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The Impact of Dependency Analysis on Prospect Ranking and Portfolio Evaluation: A Case Study in Offshore Brazil

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The Impact of Dependency Analysis on Prospect Ranking and Portfolio Evaluation: A Case Study in Offshore Brazil

by

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Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Energy and Earth Resources

The University of Texas at Austin

August 2017

Dedication

To Joana Gisbert, geologist and beloved wife, for her unconditional support and dedication.

To my children, João, Rafaela and Maria Julia, my precious gifts and eternal sources of inspiration.

To my parents, Angenila and Ubiratan, and my aunt, Maria Aurora, the main reasons of what I become today.

To the Gisbert Leão family, especially Nerusa, Raquel, Guilherme, Leão and José for supporting me all the way.

To all my friends and family.

Acknowledgements

This work would not have been possible if not for the guidance and support of Dr. Eric Bickel, my thesis supervisor. I was also honored by having Dr. Jim Dyer on my committee, and I am deeply thankful for his encouragement and guidance. I would also like to thank Dr. Richard Chuchla and Dr. John Butler, for their invaluable support.

I convey my special thanks to my advisor Dr. William Fisher, who was my mentor and friend since the first day I decided to start a new journey at UT. His suggestions and insights made it possible for me to realize the broad goals of research and helped me stay motivated when things did not appear very optimistic.

For funding, I would like to thank my sponsor PETROBRAS for the opportunity, support and encouragement. This project would not have been possible without commitment and support from the following professionals that I had the opportunity to work, study and learn from: Drs. Mario Carminatti, Otaviano Pessoa, Luciano Costa, Cleomar Fernandes, Jonilton Pessoa, Jorge Della Favera, Ricardo Jahnert and Sylvia dos Anjos.

Thanks to all professionals from the University of Texas at Austin Graduate School, Jackson School of Geosciences and Energy and Earth Resources Program (EER), especially to my friends Aziz Almansour, Enrique Arce, Erin Poteet, Harshit Jayaswal, Hector Arreola, James Jang, Jonathan Ly, Mafer De La Fuente, Majo Martinez Pinanez, Pamela Daitch, Parker Brant and Prathaj Haputhanthri for their friendship and support.

Special thanks to my friends and family in Brazil who continued to cheer me up while being thousands of miles away. I am also thankful to Jodi and Rafi Campana for being our family in Austin.

Finally, to my wife and favorite geologist, Joana Gisbert: this achievement is also yours. You left everything behind, even pausing your brilliant career, to live this adventure with me and our children Joao, Rafaela and Maria Julia. I have no words to say how thankful I am. Your unconditional love, kindness and support give me strength and courage to face any challenge that may lie ahead. I love you everything I know, and I always will.

Abstract

The Impact of Dependency Analysis on Prospect Ranking and Portfolio Evaluation: A Case Study in Offshore Brazil

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The University of Texas at Austin, 2017

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In general, prospects belonging to the same basin or play tend to have geological similarities so that the first results may affect chances of success in remaining opportunities. For example, when confirming the presence of porous reservoir in a stratigraphic objective of a particular well, we can expect an increase in the geological chances of another prospect with similar seismic facies, consequently increasing its expected value and the value of the remaining portfolio.

After analyzing public geological data and volumetric estimates in the Foz do Amazonas Basin, in addition to the results of one of the bid rounds offered by the Brazilian government, the author developed a model to quantify changes in the value of an exploratory portfolio when considering possible relationships of dependence and synergy between prospects. When testing a fictitious portfolio of thirteen prospects with different dependency relationships through a Monte Carlo routine, an increase of about 30% in net present value was observed, compared to a portfolio of independent opportunities. Moreover, when considering dependence between prospects, we obtained better success rates and a more efficient use of available resources in all four different ranking methods tested, thus highlighting the importance of this approach to a more accurate portfolio evaluation and informed business decisions.

TABLE OF CONTENTS

List of Tables

List of Figures

1 Introduction and Objectives

1.1 INTRODUCTION

During low oil price scenarios, all major companies are forced to focus on efficiency improvements, trying to extract the most of their exploration and production's lower investments. In this delicate frame, every single decision based on portfolio evaluation and prospect ranking become crucial to achieving higher performance and profitability, so most companies are considering different approaches and tools that could be used as a guide for efficient decision-making when appraising a concession, play or basin.

Normally, most exploratory decisions are made by a single individual or an action-oriented group of managers who, after judging the alternatives proposed by geoscientists and other technicians, decide for an exploration strategy just based on each opportunity's Expected Monetary Values (EMV). Although quick and efficient, this methodology does not take into account how the first possible results may affect other alternatives, and failing to evaluate this dependence in advance can lead to poor business decisions and leave considerable value behind. When analyzing multiple prospects, it is important to consider workflows that could properly evaluate and take advantage of dependency relationships, using post drill reviews from first wells drilled to provide more informed decisions about the subsequent well locations.

In general, prospects belonging to the same basin or play tend to have geological similarities so that the first results may affect chances of success in remaining opportunities. For instance, if a post drill report from a dry hole reveals consistent oil shows, seal presence and a reservoir with excellent porosity and permeability, we may be encouraged to continue testing similar prospects. In this trap failure example, other nearby prospects will probably have their chances of charge efficiency, reservoir presence, and, ultimately, their expected value increased, exemplifying the importance of dependence analysis and the value of learning from past results.

1.2 OBJECTIVES

This research's main objective is to calculate the impact of modeling dependence between prospects in a portfolio evaluation (**Error! Reference source not found.Error! Reference source not found.**). That is, by estimating the value of a group of opportunities without accounting for dependency and synergic relationships amongst them, what could be the value left behind?

The work also details how a group of opportunities can be tested in a Monte Carlo model, by using public geological data and volumetric estimates from the Foz do Amazonas Basin, in addition to the results of one of the bid rounds offered by the Brazilian government.

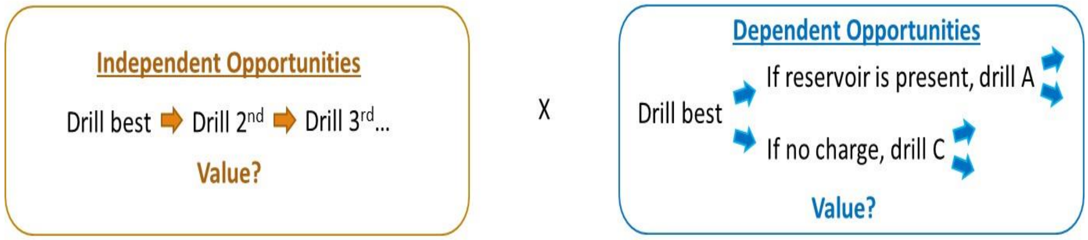


Figure 1: Comparison between the evaluation of an independent portfolio with a dependency analysis approach.

2 Literature Review

This chapter describes a literature review regarding the main characteristics of a prospect, as well as the most used methodologies for evaluating and ranking exploratory opportunities.

2.1 A Prospect and Its Value

After the acquisition of a concession or lease for hydrocarbon exploration, geoscientists of oil companies work intensively to search for geological anomalies, which may represent potential accumulations of oil. Sometimes, this job begins even before the exploratory rights to an area are acquired, through interpretation of existing well logs, seismic data, analogous accumulations, in addition to other indirect and direct methods of geological investigation. These identified locations, potential hydrocarbon accumulations, are called prospects.

One of the lines of research on the evaluation of prospects that is widely used and respected by the major oil companies was proposed by Rose (2001). The author states that the prospect identification process represents the basic value-creating act for an oil company, and it requires geotechnical skill and creative imagination. Therefore, due to data limitations and several geological uncertainties involved, the evaluation of exploratory opportunities is a determining task in the future performance of any oil business. Failures and motivational biases when evaluating an exploration asset can lead to significant losses, especially in offshore areas where well costs usually exceed hundreds of millions of dollars.

According to the same author, the process of evaluating prospects follows three basic steps:

1- To estimate the size of the yieldable reserves, assuming that an accumulation is indeed present;

2- To calculate the chance of hydrocarbon occurrence, according to the geological characteristics of the prospect and its petroleum system;

3- To estimate the financial return of the project, given that a discovery is made, in addition to the expenses incurred in case of failure.

Based on these estimates, it is possible to calculate the Expected Monetary Value (EMV) when testing a prospect, which involves balancing the probability of success and its value with the risk of failure and its expenses (Figure 2). When a prospect's EMV is positive, we are investing; when EMV is negative, we are gambling. Rose (2001) also compares the investment in negative EMV projects to gambling in a casino, where repeated-trial games are designed to favor, at the end of the night, the owner of the venue, not the gambler.

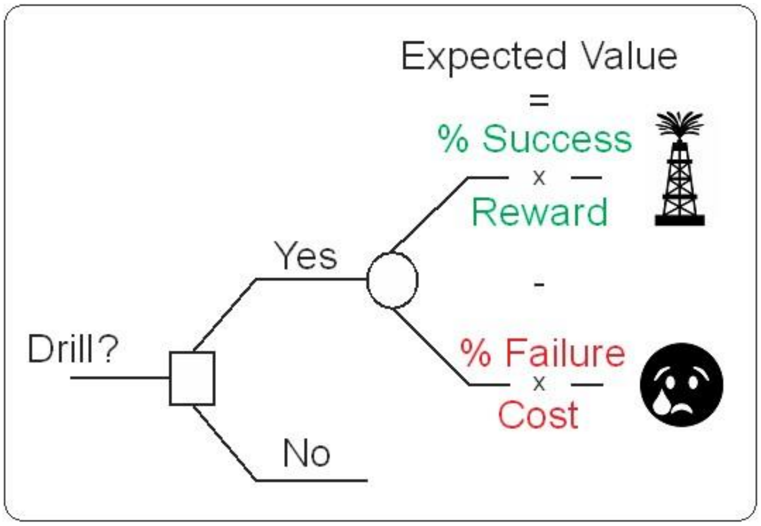


Figure 2: Simplified decision tree containing the Expected Value basic formula.

By testing a prospect, we can achieve different levels of success. The first and most broad level is the geological success, and its probability of occurrence (Pg) is described by Rose (2001) as the chance that reservoired mobile hydrocarbons are found. A prospect´s Pg comes from the multiplication of geological chance factors, which represent the minimum conditions for an accumulation of hydrocarbons to exist. According to Rudolph and Goulding (2017), up to nine independent risk elements can be multiplied to obtain a prospect's Pg, but in the simplest possible form, three main geological factors are considered:

1 - Charge: chance that hydrocarbons, generated by a source rock nearby, had reached the target section through diverse migration pathways;

2 - Reservoir: chance of reservoir occurrence, with sufficient porosity to accumulate oil in tested objective;

3 – Trap or sealed closure: likelihood that a structural, stratigraphic or mixed trap exists, with minimum sealing conditions to allow trapping of hydrocarbons in the target section.

Table 1 was extracted from Rose (2001) and exemplifies how a prospect's Pg can be calculated using three geologic factors.

Geologic Chance Factor	Probability
Reservoir Rock	0.7
	X
Hydrocarbon Charge	0.8
	X
Sealed Closure	0.5
Product = Probability of Geologic Success—Pg	0.28
Probability of Geologic Failure—Pf = (1 – 0.28)	0.72

Table 1: Example calculation of simplistic Pg using three geologic chance factors, extracted from Rose (2001).

After calculating a prospect's geological chance of success, we need to estimate the possible sizes of a future field. By predicting uncertainty ranges for different reservoir parameters, such as porosity and hydrocarbon saturation, geoscientists can calculate a reserve distribution curve using a Monte Carlo routine. According to Rose (2001), any multiplication of independent and random variables will result in a lognormal distribution, and geoscientists who are aware of this behavior tend to predict geological parameters and uncertainties more efficiently. The best representation of a lognormal distribution is its mean or average, and since this value is statistically influenced by very high outcomes with low probability of occurrence, the curve is usually truncated in the P01 and P99 percentiles.

However, a geological success does not guarantee a financial return, since some accumulations do not have enough volume to return exploration and production costs. Therefore, according to the same methodology, the next success levels and chances can be determined by either truncating the lognormal reserves distribution at a minimum commercial threshold, used to afford development costs (half-cycle), or at an economic threshold, sufficient for all exploration and development expenses (full-cycle). Respectively, these truncations will support estimates of commercial (Pc) and economic (Pe) chances of success, with different average reserves. Figure 3 was also extracted from Rose (2001) and exemplifies chances of exploration failure and success, after all truncations are made.

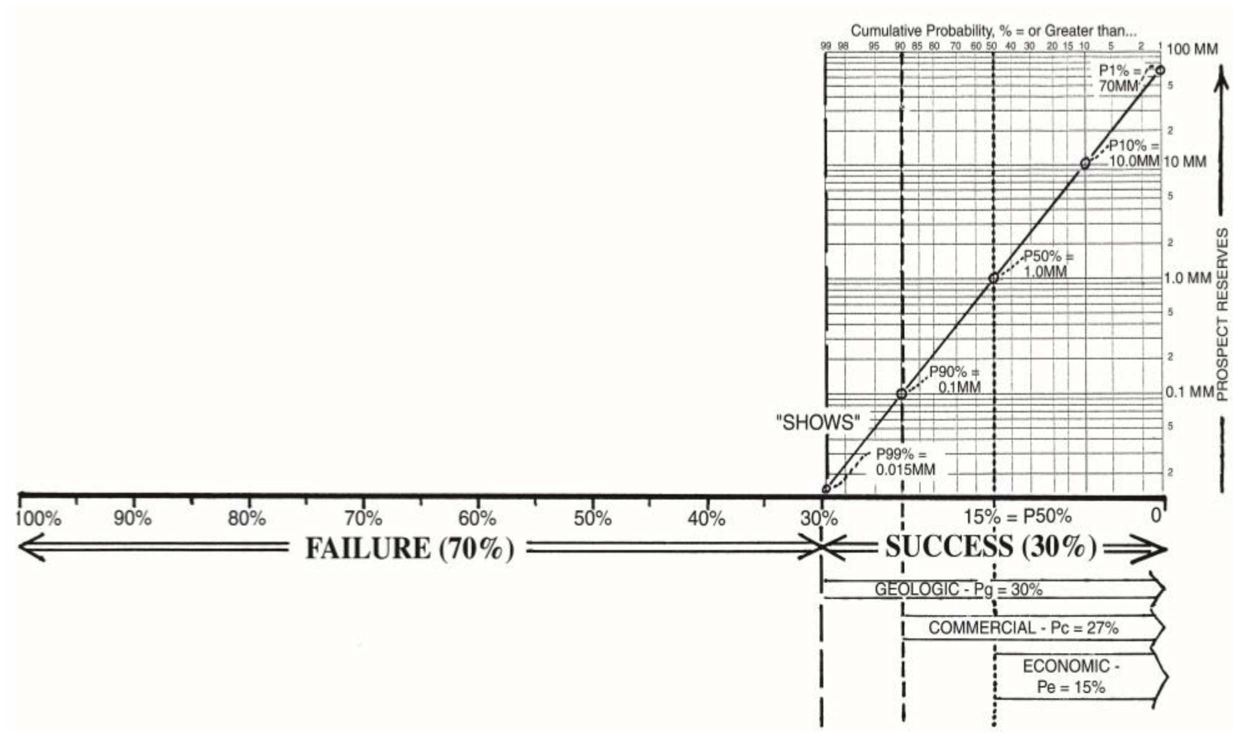


Figure 3: Exploration failure and success (geologic, commercial and economic).

The last step in the EMV calculation is the Net Present Value (NPV) estimate. It can be calculated using the economic average reserve in a discounted cash flow model. Lowry (2005) suggests a simplified methodology for obtaining NPV, in which the difference between the average truncated volume and the minimum pool size (exceeding reserves) is multiplied by an oil value. This factor represents the profit obtained for each barrel discovered above the minimum commercial volume.

2.2 PLAY ANALYSIS AND DEPENDENT PROSPECTS

According to White (1993), a play is a family of geologically similar fields, discoveries, prospects and leads. When considering multiple prospects from a common play, it is important to analyze the dependence among their geologic factors. For example, suppose we have two similar prospects mapped in a concession, both belonging to the same play. The main identified risk for this play is reservoir absence, and both prospects would test the same channel system, with similar seismic facies and burial conditions, but two different traps. If independently treated, the expected value by drilling this small portfolio is represented by the sum of the two EMVs. Now suppose one of the prospects is drilled and a discovery is made, confirming excellent reservoir conditions. For sure, the remaining prospect would have his reservoir chance positively impacted by the previous result, leading to a new and higher expected value. On the other hand, if the first well is a dry hole and the failure reason is the reservoir absence or low quality, we may decide not to invest in the remaining alternative, especially if its new EMV falls below 0.

The example above illustrates how one well result can affect the value of remaining alternatives and why post drill reviews represent powerful tools for play analysis and adequate portfolio evaluation. Rose (2001) even states that the most crucial decision, especially in international exploration, is not choosing which prospect to drill. Instead, the key decision is which new play to enter, since it involves much larger commitments of money, time, and personnel.

When evaluating a play, the same author suggests calculating the chances factors that are shared between the prospects, called play chance. In this approach, designed for play ranking, if a valid test concludes that one of the shared chance factors fails, the entire play is condemned. Other authors such as Delfiner (2003) and Keefer (2004) have also proposed frameworks that distinguish correlated risks among prospects from those assumed to be independent. Although recommended in some situations, these models are restrictive and inappropriate for modeling portfolio value and sequential drilling decisions.

Bickel and Smith (2006) and Bickel (2008) mention the construction of a joint probability distribution to delineate an optimal sequential drilling strategy that maximizes the expected value (Figure 4). By estimating conditional probabilities for each of the three geological factors, it is possible to calculate pairwise dependence correlations between prospects, enabling a group of individually unattractive opportunities to become a multiprospect attractive play. Although this approach is highly recommended for choosing an optimal strategy, we should note that dependency geologic relationships are not always represented by pairwise correlations. For example, consider two prospects depend on migration through the same carrier bed, but prospect B is deeper and closer to the source rock. The influence that an eventual success on A will exert on the charge chance in B is different from the impact of discovery B on A. Additionally, optimal drilling sequences will depend on the resources availability, such as exploration budget limitations or rig availability. Failing to consider those uncertainties can lead to larger potential losses in case unlikely but possible sequential failures occur.

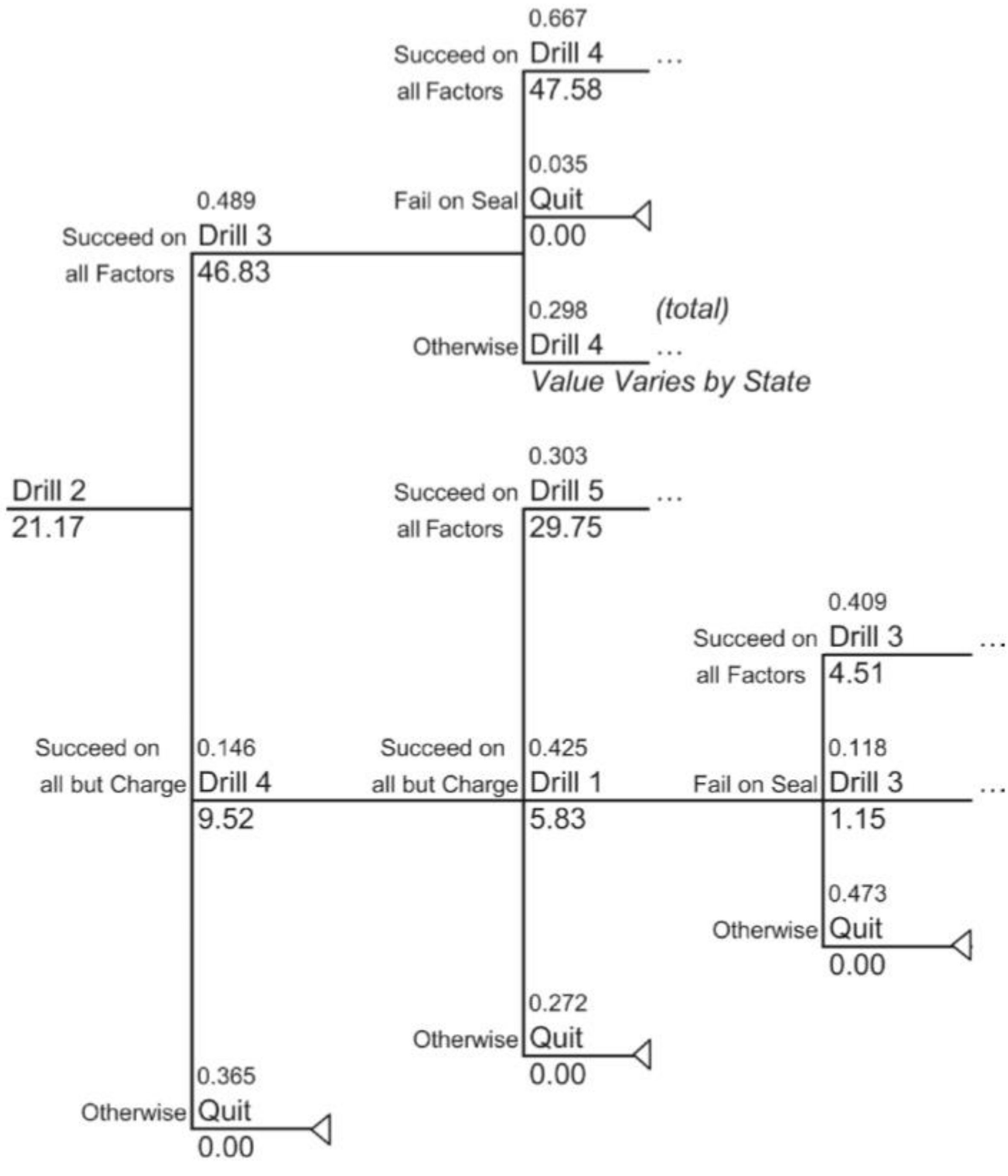


Figure 4: Optimal sequential strategy in a 5-well example, proposed by Bickel (2008).

The approach described in this thesis combines the use of a Monte-Carlo framework with the application of "if-then-else" logics described by Kokolis (1999), to simulate the decisions that would be made after each well result. As noted by Bickel (2008), Monte Carlo simulation packages are not well suited for delineating optimal drilling sequences and require a pre-determined ranking strategy. Even so, this approach makes it possible to calculate the expected value when testing a portfolio repeatedly and compare the results obtained by different ranking criteria, with the advantages of accounting for uncertainties inherent to the exploratory process and distinct levels of dependence between prospects.

2.3 PROSPECT RANKING

There are several ways of ranking exploration opportunities, and the vast majority take into consideration their EMVs. However, as pointed out by Rose (2001), some inconsistencies may occur when ranking opportunities with similar EMVs. For example, if two prospects have the same EMV even though one requires a much larger upfront investment, the use of other ranking metrics like investment efficiency becomes critical to resource optimization.

Lopes and Almeida (2013) suggested a multi-criteria decision model to support the selection of exploration projects for a portfolio, based on balancing six different metrics to meet the decision maker´s preferences:

1 – The project´s net present value (NPV) in case of success;

2 – The geological probability of success (Pg);

3 - The dry hole cost, which represents the risk capital of the project;

4 – The average reserves given a discovery is made;

5 – A synergy criterion based on the influence each prospect´s result will exert on remaining opportunities;

6 – A qualitative criterion related to the influence that external factors may exert on the project, such as political situation or local infrastructure elements.

Other metrics can be considered but, in fact, there is no right answer when selecting an opportunity to be drilled. According to Spetzler (2016), when one alternative provides everything desired by the decision maker, the choice among alternatives is easy, but it seldom happens. Companies must make trade-offs and decide how much of one value they are willing to give up in order to extract more of another.

3 Study Area

This chapter describes the main geologic features and exploratory results reported in Foz do Amazonas Basin, as well as the most recent discovery in the region, the Zaedyus oil field, located in offshore French Guiana. It also details some results from the 11th Brazilian Bid Round, in 2013, when Petrobras acquired 4 concessions blocks.

3.1 Foz do Amazonas Basin

The Foz do Amazonas Basin is located in the northern portion of the Brazilian equatorial margin, near the coast of the state of Amapá and the Island of Marajó, and has an area of 268 thousand km² (Figure 5). It is characterized by the Brazillian National Agency of Petroleum, Natural Gas and Biofuels – ANP, as a new frontier basin, with potential for both gas and light oil discoveries. The exploration activities in this basin began in 1963 and, in 1976, the Pirapema gas field was discovered, at that time classified as non-commercial and not yet developed. There have been many signs of hydrocarbons in both shallow and deep water wells so far drilled.

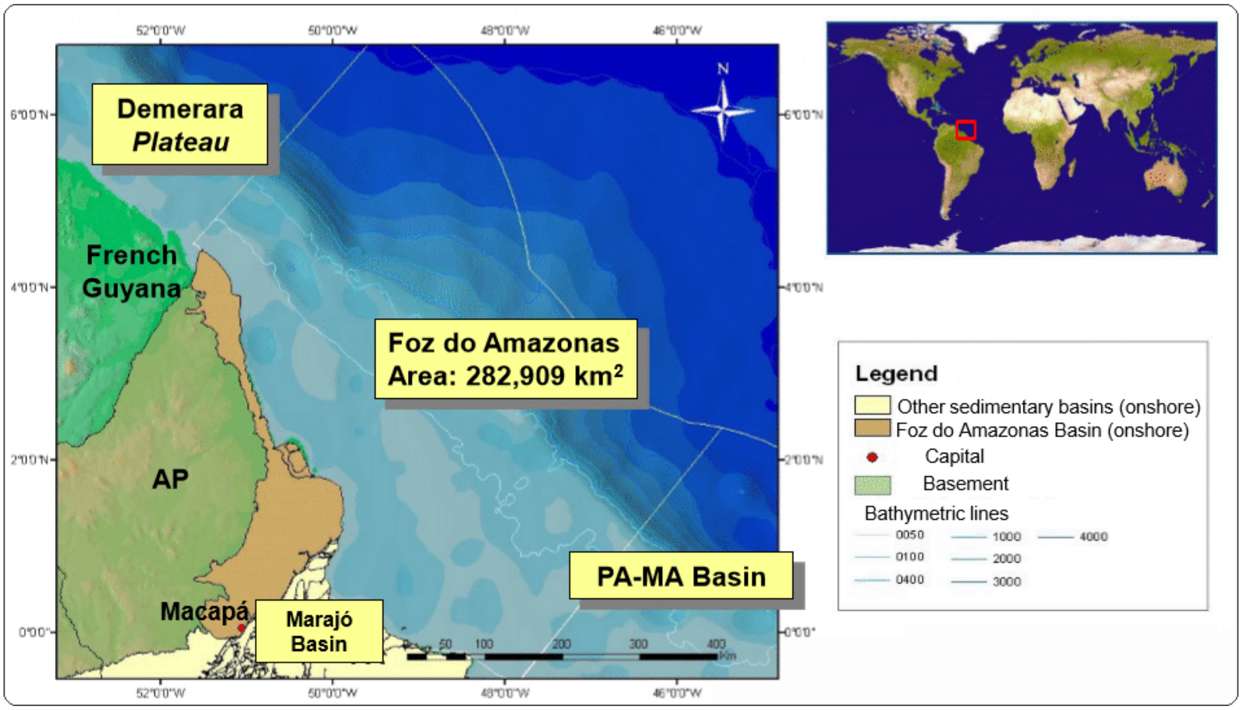


Figure 5: Location map of the offshore Foz do Amazonas Basin. Source ANP website.

The main reservoirs targeted in the basin are represented by Upper Cretaceous sandstones, and the proved source rocks are shales deposited during Cenomanian / Turonian (Figure 6). Deeper plays successfully targeted in other basins, like the Albian carbonates and sandstones, were also recognized but remain untested, as well as deeper source rocks like the Aptian shales.

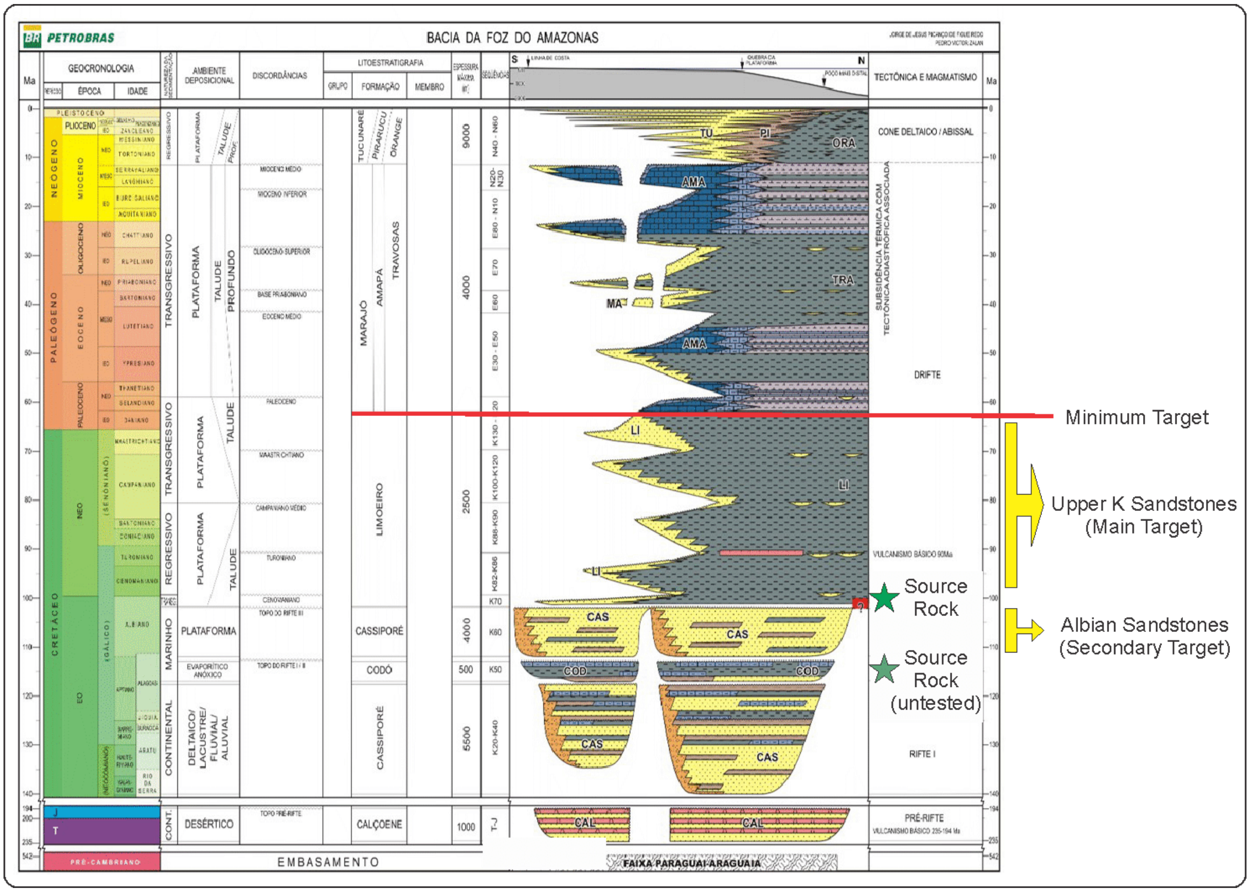


Figure 6: Stratigraphic chart of the Foz do Amazonas Basin, highlighting main targets, source rocks and the minimum depth commitment. Source ANP Website.

The types of prospects identified are similar to those that resulted in discoveries in West Africa (Côte d'Ivoire and Ghana), French Guiana, and Sergipe/Alagoas Basin, represented by turbidites deposited along the deepwater portion of the basin (**Error! Reference source not found.**). The public interpreted seismic sections available in ANP's website shows that most of the observed traps have a predominant stratigraphic component, in which a pinch out up dip is expected. Migration pathways rely on normal and thrust faults that could connect the source rocks to overlying carrier beds and reservoirs.

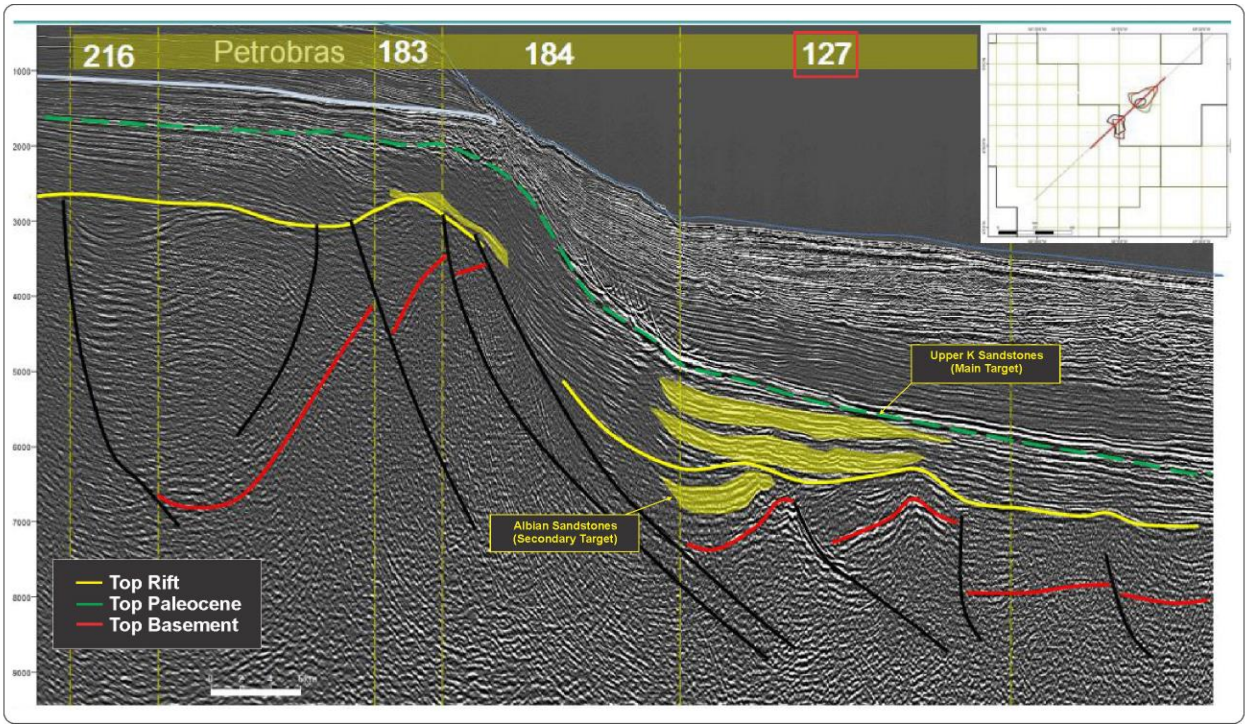


Figure 7: Interpreted seismic section in time, offshore Foz do Amazonas Basin. Source ANP Website.

3.2 THE ZAEDYUS DISCOVERY IN OFFSHORE GUIANA

The Zaedyus oil field was discovered in 2011 by a joint venture operated by Tullow Oil plc (Tullow) in the offshore French Guiana, and it is located about 50 Km from the northwestern limit of the Foz do Amazonas Basin (Figure 8). According to the company's website, the Zaedyus exploration well (GM-ES-1) was drilled in water depths of 2,048 meters and encountered 72 meters of net oil pay in two turbidite fans. Based on these first results, ANP's public report of Bid Round 11 has estimated a volumetric potential of the order of 700 million barrels of oil in place.

Figure 8: Location map of Zaedyus oil field in offshore French Guiana.

However, one year after the discovery was made, Tullow announced that the Zaedyus-2 appraisal well (GM-ES-2) had not confirmed the extension of the accumulation.

The well, drilled 5km up-dip from the Zaedyus-1 well, encountered a total of 85 meters of reservoir quality sands with oil shows in several objectives, but further seismic and well-log interpretations pointed out that the reservoirs at this location are not in communication with Zaedyus-1. Also, according to Tullow's announcement, as Zaedyus-2 is up-dip and disconnected from Zaedyus-1, this result has no bearing on the bulk of the undrilled prospectivity, downdip of Zaedyus-1. Future drilling on the Zaedyus fan system should therefore target the upside in the Zaedyus down-dip prospects (Figure 9) and the down-dip elements of Zaedyus Deep.

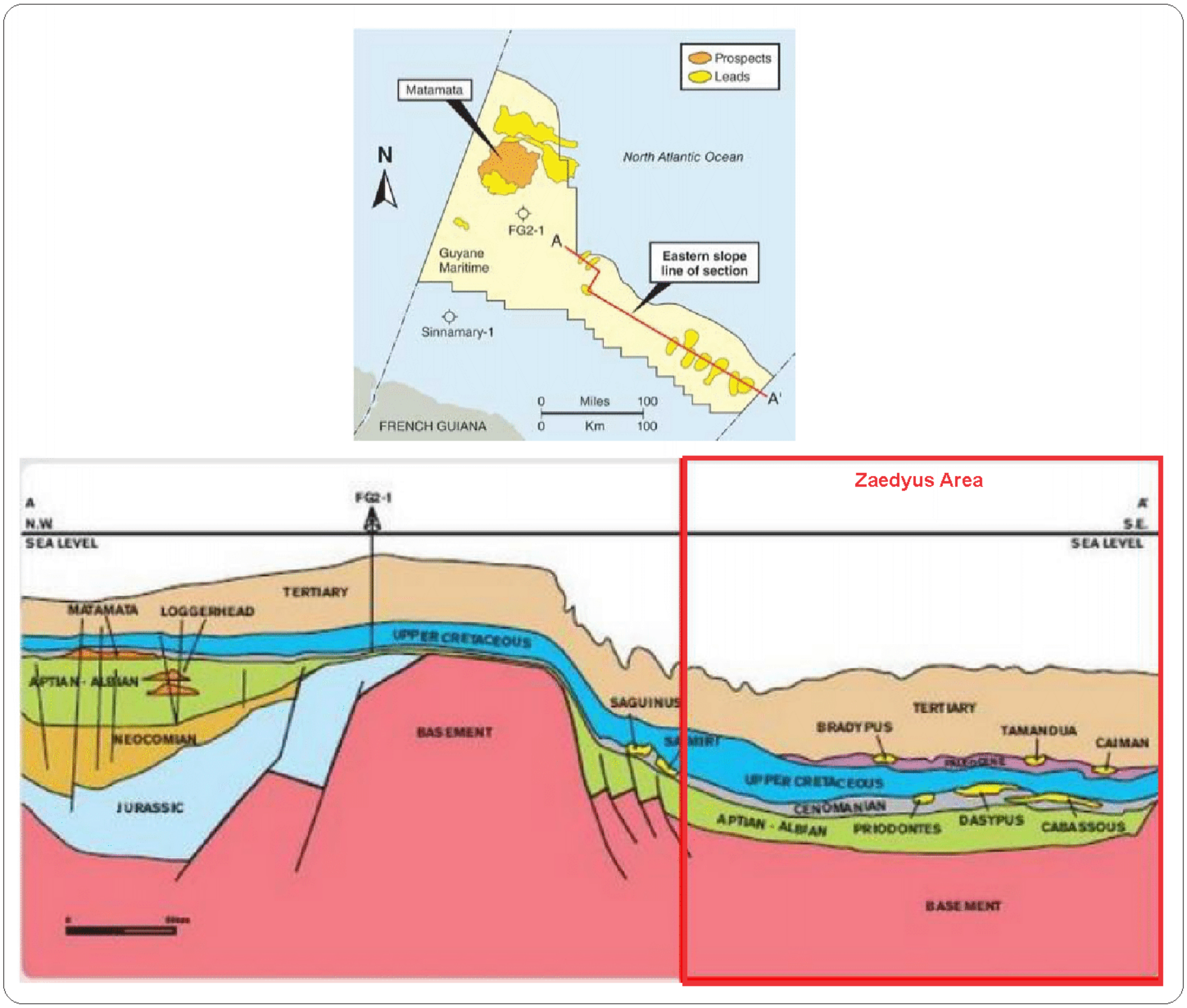


Figure 9: Location map and schematic cross section of the Zaedyus discovery area and its remaining prospects.

Despite the appraisal well results, Zaedyus represents the closest oil field and main analog to the study area, and has opened a new exploration perspective for both French Guiana and Foz do Amazonas Basins. Additionally, the discovery in the turbidite play has proved the extension of the Jubilee-play, successfully established in West Africa, across the Atlantic (Figure 10).

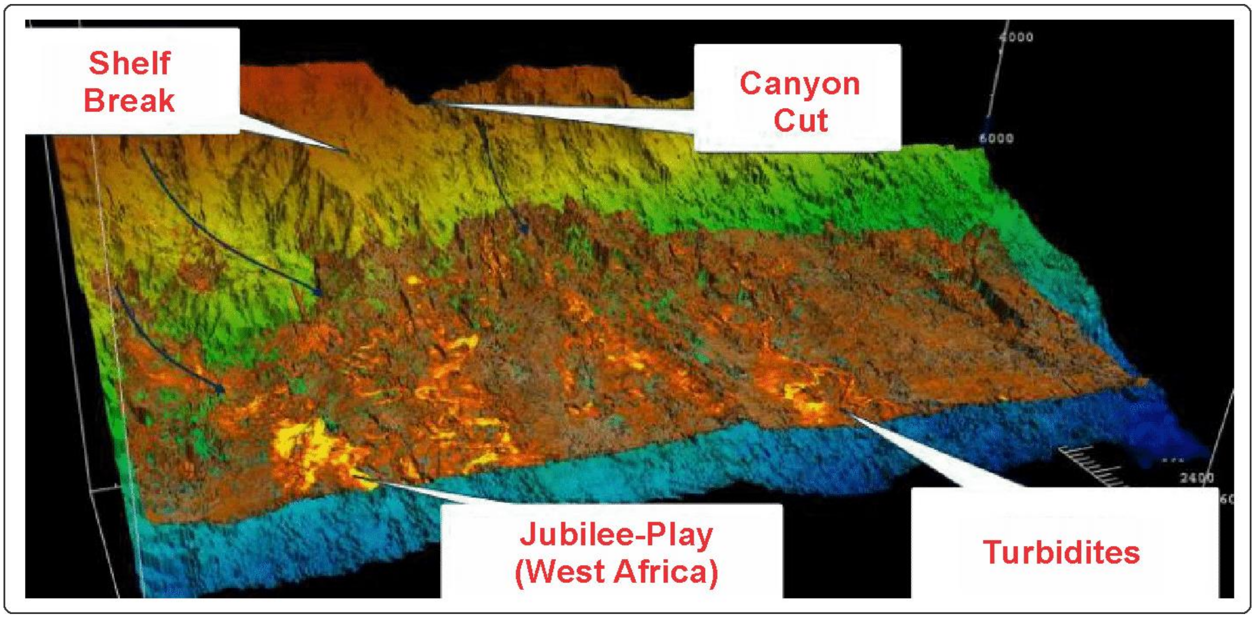


Figure 10: 3D view of the Jubilee field, offshore Ghana.

3.3 THE BRAZILIAN BID ROUND 11

According to the results of the 11th ANP Bid Round held in 2013, Petrobras has acquired the concession of 4 blocks in the Foz do Amazonas Basin, in conjunction with other partner companies (Figure 11). Due to the investments made in each of the blocks and minimum work obligations proposed, it was possible to identify the number of wells that the joint venture has committed to drill in each block during the exploratory phase, valid until the end of 2018. Also, according to ANP's website, the penalty cost for not drilling a commitment well in this area is close to 100 million reais (about 30 million dollars).

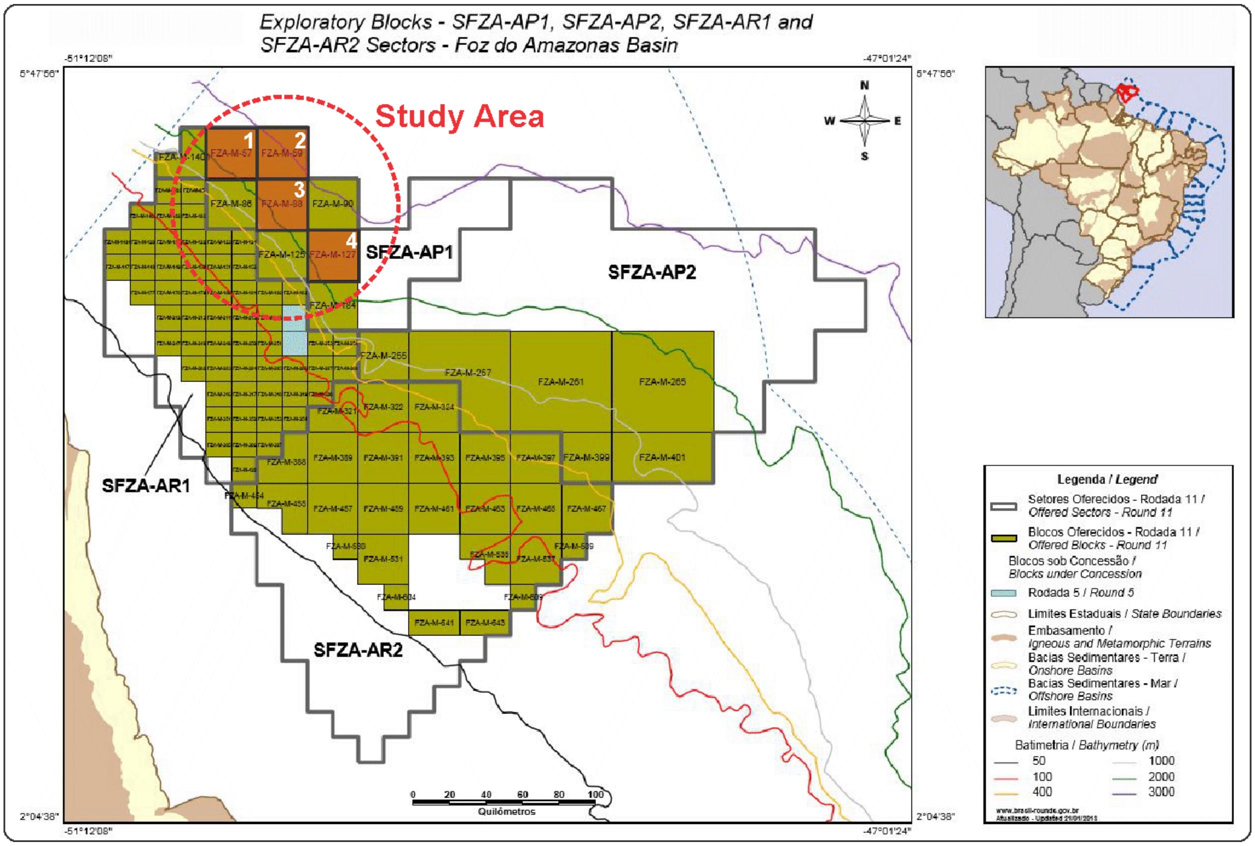


Figure 11: Location map of the 4 blocks acquired by Petrobras and partners in 2013.

It is important to note that, up to the present moment, no results of any exploratory activities regarding the 4 blocks analyzed have been reported. Finally, all information described in this research about Foz do Amazonas Basin, Zaedyus and Jubilee discoveries, and the Bid Round 11 are public and available on the following websites:

http://www.brasil-
rounds.gov.br/arquivos/Seminarios_r11/tec_ambiental/Bacia_da_Foz_do_Amazonas.pdf

http://www.brasil-rounds.gov.br/arquivos/relatorio_r11/Relatorio_Analise_R11.pdf

http://www.tullowoil.com/media/press-releases/zaedyus-exploration-well-makes-oil-discovery-offshore-french-guiana

http://www.tullowoil.com/media/press-releases/well-result-zaedyus-2-offshore-french-guiana

4 Methodology

This chapter explains the step-by-step approach for creating the model used to calculate the value of the exploratory portfolio, include the inputs related to each of the prospects and the application of the Monte-Carlo routine. The software used were Microsoft Office and @Risk, from Palisade.

4.1 BASIC INPUTS

To create an exploration portfolio and a Monte Carlo model, the first step is to define the minimum inputs needed from each of the prospects to calculate the EMVs and the first ranking. Therefore, based on the geological information available on ANP's website and literature about the hydrocarbon potential in Foz do Amazonas Basin, and average size and characteristics of analogous turbiditic accumulations, a fictitious portfolio composed by 13 prospects were created and randomly positioned in each of the blocks (Figure 12). Also, for the model to reflect a real challenge faced by oil companies in ranking and evaluating portfolios, the model used some information from Brazilian Bid Round 11, such as the minimum well commitment in the exploratory phase for each block, its duration (2 years) and penalty costs in case of noncompliance (US$ 30 million/well not drilled).

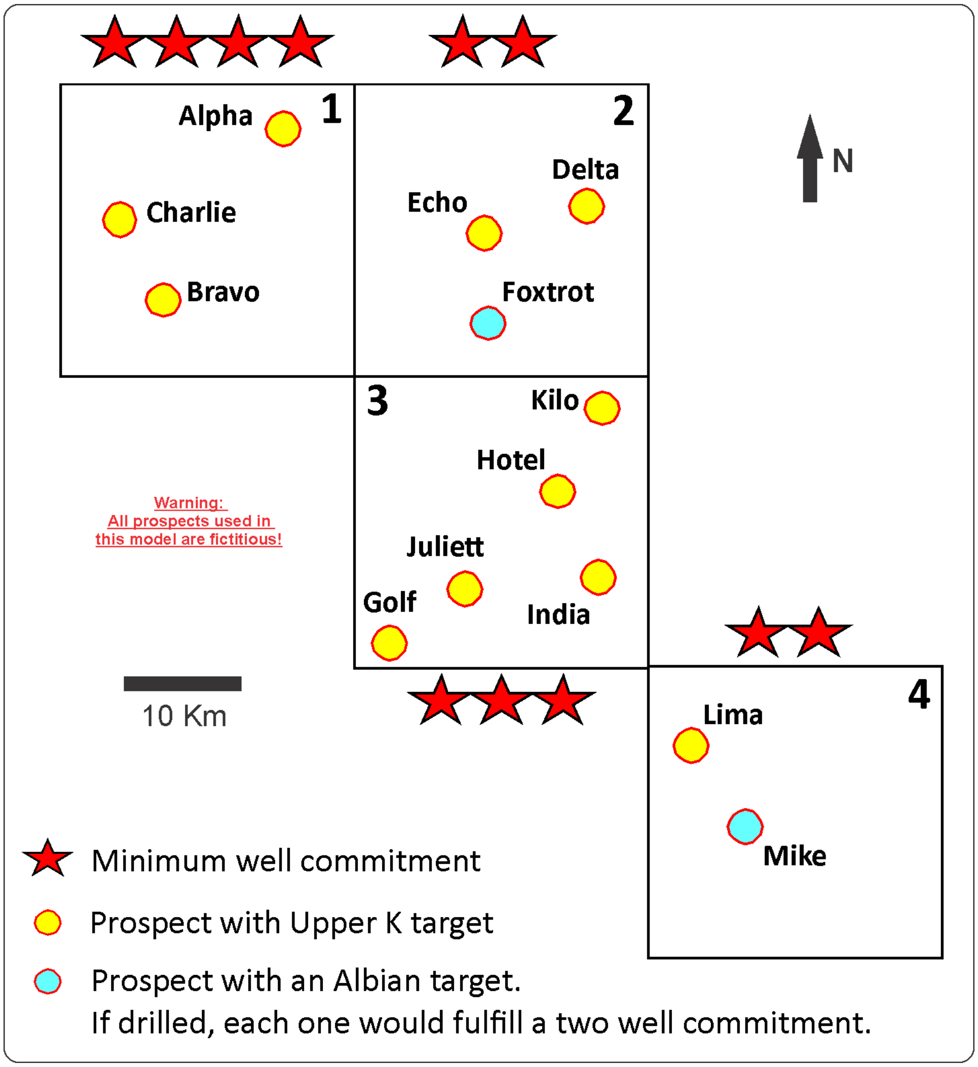


Figure 12: Location map of prospects and blocks minimum commitments.

To facilitate the model creation but without diminishing similarity with real exploration portfolios, the following premises were defined:

- Each opportunity has only one target (Upper K or Albian sandstones);
- Oil is the only expected hydrocarbon type for the listed prospects.

Once the location and objectives of each prospect have been defined, the next step is to estimate their water and target depths. These data are relevant in the calculation of the sedimentary thickness to be drilled and consequently in the drilling and appraisal costs. Figure 13 represents the bathymetric map of the study area, which guided water depth estimates at each location. For example, Golf represents the shallowest prospect, positioned in water depths of 1100m, whereas Delta was the deepest opportunity, located 2150m deep. Additionally, the total depths estimates were based on nearby accumulations (Zaedyus) and seismic sections available on the ANP website, and they range from 3900m (Golf) to 6500m (Mike).

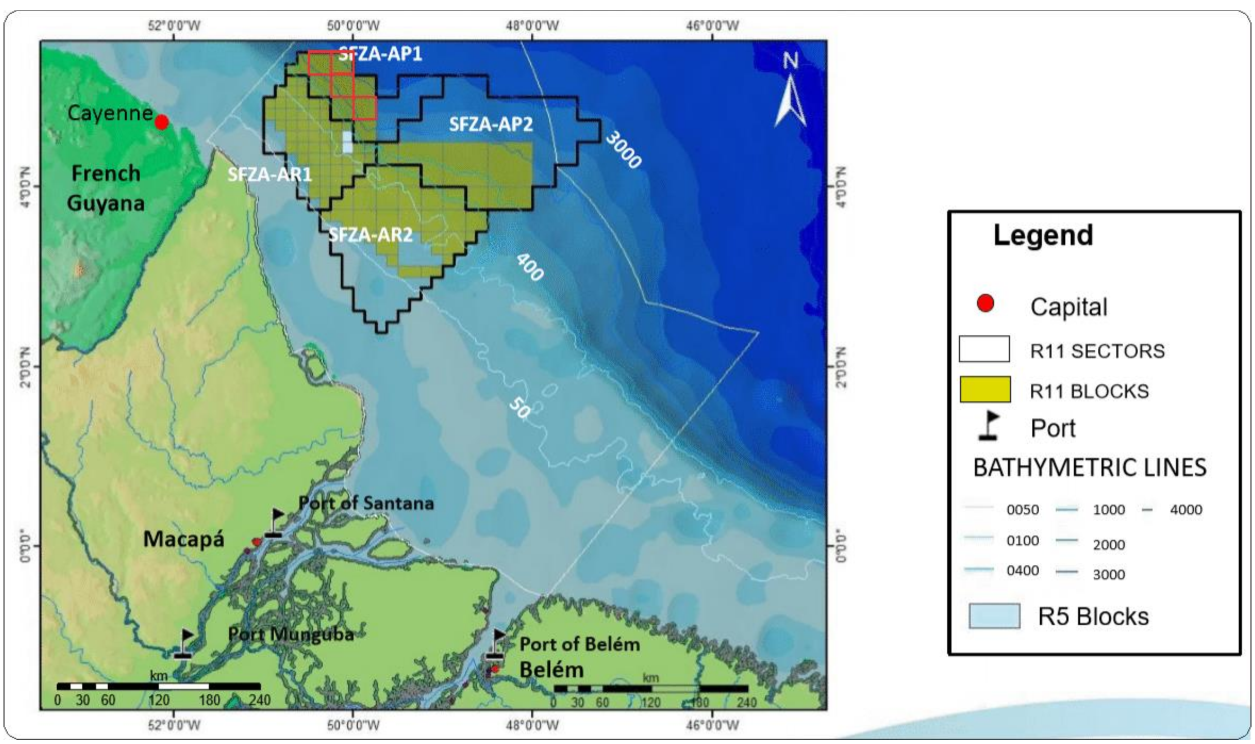


Figure 13: Bathymetric map of Foz do Amazonas Basin.

It is important to mention that both Foxtrot and Mike prospects target the Albian section, deeper and thus more expensive. Because of this higher cost estimates and the interest in testing this new exploratory play, it was considered that, when testing one of these two opportunities, the well commitment for that block will be fulfilled by two points instead of just one. In fact, some ANP reports show that this type of commitment compliance has been already done in the past by the agency. Table 2 summarizes the inputs collected so far for each one of the prospects.

	Alpha	Bravo	Charlie	Delta	Echo	Foxtrot	Golf	Hotel	India	Juliett	Kilo	Lima	Mike
Corresp. block		**1**			**2**				**3**				**4**
Well commitment reduction if drilled	**1**	**1**	**1**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**2**
Water depth (m)	**1390**	**1150**	**1200**	**2250**	**2100**	**2010**	**1100**	**1840**	**1710**	**1220**	**2090**	**1560**	**1580**
Total depth (m)	**4900**	**4050**	**4200**	**5200**	**4800**	**6900**	**3900**	**4400**	**4600**	**4300**	**5000**	**5100**	**6500**

Table 2: Prospects basic inputs.

4.2 FINANCIAL PARAMETERS

In the study area, each wildcat well would cost about 30 to 50 dollars per meter drilled, and two appraisal wells are necessary, in average, to delimit any discoveries. Based on this information and at the estimated depths, it was possible to calculate all exploration and appraisal investments for each prospect in a simplified form, without considering discount or inflation rates.

For each barrel discovered above the minimum commercial volume, the oil company would make an estimated profit of 1 to 3 dollars, on average, after paying for operating expenses, transportation costs and other expenses. This parameter, here called profit per barrel, is one of the most important rates to be calculated in assessing the attractiveness of an exploratory opportunity, and unfortunately one of the most difficult to estimate, due to various uncertainties involved in the long development phase.

Because of the associated uncertainty, both cost per meter and profit barrel were modeled considering a discrete probability distribution of 30% chance for low and high cases and 40% chance for the base scenario. That is, for each iteration, the model will choose one of these values for use in the exploratory campaign according to the proposed likelihood.

Finally, the Brazilian taxes for exploratory activities are fixed in 34%, and because it can be compensated in other projects, these exploratory expenses will be deducted from the costs in present value. Table 3 contains all financial parameter modeled in their low, base and high cases.

Financial Parameters	Unit	Low	Base	High
Tax Rate	%		34%	
Cost per meter drilled	Thousands US$/meter	$30.00	$40.00	$ 50.00
Profit barrel above threshold	US$/barrel	$ 2.00	$ 3.00	$ 4.00

Table 3: Financial parameters used in EMV calculations.

4.3 CHANCES OF SUCCESS

In this work, the chance of geological success of each prospect results from the multiplication of the probabilities of occurrence of three independent geological parameters:

1 - Charge: chance that hydrocarbons, generated by a source rock nearby, had accessed the target trap through diverse migration pathways;

2 - Reservoir: chance of occurrence of reservoir rock with sufficient porosity to accumulate oil in tested objective;

3- Trap: likelihood that a structural, stratigraphic or mixed trap exists, with sufficient sealing conditions to allow trapping of hydrocarbons in the target section.

After randomly assigning risks for each parameter, the resulting average Pg was 20%, lower than the average success rate of 35% of offshore turbidite play in Latin America (Weimer and Pettingill, 2007). This difference can be justified by the fact that the Foz do Amazonas Basin represents a new exploratory frontier of the Brazilian coast, when compared to the other mature basins of Campos or Sergipe-Alagoas, for example.

At time 0, that is, before start of drilling campaign, the main geological risk is trap absence, with an average chance of 52%, followed by the lack of porous reservoir (59% on average). Note that Foxtrot and Mike prospects present low probabilities for reservoir occurrence (40%), because of the Albian play's burial conditions. Due to a large number of oil shows observed in past wells, the charge factor presents the highest average chance of occurrence (67%). **Error! Reference source not found.** summarizes the prior chances of success of each opportunity.

Prior chances of success	Prospect Data													
	Alpha	**Bravo**	**Charlie**	**Delta**	**Echo**	**Foxtrot**	**Golf**	**Hotel**	**India**	**Juliett**	**Kilo**	**Lima**	**Mike**	**Average**
Charge	70%	70%	60%	60%	70%	70%	60%	60%	60%	60%	60%	90%	80%	**67%**
Reservoir	50%	70%	60%	50%	60%	40%	80%	60%	70%	70%	70%	50%	40%	**59%**
Trap	60%	40%	50%	50%	40%	80%	40%	50%	40%	60%	50%	50%	60%	**52%**
Prospect Pg	**21%**	**20%**	**18%**	**15%**	**17%**	**22%**	**19%**	**18%**	**17%**	**25%**	**21%**	**23%**	**19%**	**20%**

Table 4: Prospect chances regarding charge, reservoir and trap, with overall probabilities of success in bold.

4.4 VOLUMETRIC ESTIMATES AND EMV CALCULATIONS

According to Rose (2001), since the prospect reserves distribution involves the multiplication of constituent independent variables such as area and porosity, it is expected to take a lognormal form, where the mean represents the best single expression of the distribution's value. Therefore, each prospect was assigned a volumetric distribution with lognormal behavior, based on the size of the Zaedyus accumulation and other discoveries in the same play.

The curve was generated through the mean expected reserves and a variance number, corresponding to half of the reported mean. This curve is later truncated in the P99 and P01 values, which are extremely unlikely, but possible (checkpoints), and then the minimum commercial volumes of each prospect is defined, sufficient to warrant platform installation and development drilling (half-cycle). In the study area, a rough estimate was made based on the modal value of the parent-reserves distribution. Thus, for being shallower thus having cheaper wells, the commercial volume is lower in the Upper

Cretaceous play (between 200 and 250 million barrels), when compared to the volume necessary for commerciality in the Albian play (400 million barrels).

Finally, following the methodology proposed by Rose (2001), each reserve distribution curve was truncated using minimum commercial volumes, to obtain commercial chances of success and mean commercial discovery sizes for each prospect. These values are necessary for calculating the EMVs at time 0, in a slightly different formula than the proposed by Rose (2001) due to the inclusion of exploration and appraisal costs, the latter in case of geological success (Figure 14).

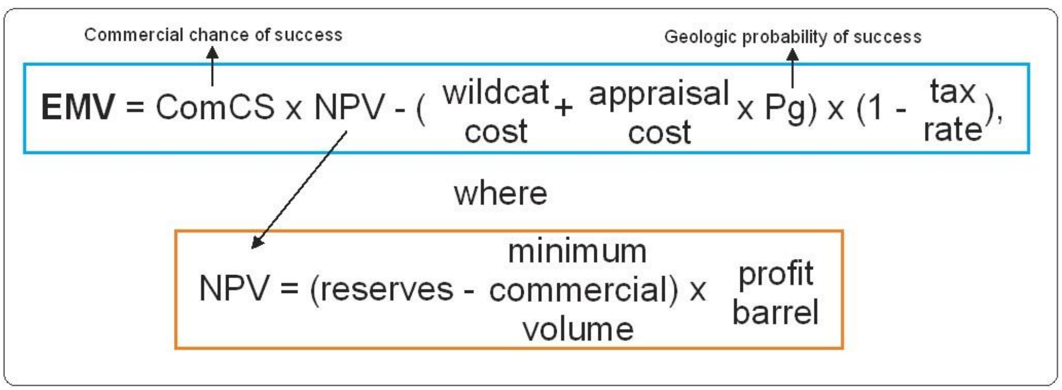


Figure 14: EMV formula, adapted from Rose (2001).

Table 5 contains all the values calculated from the geological, financial and volumetric inputs of each of the prospects, especially EMV. Note that not all opportunities are attractive a priori, that is, some have a negative expected value at time 0.

Model Inputs

General info	Unit	Alpha	Bravo	Charlie	Delta	Echo	Foxtrot	Golf	Hotel	India	Juliett	Kilo	Lima
		Prospect Data											
Block location	Block number		1			2				3			4
Prospect name	Prospect name	Alpha	Bravo	Charlie	Delta	Echo	Foxtrot	Golf	Hotel	India	Juliett	Kilo	Lima
Target play	Play name	Upper K	Upper K	Upper K	Upper K	Upper K	Albian	Upper K	Upper K	Upper K	Upper K	Upper K	Upper K
Well design and cost estimates													
Water depth	Meters	1390	1150	1200	2250	2100	2010	1100	1840	1710	1220	2090	1560
Well total depth	Meters	4900	4050	4200	5200	4800	6900	3900	4400	4600	4300	5000	5100
Prior chances of success													
Reservoir	%	50%	70%	60%	50%	60%	40%	80%	60%	70%	70%	70%	50%
Charge	%	70%	70%	60%	60%	70%	70%	60%	60%	60%	60%	60%	90%
Seal/Trap	%	60%	40%	50%	50%	40%	80%	40%	50%	40%	60%	50%	50%
Volume estimates													
Expected mean recoverable volume	Millions of barrels	450	350	310	385	370	850	480	560	350	420	650	490
Std deviation for lognormal distrib.	Millions of barrels	225	175	155	192.5	185	425	240	280	175	210	325	245
Minimum commercial volume	Millions of barrels	250	200	200	250	250	400	250	200	250	200	200	250

Financial Parameters	Unit	Low	Base	High
Tax Rate	%		34%	
Cost per meter drilled	Thousands US$/meter	$30.00	$40.00	$ 50.00
Profit barrel above threshold	US$/barrel	$ 2.00	$ 3.00	$ 4.00

Calculations

(example)

Model Calculations	Units	Alpha	Bravo	Charlie	Delta	Echo	Foxtrot	Golf	Hotel	India	Juliett	Kilo
Burial	Meters	3510	2900	3000	2950	2700	4890	2800	2560	2890	3080	2910
Wildcat cost	Millions of US$	105	87	90	89	81	147	84	77	87	92	87
Prior chance of success	%	21%	20%	18%	15%	17%	22%	19%	18%	17%	25%	21%
NPV Calculations												
NPV success case (mean)	Millions of US$	600	450	330	405	360	1350	690	1080	300	660	1350
Estimated appraisal cost	Millions of US$	211	174	180	177	162	293	168	154	173	185	175
Prior commercial chance of success	%	18%	16%	14%	11%	12%	21%	17%	18%	12%	23%	21%
Ranking Calculations - Time 0												
Expected monetary value	Millions of US$	8.5	-6.3	-35.6	-30.0	-27.4	138.4	40.0	122.3	-41.8	60.8	201.1
Capital efficiency	US$ profit/US$ invest	$ 0.06	$ (0.05)	$ (0.29)	$(0.26)	$ (0.25)	$ 0.65	$ 0.34	$ 1.17	$(0.36)	$ 0.44	$ 1.62
Reserve efficiency	Barrels/US$ invest	0.63	0.57	0.46	0.50	0.57	0.90	0.79	0.97	0.51	0.76	1.10

Table 5: Model inputs and derived calculations for each prospect at time 0.

4.5 Ranking Strategies

Once all the initial calculations are made, we can select which opportunities should be tested first. There are several ways of ranking exploratory opportunities, and the vast majority of them take into consideration the Expected Monetary Value (EMV), widely used in the oil industry. However, some inconsistencies may occur when ranking opportunities with similar EMVs. For example, if two prospects have the same EMV but one costs ten times more than the other, additional tools like capital efficiency (profit per investment ratio) or volume efficiency (reserve per investment ratio) become critical to resource and budget optimization. In this model, the portfolio was ranked according to 4 different metrics:

1 - Expected Monetary Value: drill highest EMV first;

2 - Capital Efficiency: test highest EMV / Capex first;

3 - Volume Efficiency: drill highest risked volume / Capex first;

4 - Commitment or Block Ranking: test best EMV in each block, then second, and so on.

Table 6 displays the prospect ordering at time 0, according to all four ranking strategies modeled.

Rank	EMV	Capital Efficiency	Volume Efficiency	Block Ranking
1st	Kilo	Kilo	Kilo	Kilo
2nd	Foxtrot	Hotel	Hotel	Foxtrot
3rd	Hotel	Foxtrot	Foxtrot	Lima
4th	Juliett	Juliett	Golf	Alpha
5th	Lima	Golf	Juliett	Hotel
6th	Golf	Lima	Lima	Mike
7th	Mike	Mike	Mike	Bravo
8th	Alpha	Alpha	Alpha	Echo
9th	Bravo	Bravo	Echo	Juliett
10th	Echo	Echo	Bravo	Delta
11th	Delta	Delta	India	Charlie
12th	Charlie	Charlie	Delta	Golf
13th	India	India	Charlie	India

Table 6: Prospect ranking at time 0 according to the four criteria selected.

4.6 DEPENDENCE RELATIONSHIPS

There are diverse ways of calculating the impact that well results exert on remaining prospects. In this work, those relationships were classified as strong, weak or nonexistent (independent opportunities). For example, Bravo and Charlie are positioned on a prominent focalization high and therefore have been classified as heavily dependent on charge. So, if Bravo succeeds in this parameter, Charlie's chance of success (charge) increases considerably. On the other hand, if Bravo is a dry hole and its post-mortem analysis shows that the failure reason was the absence of charge, Charlie's chance of success on this parameter would decrease considerably. Figure 15, Figure 16 and Figure 17 show the dependence relationships between each of the prospects regarding the charge, reservoir and trap categories, respectively.

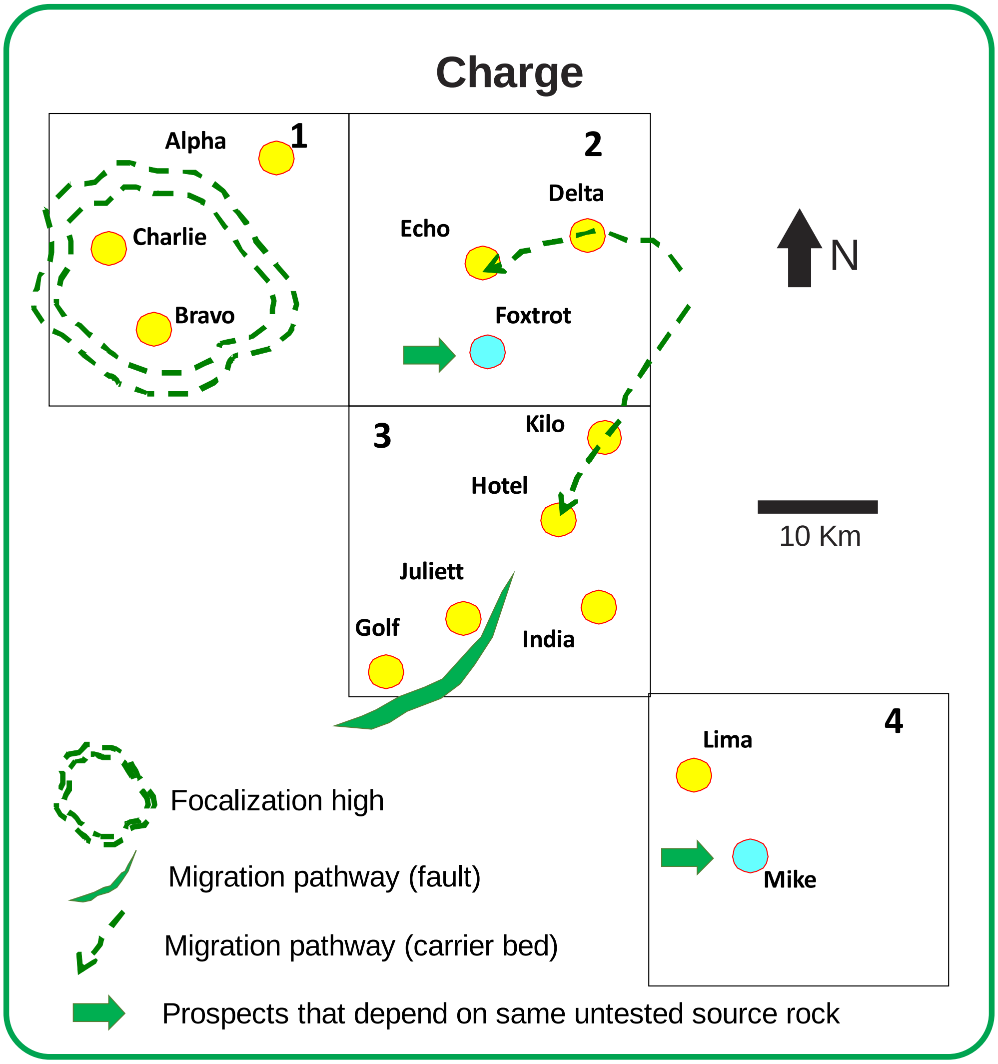


Figure 15: Charge and migration dependence relationships considered.

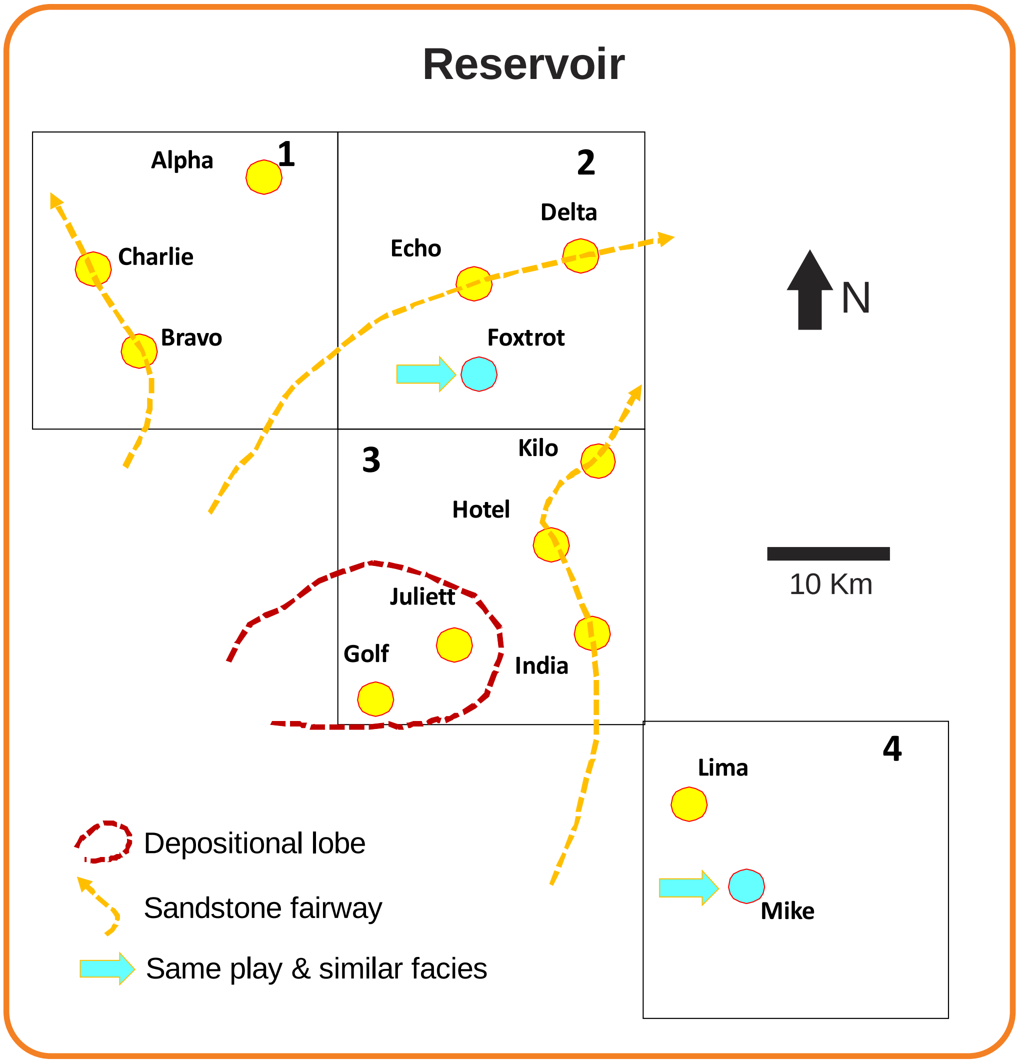


Figure 16: Reservoir dependence relationships considered.

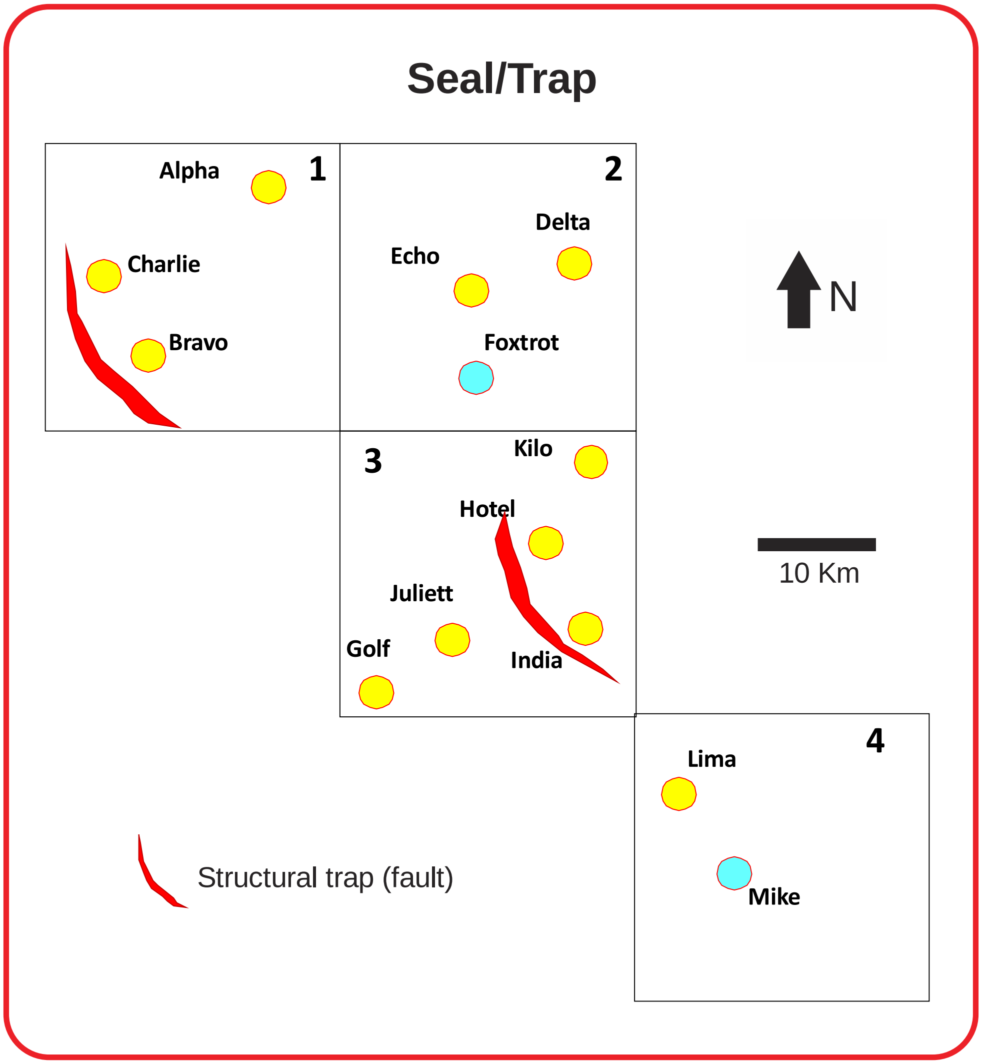


Figure 17:Trap dependence relationships considered.

Each dependence relationship is then inserted into the model through an influence matrix, detailing the impact that each result will exert on the other opportunities regarding the three geological parameters (Table 7, Table 8 and Table 9). The model was adapted so that no posterior chance should exceed 95% or fall below 5% after consecutive successes or failures.

CHARGE

x		...on the charge result of this well?												
		Alpha	Bravo	Charlie	Delta	Echo	Foxtrot	Golf	Hotel	India	Juliett	Kilo	Lima	Mike
At what level is this prospect dependent...	Alpha		0	0	0	0	0	0	0	0	0	0	0	0
	Bravo	0		2	0	0	0	0	0	0	0	0	0	0
	Charlie	0	2		0	0	0	0	0	0	0	0	0	0
	Delta	0	0	0		1	0	0	0	0	0	0	0	0
	Echo	0	0	0	2		0	0	0	0	0	0	0	0
	Foxtrot	0	0	0	0	0		0	0	0	0	0	0	1
	Golf	0	0	0	0	0	0		0	0	2	0	0	0
	Hotel	0	0	0	0	0	0	0		0	0	2	0	0
	India	0	0	0	0	0	0	0	0		0	0	0	0
	Juliett	0	0	0	0	0	0	2	0	0		0	0	0
	Kilo	0	0	0	0	0	0	0	1	0	0		0	0
	Lima	0	0	0	0	0	0	0	0	0	0	0		0
	Mike	0	0	0	0	0	1	0	0	0	0	0	0	

Dependence level multipliers*	Success case	Failure case
If weak dependence, multiply prior chance by	1.4	0.6
If strong dependence, multiply prior chance by	1.8	0.2

Dependence levels

0 = Independent
1 = Weakly dependent
2 = Strongly dependent

Table 7: Charge relationships and multipliers for success and failure cases.

RESERVOIR

x		...on the reservoir result of this well?												
		Alpha	Bravo	Charlie	Delta	Echo	Foxtrot	Golf	Hotel	India	Juliett	Kilo	Lima	Mike
At what level is this prospect dependent...	Alpha		0	0	0	0	0	0	0	0	0	0	0	0
	Bravo	0		1	0	0	0	0	0	0	0	0	0	0
	Charlie	0	2		0	0	0	0	0	0	0	0	0	0
	Delta	0	0	0		2	0	0	0	0	0	0	0	0
	Echo	0	0	0	1		0	0	0	0	0	0	0	0
	Foxtrot	0	0	0	0	0		0	0	0	0	0	0	1
	Golf	0	0	0	0	0	0		0	0	0	0	0	0
	Hotel	0	0	0	0	0	0	0		2	0	1	0	0
	India	0	0	0	0	0	0	0	1		0	1	0	0
	Juliett	0	0	0	0	0	0	0	0	0		0	0	0
	Kilo	0	0	0	0	0	0	0	2	2	0		0	0
	Lima	0	0	0	0	0	0	0	0	0	0	0		0
	Mike	0	0	0	0	0	1	0	0	0	0	0	0	

Dependence level multipliers*	Success case	Failure case
If weak dependence, multiply prior chance by	1.4	0.6
If strong dependence, multiply prior chance by	1.8	0.2

Dependence levels

0 = Independent
1 = Weakly dependent
2 = Strongly dependent

Table 8: Reservoir relationships and multipliers for success and failure cases.

TRAP

x	...on the trap result of this well?												
At what level is this prospect dependent...	Alpha	Bravo	Charlie	Delta	Echo	Foxtrot	Golf	Hotel	India	Juliett	Kilo	Lima	Mike
Alpha		0	0	0	0	0	0	0	0	0	0	0	0
Bravo	0		2	0	0	0	0	0	0	0	0	0	0
Charlie	0	2		0	0	0	0	0	0	0	0	0	0
Delta	0	0	0		0	0	0	0	0	0	0	0	0
Echo	0	0	0	0		0	0	0	0	0	0	0	0
Foxtrot	0	0	0	0	0		0	0	0	0	0	0	0
Golf	0	0	0	0	0	0		0	0	0	0	0	0
Hotel	0	0	0	0	0	0	0		2	0	0	0	0
India	0	0	0	0	0	0	0	2		0	0	0	0
Juliett	0	0	0	0	0	0	0	0	0		0	0	0
Kilo	0	0	0	0	0	0	0	0	0	0		0	0
Lima	0	0	0	0	0	0	0	0	0	0	0		0
Mike	0	0	0	0	0	0	0	0	0	0	0	0	

Dependence level multipliers*	Success case	Failure case
If weak dependence, multiply prior chance by	1.4	0.6
If strong dependence, multiply prior chance by	1.8	0.2

Dependence levels

0 = Independent
1 = Weakly dependent
2 = Strongly dependent

Table 9: Trap relationships and multipliers for success and failure cases.

Finally, prospects could benefit by sharing production facilities in the future, so their minimum commercial volume would decrease, in this work by 20%, if a discovery was previously made nearby (Figure 18).

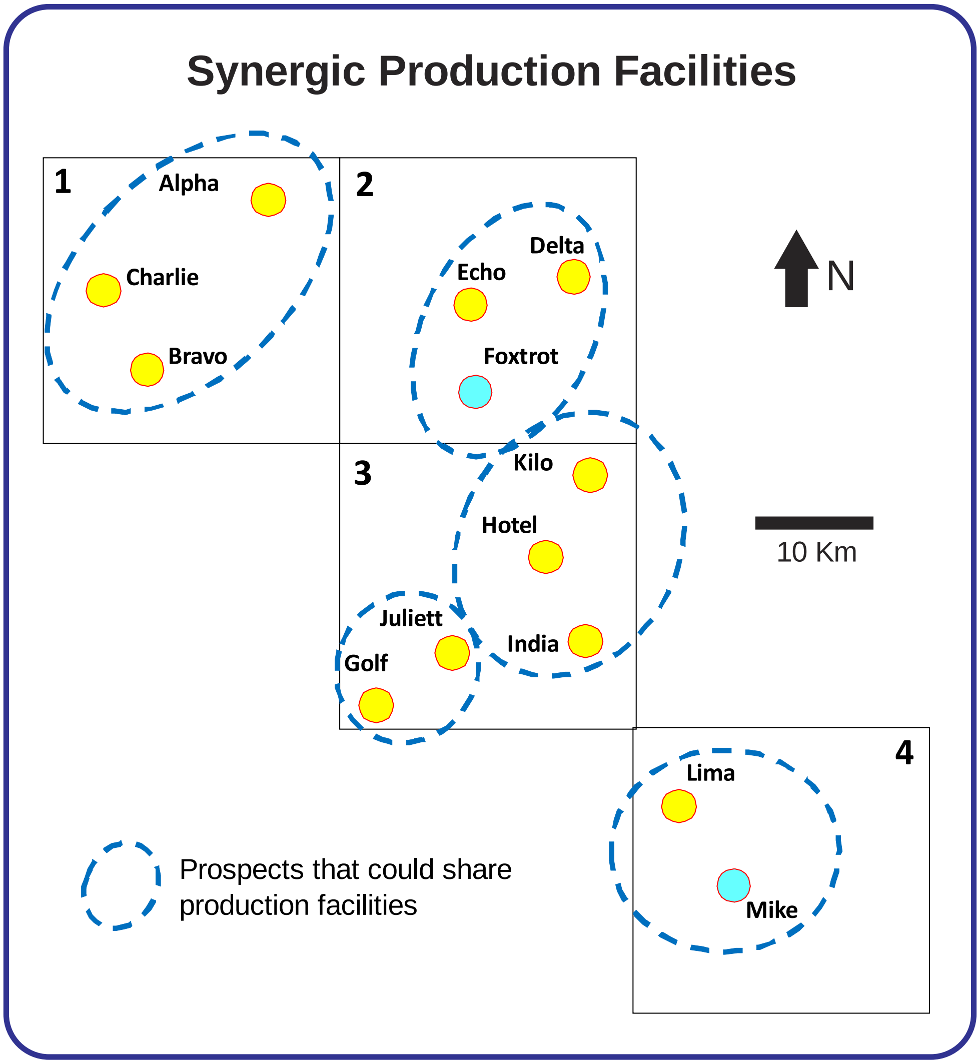


Figure 18: Synergic groups of prospects, due to proximity.

4.7 Failure Analysis

This work proposes a logical order for the post-mortem analysis of dry holes, to extract as maximum geologic information as possible from eventual failures (Figure 19). With this methodology, very similar to conventional post drill reviews, even failures can provide positively impact some of remaining alternative's chances and, ultimately, portfolio value.

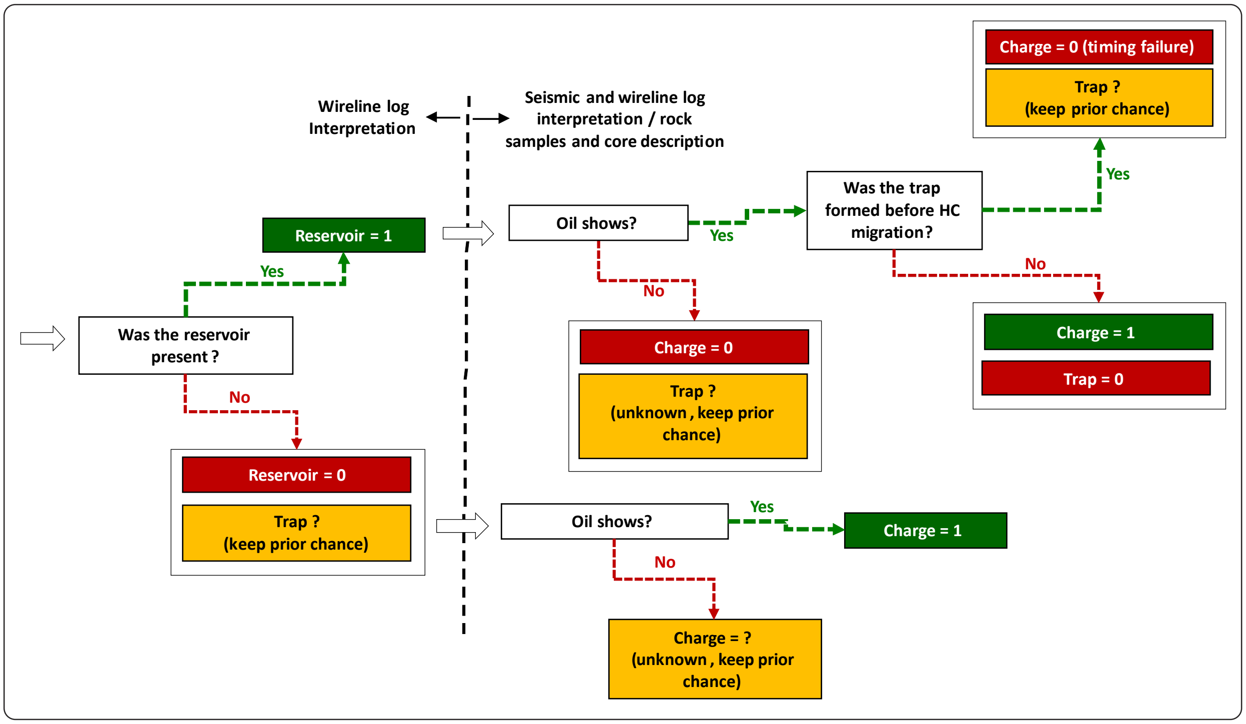


Figure 19: Failure post-drill review for conventional wells.

In a post-mortem analysis of a dry hole, the first parameter to be analyzed is the reservoir presence.

- If there is no porous reservoir in the target section:

a) Reservoir absence is automatically considered the failure reason;

b) Seal and trap conditions cannot be evaluated. To be properly tested, these parameters need an underlying containment rock with effective charge;

c) Strong HC shows can occur even in poor reservoir conditions (ex.: thin bedded sandstones or intensively fractured rocks), suggesting that charge was efficient.

- If porous reservoir is present, the next step is to look for hydrocarbon evidence:

a) Charge failed if no oil or gas shows were observed in target section. In that case, seal and trap cannot be described;

b) If oil or gas shows were evident, the bad result was caused either by timing problem or trap failure. In this model, we considered that all traps were already formed when migration occurred.

4.8 Monte Carlo Routine, Model Constraints and Outputs

An exploratory campaign may cease for many factors, such as loss of area due to noncompliance with the minimum program, when enough discoveries are made, low remaining potential or negative EMVs, among others. To better reflect these real-life limitations, the model was set so that each drilling sequence will be interrupted when there is insufficient budget, no available rigs or when remaining opportunities are no longer attractive. Note that, in some situations, it is better to test a slightly negative EMV than paying the penalty for not drilling a commitment well. Table 10 displays the model constraints that, if reached, would stop the exploratory campaign:

Constraints	Unit	Low	Base	High
Rig slots per year	Rig slots	3	4	5
Maximum budget	Millions of US$	500	750	1000

Table 10: Constraints for low, base and high cases.

After all inputs and initial calculations, the portfolio has been tested 10,000 times according to each ranking strategy, in 2 different ways:

- by considering independent prospects, that is, the drilling order will always be the same regardless of the results obtained (drill best, then second best, and so on);
- with dependency analysis, where the ranking is dynamically affected by each well result.

The Monte Carlo routine has 5 main steps (Figure 20**Error! Reference source not found.**), described below:

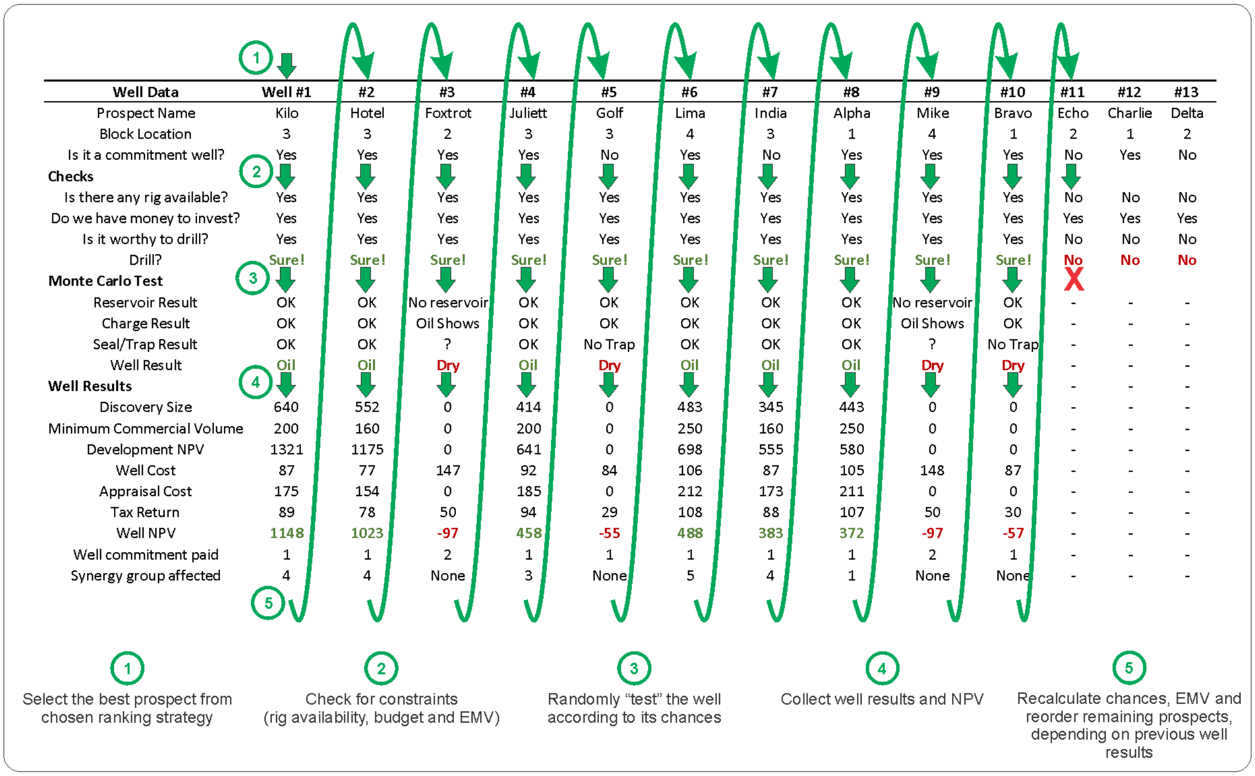
1 - Select the best prospect from one of the four ranking strategies (best EMV, best capital efficiency, etc.);

2 - Check for constraints (rig availability, budget, and EMV attractiveness);

3 - Randomly “test” the well according to its chances. For each geologic risk, we randomly pick a number between 0 and 1, and if it is smaller than the chance of success, we “succeeded” in that parameter;

4 - Collect well result and calculate NPV by randomly picking a volume from the reserves distribution of tested opportunity, in case of success;

5 - Recalculate chances, minimum commercial volumes and EMVs, thus reordering remaining prospects depending on the previous result.



Well Data	Well #1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13
Prospect Name	Kilo	Hotel	Foxtrot	Juliett	Golf	Lima	India	Alpha	Mike	Bravo	Echo	Charlie	Delta
Block Location	3	3	2	3	3	4	3	1	4	1	2	1	2
Is it a commitment well?	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No	Yes	No
Checks													
Is there any rig available?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Do we have money to invest?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Is it worthy to drill?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Drill?	Sure!	Sure!	Sure!	Sure!	Sure!	Sure!	Sure!	Sure!	Sure!	Sure!	No	No	No
Monte Carlo Test													
Reservoir Result	OK	OK	No reservoir	OK	OK	OK	OK	OK	No reservoir	OK	-	-	-
Charge Result	OK	OK	Oil Shows	OK	OK	OK	OK	OK	Oil Shows	OK	-	-	-
Seal/Trap Result	OK	OK	?	OK	No Trap	OK	OK	OK	?	No Trap	-	-	-
Well Result	Oil	Oil	Dry	Oil	Dry	Oil	Oil	Oil	Dry	Dry	-	-	-
Well Results											-	-	-
Discovery Size	640	552	0	414	0	483	345	443	0	0	-	-	-
Minimum Commercial Volume	200	160	0	200	0	250	160	250	0	0	-	-	-
Development NPV	1321	1175	0	641	0	698	555	580	0	0	-	-	-
Well Cost	87	77	147	92	84	106	87	105	148	87	-	-	-
Appraisal Cost	175	154	0	185	0	212	173	211	0	0	-	-	-
Tax Return	89	78	50	94	29	108	88	107	50	30	-	-	-
Well NPV	1148	1023	-97	458	-55	488	383	372	-97	-57	-	-	-
Well commitment paid	1	1	2	1	1	1	1	1	2	1	-	-	-
Synergy group affected	4	4	None	3	None	5	4	1	None	None	-	-	-

Figure 20: Monte Carlo routine for portfolio testing, with steps highlighted in green.

We then repeat steps 1 to 5 on remaining prospects until a constraint is reached, then the campaign restarts and total results are collected for analysis. Table 11 exemplifies the results that can be obtained for each model iteration.

Strategy Results	(Example)
Number of Wells Drilled	**10**
Number of Discoveries	**6**
Success Rate	**60%**
Strategy NPV ($Millions)	**3'506**
Capital Efficiency ($/$Capex)	**$ 1.65**
Average Reserves (MMbbl)	**288**
NPV per Barrel	**$ 12.18**
Failure Causes	
No Reservoir	**50%**
No Charge	**0%**
No Trap	**50%**

Table 11: Example of output list collected for each one of the 10,000 iterations.

5 Results

This chapter details the results obtained after we test the portfolio 10,000 times in each model (independent prospects x dependency analysis) through a Monte Carlo routine.

5.1 NPV RESULTS

After 10,000 iterations made in each model, we can see significant differences in the resultant NPV. Regardless of the ranking strategy selected, the average financial return when considering dependent prospects was close to 482 million dollars, almost 30% higher than the mean result when the leads are considered independent (Figure 21). Besides, the minimum NPVs obtained in the dependent model are also more attractive by 14%, showing less exposure to losses and minimizing risks. Finally, the best NPV result obtained in the dependent model is about 3.3 billion dollars greater than the best outcome observed in the independent model, which corresponds to a 32.6% upside.

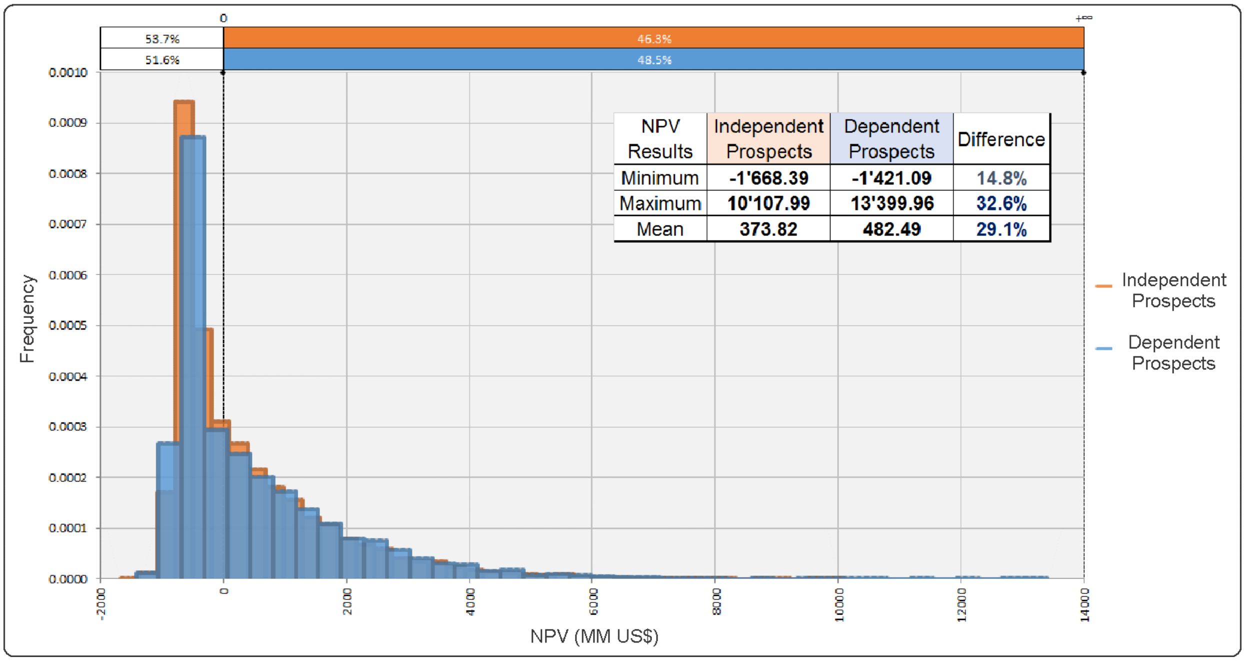


Figure 21: NPV frequency histogram for all strategies.

When considering only the maximize EMV strategy, the modeled drilling campaign would result in an average NPV of almost half a billion dollars when we use dependency analysis, about 1/3 greater than the average result obtained in the model without dependence (Figure 22). The chance of achieving a positive NPV is also greater when we consider dependency relationships between opportunities (48.2% x 45.8%).

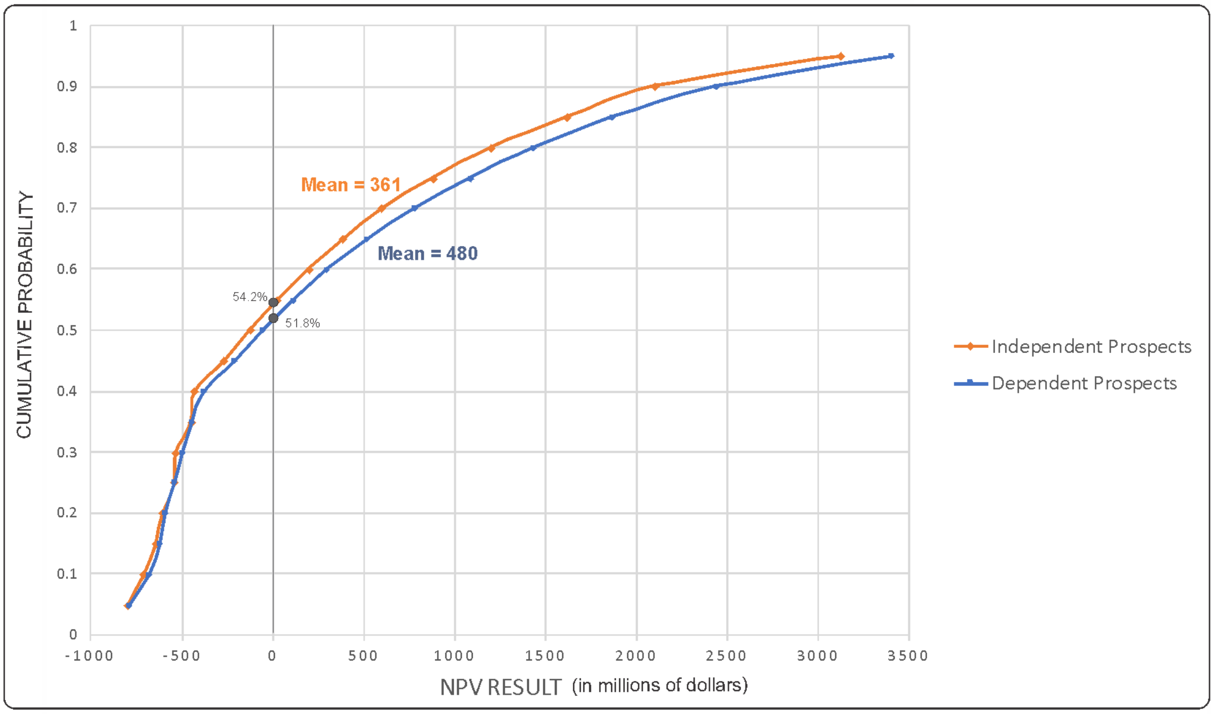


Figure 22: Cumulative probability distribution for NPV for the "maximize EMV" strategy.

Although the four modeled ranking strategies show very similar financial returns in each model, the average NPVs are also about 30% larger when considering dependent opportunities (Figure 23). When comparing ranking styles, we obtained slightly greater average values by using the maximize EMV strategy of prospect ordering, followed by capital efficiency and volume efficiency metrics.

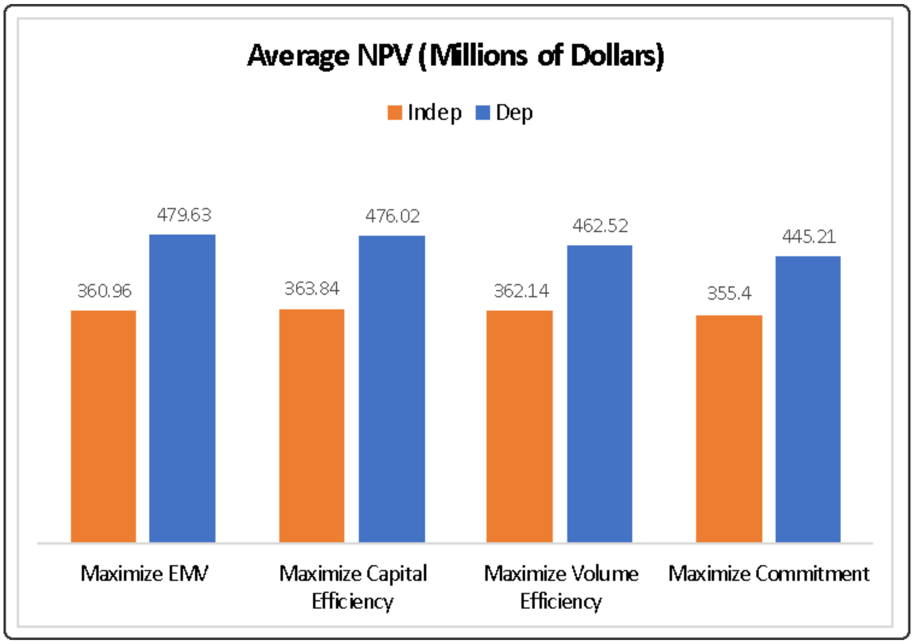


Figure 23: Average NPV results in each model and strategy.

5.2 Success Rate and Average Reserves

In general, the results observed show that by considering dependency we become more efficient in the use of resources. Although the average number of wells drilled was lower in this case, the number of discoveries made increased by 10% on average (Figure 24).

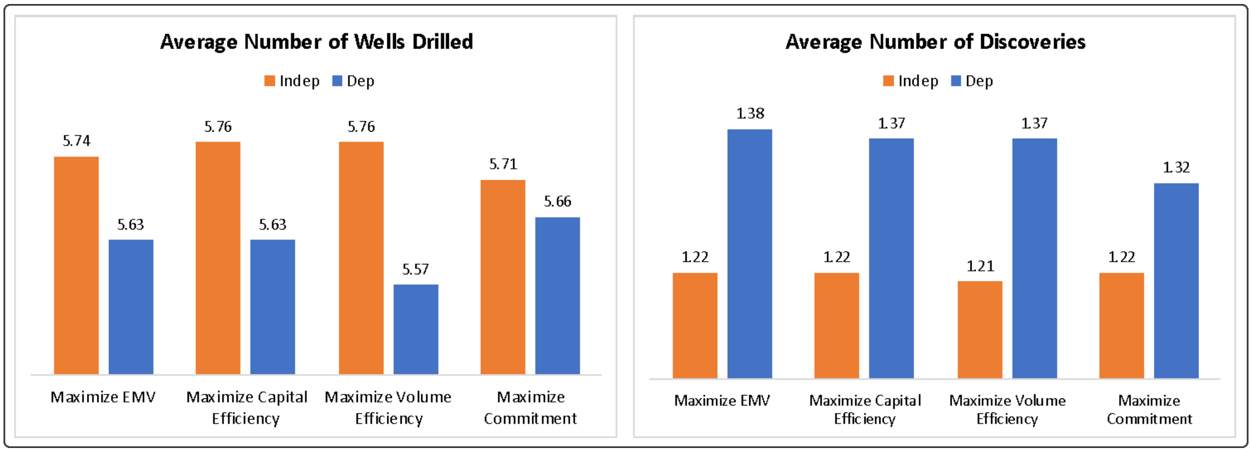


Figure 24: Average number of wells drilled and discoveries obtained in each strategy.

We also observed efficiency improvements in the success rate and average reserves discovered when considering dependency (Figure 25). In the first three ranking strategies modeled, the success rate increased about 3%, and the average reserves discovered jumped from 123 MMbbl to 138 MMbbl (12%). Although also showing better results in the dependent model, the maximize commitment strategy experimented smaller increases, of 1.6% and 6% respectively, in the same parameters.

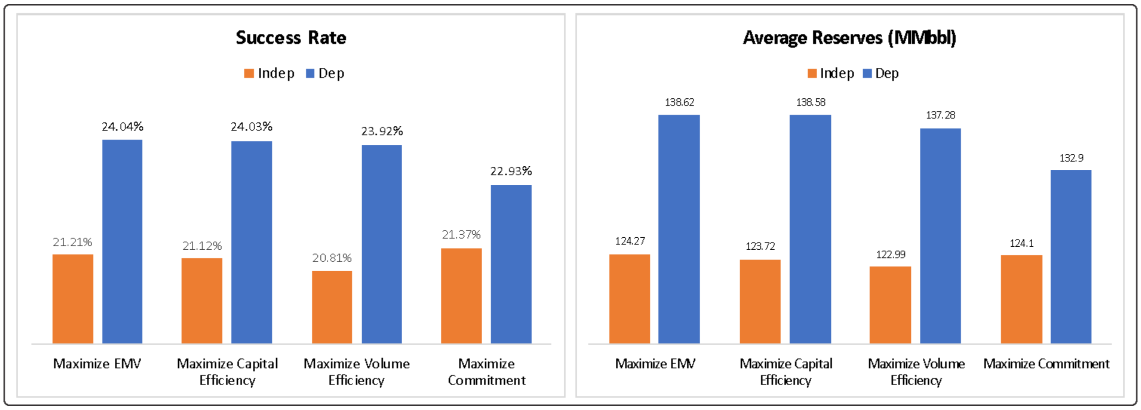


Figure 25: Success rate and average reserves discovered in each strategy.

5.3 Main Failure Reasons

Before the exploratory campaign, it was believed that the main reason for failures would be the lack of effective traps, since, with an average chance of 51.5%, this was the greatest geological risk in the study area (Figure 26). However, the reservoir absence resulted in more than 50% of dry holes, mainly because trapping conditions are only tested when the other two geologic parameters succeed, according to the proposed post-mortem methodology.

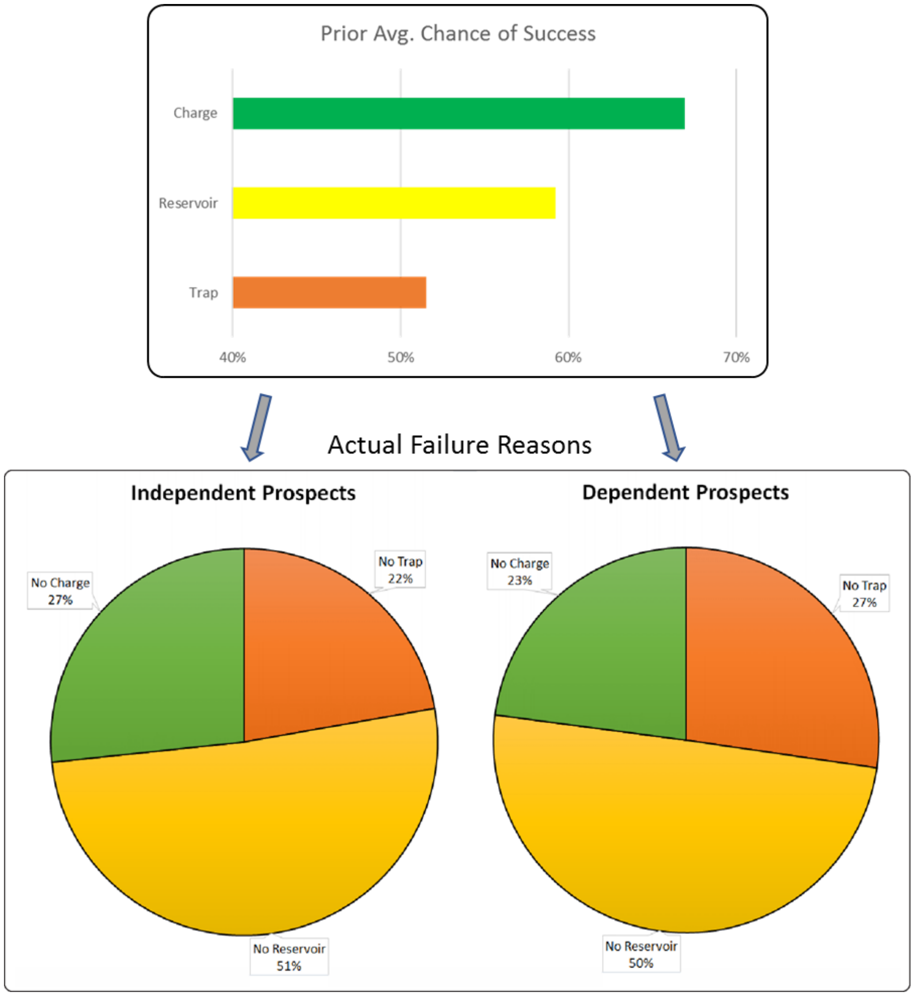


Figure 26: Prior average chances of success and actual dry hole reasons for each model.

5.4 Testing Frequency for each Prospect

When comparing EMV at time 0 with the testing frequency of each opportunity in both models, it is noticed that dependency analysis can significantly alter the attractiveness of some prospects (Figure 27). For example, even with the lowest base EMV at the start of the campaign, India prospect was tested about 4% of the time on the second model, since its chances were dependent and thereby affected by previous positive results.

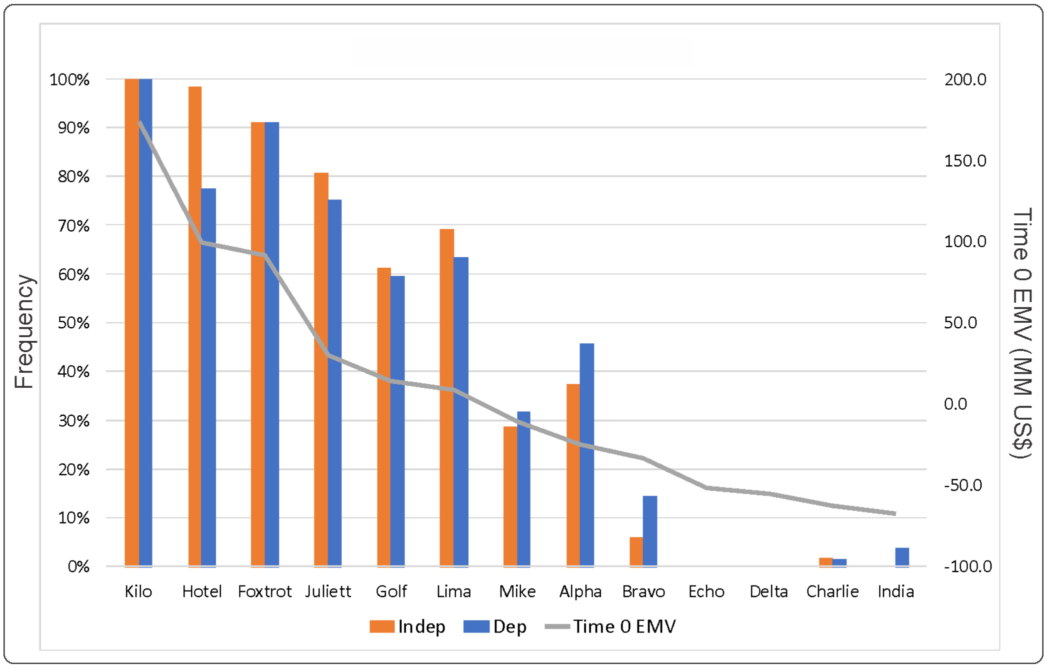


Figure 27: Testing frequency and time 0 EMV for each prospect.

Another interesting result obtained from the testing frequency analysis is that, while Kilo lead was the only prospect drilled in all scenarios, Echo and Delta were not considered sufficiently attractive in any of the 10,000 iterations.

6 Conclusions

6.1 Conclusions

The results of this research reinforce the importance of dependency analysis in evaluating an exploratory potential of a basin, concession or play. Especially in areas where opportunities can be discarded due to low potential, good initial results can improve the chances of success of other prospects, thereby increasing attractiveness and EMV of remaining alternatives. Besides, when considering possible dependencies and synergies, the use of resources such as rig slots becomes more efficient, even after failures in the first tests. In those cases, the untested potential can be discarded more quickly, avoiding additional losses and minimizing risks.

It was also noticed that, when considering dependent opportunities, fewer tests are necessary to evaluate the portfolio. This is because failures that may occur at the beginning of the campaign will decrease the attractiveness of the remaining leads. On the other hand, favorable initial outcomes will not compensate this effect due to model constraints.

Another result that deserves attention is the importance of the post-mortem analysis in the evaluation of an exploratory potential. This work has proposed a methodology that focused on the extraction of the greatest amount of geological information possible, in which even a dry hole can provide valuable and positive information for other prospects. However, this approach must be used with caution, especially in non-conventional plays and areas with limited wireline log information and low-quality seismic data. In these situations, few inferences can be made about oil shows, charge effectiveness or trap existence.

Finally, the frequency analysis showed that even opportunities with negative EMV should not be ignored since their chances of success and attractiveness can be positively impacted after the first few. When calculating portfolio value only by adding the initially positive VMEs, significant upsides can be discarded in precipitous strategic decisions.

6.2 Next Steps

An interesting breakdown of this work is to apply the suggested model in other basins and plays, especially using real portfolios and past drilling campaign forecasts and results. Also, different ranking strategies originated by efficient frontier models could be incorporated into the proposed model, increasing its versatility and applicability for evaluating more diversified and complex portfolios.

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Vita

Rafael Lima was born in Rio de Janeiro, Brazil, in 1980. He earned his bachelor degree in Geology at State University of Rio de Janeiro (UERJ) in 2004, when he joined Petrobras's exploration team. In 2010, he was designated consultant due to his achievements, and after 12 years of positive work, Petrobras supported his master degree at the University of Texas at Austin, in the Energy and Earth Resources Program. Rafael's research interests include prospect evaluation, ranking and portfolio optimization.

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