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A MULTICRITERIA DECISION MODEL FOR SELECTING A PORTFOLIO OF OIL AND GAS EXPLORATION PROJECTS

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ABSTRACT. As well as exploratory activity being at the heart of and guiding the future of the oil industry, it is fundamental that there be a comprehensive analysis covering the various factors and nuances that arise in the selection of exploration projects. Moreover, it is essential that a decision model enables the decision-maker's preferences to be addressed in a structured (and methodologically correct) way, and one which is easy to understand and to apply in a real-world. Therefore, this paper proposes a multicriteria decision model which underpins using a deterministic procedure for selecting a portfolio of oil and gas exploration projects and thereafter a reality-based application is set out, based on a decision making context within Petrobras.

Keywords: portfolio selection, exploration projects, multicriteria decision aid.

1 INTRODUCTION

Portfolio management is the centralized management of one or more portfolios, which includes identifying, prioritizing, approving, managing and controlling projects, programs, and any related works, in order to achieve specific, strategic business objectives (PMI, 2008). Specifically, the step of selecting and prioritizing projects and portfolios is a theme that has been widely discussed in the literature (Lin & Ji, 2007; Gomes *et al.*, 2010; Almeida & Duarte, 2011; Vetschera & Almeida, 2012). According to Levine (2005), the goal of this step is to create the most appropriate set of projects to support achieving organizational goals, aligned with the preferred strategies and resource constraints of the company. Several studies note a very significant move in order to prioritize projects. This uses not only a financial analysis of the return on investments but should also consider strategic issues, the characteristics of the projects, the implications of research and development projects, marketing conditions, use of resources, the probabilities of success of the projects and non-financial benefits arising from successful projects. The process of allocating capital and the quality of related decisions remain a critical factor influencing the

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overall performance of an organization (Walls, 2004). This is particularly true for oil companies in which characteristics of risk and uncertainty are inherent in shaping their capital investment.

The petroleum Exploration and Production (E&P) industry is characterized as having high volatility in the pricing of its products and being under severe pressure to provide minimized cost structures. When dealing with oil and gas exploration projects, it is fundamental that there be a comprehensive analysis covering the various factors and nuances that arise in the selection phase of such projects. This requires a correct understanding of the decision-maker's preferences and the business environment to which the decision-maker belongs. Therefore, the routine use of EMV (Expected Monetary Value) as a criterion does not include evaluating the trade-off on the decision-maker's preferences between the Net Present Value (NPV) of a successful exploration project, the project's geological chance factor and the Dry Hole Cost (DHC) of an unsuccessful project. Thus, it is essential that a decision model enables the decision-maker's preferences to be addressed in a structured way, and one which is easy to understand and to apply in a real-world situation.

This paper proposes an alternative multicriteria decision approach for selecting a portfolio of oil and gas exploration projects. The geological chance factor (or probability of success), which is the fundamental uncertainty element for evaluating exploration projects and normally used to calculate the EMV of projects, is tackled in an alternative way: it is added to the hierarchy of the decision-maker's objectives in order to formally evaluate his/her preferences over this uncertainty characteristic. Moreover, a SMARTER-based multi-attribute additive value is constructed for each project, which facilitates the procedure for eliciting one dimensional and multicriteria preferences. This consideration underpins using a deterministic approach for selecting exploration projects.

The proposed model is described for tackling the problem and thereafter a reality-based application is set out, based on a decision making context within Petrobras. Questions relating to taking multiple objectives into consideration are analyzed within the SMARTER approach, which includes using the chance factor as a fundamental criterion. After that, a knapsack optimization model is constructed using multi-attribute values and some specific conditions set out which must be added in choosing projects for the portfolio (such as the technological, management, financial and budget constraints).

2 PROJECT PORTFOLIO SELECTION AND PRIORITIZATION

The modern concept of risk diversification and portfolio selection and prioritization is credited to Harry Markowitz, whose paper entitled Portfolio Selection was published in 1952 (Markowitz, 1952). According to Markowitz, the risk of a portfolio depends not only on each element and its participation in total investment, but also how its components relate to each other. This is the main concern when dealing with the portfolio problem.

In general terms, a portfolio problem may be defined as: a problem which involves selecting one or several out of a set of possible items, under some constraints, which limit the possibility of selecting items and where outcomes are determined by some form of aggregating the properties of the items selected (Vetschera & Almeida, 2012). Archer & Ghasemzadeh (1999) defined a project portfolio as a group of projects that are conducted under the sponsorship and/or management of an organization. Based on this, Blichfeldt & Eskerod (2008) cited project portfolio management as the management activities related to initially screening, selecting and prioritizing project proposals, simultaneously reprioritizing projects belonging to the portfolio, and allocating and reallocating funds to projects in accordance with the priorities established.

In a project management context, project selection is the periodic activity involved in selecting a portfolio from available project proposals and ongoing projects, which somehow adhere to the goals established by the organization, do not exceed available resources or violate other constraints (Archer & Ghasemzadeh, 1999). Lin & Ji (2007) discussed two visions for the portfolio problem: on the one hand, there are procedures for capital investment which use traditional operational research techniques to guide and support decisions; on the other hand, executives admit that management makes selections intuitively based on their gut feelings. What is common is to construct models based on structured plans which measure the benefits of the investment – returns and risk.

Mavrotas *et al.* (2008) used a different approach. According to them, the intention is not to maximize aggregate performance by combining projects, but rather to maximize the compatibility of the final selection to the initial ranking of the projects. They also relate why the basic difference between the two concepts is due to the inevitable budget constraints, which cause a bias toward selecting low-cost projects. This bias, however, can be monitored and controlled by adding specific constraints during the optimization step, thus avoiding this kind of problem.

It should be noted that exploration projects can commonly present positive or negative correlations. A project's success or failure can adversely affect other geological and engineering interpretations, the probability of success, and so forth. This possibility is different to risk considerations in Finance Portfolio Theory, based on Markowitz (1952), which minimizes financial portfolio risk by diversifying the projects selected, assuming that selecting high covariance projects is potentially prejudicial to the portfolio. In the context of a portfolio of exploration projects, positive, negative or even no correlation and synergies between the projects may occur and this may even be desirable.

Coldrick *et al.* (2005) affirmed that a wide variety of project selection models has been developed in recent years, including linear programming, scoring models and checklists. In their research on the use of portfolio management models, Cooper *et al.* (2001) concluded that the use of any tool or system for portfolio selection is quite beneficial. These benefits culminate in a more balanced portfolio aligned with the organization's strategic goals. The authors claimed that cases in which more than one method is used in selecting the portfolio have the best results, due to the fact that not every method has best performance in all areas.

An important operational consideration is that while there are several methodologies that can be used in selecting a portfolio, there is no consensus on which is the most effective (Archer

& Ghasemzadeh, 1999). Moreover, the methodologies that are the most useful in developing the portfolio for one class of projects may not be the best ones for another class. The choice of method depends greatly on the decision context, stakeholders and what is sought from the decision. This situation is also typical in a multicriteria decision problem, where the preferences of the analyst and the decision-maker directly influence what multicriteria method is chosen.

Selecting a subset of candidate projects for financial support, within the limitations of the reality of a budget is a typical multicriteria ranking problem, where the decision-maker must decide which portfolio would provide the most attractive alternatives after different aspects of the efficiency of the projects are taken into account (Mavrotas *et al.*, 2008). Xidonas *et al.* (2009) affirmed that the multidimensional nature of the problem is emphasized by researchers in finance, as well as by those in MCDM research. Elaborate and exhaustive justifications are provided for modeling portfolio management problems within the MCDM framework. Indeed, the authors explain why an MCDM framework provides a sound, methodological basis for tackling the inherent multicriteria nature of the portfolio selection problem. For them, MCDMs have the advantage of taking into account any given investor's objectives and preferences, besides the two basic criteria of return on investment and risk.

3 EXPLORATION PROJECTS

The petroleum industry is one of the most powerful industries in today's economy, and mobilizes large and small countries and multinational companies, political and environmental organizations, etc. In particular, oil and gas Exploration and Production (E&P) activities are typically risk activities, which may well have high financial returns. They involve high levels of investment which need investment over long periods of time and often high-tech resources. This is particularly true when dealing with offshore projects.

Investments in E&P projects involve a large number of technical matters such as the probability of finding oil in a given prospect, the amount of oil in place in a field and the technology necessary to exploit this field and bring it into production. Moreover, the oil industry's activities require that environmental and social aspects and their inherent impacts be monitored, as well as providing for an effective response to any accidents, including serious accidents such as the one that occurred recently in the Gulf of Mexico (BP, 2011).

E&P activities can be grouped into three main phases: exploration; the development of production; and the production period. During the exploration phase, geological and geophysical studies are carried out to map and define the opportunities within the region studied, and may include drilling one or more exploration wells. If the exploratory phase is successful and the company wishes to continue the project, the production development phase follows. In this stage, the design and construction of facilities take place, besides drilling production and injector wells. Then, after setting up the necessary infrastructure, the production phase generates the regular production of hydrocarbons.

According to Rose (1992), exploration can be seen, idealistically, as a series of investment decisions made under decreasing uncertainty where every exploration decision involves considerations of both risk and uncertainty. Replacing reserves remains a key challenge for international oil and gas companies (Mohn & Osmundsen, 2006). Thus, exploratory activity lies at the heart of and guides the future of the oil industry. This is what drives proposals for a focused analysis of exploration opportunities. There is a major difference between the nature of exploration projects and other kinds of E&P projects: exploratory projects have a greater degree of uncertainty, either technically or economically. Furthermore, during the exploration phase, E&P projects present stronger subjective aspects involving their activities, such as possible synergies between the project and other projects in the company portfolio. Thus, a separate analysis is needed for selecting exploration projects.

According to Suslick & Furtado (2001), exploring and producing oil involves risky investments. The authors affirmed that when petroleum executives make investment decisions on petroleum projects, they face several uncertainties including future oil prices, reserves, environment, the chances of finding petroleum, fiscal terms, current degree of exploration and operational peculiarities. For each exploration project, estimates are made of the risk (chance) that an exploration well will be a dry hole and the risk that, if a discovery is made, it will be too small to be commercially viable (Ross, 2004).

Gomes *et al.* (1999) applied two multicriteria decision methods (Promethee and Todim) to ranking production development projects, which were in the project portfolio of Petrobras. The authors addressed the differences between these approaches in ranking the projects, and they analyzed and compared the results obtained. Gomes *et al.* (2009) evaluated the selection of the best development option of the natural gas reserves recently discovered in the Santos basin, in Brazil. These options differed and are dependent on whether the development of the discoveries will be accelerated or normal, as well as on the market that will consume the gas produced, and on whether this market will be domestic and/or foreign. They affirmed that the decision criteria traditionally used in a problem of this nature, which basically deal with economic and financial questions, do not consider other equally important features, such as: the political and economic stability of a country, the in-country regulatory environment, tax regime or supply and demand, and so forth.

Suslick & Schiozer (2004) affirmed that, in the petroleum industry, managers are increasingly using decision-analytic techniques to aid making such decisions. In their paper, the authors showed some of the contributions and developments of risk analysis as applied to petroleum exploration, appraising and developing fields, forecasting production under uncertainty, the decision-making process, portfolio management, and a real options approach. Margueron & Carpio (2005) argued in favor of theoretical developments in techniques of decision-making analysis in petroleum exploration and production projects. A case study using Multi-attribute Utility Theory (MAUT) was developed and applied so as to define priorities among ten offshore exploration opportunities according to decision-makers' preferences regarding operational, political and technological issues. The authors argued how important it is that typical risks and uncertainties should be considered in international petroleum upstream investments in competitive situations. Nepomuceno Filho *et al.* (1999) proposed a model that enables decision-makers to include the value of technological advances systematically into the process of allocating capital among a set of exploration and production projects. This model is based on multi-attribute utility and enables the company to formally incorporate its willingness to take both financial and technological risks.

Ross (2004) presented an example of a probability distribution function that reflects two fundamental results of an exploratory project (see Fig. 1), in relation to the geological risk (success and failure) as well as the uncertainties arising in these two outcome values (NPV and DHC). The author affirmed that the use of the EMV (Expected Monetary Value) concept requires a significant number of projects to be included in the portfolio so that the EMV values make sense. The author points out that although this fact is understood by most practitioners, it is surprising that it is almost always overlooked or ignored.

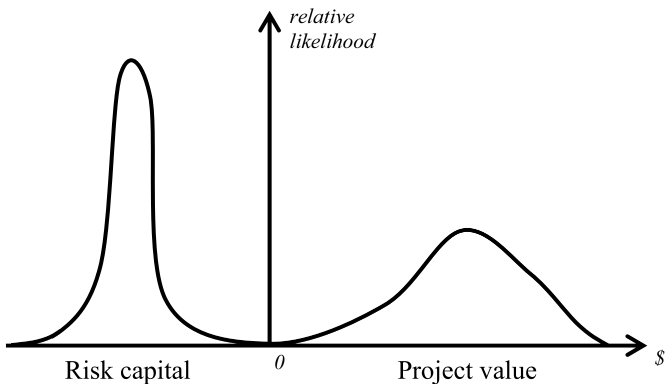

Figure 1 – A probability density function of an oil exploration project (adapted from Ross, 2004).

In the exploration context, three types of technical uncertainty about hydrocarbon reserves are present (presence, volume and quality); and, first and foremost, the greatest uncertainty is whether or not an oil field exists, which is normally modeled by an exploratory factor chance or probability of success. Because this factor constitutes, in general, the most important and crucial element of uncertainty when evaluating exploratory projects and portfolios, there are situations in which the analysis may concentrate on this risk dimension and consider it unique. Thus, uncertainty parameters of the NPV (oil/gas selling price and the reserve volume, etc.) and of the risk capital (wildcat cost) should be disregarded: the probability density function of the outcome of an exploration project becomes a binomial distribution: if successful geologically, the value of the result corresponds to a single NPV; otherwise, to a single value of DHC.

Figure 2 shows a common and simple decision tree of an oil exploration project. It is a dichotomous situation: in case of success (S), there is an oil discovery and the NPV of the project considers the prospect development, the necessary investments and future oil revenues; in case of failure (F), the NPV considers only the dry hole cost (DHC) as a project's risk capital. Thus, the expected monetary value (EMV) is calculated using the probability of each situation.

As to the EMV criterion to evaluate exploration projects, a more comprehensive analysis should be performed. For instance, consider projects A, B and C presented in Figures 2 and 3: the EMV value is the same for both all 3 projects. When comparing projects A and B, which have the same risk capital, project B has a higher chance factor than project A and project A presents a higher NPV outcome in case of geological success. Although project C has the same NPV as project A, in a success case, the projects have different success probabilities and risk capitals. Among the three projects presented, a decision-maker may prefer project A relative to project B, due to the higher NPV if it is successful, and when compared to project C, due to its higher risk capital. On other hand, another decision-maker will prefer project B compared to project A because he/she accepts a lower NPV since the project's success probability is considerably higher. Risk capitals and, principally, success probabilities are key factors that must be considered separately when selecting an exploratory portfolio. More details of this approach are given in Section 5.1.

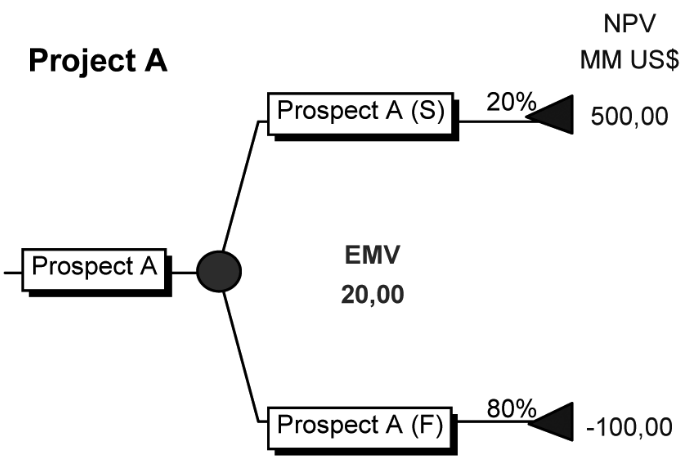

Figure 2 – A decision tree of an oil exploration project.

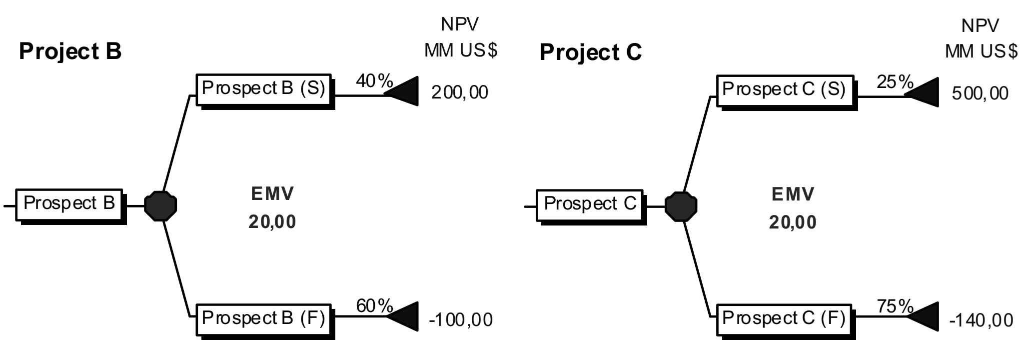

Figure 3 – Different projects with the same EMV.

Moreover, the EMV criterion cannot capture other aspects that involve selecting exploratory projects which are, depending on the situation, as important as purely financial aspects, or are even more critical. For example, a project that is located in an exploration frontier (a region where there is little or no exploration activity) cannot be analyzed only by financial indicators. This is because what is learned about this exploration will add more comprehensive knowledge about the area studied. Thus, it may well provide improvements and positive synergies for future projects.

In the global market, E&P activity must add, in its considerations, economic aspects to the technical points. An economic analysis is mandatory in almost all investment decisions, which require special attention being given to choosing: the valuation method; the fiscal terms used in the country where the investment opportunity is located; and macroeconomics parameters, such as oil prices and market alternatives for oil revenues. Another indicator often used for selecting E&P projects is the necessary CAPEX (Capital Expenditures) for all phases of the project. The CAPEX of the project development phase, which occurs after an exploration success, is different from the CAPEX needed for the exploration phase, which requires strictly less financial effort. These two types of CAPEX are considered due to the budget being limited which may vary according to the project phases and determine the limit of the company's investments.

What must be added to the factors described above is the importance of choosing the appropriate methodology to aid this investment decision. The Exploration and Production industry commonly uses the EMV criterion and traditional financial theory, since this analyzes the projects' discounted cash flows, profitability indicators and related decision trees.

In a group of potential exploratory investment projects, each with its own potential and weaknesses, investment selection becomes a trade-off decision: one type of benefit is gained only if something in another aspect is lost. These trade-off decisions on choices of strategic points can be agonizing, and normally are resolved only after long and careful consideration of the pros and cons of each project. Besides the number of factors involved, there are different options for selecting projects and what is wanted is to choose those for the portfolio which maximize the decision-maker's and organization's objectives.

4 MULTICRITERIA DECISION AID

Multicriteria Decision Aid (MCDA) or Multicriteria Decision Making (MCDM) is a set of methods and techniques to aid and support people and organizations to make decisions under the influence of a variety of criteria. Multiple Criteria Decision Making (MCDM) is firmly rooted in an alternative concept of optimality where multiple (rather than single) criteria characterize the notion of "the best" (or optimal), as is prevalent in the areas of economics, engineering, management and business (Zeleny, 1998).

MCDA involves other aspects besides the appropriate treatment for multicriteria problems. According to Roy (1996), decision support is the activity of a person who, by using explicit, but not necessarily completely formalized models, helps in detecting the elements that respond to issues raised by stakeholders in decision-making. These elements help make the decision clearer and recommend a behavior that will increase consistency between the evolution of the process and stakeholders' goals and system values. As pointed out by Belton & Stewart (2002), the main benefit of MCDA is to facilitate the learning of the decision-maker about problems in their priorities, values and goals, as well as those of other stakeholders and the organization, and how to use MCDA in the context of a problem in order to guide identifying a preferred course of action. The key aspect that should be emphasized is that MCDA provides tools for decision support, not decision making tools.

Traditionally, MCDA methods can be classified into compensatory and non-compensatory ones. The first group, better known as the American School, assumes that the decision-maker is able to explain his preferences rationally; there is a global preference function which aims to synthesize the multiple criteria into a single criterion. Non-compensatory methods (the European School) adopt different procedures and do not consider a single synthesis criterion.

The selection of a multicriteria method depends on the decision-maker's preferences being aggregated, and not being restricted to a single criterion, namely, reducing everything to just one measure. In many cases, the decision-maker has great difficulty in dealing with the trade-offs of a problem. The problems of portfolio selection and prioritizing projects is the subject of research among scholars of MCDA in the development of models that tackle these decision trade-offs, by structuring and aggregating the decision-maker's preferences and processing quantitative and subjective factors (Almeida, 2011).

Multi-objective aggregation is a complex procedure which is all the greater when dealing with strategic issues and where the impact of the decision is much greater on the longevity of an organization, such as when selecting projects for a portfolio. Defining the projects that will receive investments is a strategic and organizational decision that involves, invariably, the analysis of several factors beyond the traditional technical and financial aspects, thus characterizing the problem as a multicriteria decision. Moreover, this analysis must be sufficiently structured and should provide methodological consistency with regard to the decision-maker's preference structure.

4.1 Multi-attribute additive model

American School methods base their analysis on a single synthesis criterion, for example V, the value of which is obtained by a function f, aggregating all criteria considered:

$$V(a) = f\big(v_1(a), v_2(a), \ldots, v_n(a)\big) . \tag{1}$$

Function V depends on the values of the action/alternative in each criterion and the information between criteria, such as weights, conversion rates and the evaluation of alternative performance in each criterion, individually and synergistically. Higher values of V indicate that the performance of an analyzed alternative is good. For each criterion n, there is a value or utility function which determines the performance of an alternative and a procedure is needed to elicit the decision-maker's preferences in order to assess these functions for each criterion (Keeney & Raiffa, 1976).

Eliciting the details of value or utility functions can be tedious and demanding, but the contribution of those details to wiser or more valuable choices is often negligible (Edwards & Barron, 1994). Therefore, the use of linear single dimensional utilities $v_n(a)$ is advisable, since it is extremely difficult to involve high-level decision-makers in elicitation procedures. It is clear that this consideration must undergo prior analysis and, if linear approximation is not usable, well-known methods for eliciting single dimensional value and utility functions should be used as described by Keeney & Raiffa (1976). Edwards & Barron (1994) proposed four different single dimensional value functions, which are presented in Figure 4.

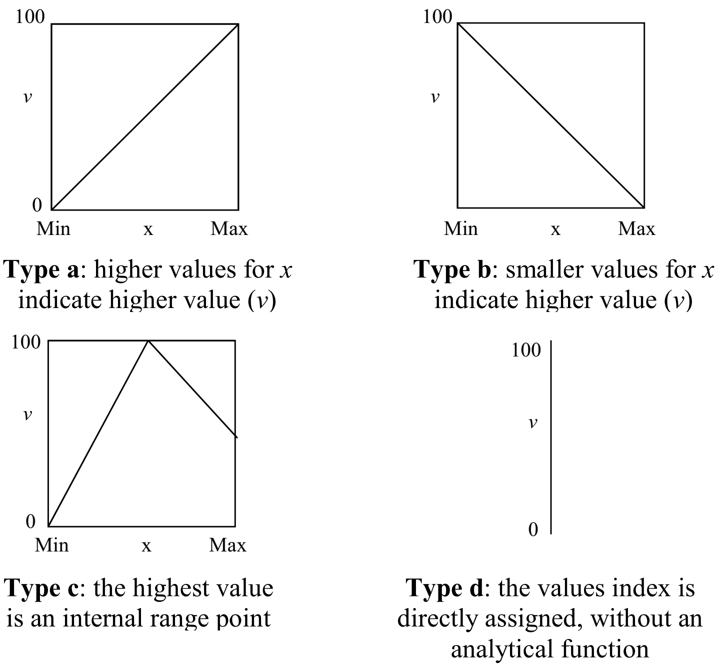

Figure 4 – Single dimensional utilities (adapted from Edwards & Barron, 1994).

The task of eliciting value functions of types ***a*** and ***b*** is reduced to that of assessing two extreme values of the criteria, their maximum and minimum values in the context at hand. For type ***c*** functions, these extreme values must be complemented by the best criteria value and by judgments that specify which branch of the function reaches 0 and by how much the other branch does not. Finally, for type ***d***, the value is directly assessed for each object of evaluation rather than a function of some physical meaning being established. It is applicable, for instance, when evaluating the performance of an alternative from a qualitative scale (*e.g.* the Likert scale) or from an ordinal scale, without specifying physical values. The use of a multi-attribute additive model to evaluate oil and gas exploratory projects, based on the value functions described in Figure 4, is justified by practical and theoretical aspects.

The assumed simplifications facilitate how the decision-maker understands the model while the effectiveness of the model is not compromised provided that its potential errors are checked and mitigated, such as by using sensitivity analysis. For Edwards & Barron (1994), the more nearly that the quantities desired are assessed directly, the easier and less likely it is that the model will produce errors. According to the authors, it is more complicated to elicit a non-linear single utility or value function and a non addictive multi-attribute function because of the accumulation of uncertain elements accumulate during the processes of elicitation and calculation.

Moreover, in accordance with Keeney & Raiffa (1976), the set of attributes Y is preferentially independent of the complementary set Z if and only if the conditional preference strucutre in the y space given z' does not depend on z'. Furthermore, given attributes $X_1, \ldots, X_n$, an additive value function (equation 2) exists if and only if the attributes are mutually preferentially independent. Although the assumptions required for justifying an additive multi-attribute function may seem restrictive, Keeney (1992) affirmed that if additive independence is violated, one probably does not have the appropriate set of fundamental objectives.

$$V(a) = \sum_j k_j v_j(a) \,. \tag{2}$$

The measures k_j that multiply each unidimensional function (see equation 2) are scaling constants, usually cited as criterion weights. In particular, methods that seek to use a single synthesis criterion, have a differential in obtaining the "weights". It is essential to differentiate the concept of scaling constants: they do not indicate the relative importance of attributes (Keeney and Raiffa, 1976). According to Vincke (1992), the choice of an aggregating multicriteria procedure is equivalent to choosing a type of compensation among the criteria, a trade-off decision. This point of view is even more evident when using additive models: $k_j/(k_j + 1)$ indicates the amount that must be incorporated into the alternative in question, according to a criterion $j + 1$, to compensate for the loss of a unit in the alternative performance in criterion j.

To aid the decision process of selecting oil and gas exploration projects for a portfolio, an additive value function should be assessed which combines two procedures. First, use should be made of a procedure called "*swing weights*", which is widespread in the multicriteria decision making literature (Edwards & Barron, 1994; Belton & Stewart, 2002; Almeida, 2011). This allows the attributes to be ranked, by analyzing the performances of the projects in each criterion and the range of performance values in each of these criteria.

Based on the consequences or the performances of the alternatives for each criterion k, ranked from best $(b_1, b_2, \ldots, b_k)$ to worst $(w_1, w_2, \ldots, w_k)$, the decision-maker should be asked : "Is there an exploratory project that has the worst score for all the criteria analyzed. Given the opportunity to exchange only one dimension performance from the worst value to the best value, what dimension performance would you improve?" Figure 5 illustrates this step. The answer is a k^{th} criterion and the decision-maker is now questioned about which criteria, except the one given as an answer to the previous question, would be improved. The questioning process should continue until all the dimensions are ranked.

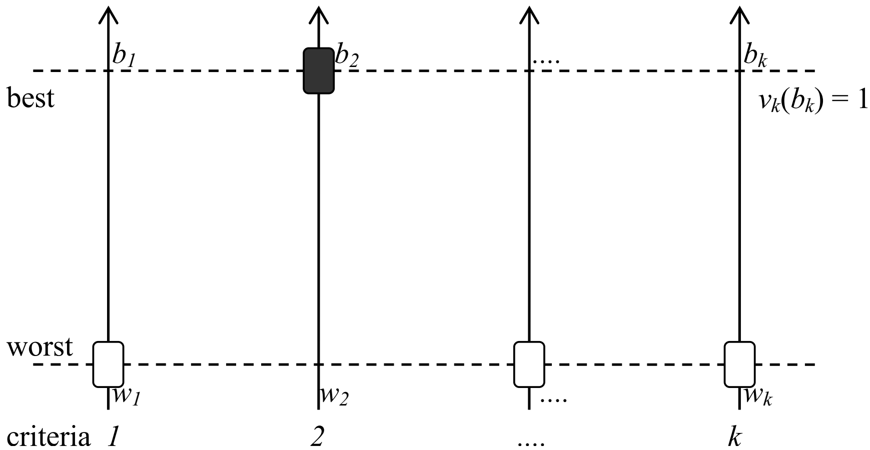

Figure 5 – Swing procedure.

Thereafter, the use of pre-determined values called "ROC weights" (Rank Order Centroid weights) is considered in order to assess scaling constant values, thus simplifying how the scaling constants are calculated and, consequently, the calculation of the multi-attribute value function. If K is the number of attributes, then the scaling constants are:

$$k_j = \left(\frac{1}{K}\right) \sum_{m=j}^{K} \frac{1}{m} \qquad k_1 \geq k_2 \geq \cdots \geq k_j \,. \tag{3}$$

Edwards & Barron (1994) affirm that ROC weights lead to identifying the best alternative 75-87% of the time, depending on simulation details, and the loss in global value is under 2%. In the worst case, when ROC weights do not select the best option, they do not choose a bad one (Stillwell *et al.*, 1981; Barron & Barret, 1996).

For Edwards & Barron (1994), the use of ROC weights can lead to conclusions being drawn about the alternatives without the need for the decision-maker to determine weights or scaling constant values. The authors used this concept in SMARTER (Simple Multi-Attribute Rating Technique using Exploiting Rankings) and affirm that it is likely to appeal to those for whom easy remote elicitation is useful.

The combination of these two procedures follows a well-structured theoretical methodology so as to construct the multi-attribute value function, in addition to which it presents the problem to the decision-maker in an attractive way. Thus, it is opportune to use this multi-attribute additive model in decision-making on electing exploration projects for a portfolio. It must be realized that there are numerous alternatives which form a finite set which the decision- maker should analyze from a multicriteria point of view, and is essential that the decision-maker is able to make his/her preferences explicit and accepts the compensatory nature of the method.

5 DECISION MODEL

The main purpose of the multi-criteria decision model described in this paper is to use it to support the selection of exploration projects for a portfolio. In the first step, an additive multi-attribute approach is proposed in order to tackle the problem in its different aspects, considering the various criteria for evaluating investment alternatives of the exploration. In addition to the multicriteria evaluation, there are specific restrictions that must be considered for choosing projects for the portfolio, which determine the combinatorial nature of the problem. Based on the multicriteria evaluation, an optimization model will seek to maximize the value of the investment portfolio while observing some constraints related to the resources available, management issues, and the planners and policy makers involved in the context of this portfolio.

The use of the proposed model is generic and seeks to analyze investment aspects of the exploration in a more comprehensive way than purely by financial analysis. The model is adaptable so that it can include special features of some problems, such as including and excluding criteria and alternatives. Thus, the decision model described in Figure 6 is proposed.

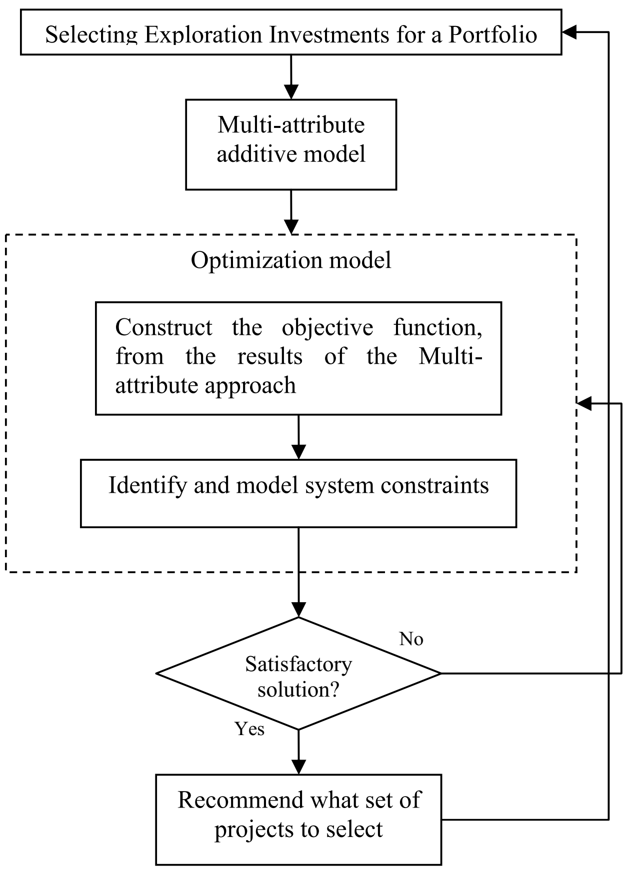

Figure 6 – Decision Model workflow.

5.1 Alternative approach for evaluating uncertainty in exploration

As mentioned in Section 3, exploratory projects have a fundamental element of uncertainty, namely whether or not there is a hydrocarbon reserve. This uncertainty is normally considered in the geological chance factor (or probability of success) and is used for calculating expected monetary values and constructing decision trees. Defining objectives is a specific step in each decision process; however, Figure 7 illustrates some common objectives that are commonly discussed when evaluating almost all exploration projects and selecting a portfolio. The EMV parameter aggregates aspects of these exploration projects such that the EMV is used as if it were a unique synthesis criterion as well as a value or utility function. The difference is the implicit multicriteria aggregation procedure used by an EMV criterion, which uses a monetary scale and does not make the decision-maker's preferences over hidden objectives explicit, for example the possible objective of maximizing the discovery of new petroleum reserves (which is related to the probability of success).

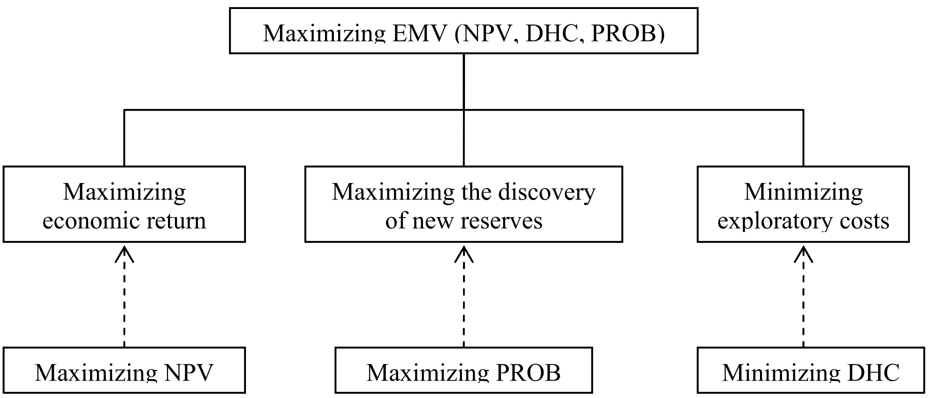

Figure 7 – The EMV and the objectives hierarchy of exploratory activities.

In this application, the decision-maker opted to use the probability of success as an attribute, instead of calculating expected monetary values. This is a practical consideration, because, depending on the context to which this portfolio decision belongs, it may be more interesting to conduct a project which is less profitable but has greater chances of finding petroleum than a project which could be highly profitable but has few geological chance factors. Therefore, one criterion is the project's net present value if due to a hydrocarbon discovery and another is the exploratory chance factor which is related to the objective of maximizing the discovery of new reserves. A similar approach is discussed by Keeney (1992), who affirmed that in many decision situations it is reasonable to use an attribute defined as the probability of the occurrence of some event.

This assumption is an important consideration, with theoretical and practical consequences. It enables a deterministic approach to portfolio selection to be used, while it eliminates the analyses of less important uncertainties, which have a lower impact on the performance of projects and are not immediate when considering the time horizon of exploratory decision making. At the same time, it maintains the most important uncertainty element under analysis, represented on the performance matrix for the projects. Moreover, using the deterministic paradigm may represent important advantages with regard to the procedure for eliciting preferences and aggregating multicriteria, since the decision-maker finds these more acceptable and understandable.

5.2 Application

Petrobras is a publicly traded corporation, whose majority stockholder is the Government of Brazil. It operates in twenty eight countries, on the five continents, as an integrated energy company in the following sectors: exploration and production, refining, trading and transportation of oil and natural gas, petrochemicals, distribution of oil derivatives, electricity, biofuels, and other sources of renewable energies (Petrobras, 2011). In particular, analysis in this paper focuses on the International Business Directorate of Petrobras, which manages the company's projects and activities outside Brazil and seeks to complement the company's in-country portfolio. Thus, the decision model proposed was applied in order to formally apply a multicriteria methodology to aid decision making when selecting exploration projects that will compile a portfolio, and, in addition, tackles issues which are commonly discussed in this decision process, besides technical and financial ones.

The model put forward sets out to aid the process of selecting exploration projects, during which wildcat wells will be drilled and, to this end, will take into account some objectives, possible synergies and interdependencies between such projects. Due to issues of confidentiality, the application presented below is not a specific real case, but considers realistic data, based on a particular context of Petrobras decision making and the structure of the relationship between the variables and parameters considered.

What criteria are set may differ from problem to problem. A hierarchy of objectives/attributes or a value tree should be elicited and if there are too many objectives, the decision-maker should reduce this quantity (Keeney & Raiffa, 1976; Edwards & Barron, 1994). As already mentioned, this paper sets out to look at qualitative and quantitative criteria which decision-makers commonly consider when discussing how best to address selecting exploratory projects for a portfolio. This can be adjusted in accordance with the problem and modeled as per Figure 4. The attributes are:

- The project's net present value (NPV) in case of success during the exploration phase, that is, it will consider the full development of the project. This is a type *a* criterion;
- The probability of success (PROB) or exploratory factor chance of the project. This is a type *a* criterion;
- The dry hole cost (DHC), which is the risk capital of the project. This is a type *b* criterion;
- An estimate of the size of the hydrocarbon reserves (RES) when a successful geological scenario is considered. This is a type *a* criterion;

– A synergy criterion (SYN) related to the influence of the project on other projects, as well as to knowledge acquired for future activities and investments. As previously mentioned, the International Business Directorate of Petrobras seeks to complement to the company's activities in Brazil. Thus, an index should be defined which indicates the degree of the relationship between the project and two different exploration project groups, namely projects within Brazil and those outside the country. For this application, the degree of this relationship varies gradually between one and five (Likert scale), where one is when there is no positive synergy and five when there are strongly positive synergies. The decision-maker should directly assign the relationship degrees and a value measure should be determined in accordance with a type *d* criterion;

– A qualitative criterion related to the influence of external factors (EXT) on the projects, so as to score the political situation in the country where the project is located and its infrastructure elements. This score should vary between one and five, on a Likert scale, where one is when these external factors are very bad influences on the project and five when they are very good. The decision-maker should directly assign the relationship degrees considered, after which a value measure can be determined in accordance with a type *d* criterion;

The company's participation in each project, *i.e.* the Work Interest (WI) of the company, which is defined previously under the contract, was considered on assigning the criteria for the net present value, dry hole cost and reserve size. After defining the attributes, the set N of thirty ($n = 30$) selectable alternatives, *i.e.* exploration projects, were listed and a matrix for evaluating projects by attributes was established, as set out in Table 1.

The first requirement was to assess the Matrix dimensional value functions for the Matrix in order to construct a multi-attribute additive function. As discussed in Section 4.1, the linearity of a one dimensional value function was considered. The performance of the projects in each attribute must be ranked and one of the four different value functions, which were described in Figure 4, was adopted. On conducting the task of eliciting single dimensional value functions, the decision-maker assessed two extreme values of NPV, PROB, DHC and RES criteria, and directly assessed value measures for SYN and EXT criteria. Thus, the performance of the project in accordance with one dimensional value functions was calculated and the results are presented in Table 2.

The multicriteria aggregation procedure began with the swing procedure so as to rank the attributes. The decision-maker was questioned, based on two fictitious alternatives that aggregate the best and worst project performances in the criteria adopted, about what dimension performance he would improve if he had an opportunity to change only one performance from the worst to the best value. This step is illustrated in Figure 8.

Thus, ROC weights are calculated directly from the ranked attributes and from equation (3) (see Table 3). The multi-attribute values were obtained (from equation 2) and the values of the projects are presented in Table 4.

Table 1 – Matrix of the performance of projects.

	NPV (US$ MM)	Probability of success (%)	Size of the reserves (MM BOE)	Synergy	DHC (US$ MM)	External factors
P_1	1,086	10.8	1,311	5	85	2
P_2	670	31.8	582	1	145	5
P_3	2,131	9.0	1,710	4	180	2
P_4	991	8.1	799	2	95	3
P_5	1,172	11.3	750	2	120	4
P_6	385	31.4	512	4	80	2
P_7	1,164	9.8	850	5	120	4
P_8	1,639	12.3	1,355	4	110	1
P_9	451	26.8	678	2	150	2
P_{10}	829	31.6	700	4	55	1
P_{11}	752	14.0	708	5	60	5
P_{12}	457	29.8	510	4	90	5
P_{13}	463	29.0	480	1	90	4
P_{14}	709	7.4	800	1	60	1
P_{15}	557	9.4	850	5	50	1
P_{16}	430	9.8	651	2	35	1
P_{17}	383	12.6	575	3	35	3
P_{18}	374	17.3	550	5	40	4
P_{19}	320	17.4	423	1	40	2
P_{20}	338	22.4	500	3	100	3
P_{21}	455	30.3	450	3	105	3
P_{22}	337	12.2	492	5	80	4
P_{23}	56	17.7	101	1	41	3
P_{24}	28	24.8	580	3	25	2
P_{25}	155	5.6	304	4	30	5
P_{26}	95	15.8	180	1	41	2
P_{27}	266	28.2	204	5	40	3
P_{28}	35	25.2	50	2	18	4
P_{29}	185	11.1	176	5	22	1
P_{30}	153	8.4	165	4	30	3

The uses of these two concepts provide the decision-maker with a procedure that is easy to understand and apply with regard to eliciting a multi-attribute value function, while both are grounded in methodologically correct concepts for multicriteria aggregation. The swing procedure tackled analyzing the range of performance of a project in each criterion. On the other hand, defining ROC weights does not require a large amount of information on preferences because all that is needed is the result of the swing procedure.

Furthermore, the elicitation process described above is totally appropriate for the decision problem's context, since high level decision-makers prefer more practical and intuitive methodologies

Table 2 – The performance of the projects in accordance with one dimensional value functions.

	NPV (US$ MM)	Probability of success (%)	Size of the reserves (MM BOE)	Synergy	DHC (US$ MM)	External factors
P_1	0.50	0.20	0.76	1.00	0.59	0.25
P_2	0.30	1.00	0.32	0.00	0.22	1.00
P_3	1.00	0.13	1.00	0.75	0.00	0.25
P_4	0.46	0.10	0.45	0.25	0.52	0.50
P_5	0.54	0.22	0.42	0.25	0.37	0.75
P_6	0.17	0.99	0.28	0.75	0.62	0.25
P_7	0.54	0.16	0.48	1.00	0.37	0.75
P_8	0.77	0.25	0.79	0.75	0.43	0.00
P_9	0.20	0.81	0.38	0.25	0.19	0.25
P_{10}	0.38	0.99	0.39	0.75	0.77	0.00
P_{11}	0.34	0.32	0.40	1.00	0.74	1.00
P_{12}	0.20	0.93	0.28	0.75	0.56	1.00
P_{13}	0.21	0.89	0.26	0.00	0.56	0.75
P_{14}	0.32	0.07	0.45	0.00	0.74	0.00
P_{15}	0.25	0.14	0.48	1.00	0.80	0.00
P_{16}	0.19	0.16	0.36	0.25	0.90	0.00
P_{17}	0.17	0.26	0.32	0.50	0.90	0.50
P_{18}	0.16	0.45	0.30	1.00	0.86	0.75
P_{19}	0.14	0.45	0.22	0.00	0.86	0.25
P_{20}	0.15	0.64	0.27	0.50	0.49	0.50
P_{21}	0.20	0.94	0.24	0.50	0.46	0.50
P_{22}	0.15	0.25	0.27	1.00	0.62	0.75
P_{23}	0.01	0.46	0.03	0.00	0.86	0.50
P_{24}	0.00	0.73	0.32	0.50	0.96	0.25
P_{25}	0.06	0.00	0.15	0.75	0.93	1.00
P_{26}	0.03	0.39	0.08	0.00	0.86	0.25
P_{27}	0.11	0.86	0.09	1.00	0.86	0.50
P_{28}	0.00	0.75	0.00	0.25	1.00	0.75
P_{29}	0.07	0.21	0.08	1.00	0.98	0.00
P_{30}	0.06	0.11	0.07	0.75	0.93	0.50

to aid decision making. Even so, another elicitation procedure can be conducted if the analyst or decision-maker believes that this is necessary. (Keeney and Raiffa, 1976; Gomes *et al.*, 2006).

In this application, ranking the alternatives according to their global values is not enough. Financial, structural, technical and management constraints should be taken into account when selecting exploratory projects. These aspects are considered in the 0-1 linear programming model formulated below, which lays down the constraints that may be included in the decision model. The main concern is to choose a subset of projects that maximizes the value of the portfolio (represented by the sum of the values of the projects selected), without exceeding budget limita-

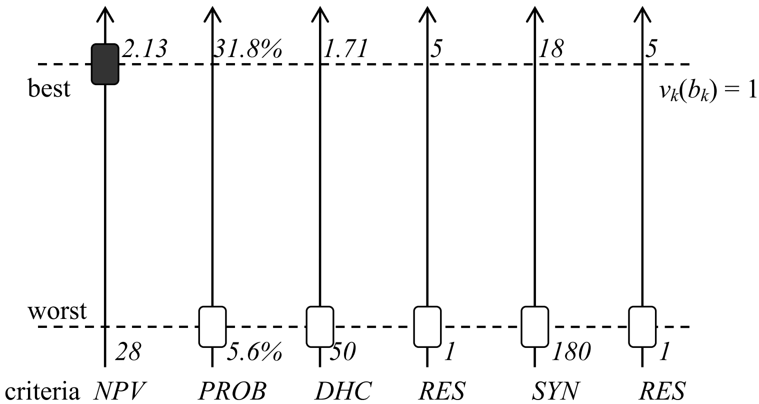

Figure 8 – Application of the swing procedure.

Table 3 – Calculated ROC weights.

	NPV (US\$ MM)	Probability of success (%)	Size of the reserves (MM BOE)	Synergy	DHC (US\$ MM)	External factors
Worst	28	5.6	50	1	180	1
Best	2,131	31.8	1,710	5	18	5
k_j	0.408	0.242	0.158	0.103	0.061	0.028

Table 4 – The multi-attribute values of the projects.

Projects	$V(p)$	Projects	$V(p)$	Projects	$V(p)$
P_3	0.682	P_{27}	0.439	P_{17}	0.303
P_8	0.602	P_5	0.411	P_{28}	0.290
P_{10}	0.582	P_{18}	0.399	P_{14}	0.265
P_1	0.519	P_{13}	0.396	P_{19}	0.261
P_{12}	0.490	P_9	0.382	P_{29}	0.256
P_7	0.481	P_{15}	0.366	P_{16}	0.254
P_6	0.473	P_{20}	0.353	P_{25}	0.210
P_2	0.458	P_4	0.353	P_{30}	0.208
P_{11}	0.456	P_{24}	0.344	P_{23}	0.188
P_{21}	0.442	P_{22}	0.324	P_{26}	0.179

tions, in addition to obeying a certain balance between the departments of the company that will develop projects and technical precedence constraints. Therefore, the model sets out to:

$$\text{Max} \quad \sum_{i=1}^{n} V_i \cdot x_i \qquad n = 30 \tag{4}$$

$$\text{s.t.:} \quad \sum^{n} i = 1 x_i \cdot capex_i \leq CapexExp^{total} \qquad n = 30 \tag{5}$$

$$\sum^{n} x_i \in A^k x_i \cdot capex_i \leq CapexExp^{A^k} \qquad k = 1, 2, \ldots, m \tag{6}$$

$$\sum_{i \in A^k} x_i \leq MaxInvest^{A^k} \qquad k = 1, 2, \ldots, m \tag{7}$$

$$\sum_{i \in A^k} x_i \geq MinInvest^{A^k} \qquad k = 1, 2, \ldots, m \tag{8}$$

$$\sum_{i=1}^{n} x_i \leq MaxOper^{total} \qquad n = 30 \tag{9}$$

$$x_j \leq x_i \qquad \text{if project } j \text{ is dependent on project } I \tag{10}$$

$$x_{i \in M} = 1 \qquad M \text{ is the set of mandatory projects} \tag{11}$$

$$x_i \in \{0, 1\}, \quad \forall i \in N \qquad N \text{ is the set of selectable projects} \tag{12}$$

where $x_i = 1$, if the project i is selected for inclusion in the portfolio, and 0, if not (constraint 12). Constraint (5) sets the boundary budget for exploration projects, in addition to which Constraint (6) sets the boundary budget for each pre-established area (A^k is the set of projects that are located in the kth area, each project belongs to only one area and there are m areas). Constraint (6) was necessary, especially, because the company wishes to have a balanced global portfolio. In the same way, the decision-maker defined the maximum and minimum number of projects that may be selected for the kth area (constraints 7 and 8), and the maximum number of projects which the company would operate (Constraint 9). Constraint (10) provided management and technical dependencies between projects, such as technical precedence. The mandatory projects, which must be selected, are related to Constraint (11), where M is the set of mandatory projects or projects that have obligatory commitments, as laid down in the contract.

It is important to point out that in order to use this optimization model effectively, a knapsack problem should be carefully constructed and an assessment made of its parameters so as to properly represent the company's budget constraints, and management and technical issues. By applying the model, the solution is the subset of exploration projects that maximizes the decision-maker's values under some identified constraints. This result is shown in Table 5.

Table 5 – Selected portfolio.

Projects	$V(p)$	Projects	$V(p)$	Projects	$V(p)$
P_3	0.682	P_{12}	0.490	P_{18}	0.399
P_8	0.602	P_7	0.481	P_{13}	0.396
P_{10}	0.582	P_{21}	0.442	P_{22}	0.324
P_1	0.519	P_{27}	0.439	P_{25}	0.210

Finally, a sensitivity analysis was conducted so as to evaluate the possible effects of changing some parameters of the decision model, especially those of the scaling constants, in order to verify the robustness of ROC weights. This emphasis on a sensitivity analysis of the ROC weights occurred for two reasons: the need to evaluate the robustness of the proposed multicriteria approach to determine a solution for the problem and the non-flexible nature of technical and managerial constraints identified during the application process. Variations in portfolio selecting were verified with respect to variations of between plus or minus twenty percent in the value of each scaling constant. By analyzing these variations, it should be noted that the selected portfolio almost remains unchanged, even with these changes in scaling constant values. Table 6 presents the frequencies at which each projects is selected for inclusion in the portfolio, when variations in ROC weight values are considered: each column represents the selected portfolio after the corresponding change in the scaling constant value. Other analysis should be conducted to verify the consistency of the results from the model, such as post optimal analysis and the inclusion or exclusion of constraints and decision variables.

6 CONCLUSION

The main purpose of this article is to put forward a multicriteria decision model to select oil and gas exploration projects for a portfolio and to apply the model to a real-world situation within Petrobras. Also, this paper has sought to describe the problems of selecting exploration projects for a portfolio in accordance with different views that are found in the literature, the varied nature of their decision context and their methods for resolving them.

This paper analyzed methodological aspects that arise when choosing a multi-attribute aggregation procedure to aid selecting exploration projects for a portfolio: the trade-off between a theoretically more rigorous multicriteria approach (*e.g.* MAUT) and a theoretically and practically simplified approach, which is more easily applicable and assimilated by the decision-maker (yet methodologically correct). In addition, the connection between the fundamental uncertainty of an exploration project, *i.e.* the geological factor chance or probability of success, and one of the adopted criteria underpins using a deterministic approach and this facilitated the conduct of the decision making process.

The proposed multi-attribute approach increases the decision-maker's confidence to analyze the problem, since it facilitates understanding the problem and helps to clarify his preferences. It combines the benefits of MCDA in structuring and analyzing the multiple value dimensions involved in the portfolio selection problem with the inclusion of technical, economics, and managerial constraints. To exemplify the use of the proposed model, a numerical application with realistic data, based on a particular context of Petrobras decision making, was set out. The model was quite effective in tackling the decision problem, and its application showed that it is a simple and methodologically correct procedure for multi-attribute aggregation. Furthermore, applying the model in a real case was shown to be a completely appropriate and a reasonable option.

Table 6 – Sensitivity analysis of ROC weights.

	Base	k_1				k_2				k_3				k_4				k_5				k_6				Frequency
	case	–20%	–10%	+10%	+20%	–20%	–10%	+10%	+20%	–20%	–10%	+10%	+20%	–20%	–10%	+10%	+20%	–20%	–10%	+10%	+20%	–20%	–10%	+10%	+20%	
P_1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100
P_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100%
P_4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_6	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17%
P_7	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	83%
P_8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100%
P_9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_{10}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100%
P_{11}	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4%
P_{12}	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	96%
P_{13}	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	96%
P_{14}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_{15}	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4%
P_{16}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_{17}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_{18}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100%
P_{19}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_{20}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_{21}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100%
P_{22}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100%
P_{23}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_{24}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_{25}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100%
P_{26}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_{27}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100%
P_{28}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_{29}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
P_{30}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%

In conclusion, with a view to applying the proposed model in other real world situations, the following possibilities are recommended for future studies:

- Adapting and applying the proposed model for selecting an E&P portfolio that also includes other types of E&P projects, such as development projects;
- The use of other criteria, in order to adapt the model to different contexts;
- Using multi-criteria methods that utilize partial information in decision-aid, such as ELECTRE IV and VIP Analysis;
- Adapting the model for group decision making;
- Tackling the problem with a non-compensatory notion, by applying methods from the European School of MCDA.

REFERENCES

[1] ALMEIDA AT. 2011. O Conhecimento e o Uso de Métodos Multicritério de Apoio a Decisão. Recife: Editora Universitária UFPE.

[2] ALMEIDA AT & DUARTE MDO. 2011. A multi-criteria decision model for selecting project portfolio with consideration being given to a new concept for synergies. *Pesquisa Operacional*, **31**: 301–318.

[3] ARCHER NP & GHASEMZADEH F. 1999. An integrated framework for project portfolio selection. *International Journal of Project Management*, **17**: 207–216.

[4] BARRON AH & BARRETT BE. 1996. The efficacy of SMARTER – Simple Multi-Attribute Rating Technique Extended to Ranking. *Acta Psychologica*, **93**: 23–36.

[5] BELTON V & STEWART TJ. 2002. Multiple Criteria Decision Analysis. Kluwer Academic Publishers.

[6] BP (BRITISH PETROLEUM). 2011. Available on: http://www.bp.com/. Accessed on 27/10/2011.

[7] BLICHFELDT BS & PERNILLE E. 2008. Project Portfolio Management – There's more to it than what management enacts. *International Journal of Project Management*, **26**: 357–365.

[8] COLDRICK S, LONGHURST P, IVEY P & HANNIS J. 2005. An R&D options selection model for investment decisions. *Technovation*, **25**: 185–193.

[9] COOPER R, EDGETT S & KLEINSCHMIDT E. 2001. Portfolio Management for new product development: results of an industry practices study. *Research & Development Research*, **34**.

[10] EDWARDS W & BARRON FH. 1994. SMARTS and SMARTER: Improved Simple Methods for Multi-attribute Utility Measurement. *Organizational Behavior and Human Decision Processes*, **60**: 306–325.

[11] GOMES FS, GOMES LFAM & MARANHÃO FJC. 2010. Decision analysis for the exploration of gas reserves: merging Todim and Thor. *Pesquisa Operacional*, **30**: 601–617.

[12] GOMES LFAM, DUARTE VCA & MORAES LFR. 1999. Análise Multicritério de Projetos de Produção de Petróleo: Os Métodos PROMETHÉE e TODIM. *Pesquisa Naval*, **12**: 251–262.

[13] GOMES LFAM, RANGEL LAD & MARANHÃO FJC. 2009. Multicriteria analysis of natural gas destination in Brazil: An application of the TODIM method. *Mathematical and Computer Modelling*, **50**: 92–100.

[14] GOMES LFAM, GOMES CFS & ALMEIDA AT. 2006. Tomada de Decisão Gerencial: Enfoque Multicritério. Rio de Janeiro: Editora Atlas.

[15] KEENEY RL. 1992. Value-focused thinking. Harvard University Press.

[16] KEENEY RL & RAIFFA H. 1976. Decision with Multiple Objectives: Preferences and value trade-offs. John Wiley & Sons.

[17] LEVINE HA. 2005. Project Portfolio Management – A guide to selecting projects, managing portfolios and maximizing benefits. San-Francisco: Jossey-Bass.

[18] LIN Z & JI J. 2007. The portfolio selection model of Oil/Gas projects based on real option theory. In: ICCS '07 Proceedings of the 7th International Conference on Computational Science, Part III.

[19] MARGUERON MV & CARPIO LGT. 2005. Processo de Tomada de Decisão sob Incerteza em Investimentos Internacionais na Exploração & Produção Offshore de Petróleo. *Pesquisa Operacional*, **25**(3): 331–348.

[20] MARKOWITZ H. 1952. Portfolio selection. *Journal of Petroleum Science and Engineering*, **44**: 55–65.

[21] MAVROTAS G, DIAKOULAKI D & KOURENTZIS A. 2008. Selection among ranked projects under segmentation, policy and logical constraints. *European Journal of Operational Research*, **187**: 177–192.

[22] MOHN K & OSMUNDSEN P. 2006. Exploration economics in a regulated petroleum province. The case of the Norwegian Continental Shelf. *Energy Economics*, **30**: 303–320.

[23] NEPOMUCENO FILHO F, SUSLICK SB & WALLS MR. 1999. Managing Technological and Financial Uncertainty: A Decision Science Approach For Strategic Drilling Decisions. *Natural Resources Research*, **8**: 193–203.

[24] PETROBRAS. 2011. Petróleo Brasileiro S/A. Available on: http://www.petrobras.com/en/about-us/. Accessed on: 27/10/2011.

[25] PMI. 2008. A Guide to the Project Management Body of Knowledge Section 1 – The project management framework. Pennsylvania: Project Management Institute.

[26] ROSE PR. 1992. *Risk behavior in petroleum exploration*. The business of petroleum exploration: AAPG Treatise of Petroleum Geology. Handbook of Petroleum Geology, 95–104.

[27] ROSS JG. 2004. Risk and uncertainty in portfolio characterisation. *Journal of Petroleum Science and Engineering*, **44**: 41–53.

[28] ROY B. Multicriteria Methodology for Decision Aid. Kluwer Academic Publichers.

[29] STILLWELL WG, SEAVER DA & EDWARDS W. 1981. A comparison of weight approximation techniques in multi-attribute utility decision making. *Organizational behavior and human performance*, **28**: 62–77.

[30] SUSLICK SB & FURTADO R. 2001. Quantifying the value of technological, environmental and financial gain in decision models for offshore oil exploration. *Journal of Petroleum Science and Engineering*, **32**: 115–125.

[31] SUSLICK SB & SCHIOZER DJ. 2004. Risk analysis applied to petroleum exploration and production: an overview. *Journal of Petroleum Science and Engineering*, **44**(2): 1–9.

[32] VETSCHERA R & ALMEIDA AT. 2012. A PROMETHEE-based approach to portfolio selection problems. *Computers and Operations Research*, **39**: 1010–1020.

[33] VINCKE P. 1992. Multiciteria decision-aid. John Wiley & Sons.

[34] XIDONAS P, MAVROTAS G & PSARRAS J. 2009. A multicriteria methodology for equity selection using financial analysis. *Computers & Operations Research*, **36**: 3187–3203.

[35] WALLS RW. 2004. Combining decision analysis and portfolio management to improve project selection in the exploration and production firm. *Journal of Petroleum Science and Engineering*, **44**: 55–65.

[36] ZELENY M. 1998. Multiple criteria decision making: eight concepts of optimality. *Human Systems Management*, **17**: 97–107.