Uncertainty and Risk Analysis in Petroleum Exploration and Production

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Abstract *During the past decades, there have been some significant improvements in uncertainty and risk analysis applied to petroleum exploration and production. This paper presents a brief overview of the main contributions made in the exploration and production stages, followed by a summary of the main trends in the context of an exhaustible resource. Decisions related to petroleum exploration and production are still very complex because of the high number of issues involved in the process. However, uncertainty and risk analysis are becoming more popular as new hardware and software advances appear, contributing in an important manner to clarify the range and the impacts of new discoveries as well as development and production assets.*

Keywords *uncertainty, risk analysis, decision analysis, portfolio.*

Introduction

Exploration and production of hydrocarbons[1] is a high-risk venture. Geological concepts are uncertain with respect to structure, reservoir seal, and hydrocarbon charge. On the other hand, economic evaluations have uncertainties related to costs, probability of finding and producing economically viable reservoirs, technology and oil price. Even at the development and production stage the engineering parameters embody a high level of uncertainties in relation to their critical variables (infrastructure, production schedule, quality of oil, operational costs, reservoir characteristics etc.). These uncertainties originated from geological models and coupled with economic and engineering models involve high-risk decision scenarios, with no guarantee of successfully discovering and developing hydrocarbons resources.

Corporate managers continuously face important decisions regarding the allocation of scarce resources among investments that are characterized by substantial geological and financial risk. For instance, in the petroleum industry, managers are increasingly using decision analysis techniques to aid in making these decisions. In this sense, the petroleum industry is a classic case of uncertainty in decision-making; it provides an ideal setting for the investigation of corporate risk behavior and its effects on the firm's performance. The wildcat drilling decision has long been a typical example of the application of decision analysis in classical textbooks.

Future trends in oil resource availability will depend largely on the balance between the outcome of the cost-increasing effects of depletion and the cost-reducing effects of new technology. Based upon that scenario, new forms of reservoir

1 Exploration and production of hydrocarbons in this paper encompass all the activities, such as: basin and play analysis, leads, prospect evaluation, development stages, facilities, logistics, management, etc.

exploitation and management will appear where the contributions of risk and decision models are one of the important ingredients. This trend can be seen in the last two decades. The new internationally focused exploration and production strategies were driven in part by rapidly evolving new technologies. Technological advances allowed exploration in well-established basins as well as in new frontier zones such as ultra-deep water. Those technology-driven international exploration and production strategies combined with new and unique strategic elements where risk analysis and decision models represent important components of a series of investment decisions.

This paper covers a brief review of previous applications involving the following topics: (1) Risk and Decision Analysis in Petroleum Exploration; (2) Field Appraisal and Development, and Uncertainty in Production Forecasts, (3) the Decision Making Process and Value of Information and (4) Portfolio Management and Valuation Option Approach. This paper describes some of the main trends and challenges and presents a discussion of methodologies that affect the present level of risk applied to the petroleum industry aimed at improving the decision-making process.

Risk Analysis: Exploration

The historical origins of decision analysis can be partially traced to mathematical studies of probabilities in the 17th and 18th centuries by Pascal, Laplace, and Bernoulli. However, the applications of these concepts in business and general management appeared only after the Second World War (Covello and Mumpower, 1985; Bernstein, 1996). The problem involving decision-making when there are conditions of risk and uncertainty has been notorious since the beginnings of the oil industry. Early attempts to define risk were informal.

The study by Allais (1956) on the economic feasibility of exploring the Algerian Sahara is a classic example because it is the first study in which the economics and risk of exploration were formally analyzed through the use of the probability theory and an explicit modeling of the sequential stages of exploration. Allais was a French economist who was awarded the Nobel Prize in Economics in 1988 for his development of principles to guide efficient pricing and resource allocation in large monopolistic enterprises. Allais' work was a useful means or preview to demonstrate Monte Carlo methods of computer simulation and how they might be used to perform complex probability analysis, instead of simplifications of risk estimation of large areas.

During this period, there were several attempts to define resource level probabilities at various stages of exploration in a basin using resource distribution and risk analysis (Kaufman, 1963; Krumbein and Graybill, 1965; Drew, 1967; Harbaugh et al., 1977; Harris, 1984; Harbaugh, 1984, Harris 1990). At that time governmental agencies (U.S. Geological Survey, Institut Français du Pétrole, etc.) were also beginning to employ risk analysis in periodic appraisals of oil and gas resources (Figure 1).

During the 1980's and 1990's, new statistical methods were applied using several risk estimation techniques such as: (1) lognormal risk resource distribution (Attanasi and Drew, 1985), (2) Pareto distribution applied to petroleum field-size data in a play (Crovelli, 1995) and (3) fractal normal percentage (Crovelli et al., 1997). Recently, USGS has developed several mathematical models for undiscovered petroleum resource assessment (Ahlbrandt and Klett, 2005) and forecast reserve growth of fields both in the United States (U.S.) and the world (Klett, 2005).

Throughout 1960's, the concepts of risk analysis methods were more restricted to academia and were quite new to the petroleum industry when contributions appeared from Grayson (1960), Arps and Arps (1974), Newendorp (1975, edited as Newendorp and Schuyler, 2000) and Megill (1977). Newendorp (*op.cit.*) emphasized that decision analysis does not eliminate or reduce risk and will not replace professional judgment of geoscientists, engineers, and managers. Thus, one objective of decision analysis methods, as will be discussed later in this paper, is to provide a strategy to minimize the exposure of petroleum projects to risk and uncertainty in petroleum exploration ventures.

The assessment to risk model preferences of decision makers can be achieved using a utility function provided by Utility Theory. If companies make their decisions rationally and consistently, then their implied risk behaviors can be described by the parameters of a utility function. Despite Bernoulli's attempt in the 18th century to quantify an individual's financial preferences, the parameters of the utility function were formalized only

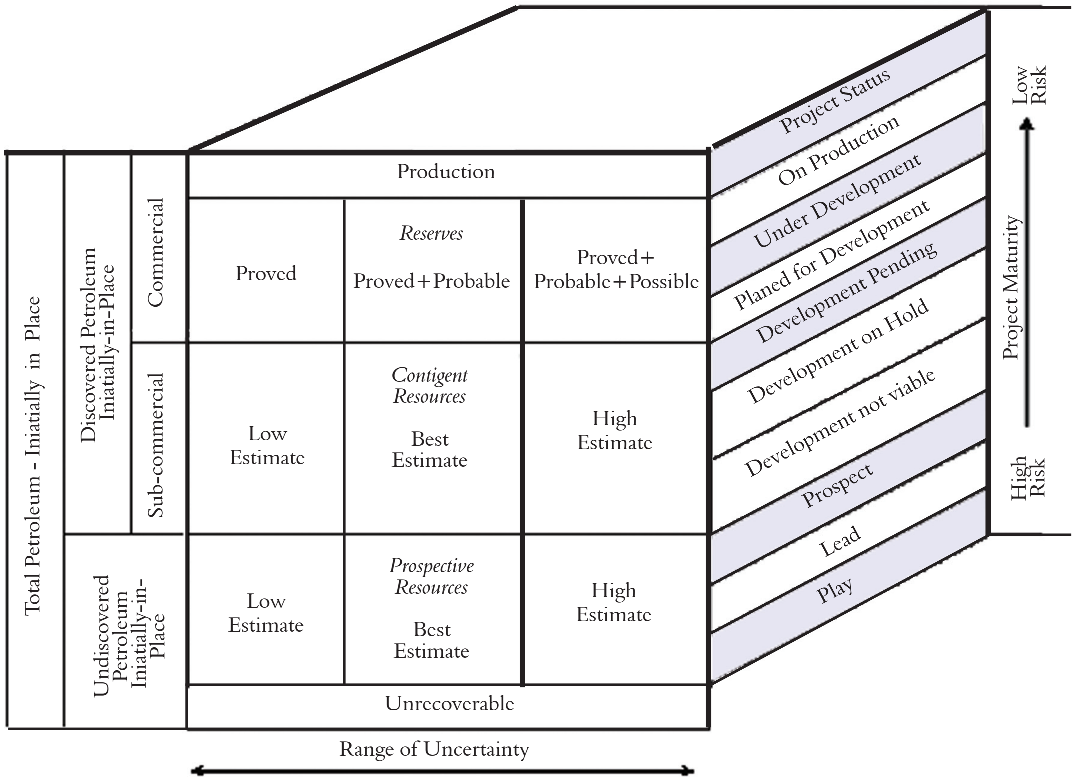

Figure 1 – Petroleum Resource Classification Scheme (modified from Ross, 2004 and SPE/WPC/AAPG, 2000)

300 hundred years later by von Neumann and Morgenstern (1953) in modern Utility Theory. This seminal work resulted in a theory specifying how rational individuals should make decisions in uncertain conditions. The theory includes a set of axioms of rationality that form the theoretical basis of decision analysis. Descriptions of this full set of axioms and detailed explanations of decision theory are found in Savage (1954), Pratt (1964), and Schailfer (1969). Cozzolino (1977) used an exponential utility function in petroleum exploration to express the certainty equivalent that is equal to the expected value minus a risk discount, known as the risk premium. Acceptance of the exponential form of risk aversion leads to the characterization of risk preference (risk aversion coefficient), which measures the curvature of the utility function. Lerche and MacKay (1999) showed a more comprehensible form of risk tolerance that could intuitively be seen as the threshold value, whose anticipated loss is unacceptable to the decision maker or to the corporation.

An important contribution that provides rich insight into the effects of integrating corporate objectives and risk policy into the investment choices was made by Walls (1995) for oil and gas companies using the multi-attribute utility methodology (MAUT). Walls and Dyer (1996) employed the MAUT approach to investigate changes in corporate risk propensity with respect to changes in firm size in the petroleum industry. Nepomuceno F^{o} et al. (1999) and Suslick and Furtado (2001) applied the MAUT models to measure technological progress, environmental constraints as well as financial performance associated with exploration and production projects located in offshore deep waters.

More recently, several contributions devise petroleum exploration consisting of a series of investment decisions on whether to acquire additional technical data or additional petroleum assets (Rose, 1987). Based upon these premises exploration could be seen as a series of investment decisions made under decreasing uncertainty where every exploration decision involves considerations of both risk and uncertainty (Rose, 1992). These aspects lead to a substantial variation in what is meant by risk and uncertainty. Some authors such as Knight (1921) make a distinction between risk (where probabilities are known) and uncertainty (where one is unable to assign probabilities) focusing their analysis on uncertainty. Meanwhile, Megil (1977) considered risk an opportunity for loss. Risk considerations involve size of investment with regard to budget, potential gain or loss, and probability of outcome. Uncertainty refers to the range of probabilities in which some conditions may exist or occur.

Rose (2001) pointed out that each decision should allow a progressively clearer perception of project risk and exploration performance that can be improved through a constructive analysis of geotechnical predictions, review of exploration tactics versus declared strategy, and year-to-year comparison of exploration performance parameters. These findings showed the importance of assessing the risk behavior of firms and managerial risk attitudes. Continued monitoring of the firm's level of risk aversion is necessary due to the changing corporate and industry environment as well as the enormous contribution generated by technological development in E&P. Over any given budgetary period, utilization of an established risk aversion level will result in consistent and improved decision making with respect to risk.

Risk Analysis: Field Appraisal and Development

During the exploration phase, major uncertainties are related to volumes in place and economics. As the level of information increases, these uncertainties are mitigated and, consequently, the importance of the uncertainties related to technology and recovery factor increases. The situation is more critical in offshore fields and for heavy-oil reservoirs, where investments are higher and there is a lower operational flexibility (Pinto et al., 2001).

In the preparation of development plans, field management decisions are complex issues because of (1) the number and type of decisions, (2) the great effort required to predict production with the necessary accuracy and (3) the dependency of production strategy definition on several types of uncertainty with significant impact on risk quantification.

In order to avoid excessive computation effort, some simplifications are always necessary. The key point is to define the simplifications and assumptions that can be made to improve performance without significant precision loss. Simplifications are possible, for instance, in the modeling tool, treatment of attributes and in the way several types of uncertainties are integrated.

One of the simplest approaches is to work with the recovery factor (RF) that can be obtained from analytical procedures, empirical correlations or previous simulation runs, as presented by Salomão and Grell (2001). When higher precision is necessary, or when the rate of recovery significantly affects the economic evaluation of the field, using only the expected recovery factor may not be sufficient.

Techniques such as experimental design, response surface methods and proxy models have been used by several authors (Damsleth et al., 1991; Dejean, 1999; Ligero et al., 2007) in order to accelerate the process. Another possible approach is to use faster models such as a streamline simulation or a fast coarse grid simulation as proposed by Hastings et al. (2001), Ballin et al. (1993), Subbey and Christie (2003), and Ligero et al. (2003).

The integration of risk analysis into the definition of production strategy can also be very time consuming because several alternatives are possible and restrictions have to be considered. Alternatives may vary significantly according to the possible scenarios. Schiozer et al. (2004) proposed an approach to integrate geological and economic uncertainties with production strategy using geological representative models to avoid large computational effort.

Integration is necessary in order to (1) quantify the impact of decisions on the risk of the projects, (2) calculate the value of information, as proposed by Demirmen (2001) and (3) quantify the value of flexibility (Begg and Bratvold, 2002; Hayashi et al., 2007). The understanding of these concepts is important to correctly investigate the best way to perform risk mitigation and to add value to E&P projects.

Therefore, risk analysis applied to the appraisal and development phase is a complex issue and it is no longer sufficient to quantify risk. Techniques today are pointing to: (1) quantification of value of information and flexibility, (2) optimization of production under uncertainty, (3) mitigation of risk and (4) treatment of risk as an opportunity. All these issues are becoming possible due to hardware and software advances, allowing an increasing number of simulation runs of reservoir models with higher complexity (Gorell and Basset, 2001).

Decision Making Process, Value of Information and Flexibility

Making important decisions in the petroleum industry requires incorporation of major uncertainties, long time horizons, multiple alternatives, and complex value issues into the decision model. Decision analysis can be defined on different and embedded levels in petroleum exploration and production stages. Raiffa (1968) and Keeney (1982) defined decision analysis as a philosophy, articulated by a set of logical axioms, and a methodology and collection of systematic procedures, based upon those axioms, for responsibly analyzing the complexities inherent in decision problems. Several textbooks can be found in Raiffa, 1968; Keeney, 1982; Keeney and Raifa, 1976; Howard, 1988; Kirkwood, 1996, and Clemen, 1990. In the last two decades, the theoretical and methodological literature on various aspects of decision analysis has grown substantially in many areas of petroleum sector, especially in applications involving health, safety, and environmental risk.

Many complex E&P decision problems involve multiple conflicting objectives. Under these circumstances, managers have a growing need to employ improved and systematic decision processes that explicitly embody the firm's objectives, desired goals, and resource constraints. Over the last two decades, the advances in computer-aided decision making processes have provided a mechanism to improve the quality of decision making in the modern petroleum industry. Walls (1996) developed a decision support model that combines toolbox system components to provide a comprehensive approach to petroleum exploration planning from geological development through the capital allocation process.

An effective way to express uncertainty is to formulate a range of values, with confidence levels assigned to numbers comprising the range. Although geoscientists and engineers may be willing to make predictions about unknown E&P situations, there is a need to assess the level of uncertainty of the projects. So, it's necessary to define the value of information associated with important decisions such as deferring drilling of a geologic prospect or seismic survey. Information only has value in a decision problem if it results in a change in some action to be taken by a decision maker. Furthermore, this change must bring an expected benefit greater than the cost of information. The information is seldom perfectly reliable and generally it does not eliminate uncertainty, so the value of information depends on both the amount of uncertainty (or the prior knowledge available) and payoffs involved in E&P projects. The value of information can be determined and compared to its actual cost and the natural path to evaluate the incorporation of this new data is by Bayesian analysis.

As the level of information increases, the decision making process becomes more complex because of the need for (1) more accurate prediction of field performance and (2) integration with production strategy. At this point, the concept of Value of Information (VoI) must be integrated with the Value of Flexibility (VoF) as shown by Hayashi et al. (2007). Therefore, risk may be mitigated by more information or flexibility in the production strategy definition. Reservoir development by stages and smart wells are good examples of investments in flexibility. The decision to invest in information or flexibility is becoming easier as more robust methodologies to quantify VoI and VoF are developed.

Risk Mitigation through History Matching

The integration of risk analysis and production history matching is also a subject that has recently been receiving special attention (Schiozer et al., 2005; Maschio et al., 2005; Suzuki and Caers, 2006; MA et al., 2006; Kashib and Srinivasan, 2006). The general idea is to integrate the processes of reservoir development when uncertainties exist and the reservoir management process in order to mitigate risk gradually as production is observed and used to reduce uncertainties in geologic attributes. This type of procedure has a great potential of improvement as new tools are being developed to speed up the process, which requires high computational effort.

Portfolio Management and the Real Options Valuations

Asset managers in the oil and gas industry are looking to new techniques such as portfolio management to determine the optimum diversified portfolio that will increase company value and reduce risk. Under this approach employed extensively in financial markets, projects are selected based upon quantitative information on their contribution to the company's long-term strategy and how they interact with the other projects in the portfolio. The financial market and efficient portfolio theory was proposed by Markowitz (1952), winner of the 1990 Nobel Prize in Economics. This work has been adapted for the petroleum industry. A portfolio is said to be efficient if no other portfolio has more value while having less or equal risk, and if no other portfolio has less risk while having equal or greater value. The most important principle in portfolio analysis theory is that the emphasis must be placed on the interplay among the projects (Ball and Savage, 1999). The original idea states that a portfolio can be worth more or less than the sum of its component projects and there is not one best portfolio, but a family of optimal portfolios that achieve a balance between risk and value.

As the number of project opportunities grows, the petroleum industry is faced with an increasingly difficult task in selecting an ideal set of portfolios. Figure 2 pointed out the complexity of integration of geological, engineering, economic, and fiscal modeling - all in the context of the firm's strategic objectives.

Mathematical search and optimization algorithms can greatly simplify the planning process. A particularly well-suited class of algorithms has been developed recently for oil and gas applications in portfolio management (Davidson and Davies, 1995; Chorn and Croft, 1998; Orman and Duggan, 1998; Fichter, 2000; Back, 2001; Erdogan and Mudford, 2001; Garcia and Holtz, 2003). Combined optimal portfolio management with probabilistic risk-analysis methodology are thus helping to guide managers in evaluating a portfolio of E&P projects, not just according to their value, but also by their inherent risk. Knowing the firm's attitude about taking financial risk is important in terms of selecting the appropriate portfolio of activities. These linkages between decision analysis and portfolio management can improve the overall decision process, and ultimately, firm performance as pointed out by Walls (2004). Ross (2004) provided a better characterization of a portfolio of oil and gas assets using a consistent definition of risk and uncertainty, combined with resource classification based on a clear distinction between project maturity and volumetric uncertainties.

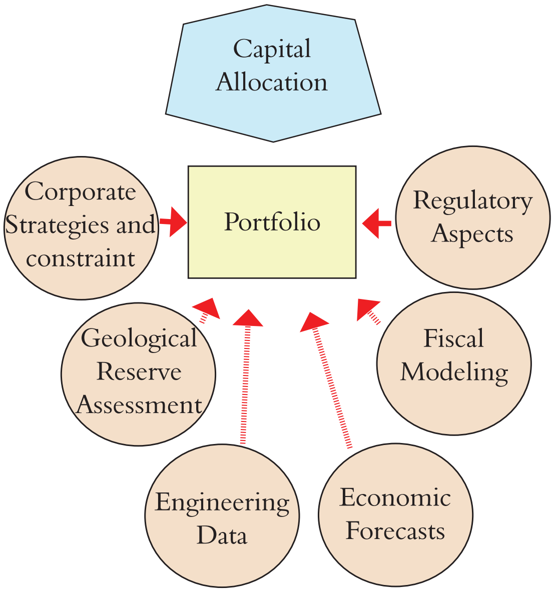

Figure 2 – Integrated decision process and portfolio optimization for E&P projects

For several decades in the petroleum industry, the most common form of asset valuation has been the standard discounted cash-flow (DCF) analysis (Figure 3). However, over the past few years, an increasing number of institutions and organizations have been experimenting with other valuation approaches to overcome some limitations imposed by the DCF approach. The real options approach is appealing because exploration and production of hydrocarbons typically involve several decision stages, each one with an investment schedule and with associated success and failure probabilities. For example, in the exploration phase the project can be viewed as an infinitely compounded option that may be continuously exercised as the exploration investment is undertaken. Traditional methods based upon discounted cash flow, reported in the finance literature, are always supported by static assumptions – no mention about the value of embodied managerial options. Kester (1984) was the first to recognize the value of this flexibility. Mason and Merton (1985), and Myers (1987), among others, suggested the use of option-based techniques to value implicit managerial flexibility in investment opportunities, such as those of abandonment reactivation, mothballing and timing.

Some important earlier real options models in natural resources include Tourinho (1979), first to evaluate oil reserves using option-pricing techniques. Brennan and Schwartz (1985) applied option techniques to evaluate irreversible natural resource assets and McDonald and Siegel (1985) developed similar concepts for managerial flexibility. An important aspect of the majority of exploration and production projects is the value of waiting until new options may emerged (i.e., technology, price, cost reduction) has been modeling by McDonald and Siegel (1986). After real options theory became widely accepted in financial markets, applications in the oil industry followed rapidly. Siegel et al. (1987) and Paddock et al. (1988) evaluated offshore oil leases. By the mid 1990's, several textbooks had been published (Dixit and Pindyck, 1994; Trigeorgis, 1996; and Luenberger, 1998) and the range of applications had widened to include applications in several economic sectors. Bjerksund and Ekern (1990) showed that it is possible to ignore both temporary stopping and abandonment options in the presence of the option to delay the investment for initial oilfield development purposes. Galli et al. (1999) discussed real options, decision-tree and Monte Carlo simulation in petroleum applications. Laughton (1998) found that although oil prospect value increases with both oil price and reserve size uncertainties, oil price uncertainty delays all option exercises (from exploration to abandonment), whereas exploration and delineation occur sooner with reserve size uncertainty. Chorn and Croft (2000) studied the value of reservoir information.

Armstrong et al. (2004) developed a type of Bayesian analysis and coupled it with real options theory to address the question of how to evaluate the option to acquire more information. The results applied in the case of an oil company that has the option to gather information from the production logging tool before carrying out a workover, for example, showed that the value of the option was less under conditions of high oil prices than for lower oil prices. Dias (2004) presented a set of selected real options models to evaluate investments in oil exploration and production under market and technical uncertainties. In his paper, the author summarized the classical model of Paddock, Siegel and Smith that exploits a simple analogy between American call options and real options model for oilfield development.

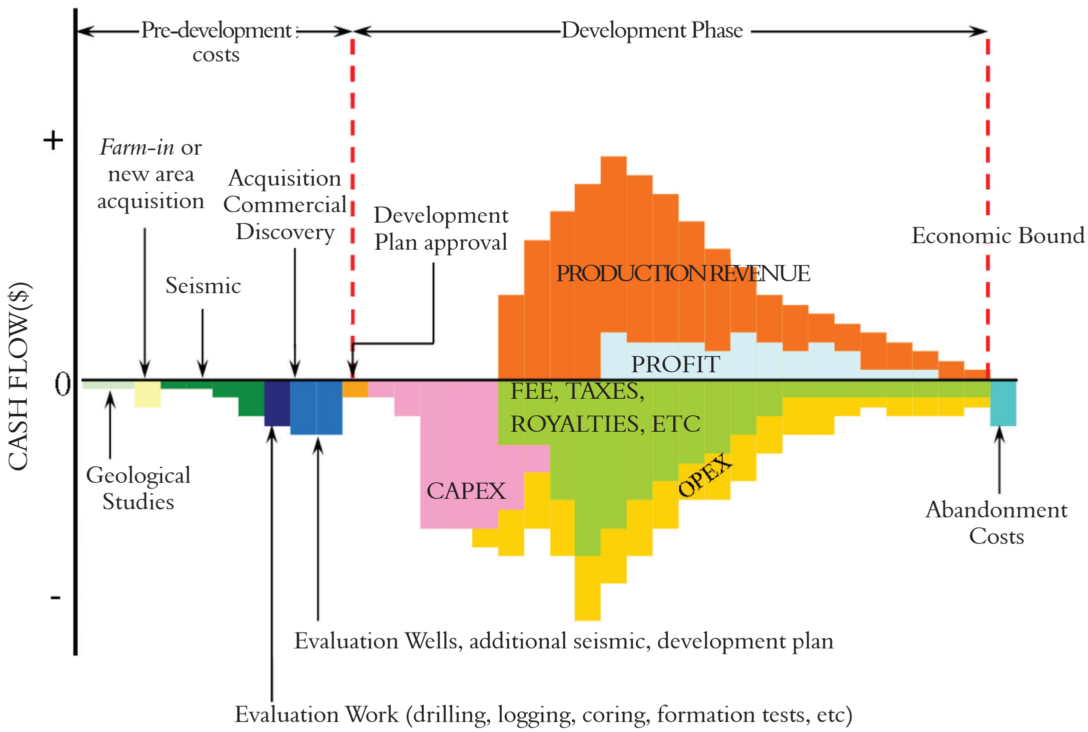

Figure 3 – A typical E&P cash-flow project based upon the Brazil Fiscal System (Suslick, 2005)

In oil project valuation and investment decision-making, volatility is a key parameter, but it is difficult to estimate. From a traditional investment viewpoint, volatility reduces project value because it increases its discount rate via a higher risk premium. Contrarily, according to the real-option pricing theory, volatility may aggregate value to the project, since the downside potential is limited whereas the upside is theoretically unbounded. Costa Lima and Suslick (2006) suggest an alternative numerical method based on present value of future cash flows and Monte Carlo simulation to estimate the volatility of projects. Results obtained indicate that commodity volatility usually undervalues that of the project. For the set of offshore projects analyzed by the authors, project volatility is at least 79% higher than that of oil prices and increases dramatically in those cases of high capital expenditures and low price.

General Discussion

Over the coming decades, the world will continue to rely heavily on large-scale supplies of oil and gas. As the industry moves on to more and more "difficult" oil and gas deposits, the pace of technological progress will need to accelerate significantly if past production trends are to be maintained. So, decisions related to petroleum exploration and production are becoming very complex because of the high number of issues involved in the process. However, concepts of risk analysis applied to exploration, appraisal and development phases are becoming more popular as new hardware and software advances appear. New methodologies are being developed to help to mitigate risk, and the academic and industrial sectors are substantially contributing to improve the overall process.

Most organizations have settled on using consistent risk analysis procedures to assess all E&P projects. Some oil companies have developed their own risk analysis software and algorithms. Other companies have licensed customized software from several different vendors or consulting firms. An important result of this trend is that geological, technical and economic parameters can be preserved, thus facilitating subsequent project review for purposes of performance analysis. According to Rose (2001) this provokes some inevitable changes in corporate culture, operating values and tactics, and the reward system.

Risk analysis has several limitations, pitfalls and practical difficulties that affect its value as a decision tool. In some cases, these limitations are due less to inherent limitations in decision analysis than to deficiencies in specific applications of the approach in upstream petroleum projects. There is a need to understand how most effectively to model project level risks, whether they are those that affect output possibilities or those that directly influence costs. At the same time, this trend generates a need to fine-tune risk analysis methods by finding out how to use more discretization without intolerable loss of accuracy yielding a search for a next generation of tools for more complex simulation models. These developments will stimulate new progress as better models and methods make the analytical tools more flexible and accurate, and thus more attractive. This will increase the demand for the development of better risk and decision analysis software and training tools, the development of which will make the analyses more attractive and will encourage the development of better models and methods.

Most of the methodologies described in this paper are applied to geological and economic uncertainties which are the most important parameters of the process; however, there is still need for research on dealing with operational and technology uncertainties and also for better reservoir characterization procedures when uncertainties exist.

Despite these limitations and difficulties, risk analysis has several major strengths and achievements in petroleum exploration and production, as has been shown in this paper. First, risk analysis provides a means for handling highly complex decisions characterized by multiple objectives and high degrees of uncertainty in diverse stages of petroleum upstream. Second, risk analysis provides an approach for dealing with complex value tradeoff and preferences of the stakeholders in the decision process in oil exploration and production. Third, risk analysis provides a systematic and comprehensive way for considering all relevant factors in E&P process decision.

Currently unknown technologies can be expected to be available for future exploitation of oil resources in new frontiers (especially ultra-deep water and heavy oil) with important impacts on risk mitigation and economics. While the timing and frequency of these yet unknown technologies are speculative, longer trend cycles favor the use of technological risk models. Recently obtained results indicate that the technological progress for these new environments can be used to measure the firm's strategic decision for technological risk aversion as well as ranking projects with several technological characteristics.

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Suslick, S.B., Schiozer, D. and Rodriguez, M.R. (2009) Uncertainty and Risk Analysis in Petroleum Exploration and Production. Terrae, 6, 30-41. has been cited by the following article: TITLE: Methods in Oil Recovery Processes and Reservoir Simulation. AUTHORS: Pablo Druetta, Pietro Tesi, Claudio De Persis, Francesco Picchioni.Â Production of Ca2AlNbO6 Ceramics and Study of Their Stability in Crude Petroleum for the Conservation of Metallic Sensing Elements used in Petroleum Extraction. Yogendra P. Yadava, Marilaine M. de Lima, JosÃ© Carlos S. Oliveira, Ricardo A. Sanguinetti Ferreira. DOI: 10.4236/msa.2012.36058 4 933 Downloads 6 723 Views Citations. To counter these issues in petroleum exploration and production (E&P), companies need to integrate disciplines and rely on approaches that include data integration, risk assessment and quantification of uncertainty. Soft computing methods offer an excellent opportunity to integrate information from various sources with varying degrees of uncertainty. These methods also help to establish relationships between measurements and reservoir properties in a multidimensional, multivariate and stochastic environment, and to assign risk factors to predictions. By applying analytics, you can optimize Petroleum Economics. Decision and Risk Analysis. Print Email. Course Progression Map - Petroleum Economics. Advanced. Portfolio Management. Skill. Economics of Petroleum Exploration. Foundation. Petroleum Economics.Â Participants will gain an overview of important concepts and examples of decision analysis. Uncertainties, risk, and the various ways to incorporate them in oil and gas project evaluations will be discussed throughout the course. A key concept that will be covered is the use of a proven decision analysis process, incorporating sensitivities, decision trees, and the value of information, in both deterministic and probabilistic approaches to evaluating oil and gas projects. This course uses Excel, as well as the Merak software Peep and Decision Tool Kit.