COB09-1841 - USE OF MULTI-ATTRIBUTES FUNCTIONS FOR WATER MANAGEMENT IN PETROLEUM RESERVOIRS

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Abstract. *Water management is an important step of the development planning of E&P projects. Technical, economic and environmental aspects related to the use of water in the petroleum industry imply in the necessity of more detailed analysis in order to set up optimal water management strategies. Besides, the amount of variables involved in the process and their interdependency lead to a situation in which the evaluation of simultaneous variation of different factors is necessary. The decision analysis tools give a consistent basis for the comparison of several alternatives for a single project, considering the objectives and restrictions proposed. When more than one objective function is considered, one of the best options is the construction of multi-attributes functions considering the criteria and the preferences established for the development of the project. The objective of this work is to use the multi-attributes technique in the production strategy selection, whose premises are high profitability and recovery factor, and lower water injection and production volumes. Individual utility functions are proposed for the indicators used in the analysis and combined in a multi-attributes function whose weight factors are dependent on the main objectives of the decision process. The results show that in scenarios with several objectives considered simultaneously, the decision making is highly dependent on the decisor's priorities. With this model, it is possible to simulate several alternatives and choose the most adequate, according to the preferences of the decision maker, taking into account economic, technical and environmental attributes.*

Keywords*: Water Management; Decision Analysis; Reservoir Simulation*

1. INTRODUCTION

It is known that choosing a production strategy for petroleum reservoirs is a process of high complexity due to the constant interaction of the amount of involved variables, since the properties and characteristics of the reservoir and fluids in it contained; the amount, type and localization, schedule and operation conditions of the different wells; the technological scenario and the economic considerations for the project. These factors lead to a complex process in order to make the right decisions, involving the actions to be executed, throughout the process of proposal and posterior optimization of the production strategy.

The choice of the correct water management strategy for an oil field can increase the economic horizon of the project by means of the costs reduction and the increase of the incomes in the cash flow. Nowadays, due to current concern with the increasing amounts of water produced in the oil fields and with the intention of maximize the reservoir productivity, it is necessary to implement strategies that lead to a correct management of the water.

Thus, it is possible to establish the proper conditions in order to optimize the operational, economic, and environmental performance of an E&P project. In this form, the determination of operational limits for water production and injection, considering the economic scenario, becomes important since the handling of an eventual water over-production, or an injection that is not in accordance with the necessities of the field can affect, in negative way, the cash flow and the final recovery.

In the development of petroleum reserves, it is common to handle increasing amounts of water along the productive life of the reservoir and, according to Khatib and Verbeek (2002); the excessive production of water is the main criterion to determine the abandonment point of producer wells, leaving behind significant volumes of hydrocarbons.

The purpose of water management is to develop a strategy that takes effective measures for handling injected and produced water efficiently, taking into consideration the technical, geological, economic and environmental characteristics of the project. These actions include the produced water re-injection (PWRI), water disposal in depleted reservoirs, water treatment for further discard in surface, water injection with fracture propagation, among others.

The designing of a water management strategy makes necessary to take decisions based on technical and economic aspects. Nevertheless, these decisions involve conflicting objectives, which shall be carefully analyzed in order to obtain a solution that establishes an agreement between them fulfilling the project proposal.

Decision analysis provides several tools that allow finding an optimal solution based on the properties and limitations of the project. In this sense, the Multi-Attributes Analysis, that consists into identifying the best solution considering simultaneously multiple confronted criteria, aims to select, among several possible alternatives, the best (but not always optimal) option to satisfy the decisor preferences and the proposed objectives for the project.

One of the most common problems in the application of the Multi-Attributes Analysis approach is to represent quantitatively the preferences of the decision maker, whose interpretations are guided, primarily, by its expertise and the knowledge of the expected behavior of the project.

In this work one brief revision on the main aspects of the water management is presented and are illustrated some alternatives for the analysis of the different factors involved, aiming to point the most critical aspects of the process and its treatment, in order to determine the appropriate conditions so that the best water management strategy can be proposed and implemented. In this form a bigger technical and economic performance is expected for the processes that involve water use in oil fields.

2. LITERATURE REVIEW AND THEORETICAL BACKGROUND

In this section a summary of the bibliographical review about the use of multi-attributes functions as decision tool in the determination of a strategy for water management in an oil field is shown. For Furtado (2000) the use of multi-attributes functions provides a logical and reliable solution when a process in which diverse contradictory objectives are involved is analyzed. Hence, the process is formulated from the preferences of the decision maker, being necessary, to define and quantify the impact that each one of these preferences has in the final decision.

Normally, the impact of each one of the preferences to be adopted by the decision maker is quantified in the form of weights, whose determination is subject for different studies, since the process must be analyzed in an individualized form, that is, in accordance with the knowledge, the hierarchy and the orientation of the process that the decision maker presents. In this work, it is considered to carry out a multi-attributes analysis of the different variables that take part in water management.

This analysis is based on the Multi-Attributes Utility Theory (MAUT), with the difference that the functions proposed for the analysis of the involved variables do not deal with them as utility functions, this is, it does not incorporate the elements of Expected Monetary Value (EMV) nor the involved risk.

In this work Multi-Attributes Functions are used as discrete decision tools due to the problem nature, which presents a finite number of alternatives that can be considered as feasible for water management. In this form, the solution is chosen from a set of options that satisfies the restrictions and premises of the problem, analyzed under established criteria and following the decision maker preferences (weights) and establishing a system in which the preferences can be ordered (hierarchy).

The theory of the multi-attributes utility has been widely studied for several authors, who analyze the different aspects of the process, since the choice and hierarchy of the attributes to be studied (Newendorp, 1975; Nepomuceno and Suslick, 2000), until the characteristics that the same ones must have to guarantee reliable results that reflects aspects as: a) the references of the decision makers (Keeney and Raiffa, 1976), b) the mathematical formulation of the functions that can be applied to relate them (Clemen, 1990), and c) the applications of this methodology in decision processes for the allocation of investments in development of E&P of petroleum projects (Nepomuceno, 1997; Furtado, 2000; Lima 2004).

3. METHODOLOGY

For the accomplishment of this work different types of multi-attributes functions are analyzed, where two or more parameters can interact in accordance with the preferences of the decision maker. It is intended, then, that these preferences are represented by both, the type of function to be used in the study and the distribution of the weights applied to the studied attributes.

In this study, that it aims to the use of this type of analysis to determine the strategy of water management to be adopted for one determined field case, the attributes to be studied initially are the cumulative production of water and oil, as well as the cumulative injection of water and the net present value of the project, which interact aiming three basic premises:

1. Maximization of the profit.
2. Maximization of the final recovery.
3. Reduction of the water production.

In this work linear and non-linear functions, with two or more attributes are studied. The objective is to analyze the relations between the attributes and to determine ways to establish the weights for the different cases. The use of functions of the linear type allows carrying out the proposed analyses in a simplified way, establishing an analysis methodology that can later be used with more complex functions.

The value of the multi-attributes function for this work is the weighed additive type and it is calculated as it is shown in Equation 1.

$$Z = \sum_{i=1}^{n} \lambda_i U_i(x_i) \qquad \text{Equation (1)}$$

In Eq. (1) Z represents the value obtained from the multi-attributes analysis, $U_i\ (x_i)$ is the function of attribute i and λ_i is the weight established for attribute i. For the development of the project, it is important to set up the distribution of the weights accordingly with the expectations of the decision maker, always regarding that the sum of the weigths must be equal to 1.

Initially, the use of multi-attributes functions is illustrated for the linear case with two parameters. Then, other function types (exponential and logarithmic) are used with two or more parameters. These functions are shown in Equations (2), (3) and (4), for linear, exponential and logarithmic respectively.

$$U_i(x_i) = c * x \qquad \text{Equation (2)}$$

$$U_i(x_i) = e^{cx} \qquad \text{Equation (3)}$$

$$U_i(x_i) = \ln(x+c), c > 0, x > -c \qquad \text{Equation (4)}$$

In those equations the constant c could be empirically proposed and the its calculation is specific for every case. In this case study the value of c is 1.

The methodology is applied to the simulation results of a synthetic maritime field in deep waters, with oil of 28ºAPI and implementing water injection. Several production strategies with total number of wells varying between 13 and 24 horizontal wells are simulated, for three production paths (Five-spot, Inverse Five-spot and Peripheral injection). The horizontal section of the wells is located in different layers for both injection and production wells, and production and injection rates varying between 1000 and 2000 m³/day per well for a simulation time of 20 years. An economic scenario is considered for the calculation of NPV.

4. APPLICATION

4.1. Simulation model

The reservoir model studied, in this work, is a synthetic model corresponding to a fluvial deposition; the reservoir has a size of 4,5km x 2,5km x 100m, discretized in a simulation grid of 50 x 90 x 10 blocks, as it is observed in Figure 1.

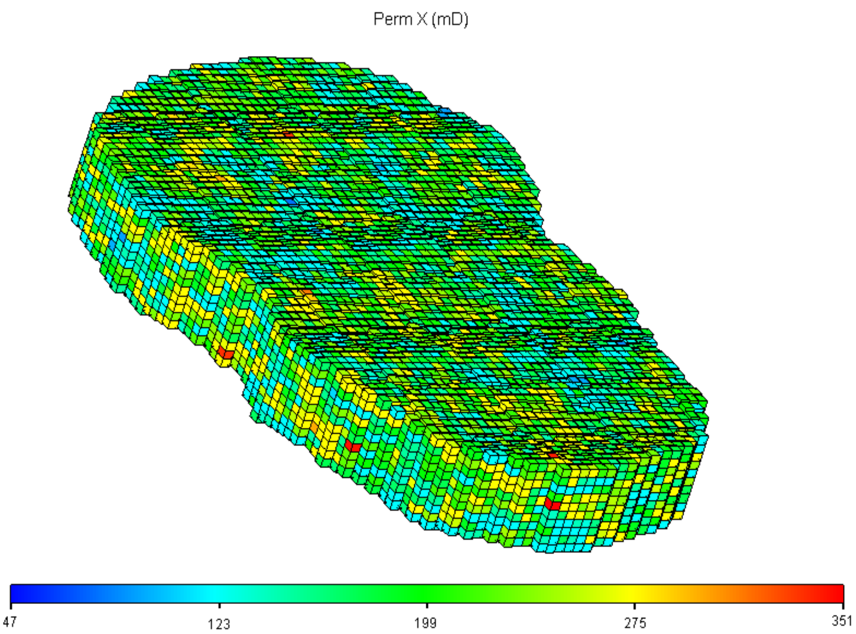

Figure 1. Simulation grid showing the horizontal permeability distribution.

Other properties of the model are:

- Mean porosity: 22%
- Mean horizontal permeability: 200 mD.
- kh/kv ratio: 0.1.
- API gravity of the fluid: 28.

The economic scenario used in this work is shown in Table 1.

Table 1. Economic parameters.

Taxes	
Discount rate	10
Royalties (%)	10
Government Taxes (%)	36.65
Investments	
Platform & CAPEX (US$ Million)	400 to 830
Producer Well (US$ Million)	40
Injector Well (US$ Million)	40
Revenues	
Oil price (US$/m³)	250
Costs	
Oil production (US$/m³)	30
Water production (US$/m³)	3.4
Gas production (US$/m³)	0.002
Water injection (US$/m³)	3.4
Abandonment (% of investment)	1

4.2. Production Strategy

Since the model is divided into 10 layers, different completion layers combinations are tested as shown in Table 2.

Table 2. Combination of completion layers.

Producing wells	Injecting wells
Layer 1	Layer 10
Layer 1	Layer 9
Layer 2	Layer 10
Layer 2	Layer 9

In the initial production strategies launching phase, three different patterns of horizontal wells are proposed: (a) 5-spot, (b) inverted 5-spot and (c) peripheral injection. In the 5-spot and inverted 5-spot configurations well spacing is constant and defined according to the field dimensions and well drainage radius.

The simulations are carried out varying the total number of wells according to their configuration, as can be seen in Table 3.

Table 3. Number of wells.

Configuration	Total wells	Production wells	Injection wells
5-spot	13 to 23	9 to 12	4 to 11
Inverted 5-spot	13 to 23	4 to 11	9 to 12
Peripheral injection	13 to 24	7 to 14	6 to 10

The operation constrains considered are production and injection rates. The established limits are:

- Production wells: 1000 to 2000 m3/day
- Injection wells: 1000 to 2000 m3/day

5. RESULTS AND DISCUSSION

The simulation process, in which the variation of the production parameters and the economic model cited above were implemented, resulted in 150 simulations, whose results for Recovery Factor, NPV, produced water and injected water are shown in Figure 2.

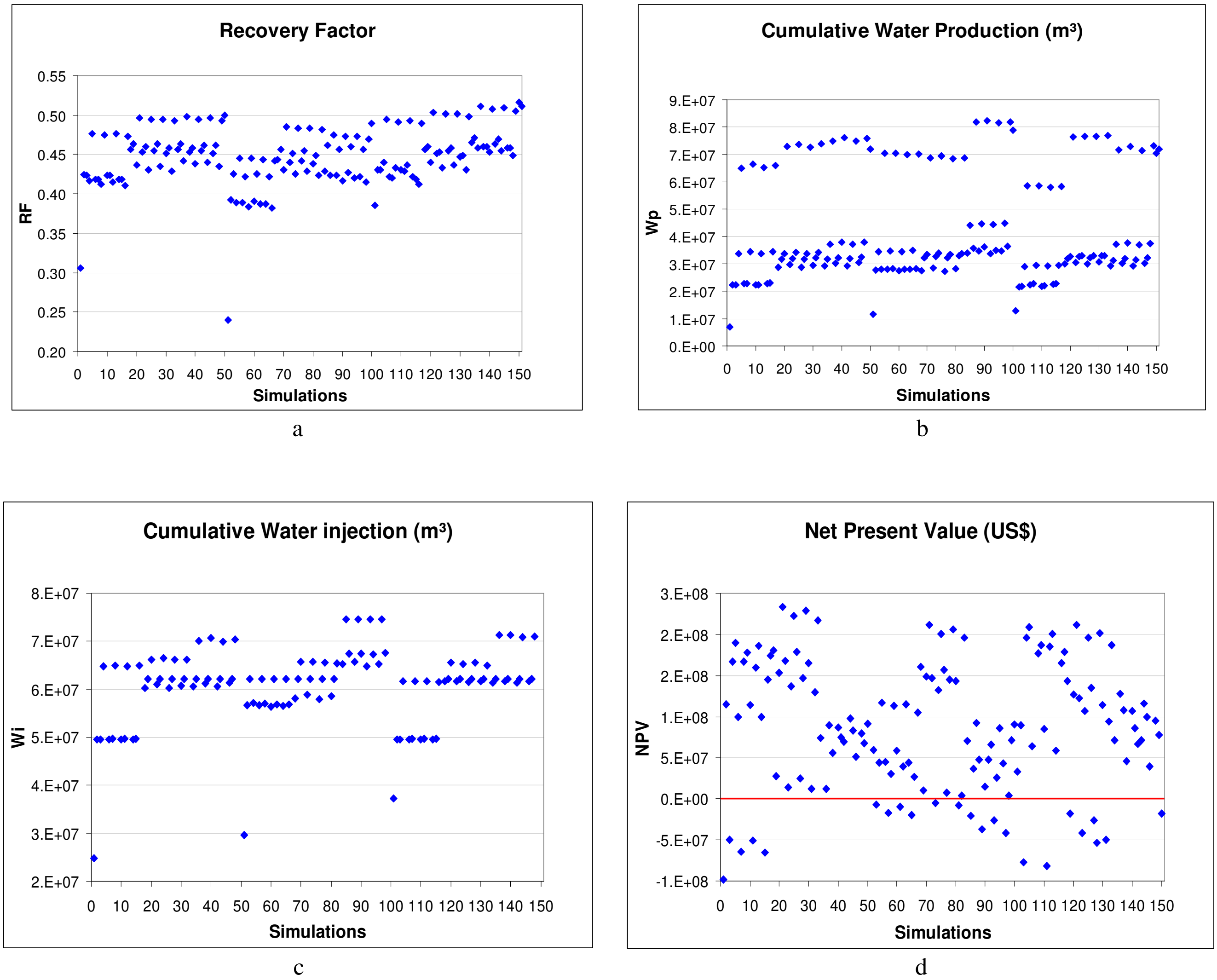

Figure 2. Results for the simulated strategies: (a) RF, (b) Wp, (c) Wi, (d) NPV.

In order to better illustrate the use of multi-attributes functions, the results for the properties are normalized, in order to put the data in the same scale, allowing the graphic interpretation of the multi-attributes function plot, being obtained values between 0 and 1 for every attribute. The normalization is calculated as shown in Equation (5).

$$H_{i\,norm} = \frac{H_i - H_{\min}}{H_{\max} - H_{\min}} \qquad \text{Equation (5)}$$

Where H is any of the attributes cited above.

The comparative results for RF vs. Wi and NPV vs. Wp are shown in Figure 3.

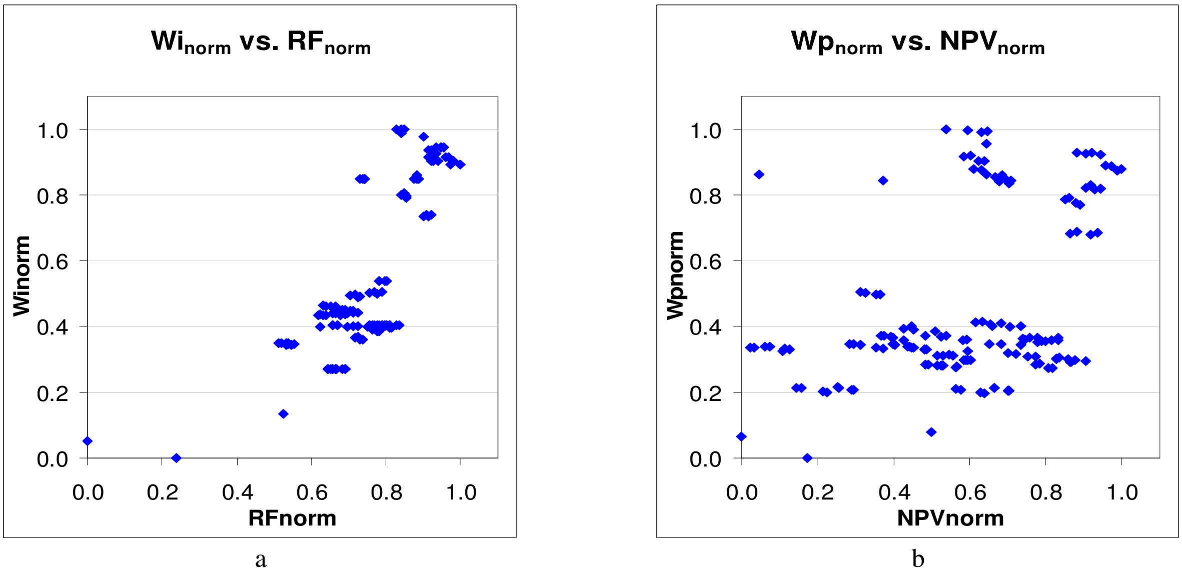

Figure 3. Comparative results for RF and Wi (a), and NPV and Wp (b).

From Figure 3, it can be observed that the maximum values for the attributes are reached by different strategies, this is, the maximum RF corresponds to a strategy with 24 wells (14 producers) in peripheral injection, the maximum Wi and Wp to an Inverted Five-spot strategy with 22 well (10 producers), and the maximum NPV is obtained with a Five-spot strategy with 20 wells (10 producers).

These results show that when the oil recovery is the main objective of the project, the higher investment in producing wells and the additional costs of producing water affect negatively the cash flow, reducing the NPV. On the other hand, reducing the water injection and production could improve the economic behavior by diminishing the well drilling or the injection rate.

It is important to note the dependency of the cash flow and the NPV on the oil production and water injection and production. This makes that the distribution of the weights for the multi-attributes analysis shall be carefully designed, in order to increasing the reliability of the obtained results. According to Mezzomo (2003), the weight distribution can be established empirically or analytically. The empiric definition requires knowing the decision maker preferences and, hence, a direct interaction that allows establishing the attributes and their importance for the decision process, such as an interview, is needed.

For this study, the weight selection is based on the decision maker expertise and preferences. The mathematical models for weight distribution can be used when the importance of the different attributes is uncertain and the decision maker preferences are unknown. In this case study of multi-attributes analysis for NPV and RF the weights are, respectively, 0.7 and 0.3. In this way, and due to the dependency of NPV on oil production, as well on water injection and production, the result is not over-influenced by recovery factor, and the effect of the project life time and the economic parameters can be observed.

Using Eq. (2) for a linear solution with $c = 1$ for both the attributes, and calculating the multi-attributes function by Eq. (1) with the weights cited above, the best alternative is a Five-spot strategy with 20 wells (10 producers, completed in the most upper layer and the injector in the bottom of the grid), with injection and production rates of 2000 m³/day per well. The behavior of the linear multi-attributes function for this case is shown in Figure 4.

In Figure 4 the multi-attributes function shows that two strategies can be selected regarding the attributes studied. In this case, one of the strategies has a higher NPV, and the other has a slightly lower NPV and a higher RF. Thus, the decision maker shall to select between to have a higher net present value or to pay a certain quantity of the project revenue in order to increase the final oil recovery. This decision can obey to the economic and technologic conditions at the moment of the decision, since in the perspective of a future increase on the oil price, a higher production can be more profitable, but in cases of technological uncertainty, the strategy with higher NPV can be more reliable due to the eventual difficulty of a further increase in oil production.

For this case, the linear function can be used because, even when the values of the normalized attributes tend to zero and the function give over-estimated values of NPV, which are not in accordance with the observations made during reservoir simulation, the segment of the line near the intercept with the efficient border (green curve) can be used to approximate the behavior of other kind of functions, helping in the analysis.

For the case of water production and its influence on NPV, the weights for the linear multi-attributes function are 0.7 for NPV and 0.3 for Wp. The values choice follows the same criteria as the case of NPV vs. FR, and the results are shown in Figure 5.

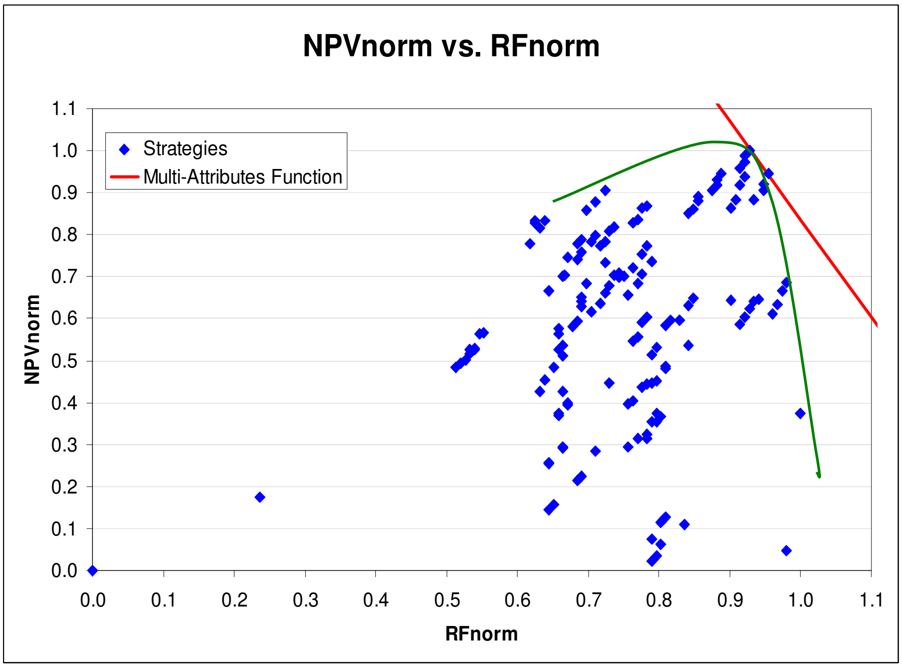

Figure 4. Multi-attributes analysis for NPV and RF (linear function).

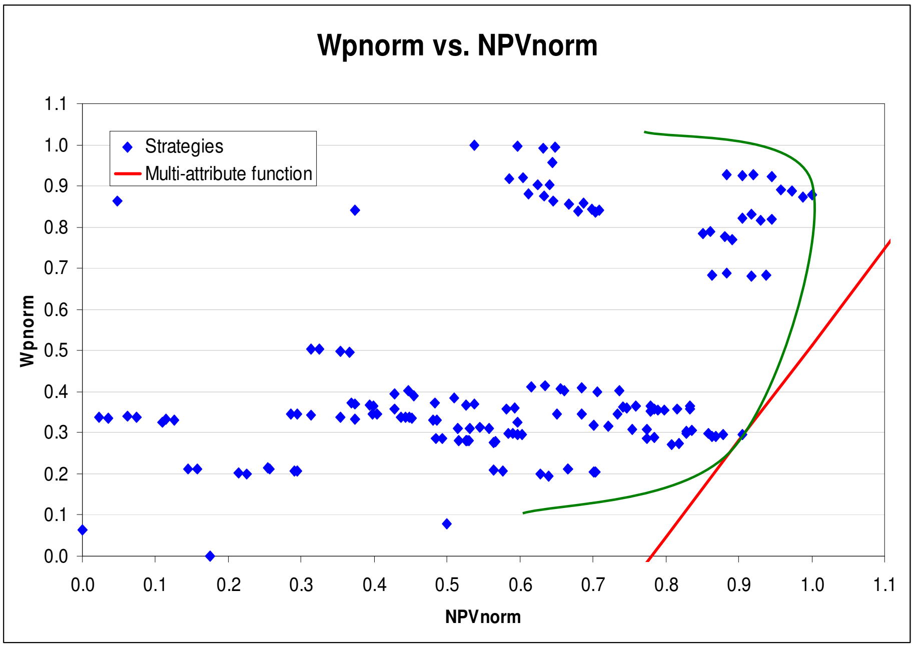

Figure 5. Multi-attributes analysis for Wp and NPV (linear function).

The analysis for the attributes give a strategy of 18 wells (10 producers) arranged in a peripheral injection pattern, with an injection rate of 2000 m³/day and a production rate of 1000 m³/dat per well. The choosing of this strategy is supported by the necessity of reducing the water production, since there is a strategy with higher NPV but also has a higher Wp, and the decision can be made regarding the environmental benefits that a lesser water production can give in terms of governmental incentives and the public image of the company, hence, the amount of profit that can be "lost" by choosing this strategy can be seen as an investment in other segments of the E&P industry.

It can be seen that depending on the criteria that are adopted for the realization of the multi-attributes analysis, different solutions can be obtained, hence, it is necessary to compare these solutions considering the objectives of the project and the development perspectives. For example, the strategy obtained in the analysis of NPV vs. Wp has an oil production and an NPV lower than the strategy obtained from the NPV vs. RF analysis, even with less water production and less investments and costs.

A multi-attributes function is calculated considering NPV, Wp and Wi simultaneously. Here, due to the difficulty of visualize the results in a graphic way, the result is only reported. As cited in the previous analyses reported in this work, the weight used for the NPV is 0.7, and for Wp and Wi are 0.15.

Linear multi-attributes functions are used for evaluating the simultaneous effect of the four attributes tested in this study on the decision analysis. Also, exponential and logarithmic functions shown in Eq. (3) and (4) are used for the calculation of the multi-attributes function for three (NPV, Wp and Wi) and four (NPV, RF, Wp and Wi) parameters.

The attributes and weights of the tests are shown in Table 4, and the multi-attributes values obtained are shown in Figure 6.

Table 4. Multi-attributes analysis parameters.

Function type	Weight per attribute			
	NPV	RF	Wp	Wi
Linear	0.7	0.0	0.15	0.15
Linear	0.7	0.1	0.1	0.1
Exponential	0.7	0.1	0.1	0.1
Exponential	0.6	0.2	0.1	0.1
Logarithmic	0.7	0.0	0.15	0.15
Logarithmic	0.6	0.2	0.1	0.1
Logarithmic	0.7	0.1	0.1	0.1

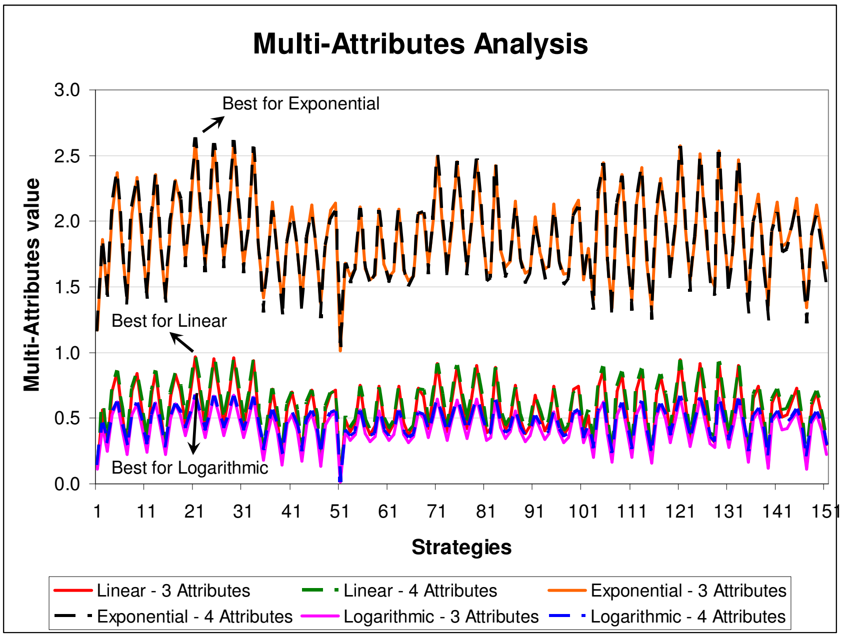

Figure 6. Multi-attributes values for the studied functions with 3 and 4 attributes.

The results in Figure 6 show, for all the logarithmic and exponential functions tested, as well for the linear function with 3 and 4 attributes, that the strategy with 20 wells (10 producers) in a Five-spot pattern, with injector and producer wells completed in layers 1 and 10 respectively, which have been obtained from the analysis of two attributes (NPV and RF), is the best option to implement as a production/water management strategy.

This can be explained by the following facts.

- The strategy presents the highest profitability among the 151 strategies tested.
- Even when there are strategies with a higher recovery factor (24 wells, 14 producing in a peripheral injection arrangement), the magnitude of the investments in wells and facilities, and the elevated production costs affect negatively the cash flow, leading to a diminution in the profitability.
- The strategies with the lowest water production (13 wells, 9 producers in Five-spot arrangement) also present the lowest water injection. Knowing that for this study the water injection is important for oil production, a low injection affects negatively the final oil recovery and the economic behavior of the project.

It can be observed From Figure 6 that based on the values of the multi-attributes function obtained, the best strategies are the same regardless the function type. This may suggest that, under certain conditions, the decision process can be made using a specific type of function leading to reliable results. Also, it can be seen that the exponential function can show in a clearest manner the differences between the strategies, since this function accentuates the effects of the attributes, contrary to the logarithmic function that smooth the results, and can lead to miscalculations of the importance of the attributes on the analysis.

It is important to note that the results may vary accordingly with the objectives of the project, the decision maker preferences, the associated uncertainties (geological, technical, technological), and variation on the conditions of the economic scenario. Hence, this analysis shall be made for every case in specific form, avoiding generalizations and maintaining a constant feedback between the results, the methodology, the characteristics and the restrictions of the cases, in order to improve the reliability and usefulness of the obtained results.

6. CONCLUSIONS

- The use of NPV as the base for decision processes is well known, and may lead to good solutions when used as criterion for the proposal and implementation of a water management strategy. In cases more critical, such as low oil prices, high costs and investments and uncertainties, the analysis of NPV jointly with other parameters as RF, Wp, or Wi permits to have a better understanding of the project performance and leads towards a solution in agreement to the decision maker preferences.
- In some cases, the analysis of multiple parameters involves conflictive objectives that make the decision process difficult. In the case of water management, the minimization of the costs related to the water handling in oil fields can affect negatively the oil recovery and the cash flow of the project, making necessary tools to analyze simultaneously the effect of variations in this parameters on the behavior of the project, regarding the objectives and preferences established by the decision maker.
- Since the effects of water management strategies are not only technical or economic, the impact of the process in the environment shall be taken into consideration. In this way, investments on practices that can add environmental value to the project can be evaluated accordingly to the technical and economic premises of the project.
- As observed, it is possible to carry out the multi-attributes analysis process in order to obtain a solution whose characteristics are near to the optimum and point the main aspects to take into consideration in further optimization of water management strategies.
- In a general manner, the definition of a water management strategy involves a huge amount of variables. In this sense, the utilization of other techniques to complement the multi-attributes analysis, such as sensitivity analysis, economic risk calculations, environmental impact studies, among others, can aid the process, offering results for a wide variety of technical and economic scenarios, facilitating the decision making and improving the reliability of the results.
- Results show that the viability of finding solutions for the analysis of multiple conflictive objectives depends, mainly, on the technical-economic scenario for the case, the restrictions of the project and the objectives of the decision maker, and can be found in the most of the cases.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE

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