounted cash flow (DCF) approach and real options valuation methods. The real options valuation method takes account of the fact that the refiner has some managerial flexibility or a real option in its operation. Finally, we develop the formal dynamic programming model and show its results.

1. Valuation of Managerial Flexibility

Both researchers and managers have come to realize that traditional discounted cash flow (DCF) approaches cannot properly capture management's flexibilities such as decisions to shut down, abandon, or expand a plant, or to change a technology. Yet these are decisions that affect a project's or a plant's future cash flow and consequently its present value. Hayes and Abernathy (1980) and Hayes and Garvin (1982), for example, argue that the DCF method fails to capture the strategic impact of projects, and hence undervalues projects that include *real* options.

Under DCF techniques, managers are simply assumed to initiate a project and to operate it continuously until the end of a prespecified expected useful life. Uncertainties that future cash flows will probably differ are not considered. In fact, the flexibility to revise future decisions in response to unexpected future market conditions adds to a project's value by improving its upside potential while limiting downside losses that result from the initial expectations (under passive management).

Researchers have applied the financial options valuation approach to capital budgeting in an effort to quantify the value of real options attention on active management. Myers (1987) explains that traditional DCF methods have limitations for valuing projects with significant operating or strategic options; he suggests that option pricing technique is more suitable for valuing such projects. General ideas about real options and their valuation frameworks are discussed in Kulatilaka and Marcus(1992, 1988), Kogut and Kulatilaka (1994), Mason and Trigeorgis (1987), and Shimko (1994). More specifically, Brennan and Schwartz (1985), Kulatilaka (1993), McDonald and Siegel (1986. 1985), and Paddock, Siegel, and Smith (1988) provide good discussions about various managerial flexibilities in large-scale energy projects.

2. Valuation with a Shutdown Option

Because a refinery's activity offers operational and shutdown choices to refiners that are similar to the hold-or-exercise choices available to options holders, it is logical to apply both financial option valuation and dynamic programming techniques to study valuation in the presence of shutdown flexibility.

Dynamic programming is a very general tool for dynamic optimization that is particularly useful in treating uncertainty. The dynamic programming method breaks a whole sequence of decisions into two parts. The first component is the immediate decision. The second part is a valuation function that represents the consequences of all subsequent decisions, starting with the position that results from the immediate decision.

If the valuation horizon is finite, say, three months, the very last decision at time 3 has no decision or action following it, and can therefore be found using standard static optimization methods. This solution, in turn, serves for the decision at time 2, and so on. We thus work backward all the way to the initial condition of time 0. (For more details, see Dixit and Pindyck (1994), chapter 4.)

3. Dynamic Programming Model

We start with a two-period model in which a refiner has two operating modes and makes decisions at two dates: time 1 and time 2. At the beginning of each period, a refiner may choose one of two modes : operation (OP) and shutdown (SD). The OP mode simply means "operate the refinery process" ; the SD mode means "shut down the refinery process."

The optimal choice of mode is determined by the value of a state variable (the crack spread) that evolves in a stochastic process. As the crack spread changes, mode choices may also be changed. If mode switches are costly, the choice of the current mode must take into consideration possible future switching costs. <Table 3-1> indicates all relevant costs involved in mode switching.

〈Table 3-1〉 Switching and Maintenance Costs

Mode switching from	Mode switching	
	Operation(OP)	Shutdown(SD)
Operation(OP)		γ^{SD}
Shutdown(SD)	γ^{SU}	K*

* K represents production line maintenance costs.

If a refiner is currently in the OP mode, it incurs shutdown costs (γ^{SD}) of switching to the SD mode. Conversely. start-up costs (γ^{SU}) are incurred when switching from SD mode to OP mode. These costs could arise from refinery work interruptions due to shut down the operation, for instance, labor recon-tracting. And, a major component of the start-up costs is initial fuel cost to warm up a furnace (a distillation tower). Additionally, a refiner must account for the occurrence of maintenance costs (K) when the plant is in shutdown mode.

At the start of each period, a refiner generates a net cash flow that is a function of the current managerial mode and a stochastically evolving state variable of crack spreads $\Phi(t)$. Suppose a refiner is currently in the OP mode. its value with shutdown flexibility at time 2, V_2^{OP} is described as Max[$\Phi(2)$- X, $-\gamma^{SU}$ - K], where $\Phi(2)$ - X is the expected cash flow assuming the refiner stays in the OP mode and, $-\gamma^{SU}$-K is cash flow for the SD mode. In other words, at time 2, the refiner may operate the production process if the refining gross margin is greater than the switching costs; otherwise the plant may shut down. [Figure 7-2] shows the binomial tree for the refiner's value considering its managerial flexibilities.

Equations (3-1) and (3-2) illustrate the value of the refiner at time 2 under the two possible current managerial modes:

$$V_2^{OP} = \text{Max}[\Phi(2) - X, -\gamma^{SD} - K] \qquad (3\text{-}1)$$

$$V_2^{SD} = \text{Max}[\Phi(2) - X, -\gamma^{SU} - K] \qquad (3\text{-}2)$$

The notations V_2^{OP} and V_2^{SD} imply the values at time 2 under the current modes of OP and SD. The values at time 1. V_1^{OP} and V_1^{SD}, an affected not only by managerial decisions at time 1 but also by the time 1 expectation values far V_2^{OP} and V_2^{SD}. To obtain the V_1^{OP} and V_1^{SD}, we need to consider the values of the options associated with the ability to switch modes in the next period. The value function at time 1 given current managerial modes of OP or SD would be : [4)]

$$V_1^{OP}[\Phi(1)] = \text{Max}\{\Phi(1) - X + \rho E_1[V_2^{OP}],\ -\gamma^{SD} - K + \rho E_1[V_2^{SD}]\} \qquad (3\text{-}3)$$

$$V_1^{SD}[\Phi(1)] = \text{Max}\{- K + \rho E_1[V_2^{SD}],\ -\gamma^{SU} + \Phi(1) - X + \rho E_1[V_2^{OP}]\} \qquad 3\text{-}4)$$

where ρ is the riskless discount factor, and $E_t[.]$ is the risk-neutral expectations operator at time t.

Finally, at time 0, the value function for an initial choice of OP mode or SD mode would be : [5)]

$$V_0^{OP}[\Phi(0)] = \text{Max}\{\Phi(0) - X + \rho E_0[V_1^{OP}],\ -\gamma^{SD} - K + \rho E_0[V_1^{SD}]\} \qquad (3\text{-}5)$$

$$V_0^{SD}[\Phi(0)] = \text{Max}\{- K + \rho E_0[V_1^{SD}],\ -\gamma^{SU} + \Phi(0) - X + \rho E_0[V_1^{OP}]\} \qquad (3\text{-}6)$$

The choice of the optimal initial mode is determined only partly by identifying the mode that currently is "in the money," i.e., is more profitable. given the current value of the state variable $\Phi(0)$. The value in Equation (3-5) is the value of the OP mode plus the value of the option to switch modes in the next period. This option is a compound option, because V_1^{OP} and V_1^{SD} themselves embody options to change modes in the following period.

In the case of the three-period model, we identify the terminal valuation functions (V_3^{OP} and V_3^{SD}). By starting at time 3 and working backward we obtain the value functions(V_2^{OP} and V_2^{SD}) at time 2. Then we solve the maximization problem for each managerial mode at time 2, leading to the value functions (V_1^{OP} and V_1^{SD}). At the last step of working backward, we get the

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4) More specifically, we have :

$$V_1^{OP}[u\Phi(1)] = \text{Max}\ \{u\Phi(0) - X + \rho[pV_2^{OP}(u^2\Phi[0]) + (1-p)V_2^{OP}(ud\Phi[0])],$$
$$-\gamma^{SD} - K + \rho[pV_2^{SD}(u^2\Phi[0]) + (1-p)V_2^{SD}(ud\Phi[0])]\}$$
$$V_1^{SD}[u\Phi(1)] = \text{Max}\ \{ - K + \rho\{pV_2^{SD}(u^2\Phi[0]) + (1-p)V_2^{SD}(ud\Phi[0])],$$
$$-\gamma^{SU} + u\Phi(0) - X + \rho[pV_2^{OP}(u^2\Phi[0]) + (1-p)V_2^{OP}(ud\Phi[0])]\}$$

5) More specifically. we have:

$$V_0^{OP}[u\Phi(0)] = \text{Max}\ \{\Phi(0) - X + \rho[pV_1^{OP}(u\Phi[0]) + (1-p)V_1^{OP}(d\Phi[0])],$$
$$-\gamma^{SD} - K + \rho[pV_1^{SD}(u\Phi[0]) + (1-p)V_1^{SD}(d\Phi[0])]\}$$
$$V_0^{SD}[u\Phi(0)] = \text{Max}\ \{ - K + \rho\{pV_1^{SD}(u\Phi[0]) + (1-p)V_1^{SD}(d\Phi[0])],$$
$$-\gamma^{SU} + \Phi(0) - X + \rho[pV_1^{OP}(u\Phi[0]) + (1-p)V_1^{OP}(d\Phi[0])]\}$$

value functions (V_0^{OP} and V_0^{SD}) at time 0, and we call the magnitude of these values the refiner's value in the presence of shutdown flexibility.

More generally, if we assume that a refiner's current managerial mode is OP, we can express a maximization equation at time t :

$$V_1^{OP}[\Phi(t)] = \mathrm{Max}\{\Phi(t) - X + \rho E_t[V_{t+1}^{OP}],\ -\gamma^{SD} - K + \rho E_t[V_{t+1}^{SD}]\} \quad (3\text{-}7)$$

Equation (3-7) is called the Bellman equation, or the fundamental equation of optimality. Dixit and Pindyck (1994) explain the Bellman principle of optimality as follows. An optimal policy has the property that whatever the initial action. the remaining choices constitute an optimal policy with respect to the subproblem starting at the state that results from the initial actions. Here the optimality of the remaining choices implies optimal mode choices in each decision period.

Equation (3-7) has two parts : 1) the cash flow at time t, and 2) the expectation value for time t + 1, given the possibility of mode changes in the future. Dixit and Pindyck (1994) call the second part the continuation value. Hence the optimum action at time t is the one that maximizes the sum of the two parts.

4. A Refiner's Production Strategy

Assume that a refiner has a certain level of crack spread as a production cost called X. It can operate the refinery process basically with two alternative strategies. Firstl, the refiner simply operates the process continuously, regardless of the changes of crack spreads. We call this strategy a "naive producing strategy." Under the naive strategy, the refinery will have a positive (negative) net cash flow if a crack spread is higher (lower) than the production cost.

Second, the refiner can use managerial flexibility (e.g., shutdown option) to avoid an operational risk that results from the negative net cash flow. In other words, the refiner can temporarily shut down its process if the current crack spread is lower than production costs. We call this strategy under which the refiner has shutdown flexibility a "real operating strategy." The refiner's value with a real operating strategy is much higher than its value with a naive producing strategy. The reason is that the real operating strategy incorporates not only the passive or direct net present value (NPV) of expected cash flows from the naive producing strategy, but also the flexibility value of the combined options of the refinery. That is :

$$\text{Real Operating Strategy} = \text{Naive Producing Strategy} + \text{Flexibility or Option Value} \qquad (3\text{-}8)$$

Since the real operating strategy requires high switching costs such as shut-down costs. start-up costs, and maintenance costs, the actual value of crack spread at which the refiner may shut down or reoperate its process is different from the production cost. As we will discuss later, the currently operating (non-operating) refiner may not shut down (reoperate) its process even though crack spreads fall below (rise above) $4.00/barrel, the break-even costless switching value, for each period because of the hysteresis condition. This implies that the presence of high switching costs causes a refiner to decline the advantage of its shutdown flexibility.

IV. Results

Here we show the refiner's value in the presence of shutdown options, calculated using dynamic programming methods, to indicate the sensitivity of values to changes in key parameters. We also compare the values obtained using the real options method and the discounted cash now method. Finally, we illustrate a condition of hysteresis, where no managerial decisions (ie., mode switching) are made.

1. Base-Case Parameters

<Table 4-1> summarizes the base-case parameters. We assume there are managerial mode switching costs (γ^{SD} and γ^{SU}) and maintenance costs (K). which are some proportion of the production cost (X). Intuitively, a large-capacity refiner would expect higher shutdown. start-up, and maintenance costs than a small-capacity refiner. In this study, both shutdown costs and stan-up costs are assumed to be identical, at 5% of production cost, while maintenance costs are 10% of production costs.[6]

〈Table 4-1〉 Base-Case Parameter

Parameter	Value	Parameter	Value
$\Phi(0)$	\$2.00-\$6.00/barrel	σ	0.4402/month
X	\$4.00/barrel	λ_{Φ}	0.5221/month
γ	0.05/year	γ^{SD}	\$0.2/barrel
T	3 (month)	γ^{SU}	\$0.2/barrel
$\bar{\Phi}$	\$4.217/barrel	K	\$0.4/barrel

2. Refiner's Value

To obtain the refiner's value, we solve Equation (3-7) using the revised binomial model ($\triangle t$ = 1/48) and dynamic programming techniques. When the current value of the crack spread is \$4.25/barrel, the refiner's value for three months with a shutdown option and considering switching costs is \$1.60/barrel from <Table 4-2>.[7] Furthermore, we define this value as the refiner's value under the real operating strategy.

6) We infer these percentages on the basis of the refinery experts' opinions.
7) Because the long-term mean value of crack spreads ($\bar{\Phi}$) is \$4.22/barrel we take \$4.25/barrel as a base-case parameter for $\Phi(0)$.

<Table 4-2> Refiner's Value for Three Months

($/barrel)

$\Phi(0)$	a	b	c	d	e
2.00	1.0821	0.7922	0.1856	-0.0636	-1.4707
2.25	1.0845	0.8319	0.2351	-0.0548	-1.2207
2.50	1.1300	0.8560	0.4422	0.2048	-0.9707
2.75	1.3140	1.0621	0.7184	0.4665	-0.7207
3.00	1.5733	1.3162	0.8872	0.6302	-0.4707
3.25	1.7380	1.48112	0.9768	0.7199	-0.2682
3.50	1.8345	1.5804	1.0114	0.7943	-0.0165
3.75	1.8832	1.6332	1.2176	1.0605	0.2387
4.00	2.0325	1.7726	1.5229	1.3451	0.4928
4.25	2.2424	2.0279	1.7872	1.5982	0.7472
4.50	2.4963	2.2989	2.0139	1.8165	1.0026
4.75	2.7366	2.5330	2.2074	2.0038	1.2592
5.00	2.9442	2.7360	2.3723	2.1642	1.5169
5.25	3.1235	2.9122	2.5129	2.3015	1.7757
5.50	3.2789	3.0653	2.6331	2.5040	2.0353
5.75	3.4141	3.1989	2.8633	2.7778	2.2957
6.00	3.5322	3.3245	3.1545	3.0515	2.5568

a. Value with shutdown option without considering shutdown costs.
b. Value with shutdown option considering shutdown costs.
c. Value with shutdown option considering maintenance costs only.
d. Value with shutdown option considering shutdown costs and maintenance costs.
e. Value with shutdown option (DCF value).

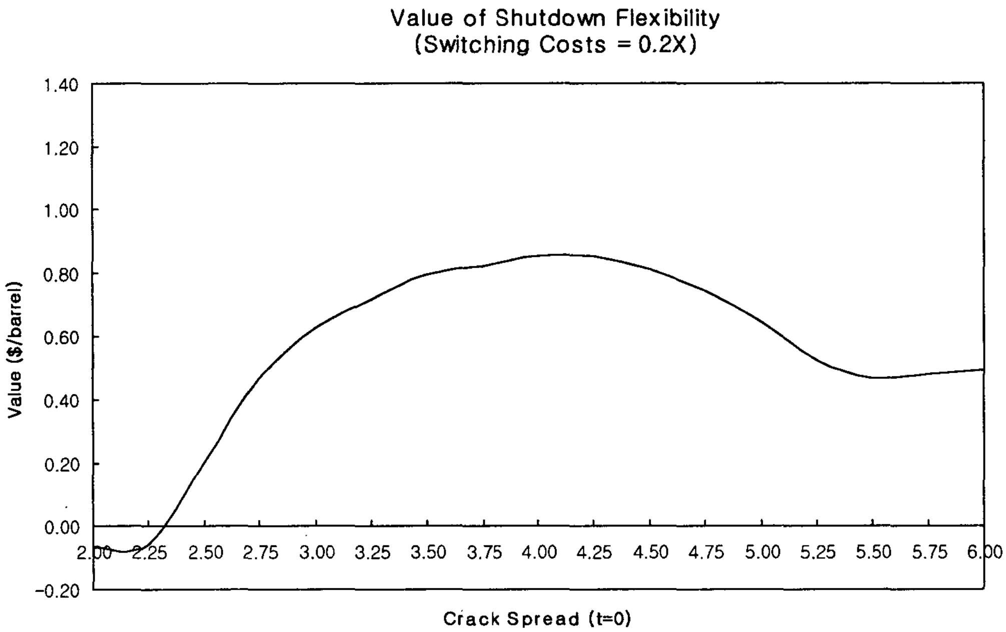
If we ignore switching costs, solution of the optimization problem would be simple. Choose in each period the managerial mode (OP or SD) that maximizes $V[\Phi(t)]$ or $V[\Phi(t)]$ in the period. Without considering switching costs, the value increases to $2.22/barrel. As we will see in analysis of the hysteresis band, the amount of switching costs becomes a crucial factor when a refiner makes a managerial decision.

For example, an operating refiner may decide not to switch to the shutdown mode if the possibility of reversing the decision due to subsequent crack spread movements is high. In other words, the presence of switching costs causes the threshold value of crack spreads for switching between managerial modes to differ from the break-even value of crack spreads for costless switching.

When the refiner has no option to shut down the refinery process. the value is \$0.74/barrel. In other words, \$0.74/barrel is the value calculated using the traditional DCF valuation method under a naive producing strategy.[8] The refiner's value with managerial flexibility, considering shutdown (SD) and costs only). You can see that the refiner's value under managerial flexibility start-up (SU) costs, is \$2.03/barrel (and \$1.79/barrel considering maintenanceis almost two times its value with no options when Φ(O)is set equal to \$4.25/barrel.

A refiner can also obtain the managerial flexibility value itself, which is expressed as the difference between its value with a shutdown option considering switching costs and its value with no real options (i.e., the DCF value). [Figure 4-1] plots the shutdown value against the current crack spreads. Note

[Figure 4-1] Value of Shutdown Flexibility (Switching Cost = 0.2X)



8) In each period. we discount the risk-adjusted net cash flows back to lime O.

that the option to shut down is most valuable around the point ($4.00/barrel) at which production cost and crack spread are the same. Intuitively, based an the options valuation logic, this is because the probability of a shutdown is the highest at this point (exercise price), making flexibility most valuable.

We also perform comparative statics to study the effect of changes in volatility

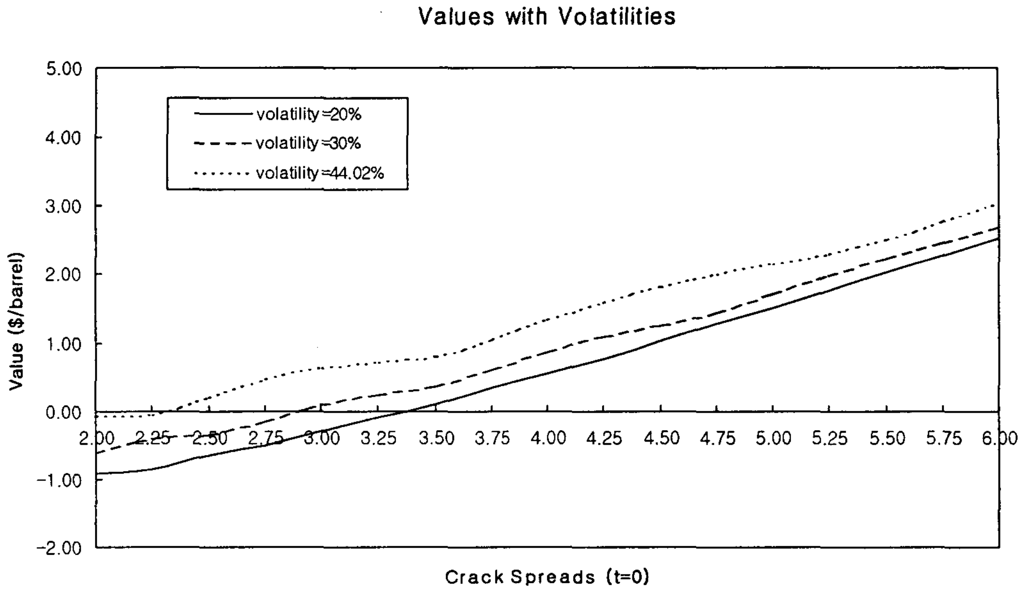
〈Table 4-3〉 Refiner's Value with Different Volatilities

($/barrel)

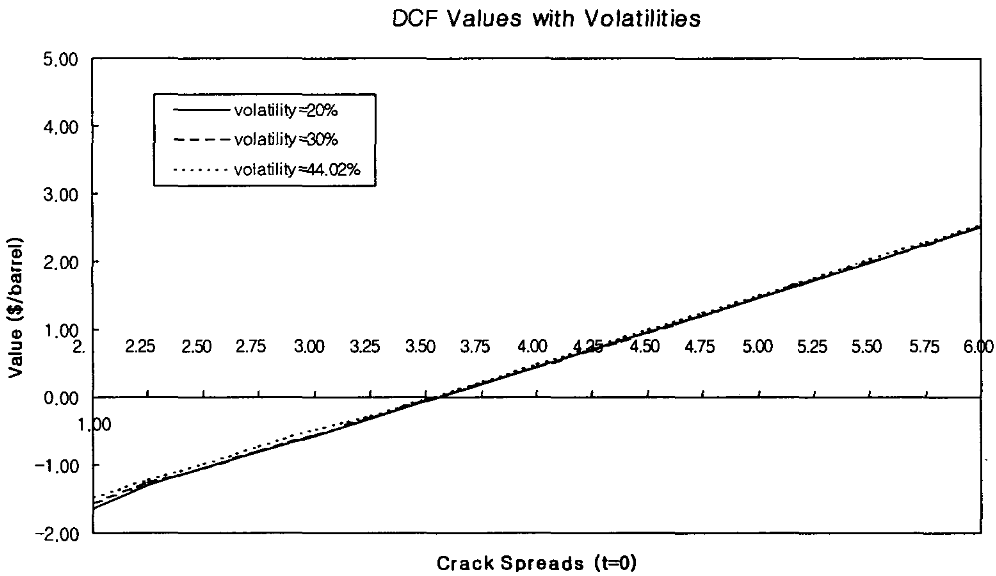
$\Phi(0)$	a	b	c	d	e	f
2.00	-0.9144	-1.6362	-0.6051	-1.5548	-0.0636	-1.4707
2.25	-0.8506	-1.2902	-0.3989	-1.2633	-0.0548	-1.2207
2.50	-0.6538	-1.0506	-0.3313	-1.0327	0.2048	-0.9707
2.75	-0.5105	-0.8088	-0.1433	-0.7903	0.4665	-0.7207
3.00	-0.2865	-0.5639	0.0974	-0.5456	0.6302	-0.4707
3.25	-0.0900	-0.3164	0.2451	-0.2983	0.7199	-0.2682
3.50	0.0931	-0.0666	0.3637	-0.0488	0.7943	-0.0165
3.75	0.3422	0.1850	0.6219	0.2027	1.0605	0.2387
4.00	0.5619	0.4383	0.8766	0.4558	1.3451	0.4928
4.25	0.7685	0.6931	1.0876	0.7104	1.5982	0.7472
4.50	1.0339	0.9492	1.2512	0.9663	1.8165	1.0026
4.75	1.2833	1.2065	1.4459	1.2234	2.0038	1.2592
5.00	1.5107	1.4648	1.7156	1.4816	2.1642	1.5169
5.25	1.7592	1.7240	1.9794	1.7407	2.3015	1.7757
5.50	2.0251	1.9841	2.2331	2.0006	2.5040	2.0353
5.75	2.2845	2.2450	2.4685	2.2613	2.7778	2.2957
6.00	2.5366	2.5066	2.6854	2.5227	3.0515	2.5568

a. Embedded option value considering all costs with σ = 20%.
b. DCF value with σ = 20%.
c. Embedded option value considering all costs with σ = 30%.
d. DCF value with σ = 30%.
e. Embedded option value considering all costs with σ = 44.02%
f. DCF value with σ = 44.02%.

[Figure 4-2] Option- Embedded Values with Volatilities



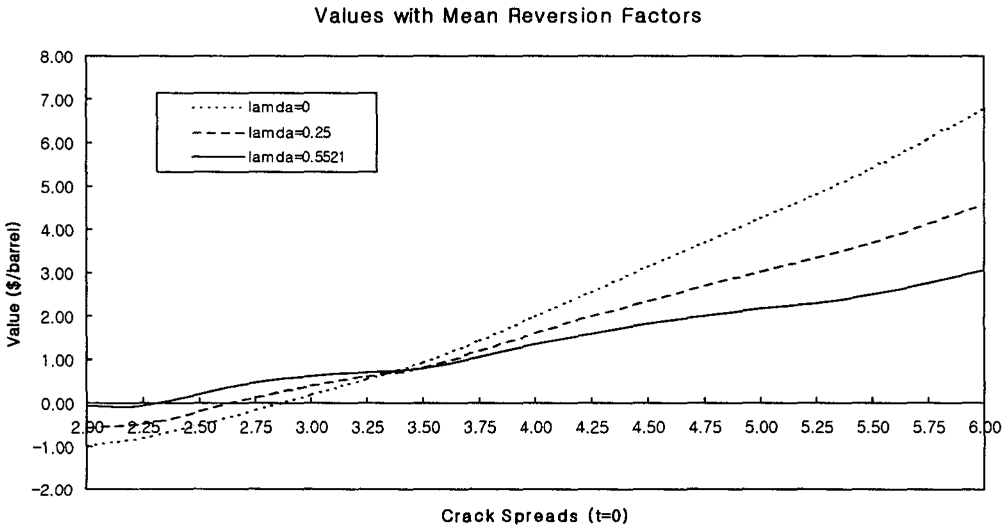
[Figure 4-3] DCF Values with Volatilities



and the mean reversion factor. In the case of volatility sensitivity, as would be expected, both the refiner's value with a shutdown option considering switching costs and the DCF value increase with increasing volatility. When the crack spread at time 0 is $4.25/barrel, the values with options are $0.77/barrel for 20% volatility, $1.09/barrel for 30% volatility, and $1.60/barrel for 44.02% volatility, while the DCF values are $0.69/barrel for 20% volatility, $0.71/barrel for 30% volatility, and $0.75/barrel for 44.02% volatility (see <Table 4-3>, [Figure 4-2], and [Figure 4-3]). The variations in option-embedded values in response to changes in level of volatility are larger than for the DCF values. You can see this in [Figures 4-2] and [Figures 4-3] (constant mean reversion factor of 0.5521).

We also examine the relationship between changes in the mean reversion factor and the option-embedded values and DCF values. As the reversion factor increases, values decrease, indicating the dampening effect of mean reversion. This phenomenon implies that when an exercise price (production cost) is small-er than the underlying asset of the crack spread, i.e., an option is out-of-the- money, there is a positive relation between the mean reversion factor and the refiner's value. When $\Phi(0)$ is equal to $4.25/barrel. the option-

[Figure 4-4] Option- Embedded Values with Mean Reversion Factors



〈Table 4-4〉 Refiner's Value with Different Reversion Factors

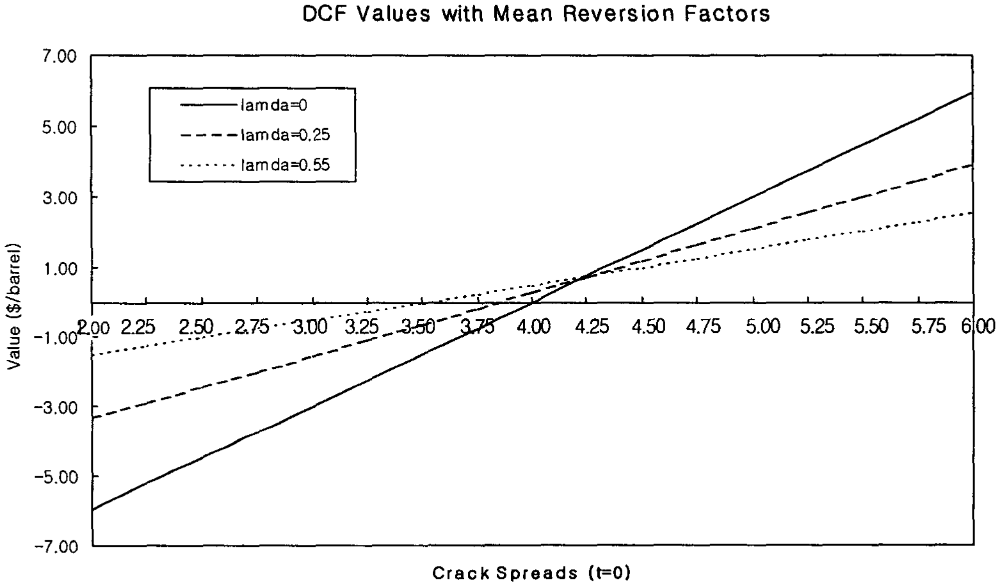
($/barrel)

$\Phi(0)$	a	b	c	d	e	f
2.00	-0.9605	-5.9502	-0.5583	-3.3040	-0.0636	-1.4707
2.25	-0.7998	-5.2065	-0.4583	-2.8631	-0.0548	-1.2207
2.50	-0.4963	-4.4627	-0.1656	-2.4195	0.2048	-0.9707
2.75	-0.1415	-3.7189	0.1507	-1.9736	0.4665	-0.7207
3.00	0.2112	-2.9751	0.4099	-1.5260	0.6302	-0.4707
3.25	0.5650	-2.2313	0.6279	-1.0768	0.7199	-0.2682
3.50	0.9285	-1.4876	0.8362	-0.6264	0.7943	-0.0165
3.75	1.4543	-0.7438	1.2131	-0.1749	1.0605	0.2387
4.00	2.0110	0.0000	1.6134	0.2775	1.3451	0.4928
4.25	2.5723	0.7438	1.9946	0.7306	1.5982	0.7472
4.50	3.1336	1.4876	2.3550	1.1844	1.8165	1.0026
4.75	3.6949	2.2313	2.69778	1.6388	2.0038	1.2592
5.00	4.2562	2.9751	3.0256	2.0936	2.1642	1.5169
5.25	4.8175	3.7189	3.3405	2.5490	2.3015	1.7757
5.50	5.4240	4.4627	3.7062	3.0047	2.5040	2.0353
5.75	6.1017	5.2065	4.1421	3.4608	2.7778	2.2957
6.00	6.7839	5.9502	4.5784	3.9172	3.0515	2.5568

a. Embedded option value considering all costs with $\lambda_\Phi = 0$.
b. DCF value with $\lambda_\Phi = 0$.
c. Embedded option value considering all costs with $\lambda_\Phi = 0.25$.
d. DCF value with $\lambda_\Phi = 0.25$.
e. Embedded option value considering all costs with $\lambda_\Phi = 0.5521$.
f. DCF value with $\lambda_\Phi = 0.5521$.

embedded values (the DCF values) for λ_Φ=0, λ_Φ= 0.25, and λ_Φ= 0.5521 are $2.57/barrel ($0.74/ barrel), $1.99/barrel ($0.73/barrel), and $1.60/barrel ($0.75/barrel), respectively (see <Table 4-4>, [Figure 4-4], and [Figure 4-5]).[Figures 4-4] and [Figures 4-5] graph the refiner's values for three values of the mean reversion factor : λ_{Φ},=0, λ_{Φ}=0.25, and λ_{Φ}=0.5521 (volatility is held at 44.0246).

[Figure 4-5] DCF Values with Mean Reversion Factors



3. Hysteresis Condition

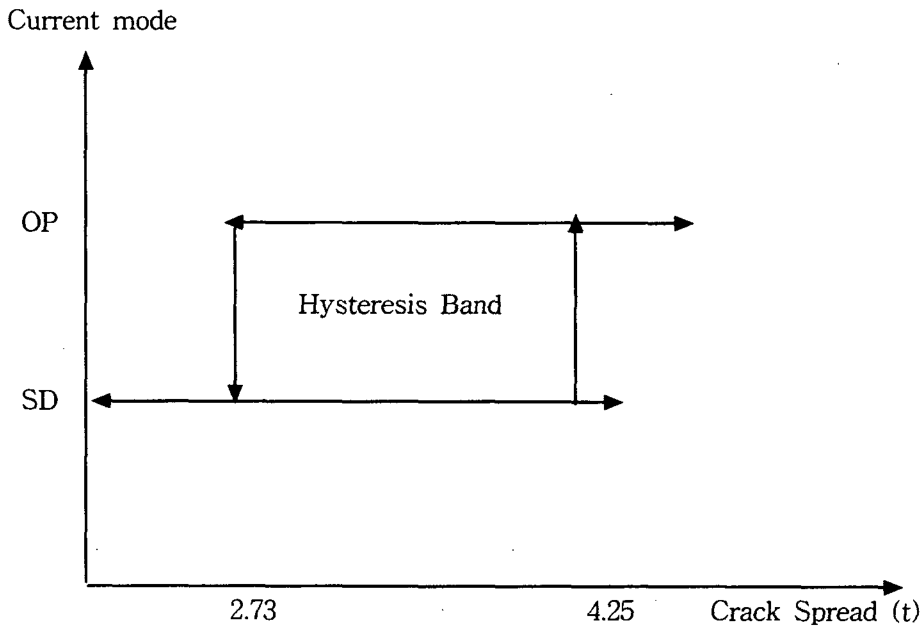
A hysteresis band is a range of underlying asset values causing mode switching to be postponed even when short-term cost conditions make switching appear profitable. In other words, a hysteresis band represents a range of crack spread values where mode switching may show as optimal on a short-term basis, but, because of reswitching costs in the future. not yet be advisable. Hysteresis band values can be obtained by calculating the critical boundaries of the state variables at which refiners may switch managerial modes.

We compute the critical boundaries of the crack spreads at which a refiner would switch between the OP mode and the SD mode. For the base-case parameters, a refiner currently in the OP mode would switch to the SD mode if crack spreads were to fall below $2.74/barrel for each period; it will switch from SD made to OP mode if crack spreads were to rise above $4.25/barrel for each period. As expected the hysteresis band between the critical crack spreads widens with increasing volatility (degree of uncertainty).

Suppose volatility decreases to 20% because of stability in the oil markets, and switching costs are held constant. A refiner in the OP mode would shut down its operation if crack spreads fall below $3.48/barrel. Conversely, the refiner will operate its production process again if crack spreads rise above $4.25/barrel. As volatility decreases, the critical values of crack spreads approach to the $4.00/barrel that is the break-even costless switching value.

[Figure 4-6] provides a stylized representation of the hysteresis band for the base-case of managerial mode switching between OP and SD modes. <Table 4-5> shows hysteresis bands, i.e.. critical switching points for each volatility of crack spreads.

[Figure 4-6] Hysteresis Band Crack Spread (Base-Case)



⟨Table 4-5⟩ Hysteresis Band and Crack Spread Volatility

Volatility	σ = 20%	σ = 30%	σ = 44.02%
Hysteresis Band ($/ barrel)	(3.48, 4.25)	(3.15, 4.25)	(2.73, 4.25)

The magnitudes of switching costs also cause the threshold values of crack spreads for switching from OP to SD mode (or the reverse) to differ from the break-even value of crack spreads of $4.00/barrel far costless switching. In this case, there is a relatively wide hysteresis band for refiners, due to both high volatility in crack spreads and high switching costs in refinery processing. In other words, under the "real operating strategy" that allows a refiner to use a shutdown option, the critical values of the crack spreads at which the refinery should switch ifs managerial modes are very fat apart. This fact implies that it is not optimal for a refiner to choose the actual shutdown option.

Ⅴ. Conclusions

Dynamic programming and the revised binomial model are implemented to value refiners that have the managerial flexibility of shutdown. Our result illustrates that the value for the base-case with real options (a shutdown option) is approximately two times the value produced by the traditional DCF valuation method. A refiner's value is positively related to the magnitude of crack spread volatility and negatively related to the magnitude of the mean reversion factors when the option is in-the-money.

We also recognize that the presence of switching costs causes the threshold values of crack spreads for switching from operation to shutdown mode (or the reverse) to differ from the break-even value of crack spreads of $4.00/barrel for costless switching. The value range where switching is not optimal due to the high likelihood of reswitching in the short run is called the hysteresis band. There is a relatively wide hysteresis band for refiners, due to both high volatility in crack spreads and high switching costs in refinery processing.

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.

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