An Analysis and Comparison of Real Option Approaches for Project Valuation under Uncertainty

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Abstract

Several different real option valuation approaches appear in the literature to address valuation problems under uncertainty. This diversity, however, has created a confusion regarding their applications across different types of settings. We propose a real option valuation taxonomy to clarify these issues by analyzing and comparing the limitations, advantages and correct application conditions of four selected real option approaches. The analysis and comparison is based on three criteria: the nature of the capital market, the classification of project-specific uncertainty, and the source of the data. Through systematic comparison, we specify the appropriate choice of valuation framework and the reasons that drive this choice. We also give some simple numerical examples to illustrate these points. Understanding which approaches should be used to value which projects and how to apply an approach appropriately can effectively enhance the value of the investment and improve strategic decision-making.

Thesis Supervisors: Professor Timothy Falcon Crack and Dr David Alexander

Key Words: Real Option Analysis, Decision Analysis, Marketed Asset Disclaimer, Hybrid Real Option Valuation Approach, Integrated Real Option Valuation Approach

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Chapter 1: Introduction

1.1. The Background for Project Valuation under Uncertainty

The importance of project valuation has been recognized long ago in both the finance and management science literatures. This is because valuation constitutes an important step during the project development stage. Sound project valuation can inform the firm to make sound investment decisions which ultimately create value. In the literature, there are a wide variety of valuation approaches that attempt to determine the value of an investment. From the traditional Discounted Cash Flow (DCF) techniques to the modern Real Option Analysis (ROA), continuing efforts have been made to develop better methodologies and to support decision making. Practices in many industries also reflect this kind of diversity and progress.

A natural evolution of project valuation has taken place. This is largely due to the inadequacy of the traditional approaches, namely, the Discounted Cash Flow technique. Prior to the 1960s, Payback and Accounting Return on investment were the two primary investment evaluating methods used by large firms (Bierman & Smidt, 2007). In 1951, two books "Capital Budgeting" (Dean, 1951) and "The Theory of Investment of the Firm" (Lutz & Lutz, 1951) were published that opened the door to new managerial techniques for evaluating investments using DCF methods (Bierman & Smidt, 2007). Discounted Cash Flow (DCF) based approaches, such as Net Present Value (NPV), are quite simple and easy to understand. Typically, they predict a stream of cash flows (both cash inflow and cash outflow) over the expected life of a project, discount them at a rate that reflects both the time value of money and the riskiness of those cash flows, and then calculate a net present value. The investment decision rule is then based on simple logic: given two mutually exclusive projects, the one with the larger NPV should be preferred. Also, any project with a positive NPV should be viewed as a good investment. Despite the popularity and simplicity of DCF approaches, they are only acceptable if the expected future prevails. However, they are inherently flawed when analyzing projects with high levels of uncertainty. In these cases, the realized future cash flows may be vastly different from prior expectations. Hence, instead of simply coming up with the value of the project, decision makers must expect that the project will have to serve any one of a range of possibilities, and manage uncertainties proactively (Wang, 2005). In fact, by considering the effect of uncertainty on the valuation process, a growing body of recent research shows that some of the most important aspects of most capital investments are in fact the timing of the investment and the managerial flexibility involved.[1] Thus, it is imperative that a richer framework be established, one that enables decision makers to better understand the effect of uncertainty and to address the issues of managerial flexibility and investment timing more directly.

Indeed, Real Option Analysis has received considerable attention in the project management literature in recent years. The term "real option" was coined in the paper "*Determinants of Corporate Borrowing*" by Professor Stewart Myers at the MIT Sloan School of Management in 1977. The concept of a real option was developed, at least partly, as a response to the inadequacy of the traditional DCF approaches for the valuation of projects under uncertainty. By using the methods provided by financial option pricing theory, ROA allows analysts to account for traditionally non-easily quantifiable elements such as managerial flexibility and strategic interventions during the development of an investment (Ramirez, 2002). Relative to a passive managerial strategy, in a world in which unexpected change is a rule, an investment strategy that incorporates managerial flexibility in decision-making will respond most efficiently to various possible futures. In many circumstances, if option-like features such as deferment or staged investment are embedded in an investment opportunity, then quantifying the value of these features is significant in the valuation of the investment. Hence, ROA constitutes an advanced way of recognizing how projects are structured and managed, and incorporating this into the valuation method.

[1] Managerial flexibility is the ability to defer, abandon, expand, or contract an investment opportunity.

1.2. Confusion about Real Option Valuation Approaches

Over the last twenty years, a great deal of theoretical work has been done to model the value of real options and also to determine optimal investment strategies. This work has been done in such areas as natural resources, real estate, research and development, merger and acquisition, infrastructure, venture capital, engineering, etc. Unfortunately, despite the popularity of ROA among academics, only a few firms in very selective industries have begun to employ this advanced framework in their capital budgeting practices. Among these few implementations, a variety of contradictory ideas have been suggested for putting option theory into practice. Many of these applications are actually ill founded or poorly constructed (Bratvold *et al.*, 2005). The use of real option valuation in practice remains modest. This may be caused by many factors (e.g., complexity), but it is clear that the lack of an obvious and theoretically satisfactory link between the theoretical formulations and the practical applicability is a challenge that remains largely unsolved (see Borison, 2005 and Triantis, 2005).

Several different real option valuation approaches have been documented in the literature. This diversity allows practitioners to choose among approaches based on the features of project, but also has created a confusing outlook of their applications across different types of settings (Borison, 2005). At the early development stage, Real Option Analysis is a natural extension of financial option pricing techniques to value real/physical assets. The main idea behind this Classic approach is the no arbitrage principle based on the construction of a replicating portfolio whose value matches the value of the investment. However, recently, the inadequacy of this Classic Real Option approach has been widely pointed out by many researchers (see, for example, Simth & Nau, 1995; Borison, 2005; Mattar & Cheah, 2006). In particular, investment opportunities may involve project-specific aspects (e.g., technology) and/or may be purely commercial in nature. Therefore, the project might not be replicated by securities in the capital market or might only be partly replicated by securities in the capital market (e.g., only in some states of the world). Clearly, the treatment of these various types of project uncertainties may affect the choice of valuation approaches. Researchers over the past decade have developed several real option approaches to make up for the deficiency of the Classic Real Option approach in increasingly more realistic investment problems where strict analogies with financial options begin to break down. In particular, the link between Real Option Analysis and Decision Analysis (DA) has been debated in recent years. Decision Analysis is about modeling the sequence of decisions and uncertainties related to an investment opportunity by considering the decision marker's subjective briefs and preferences. Nau and McCardle (1991) and Smith and Nau (1995) found that the two approaches could be profitably integrated when the project is confronted with partially complete market conditions. Moreover, realizing the fact that searching for a twin security in the marketplace is often impractical, Copeland and Antikarov (2001) proposed using the assumption that the present value of the project without options is the best-unbiased estimator of the market value of the project. This is known as the Marketed Asset Disclaimer (MAD). These valuation approaches are based on different conceptual underpinnings and should be used in different application conditions. However, as Borison (2005) concluded, given the current state of practice, there is a good chance that one could either apply an unsound approach or make inappropriate use of a sound one. Given that the success of a firm is highly dependent on its capital budgeting process, understanding which approaches should be used to value which projects and how to apply an approach appropriately are of the utmost importance during the project development process.

1.3. The Purpose and Structure of the Thesis

The objective of this thesis is to enhance current thinking about real option evaluation techniques, clarify some of the confusion about the choice of the valuation approaches and improve strategic decision-making. To achieve its objectives the thesis undertakes an extensive literature review of four major real option approaches: Classic Real Option approach, Marketed Asset Disclaimer (MAD) (Copeland & Antikarov, 2001), Hybrid Real Option approach (Neely & de Neufville, 2001) and Integrated Real Option approach (Smith & Nau, 1995). The review aims to examine and compare the conceptual underpinnings of these approaches, with the objective of revealing their limitations, advantages and correct application conditions. In order to get a comparatively deep understanding of selected real option approaches, we explain several important concepts and cornerstones of option theory and decision analysis in some detail and try to show how they are connected to develop these selected real option approaches. Furthermore, in comparing the application conditions among these selected approaches, a classic offshore petroleum lease example by Paddock *et al.* (1988) is employed. In this example, the comparison of selected real option approaches is based on three criteria: the nature of the capital market, the classification of project-specific uncertainty, and the source of the data. More specifically, the selected real option valuation approaches are categorized by:

1) Whether and how they use capital market replication to construct the overall valuation. This is subject to the condition of the capital market.
2) How they treat the effect of project-specific uncertainty on value. This is largely dependent on the classification of project-specific uncertainty.
3) What data they use to parameterize the valuation model (e.g., market data or subjective data).

It is apparent that two types of project scenarios are considered in the example: a market uncertainty dominated scenario and a mix-uncertainty scenario, where project-specific and market uncertainties both exist. Some modifications will be made to reflect the realism of business conditions and to satisfy the requirements of implementation in both structure and data. Finally, we compare our results regarding the choice of valuation approaches in different valuation scenarios with two well-known taxonomies: Borison (2005) and the Banff taxonomy (Bratvold *et al.,* 2005 and Laughton, 2007).

The thesis is organized as follows. Chapter 2 begins by addressing some problems of valuing capital investments under uncertainty by using traditional DCF methods. It then develops the literature review of two dynamic valuation models: Decision Analysis and Real Option Analysis, and compares their strengths and weaknesses. Chapter 3 reviews previous studies of real option applications in three typical industries: petroleum, engineering, and research and development. Through a brief review, this chapter shows why these industries need to apply ROA in their capital budgeting practices and what kind of difficulties they face in implementation. Chapter 4 has two main parts. The first part provides the definitions and classifications of capital markets and of project uncertainties. Further it describes and contrasts the selected analytic real option approaches in terms of their underlying assumptions, application conditions and mechanics. The second part presents the valuation taxonomy in this study based on the above-mentioned three criteria: the nature of the capital market, the classification of project-specific uncertainty, and the source of the data. Chapter 5 applies the selected real option approaches to value an offshore petroleum lease project. Chapter 6 compares our results with Borison (2005) and the Banff taxonomy, and discusses real option valuation using a New Zealand grid network investment case. Chapter 7 summarizes the study and suggests some additional research areas.

Chapter 2: A Review of Project Valuation Approaches under Uncertainty

2.1. The Limitations of Traditional Discounted Cash Flow Methods

Decision makers usually face several difficulties in the process of making decisions regarding capital investments. These difficulties largely stem from the high level of uncertainty of cash flows associated with these investments, and the inadequacy of traditional Discounted Cash Flow methods to evaluate these investments and to support decision making under these conditions.

In the presence of a high level of cash flow uncertainty, traditional Discounted Cash Flow methods, such as NPV, cannot generate an appropriate value of the investment. This is because: 1) they cannot determine the value of the project accurately, 2) and they do not account for managerial flexibility, thereby failing to capture the value generated by it. Firstly, the NPV approach assumes at the outset that all future outcomes are clearly predictable, while this is typically not the case in a highly uncertain business environment. The existence of uncertainty implies that neither investment costs nor project cash flows (parameters used to conduct the NPV valuation) can be estimated with precision. In addition, point estimates based on the NPV approach may fail to reveal the range of possible values of the project. In practice, an important step in recognizing the variations associated with input parameters and the resulting outputs in DCF model is to conduct cash flow Monte Carlo Simulation. Secondly, and more importantly, NPV does not take into account managerial flexibility. NPV typically presumes one line of action (rather than a course of actions) from the beginning, rules out the possibility of changes and adaptations and therefore, does not take into account value created by flexibility (Ramirez, 2002).

However, in fact, managerial flexibility is an important value-adding part for many capital investments. The ability of management to abandon, defer and/or scale up or down a project introduces beneficial asymmetry in the distribution of project value. Flexibility may limit the downside losses, while exploiting the benefits from the upside potential. However, the NPV approach only considers the downside risk of a project by means of a premium in the discount rate, it ignores the positive side of uncertainty and, more importantly, managerial control. Although NPV assumes that project risks can be captured by the appropriate discount rate, calculating the value of managerial flexibility to actively manage future opportunities is not simply a matter of discounting.

In the presence of a high level of cash flow uncertainty, traditional Discounted Cash Flow methods, such as NPV, may fail to provide an adequate decision-making framework. This is because NPV is an all-or-nothing approach. It only presumes management's passive commitment to a certain operating strategy. Decisions based on NPV, are usually inflexible and irreversible. Inflexible means all the sequential decisions are fixed in advance. Irreversible means all these decisions are unchangeable throughout the lifetime of the project. However, real-life business conditions are a lot more complicated than the traditional DCF model assumes. Business conditions are fraught with uncertainties. Uncertainties are the reasons why planning is difficult and why fixed plans are not optimal (Dowlatabadi & Toman, 1990). For instance, effective decision-making often cannot be made completely and accurately at the initial stage because the knowledge about future conditions is unavailable or inadequate. In addition, when uncertainty becomes resolved through the passage of time, actions and events, managers can make appropriate midcourse corrections through changes in business decisions and strategies (Mun, 2006). Thus, rather than comprehensive decisions made upfront, firms usually make a series of investment decisions as the uncertainties resolve over time. Traditional DCF based approaches are inadequate to support this multi-stage decision making.

Hence, traditional DCF models are inadequate for uncertain projects both conceptually and mechanically (Neely & de Neufville, 2001). Mechanically, they are in error because they are unable to determine the future conditions of the project accurately and completely. Conceptually, they are in error because they fail to provide an adequate decision-making framework especially when managerial flexibility (or option) is present. Consequently, successfully valuing and managing project usually requires dynamic/proactive approaches that perceive and model multiple possible future outcomes, manage and shape the uncertainties of the project, outline the strategies for coping with uncertainties and their resolutions, and guide managers to make a series of optimal decisions.

2.2. Decision Analysis and Real Option Analysis

In order to overcome the inadequacy of traditional DCF approaches in valuation and decision-making, analysts tend to employ dynamic/proactive approaches to value risky projects where managerial flexibility plays an important role. Two major approaches are Decision Analysis and Real Option Analysis. Both Decision Analysis and Real Option Analysis acknowledge upfront that the future is inherently uncertain. So, they impose analytical frameworks to incorporate managerial flexibility into the analysis. By mapping out both uncertainties and decisions over time, they allow management to continually modify the policy to deal with a wide variety of possible outcomes. Despite this similarity in goals, these two approaches are founded on different theoretical foundations. They have complementary strengths and weaknesses. In this section, the theoretical underpinnings of these two approaches will be presented, with the aim of revealing their advantages and disadvantages. We shall discuss these two approaches in some detail as they are the important theoretical basis for our selected real option approach.

2.21. Decision Analysis

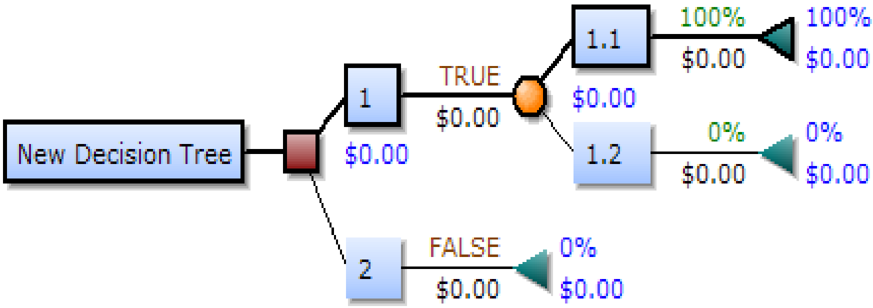
Decision Analysis is an analytical framework comprising a collection of principles and methods aiming to help decision makers in the performance of decision problems under uncertainty. The term “decision analysis” was coined in the1960s by Ronald Howard. This approach has its roots in decision theory and has a long history of modeling and valuing contingent decisions in the area of capital investment. DA decomposes complex decision problems into smaller elements or ingredients of different kinds (Brachinger & Monney, 2002). It effectively accounts for the value of managerial flexibility by shedding insights onto a decision problem through a logical process that structures information and alternatives: information includes subjective assessment on uncertainties such as cost, revenue, and the probability of the project’s success; alternatives represent a set of mutually exclusive and exhaustive actions that a firm can undertake within the time frame.

Typically, in the Decision Analysis approach, the analyst values a decision problem by constructing a decision tree (or “dynamic program” or “influence diagram”) that describes uncertainties, alternatives and the sequence of decisions surrounding the project (Smith & McCardle, 1998). A decision tree is a tree-like graph or model (see figure 2.1) consisting of a sequence of decision (square) and chance nodes (circle), ending in terminal nodes (triangle). The decision maker's beliefs about the project are captured by assessing subjective probabilities for the uncertainties and preferences for project cash flows are captured by using some kind of risk-adjusted discount rate or utility function (Smith & McCardle, 1998). Project values and optimal strategies are then found by solving the tree backwards and calculating expected values or certainty equivalents.[2] The decision rule in DA is simple: choose the best alternative that offers the best average value or highest certainty equivalent. In this way, the optimal decisions at each step for all the identified states of nature are determined.

[2] The certainty equivalent is the value when a decision maker is indifferent between taking an uncertain alternative and receiving the certainty equivalent for sure.

FIGURE 2.1

Decision Tree Structure



Source: http://en.wikipedia.org/wiki/Decision_trees

Decision Analysis has obvious strengths and weaknesses for valuation and decision making. It has a significant advantage in framing the decision problem based on sound logic, which otherwise would be very confusing due to the complexities introduced by uncertainty (de Neufville, 1990). The major strength of the Decision Analysis approach is its intuition and generality. The decision analysis paradigm provides a systematic and logical framework for making all kinds of decisions from oil exploration to pharmaceutical R&D. The major weakness of this approach is that Decision Analysis tends to narrowly focus on the preferences and beliefs of the decision maker and rarely takes into account broader market information and its effect on the project values as well as on the optimal investment strategies.

2.22. Real Option Analysis

Unlike Decision Analysis, Real Option Analysis pays careful attention to market opportunities related to the investment at hand. In this approach, rather than using the decision maker's subjective beliefs and preferences, analysts seek objective market information to determine project values, real option values and optimal strategies. This approach has its roots in financial option pricing theory. The main idea underlying this approach is the no arbitrage principle. The no arbitrage principle states that two different assets (or combinations of assets) with identical cash flows must have the same price. The principle that there cannot exist arbitrage opportunities in security markets is one of the most basic ideas of financial economics. In the context of real option valuation, the no arbitrage principle allows pricing of real options by constructing a portfolio of perfect substitutes that provides the same payoffs as the real underlying asset and whose payoffs can be directly observed in the marketplace (Dixit & Pindyck, 1994). Once this "tracking portfolio" is identified, the real options embedded in the investment opportunities can be priced using standard financial option pricing techniques (e.g., Black-Scholes model).

2.221. Factors Affecting Option Value

Typically, standard financial option pricing techniques calculate the value of a financial option as a function of six variables: 1) the value of the underlying asset *(S)*, 2) the exercise price *(X)*, 3) the time to maturity *(t)*, 4) the risk-free interest rate *(r)*, 5) the volatility of the underlying asset *(σ)* and 6) dividend *(δ)*. Based on the work of Luehrman (1994), the correspondence between the investment's characteristics and the parameters that determine the price of a financial option is presented in figure 2.2.

FIGURE 2.2

Equivalence between Real Options and Financial Options

Financial Option Value Drivers		Real Option Value Drivers
Financial asset Price	S	Real Asset Value
Exercise Price	X	Investment Cost or Abandonment Value
Time to Expiration	t	Time to Expiration
Risk Free Interest Rate	r	Risk Free Interest Rate
Volatility of financial asset value Movement	σ	Volatility of Real Asset Value Movement
Dividend	δ	Value Loss to Preserve the Option

The underlying asset is the instrument on which the option is based (Ramirez, 2002). For financial options, underlying assets include stocks, stock indices, foreign currencies, debt instruments, commodities, futures contracts, and other assets (Hull 1999). These financial underlying assets are traded on capital markets. Hence value can be clearly determined. However, for real options, the value of underling asset often represents the value of the project without flexibility or the present value of expected cash flows. Because most real assets are not freely tradable or marketable, the values of these real underlying assets usually cannot be directly observed from the marketplace. Therefore, in order to value real options through the concept of no arbitrage, an analyst must obtain the market value of the real underlying asset by constructing perfect substitutes which can be observed in the marketplace. However, identifying this "market proxy" is not easy, and is sometimes impossible. This represents the greatest theoretical difficulty of the Classic Real Option approach.

The exercise price is the investment cost (revenue in the case of a put) to exercise the option. For a financial option the exercise price is the set agreed price that would be paid/received to acquire/sell a security in the future. In the case of a real option, it commonly represents the cost of implementing a next phase or the revenue received from an abandonment option. An increase in the exercise price has a negative impact on the value of a call option,[3] and has a positive impact on the value of a put option,[4] other things being equal.

Expiration[5] is the date on which the financial option contract or real investment opportunity expires. Typically, financial option contracts expire according to a pre-determined calendar. In real options, the time to expiration is the maximum period that an investment decision can be made without losing the embedded flexibility. Usually, the

[3] A call option gives the holder the right, but not the obligation, to buy the underlying asset for a specified price within or at a specified time.

[4] A put option gives the holder the right, but not the obligation, to sell the underlying asset for a specified price within or at a specified time.

[5] Based on the specified exercise time, plain vanilla financial options can be divided into two categories: American-style option and European-style option. An American option can be exercised at any time up to the expiration date. A European option can be exercised only on the expiration date.

longer the term to expiration, the higher the value of the real options because there is more opportunity to receive material information.[6]

The risk-free interest rate is the interest rate obtained by investing in financial instruments with no default risk. It is the rate of return on an asset that has the same payoff in all states. In practice the most approximate substitute is short-term government rate such as US Treasury bill. According to Hull (1999), an increase in the risk free interest rate has a positive influence on call option value and a negative influence on put option value, other things being equal.

The volatility, roughly speaking, is a measure of how uncertain is the underlying value. Plain vanilla options increase in value given an increase in volatility.[7] This is because an option is the right, but not the obligation to take an action. Hence, increased uncertainty improves upside potential while limiting downside losses. Owing to this nature of real options, option thinking seeks gain from uncertainty. However, in many circumstances, estimating volatility is very difficult for real options since no historical/market information is available. The common real option approaches for estimating volatility are: twin security information (Kelly, 1998 and Smit, 1997), Monte Carlo Simulation (Copeland & Antikarov, 2001), and closed form expression (Davis, 1998).

Cash dividends on stocks are cash payments made by a firm to its shareholders. Dividends have the effect of reducing the financial asset value if paid before the expiration date. This decreases the value of a call option, but increases the value of a put option. Real option dividends (e.g., a project's free cash outflows) can be attributed to the project value loss during the time that the option is alive (Brealey & Myers, 2000). Like financial options, real option dividends would reduce the value of a call option, but enhance the value of a put option.

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[6] Two exceptions include a deep in-the-money European-style put and also a deep in-the-money European-style call when future dividends are large.

[7] Note that for exotic options, an increase in volatility can be a bad thing. For example, higher volatility will decrease the value of a "knock out" option if the underlying asset price is close to the knock out barrier.

2.222. Option Pricing Methodologies

The pricing of real options contingent on an underlying asset can be determined by several methodologies. Mainstream valuation methodologies are Partial Differential Equation (PDE), Monte Carlo Simulation, and Lattice or Tree models. PDE methodology requires the derivation of a partial differential equation that describes the behavior of the underlying asset. We then solve this equation subject to a set of boundary conditions related to the features of the option. This approach is the most complicated method that transforms from an intuitive consideration of strategic issues into mathematical manipulation, and may require that the analyst have a deep understanding of advanced stochastic calculus. In the best case, a closed-form solution exists for the PDE, thus allowing it to be solved analytically (Garvin & Cheah, 2004). However, when a project has many complex features (e.g., several sources of uncertainties, many types of embedded options); analysts have to resort to numerical methods, such as Monte Carlo Simulation and Lattice or Tree models. Simulation techniques replicate the underlying asset's stochastic process by using random numbers to sample many different paths that the underlying asset's value may follow in a risk-neutral world (Ramirez, 2002). For each path the option payoff is calculated. The estimated value of the option is the arithmetic average of the discounted payoffs (Hull, 1999). Monte Carlo Simulation is a powerful method that can be used in many complex situations, such as multiple uncertainties and complex distributions. For instance, Longstaff and Schwartz (2001) propose a least squares Monte Carlo (LSM) approach, which can handle complex American options with path-dependent and multifactor situations. Lattice or Tree models (e.g., Binomial Lattice developed by Cox *et al.* (1979)) apply the lattice or tree structure to approximate the underlying stochastic process and then calculate the option value through the use of risk-neutral pricing techniques. The main advantage of these models is that their approximations to the underlying stochastic processes rely only on basic algebra and therefore are more transparent and computationally efficient. In the limit, results obtained through the use of these discrete-time models tend to approach those derived from closed-form solutions. A high level of accuracy can be obtained by using high number of steps, but acceleration techniques exist (Hull, 1999). The main disadvantage of these models is that they are cumbersome as the number of time periods increases, especially if the tree is not recombining; and require an intensive labour in dealing with problems involving multiple uncertainties, “path-dependent” uncertainties, and complex options.

2.223. Summary of Real Option Analysis

In sum, the main theoretical superiority of ROA over DA is that it provides the decision maker with a unique tool for linking market values to strategic investment decisions. However, this is also a major weakness of this approach due to its lack of generality. In order to determine the market value of a project, an analyst must be able to find a portfolio or trading strategy that perfectly replicates the project's cash flows. However, it is not always possible to find a “twin security” in the marketplace. For instance, some innovations may be not correlated to any market trading assets. Hence, the application of ROA is very restricted by the market conditions. Traditionally, this approach is typically applied in areas where market data sets are well-developed, such as commodities, including oil and gold.

2.3. Summary

Traditional DCF methods are inherently flawed when analyzing projects with future uncertainties because they do not take into account managerial flexibility to respond to these uncertainties in different ways (Ramirez, 2002). By recognising the value of managerial flexibility, Decision Analysis and Real Option Analysis are superior to traditional DCF methods. Decision Analysis and Real Option Analysis are both about modeling the sequence of decisions and uncertainties related to investment opportunities. Decision Analysis has an advantage in terms of generality. But DA typically overlooks the market opportunity related to the investment. On the other hand, ROA uses objective market information to determine project values and optimal strategies, but the application of this approach is restricted by the fact that for most capital investments no such replicating portfolio of securities exists.

In fact, many capital investments in various industries have both project-specific and market components (the next chapter provides more details about this point). Project valuation must account for both market information and project-specific information. Therefore, taking the advantages of both approaches and melding them into an overall valuation strategy seems natural because of the complementary strengths and weaknesses of these two approaches. More details about why and how these two approaches are integrated to deal with real-life projects are addressed in the following chapters.

Chapter 3: The Real World Applications of Real Option Valuation – Strengths and Weaknesses

3.1. Why Real Options Are Important for Capital Investments under Uncertainty

The future business environment is uncertain. Decision makers cannot therefore commit to a static operating strategy for the realization of a long-term plan. Instead, they must tailor their investment decisions to the realized events, not to the estimated/forecasted ones. It is clear that many investment opportunities need to revised as future unfold, not all decisions can be effectively made at the beginning of the project. Because of this, ROA is becoming a more important valuation and decision making tool. Real option analysis not only increments the precision of the analysis but incorporates a learning process that supports multi-stage decision making. ROA encourages decision makers to think more broadly about the dynamic nature of future business conditions. ROA therefore has the potential to improve corporate strategic investment decision making in the following ways:

- Providing insights into the role of uncertainty in corporate investment decision making, and improving the understanding of how decision makers can benefit from the uncertain business environment. The role of uncertainty in the presence of managerial flexibility is not necessarily penalizing - as conventional wisdom would have it. In contrast, greater variability of potential outcomes may be beneficial in the presence of real options. That is, managerial flexibility to revise decisions introduces beneficial asymmetry in the distribution of project value returns by enabling upside opportunity while limiting downside losses (Trigeorgis, 2002). Hence, ROA views the uncertainty as a potential source of value.

- Providing an improved interface between decision making and long-range strategic planning. ROA does this by recognizing that corporate investment strategy is much more like a series of real options than a series of static or isolated cash flows. This point is very important for making decisions regarding strategic investments (e.g., R&D, investment in information, and innovation). This is because the value in the early-stage investment derives not so much from the expected directly measurable future cash flows but from the future growth opportunities that the early investment may unlock.

- Connecting the firm's capital budgeting and financial strategy. ROA does this by comparing the value of the real investment with the market trading opportunities.

Consequently, identification of material real options embedded in a project can help decision makers to effectively allocate scarce resources through considering strategic flexibility. The types of real options that can be identified in the literature are investment timing options (e.g., deferment and time-to-build options), operational options (e.g., scale, abandon or switch) as well as strategic growth options. Some of these real options may occur naturally (such as deferment, abandon), and some of these options have to be planned and built in at some extra costs (such as a switch option). In addition, many projects often involve a "collection" of various options (multiple interacting options). These real options are aimed at capturing the flexibility and value-enhancement associated with different types of strategic decisions. The fundamental idea behind all these options is that managerial flexibility can create value given an uncertain environment. We now discuss briefly a few broad types of real options.

Investment Timing Option

Investment timing options occur if uncertainty can be resolved by waiting for or acquiring more information before making irreversible commitments. For example, the deferment option is particularly valuable in industries where high uncertainties and long investment horizons exist (Trigeorgis, 1996). If the firm retains an exclusive right as to whether and when to invest a certain project, then this project effectively competes with itself over time. However, if competitive pressure is intense (e.g., low barriers to entry for competitors), then the deferment option may carry no value. For example, some investment opportunities may be jointly held by a number of competing firms. The firm that first launches the product may take a large amount of market share (i.e., first mover advantage). In this case, some very interesting game theoretic considerations enter the investment decision (Trigeorgis, 1996). The competitive loss suffered by a firm as a result of competitive interaction needs to be considered in the valuation and decision making. Another type of investment timing option is time-to-build option (e.g., staged investment option). In this case the investment can be divided into a series of stages creating valuable options to default at any given stage if new information is unfavorable to future development.

Operational Options

Most projects will, by nature or by design, include operational options (Trigeorgis, 1996), such as the opportunity to scale (e.g., expand and contract), abandon or some sort of switching option. The presence of these operational options can create value. The ability to exercise managerial flexibility can provide protection against future events turning out differently from expected by mitigating losses and capturing more value from favorable conditions (Trigeorgis, 1996).

Strategic Growth Options

Growth options are options on investments that open up the possibility of follow-on investments or create future growth opportunities. The typical investment types falling into this category are strategic investments (e.g., R&D, investment in information). These investments are typically not made with the expectation of immediate payoffs, but rather with the expectation of creating future profitable investment opportunities (Miller & Park, 2002).

3.2. Real Options Applications

Over time, recognizing managerial flexibility has brought a major cultural change in thinking about investment opportunities in many industries. According to the discussion of Triantis and Borison (2001), the firms that have shown broad interest in real options have some common characteristics:

1) They operate in capital-intensive industries with highly uncertain cash flows (e.g., natural resources and engineering).

2) They are in industries that have undergone major structural reform that makes more traditional valuation techniques less helpful (e.g., power industry).

3) They operate in industries where strategic prospects are major value-drivers (e.g., high-technology, innovation and R&D).

This section reviews the applications of ROA in three typical industries: petroleum, engineering, and research & development. The review aims to show why these industries need to apply ROA in their capital budgeting practices and what kind of difficulties they face in implementation.

3.21. Petroleum Applications

The petroleum industry is highly capital-intensive. It entails large, irreversible investments in exploration, development and production of oil and gas products. The investment decisions are almost always based on imperfect and limited information and subject to a high level of uncertainty at each stage of development. For example, the firm may face significant geological uncertainties (e.g., size of oilfield, quality of reserves) in the exploration stage, as well as considerable market uncertainties (e.g., price of oil, demand) in the production stage. The existence of a publicly traded commodity/futures market allows some option parameters to be proxied (e.g., implied volatility of options on oil). At each stage, the existence of operating flexibility means decision markers must make critical decisions to try to choose the best alternatives. Therefore, petroleum investment valuations are often thought of as a multi-stage real option pricing problem, where the process and discipline of ROA captures the presence of uncertainty, the limited information, and the existence of different, but valid, development scenarios (Mun, 2006).

The real world application of real option approach dates back to the mid-1980s. In early applications, analysts typically used standard financial option pricing techniques by considering the market-priced uncertainty and constructing a "tracking portfolio" in the marketplace. For example, Brennan and Schwartz (1985) develop a Classic Real Option approach to evaluate natural recourse investments. In their model, they treated output price, a market-priced uncertainty, as stochastic and they constructed a "self-financing" portfolio to value investment opportunity. But this is inadequate because petroleum firms also face a considerable level of project-specific uncertainty (e.g., the uncertainty about the size of reserve). These uncertainties are unrelated to the overall economy, and are therefore not priced by the capital market. Standard option pricing techniques typically overlook these project-specific uncertainties in the process of valuation and decision making. In Amram and Kulatilaka (1999) project-specific uncertainties were treated as one source of tracking leakage (i.e., measurement error in the tracking portfolio). However, in the case of petroleum investment, these untracked uncertainties are as important as the market-priced uncertainties and management has a great deal of flexibility to adapt as these uncertainties are resolved (Smith & McCardle, 1998).

It is clear that both types of uncertainties (market priced and non market priced) are important in the case of petroleum investments. Therefore, careful specification of uncertainties is necessary to obtain better estimates and more importantly avoid errors in decision judgment. Dixit and Pindyck (1994) and Copeland and Antikarov (2001) also made this distinction. Many researchers applied integrated valuation models to treat these different types of uncertainties. Smit (1997) valued an undeveloped oilfield as a multi-stage investment problem by applying a standard option pricing technique to measure oil price uncertainty and using both the risk-free rate and the actual probabilities of the distribution to estimate the reserve size uncertainty. Smith and McCardle (1998) applied an integrated model to value oil properties. They applied standard option pricing technique to value market-priced uncertainty and use a Decision Analysis approach to value project-specific uncertainty. There is no doubt that option pricing techniques provide a simple and direct way to compute market-priced uncertainty. The pricing of project-specific uncertainty, however, is somewhat unclear. For many petroleum investments, different treatment of project-specific uncertainty could lead to decisively different project values and operating strategies. Later in this thesis, we will further discuss and compare these integrated valuation models in terms of their treatment of project-specific uncertainty.

3.22. Engineering Applications

Large-scale engineering projects such as a dam, highway, electricity transmission network, or satellite system are characterized by long construction, operation and payback periods are fraught with uncertainties. The most important of these uncertainties relate to technical challenges (such as technical problems, accidents and unforeseen failures), project economics (such as construction cost and time, maintenance and operating cost) and project demand (Ramirez, 2002). The need for real options is increasingly gaining attention within the engineering community (de Neufville, 2003, 2004). Thinking in terms of real options can lead to fundamental changes in the way engineers do systems planning and design. Firstly, thinking in terms of real options leads designers to manage both technical and market uncertainties. Traditionally, engineering planning and design pays too much attention to technical aspects of the project and too little attention to bundles of market risks. de Neufville (2003, 2004) noted that considering market conditions in engineering systems design is outside of most engineering analyses and perspectives. This ignorance could result in costly mistakes. A typical example is Motorola's Iridium satellite system. The system is clearly a triumph of modern engineering but commercially it has been a disaster (nearly $5 billion losses). The Iridium communications service launched on November 1, 1998 was based on a forecast of 3 million subscribers. It aroused the interest of only 50,000 initial subscribers and filed for bankruptcy nine months later (Wang, 2005). de Neufville and his colleagues at MIT say that this could have been avoided if the system planners had been aware of the market demand uncertainty and had built in the flexibility to cope with it. For example, they can design a smaller system with expansion option built in, and excise this option when market demand meets the prior expectations. Hence, thinking in terms of real options leads designers to build much more flexibility into an engineering system than is common in current practice (de Neufville, 2003, 2004). The notion of flexible systems design has been the object of much recent engineering research. Wang (2005) defined the options created by changing the actual design of the engineering system as real options in projects (similar to switch options). Real options in projects do not emerge naturally. They should be effectively designed at the outset at some extra cost to manage the future turning out differently to initial expectations. Building flexibility into engineering systems is attractive if the present value of the cost of modifications that may be required later is far greater than the additional cost of designing flexibility into the system at the outset. For example, dual-fuel burners that can use either oil or gas give the operators of power plants the right to switch between fuels whenever it is economical to do so (Kulatilaka, 1993). In New Zealand, Transpower's North Island Grid Upgrade Project (GUP) is another typical example of designing flexibility into the system. Transpower's GUP is to build a new 400kV line between Pakuranga and Whakamaru, operated at 220kV initially, with 400kV transformers installed when required by future demand growth. Therefore, ROA implies re-framing of the ways engineers approach design and effectively expands the value of an engineering project by actively managing uncertainty and designing flexibility into the system.

Although real options are important for engineering projects, the data available for conducting option valuation is of much poorer quality than that for financial options or petroleum investments. There is often little or no historical/market data to draw upon for many engineering projects. Hence, in many cases, searching for a "market proxy" to parameterize an option valuation model may be a waste of effort. Analysts have to use subjective estimates and assumptions to analyze these investments. Although the validity of the analysis in the absence of objective market information may be questionable, the insight derived from option thinking may contribute to shaping strategy (Luehrman, 1998). de Neufville (2003, 2004) emphasized that the valuation of engineering projects typically does not require great accuracy. The focus of the analysis should be on recognizing the implicit and explicit real options surrounding the engineering project and identifying an appropriate strategy to capture their values. Many engineering projects are thus valued based on subjective data and intuition. Wang (2003) valued a hydropower construction project using a subjective real option approach based on the MAD assumption. The value of the underlying asset was derived from a NPV calculation, and the volatility of the underlying asset was determined through the use of a Monte Carlo Simulation. Ramirez (2002) applied the same approach to value a water supply expansion project. In these applications, the most important contribution from the real option analysis was to broaden the decision makers' views of future possibility and sharpen the logic of their thinking about various strategic prospects (Ramirez, 2002). Hence, we believe, in engineering, the strategic process itself is more important than the particular analytic results generated by the ROA. Later in this thesis, we will provide further evidence to support the use of subjective data to value real option problems when the "market proxy" is not available.

3.23. Research & Development (R&D) Applications

The most relevant option embedded in the valuation of R&D is a strategic growth option. Strategic investments, such as R&D typically involve high initial investment. These initial investments seem to be cashless and unprofitable when considered on a standalone basis under the myopic lenses of a traditional DCF method but in fact have the potential to create profitable investment opportunities in the future. This is a widely accepted investment philosophy in R&D. Myers (1984) emphasized that the value of R&D is almost all option value. Pettit (1999) noted that the term strategic has become almost synonymous with negative-NPV projects, but managers intuitively understand that these projects nevertheless create value. Hence, ROA is a very important tool in the context of R&D, which can help decision makers to recognize as well as quantify the intrinsic strategic value in research and development.

The major difficulty in valuing R&D investments using ROA is that there is frequently no direct market information about the underlying asset value and no historical data to deduce important inputs (e.g., volatility of underlying). This is because most R&D projects are not traded on capital markets. Trigeorgis (1996) determined that it is almost impossible to build a tracking portfolio to determine option value if the underlying is not traded and if it therefore has no market price. In the literature, there are two main propositions to deal with the problem of a non-traded underlying asset, but neither of them seems correct in principle.

The first proposition is that traded securities are sufficient for *dynamic* spanning of the non-traded underlying asset and to use standard financial option pricing techniques to value real options. This is analogues to delta hedging done by options market makers. Mason and Merton (1985), Dixit and Pindyck (1994), and Trigeorgis (1996) propose that real options could be valued similarly to financial options when there exists a traded asset that has the same risk characteristics (e.g., perfectly correlated returns) as a non-traded real asset. Even if the perfectly correlated asset is not explicitly traded, however, if the capital market is sufficiently complete regarding the project being valued, in that the traded securities are sufficient for dynamic spanning of the underlying asset, the standard option pricing method can still be applied. But this proposition is problematic because many R&D innovations may be not correlated to any traded securities and therefore spanning will not be possible. If some traded securities do a reasonable job of replicating then the use this kind of portfolio may give a reasonable approximation to real option value. However, it is not at all obvious how to empirically identify these securities in practice. Borison (2005) also questioned this approach; he noticed that none of the authors (who applied Classic Real Option models) presented any reasoning based on principles or any empirical evidence regarding the validity of the "replicating portfolio" argument. Hence, more research is needed to justify this "replicating" approach.

The second proposition is to use judgemental approaches to determine the value of a non-traded underlying. For many of these judgemental approaches, the value of the underlying is derived from the result of a traditional DCF method (see Sharp, 1991, and Copeland & Antikarov, 2001). This approach is also problematic partly because the value of underlying asset is very hard to estimate in the absence of market information. In addition, when valuing in this way, there is no continuously market-based benchmark available to guide the option exercise policy.

However, the literature on real options concurs in pointing out that the most important contribution of this framework for R&D is changing decision makers' views about future growth opportunities. Hence, the focus of the real option analysis should be on a series of decisions to be made or optimal strategies to implement and not on the exact valuation number generated - as long as the signals given are consistent in terms of general magnitude and direction of exercise policy of real option (Lander & Pinches, 1998).

3.3. Summary

This chapter illustrates many types of real options embedded in investment opportunities from different industries. It is clear that the adoption of real options for project valuation and decision making is valuable. Decision makers of petroleum firms can apply real options to guide the multi-stage decision making process. Engineers can design much more flexibility into an engineering system to enhance the value of the investment. For R&D investments, the adoption of real option thinking can help decision makers to recognize the intrinsic strategic value in a research and development program. In all these cases, ROA can effectively enhance the analysis via implications for the design of the project and of corporate strategy.

In the face of real world complexity, however, the strict application of Real Option Analysis based on standard financial option pricing theory is probably limited. The existence of different types of uncertainties or the absence of direct market information may violate the most important fundamental assumption behind all option valuation models: the no arbitrage principle. As mentioned earlier, many petroleum investments may face both significant market and project-specific uncertainties. Hence, the appropriate valuation model (e.g., the combination of Real Option Analysis and Decision Analysis) need account for these two different types of uncertainties. Many engineering and R&D investments may lack directly observable market information to determine the critical inputs in option valuation models. In these cases, analysts may have to resort to subjective assumptions and data to determine the value of the project. In practice, it is difficult, or unrealistic to modify a project to fit the assumptions of a Classic Arbitrage-enforced Real Option Analysis. To the contrary, project valuation models must be modified to fit the special features of a project. The main objectives of valuation are to help decision makers to discover the real value of the investment opportunity, and inform them step-by-step of to exploit this intrinsic value.

Chapter 4: Real Option Valuation Approaches

The previous chapter studied the importance of ROA in capital investment under uncertainty but the review of the applications in three typical industries indicates that Classic Real Option approach often cannot be applied in a straightforward manner. This is because the input parameters (e.g., the value of the underlying asset) for option valuation models often cannot be determined precisely. This in turn is because many projects have no directly observable market information (i.e., they are non-traded) or they involve uncertainty that is not priced in the market. This chapter clarifies these issues regarding valuation and decision making under these conditions. Firstly, we present some important concepts related to real options: the classification of project uncertainty and varying notions of completeness in capital markets. Secondly, we examine and compare several proposed real option pricing approaches. Finally, we discuss three important real options criteria for real world implementations: the nature of the capital market (i.e., type of completeness), the classification of project-specific uncertainty, and the source of the data.

4.1. Basic Concepts

4.11. Risk and Uncertainty

4.111. General Definition of Risk and Uncertainty

For the purposes of this thesis, risk and uncertainty are treated as two different and interrelated concepts. Based on the work of Ku (1995), we define uncertainty as an unknown that cannot be solved deterministically or an unknown that can only be resolved through time, action or obtaining more information.[8] We define the adverse consequence of a project's exposure to uncertainty (i.e., uncertainty about demand, cost and timing) as risk. Many researchers also have similar views about risk and uncertainty in terms of project valuation. For example, Merril and Wood (1991) define uncertainty as those factors not known with certainty, and risk as the hazard posed because of the uncertainty. Amram and Kulatilaka (1999) define risk as the adverse consequence of a firm's exposure to uncertainty (Ramirez, 2002).

For project valuation and decision making, uncertainty is an inherent character and usually unavoidable. However, project uncertainty is not necessary something purely adverse. There is upside 'opportunity' as well as downside 'risk', relating to the possibility of returns above or below the expected. Ward and Chapman (2003) emphasize that opportunity and risk are seldom independent regarding a project. Therefore, it is rarely advisable to concentrate on reducing risk without considering associated opportunity, just as it is inadvisable to pursue opportunity without regard for the associated risk (Ward & Chapman, 2003). Traditional DCF methods usually induce a limited focus on project valuation and the decision making process, focusing more on risk (see Ward & Chapman, 2003). Van Putten and MacMillan (2004) point out that DCF analysis captures the risk of uncertainty by applying a high discount rate for a high uncertainty project, but does not capture the rewards when actual cash flows are higher than forecast. This inherent bias can lead managers to reject highly promising, if uncertain, projects (Triantis, 2005). ROA provides, however, a systematic framework that proactively recognizes and incorporates uncertainty in project valuation and decision making by limiting risk while harvesting opportunity.

4.112. The Classification of Uncertainty in This Thesis

The board view of project uncertainty presented in the previous section is useful for

[8] Frank Knight's "Knightian uncertainty" (Knight, 1921) is essentially the same as this.

decision makers to expand their perspective about uncertainty embedded in a project from a narrow focus on risk to a broader view that incorporates opportunity. To avoid the narrow focus, we replace the word "risk" with the word "uncertainty" when discussing the unknown aspects of a project. For the purposes of this thesis, project uncertainties are in turn classified into three categories: market, unique and private uncertainties.

Market uncertainty is similar to systematic risk. It is an uncertainty that can be perfectly tracked by trading securities. For project valuation, market uncertainty is usually a function of factors exogenous to the project and is correlated with the general movements of the economy (e.g., market demand, price levels) (Piesse *et al.,* 2002). Assets with market-priced uncertainty are associated with a wide set of opportunities in the economy because one can always acquire, reduce, or reshape the uncertainty through a position in trading securities (Amram *et al.*, 2000). Hence, in principle, the value of a project with pure market uncertainty can be determined via no arbitrage principles.

Many capital investments involve, however, some degree of project-specific uncertainty that is not replicable with the set of traded securities. For project valuation, project-specific uncertainty is usually a function of factors endogenous to the project and is not correlated with the general movements of the economy (e.g., the yield of a copper mine) (Piesse *et al.*, 2002). In finance, these uncertainties are commonly known as unique risk, diversifiable risk or unsystematic risk. The treatment of unique uncertainties in ROA in this thesis is similar to the treatment of unsystematic risk in portfolio theory. That is, unique uncertainty is assumed to be a diversifiable uncertainty that is not spanned by the traded securities; hence, it is not priced by the capital market. In addition, it can be almost completely eliminated by holding a well diversified portfolio. Therefore, a diversified investor should not require a higher expected return (other than a risk free rate) for bearing unique uncertainty. These classifications of market and unique uncertainty are consistent with the risk definitions and classifications in the Capital Asset Pricing Model (CAPM).

Mattar and Cheah (2006) claim, however, that classifying each type of project uncertainty strictly under a dichotomy of market and unique uncertainties is a gross simplification of the real world. They observe that the arguments of diversification for project-specific uncertainty are frequently inapplicable for many large scale engineering and infrastructure projects because these projects usually constitute a substantial proportion of the firm's portfolio and diversification is thus not possible. In many circumstances, the firms either cannot trade the project on the marketplace to share the risk with other market participants or they cannot diversify their project-specific uncertainties by holding a well diversified portfolio. In these cases, decision makers often behave in a risk-averse fashion towards these project-specific uncertainties. This is similar to the inability of executives to diversify firm-specific risk associated with executive option-based compensation where the options have not yet vested (Ingersoll, 2006). Lima and Suslick (2008) also show that the firms are risk-averse towards project-specific uncertainty when the magnitude of the project is large relative to the size of the firm. To achieve diversification, in practice, most large projects are owned by a pool of firms (Lima & Suslick, 2008). This phenomenon is documented by many researchers (e.g., Walls, 1995, Lerche & Mackay, 1996 and Lima & Suslick, 2008). These researchers demonstrate that firms may prefer to participate with less than 100% working interest in projects that are capital-intensive and/or have high cash flow uncertainty. On the other hand, Lessard and Miller (2001) classify the types of uncertainties faced in large engineering projects. They say that firms often intentionally embrace and retain some of the project-specific uncertainties after strategizing to reduce, shift, transform and diversify away identifiable uncertainties. This is because some comparative advantages or strategic advantages can be exploited in bearing these residual uncertainties. For example, a firm has more information or special knowledge about proprietary firm-specific uncertainties than its competitors; it could intentionally hold these uncertainties and usually requires a high rate of return to bear these uncertainties. Hence, the distinction between different types of project-specific uncertainty indeed bears significant real world implications.

Based on the work of Mattar and Cheah (2006), Kaufman and Mattar (2003), and Lessard and Miller (2001), the third type of uncertainty in this thesis, private uncertainty, is defined as a non-diversifiable (either non-diversifiable or intentionally retained) project-specific uncertainty with the following characteristics: (1) it constitutes a substantial proportion of the firm's portfolio, and it is either not tradable in the capital market or inhibited from trading by large agency costs; (2) it is intentionally retained by the firm (even though it may be diversified away) because of some comparative advantages or strategic reasons (Mattar & Cheah, 2006). In facing of private uncertainty, decision makers' subjective beliefs and preferences for bearing this uncertainty come into play. This uncertainty can be priced through, for example, a Utility-based Decision Analysis approach (see Smith & Nau, 1995 or Mattar & Cheah, 2006).

4.12. The Classification of Market Conditions for the Project

In this section, three types of market conditions (complete market, partially complete market and incomplete market) related to the project being valued are discussed. The classification of market conditions for a project is closely related to the classification of project uncertainty, and more importantly, to the choice of project valuation approaches. A summary appears in Figure 4.1 at the end of this chapter.

Firstly, a complete market is one where every project uncertainty can be perfectly hedged by trading securities. In other words, a project confronted with a complete capital market condition means there exists a 'twin security' (which could be a portfolio), whose risk characteristics and payoffs at each state of nature over the project lives can sufficiently replicate the dynamic spanning of the real underlying asset (e.g., dynamic completeness). However, for many projects in practice, this complete market assumption is obviously unrealistic, especially in the developing economies. The valuation of a project in a complete market can be conducted in a straightforward manner by using standard option pricing techniques via no arbitrage principles. In some cases, if the market trading opportunities are taken into account in a Decision Analysis approach, the asset values given by the Decision Analysis are the same as those given by the Real Option Analysis. However, the valuation procedure for Decision Analysis is typically more complex than it for Classic Real Option Analysis (see Smith & Nau, 1995 for more details).

Secondly, a project facing a partially complete market condition means its uncertainties can only be partially hedged by trading securities (Smith & Nau, 1995). In general, project uncertainties are divided into two parts: project-specific uncertainties and market uncertainties. By definition, the capital market is complete with respect to market uncertainties. However, without a market span for project-specific uncertainty, a perfectly replicating trading strategy cannot be constructed. Thus, a unique option pricing value for the project cannot be determined via pure replication. More specifically, when option pricing models are confronted with a partially complete market, an upper and lower bound on a real asset's value exist and these bounds are dependent upon how much of the uncertainty can be hedged by trading securities. The upper bound (the value of a super replicating portfolio) is the cheapest value of a trading portfolio that dominates (or at least equals) the real asset cash flow. The lower bound (the value of a sub replicating portfolio) is the most expensive value of a trading portfolio that is dominated (or at most equals) the real asset cash flow. The less the uncertainty hedged by the traded securities, the wider the bounds and vice verse. The usefulness of these bounds depends upon how much of the project uncertainty can be hedged by trading securities and whether the bound ranges are narrow enough to produce the values that justify the investment strategy. If the pure replicating strategy produces a very wide range, analysts may have to integrate some other valuation models (e.g., Decision Analysis) to generate an asset value within the bounds and to support decisions. These integrated models are introduced in the next section.

Thirdly, a capital market is incomplete for a project if there is no market related information available to describe the project uncertainties and to determine the value of the project. In other words, the project related uncertainties are out of the market span (i.e., they are project-specific uncertainties); hence, there is no objective market information available to parameterize the option pricing models. The valuation procedure may have to rely on subjective assumptions and estimates. In this case, a Decision Analysis approach is more appropriate than an option pricing approach. Pricing a project under incomplete market condition is well documented in the project valuation literatures (see Smith & Nau, 1995 and Smith & McCardle, 1998 for more details).

4.2. Various Real Option Approaches

To enhance value and improve decision making regarding an uncertain project, it is necessary to understand the basic underlying assumptions of the different valuation approaches and to use the correct approach for valuation and decision making. In chapter 2, we introduced two basic valuation approaches: Decision Analysis (DA) and Real Option Analysis (ROA) and we discussed their strengths and weaknesses. These two approaches seem, however, to be incomplete because they fail to deal with real world complexity. DA is a good choice when all project uncertainties are unrelated to the overall economy. Valuation and decision making can then be conducted using the decision marker's subjective beliefs and preferences. Conversely, Classic Real Option approach can be applied in the case where a tracking portfolio can be constructed from traded securities in the marketplace. Valuation and decision making is then wholly based on objective market information. There are many real world difficulties regarding valuation and decision making. These include the existence of both project-specific and market uncertainties, and difficulties in constructing a tracking portfolio for market-related uncertainty. In this section, we further examine three additional valuation approaches: the Marketed Asset Disclaimer (MAD), the Hybrid Real Option approach and the Integrated Real Option approach. These three approaches are extensions of standard DA and ROA to deal with more realistic and complex valuation situations.

4.21. Marketed Asset Disclaimer (MAD)

For many non-traded capital investments, searching for a twin security in the marketplace is impractical. Copeland and Antikarov (2001) develop the assumption that the present value of the cash flows of the project without flexibility (i.e., traditional NPV) is the best unbiased estimator of the market value of the project were it a traded asset. The traditional NPV then serves as the value of underlying asset for an option valuation model.

This is the marketed asset disclaimer. In a case where directly observable market information is absent, the justification of this statement is acceptable and logical: "*what is better correlated with the project than the project itself?*" (Copeland & Antikarov, 2001). The analysis of flexibility in the MAD approach is treated as an "add-on" to a traditional DCF valuation. That is, the value of the project with flexibility is the value of the project without flexibility plus the value of the embedded options. Hence, it requires an additivity argument. This additivity argument can be found in Williams (1938) or Schall (1972). In addition to the MAD assumption, Copeland and Antikarov made a second important assumption. That is, the evolution of the underlying asset value over time follows a random walk behaviour, specifically Geometric Brownian Motion (GBM). They built this argument on Samuelson's proof that "properly anticipated prices fluctuate randomly". This is a common statement regarding efficient markets. In an efficient market, current asset price already incorporates all relevant information available at this point in time, and that future changes will be the effect of random and thus unpredictable shocks, which are modelled as a random walk (Hull, 2003).[9]

Based on Copeland and Antikarov (2001) and Borison (2005), the typical process for evaluating real option problems through this approach involves the following steps:

1. Build a spreadsheet cash flow model of the underlying asset using both subjectively estimated and market observed inputs, and calculate its NPV (or present value of cash flows) using a CAPM-based beta.

2. Estimate the uncertainties associated with the inputs to the cash flow model, and conduct a Monte Carlo Simulation[10] to determine the volatility of the underlying asset.

[9] Samuelson's (1965) argument that properly anticipated prices fluctuate randomly is sometimes taken to mean that efficient markets imply a random walk. In fact, the argument follows only if investors are assumed risk neutral (see Crack & Ledoit, 2009). Lucas (1978), LeRoy (1973), and Lo and MacKinlay (1988) also show that rational prices need not follow random walks under the Efficient Market Hypothesis (EMH).

[10] By examining the sensitivity of project returns to simultaneous changes in several input parameters, Monte Carlo Simulation can be used to find the volatility of a project's returns. Then this volatility is applied to generate the evolution of the project's value over time (see Copeland & Antikarov, 2001). Note that the Monte Carlo Simulation described here is different than Monte Carlo Simulation used in Chapter 2 in the context of option pricing methodology.

3. Build a risk-neutral lattice/tree (usually a binomial approximation to a GBM), and estimate the project value and real option value by solving the lattice/tree backwards.

The MAD approach offers an alternative way to solve real option valuation problems based on the no arbitrage principle when the underlying asset is not traded in the capital market. Instead of searching for a twin security in the marketplace, it replaces the market value of the underlying asset with a traditional DCF valuation. This has been called a truly remarkable departure from reliance upon capital market data (Borison, 2005). The MAD approach can, thus, solve a much wider set of real problems than was previously possible, in a way that is fairly easy to understand from a decision marker's point of view. However, the major weakness with the MAD approach is that use of the MAD assumption as the basis for creating a complete market for an asset that is not traded could lead to significant errors (Brandão, *et al*., 2005). This is because the Law of One Price is only maintained internally between the asset and the option; they may both be mis-priced relative to the market (Borison, 2005). In addition, the optimal investment strategy is not directly observable, but only approximated. This is because, unlike options on stocks, the DCF value of the project is not readily observable; different analysts may get different values for the underlying asset and recommend different exercise strategies.

4.22. Hybrid and Integrated Real Option Approaches

In practice, applications of the standard arbitrage-enforced option pricing approaches are further complicated by the fact that, for many projects involving real assets, perfect hedging is not always possible. Project payoffs may only be partially hedged by traded securities (i.e., a partially complete market). This situation is discussed in the previous chapter for the valuation of petroleum investments. In this section, we introduce the Hybrid Real Option approach and the Integrated Real Option approach to deal with valuation under partially complete market conditions. These two approaches typically assume in advance that there are two types of uncertainty associated with most capital investments: market-priced uncertainty and project-specific uncertainty. They both suggest the use of real option approaches to deal with market-priced uncertainty and they both apply Decision Analysis approaches to extend option pricing approaches to problems with project-specific uncertainty. Their treatments of project-specific uncertainty differ however. The Hybrid Real Option approach treats project-specific uncertainty as a unique diversifiable uncertainty, while the Integrated Real Option approach captures the decision makers' risk attitudes when analyzing project-specific uncertainty (i.e., it treats it as a private uncertainty and uses a utility function).

The Hybrid Real Option approach was developed by Neely and de Neufville (2001) for valuing uncertain engineering projects with both market uncertainties and project-specific uncertainties. To implement this approach for valuing projects in partially complete markets, analysts must distinguish between market uncertainties and project-specific uncertainties. Market uncertainty is valued through the standard Real Option approach based on the no arbitrage principle. Project-specific uncertainty is analyzed through an Expected Value Decision Analysis approach using the risk free rate to discount. The rationality of using the risk free rate to discount project-specific uncertainty is that project-specific uncertainty is not correlated with the overall economy. This results in a CAPM beta of zero. Project-specific uncertainty is viewed as being almost completely eliminated in a well diversified portfolio, and therefore the investor should not require additional compensation for bearing this uncertainty (i.e., a zero risk premium).

The Integrated Real Option approach was developed by Nau and McCardle (1991) and Smith and Nau (1995) in the field of management science. This approach, like the Hybrid Real Option approach, uses market information and standard Real Option approaches to evaluate market uncertainty. However, project-specific uncertainties are treated as private uncertainty, and are priced through a Utility-based Decision Analysis approach. Hence, this approach captures the decision marker's beliefs and preferences towards the project-specific uncertainty.

Based on Smith and Nau (1995), Neely and de Neufville (2001), and Borison (2005), the typical process for evaluating real option problems by Hybrid and Integrated Real Option approaches involves the following steps:

1. Identify the project uncertainties, decompose these uncertainties into market uncertainty and project-specific uncertainty components, and build a decision tree structure representing the investment alternatives.

2. For market uncertainty, identify the value through objective market information, and assign risk neural probabilities.

3. For project-specific uncertainty, identify the value through subjective judgement, and assign actual probabilities. For the Hybrid Real Option approach, take the expected value of payoffs driven by the project-specific uncertainty and discount it at the risk-free rate. For the Integrated Real Option approach, apply a utility function and calculate the certainty equivalents to the payoffs driven by the project-specific uncertainty.

4. Propagate the decision tree backwards to determine the optimal strategy and its associated value.

The Hybrid Real Option approach and the Integrated Real Option approach are very useful for valuing projects which have both market and project-specific components. Many real-world capital investments exhibit this characteristic. The difference between these two approaches is related to the classification of project-specific uncertainty as unique or private. The classification criterion is dependent on several critical issues such as "whether diversification is possible or not" or "whether some sort of comparative advantages or strategic advantages can be exploited in bearing these project-specific uncertainties." (see Mattar & Cheah, 2006). The difficulty in applying these two approaches is that, for many real projects, there is no clear-cut characteristic to distinguish the market and project-specific uncertainties (Brandão, *et al*., 2005). Some project uncertainties are very vague and may fall somewhere in between the notions of market uncertainty and project-specific uncertainty. For example, in a hydro development project, if uncertainty about the generation output is due to uncertainty about the level of water flow, then it is a project-specific uncertainty. If, however, uncertainty about generation output is because of uncertainty over the market demand for power, then it is a market uncertainty. In addition, given the size and complexity of the decision tree structure, the computation cost may be very high for some projects. As the modeling variables and decision nodes increase, the decision tree structure rapidly approaches a "messy bush" (Lander & Pinches, 1998). This makes it analytically challenging, but worse it causes a loss of intuition and clarity in outlining the optimal strategy (Mittal, 2004).

4.3. Three Criteria of Valuation Taxonomy in This Study

Based on the discussion thus far, it is important to understand that different valuation approaches with different underlying assumptions should be applied in different application conditions. A one-size-fits-all analytic approach to value uncertain projects is simply inadequate. Since firms in different industries face investment problems that have varying levels and types of uncertainties, it is vitally important that strategic analysis be tailored to the level and type of project uncertainty (Courtney *et al.,* 1997). Consequently, the choice of valuation approaches for different situations is pivotal. Based on the literature we propose three criteria for making this choice: the nature of the capital market, the classification of project specific uncertainty, and the source of the data. The nature of the capital market indicates whether or not the project and associated real options can be valued based on objective market information. The classification of project-specific uncertainty is related to how different approaches treat non-market priced uncertainty. The source of data concerns how the valuation models acquire market data, especially when the project is not traded in the marketplace. We now discuss these three criteria in more detail.

4.31. The Nature of the Capital Market

The nature of the capital market determines whether the valuation process can be totally or partially based on objective market information, or whether we have to resort to subjective assumptions or estimates. As mentioned previously, there are three possible market conditions for the project being valued. Firstly, the capital market is complete for the project (i.e., pure market uncertainty). In this case, the information and data sets regarding valuation can be , at least in theory, obtained from the marketplace; therefore, analysts can directly apply standard option pricing techniques to value the project via the no arbitrage principle. Secondly, the capital market is partially complete for the project (i.e., there exist both market and project-specific uncertainties). In this case, judgmental estimates and assumptions, and market-related information must be integrated in order to allow a more realistic treatment of project uncertainty. For example, analysts can use an integrated valuation approach to determine the value of the project and real options by using option pricing techniques to value market uncertainty and judgmental approaches (e.g., Decision Analysis) to value project-specific uncertainty. Finally, the capital market is incomplete for the project (e.g., pure project-specific uncertainty). In this case, there is no market information available to determine the input parameters for valuation models; therefore, analysts may have to resort to subjective assumptions and estimates, and apply judgmental approaches (i.e., Decision Analysis) to value this project and its associated flexibility.

4.32. The Classification of Project-specific Uncertainty

In this thesis, we classify project-specific uncertainty as unique or private. In terms of unique uncertainty, the firm or the investor can effectively diversify these project-specific uncertainties. The decision marker is then effectively risk neutral toward these project-specific uncertainties. In practice, if a firm holds a well-diversified portfolio of similar investments or a public firm has well-diversified shareholders, then the project-specific uncertainty should be treated in a risk neutral manner by discounting its expected value at the risk free rate. [11] The former case means that the firm can achieve diversification by itself, while the latter case means that the shareholders can achieve diversification of their portfolios by investing in different projects or firms. In terms of private uncertainty, the firm or the investor either cannot diversify these project-specific uncertainties or intentionally retains them because of some comparative advantages or strategic reasons. Then the decision maker needs to consider these issues in pricing private uncertainty. In practice, if the project constitutes a significant part of the firm's portfolio, especially for a private firm, or if the firm can exploit some comparative advantages or strategic advantages in bearing these project-specific uncertainties, then these uncertainties should be viewed as private. [12] The pricing of private uncertainty should take into account the decision makers' risk attitudes towards these uncertainties via the use of utility assumptions (see Von Neumann & Morgenstern, 1953). The distinction between unique uncertainties and private uncertainties can help the decision maker to recognize the advantages and disadvantages of bearing these project-specific uncertainties, and to incorporate these issues into the valuation and decision making process. In a partially complete market, the Hybrid Real Option approach can be applied to value a project with market and unique uncertainties, and the Integrated Real Option approach can be applied to value a project with market and private uncertainties (See Figure 4.1).

4.33. The Source of the Data

The source of the data is used to determine the degree of reliability of the valuation

[11] A public firm is one that has issued securities through an initial public offering and is traded on at least one stock exchange or in the over the counter market. A public firm allows the market to determine the value of the entire firm through daily trading. Source: http://www.investopedia.com/ [accessed 25 June 2010].

[12] A private firm is one whose ownership is private. As a result, it does not need to meet the strict Securities and Exchange Commission filing requirements of public firms. Private firms may issue stock and have shareholders. However, their shares do not trade on public exchanges and are not issued through an initial public offering. In general, the shares of these businesses are less liquid and the values are difficult to determine. Source: http://www.investopedia.com/ [accessed 25 June 2010].

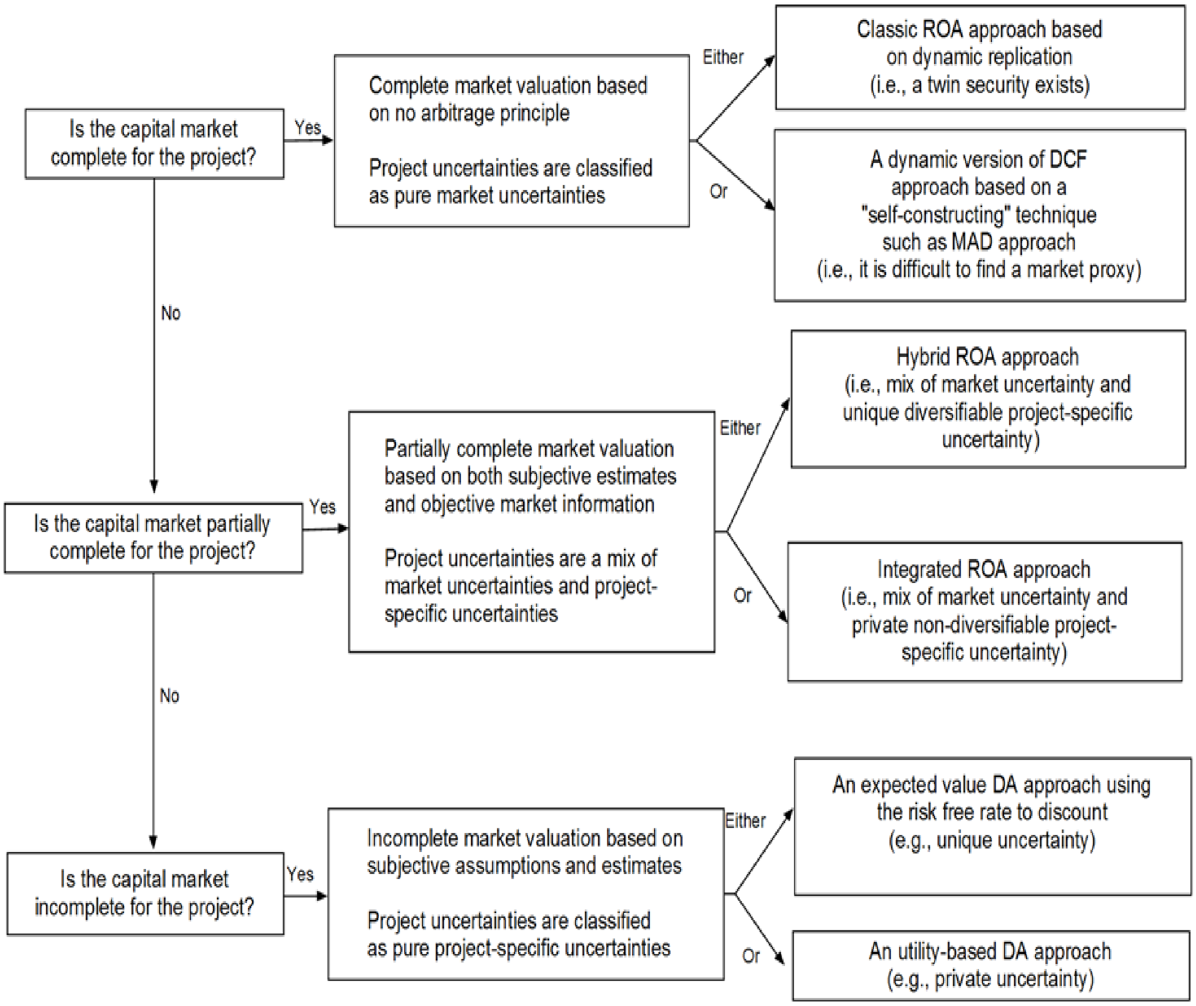
process. For the purpose of this thesis, "market data" refers to the historical/spot data, and "subjective data" refers to the subjective estimates provided by management or experts. Project-specific uncertainty is a function of factors endogenous to the project. So, there is usually no objective market information available to measure it. The valuation process therefore has to rely on subjective estimates. Market uncertainty is generally correlated with the general movements of the economy. So, there is some relevant market information available to measure it. Unfortunately, in many cases, because of the non-traded nature of the real project, there is frequently no directly observable market information available. Hence, it is often hard to parameterize option valuation models in a purely objective manner. The straightforward valuation is very limited in practice. Typically, for a non-traded real project, there are two ways to parameterize option valuation approaches to deal with market uncertainty. The first method used to parameterize the option valuation approaches is based on dynamic replication. If the project uncertainties are within the market span (e.g., pure market uncertainties), analysts may, at least in theory, construct a "twin security" which perfectly replicates the value of the project. Although this approach uses objective market data, the way it indentifies this market proxy in practice often involves some degree of subjectivity. For instance, some practitioners use a relevant asset such as oil futures, which is traded in commodities' markets to serve as a "twin security" for a producing oilfield. However, this is problematic because the value or the volatility of an oilfield is not necessarily replicated by the value or the volatility of the traded oil futures. Hence, we call this approach an "Objective-Data-Subjective-Identification" (ODSI) approach. The second method used to parameterize the option valuation approaches is based on a "self-constructing" technique, usually a traditional DCF valuation. For example, if the value of the project cannot be directly found in the marketplace, an analyst may calculate the value of the project based on market information and subjective estimates via traditional DCF models. Although this approach does not use pure objective market data, the way it calculates the value is very relevant to the feature of the project. We call this approach the "Subjective-Data-Relevant-Construction" (SDRC) approach. In practice, the ODSI approach can be applied when some traded securities do a reasonable job of replicating, while the SDRC approach can be applied when it is difficult to find a market proxy. In principle, these two approaches are based on the same rationale: If the value of a non-traded asset can be perfectly replicated through a corresponding traded asset, then the same value also can be deduced in DCF models by employing an appropriate discount rate which is the equilibrium expected rate of return on securities equivalent in risk to the project being valued (Myers, 1984).

4.4. Summary

In sum, no single valuation model is equipped to deal with all real-life situations, especially in an increasingly uncertain and rapidly evolving environment (Piesse *et al.*, 2002). Therefore, a firm should select the most appropriate valuation model depending on the nature of the capital market, the types of uncertainties, and the source of the data that are encountered in a given project. Figure 4.1 summarizes the proposition about the choice of valuation models for an uncertain project with embedded real options. We shall use this valuation taxonomy to analyze an offshore lease project in the next chapter.

FIGURE 4.1

The Choice of Valuation Models for an Uncertain Project with Embedded Real Options



ROA = Real Option Analysis, DCF = Discounted Cash Flow, MAD = Marketed Asset Disclaimer, DA = Decision Analysis

Chapter 5: Real Option Valuation – An Offshore Petroleum Lease Example

In this chapter, we use an offshore petroleum lease project to illustrate the correct application conditions for the selected real option approaches. The empirical example is constructed based on the pioneering papers of Paddock *et al.* (1988) and Smit (1997). The development of an offshore petroleum lease consists of sequential investments in exploration, development and extraction (production) of oil. During the stages of development, managers are often able to get a better sense about revenues or costs regarding the investment, and so review and change their decisions based on new information. Traditional DCF techniques are unable to capture all important aspects of the investment and often cannot generate a proper value of the investment. They fall short in reflecting the varying uncertainty of future cash flow and capturing managerial flexibility. As a result, application of the standard DCF to such investment decisions would not maximize the value of a firm. For example, the firm would only choose to continue with the investment if the current expectations for future revenue are such that the further investment remains profitable. As such, an offshore petroleum lease project is often modeled as a sequential compound real option problem. That is, ROA can explicitly incorporate the various sources of managerial flexibility that are attached to the investment opportunity and that allow the firm to commit itself sequentially to further investment decisions.

From a methodological standpoint, a real option approach offers a rich understanding of the dynamic nature of investment and its relationship with the capital market. In terms of real options, analysts seek objective market information to determine project values, real option values and optimal strategies. One of the major theory-practice gaps of the real option approach is, however, that the process of identifying objective market information can be difficult to execute in many real-world situations. This is particularly true when the uncertainties are not well-defined by the capital market, and hence are difficult to characterize, or the uncertainties are out of the market scope, and hence are unable to be characterized. Thus, there are unresolved methodological gaps that constrain the application of real options to major investment decisions (Mahnovski, 2006) and a Classic Real Option approach can rarely be used as the sole basis for project valuation. The practical solutions offered in this thesis are to relax some severe assumptions regarding perfect replication by allowing for a "self-constructing" technique if the market proxy is difficult to determine precisely; and/or the combination of some supplemental methods (e.g., Decision Analysis) to deal with un-tracked uncertainty.

The development of an oil reserve requires substantial investments which are subject to at least two important sources of uncertainties: market uncertainty (mainly oil prices), and geological uncertainty (the properties of the reserve). Uncertainties and managerial flexibility (options) are critical in order to maximize the value of the investment opportunity. Hence, an offshore petroleum lease project needs to be valued by a dynamic option pricing framework in a partially complete market condition.[13] For market uncertainty, the valuation process relies either upon finding information about the traded asset (e.g., oil), or by assuming that the present value of the cash flows of the project without flexibility is the market price, as if the project were traded (i.e., MAD assumption). For geological uncertainty, the valuation process has to rely on subjective assumptions and estimates. Hence, for an offshore petroleum lease project, the valuation process typically requires different kinds of real option valuation approaches in order to properly capture market uncertainty, geological uncertainty, and different types of flexibility. This chapter is organized as follows: Section 5.1 discusses the various stages of the offshore petroleum development. Section 5.2 models the critical uncertainties which the project confronts. Sections 5.3 outlines the valuation procedure for the example. Section 5.4 and section 5.5 perform detailed valuation to model a sequential staged-investment real option problem using our selected real option valuation approaches. Section 5.6 summaries the results and findings.

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[13] An offshore petroleum lease refers to the exploration and exploitation of an oilfield under leasehold offshore field.

5.1. Stages of an Offshore Petroleum Development

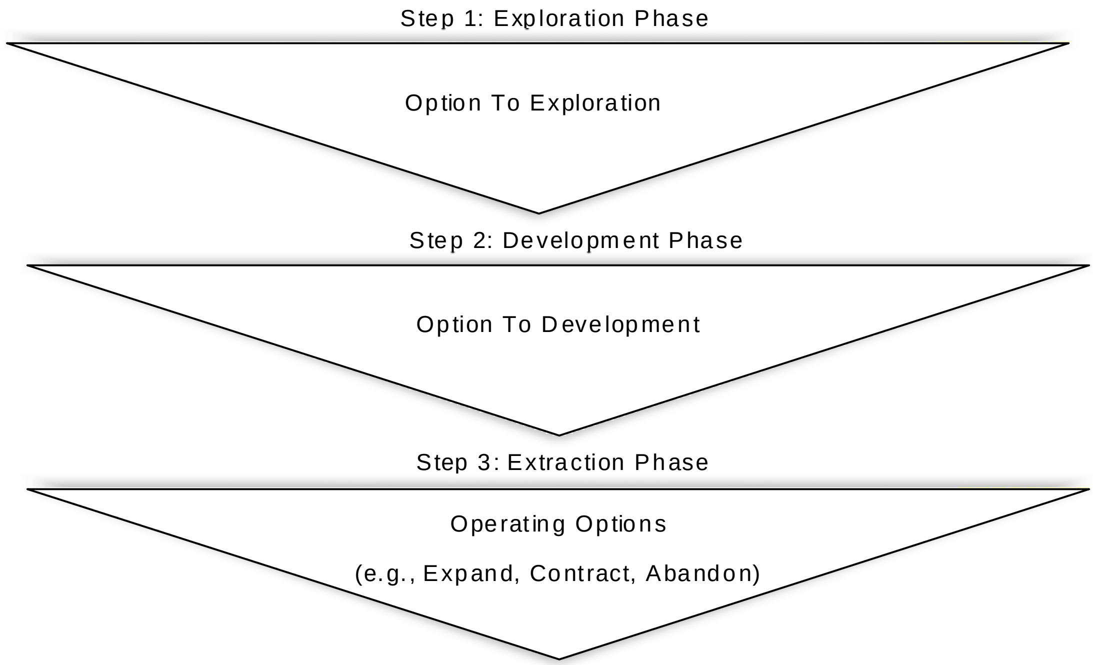
Oil production is a multi-stage process involving sequential investment decisions. According to Paddock *et al.* (1988), a typical offshore petroleum lease has three sequential development stages: the exploration, development and extraction (production) of oil. The stage-investment decisions are determined by joint geological and market uncertainty. Option-based valuation approaches are appealing because each stage typically involves different kinds of market conditions, project uncertainties and managerial flexibilities. An analysis of flexibility must therefore account for these factors before making irreversible investments. There are three stages as follows.

Firstly, the exploration stage involves seismic and drilling activities to obtain geological information on the presence of hydrocarbons, the size of the reserves, and the cost of extracting oil. When the firm acquires an unexplored reserve, it has the option to decide whether and when to invest in the exploratory drilling (e.g., the option to start test drilling and the option to invest in appraisal wells) to receive an explored but undeveloped reserve. This is analogous to a financial call option, where the stockholder has the right to pay the exercise price and receive the stock. Since the decision to explore a reserve entails an irreversible investment, the firm should accurately analyze the project's future cash flow expectations, which in turn depend on both geological and market uncertainty.

Secondly, the development stage involves development activities (e.g., construct platforms) to convert an undeveloped reserve into a developed reserve. This stage only occurs if the quantity of hydrocarbons, the magnitude of development costs and the current expectations for future revenue are favorable. As the development stage requires the largest capital expenditures, and they are not easily recovered once investment is undertaken, this is where option value is most important (Smit, 1997). Dixit and Pindyck (1994) argue that the option to delay the development stage is the most valuable option in the oil industry. For example, given that a firm inherits some flexibility in deciding whether and when it is optimal to develop, such a project is always worth more than a project without this flexibility.

Finally, the extraction (production) stage involves using the installed capacity to extract oil over some period of years. At this stage, most geological and technical uncertainties have already been resolved through exploration and development. As such, the project uncertainty is now dominated by exogenous market uncertainty (e.g., oil price uncertainty). As the market uncertainty evolves over the life of the project, the firm may have the operating options to scale (e.g., expand or contract) or abandon the producing field. For instance, the firm may alter the production rate in response to oil price changes. In addition, it may be possible to expand or contract the capacity of the facility. More extreme options may involve shutting down reserves temporarily or even abandoning the producing field early. Figure 5.1 gives an overview of the staged development processes.

FIGURE 5.1
Staged Investment Processes for an Offshore Petroleum Lease Project



5.2. Modeling of Uncertainty

Performing a real option valuation requires that we make assumptions about which variables affect the value of the project and its associated real options (Grafström & Lundquist, 2002). In the real option literature, the evolution of these variables over time is typically modeled as some sort of stochastic process. Option-based models may be highly sensitive to the way the behavior of the critical variables is modeled (Triantis, 2005). In our case, three critical variables are considered: the oil price, the variable operating costs and the reservoir volume. They are specified as follows:

Oil Price. Oil price uncertainty is clearly a market-priced uncertainty, which evolves and changes over time. It has long been modeled using no-arbitrage finance models in both continuous-time and discrete-time settings. The vast majority of real option applications model the commodity price stochastic process as a Geometric Brownian Motion (GBM) [See, for example, Paddock *et al.* (1988) and Smit (1997)]. This assumption implies that future commodity price is lognormal distributed. Another way of modeling the evolution of commodity price is to assume that it follows an Ornstein-Uhlenbeck (OU) mean-reverting process [See, for example, Laughton & Jacoby (1993) and Smith & McCardle (1999)]. The OU process describes a commodity price that has a tendency to revert back to some long-run average level over time. The commodity price could also be modeled by a jump process, given that the commodity has a tendency to be exposed to price shocks (Grafström & Lundquist, 2002). In addition, Arnold, Crack and Schwartz (2007) show how to model a commodity price using an implied binomial tree that allows for general distributions. More advanced modeling practice assumes that oil price uncertainty is driven by several sources and applies multi-factor models to capture its resolution over time. For example, Gibson and Schwartz (1990) develop a two-factor model where the spot prices follow a GBM stochastic process and the instantaneous convenience yields are mean reverting. Detailed mechanics of these stochastic processes can be found in Dixit and Pindyck (1994), Hull (1999), McDonald (2002), Gibson and Schwartz (1990), and Wilmott (1998).

In this study, we are interested in keeping the option valuation process simple, thus we model the spot prices as a one-factor GBM stochastic process (see equation 5.1).[14] We take, however, a discrete time approximation using a multiplicative binomial process developed by Cox *et al*. (1979) (see equation 5.3, equation 5.4 and figure 5.2). We choose this because of its convenient mathematical properties, rather than two-factor (Gibson & Schwartz**,** 1990) and three-factor (Schwartz, 1997) alternatives. In this setting, the dynamic movements of the future oil prices are largely affected by time and volatility. We assume that volatility is constant over the modeling period (see table 5.1). In addition, the existence of well-functioning markets that include spot, futures, and a host of derivative instruments allows the modeling parameters to be proxied or reasonably constructed based on objective market information.

$$dS=(r-\delta)Sdt+\sigma Sdz_t \qquad \text{(Equation 5.1)}$$

S = Spot Price, r = Risk Free Rate, δ = Convenience Yield, σ = Volatility of Oil Price, dt = Infinitesial Time Interval, dz = Wiener Process

Spot price *(S)* can be directly observed from the financial market. In our case, the spot price of oil is assumed to be $28 per barrel. The risk free rate *(r)* is assumed to be 5% per annum and constant over the life of the project. Convenience yield *(δ)* measures the benefits and costs of owning a physical commodity instead of holding a futures contract. The short-term convenience yield can be estimated using market data by inverting the well-known arbitrage relationship between the spot price and the short-term traded futures (see equation 5.2). But the longer-term convenience yield is hard to estimate as it is not deterministic and it may change from period to period along with the changes in the relationship of demand and supply of oil (e.g., convenience yields are often modeled as a mean reverting process). For simplicity, we assume a constant 5.5% convenience yield per annum. The drift rate *(r-δ)* is the expected return on the spot price *(S)*.

$$F_T = S_t e^{(r-\delta)(T-t)} \qquad \text{(Equation 5.2)}$$

F_T = oil future, S_t = spot price, r = risk free rate, δ = convenience yield, T-t = time to maturity of the

[14] In the real world, an analyst needs to use market information to estimate the process for oil price evolution.

futures contract.

Another important parameter to model the evolution of oil prices in the GBM setting is the volatility of the oil price. One problem encountered when estimating the volatility is that there are no long-term financial instruments (such as long-term oil futures or oil options) available, which match the time horizons of the project, and allow us calculate the implied volatility.[15] Alternatively, we can use the historical spot oil prices to estimate the volatility. Based on the discussion of Smit (1997), one way to obtain the volatility of the oil price is to calculate the standard deviation from the time series of spot-market oil prices and use this historical standard deviation as an estimate for the volatility of oil prices. The actual volatility may change over time and the historical data may or may not be a good predictor of the future (see Sharma, 1998 and Kroner *et al.*, 1995 about the comparisons of historical volatility, implied volatility and realized volatility for commodity price). For the purpose of this thesis, we assume a constant volatility (σ) of 8% per annum for future oil prices over the life of the project.

To mimic a GBM stochastic process in a discrete-time model, we assume that over each time step Δt the future oil price can move up or down by multiplicative factors u or d respectively. These factors u and d are determined by the estimate of the oil price's volatility (equation 5.3). The risk neutral probability, p, is based on a dynamic replication strategy using a traded oil instrument and a risk-free bond (equation 5.4).

$$u = e^{\sigma\sqrt{\Delta t}},\ d = 1/u \qquad \text{(Equation 5.3)}$$

$$p = (e^{(r-\delta)\Delta t} - d) / (u-d) \qquad \text{(Equation 5.4)}$$

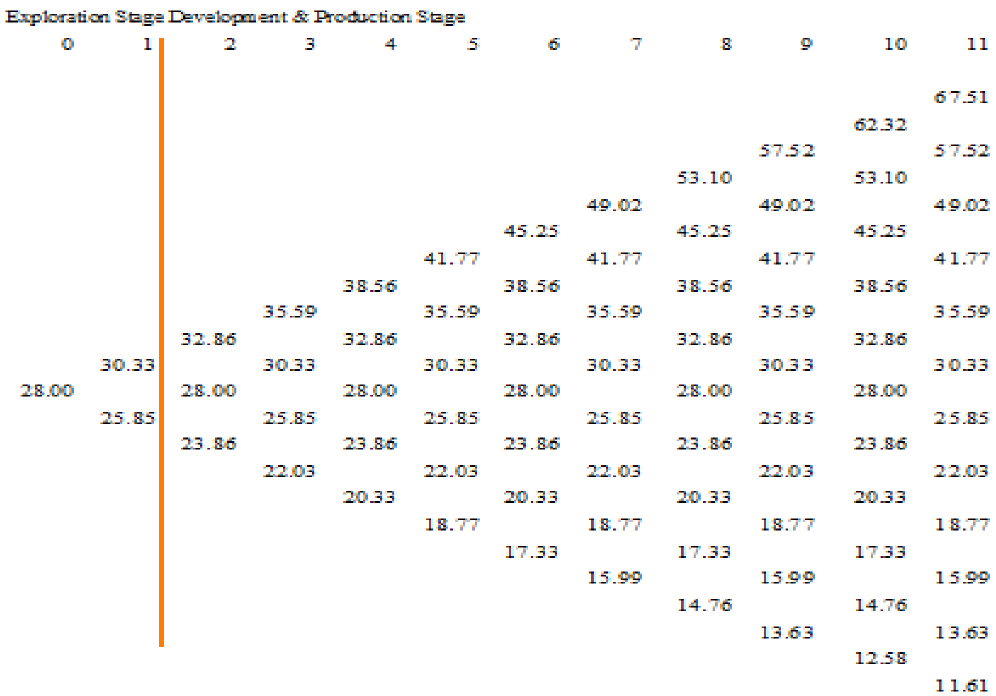
The input parameters and calculated parameters to deduce the evolution of future oil prices are summarized in table 5.1. The evolution of the future oil prices is reported in figure 5.2.

[15] The time to maturities of the light sweet crude oil futures traded on the Chicago Mercantile Exchange (CME) are up to nine-year. Available: http://www.cmegroup.com/trading/energy/crude-oil/light-sweet-crude_quotes_timeSales_globex_futures.html [accessed 23 June 2010]

TABLE 5.1
Parameters for Oil Price Evolution

Input Parameters	
Risk Free Rate (per annum)	5%
Convenience Yield (per annum)	5.50%
Oil Price Volatility (Standard Deviation) (per annum)	8%
Current Oil Price ($)	28
Project Operating Life (yrs)	10
Exploration Period (yrs)	1
Calculated Parameters	
Number of Time Steps	11
Length of One Period *(Δt)*	1
Upward Price Multiplicative Factor *(u)*	1.08
Downward Price Multiplicative Factor *(d)*	0.92
Change in the Expected Price in One Time Period	-0.50%
Risk Neutral Probability of Upward Change *(p)*	0.45
Risk Neutral Probability of Downward Change *(1-p)*	0.55

FIGURE 5.2
Evolution of Future Oil Price



Variable operating costs. Due to the high uncertainty about the operating cost structure of the project (e.g., unexpected cost and labour cost etc), we assume that the project has an additional source of market uncertainty: variable operating costs. However, unlike the evolution of future oil prices, the uncertainty about the variable operating costs does not have rich and observable market information with which to measure it. Thus, we project this uncertainty and its evolution over time based on the management's subjective opinion. We assume it follows a GBM stochastic diffusion process with a mean annual rate of increase of 1% and an annual volatility of 3% (see Brandão *et al.* (2005) and Borison, (2005) who make similar assumptions). The variable operating cost is assumed to be $20 per barrel at the first year of operating.

Reservoir volume. Reservoir volume uncertainty is unrelated to the overall economy, and is therefore project specific. Reservoir volume uncertainty is high during the initial exploration phase. Once exploration investment is undertaken, uncertainty on the reservoir volume decreases and the market uncertainties such as oil prices become comparatively more important in the later phases. In our case, we assume that the reservoir volume has an expected value of 90 million barrels, with probability distribution as shown in table 5.2. This distribution is based on the prior geological and geophysical data, which is before any exploration is carried out.

TABLE 5.2
A Prior Probability Distribution of Reservoir Size

Volume (Million Barrels)	50	70	90	150
Probability	25%	25%	25%	25%

5.3. Real Option Valuation Procedure

The valuations and decisions relating to whether, when and how the investment should actually proceed depend on a series of development milestones being successfully achieved. At each stage, the uncertainties surrounding the project resolve, evolve and change over time. For example, the initial decision to invest in exploration is reached by analyzing all the future consequences taking into account geological uncertainty and market uncertainty over the life of the project. If the exploration phase proves economically exploitable reserves, the decision to invest in development can be based on the geological information discovered during the exploration phase, the capital expenditures required for development and the uncertainty about future market conditions. It indicates that an offshore petroleum lease project can be modeled as a sequential compound option; each stage provides an option to complete the next stage (Paddock *et al.*, 1988). There are many important previous studies which demonstrate how the theory and methods of real options are applied in an oil project. For example, Paddock *et al*. (1988) evaluates an offshore oil reserves using standard option-pricing technique. Smith and McCardle (1998, 1999) illustrate how to apply an integrated option pricing approach in the context of oil projects and give a discussion of lessons learned in the application.

In order to perform real option valuation and quantitatively analyze the value of the real option embedded in the offshore petroleum lease project, we apply a backward induction process. That is, the analytical convention is to start valuing the producing fields at the extraction (production) stage and the undeveloped reserves at the development stage with each potential size of reserves, and then working backward in time to value the unexplored reserve at the exploration phase. For the purpose of this thesis, we make some assumptions to simplify the valuation process. The structure of the valuation process proposed in this thesis is, however, able to deal with more complex situations. To conduct the valuation, like many real world oilfield applications, we separate the staged investment into two market scenarios. At the extraction (production) and development stages, the geological uncertainty regarding the quantity of the reserve is largely resolved by exploratory drilling. So, we assume that the project uncertainty is dominated by market uncertainty. This is called the "market uncertainty dominated scenario". At the initial exploration stage, the option to invest in exploration highly exposes us to market uncertainty but also geological uncertainty. This is called the "mix-uncertainty scenario". At section 5.4, we deduce the market value of a producing field in two ways: a dynamic replication strategy and a DCF calculation based on the MAD assumption, and we apply a standard option valuation tool to value an operating abandonment option at the extraction (production) stage and a deferment option at the development stage. We shall examine and compare the application conditions for these two methods under a complete market scenario. Then, for the valuation of an unexplored reserve, as both market and geological uncertainties are important at this stage, to avoid errors in valuation and decision-making, valuation approaches which account for both types of uncertainty are employed. In section 5.5, we apply both Hybrid and Integrated Real Option approaches to value an unexplored reserve. The different treatment of project-specific uncertainty and how it could affect the value of exploration will also be investigated. We now outline these different real option approaches to assess the options for this offshore petroleum lease project.

5.4. Valuation of Undeveloped Oilfields under a Complete Market Scenario

According to the discussion of the previous section, in order to value an unexplored reserve we start by valuing a set of undeveloped oilfields. Then, we value the option to invest in exploration based on the valuation results and the probability distribution of potential reserves based on the prior geological and geophysical data. In this section, we apply two common real option valuation approaches to value undeveloped oilfields. One implements the Classic Real Option approach through a dynamic replication strategy, and the other uses a DCF calculation with "add-on" flexibility based on the MAD assumption. We shall examine and compare the application conditions for these two methods under a complete market scenario.

5.41. Classic Real Option Approach through Replication

In this experiment we apply the Classic Real Option approach based on dynamic replication to value undeveloped oilfields contingent on oil price. The basic idea behind this approach is to develop the market value of the project and its associated value of flexibilities through the value of traded securities based on the no arbitrage principle. According to the valuation taxonomy in chapter 4, in order to determine the market value of the asset through replication, it has to meet two basic requirements: 1) The capital market is complete with respect to the project uncertainties. 2) A "twin-security" can be constructed and do a reasonable job of replicating. In the literature, a common replication strategy is to assume that the values of the project and the real options are driven solely by the fluctuation of oil price (see, for example, Kemna, 1993 and Smit, 1997). Other variables such as development costs, operating costs and the production rate are considered as deterministic. In this way, the uncertainty of the operating cash flow of the project is determined only by the movement of the oil prices. The modeling practice regarding the movement of oil prices can be based on the publicly traded instruments that include spot oil, oil futures, and a host of derivatives. Hence, in this experiment, the option to develop an oilfield can be well-tracked by a portfolio of traded oil securities.

5.411. Estimating the Market Value of the Producing Field

In this case, the value of the underlying asset (the value of the producing field) and its resolution over time can be determined based on operating cash flows, which in turn relate to the fluctuation of oil price. It is clear that the oil price dynamics would result in a closely related, dynamic movement of the operating cash flows. For the future oil price in each state, the operating cash flow equals the oil price times the production rate, minus the operating cost and the fixed cost (For simplicity, we ignore some real world costs such as royalties and taxes). In this example, the production rate is assumed to be 10% of the size of the proven reserve per annum. The operating variable costs are initially assumed to be $20 per barrel in the operating stage with an annual increase of 1%. The fixed costs are $10 million each year over the 10-year operating life. Then, we can easily determine the market value of the producing field in each state of operating cash flow. The procedure to determine the market value of the producing field can start at the terminal nodes of the cash flow tree and work backward to the beginning of the production phase. At the terminal nodes, the state project value equals the corresponding state operating cash flow. For the early nodes, equation 5.5 is applied to sum the state operating cash flow when stepping backward in time. For example, the project value at time t is simply the present value of the remaining project cash flows. In this way, the value of the producing field is replicated by the tracking portfolios comprised of oil securities.

$$PV_t = CF_t + (pPV^{+}_{t+1} + (1\text{-}p)PV^{-}_{t+1})/e^{r\Delta t} \qquad \text{(Equation 5.5)}$$

Where PV = Project Value, p = risk neutral probability, CF = Operating Cash Flow and the "+" and "-" superscripts refer to value in up and down states respectively at the next node of the tree

5.412. Real Option Valuation

After determining the value of the underlying asset and its resolution over time, we now can solve for a set of real options. At the extraction (production) stage, we assume that the firm holds an abandonment option with the rebate value of $20 million from operating year 6 to year 10. We use a recursive valuation procedure to determine the value of the producing field with the abandonment option through risk neutral valuation. Equation 5.6 is used to determine the value at the terminal nodes. Equation 5.7 is used to determine the value at the intermediate nodes when stepping backward in time. FPV_0 is the current value of the producing field with the abandonment option.

$$FPV_{t+1} = MAX\,(AV, PV_{t+1}) \qquad \text{(Equation 5.6)}$$

$$FPV_t = MAX\,(AV, (pFPV^{+}_{t+1} + (1\text{-}p)FPV^{-}_{t+1})/e^{r\Delta t} + CF_t) \qquad \text{(Equation 5.7)}$$

Where FPV = Project Value with flexibility, PV = Project Value, AV = Abandonment Value, p = risk neutral probability, CF = Cash Flow

Now we move to the early development phase. To commence the production, the firm has to decide whether and when to make capital investment in infrastructure (e.g., a drilling platform). There is, of course, no obligation to start the development of the oilfield immediately, but rather a right which will only be excised when the expectations for future revenue are most favorable (Kemna, 1993). The time to maturity of the deferment option is not always so clear-cut for most real applications. In our case, we assume that the period that the firm holds the right to defer the investment is one year. This is similar to a call option where the development cost ($300 Million) is equivalent to the exercise price. The total operating period for this project is 10 years, therefore, if the management decides to defer for the one-year period, then they have to forgo one year net operating cash inflows (9-year operating life). This is one major disadvantage of deferment in our case (i.e., no competitive disadvantage). However, in the light of high uncertainty of future oil price and huge irreversibility outlay, this wait-and-see approach clearly has value. For example, if the value of the deferment option is worth more the costs, management can extend the investment phase and wait for higher oil prices. In other words, if the firm invests today, it kills the opportunity of investing in the future, when the market conditions may be more favorable. To value this deferment option, we use the value of a producing field including the option to abandon as the value of the underlying asset to calculate the early deferment option. At year 1, we have the option to invest or abandon at each state (Equation 5.8). At year 0, we have the option to invest now, abandon, or wait-to-see (Equation 5.9). NPV_0 is the current value of the oilfield with the compound option.

$$NPV_1 = MAX\ (FPV_1\text{-}I,\ 0) \qquad \text{(Equation 5.8)}$$

$$NPV_0 = MAX(FPV_0\text{-}I,\ 0,\ (pNPV^{+}_{1} + (1\text{-}p)NPV^{-}_{1}) / e^{r\Delta t}) \qquad \text{(Equation 5.9)}$$

Where FPV = Project Value with The Abandonment Option, p = Risk Neutral Probability, I=Development Cost, NPV = Project Value with The Compound Option

It should be noticed that the value of this compound option is not simply the value of the abandonment option plus the value of the deferment option. This is because the multiple options embedded in a project might interact; hence value additivity may break down (Trigeorgis, 1993). In our case, the presence of a later abandonment option enhances the value of the underling asset for a prior deferment option, while exercising an earlier deferment option may alter the scale of the later option.

5.413. Valuation Results

Table 5.3 illustrates the valuation results for proven reserves of 50 million barrels, 70 million barrels, 90 million barrels and 150 million barrels. The valuation details are presented in Appendix A. The values of an undeveloped oilfield without flexibility for small quantity of proven reserves present negative NPVs, this is because the firm is locked into proceeding even in bad (e.g., low oil price) states of the world. On the other hand, the results derived from the option valuation model indicate that the valuation incorporating managerial flexibilities can significantly improve the value of the project. In particular, the options to develop or abandon are more important for the field with a small quantity of proven reserves. This is because the abandonment option and the deferment option significantly cut the possible downside loss, which is very critical for a small quantity of reserves.

TABLE 5.3
Real Option Valuation at Different Quantities of Proven Reserves at the Initial Development Stage

Volume (Million Barrels)	50	70	90	150
The value of an undeveloped oilfield without flexibility (Million $)	-134.08	-37.01	60.06	351.26
The value of an undeveloped oilfield with Flexibility (Million $)	5.71	41.50	115.39	361.27
Option Value (Million $)	139.79	78.51	55.33	10.01

5.42. MAD Approach through a "Self-construction" Technique

In the previous section, we used the traded oil securities to serve as a "twin security" for a producing oilfield. The empirical question arising from the previous example is: does the modeled oil price fluctuation really do a reasonable job of replication for a producing oilfield? The answer should vary from project to project. For example, oilfields operated in developing countries may suffer some additional market uncertainties relating to risks such as political change, uncertain inflation, and continually changeable taxes and royalties. This could potentially result in the stochastic fluctuation of the operating costs over time. In general, the real underlying variable is frequently exposed to multiple sources of uncertainty. In this section, we illustrate the MAD approach to value an undeveloped oil reserve using an expanded version of the previous example. In addition to being uncertain about oil prices, we assume that the project has an additional source of market uncertainty: variable operating costs. While there are well-developed financial markets for managing oil price uncertainty, there is very limited market opportunity for hedging operating cost uncertainty. This adds significant difficulties to the process of identifying a replicating portfolio. To address this we parameterize the option valuation approaches based on a "self-constructing" technique through a traditional DCF valuation with simulation under the assumption of MAD.

5.421. The Valuation Procedure of the MAD Approach

Roughly speaking, the MAD real option valuation approach relies on the *marketed asset disclaimer* (MAD) assumption. This assumes that the value of the project without flexibility is the best unbiased estimator of the market value of the project. This value is typically obtained through a traditional DCF calculation and serves as the value of the underlying asset for an option valuation model. Then the value of the underlying asset is assumed to evolve over time based on the characters of the uncertain factors, and is often modeled as some sort of stochastic process in a discrete-time setting. Typically, the MAD approach uses the following steps to identify the value of the real options (Copeland & Antikarov, 2001):

1. Estimate the value and volatility of the underlying asset.

2. Build an event tree to model the underlying asset's value.

3. Conduct the Real Option Analysis.

Step one: Estimation of the Value and Volatility of the Underlying Asset

Value of Underlying Asset. In our example, the value of the underlying asset is the present value of a producing oilfield without flexibility. The present value of a producing oilfield is derived from a standard discounted cash flow model that incorporates annual production level, the expected future oil price, and the ongoing operating costs over the assumed economic life of the project. We use the firm's weighted average cost of capital (WACC) as the discount rate for the project, which is assumed to be 12%. The calculated NPV then serves as the market value of the underlying asset for the option valuation model. Nonetheless it is important to bear in mind that this is a very significant assumption that may alter the precision of the results.

Leakage in Underlying Value. The leakage in the underlying value represents a series of payouts (like dividend for stock options) or competitive losses from the underlying assets. It could be the expected net cash flows accruing from a project, the opportunity cost of delaying, or the loss of market share to competitors. This is an important factor in the case of real options involving the delay, abandonment, expansion, contraction, or extension of a project. However, the accurate modelling of project payouts or competitive losses is very difficult as the timing and amount may be dependent on exogenous influences (Miller & Park, 2002). In this example, we use a constant 5.5% payout rate (equal to the convenience yield) to represent the estimated cash flow of the project. This simplified treatment can significantly reduce the modelling complexity and make the valuation procedure fit standard option valuation approaches. Kemna (1993) and Paddock *et al.* (1988) also apply a constant payout rate for an offshore petroleum lease project.

Volatility. Another important input parameter required to perform real option valuation is the volatility of the return to the underlying asset. According to Copeland and Antikarov (2001), the underlying asset volatility is the standard deviation of the rate of return on the underlying asset (in GBM setting). This standard deviation of the returns, or volatility of the underlying asset, can be estimated through a Monte Carlo Simulation of the underlying asset returns. To conduct a simulation, key project uncertainties (oil price and variable operating costs) are entered as simulation input variables in the project cash flow *pro forma* worksheet. The statistical properties of these input variables such as mean values, standard deviations and probability distributions need to be assigned before running a simulation. In our case, these two variables are assumed to follow lognormal distributions and the standard deviations increase (confidence interval widen as $\delta\sqrt{T}$) over time.[16] In addition, these two uncertainties are assumed to be

[16] The standard deviation (δ) at time T is $\delta\sqrt{T}$.

independent.[17] The next step is to define output forecasts in the model. In our case, the output variable Z (equation 5.10) is the percentage change in the value of the project from time 0 to time 1. Then the model is simulated many times (1000 trials in this case).

$$Z = ln(V_1/V_0) \quad \text{(Equation 5.10)}$$

V_1= the underlying asset value at time 1, V_0 = the underlying asset value at time 0

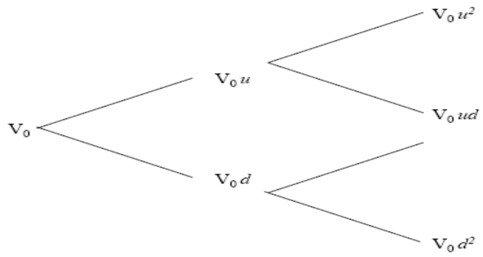
The estimate of the standard deviation of Z, denoted as s, is obtained from the simulation results. The underlying asset volatility δ *is* then defined as the annualized percentage standard deviation of the returns and is estimated from the relationship $\delta=s/\sqrt{\Delta T}$, where Δt is the length of the period in years used in the cash flow *pro forma* worksheet (Brandão *et al.*, 2005). In our case, the time period between V_1 and V_0 is one year, so $\delta = s$. The simulation results are presented in Appendix B.

Step two: Build an Event Tree to Model the Underlying Asset's Value

The second step is to build an event tree to model the evolution of the value of underlying asset over time. As mentioned in chapter 4, the application of the MAD approach implies that the value of the underlying asset follows a random walk. In our case, we apply a Geometric Brownian Motion (GBM) stochastic process to model the evolution of the present value of the producing oilfield. Quirk and Ruthrauff (2006) show that the value of oilfield reserves frequently follow a lognormal distribution. To keep it simple, we assume that the volatility of the underlying asset and project payout derived in the pervious section remain constant over the modeling period. This assumption implies that the values of the risk neutral probabilities are constant throughout the lattice. Figure 5.3 shows a binomial model for the evolution of the value of the underlying asset with a single constant volatility measure (i.e., a recombining tree structure).

[17] In general, positive correlation increases volatility and negative correlation decreases volatility. In reality, this assumption is incorrect, since most variables are linked to oil price to some degree.

FIGURE 5.3
The Evolution of the Value of the Underlying Asset



V = The Value of Underlying Asset, u = Upward Multiplicative Factor, d = Downward Multiplicative Factor

Step Three: Conduct the Real Option Analysis

The event tree in the previous step does not have any decisions built into it. The third step in the process of estimating the real option value is putting the decisions that management may make into the nodes of the event tree to turn it into a decision tree (Copeland & Antikarov, 2001). From a valuation standpoint, once the project without options is modeled as a stochastic process, options can be added to the decision tree. This is called an "add-on" approach. To calculate the option value, the risk neutral valuation technique developed by Cox *et al.* (1979) is applied. In this section, like the previous section, we value an abandonment option at the extraction (production) stage and a deferment option at the development stage.

5.422. Valuation Results

Table 5.4 illustrates the valuation results for proven reserves of 50 million barrels, 70 million barrels, 90 million barrels and 150 million barrels. Appendix C contains the complete printouts of the parameters and models used in each case, as well as the different results. The results derived in this section, like the previous results, indicate that incorporating managerial flexibility can significantly improve the valuation of the project.

TABLE 5.4
Real Option Valuation at Different Quantities of Proven Reserves at the Initial Development Stage

Volume (Million Barrels)	50	70	90	150
The value of an undeveloped oilfield without flexibility (Million $)	-172.94	-99.52	-26.10	194.17
The value of an undeveloped oilfield with Flexibility (Million $)	0	17.44	53.10	218.41
Option Value (Million $)	172.94	116.96	79.20	24.24

5.43. The Comparison of Two Approaches in Practical Implementation

Under complete market scenario, in principle, the Classic Real Option approach and the MAD approach are fundamentally the same. As we mentioned in the previous chapter, if the value of a non-traded asset can be perfectly replicated through a corresponding traded asset (i.e., Classic Real Option approach), then the same value also can be deduced in a DCF calculation by employing an appropriate discount rate (MAD approach).

However, in practice, one of the great challenges in implementing the Real Option Analysis is the fact that many market uncertainties are poorly understood and difficult to benchmark from historical/spot data. For many real world applications, whether or not the project value and the real options can be tracked in financial markets remains an operational and subjective judgment. Pendharkar (2010) classifies the market uncertainty faced by a project into two categories: the industry aspect of market uncertainty and the financial market aspect of market uncertainty. The industry aspect of the market uncertainty includes industry characteristics such as operating costs, development costs, demand, supply and competition. The financial market aspect of market uncertainty involves market trading activities such as interest rates, commodity prices and other assets traded in a well-functions market. The financial market aspect of market uncertainty usually has the richness and public availability of historic and near real time data, which allow statistical methods to be used to calculate the structural form of the uncertainty and the degree of volatility. On the other hand, the industry aspect of market uncertainty usually has poor and limited information to measure it, especially for some innovation-related investments. For example, the demand uncertainty for a new drug is hard to track due to the lack of market information. In general, the farther we move away from financial markets, the more difficult and costly it is to track assets and their real options (Amram & Kulatilaka, 1999).

The Classic Real Option approach requires that information about the real investment be projected onto the capital market. The valuation process is straightforward, once we identify the replicating portfolio and the size of the investment relative to the replicating portfolio, and apply standard financial option pricing tools. We demonstrated this approach in our first experiment (when the project is dominated by oil price uncertainty). While it is possible to use market information to track the movement of oil prices, it is doubtful whether there is enough market information available to track an entire oil project. In other words, the value or the volatility of an oilfield is not necessarily replicated by the value or the volatility of the traded oil instruments. Hence, this approach is referred to the ODSI approach in the previous chapter. In practice, finding a replicating portfolio will be very difficult, if not impossible, for a complicated project. This is because that the information that comes from the capital markets is not always the most appropriate or complete to assess a specific project with specific risk structure. For example, investment projects usually involve various types of market uncertainties with some form of correlation structure. In these situations, the MAD approach is a good alternative if the market value of the investment cannot be replicated in a meaningful way but where market valuation remains the goal. Copeland and Antikarov (2005) point out that the assumptions and conditions necessary to justify the use of the MAD assumption are the same as those that support the use of DCF analysis—and that the MAD approach can be used in any setting where DCF is appropriate. In addition, the MAD approach has great modeling flexibility to deal with muti-source uncertainty which drives the value of the underlying asset. The MAD approach can reduce many sources of uncertainty taking into account their correlations to only one in a consolidated approach, where add an additional input variable does not impact the subsequent computational burden. It also can model different sources of uncertainty and their correlation over time in a separate way (i.e., a separate approach) when it is necessary to do so. We demonstrate a consolidated MAD approach in our second experiment when the project is governed by two uncertain factors: one is an industry-driven market uncertainty (variable operating costs) and the other is a financial market-driven uncertainty (oil prices). Hence, the MAD approach can be referred to as the SDRC approach (see the previous chapter). This is because the MAD approach allows us to use both market information and subjective estimates in order to include the many aspects of the project's features into valuation.

The results derived from these two approaches (Table 5.3 and Table 5.4) indicate that changes in valuation methods (e.g., the ODSI approach or the SDRC approach) and key input variables (e.g., oil price uncertainty, the uncertainty about variable operating costs, or both) to option based approaches can lead to large revisions in estimated value and in operating strategy. Which approach is superior is determined by the unique features of the project and the market conditions. As we mentioned in the previous chapter, the ODSI approach can be applied when the traded securities do a reasonable job of replicating value, while the SDRC approach can be applied when some unique features need to be incorporated into the valuation.

5.5. Valuation of an Unexplored Oilfield – The Hybrid and the Integrated Real Option Approaches

Now we consider valuations and decisions at the earlier *exploration* phase. When the firm considers the development of a tract of land at the exploration stage, the decision problems are even more complicated than previously because the valuation problems are affected not only by exogenous market uncertainties, but also by endogenous project-specific uncertainties. For example, before the exploration phase begins, there are many alternative levels of reserves that could eventually be obtained. The no-arbitrage enforced real option models have difficulty in incorporating various possible specific characteristics of a project into the valuation. The presence of project-specific uncertainty challenges the foundation (e.g., no arbitrage principle) of option theory.[18] This is because capital market contains no information regarding the project-specific uncertainty. However, as discussed in the previous chapter, we can extend the option pricing approach to distinguish between market uncertainty and project-specific uncertainty (see, for example, Smith & Nau, 1995, Smith & McCardle, 1998). We can then value the project through an integrating valuation procedure (e.g., integrating Real Option Analysis and Decision Analysis).

This section develops the valuation for an unexplored reserve where there is joint market uncertainty and geological uncertainty. The decision problem we face is about whether to make exploration expenditures. For an oil development project, the exploration phase is the first link in the chain of subsequent investment decisions.

The Integrated Real Option approach works as follows. We first construct a decision tree that uses risk-neutral probability for market uncertainty and physical probability for project-specific uncertainty. Then we propagate the decision tree backwards (i.e., from future nodes back to today) to determine the optimal strategy and its associated values. This procedure takes into account both project-specific uncertainty and the market trading opportunities related to the project. In our case, in order to estimate the value of an unexplored oilfield, we use the corresponding values of the undeveloped reserves (including the real options) where each potential reserve size represents the potential value at the end of the exploration phase (i.e., the market state). We then multiply these values by the physical probability of finding the corresponding quantity. The values of the undeveloped reserves were obtained in the previous section, and the prior probability distributions of reservoir sizes were specified in table 5.2. To simplify matters, other geological uncertainties such as the quality of the reserve are not taken into account in the valuation. Figure 5.4 shows the corresponding decision tree for the unexplored oilfield.

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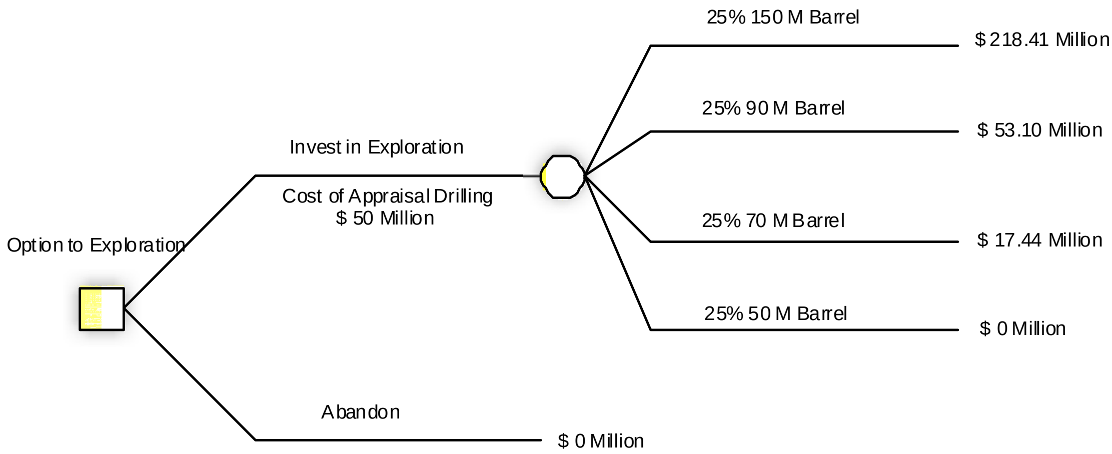
[18] As stated early, in the context of ROA valuation, the no arbitrage principle allows pricing of real options by constructing a portfolio of perfect substitutes that provides the same payoffs as the real underlying asset and whose payoffs can be directly observed in the marketplace (Dixit & Pindyck, 1994).

FIGURE 5.4
Decision Tree for the Unexplored Oilfield



In practice, considering the size of most oil companies, it is reasonable to assume that project-specific geological uncertainty can be effectively diversified. Hence, management is effectively risk neutral towards this uncertainty. Under the Hybrid Real Option approach, we can value this unexplored oilfield by discounting the expected value of the undeveloped reserves at a risk-free rate (assuming one year of appraisal drilling) and subtract the present value of the exploration costs ($50 Million in our case). This produces a value of the unexplored oilfield of $18.80 Million (see Appendix D). The corresponding development strategy is to invest in exploration.

On the other hand, as explained in chapter 4, if the firm or the investor either cannot diversify the project-specific uncertainty or intentionally retains it because of some comparative advantages or strategic reasons, decision makers' subjective beliefs and preferences for bearing this uncertainty come into play. For example, if the project constitutes a significant part of the firm's portfolio, and thus can not be effectively diversified, decision makers often behave in a risk-averse fashion towards the project-specific uncertainty. Mattar and Cheah (2006) give two possible reasons for this phenomenon: managerial self-interest and the possibility of financial distress (especially when considering large risky and irreversible investments).

In the case where the oil company cannot diversify the project-specific geological uncertainty, this uncertainty can be valued by calculating a certainty equivalent through an Integrated Real Option approach. To do so we need a utility function. Let us assume that the decision maker's time and risk preferences for consumption X_1 and X_0 can be represented by an exponential utility function:

$$U(X_0, X_1) = 1\text{-}exp\ (-(X_0+X_1/k_1)/p)\ , \qquad \text{(Equation 5.11)}$$

where p denotes the decision maker's risk tolerance and k_1 describes the decision maker's time preference. In this case, X_0 and X_1 are the time-0 and time-1 net cash flows. If we set k_1 equal to 1.05 (risk free rate), and risk tolerance equals to 100, the value of the unexplored oilfield is then $-5.95 Million (see Appendix D). The corresponding development strategy now changes to not invest in exploration. Hence, a different treatment of project-specific uncertainty not only produces the different value of the project, but also yields a different development strategy.

5.6. Conclusion

In this chapter, we presented an offshore petroleum lease example in order to develop intuition about important concepts behind real option approaches and their application conditions. The development of an offshore oilfield is a task characterized by its highly irreversible costs in exploration and infrastructure, long project life cycle in construction and operation, and high degree of uncertainty. In addition, the presence of option or option-like features means that it is difficult to derive an accurate estimate of value based on a standard DCF calculation. In response to this, many researchers recommend real option approaches to value the oil development investments.

An oil development investment typically experiences various types of uncertainties throughout its life cycle. These uncertainties may involve either geological uncertainties related to the properties of the reserve, or market uncertainties related to the future market conditions. Hence, a decision to invest in the development of an oil reserve requires an in-depth analysis of several uncertainties. The evaluation approach must be chosen appropriately. Although this example is stylized, it illustrates some important aspects regarding the choice of valuation approaches. For an undeveloped oilfield contingent on oil price, Classic Real Option approaches are useful. The tracking portfolio is made by observing traded oil securities such as oil futures and options. For an undeveloped oilfield contingent on both oil price and variable operating costs, the MAD approach is probably more suitable as the process of determining a perfect tracking portfolio is a challenge. Under the complete market scenario, data availability and quality is the key to the application of option valuation approaches. Classic Real Option approaches require collecting sufficient data to justify a replication strategy. In practice, many market uncertainties are, however, poorly understood and there is a lack of sufficient data to measure them. For example, market uncertainties highly related to the financial market (e.g., commodity price) are easier to track than market uncertainties related to industry aspects (e.g., variable operating costs). Hence, if there is no traded asset or portfolio of traded assets that tracks the properties of the project reasonably well, the MAD approach is a good alternative. Nonetheless it is important to bear in mind that an accurate modeling practice even for financial assets with a long time series data available is a complex task. Furthermore, some of the significant sources of uncertainty that affect the value of strategic options are not caused by the general movement of the market, but by project-specific events. The value of project-specific uncertainty depends on a diversification argument and/or some strategic reasons. For example, the firm will not require additional compensation other than risk-free rate if the project-specific uncertainty can be effectively diversified. However, if the firm can not diversify or intentionally retain the project-specific uncertainty, decision makers' subjective beliefs and preferences for bearing this uncertainty come into play. Hence, taking a different treatment about the project-specific uncertainty does affect the value of the project and strategies. Under a mix-uncertainty scenario, we applied both the Hybrid and Integrated Real Option approaches to value an exploration investment taking into account the uncertainty of the reserve size. The valuation results suggest that a different treatment of project-specific uncertainty (diversifiable and non-diversifiable) could lead to different value of the assets as well as different strategies to manage future uncertainties.

Chapter 6: Real Option Valuation Taxonomy

This chapter summaries the properties and application conditions of the Real Option Analysis approaches and compares our results with two well-known taxonomies: Borison (2005) and the Banff taxonomy (Bratvold *et al.,* 2005 and Laughton, 2007). In addition, we discuss real option valuation using a New Zealand grid network investment case.

6.1. Valuation Comparison in This Study

This thesis does not argue for one valuation approach over another. Despite obvious differences in selected real option approaches, they are in fact different facets of a general project evaluation framework. Each approach focuses on certain aspects or relies on certain theoretical foundations while simplifying or ignoring others. In this thesis, we use our three criteria (the nature of the capital market, the classification of project-specific uncertainty and the source of the data) to specify and compare the choice of the selected real option valuation approach.

In the finance literature, the Classic Real Option approach is frequently called "contingent claim analysis" or "valuation by arbitrage" (Smith & Nau, 1995). This approach requires that information about the real investment be projected onto the capital market, and in turn the capital market has to be sufficiently complete for the project being valued. In practice, the assumption of the existence of a "twin security" is unrealistic for most real-world applications, although it is frequently made in the academic real option literature. Most real-life projects are not traded in the market; hence there are often no direct market sources of data to allow perfect tracking of project value. In addition, the presence of project-specific uncertainty means that perfect tracking is not always possible. Thus it is important to have a clear understanding of when and why tracking might break down (Amram & Kulatilaka, 1999). When the value and exercise conditions of the investment opportunity cannot be directly or completely linked to uncertainties priced in the financial markets, the strategic valuation of the investment opportunity better aligns with the extended real option frameworks. Among these extended real option approaches, the MAD approach offers an alternative way to solve real option problems based on the no arbitrage principle when the market value of the investment cannot be replicated in a meaningful way. In this approach, instead of searching for a twin security in the marketplace, the market value of the underlying asset is replaced with a traditional DCF calculation. Monte Carlo Simulation is used to determine the volatility measure, and standard option valuation methods are used to value the real option. The MAD approach eliminates the complexity of identifying a trading security or portfolio and significantly enlarges the applicability of real option theory. It does this in a way that is fairly easy to understand from a decision marker's point of view. However, it is important to bear in mind that the MAD approach only meets the Law of One Price internally between the asset and the option; they may both be mis-priced relative to the market (Borison, 2005). In addition, it cannot offer clear-cut information regarding the option exercise policy as the value of the underlying asset is not readily observable in the market. Finally, the Integrated and the Hybrid Real Option approaches can be applied in order to capture the un-trackable uncertainties in the valuation and decision marking processes. These two approaches apply standard option valuation methods to value market-priced uncertainty and apply Decision Analysis approaches to value project-specific uncertainty. Their treatments of project-specific uncertainty differ however. The Hybrid Real Option approach treats project-specific uncertainty as a unique diversifiable uncertainty, while the Integrated Real Option approach captures the decision makers' risk attitudes when analyzing project-specific uncertainty. The difficulty in applying these two approaches is that, for many real projects, there is no clear-cut characteristic to distinguish the market and project-specific uncertainties. We now discuss two well-known valuation taxonomies and compare our results with them.

6.2. Borison Taxonomy

In the paper: "*Real Options Analysis: Where Are the Emperor's Clothes?*", Adam Borison examines and compares five real option valuation approaches: the Classic approach, the Subjective approach, the Marketed Asset Disclaimer (MAD) approach, the Revised Classic approach and the Integrated approach. His analysis is based on three fundamental issues surrounding each proposed approach: applicability, assumptions and mechanics. He undertakes an extensive review of these five valuation approaches, and employs an oil and gas example.

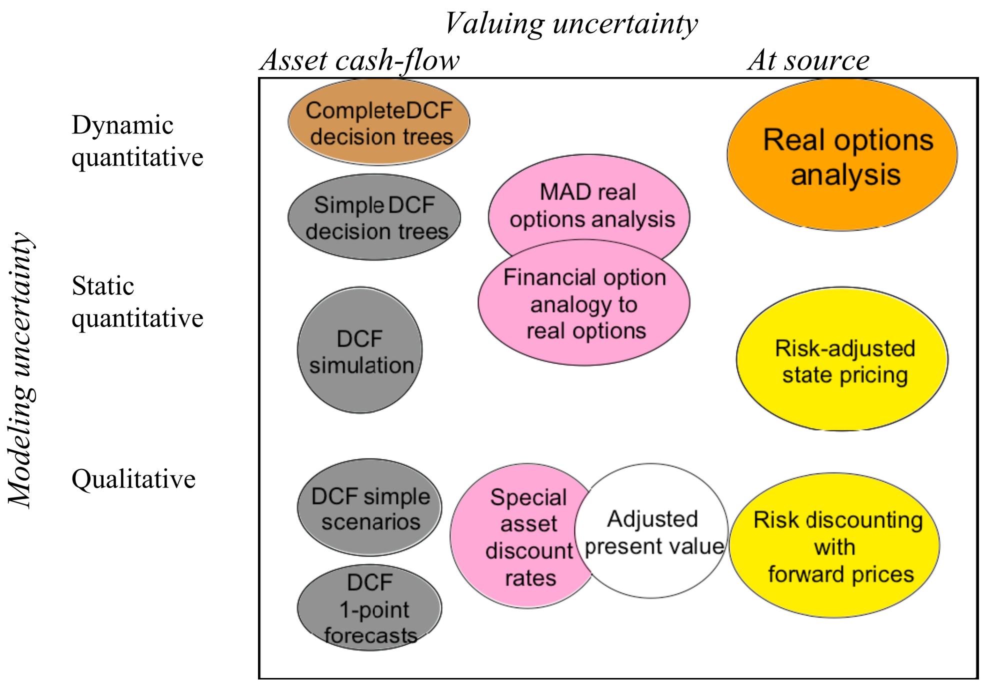
The differences of these five real option methods are as follows. The Classic approach using a "replication strategy" to value real options is based on the no arbitrage principle and market data. The Subjective approach using a "replication strategy" to value real options is based on the no arbitrage principle and subjective data. The MAD approach using a "self-constructed" value is based on the no arbitrage principle and subjective data. The Revised Classic approach applies the Classic approach in the cases where the project uncertainties are dominated by market-priced uncertainties, but applies the Decision Analysis approach in the cases where the project uncertainties are dominated by project-specific uncertainties. The Integrated approach applies the Classic approach to value market-priced uncertainty but applies the Decision Analysis approach to value project-specific uncertainty in an integrated valuation process. Borison argues against the Classic approach because of the unrealistic assumptions regarding a complete market and a "twin security". He argues against the Subjective and the MAD approaches regarding the use of subjective data and assumptions. He also argues against the "black and white" nature of the Revised Classic approach due to its lack of precision. Based on the arguments of the Borison taxonomy, only the Integrated approach is consistent, relevant and reasonably accurate.

The similarities and differences between our taxonomy and Borison's are as follows. For similarities, we agree with the Borison's argument about the unrealistic assumptions regarding the "twin security" and "market completeness". We also agree with the Borison's view regarding the existences of different types of uncertainty (market and project-specific uncertainties) for most real-world projects. For differences, we do not argue for one valuation approach or another, but specify the appropriate choice of valuation framework, and the reasons that drive this choice. The two main differences are: 1) we do not view the use of the replicated security or the subjective estimates as a "white or black" procedure to evaluate market uncertainty. Firstly, in most situations, the procedure of identifying a twin security in the marketplace could be impracticable, problematic and subject to a considerable level of subjectivity. Secondly, in practice, the identified “twin” security may or may not fully replicate the project being valued. Finally, in some applications, management opinions about the future market conditions could be more informative than historical market data, especially in a rapid changing environment. Therefore, decision makers should make their judgments regarding the use of information. For valuation, it is not necessarily wrong that we use subjective estimates to evaluate market uncertainties if there is an absence of perfect market information (e.g., we can apply the MAD approach to evaluate market uncertainty and the Decision Analysis approach to value project-specific uncertainty under an integrated valuation procedure). 2) In our taxonomy, we specified how to treat the project-specific uncertainty in valuation and decision making. Based on the properties of the project-specific uncertainty, in our taxonomy, we can value the project-specific uncertainty in a risk-neutral manner or by taking into account the decision makers’ risk attitudes. The Borison taxonomy does not, however, make a clear statement regarding the treatment of project-specific uncertainty.

6.3. Banff Taxonomy

In September 2003, the Society of Petroleum Engineers (SPE) held a workshop in Banff, Canada to discuss the evolution of valuation approaches in the petroleum industry. One of the key outputs of the workshop was the "Banff Taxonomy" (see figure 6.1). The Banff taxonomy focuses on how different valuation approaches model uncertainty (e.g., qualitative, static quantitative and dynamic quantitative) and determine the effect of uncertainty on asset value.

FIGURE 6.1
The Banff Taxonomy of Asset Valuation Methods



(Taken from Laughton, 2007)

We briefly discuss the structure of this taxonomy in terms of the choice of valuation approaches. At the left side of the Banff taxonomy, the point-estimate DCF approach is in the lower corner. Moving upwards indicates that the uncertainty of the project is modeled in a progressive and dynamic manner (from DCF with sensitivity analysis and probabilistic DCF analysis to dynamic decision tree analysis). At the right side of the Banff taxonomy, the progression is from risk discounting with forward prices to real option analysis. The shift up the taxonomy to dynamic models of uncertainty has significant effects on valuation and decision making. While static models of uncertainty can be constructed to reflect different patterns of uncertainty (e.g., the likelihoods and range of possibilities), it bears no relation to the actual resolution of uncertainty in time and gives no indications of the consequences of actions that should be undertaken. From the left side of the Banff taxonomy to the right side of the Banff taxonomy represents two kinds of shifting in valuation: 1) from subjective judgment to objective market information, and 2) from an actual risk-averse preference structure to a risk-neutral preference structure. The first shifting suggests that a firm needs to use financial market data as much, and as directly, as possible to inform value estimation (Laughton, 2007). The second shifting suggests choosing the risk-neutral preference structure to handle the dynamic change of risk structure, especially when real options are present.[19] This is because the risk characteristics of a project with options require the different structures of risk discounting. This situation is very difficult to deal with in an actual risk-averse preference structure. The choice of the risk-neutral preference structure is due to its mathematical tractability (Mattar & Cheah, 2006). Arnold and Crack (2004) show that a careful Net Present Value (NPV) using a risk-adjusted discount rates in risk-averse world produces a real option value identical to that obtained from a risk-neutral option valuation, but the implementation of risk-adjusted discount rates for NPV is often computationally infeasible. There are some valuation approaches in the middle of the taxonomy that are partial shifts. Laughton's recommendation of the choice of valuation approaches is that the petroleum industry should explore moves up and to the right in the taxonomy.

For our purposes the valuation methods located in the top of the Banff taxonomy are of interest (complete DCF decision tree, MAD real options analysis, financial option analogy to real options and real option analysis). The complete DCF decision tree is also called decision tree analysis (Smith & Nau, 1995) using a constant discount rate to discount all scenarios in a risk-averse preference structure. This approach cannot, however, provide a correct value of real options because the existence and/or exercise of real options would alter the risk characteristics of a project. Thus, using a constant discount rate is inappropriate. The financial option analogy approach to real options is similar to the Classic Real Option approach. The real option analysis in the Banff taxonomy corresponds to the Integrated Real Option approach in the Borison taxonomy. Laughton (2007) and Bratvold *et al.* (2005) argue that the financial option analogy approach to real options and the MAD real options analysis are two "dead end" approaches to real options analysis. For the financial option analogy approach to real options, very few real assets are strictly analogous to a financial option. For the MAD real options analysis, the calculated rather than directly observed parameters could result in errors in valuation and decision-making. As in the Borison taxonomy, Laughton (2007) and Bratvold *et al.* (2005) recommend applying the Integrated Real Option approach in asset valuation.

[19] The choice of a particular risk preference structure is irrelevant for option valuation. Cox and Ross (1976) state that a solution to the problem, assuming a particular risk preference structure, must also be a solution to the problem for any other preference structure.

The similarities and differences between our taxonomy and the Banff taxonomy are as follows. For similarities, we agree with the suggestions of the Banff taxonomy regarding "moving up the taxonomy" and "moving to the right of the taxonomy". Moving up the taxonomy allows us to deal with the uncertainty more dynamically. Moving to the right of the taxonomy allows us to deal with the uncertainty more objectively. For differences, we do not view the financial option analogy approach to real options and the MAD real options analysis as dead end approaches to real options analysis. This is because the first one is appealing in theory and the latter one is sound in application. They are both foundations for the Integrated Real Option approach. In addition, the project-specific uncertainty (called 'local uncertainty') is treated in a risk-neutral manner in the Banff taxonomy, while, in our taxonomy, we can value the project-specific uncertainty in a risk-neutral manner or by taking into account the decision makers' risk attitudes based on the features of the project.

6.4. The Application of Real Option Approaches

We now discuss briefly the needs and the application of ROA in the context of New Zealand electricity grid investment. We use the grid investment example to discuss the applicability of real option approaches because of the significant capital investment, high level of uncertainty, and the timing and operating options involved in such investment. These fit the structure of ROA very well. Also, there are debates regarding the suitability of the real option approaches to value such investment, which has been widely communicated by government agencies, research institutes and interested groups recently.[20] We shall discuss the current valuation models of the grid investment, the arguments and the applications of real option approaches, and how to make sure that the Real Option Analysis is really working in practice.

[20] The debates regarding the application of ROA for grid investment can be found in Electricity Commission's website: http://www.electricitycommission.govt.nz/opdev/transmis/gdps/index.html

6.41. Grid Investment and Its Current Valuation Models

In New Zealand, the grid network is operated and managed by a public-owned monopoly enterprise - Transpower. To provide a safe, secure and continuous supply of electricity, Transpower is responsible for ensuring its grid network has sufficient capacity to deliver continuous volumes of electricity to wherever it is required throughout New Zealand. Under the *Electricity Governance Rules*, Transpower must get approval from the Electricity Commission (a centralized regulator) for proposed investments. Over the last few years, Transpower has submitted to the Electricity Commission grid upgrade proposals exceeding $2.5 billion in total.[21] According to the *Electricity Governance Rules,* a proposed investment has to satisfy the Grid Investment Test (GIT). The GIT is applied to determine the sustainability of transmission investment. If a proposed investment meets the GIT this implies that the Electricity Commission is reasonably satisfied that the proposed investment maximises the expected net market benefit or minimizes the expected net market cost compared with a number of alternative projects. To access the expected net market benefit of a proposed investment or alternative project, either standard Net Present Value (NPV) or Real Option Analysis (ROA) must be applied. The type of analysis to be used in applying the GIT to a particular grid investment must be whichever of standard NPV or ROA is more appropriate.

Grid investments are irreversible decisions with high costs and long-term consequences. The uncertainties surrounding the project and their consequential effects are critical determinants of investment decisions. The most important of these uncertainties are related to: electricity demand growth (demand uncertainty), future distribution of power plants (supply uncertainty), and project economic factors (such as uncertainties in construction cost, timing, interest rate, exchange rate etc).

Both Transpower and the Electricity Commission invested considerable time and resources to forecast future electricity demand and the distribution of power plants (i.e., several market scenarios) to project the future needs for grid network. Although grid planners are usually aware of the various uncertainties affecting the future performance

[21] 2008 Statement of opportunity. Draft for consultation July 2008

of grid network, their capacity planning exercises seldom reflect this awareness. This is because grid investment decisions remain mostly traditional and rigid in their approach with an over-reliance on forecasts in advance. Transpower's current valuation methods for all proposed investments are similar to the standard NPV technique combined with extensive scenario**,** sensitivity and simulation analysis. For example, after identifying several possible future market scenarios, Transpower usually designs their grid upgrade proposals based on likeliest, worst or weighted average possible market scenarios, and applies traditional deterministic or probabilistic analysis, to evaluate the proposed project. Based on these approaches, the actual planning activities follow and are tied directly to the forecast results. However, in reality, only rarely do long-term forecasts actually hit the mark (Wang, 2005). Therefore, costly consequences, such as a mismatch between installed capacity and realized demand, electricity price fluctuations, construction-delays, cost over-runs or curtailed project life, often come forth. These errors have typically taken two forms: construction of facilities that remain underutilized for years and/or inadequate preparations for rapidly changing trends. In most cases, investment decisions based on the deterministic valuation models would neither eliminate the effect of uncertainties nor guarantee an economically optimal solution especially in those cases in which the future is vastly different from prior expectations.

6.42. Real Option Valuation and Arguments

Increasingly there has been a recognized need for flexibility for long term electricity grid planning. As Ku (1995) proposed, if learning is expected through resolution of uncertainty, reduction of uncertainty, or acquisition of additional information, then flexibility provides the ability to take advantage of that learning or new information. Ku (1995) justifies the needs for flexibility in the context of electricity infrastructure investment planning:

1. Uncertainties in capacity planning prevail in many forms, and new uncertainties may emerge over time.

2. The existing forecast models (e.g., demand forecast) and traditional valuation approaches are often inaccurate and inadequate.

3. Capacity planning is a continuous process; with revisions to existing planning constantly being made as new information arises.

Dynamic strategic grid investment planning needs to cope with high levels of uncertainty, multiple future outcomes and the strategic prospects.

Real Option Analysis as a complementary approach is widely communicated by the Electricity Commission, Transpower, government agencies, research institutes and interested groups. In 2005, the New Zealand Institute of Economic Research (NZIER) proposed a Real Options Analysis approach for grid investment. But Transpower was not satisfied with the results due to its over-simplified valuation process and significant assumptions (e.g., a complete market). In 2006, Boyle, Guthrie and Meade proposed a three-stage theoretic-focused real option analytical framework for grid investment. However, Transpower was concerned about the feasibility and applicability of the real option framework. As stated in their report:[22] "*A textbook treatment of real options is not tractable for transmission investment analysis. Integration of the power systems analysis required to compare transmission alternatives with the economic modeling would not be practicable.*" In addition, other researchers argued that the assumptions of the real option approach were false. For instance, "*it is not clear to us that real options analysis is appropriate for grid investment. In particular the construction of a martingale measure for valuation (whether in a binomial lattice or continuous time) relies on the existence of complete markets in which the risks of the benefits can be perfectly hedged by tradeable instruments. We are concerned about the validity of the analysis in the absence of these conditions.*" (Professor Andy Philpott, Dr Geoffrey Pritchard, and Dr Golbon Zakeri, Electric Power Optimization Centre, University of Auckland). Finally, many consultants recognized the potential value of applying real option for transmission investment, but they were worried about the valuation transparency of the real option approach as well as the lack of rules to guide the analysis and to exercise future options. For example, the Major Electricity Users' Group

[22] Attachment E: Economic Assessment of the North Island Grid Upgrade Project

(MEUG)[23] stated in their report that the "*Commission should ensure that independently verified real options analyses of Transpower's investment plans will be undertaken. Without this safeguard, we believe that the potential costs to the nation of a longer planning period would be likely to outweigh any advantages"*.

6.43. Implementation of Real Options

For electricity grid investment, it is clear that there are no rich sources of information to precisely determine the market value of the underlying asset and its resolution of uncertainty over time. Hence, the Classic Real Option approach by searching for a "twin security" from the marketplace is often inapplicable. This is probably the reason why "*a textbook treatment of real options is not tractable"*. However, it is not necessary to justify "*the validity of the real option analysis in the absence of the perfect market conditions"*. This is because, like most engineering projects, the strategic process itself is more important than the particular analytic results. For the grid investment, for example, the most important contribution of the real option framework is the process of describing and understanding the project and the uncertainty embedded therein, and this helps managers formulate their strategic options created by today's investments.

Based on our valuation taxonomy, we can apply an extended real option framework in the case when there is only limited market information. For a grid investment, we believe that real option analysis is a way of thinking. For the valuation, we draw upon the market information as much as possible, and use the subject data if the market information is absent. We then classify the type of uncertainties, the key valuation determinates (e.g., volatility) and apply the most suitable approach to value the investment. At the current stage, the application of the real option approach for New Zealand grid investment can be grounded on Transpower's current valuation and forecast results. The deterministic valuation results in different market scenarios have calculated reasonable market values of the investment in each scenario (in the case

[23] http://www.comcom.govt.nz/IndustryRegulation/Electricity/ElectricityLinesBusinesses/ContentFiles/Documents/MEUGxsub.pdf

where there is no market observable value). The extensive scenario, sensitivity and simulation analysis create a picture of how the future might be and how the uncertainties might evolve (i.e., project the volatility measure). In addition, the key uncertainties which could affect the performance of grid investment have been well modeled and monitored by both the Commission and Transpower (e.g., electricity demand growth and future distribution of power plants). All this information can reasonably enable us to apply real option approaches for grid investment. In the future, the opportunity for real option approaches in grid investment is perceivable; hence grid planners need to be well prepared to adopt this investment philosophy change both in valuation methods and in thinking. In particular, for real option analyses to be made available to grid planners we need the following:

(1) A comprehensive education process will be required for these current real option approaches to be used and accepted among interested parties. A fairly good understanding of these current real option models (e.g., conceptual underpinnings and application conditions) can guide managers to make complicated decisions under uncertainty and guide regulatory agencies to supervise these decisions.

(2) Both Transpower and the Commission need to keep investing in gathering and analyzing information for critical determinants regularly at reasonable costs (e.g., monitor demand growth and future distribution of power plants) to facilitate the adoption of new processes. Data availability and quality is the key for the reliability of the valuation process and the justification of the assessment.

(3) Transpower and the Commission need to continuously modify the real option models to be more transparent and practically feasible. Any approaches used for grid investments must be reasonably simple, transparent and accurate so that the valuation procedure can be performed routinely within the firm, and can be widely communicated by interested parties.

(4) A regulation policy must be set up in order to both verify real options analysis in terms of key assumptions and valuation procedures, and specify the option exercise policy in terms of trigger events and critical points in demand growth. If the additional resources are not available to cope with the increased complexity, the potential benefit of the adoption of the new process will be limited.

6.5. Summary

In this chapter, we compare the similarities and differences of our taxonomy with the Borison taxonomy and the Banff taxonomy, and discuss the application of real option valuation using a New Zealand grid network investment case. For the natural of the capital market, we all agree that most capital investments commonly face non-perfect market conditions. Hence, the real option valuation approach must be extended to ensure that valuation can be performed in these market conditions. For the classification of project-specific uncertainty, in our taxonomy, we can value the project-specific uncertainty in a risk-neutral manner or by taking into account the decision makers' risk attitudes based on the features of the project, while the Borison taxonomy does not make a clear statement regarding the treatment of project-specific uncertainty and the Banff taxonomy treats it in a risk-neutral manner. For the source of data, we all agree that the firm needs to use financial market data as much, and as directly, as possible to inform value estimation. However, in our taxonomy, the use of the subjective data to perform valuation is still acceptable in the cases where the perfect market information is absent. In our views, ROA refers to a distinct framework that includes a whole set of techniques (e.g., merging with Decision Analysis) is used to address decision-making in a world of uncertainty. And more importantly, ROA is a way of thinking that provides a promising philosophy to help decision makers to identify strategic options and investment opportunities.

Chapter 7: Conclusion

In this thesis we have introduced a taxonomy of real option valuation approaches based on three criteria: the nature of the capital market, the classification of the project-specific uncertainty, and the source of the data. We use these three criteria to examine and compare four selected real option approaches based on the theoretical underpinnings and application conditions. Through systematic comparison, we specify the appropriate choice of valuation framework and the reasons that drive this choice. We also give some simple numerical examples.

7.1. Thesis Summary

Most real world investments are exposed to multiple sources of uncertainties and the managers have some leeway about timing and altering of the investments (Dixit & Pindyck, 1993). Traditional DCF methods are limited in the way they deal with uncertainties and flexibilities associated with these investment opportunities. Real Option Analysis is a promising tool to formulate investment problems and strategic decisions in uncertain environments. When we apply ROA, we both estimate the value of the investment and we get a "road-map" on how to optimally act in the future to maximize the value of the investment.

The Classic Real Options approach is generally benchmarked to financial equivalent. The parameters of Classic Real Option approach therefore have to be projected onto the capital market. Most real world valuation problems are, however, more complicated than can be captured by a traditional replicating strategy (no arbitrage). Reviews of the applications of real option approaches in three typical industries (Petroleum, Engineering, and Research & Development) indicate that decision markers face two critical issues in order to value a project purely based on the no arbitrage principle: 1) many projects have no or little directly observable market information regarding the value of the underlying asset and critical parameters (i.e., they are non-traded) and/or 2) many projects involve uncertainties that are not priced in the capital market. Therefore, in order to be applicable and realistic, real option valuation models need to be modified to incorporate project-level information into valuation.

Several extended real option valuation approaches appear in the literature to address these issues. Implement of these different real option approaches is limited in practice. This is because: 1) the theoretical underpinnings of these different real option approaches are not explored adequately in the literatures, and 2) the correct application conditions of these different real option approaches are not specified adequately in the literature. In order to solve these practical issues, we present several important cornerstones and concepts of options theory. Based on the discussion and systematic literature summarization, we propose a valuation taxonomy based on three criteria: the nature of the capital market, the classification of project-specific uncertainty, and the source of the data. We use these three criteria to guide the choice of valuation framework and discuss the reasons that drive this choice.

The main reason for using the different real option approaches in different valuation scenarios is the degree of imperfection of the capital market. As we discussed in our offshore petroleum lease example, in some cases, if the project can be tracked well by a market proxy, the valuation can be based on the classic replicating strategy. However, in some other cases, limited market information means we cannot fully capture the reality of the project then the decision makers need to incorporate subjective judgment into the valuation in order to avoid decision errors. In these cases, we have to relax some severe assumptions regarding perfect replication by allowing for a "self-constructing" technique if the market proxy is difficult to determine precisely (e.g., the MAD approach) and/or the combination of some supplemental methods (e.g., Decision Analysis) to deal with un-tracked uncertainty (e.g., the Hybrid and Integrated Real Option approaches). Although the validity of the analysis in the absence of objective market information may be questionable, the insight derived from option thinking may contribute to shaping strategy (Luehrman, 1998). As Amran and Kulatilaka (1999) stated, "Real Options are a way of thinking". In addition, we found that the classification of project-specific uncertainty bears significant real world implications. The treatment of unique or private uncertainty would result in a significantly different value and strategy. We make clear statements regarding valuation for project-specific uncertainty and the choice of the valuation approaches.

Real option theory provides a set of analytic frameworks and a promising philosophy to help decision makers identify, value and realize the strategic options embedded in the investment opportunities. Hence, it is important for decision markers to understand the conceptual underpinnings of these different real option approaches and their correct application conditions, and to improve their strategic decision-making procedures. The main contributions of this thesis are specified as follows:

1) We clarify several important conceptions regarding real option approaches to valuation and decision making.

2) We offer a clear understanding for practitioners regarding the similarities and differences between the selected real option valuation approaches and their correct application conditions.

3) We specify the choice of valuation approaches in different valuation scenarios and the reasons that drive this choice.

7.2. Future Research

In this thesis, we did not consider details about the modeling of uncertainties; an interesting extension to this study would be to include the specification of the modeling of the uncertainty. Furthermore, although we considered the link between real option approaches and decision analysis approaches in this thesis, we did not build upon the link between real option and other evaluation approaches to further expand the scope of the option valuation approaches. Finally, we believe that more research is required focusing on the relationship between industry-specific characteristics and the structure of the real option approaches so as to provide use-friendly frameworks for specific industry users.

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Appendix A: Classic Real Option Approach

PARAMETERS:

Input Parameters	
Risk Free Rate (per annum)	5%
Convenience Yield (per annum)	5.5%
Oil Price Volatility (Standard Deviation) (per annum)	8%
Current Oil Price	28
Abandonment Value ($M) (after 5 yrs)	20
Investment Cost ($M)	300
Reserve Size (MB)	50, 70, 90, 150
Production Rate	10%
Operating Cost (per barrel)	20
Fixed Cost ($M)	10
Calculated Parameters	
Number of Time Steps	11
Length of One Period (Δt)	1
Upward Price Multiplicative Factor (u)	1.08
Downward Price Multiplicative Factor (d)	0.92
Risk Neutral Probability of Upward Change (p)	0.45
Risk Neutral Probability of Downward Change (1-p)	0.55

REAL OPTION VALUATION: 50 MILLION BARRELS

CASH FLOW SPREADSHEET

	EXPLORATION STAGE		DEVELOPMENT & PRODUCTION STAGE									
Year	0	1	2	3	4	5	6	7	8	9	10	11
Remaining Reserve (M)			50.0	45.0	40.0	35.0	30.0	25.0	20.0	15.0	10.0	5.0
Production Level	0	0.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Opearting Cost (per barrel)	0	0.0	20.00	20.20	20.40	20.61	20.81	21.02	21.23	21.44	21.66	21.87
Fixed Cost ($M)	0	0.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Oil Price (per barrel)	28	27.86	27.72	27.58	27.45	27.31	27.17	27.04	26.90	26.77	26.63	26.50
Revenue ($M)	0.00	0.00	138.61	137.92	137.23	136.54	135.86	135.18	134.51	133.84	133.17	132.51
Production Cost ($M)	0.00	0.00	110.00	111.00	112.01	113.03	114.06	115.10	116.15	117.21	118.29	119.37
Investment Cost ($M)		-300.00										
Net Cash Flow ($M)	0.00	0.00	28.61	26.92	25.22	23.51	21.80	20.08	18.36	16.63	14.89	13.14

REAL OPTION RESULTS

Year	0	1	2	3	4	5	6	7	8	9	10	11
Project Value												
												218.16
											374.65	
										479.77		168.25
									542.36		284.97	
								569.95		358.90		125.73
							568.99		397.49		208.56	
						544.96		407.14		255.89		89.49
					502.50		393.29		274.05		143.45	
				445.56		360.56		268.41		168.12		58.61
			377.47		312.88		243.57		168.85		87.96	
		258.39		253.58		203.43		150.18		93.33		32.29
			185.44		151.30		115.98		79.21		40.68	
		90.61		89.98		69.53		49.44		29.59		9.87
			21.80		13.62		7.26		2.82		0.38	
		-134.08		-49.43		-44.57		-36.41		-24.72		-9.24
					-103.72		-85.39		-62.27		-33.95	
						-141.80		-109.57		-71.00		-25.52
							-164.34		-117.74		-63.21	
								-171.91		-110.44		-39.40
									-165.00		-88.14	
										-144.05		-51.22
											-109.39	
												-61.30

Project with Abandonment and Deferment Options

	0	1	2	3	4	5	6	7	8	9	10	11
												218.16
											374.65	
										479.77		168.25
									542.36		284.97	
								569.95		358.90		125.73
							568.99		397.49		208.56	
						545.17		407.14		255.89		89.49
					503.45		393.69		274.05		143.45	
				448.34		362.20		269.17		168.12		58.61
			29.79		317.41		246.36		170.31		87.96	
		12.72		263.91		210.74		154.88		96.11		32.29
			0.00		167.33		127.65		86.99		45.99	
		0.00		119.98		94.14		67.86		42.16		20.00
			0.00		57.79		44.70		31.64		20.04	
		5.71		17.07		19.66		20.00		20.00		20.00
					-12.84		6.63		20.00		20.00	
						-20.76		20.00		20.00		20.00
Option Value:			139.79				-8.41		20.00		20.00	
								20.00		20.00		20.00
									20.00		20.00	
										20.00		20.00
											20.00	
												20.00

REAL OPTION VALUATION: 70 MILLION BARRELS

CASH FLOW SPREADSHEET

	EXPLORATION STAGE		DEVELOPMENT & PRODUCTION STAGE									
Year	0	1	2	3	4	5	6	7	8	9	10	11
Remaining Reserve (M)			70.0	63.0	56.0	49.0	42.0	35.0	28.0	21.0	14.0	7.0
Production Level	0	0.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Opearting Cost (per barrel)	0	0.0	20.00	20.20	20.40	20.61	20.81	21.02	21.23	21.44	21.66	21.87
Fixed Cost ($M)	0	0.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Oil Price (per barrel)	28	27.86	27.72	27.58	27.45	27.31	27.17	27.04	26.90	26.77	26.63	26.50
Revenue ($M)	0.00	0.00	194.05	193.08	192.12	191.16	190.21	189.26	188.31	187.38	186.44	185.51
Production Cost ($M)	0.00	0.00	150.00	151.40	152.81	154.24	155.68	157.14	158.61	160.10	161.60	163.12
Investment Cost ($M)		-300.00										
Net Cash Flow ($M)	0.00	0.00	44.05	41.68	39.30	36.92	34.52	32.12	29.70	27.28	24.84	22.40

REAL OPTION RESULTS

Project Value

Year	0	1	2	3	4	5	6	7	8	9	10	11
												309.42
											532.31	
										683.10		239.55
									774.17		406.77	
								816.08		513.88		180.02
							817.85		571.36		299.79	
						787.16		588.14		369.68		129.28
					730.54		571.87		398.53		208.63	
				653.51		529.01		393.91		246.80		86.05
			560.73		465.08		362.25		251.26		130.95	
		392.45		384.73		309.02		228.40		142.08		49.21
			291.89		238.86		183.63		125.76		64.75	
		157.55		155.69		121.57		87.35		52.85		17.81
			62.80		46.10		31.42		18.82		8.34	
		-37.01		-39.48		-38.17		-32.84		-23.18		-8.94
					-118.16		-98.29		-72.31		-39.73	
						-174.30		-135.25		-87.98		-31.73
							-208.81		-149.97		-80.69	
								-222.53		-143.19		-51.16
									-216.14		-115.59	
										-190.24		-67.71
											-145.34	
												-81.82

Project with Abandonment and Deferment Options

Year	0	1	2	3	4	5	6	7	8	9	10	11
												309.42
											532.31	
										683.10		239.55
									774.17		406.77	
								816.08		513.88		180.02
							817.85		571.36		299.79	
						787.21		588.14		369.68		129.28
					730.99		571.95		398.53		208.63	
				655.43		529.83		394.08		246.80		86.05
			186.42		468.38		363.75		251.57		130.95	
		92.45		394.01		314.66		231.12		142.68		49.21
			0.00		253.88		193.17		130.70		65.90	
		0.00		187.36		145.62		103.33		61.78		20.00
			0.00		94.28		69.53		45.27		24.44	
		41.50		37.68		34.13		26.85		20.00		20.00
					-10.20		8.59		20.00		20.00	
						-27.25		20.00		20.00		20.00
							-15.38		20.00		20.00	
								20.00		20.00		20.00
									20.00		20.00	
										20.00		20.00
											20.00	
												20.00

Option Value: 78.51

REAL OPTION VALUATION: 90 MILLION BARRELS

CASH FLOW SPREADSHEET

	EXPLORATION STAGE		DEVELOPMENT & PRODUCTION STAGE									
Year	0	1	2	3	4	5	6	7	8	9	10	11
Remaining Reserve (M)			90.0	81.0	72.0	63.0	54.0	45.0	36.0	27.0	18.0	9.0
Production Level	0	0.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
Opearting Cost (per barrel)	0	0.0	20.00	20.20	20.40	20.61	20.81	21.02	21.23	21.44	21.66	21.87
Fixed Cost ($M)	0	0.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Oil Price (per barrel)	28	27.86	27.72	27.58	27.45	27.31	27.17	27.04	26.90	26.77	26.63	26.50
Revenue ($M)	0.00	0.00	249.49	248.25	247.01	245.78	244.55	243.33	242.12	240.91	239.71	238.51
Production Cost ($M)	0.00	0.00	190.00	191.80	193.62	195.45	197.31	199.18	201.07	202.98	204.91	206.86
Investment Cost ($M)		-300.00										
Net Cash Flow ($M)	0.00	0.00	59.49	56.45	53.39	50.32	47.24	44.15	41.05	37.93	34.80	31.65

REAL OPTION RESULTS

Year	0	1	2	3	4	5	6	7	8	9	10	11
Project Value												
												400.68
											689.97	
										886.44		310.85
									1005.98		528.56	
								1062.20		668.86		234.31
							1066.70		745.22		391.02	
						1029.36		769.14		483.46		169.08
					958.58		750.44		523.02		273.81	
				861.45		697.45		519.41		325.47		113.49
			744.00		617.27		480.94		333.67		173.94	
		526.50		515.88		414.62		306.61		190.84		66.12
			398.34		326.43		251.28		172.31		88.83	
		224.49		221.40		173.60		125.27		76.11		25.76
			103.79		78.59		55.58		34.82		16.30	
				-29.54		-31.78		-29.26		-21.65		-8.63
		60.06			-132.61		-111.18		-82.35		-45.50	
						-206.79		-160.94		-104.96		-37.94
							-253.29		-182.19		-98.17	
								-273.15		-175.95		-62.92
									-267.27		-143.04	
										-236.44		-84.20
											-181.29	
												-102.34
												-61.30

Project with Abandonment and Deferment Options

												400.68
											689.97	
										886.44		310.85
									1005.98		528.56	
								1062.20		668.86		234.31
							1066.70		745.22		391.02	
						1029.36		769.14		483.46		169.08
					958.89		750.44		523.02		273.81	
				863.11		698.05		519.41		325.47		113.49
			343.80		620.19		482.07		333.67		173.94	
		226.50		525.08		419.70		308.77		190.84		66.12
			58.29		341.60		260.05		176.44		88.83	
		24.89		255.77		198.40		140.24		83.98		25.76
			0.00		131.79		95.74		60.01		31.31	
		115.39		59.01		49.52		35.16		20.00		20.00
					-7.04		11.18		20.00		20.00	
						-33.48		20.00		20.00		20.00
Option Value:			55.33				-22.35		20.00		20.00	
								20.00		20.00		20.00
									20.00		20.00	
										20.00		20.00
											20.00	
												20.00

REAL OPTION VALUATION: 150 MILLION BARRELS

CASH FLOW SPREADSHEET

	EXPLORATION STAGE		DEVELOPMENT & PRODUCTION STAGE									
Year	0	1	2	3	4	5	6	7	8	9	10	11
Remaining Reserve (M)			150.0	135.0	120.0	105.0	90.0	75.0	60.0	45.0	30.0	15.0
Production Level	0	0.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Opearting Cost (per barrel)	0	0.0	20.00	20.20	20.40	20.61	20.81	21.02	21.23	21.44	21.66	21.87
Fixed Cost ($M)	0	0.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Oil Price (per barrel)	28	27.86	27.72	27.58	27.45	27.31	27.17	27.04	26.90	26.77	26.63	26.50
Revenue ($M)	0.00	0.00	415.82	413.75	411.68	409.63	407.59	405.55	403.53	401.52	399.52	397.52
Production Cost ($M)	0.00	0.00	310.00	313.00	316.03	319.09	322.18	325.30	328.46	331.64	334.86	338.11
Investment Cost ($M)		-300.00										
Net Cash Flow ($M)	0.00	0.00	105.82	100.75	95.65	90.54	85.41	80.25	75.08	69.88	64.66	59.42

REAL OPTION RESULTS

Year	0	1	2	3	4	5	6	7	8	9	10	11
Project Value												
												674.47
											1162.96	
										1496.43		524.76
									1701.41		893.95	
								1800.57		1133.81		397.18
							1813.27		1266.81		664.71	
						1755.97		1312.14		824.80		288.46
					1642.69		1286.16		896.47		469.36	
				1485.28		1202.79		895.93		561.49		195.82
			1293.78		1073.85		836.99		580.89		302.90	
		928.66		909.33		731.40		541.25		337.10		116.87
			717.68		589.11		454.23		311.97		161.05	
		425.32		418.54		329.70		239.02		145.90		49.60
			226.77		176.04		128.06		82.80		40.17	
		351.26		0.31		-12.60		-18.53		-17.04		-7.72
					-175.95		-149.88		-112.47		-62.83	
						-304.29		-237.99		-155.89		-56.57
							-386.72		-278.88		-150.60	
								-425.01		-274.20		-98.20
									-420.68		-225.40	
										-375.02		-133.67
											-289.14	
												-163.90

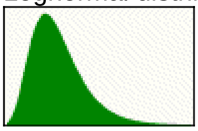
Project with Abandonment and Deferment Options

	0	1	2	3	4	5	6	7	8	9	10	11
												674.47
											1162.96	
										1496.43		524.76
									1701.41		893.95	
								1800.57		1133.81		397.18
							1813.27		1266.81		664.71	
						1755.97		1312.14		824.80		288.46
					1642.99		1286.16		896.47		469.36	
				1487.09		1203.37		895.93		561.49		195.82
			817.45		1077.04		838.09		580.89		302.90	
		628.66		920.35		737.02		543.35		337.10		116.87
			336.04		607.52		464.06		315.96		161.05	
		143.48		463.66		360.24		256.07		153.51		49.60
			0.00		247.12		178.30		112.08		54.71	
		361.27		124.90		98.10		63.42		32.59		20.00
					3.82		20.37		20.00		20.00	
						-51.54		20.00		20.00		20.00
Option Value:			10.01				-43.27		20.00		20.00	
								20.00		20.00		20.00
									20.00		20.00	
										20.00		20.00
											20.00	
												20.00

Appendix B: Monte Carlo Simulation

INPUTS:

Lognormal distribution



Parameters: Mean and Standard Deviation

Year	2	3	4	5	6	7	8	9	10	11
Oil Price (Mean)	27.72	27.58	27.45	27.31	27.17	27.04	26.90	26.77	26.63	26.50
$\delta\sqrt{T}$	11.31%	13.86%	16.00%	17.89%	19.60%	21.17%	22.63%	24.00%	25.30%	26.53%
Standard Deviation	3.14	3.82	4.39	4.89	5.32	5.72	6.09	6.42	6.74	7.03

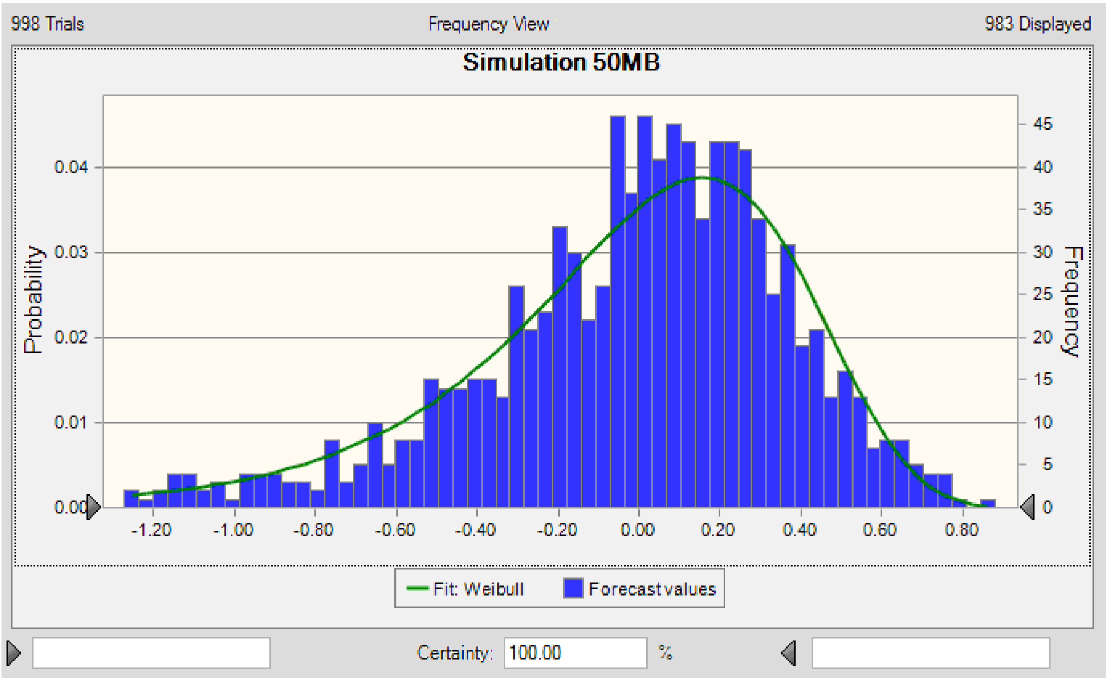
Operating Cost (Mean)	20.00	20.20	20.40	20.61	20.81	21.02	21.23	21.44	21.66	21.87
$\delta\sqrt{T}$	3.00%	4.24%	5.20%	6.00%	6.71%	7.35%	7.94%	8.49%	9.00%	9.49%
Standard Deviation	0.60	0.86	1.06	1.24	1.40	1.54	1.69	1.82	1.95	2.08

OUTPUT:

$Z = \ln(V_1/V_0)$

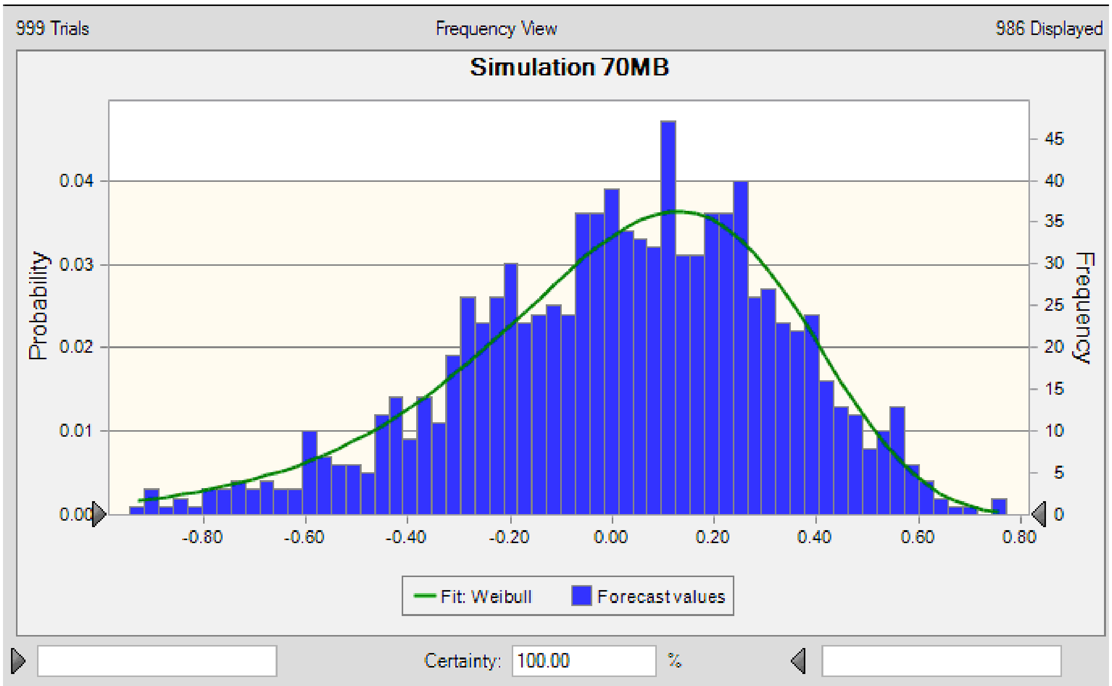
FORECAST: SIMULATION 50 MILLION BARRELS (MB) (Crystal Ball Report)

STATISTIC	FORECAST VALUES
TRIALS	998
MEAN	-0.03
MEDIAN	0.03
STANDARD DEVIATION	0.44
VARIANCE	0.20
SKEWNESS	-1.92
KURTOSIS	12.37
COEFF. OF VARIABILITY	-13.01
MINIMUM	-3.99
MAXIMUM	0.88
MEAN STD. ERROR	0.01
CELL ERRORS	2



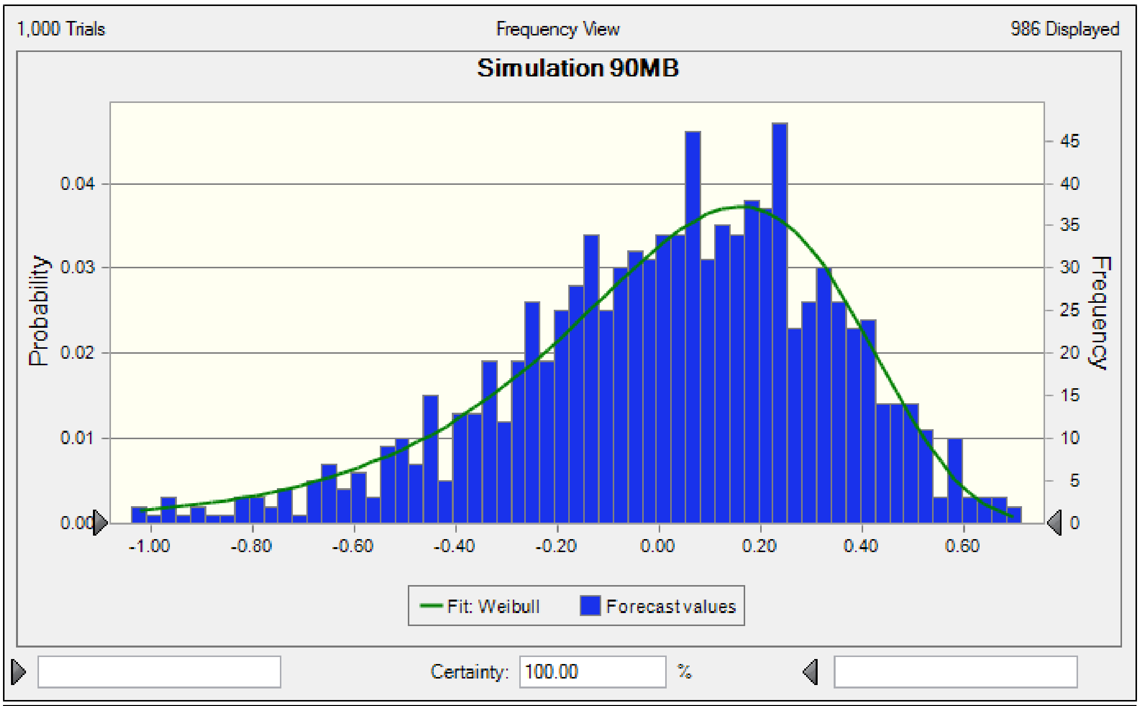
FORECAST: SIMULATION 70 MILLION BARRELS (MB) (Crystal Ball Report)

STATISTIC	FORECAST VALUES
TRIALS	999
MEAN	0.00
MEDIAN	0.04
STANDARD DEVIATION	0.34
VARIANCE	0.11
SKEWNESS	-0.9296
KURTOSIS	4.98
COEFF. OF VARIABILITY	178.53
MINIMUM	-1.63
MAXIMUM	0.77
MEAN STD. ERROR	0.01
CELL ERRORS	1



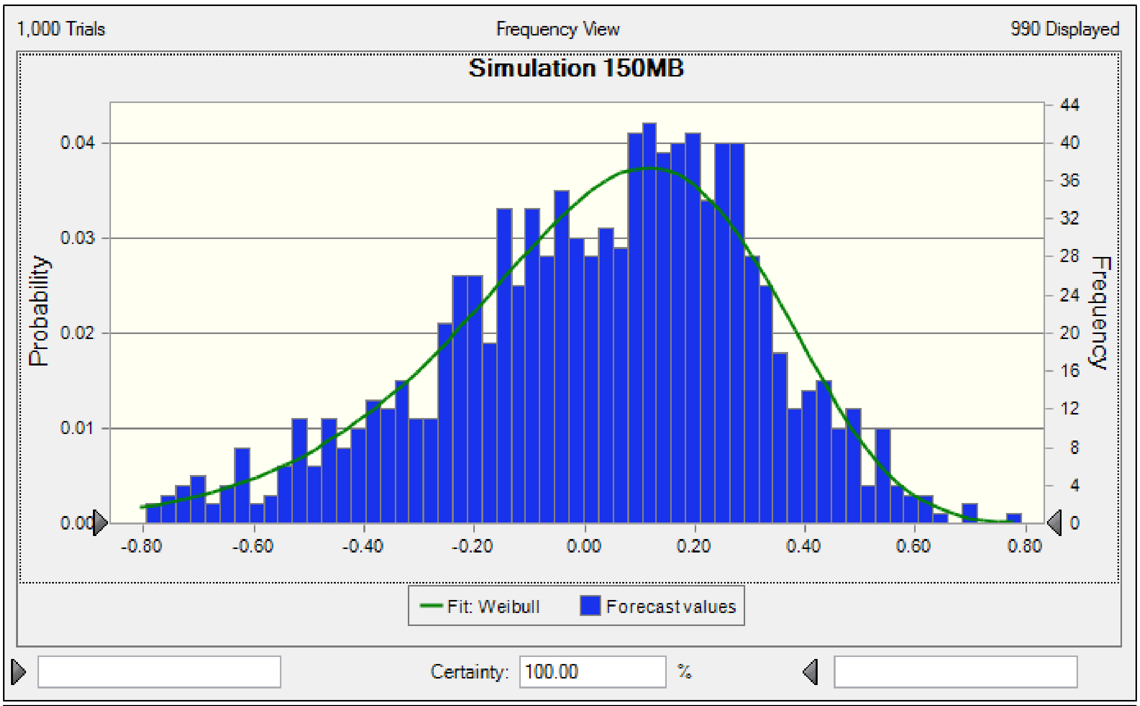
FORECAST: SIMULATION 90 MILLION BARRELS (MB) (Crystal Ball Report)

STATISTIC	FORECAST VALUES
TRIALS	1,000
MEAN	0.00
MEDIAN	0.05
STANDARD DEVIATION	0.37
VARIANCE	0.14
SKEWNESS	-1.90
KURTOSIS	14.01
COEFF. OF VARIABILITY	-111.85
MINIMUM	-3.64
MAXIMUM	0.71
MEAN STD. ERROR	0.01



FORECAST: SIMULATION 150MB MILLION BARRELS (MB) (Crystal Ball Report)

STATISTIC	FORECAST VALUES
TRIALS	1,000
MEAN	0.02
MEDIAN	0.06
STANDARD DEVIATION	0.30
VARIANCE	0.09
SKEWNESS	-0.6360
KURTOSIS	3.50
COEFF. OF VARIABILITY	18.66
MINIMUM	-1.22
MAXIMUM	0.79
MEAN STD. ERROR	0.01



Appendix C: MAD Approach

REAL OPTION VALUATION: 50 MILLION BARRELS

Input Parameters	
Risk Free Rate (per annum)	5%
The Value of the Underling Asset at the Beginning of the Development & Production Stage ($M)	127.06
Abandonment Value ($M)	20
Life of Abandonment Option (years)	5
Investment Cost ($M)	300
Life of Deferment Option (years)	1
Standard Deviation	44%
Calculated Parameters	
Upward Movement Multiplicative Factor (u)	1.55
Downward Movement Multiplicative Factor (d)	0.64
Risk Neutral Probability of Upward Change (p)	0.39
Risk Neutral Probability of Downward Change (1-p)	0.61

	EXPLORATION STAGE		DEVELOPMENT & PRODUCTION STAGE									
Year	0	1	2	3	4	5	6	7	8	9	10	11
												15285
											9844.095	
										6339.956		6339.956
									4083.163		4083.163	
								2629.71		2629.705		2629.705
							1693.63		1693.626		1693.626	
						1090.76		1090.76		1090.757		1090.757
					702.49		702.49		702.4871		702.4871	
				452.52		452.43		452.43		452.4273		452.4273
			0.00		291.53		291.38		291.3797		291.3797	
		0.00		188.31		187.92		187.66		187.6591		187.6591
			0.00		121.89		121.31		120.8593		120.8593	
		0.00		80.14		79.43		78.61		77.83779		77.83779
			0.00		53.43		52.58		51.44536		50.13037	
				37.62		36.94		36.00		34.5382		32.28579
					27.85		27.23		26.32552		24.65131	
Project Value with Flexibility		0.00				22.54		22.08		21.4502		20
Option Value:		172.94					20.25		20.01896		20	
								20.00		20		20
									20		20	
										20		20
											20	
												20

REAL OPTION VALUATION: 70 MILLION BARRELS

Input Parameters	
Risk Free Rate (per annum)	5%
The Value of the Underling Asset at the Beginning of the Development & Production Stage ($M)	200.48
Abandonment Value ($M)	20
Life of Abandonment Option (years)	5
Investment Cost ($M)	300
Life of Deferment Option (years)	1
Standard Deviation	34%
Calculated Parameters	
Upward Movement Multiplicative Factor (u)	1.40
Downward Movement Multiplicative Factor (d)	0.71
Risk Neutral Probability of Upward Change (p)	0.41
Risk Neutral Probability of Downward Change (1-p)	0.59

	EXPLORATION STAGE		DEVELOPMENT & PRODUCTION STAGE									
Year	0	1	2	3	4	5	6	7	8	9	10	11
												8028.157
											5714.204	
										4067.201		4067.201
									2894.913		2894.913	
								2060.51		2060.513		2060.513
							1466.61		1466.612		1466.612	
						1043.89		1043.89		1043.891		1043.891
					743.01		743.01		743.0105		743.0105	
				528.85		528.85		528.85		528.8528		528.8528
			76.43		376.42		376.42		376.4218		376.4218	
		35.61		267.95		267.93		267.93		267.9258		267.9258
			0.00		190.74		190.70		190.7017		190.7017	
		0.00		135.98		135.81		135.74		135.7358		135.7358
			0.00		97.02		96.75		96.6127		96.6127	
				69.90		69.44		69.00		68.76605		68.76605
					50.68		50.06		49.36406		48.94564	
Project Value with Flexibility		17.44				37.46		36.65		35.58186		34.83805
Option Value:		116.96					28.69		27.72857		26.11892	
								23.32		22.34744		20
									20.60928		20	
										20		20
											20	
												20

REAL OPTION VALUATION: 90 MILLION BARRELS

Input Parameters	
Risk Free Rate (per annum)	5%
The Value of the Underling Asset at the Beginning of the Development & Production Stage ($M)	273.90
Abandonment Value ($M)	20
Life of Abandonment Option (years)	5
Investment Cost ($M)	300
Life of Deferment Option (years)	1
Standard Deviation	37%
Calculated Parameters	
Upward Movement Multiplicative Factor (u)	1.45
Downward Movement Multiplicative Factor (d)	0.69
Risk Neutral Probability of Upward Change (p)	0.40
Risk Neutral Probability of Downward Change (1-p)	0.60

	EXPLORATION STAGE		DEVELOPMENT & PRODUCTION STAGE									
Year	0	1	2	3	4	5	6	7	8	9	10	11
												15256.67
											10538.3	
										7279.168		7279.168
									5027.971		5027.971	
								3472.99		3472.992		3472.992
							2398.91		2398.915		2398.915	
						1657.01		1657.01		1657.013		1657.013
					1144.56		1144.56		1144.556		1144.556	
				790.58		790.58		790.58		790.5839		790.5839
			246.09		546.08		546.08		546.0835		546.0835	
		111.49		377.20		377.20		377.20		377.1986		377.1986
			0.00		260.55		260.54		260.544		260.544	
		0.00		180.12		179.98		179.97		179.9667		179.9667
			0.00		124.56		124.34		124.3092		124.3092	
				86.78		86.30		85.91		85.86461		85.86461
					60.75		60.06		59.39322		59.30964	
Project Value with Flexibility		53.10				43.20		42.26		41.11412		40.9672
Option Value:		79.20					31.71		30.513		28.55571	
								24.67		23.34186		20
									21.02485		20	
										20		20
											20	
												20

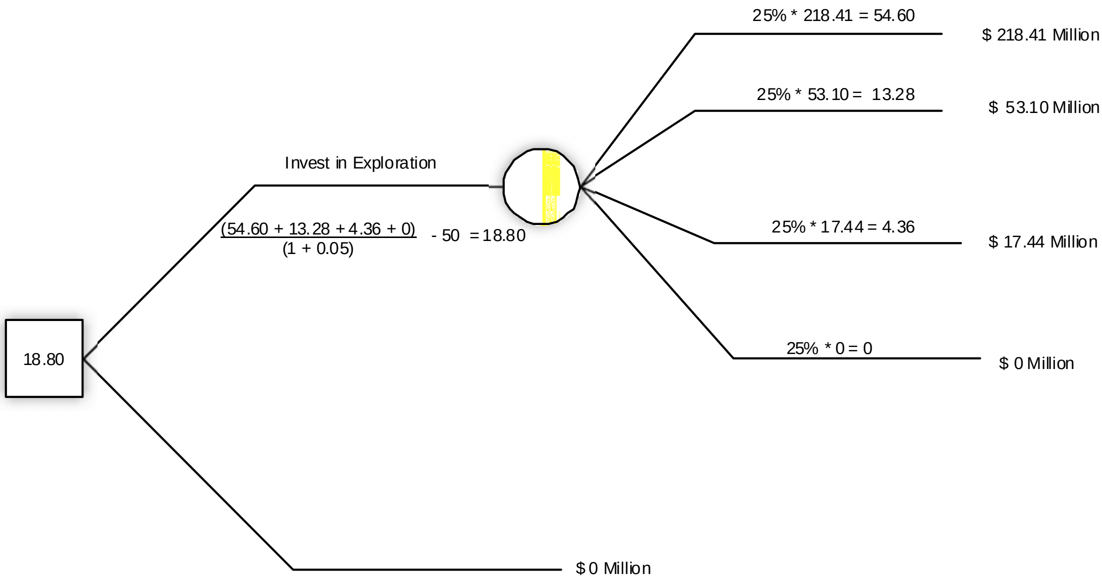
REAL OPTION VALUATION: 150 MILLION BARRELS

Input Parameters	
Risk Free Rate (per annum)	5%
The Value of the Underling Asset at the Beginning of the Development & Production Stage ($M)	494.17
Abandonment Value ($M)	20
Life of Abandonment Option (years)	5
Investment Cost ($M)	300
Life of Deferment Option (years)	1
Standard Deviation	30%
Calculated Parameters	
Upward Movement Multiplicative Factor (u)	1.35
Downward Movement Multiplicative Factor (d)	0.74
Risk Neutral Probability of Upward Change (p)	0.42
Risk Neutral Probability of Downward Change (1-p)	0.58

	EXPLORATION STAGE		DEVELOPMENT & PRODUCTION STAGE									
Year	0	1	2	3	4	5	6	7	8	9	10	11
												12744.87
											9441.63	
										6994.532		6994.532
									5181.676		5181.676	
								3838.68		3838.68		3838.68
							2843.76		2843.764		2843.764	
						2106.71		2106.71		2106.712		2106.712
					1560.69		1560.69		1560.691		1560.691	
				1156.19		1156.19		1156.19		1156.188		1156.188
			556.53		856.53		856.53		856.5254		856.5254	
		349.16		634.53		634.53		634.53		634.5296		634.5296
			170.07		470.07		470.07		470.0711		470.0711	
		82.46		348.24		348.24		348.24		348.2372		348.2372
			0.00		257.98		257.98		257.9805		257.9805	
				191.14		191.12		191.12		191.1166		191.1166
					141.63		141.58		141.5827		141.5827	
Project Value with Flexibility		218.41				104.96		104.89		104.887		104.887
Option Value:		24.24					77.84		77.70223		77.70223	
								57.81		57.56323		57.56323
									43.09709		42.64389	
										32.40911		31.59137
											24.87895	
												20

Appendix D: Valuation of an Unexplored Oilfield

HYBRID REAL OPTION APPROACH



INTEGRATED REAL OPTION APPROACH