Decision Analysis of Exploration Opportunities in the Onshore US at Phillips Petroleum Company

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Petroleum exploration managers must allocate scarce resources across a set of risky and uncertain investment alternatives. We developed a decision analysis software package, DISCOVERY, that provided an exploration division of Phillips Petroleum Company an alternative means of evaluating a mix of risky investments and selecting participation levels consistent with the firm's risk propensity. Managers at Phillips use the software to (1) evaluate projects with a consistent risk-taking policy, (2) rank projects in terms of overall preference, (3) identify the firm's appropriate level of participation, and (4) stay within their division budgets. This approach increased management's awareness of risk and risk tolerance and provided insight into the relative financial risks associated with its available investment opportunities. As a result of this project, the company has developed consistent methods of risk analysis that include companywide analysis of all exploration projects.

Petroleum exploration companies grapple daily with allocating scarce investment capital across a set of exploration projects—projects generally characterized by financial risk and uncertainty. In 1992, for example, the domestic and foreign capital budgets for 55 of the largest US-based oil companies exceeded $35 billion [Beck 1993]. The impact of the effectiveness of allocating capital on exploration business

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DECISION ANALYSIS—APPLICATIONS
INDUSTRIES—PETROLEUM/NATURAL GAS

unit performance is significant.

Risk management decisions in the oil industry are among the most conceptually difficult decisions managers face. Investment opportunities are often very different in their risk characteristics. The decision maker is faced with a mix of drilling opportunities from "low probability of success—high payoff" to "high probability of success—low payoff." How should the manager evaluate and compare these projects on the basis of risk? Until recently, managers made decisions concerning diversification and risk-sharing, the primary methods of controlling risk, principally through informal procedures, rules of thumb, and individual intuition. Efforts to measure and control risk formally have been impeded by the lack of a computer-based decision support system appropriate for a wide range of decision makers.

Modern Finance Theory and Capital Budgeting under Uncertainty

The capital budgeting problem holds a very prominent place in both the theory and practice of corporate finance. The generally accepted goal for financial decision making in the theory of finance is to maximize owner wealth. In a world of certainty, financial theorists generally agree that choosing among independent and mutually exclusive projects based on net present value is consistent with owner wealth maximization [Copeland and Weston 1983; Fama and Miller 1972; Lintner 1965]. This decision rule is optimal under ideal circumstances: certain and identifiable cash flows, no transaction costs, no taxes, and perfectly competitive capital markets.

Real-world decision making, however, involves risky or uncertain future outcomes. Modern finance theory views capital markets as the fundamental mechanism for spreading these risks. In other words, the individual investor can construct a portfolio that adequately diversifies "business-specific" risk, and managers of the firm should be concerned only about non-diversifiable or "market" risk [Brealey and Myers 1991]. Within this theoretical framework, managers in publicly held firms should maximize shareholder value by selecting those investment opportunities that have the highest expected net present value. Rigorously applied, the theory suggests that devoting corporate resources to managing the business risks associated with allocating capital is inappropriate. However, corporations appear to take risk management very seriously—recent surveys show that financial executives rank risk management as one of their most important objectives [Rawls and Smithson 1990]. In addition, corporate risk management activities appear to differ considerably from those prescribed by the theory of finance. We examine this dilemma from an empirical, a theoretical, and a behavioral perspective.

The foundation of modern finance theory, the Sharpe [1964], Lintner [1965], and Black, Jensen, and Schoales [1972] capital asset pricing model (CAPM) provides the basis for determining the appropriate discount rate to adjust for the nondiversifiable risks that ownership of a particular stock brings to the investor's diversified portfolio. Unfortunately, empirical evidence does not support this theory. Fama and French [1992] determined no detectable relation between portfolio betas and average returns. Roll and Ross [1994] raise additional risky projects in the short term [Hayes and Abernathy 1980]. Hackett [1985] noted that it is unrealistic to assume that managers are merely agents for shareholders. Instead, managers attempt to reconcile the interests of all stakeholders, including themselves, other employees, suppliers, customers, and the communities in which they operate.

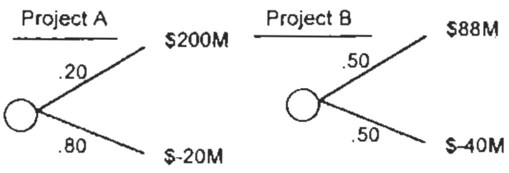
Swalm [1966] assessed utility functions for a group of 100 executives in a large industrial organization and found them to be strongly risk-averse. Spetzler [1968] interviewed 36 corporate executives in a large industrial firm (a major integrated oil company) and consistently found risk-averse attitudes among individuals and within the managerial group as a policy-making body. In a study of oil company executives, Wehrung [1989] found that more than half of the executives gave responses that were fully consistent with expected utility theory, and an additional quarter of executives were consistent within a 10-percent margin of error in their responses. At Phillips Petroleum, as in many large companies, managers often technically evaluate investments on the basis of expected value. However, in making actual capital allocation decisions involving risky investments, whose consequences are significant, they display strong risk-averse decision behaviors. Development of a theoretically robust and workable capital allocation model that incorporates the risk attitude of the firm may go a long way towards improving the quality of capital budgeting decisions.

The Problem

In the late 1980s and early 1990s, Phillips Petroleum Company's North American Division Eastern Onshore Exploration unit was responsible for oil and gas exploration along the eastern and southern coasts of the United States from New England to Texas. Most exploration during this period took place in approximately 10 geological trends (areas of petroleum potential) within the coastal plains of Texas, Louisiana, Mississippi, and Alabama. Eastern Onshore's 10 geological and geophysical staff members' primary responsibility was to initiate and develop potential drilling projects in this region. Division management hoped to drill four to six prospects per year and maintain a high-quality portfolio of oil and gas prospects. Exploration activities took place in a variety of geological settings with varying degrees of oil and gas reserve potential.

The managers faced two issues in allocating the annual exploration budget. First, they wanted to use a relatively consistent measure of risk across a broad range of exploration investments. For example, they often needed to compare the risk and relative attractiveness of a project that offered a high probability of success and low net present value payoff with another project that offered a very low probability of success and a much higher net present value (Figure 1).

Many explorationists would say that the expected value concept, which weights the financial consequences by their probabilities, adequately takes risk into account. However, to the decision maker at Phillips, risk was not just a function of the probability distribution of reserve outcomes but also the magnitude of capital exposed to the chance of loss. Where the expected values of two projects are equal, the ex-



Expected Value of A = Expected Value of B = $24M

Figure 1: Though the expected values of Projects A and B are equal, the risks associated with the projects are quite different. The expected value concept fails to give adequate weight to the firm's exposure to the chance of a very large financial loss. Utilizing the expected value rule, managers at Phillips recognized that they should be indifferent between project A and project B. However, managers readily conceded that the "risk" associated with each of these projects was quite different. Though Project B had a reasonably high probability of success (0.50), the payoff structure was much less attractive than that of Project A.

pected value concept fails to give adequate weight to the firm's exposure to the chance of a very large financial loss (Figure 1). Phillips' managers wanted a methodology that would allow them to make appropriate trade-offs between the potential and uncertain upside gains versus downside losses for individual projects and for groups of projects.

The second issue managers faced was determining the appropriate level of participation for each of the exploration projects available to the firm. In general, Phillips' Eastern Onshore Exploration unit had available more projects offering positive expected net present value than available investment capital. Most of these projects were part of the company's prospect inventory; however, from time to time managers needed to evaluate projects available through other companies. In light of capital constraints, managers talked a lot about "spreading the risk" by taking smaller working interests (participation levels) in more prospects, but they had no formal way to quantify the advantages of selling down or reducing interests in individual projects. They recognized that the traditional expected value analysis provided little or no insight into the value of diversification. They wanted a technique that would enable them to quantify the value of diversification. They wanted to select among diverse exploration projects with a variety of risk characteristics and to identify their optimal level of participation in each project. In addition, they required a methodology that would ensure that the process used to allocate exploration capital was consistent with Phillips' propensity to take on financial risk.

DISCOVERY Software

Like traditional software packages dealing with petroleum reserves and economics, the DISCOVERY software allows the division personnel at Phillips to input ownership interests, product pricing, capital and operating expenditures, information on reservoir decline, and other pertinent information concerning the investment opportunity (drilling project). It provides cash flow and net present value modeling capability for both onshore and offshore exploration projects. (The discount rate utilized by Phillips Petroleum is based on a proprietary economic and market-based estimation model developed by the company.) The user is able to model the uncertainties associated with individual investments in a number of formats. Each of these formats is designed to capture the user's subjective judgments about the principal uncertainties, which are probability of success and oil and gas reserve outcomes.

The DISCOVERY software assumes probabilistic independence among each of the individually modeled projects. The user, however, has the option to model projects on a *prospect* or *play* basis to account for certain dependencies. A prospect is a geologic anomaly known to, or thought to, contain hydrocarbon potential. A play is a collection of geologically homogeneous prospects located in the same geographic area within a petroleum basin. Prospects within the same play may not be probabilistically independent. In other words, their exploration outcomes could be correlated or one prospect's success could depend on that of another prospect within the same play. Should geologic dependencies exist among prospects within a play, the user can model these dependencies in analyzing the play. If a prospect is geologically or outcome independent of other prospects or plays, then the user can use the software to model and evaluate it independent of other projects. It is important to note that DISCOVERY does not allow the user to model probabilistic dependency between other variables such as product price. We recognize that correlation between oil and gas prices, as well as their impact on individual projects, may affect project selection and optimal share.

Corporate officers must demonstrate that their enterprises are viable.

The user can select from several reserve input formats, each of which uses a unique decision tree. The user interface allows the division geologist or engineer to model the uncertainties associated with the project without an explicit knowledge of decision-tree structuring; the result is an effective treatment of risk and uncertainty for the main variables of interest. The software interprets the inputs and constructs a decision-tree diagram that shows all the decision alternatives and subsequent chance events associated with the problem. The program computes the cash flows and net present values associated with each possible outcome modeled by the user (Figure 2). The decision-tree display is useful to managers, particularly because it shows the after-tax cost of a dry hole for each option, which was different from the cost to the capital budget.

To determine the division's best share in a given exploration project, managers calculate a sample of risk-sharing options available to Phillips for each project. The software allows the user to specify the terms of the sale or purchase of a partial interest in an exploration project, thereby computing Phillips' unique risk-sharing arrangements for each project as part of the overall model. It considers estimated financial premiums, cash considerations, and retained overriding royalties as part of the risk-sharing analysis. In addition, the user can model the specific terms of a *farmout* (a farmout is a form of risk sharing whereby the owner of an oil or gas lease agrees to assign the lease or a portion of it to another company who agrees to drill the leased acreage; the company who farms out the property generally reserves an ing as an agent for the firm) as well as the risk characteristics of the opportunity set.

EUT is appealing in that it enables the exploration manager at Phillips to use a fairly consistent measure of valuation across a broad range of risky exploration investments. Though management is evaluating projects that differ in their risk characteristics, the firm's strength of preference for outcomes and aversion to risk should be consistent in the evaluation process. The valuation measure we utilize is known in EUT as the *certainty equivalent:* that certain value for an uncertain event that a decision maker is just willing to accept in lieu of the gamble represented by the event. It is, in essence, the cash value attributed to a decision alternative that involves uncertain outcomes. The certainty equivalent of a risky investment is a function of the risk characteristics of the investment and the risk preferences of the decision maker. EUT provides us a means of mapping the risk preferences of the decision maker in the form of a utility function. While most companies do not know their utility functions, bounding or estimating their utility functions is a practical approach to obtaining the benefits of utility theory.

Choosing a functional form of utility was important in developing the DISCOVERY program. We wanted a preference function that was relatively easy to measure, a good approximation for other general forms of utility, and useful in treating multiple independent projects separately (principle of value additivity). One common form of risk aversion is known as *constant* risk aversion. An individual displays constant risk aversion if the individual's risk premium (expected value minus the certainty equivalent) for a gamble does not depend on the initial amount of wealth held by the decision maker. A special case of constant risk aversion is the linear preference function, where the risk premium is a constant at zero. The other possibility is a utility function with an exponential form. Because the exponential is the only functional form that possesses the theoretical and practical properties described above and has a convenient mathematical representation, we used this form of utility in the DISCOVERY program. Without the exponential form of utility, the certainty equivalent of the sum of payoffs is not equal to the sum of certainty equivalents of individual payoffs. Even when the exponential utility function does not describe a decision maker's attitude with complete accuracy, it has the potential to closely approximate the true utility function.

By accepting the property of constant risk aversion, we can ultimately characterize risk preference by a single number, the *risk aversion coefficient,* which loosely speaking measures the curvature of the utility function for the decision maker. Mathematically, the *certainty equivalent* (C_x) is a function of the risk aversion coefficient, c, for the decision maker and the risk characteristics (probability distribution on outcomes) of the investment opportunity. For discrete probability distributions, the formula for the certainty equivalent is:

$$C_x = -1/c \; ln\left(\sum_{i=1}^{n} p_i e^{-cx_i}\right) \qquad [1]$$

where p_i is the probability of outcome i, x_i is the value of outcome i, and ln is the natural log [Cozzolino 1977]. For example, in Figure 2 we show the calculation of certainty equivalent values, C_x, for the primary decision alternatives, drill at 100-percent participation and drill at 50-percent participation. On the basis of expected value, the 100-percent option is the dominant alternative, $1,730 M versus $1,100 M. To compute certainty equivalents, C_x, for each alternative, we utilize the decision tree rollback procedure, equation 1 and a risk aversion coefficient, c, equal to 0.06 $\times 10^{-6}$. The 50-percent participation decision alternative now dominates with a certainty equivalent value of $720 M, versus $560 M for the 100-percent participation. This example shows that when the firm incorporates its willingness to take on financial risk into the valuation model, vis-à-vis equation 1, the preferred alternative may not be consistent with expected value analysis.

To explore the impact of varying risk attitudes, managers at Phillips use DISCOVERY to compute certainty equivalents at various risk-aversion levels, c, for a given project. They compare the attractiveness of various risk-sharing scenarios for a project using the program's risk profile comparison (Figure 3). Note that the risk profile curve shows the certainty equivalent for many firms since it is a graph of certainty equivalent versus the risk-aversion coefficient.

The risk profile curve provides Phillips' management a measure of the impact of increased risk aversion on the cash value of the project at different participation levels. The precipitous decrease in certainty equivalent value with respect to risk aversion for the 100-percent working interest option, as compared to the 50-percent interest, gives the decision maker insight into the relative riskiness of these participation levels. In the past, managers had reviewed only those values associated with the zero risk-aversion level, which is equivalent to expected value analysis. They found this comparison useful in understanding how the choice of a participation level was affected by Phillips' propensity to take on financial risk, as measured by the risk-aversion coefficient, c.

Similarly, managers could evaluate certainty equivalents for each risk-sharing option at specific risk-aversion coefficients. Given that they had assessed, within some reasonable range, the risk-aversion coefficient that represented their preferences, they could arrive at the optimal share for any given project consistent with those preferences (Figure 4). Managers were able to also observe the sensitivity of optimal share to the level of risk aversion. They were quick to detect that the sensitivity of the risk-aversion coefficient to the optimal choice option was closely associated with the risk characteristics of the project. In terms of optimal share, relatively inexpensive projects with high probability of success were insensitive to the level of risk aversion. Conversely, projects requiring a relatively large amount of risk capital with a low probability of success were highly sensitive to the risk-aversion coefficient. However, we found that for all prospects in the onshore Gulf Coast area management's preference for a working interest percentage could be represented by a narrow range of risk-aversion coefficients.

For individual prospects, managers use the software to assess how they might reduce risk if they obtained additional seismic information. The software computes the value of additional information on the

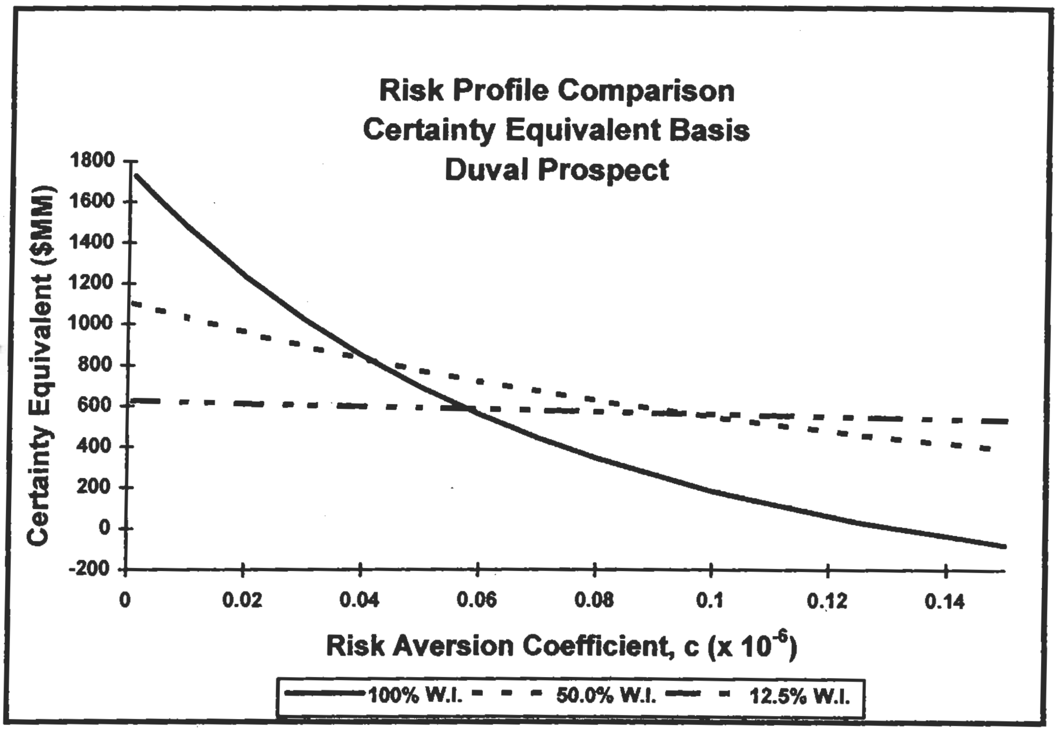


Figure 3: The risk profile curve for the Duval Prospect shows the effect of risk aversion on the valuation of different risk-sharing scenarios as well as the relative attractiveness of each of those project scenarios. Note that the certainty equivalent value at a risk-aversion coefficient of zero is equal to the expected value. In this example three different participation levels are analyzed for the Duval Prospect: 100 percent, 50 percent, and 12.5 percent working interests. If the division's risk-aversion level were between 0.04×10^{-6} and 0.10×10^{-6} then the firm should participate at the 50 percent working interest level since the certainty equivalent at that range of risk aversion dominates all other risk sharing options. However, if the division's risk aversion were greater than 0.10×10^{-6}, then among the choices shown, the manager should select the 12.5 percent working interest option, since that interest level has the highest certainty equivalent.

basis of expected value as well as certainty equivalence. In some cases, expected value increased as a result of additional seismic information; however, in many of these cases the analysis of the certainty equivalent indicated it was more appropriate for Phillips to participate at a lower level instead of investing in more seismic data. In other cases, however, managers found that a 3D seismic survey would be an excellent investment in terms of the certainty equivalent analysis and proceeded to shoot. Management has found, in general, that the certainty equivalent analysis provides rich insight into trade-offs between the cost of additional information and its impact on the overall risk characteristics of the exploration project.

Project Ranking—A Certainty Equivalent Approach

Because capital was limited, management wanted to rank exploration projects

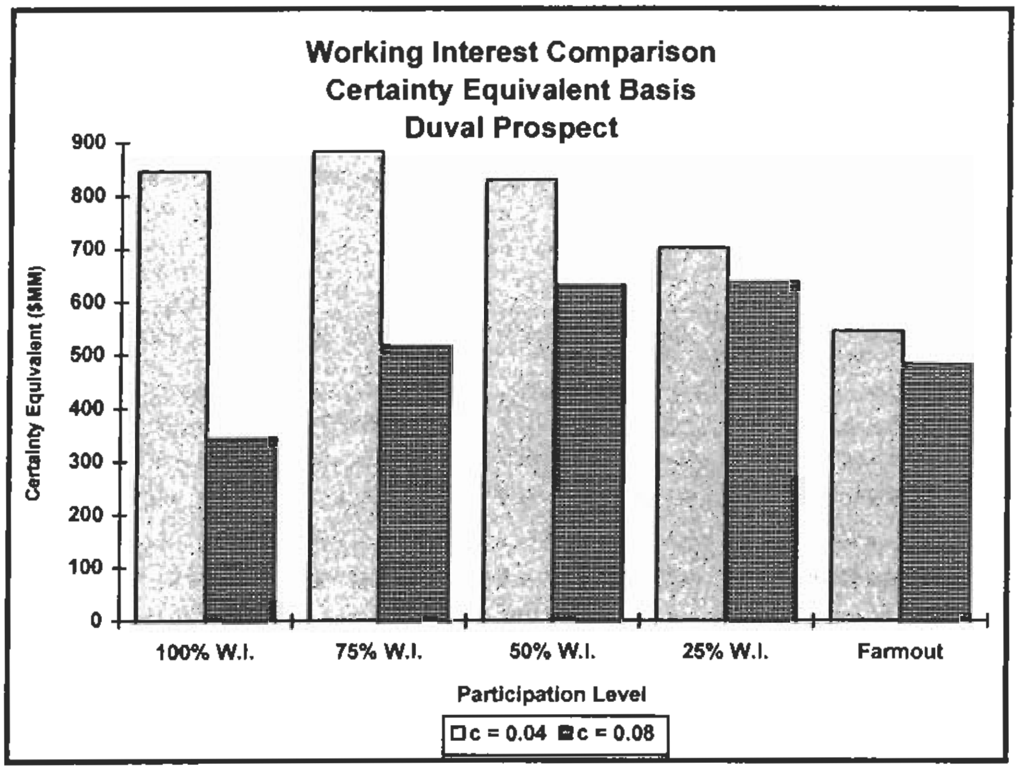


Figure 4: The working interest comparison for the Duval Prospect on a certainty equivalent basis indicates the optimal interest level consistent with Phillips' risk preferences. This graph shows certainty equivalent analysis at five distinct participation levels and for two risk-aversion coefficients, *c*. For a risk-aversion coefficient of 0.04×10^{-6}, the division would maximize its certainty equivalent at the 75 percent working interest [$875,000]. However, at the 0.08×10^{-6} risk-aversion level, the optimal level of interest is somewhere between 25 to 50 percent as the certainty equivalents for these two interest levels are very nearly the same and dominate all other interest levels.

as well as identify optimal participation levels. Also, the company wanted a valuation model that would allow it to evaluate projects as they became available. Though evaluating investments in a portfolio context may be ideal, Phillips learned about investment opportunities incrementally making it necessary for management to evaluate projects throughout the fiscal year. It uses DISCOVERY to evaluate investment opportunities in a consistent manner as they become available. The manager can select from 45 risk-aversion coefficients to rank projects on a certainty equivalent basis. For multiple projects and a specified risk-aversion level, the software identifies the risk-sharing option associated with the highest certainty equivalent for each project and then ranks the projects in descending order based on that value. (In Figure 5, the projects are based on real drilling opportunities that were available to Phillips in 1990–1992; however, to protect confidentiality, we have changed the

	Expected Value Basis			Certainty Equivalent Basis		
Rank	Prospect	Share	EV [$MM]	Prospect	Optimal Share	C_x [$MM]
1	South Louisiana	100%	18.6	Smackover	100%	1.8
2	Norphlet	100%	16.5	Yegua Shallow	100%	1.1
3	Wilcox	100%	11.8	Yegua Deep	100%	1.0
4	Frio	100%	10.8	Vicksburg	75%	1.0
5	Vicksburg	100%	4.0	Wilcox	25%	0.8
6	Yegua Deep	100%	3.0	Norphlet	12.5%	0.8
7	Smackover	100%	2.5	Frio	12.5%	0.7
8	Yegua Shallow	100%	2.2	S. Louisiana	12.5%	0.6

Figure 5: The prospect ranking report shows a comparison of the traditional expected value ranking used by Phillips and the certainty equivalent ranking generated by the software for a group of eight exploration projects. Using the certainty equivalent (C_x) valuation, the ranking report prioritizes exploration projects and identifies the best share for each project based on Phillips' risk attitude. The risk-aversion level used in this analysis is 0.04×10^{-6}.

names and special financial characteristics so that the prospects represent generic equivalents for the main geologic trends that were being explored during these years.)

Compared to expected value analysis, there are important changes in the overall ranking of the projects when we consider the certainty equivalent analysis. The South Louisiana prospect, for example, was ranked as number 1 on expected value, but it ranked number 8 on certainty equivalent. The Smackover prospect, which ranked number 7 for expected value, moved to number 1 on a certainty equivalent basis. Equally important to management was the software's identification of the firm's optimal working interest for each project based on management's risk preferences. For example, for the South Louisiana prospect the optimal level of interest for Phillips has been reduced from 100 percent to 12.5 percent.

By using the prospect-ranking report at different risk-aversion coefficients, managers gain insight into the risk characteristics of the firm's projects and their sensitivity to changes in risk propensity. They also examine the sensitivity of reported results to changes in prospect characteristics. For example, managers look at the impact on certainty equivalence, project ranking, and optimal share if costs were reduced or probability of success was increased. They conduct many of the same sensitivity analyses that anyone might on a capital project, but instead of analyzing only expected value, they look at certainty equivalents, which incorporate the firm's sensitivity to risk aversion.

Managers can also review cash-flow reports for the DISCOVERY-recommended package of projects to see how cash flow affects the exploration unit's capital constraints. They can generate these analyses based on expected value or on the assumption that all projects were successful. Though the DISCOVERY model does not explicitly optimize the prospect package to the unit's capital constraints, there is an implied relationship between the risk-aversion level used and the capital resources available. (Cash management was not the responsibility of the individual exploration unit within Phillips Petroleum. However, DISCOVERY-generated cash flow analyses for recommended projects were available to the corporate office for input into a corporate-wide cash flow model.)

Though managers at Phillips had a strong sense of the riskiness of projects, the software provides them with a formalized and systematic means of evaluating projects' relative riskiness. When exploration capital is limited, managers can use the prospect ranking report to allocate resources and identify the firm's optimal share in a diverse set of risky investments. As a result, the certainty equivalent method of ranking approximates real decision making within Phillips to a much greater degree than expected value ranking.

Measuring Risk Aversion

Measuring the firm's risk tolerance and encoding it as a utility function is imperative in using this type of decision analytic framework. Howard [1988] and Cozzolino [1977] suggest that a relationship exists between certain financial measures (shareholder equity, net income, capital budget size, and so forth) and the firm's risk-aversion coefficient, *c*, in the exponential utility function. Howard suggests that we might, at least in certain industries, be able to use financial statements to develop guidelines for establishing acceptable risk-aversion levels.

Review of past allocation decisions under conditions of risk and uncertainty provides another means of assessing the firm's utility function. In a study of a recent offshore bidding project for BP Exploration, Inc., Wilkerson [1988] found that the firm analyzed 60 investment opportunities (bid blocks) with varying degrees of risk; all 60 investments had positive expected net present values. Due to capital limitations, the firm elected to bid on only 48 of the 60 blocks and of the 48, elected to retain a 100-percent interest in only eight of these. Analysis of these data suggested that the firm's implied risk parameter, *c*, in the exponential utility function was approximately 0.033×10^{-6}. A caveat with regard to this study is that the firm probably had some prior drilling commitments, biases about certain exploratory blocks, or other confounding issues that may have affected the estimation of the risk-aversion coefficient for this set of decisions.

Another method of assessing a petroleum firm's utility function is the industry-specific questionnaire. The decision maker is asked to choose participation levels for five investment opportunities (drilling investments) that are part of the firm's annual budget alternatives. Each of these lotteries has a value of success and a value of failure that represent the present value of all future cash flows net of costs. In addition, the decision maker is presented probabilities of the chance of occurrence of the specific outcomes (success or failure). The decision maker has a choice of six discrete participation options ranging from 100 percent to zero percent. Based on the decision maker's choices, one can approximate an implied utility function assuming the exponential form of utility. The questionnaire can be modified for each firm given its size and the types of exploration projects undertaken. This type of decision framework conforms closely to the oil and gas manager's normal decision process and represents an appealing technique to managers for measuring risk attitudes. Also, unlike the BP Exploration, Inc. study, the questionnaire approach avoids the biases associated with previous exploration projects and, therefore, may provide a more accurate representation of management's attitudes about financial risk.

> Management wanted to rank exploration projects.

General findings from a group of 18 independent and integrated oil companies suggest a rule of thumb relating the firm's risk-aversion level (exponential parameter c) to the firm's budget level for the current period. Our findings indicate that as a first approximation, the firm's c value is equal to the inverse of one-fourth of the firm's annual exploration budget. For example, a firm with an exploration budget of \$40 million would have an approximate risk aversion coefficient, c, of 0.10×10^{-6}. However, this rule represents only a starting point for assessing an individual firm's risk-aversion coefficient. It would be easy to imagine two firms with identical annual exploration budgets and remarkably different risk-aversion levels. These differences are motivated by any number of factors, including managerial exploration philosophy, corporate risk policy, and exploration business unit contribution to the overall corporate portfolio.

In an empirical study, Walls and Dyer [1994] use a DA/EUT model to measure the implied risk-aversion coefficients of 55 independent and integrated oil companies over the period 1981 to 1990. This model reconstructs each firm's annual exploration budget allocations across a set of risky exploration ventures. Based on the amounts each firm was willing to pay to participate in these risky ventures, the authors estimated an implied utility function for each firm in each year. Walls and Dyer found a significant positive relationship between firm size and corporate risk tolerance. In addition, this study suggests that there is an optimal risk policy for a given firm size, in terms of exploration business unit performance. This implies that if we know an oil firm's size, we can estimate an appropriate risk-aversion coefficient, c.

No prior studies at Phillips assessed the corporate or division utility function. So that Eastern Onshore Exploration could use the DISCOVERY model, we reviewed the division's past risky prospect decisions. Using the software, we determined that almost all recent decisions regarding prospects in the onshore Gulf Coast area were consistent with a risk-aversion coefficient between 0.03×10^{-6} and 0.05×10^{-6}. This was also the risk-aversion level that management was comfortable with in evaluating its current inventory of exploration projects.

To understand how one uses this technique of inferring a risk-aversion level, consider again the risk profile curves in Figure 3. Assume that we evaluated the Duval prospect with the software after management decided its participation level. In this evaluation, we use the probability and payoff structures for each risk-sharing scenario that the decision makers used in making the decision. Now let us assume that they elected to participate at the 50-percent level. Based on the risk profile analysis in Figure 3, this implies that their risk-aversion level fell between 0.04×10^{-6} and 0.10×10^{-6}. We can infer this value because at this level of risk aversion, the 50-percent participation level dominates all other participation levels in terms of the certainty equivalent value. We can replicate this approach for a number of investment decisions to estimate a company's risk-aversion level.

Management Support and Implementation

Decision analysis software generally requires the user to have a working, and many times advanced, knowledge of the theory and methods associated with decision analysis and expected utility theory. The DISCOVERY software, however, simplified the analysis process by providing management a means to (1) analyze a variety of development scenarios associated with individual drilling projects and (2) consistently model the entire exploration project inventory, in both economic and risk terms. After we had determined that a narrow range of risk-aversion coefficients was adequate to represent risk preferences, Eastern Onshore routinely analyzed all prospects with DISCOVERY prior to making final recommendations to division exploration management. The software also provides useful guidance to first-line management during negotiations with other companies on costs and risk-sharing terms that are likely to be accepted at higher management levels within Phillips. DISCOVERY is also useful for estimating the true market value of a prospect prior to drilling and the true added value of additional risk-reducing investments in scientific data and surveys.

Currently a number of integrated and independent petroleum exploration firms use the software for purposes ranging from aiding casual individual decisions to completely analyzing the firm's entire prospect inventory. Organizational structure plays an important part in a firm's decision to use this system. Investment risk analysis in an oil company is generally the responsibility of the engineering function. Historically, this functional area has made no clear distinction between the firm's proven, relatively certain petroleum reserve potential and the more risky and uncertain exploration prospects in its economic modeling. DISCOVERY draws a distinction between these two tasks, targeting the allocation of resources for exploration projects. In firms whose exploration departments analyze risk for exploration projects such as Phillips Petroleum, the model is more likely to be accepted. Large firms that have planning and economics groups separate from engineering and exploration also generally show more interest in this type of decision model; perhaps because the software considers the firm's bundle of investment opportunities as a single integrated model—a classic problem facing this functional area in the firm.

Most of the managers' reluctance to use DISCOVERY centers around two issues. First, they are uncomfortable with the notion of measuring the firm's utility function. Moreover, firms that have undertaken a risk preference assessment to determine their utility functions often question whether the assessed function is right for their competitive and operating environments. Even though most decision makers admit that their firms are not risk neutral, they are reluctant to quantify their levels of risk aversion. Developing intuitive and workable means of measuring corporate risk preferences goes a long way towards reducing this reluctance.

Second, applications of decision analysis and utility theory models ultimately result in a trade-off between computational tractability and realism, the main factors that influence implementation of any complex problem solving model. A model for allocating petroleum exploration resources should incorporate the following essential features:

—The ability to help managers overcome some of the limitations in their unaided decision behaviors;

—Effective treatment of risk and uncertainty for the variables of interest;

—The ability to account for the firm's propensity to participate in risky projects;

—Consideration of the company's bundle of investment opportunities in a single integrated model; and

—Understandability, so that users can comprehend the model and its implications for risk management.

The problems associated with trading off computational tractability and realism are exacerbated when the software is designed to enable individuals without professional training in the DA/EUT area to be effective decision analysts in a particular problem domain. Modeling capabilities must be reduced to create a highly structured decision aid in which relationships among variables for the specific class of decision problem are basic components. For example, DISCOVERY provides users with a way to use decision-tree modeling without explicitly constructing a tree; however, this convenience puts a limit on the number of types of decision trees they can use.

Conclusion

The managers of Phillips' North American Division Eastern Onshore Exploration wanted us to integrate a comprehensive discounted cash-flow model with a risk management decision aid. Developing and applying a risk management methodology to this specific class of risky investment decisions was fascinating. We designed and developed a DA/EUT-based decision support system that allowed an exploration department within Phillips Petroleum to ensure a consistent risk attitude in evaluating projects. The DISCOVERY software allows managers to make a reasonable and systematic analysis of a wide range of risky investment opportunities, rank projects realistically, and select participation levels consistent with the firm's willingness to take on risk. We overcame implementation problems by presenting the approach in an intuitively appealing way and by providing a software interface that allows users to take advantage of the modeling and computational power of decision analysis and utility theory without an explicit knowledge of the mathematical framework for those theories. The approach has increased management's awareness of risk and risk tolerance, provided insight into the financial risks associated with its set of investment opportunities, and provided the company a formalized decision model for allocating scarce capital. As a result of this project, Phillips has developed consistent methods of risk analysis that include company-wide analysis of all exploration projects.

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James F. Fox, Geoscience Director, Worldwide Exploration, Phillips Petroleum Company, Bartlesville, Oklahoma 74004, writes, "Phillips Petroleum Company, and the rest of the oil industry, is presented with a unique challenge when exploring for oil. In a business where risks are high and capital is restrained, we must constantly find a better way to remain competitive and provide our shareholders with a good value for their investment. We evaluate many methods on how to assess the balance between risk and reward, and how best to allocate capital.

"The paper by Michael R. Walls, G. Thomas Morahan, and James S. Dyer effectively describes the impact and benefits of the DISCOVERY decision model to Phillips Petroleum Company; it is a valuable tool that works with other evaluation techniques that we use to manage risk. I am pleased that *Interfaces* is publishing this account of a very important and practical contribution to this class of decision analysis."