Bayesian Approach to the Assessment of Geological Risk in Oil and Gas Exploration

Bruno Rafael Dias de Lucena (Corresponding author)
Management Faculty, Federal Univesity of Pará,
Belém - Pará, Brazil.

Leonardo Junqueira Lustosa
Department of Industrial Engineering, Pontifical University of Rio de Janeiro,
Rio de Janeiro - RJ, Brazil.

Abstract

When assessing undiscovered oil resources, an important step is the assessment of geological risk, which is usually defined as the probability that there will be no accumulation of hydrocarbons. Some important authors have traditional ways of obtaining this probability, but these classic models are not developed on a rigorous basis. Therefore, they may present conflicting results, which are not always compatible with reality and are not able to take into account historical data from similar situations already studied. This article aims to propose a Bayesian approach to the determination of geological risk with advantages over classical approaches. The positive aspects and limitations of the Bayesian approach are discussed and an illustrative application using fictitious data is presented.

Keywords: Undiscovered Oil Resources Assessment; Risk Analysis; Geological Risk; Bayesian Approach.

1. Introduction

The oil industry has many high-risk investments (Ribeiro, Inacio Jr., Ly, Furtado, & Gardin, 2020), and this is one of its main characteristics. These risks are mostly from geological, economic, and engineering nature. As a result, it takes place a necessary meticulous probabilistic analysis of the decisions. The use of adequate proper probabilistic methods for the risk quantification process can increase the quality of available information as well as the managers' capability of making decisions.

The exploration process of oil and gas involves, in few words, the understanding of geological structure to be explored pointing to the hydrocarbons' existence and the volume of the hydrocarbon evaluation. For hydrocarbon exploration to proceed, most firms need their explorers to estimate the geological risk to segments and prospects for exploration (Zhu, et al., 2018).

The main step in the oil and gas obtaining process is exploration (Stabell & Sheehan, 2001) and the greater possibility of making value is in this phase. This occurs because of the high level of geological uncertainties, even in the presence of seismic and other tests. Another reason for this large uncertainty is the high cost of exploratory wells (Jones, 2018). It is not uncommon that 90 percent of exploratory wells result in dry wells

(Hyne, 2001).

The largest portion of the oil and gas reserves in Brazil is deposited in high deep-water fields (Li, Yun, Dufen, Jiexin, & Tao, 2016). Therefore, the exploration costs increase and so the risks. The use of probabilistic methods for decision analysis in Brazil and several countries in the world is quite incipient. Thus, it is a research product of an exceptionally good direction for the improvement of the making decisions process in the petroleum industry.

The exploration process is supported by the results of awfully expensive tests. Consequently, the decision-makers appeal to experts' opinions about indirect tests, especially seismic and other geological pieces of evidence.

Unsurprisingly, the experts' opinions are affected by biases and miscalibration (Lucena, 2006). A large literature discusses how to deal with those problems (Spetzler & Stäel von Holstein, 1975; Kahneman, Slovic, & Tversky, 1982; Hora, 2004; Daneshkhah, 2004).

After the analysis of indirect tests, the experts, supported by theories, own experience, and information about analogous oil fields; establish a model to the geological structure assessed. The next step is the economic evaluation of the oil prospects to compose a project portfolio.

A prospect evaluation involves the calculation of the geological risk and the volume of recoverable oil (Rose P. , 2017). Many relevant papers treat the calculation of the volume of the recoverable hydrocarbons (Otis & Schneiderman, 1997; Schuenemeyer, 2002; Rose P. , 2004).

The existence of a proper geological structure does not assure the hydrocarbons' occurrence (Zhu, et al., 2018). Therefore, it is necessary to define the probability that the hydrocarbons are present in the evaluated prospect; this probability is called the probability of geological success (Rose P. , 2004) and is used as a parameter to measure the geological risk.

The determination of the probability of geological success is the central subject of this paper. Even being in the base of the whole exploration process, the geological success is surprisingly not much discussed in specific literature.

The available literature suggests that geological success is a function of geological factors. However, no method rigorously justified in combining the probability of occurrence of these factors, in particular, doesn't seem any reason to affirm that the occurrence of a determined geological factor has a deterministic weight in the geological risk estimation.

We found some methods in use (Otis & Schneiderman, 1997; Rose P. , 2004), that do not consider the interrelationship between the geological factors, this is the major contribution of this paper.

This paper proposes a Bayesian methodology for determining the probability of geological risk as an alternative to the existent restricted models and, considering some restrictions, more accurate.

2. Geological Risk: Classical Approach

The geological risk (Gr) is that one which should be considerate in the process of evaluation of hydrocarbons' existence in a play.

A play is the elemental part of a petroleum system and has one or more accumulation of hydrocarbons [8] with geological common characteristics. These potential hydrocarbons accumulations are called prospects.

The probability of the geological risk is the probability of hydrocarbons occurrence in a prospect [8,10]. This probability is calculated considering that certain geological factors are present. These factors may differ according to the authors. Based in Rose (2004) and Schneiderman (1997), some geological factors are determinant to the existence of hydrocarbons accumulations, as:

a) A **source rock** that can generate the oil.
b) A **reservoir rock** that can keep the hydrocarbons.
c) A **trap**, that's a rock that seals the reservoir.
d) And the **timing**, that is the necessary time to generating the hydrocarbons e its migration.

All these factors are essentials to hydrocarbons occurrence, i.e. if someone of these probabilities is zero, there is no possibility of hydrocarbons occurrence.

Once these probabilities are estimated, they must be combined to compose the probability of hydrocarbons occurrence. To Otis and Schneidermann (1997) the probability of geological success is calculated by the product of the probability elicited of the factors, that is, the occurrence of the geological factors is considered unrelated. To Rose (2004), perhaps guided by his experience, recommends considering the probability of geological success as the lowest probability of the factors. To illustrate these models, we present the table 1 below.

Table 1. Models of Probability of Geological Success

Author	Model
Otis and Scheneidermann (1997)	$Pg = \prod_{i=1}^{n} P_i$ (1)
Rose (2004)	$Pg = Min[P_i]$ (2)

Source: Otis and Scheneidermann (1997) and Rose (2004)

Note that both models are compatible with the premise that the impossibility of the occurrence of one of the factors determines the non-existence of hydrocarbon accumulation.

Some publications assist the geologist in determining the probability of the occurrence of each of the factors. However, this is not a topic covered in this paper.

Typically, each of these factors is divided into subfactors presented in checklists. Otis and Schneidermann (1997) present a checklist that can be used to analyze all the subfactors relevant to each of the characteristics needed to evaluate. The table 2 below shows an example of how such lists are presented:

Table 2. Example of checklist to geological factor analysis

Factor A - Reservoir rock
1. Presence
a. Lithology
b. Distribution
c. Depositional Model
2. Quality
a. Lateral continuity and extension
b. Vertical thickness and cyclicality
… (so on)

Source: Adapted from Otis and Scheneidermann (1997)

After evaluating each of the elements presented in the list, the geologist should code the concepts in terms of probabilities, that is, from the evaluation of the sub-factors, he should qualify them as: unfavorable, questionable, neutral and encouraging, and with that identify the range of probabilities you are in. An example is shown in table 3.

Rose (2004) and Otis and Schneiderman (1997) indicate different qualitative concepts about the evaluator's certainty and semantic scales that help him to associate his ideas with a probability. An important point of convergence between the authors is that the probability of the geological factor will be equal to the lowest probability among its sub-factors.

In practice, a form for assessing the probability of the factors that result in the value of the geological risk takes the following appearance:

Table 3. Example of Geological Factors Probability Assessment Form

A. Reservoir Rock	**Unfavorable**	**Questionable**	**Neutral**	**Encouraging**	**Favorable**
1. Presence					X
2. Quality			X		
3.Other				X	
Range of probabilities	**0.1 to 0.3**	**0.3 to 0.4**	**0.4 to 0.6**	**0.6 to 0.7**	**0.7 to 0.9**

Source: Otis and Scheneidermann (1997)

In the case presented above, the probability of the reservoir factor is associated with the probability of the quality subfactor, that is, 0.5.

After estimating the probability of all geological factors, the probability of success is calculated using the selected model and, consequently, the geological risk. With the determination of the geological risk, the appraiser goes on to a coherence analysis that depends strictly on the appraiser's knowledge regarding the geological formation under study. If any inconsistency is found, the evaluator redoes the steps to determine where bias may have occurred.

The result of this process will be called geological risk or geological risk factor and will be interpreted qualitatively based on the indications of the model proponent. Table 4 below presents the qualitative interpretation for the result found in the models presented according to the risk range, note that the risk scale does not show the compatibility of magnitude. This difference is a result of the model applied, for example, if the probability of estimated occurrence of all geological factors is equal to $P_i = 0.8$ in the model (1) the probability $P_g = 0.41$ which is equivalent to low risk and in the model (2) $P_g = 0.8$, which represents a scenario of probable occurrence of hydrocarbons.

Table 4. Qualitative Interpretation of Geological Risk

<table>
<tr><th>Pg Range</th><th>Model (1)</th><th>Model (2)</th></tr>
<tr><td>1.0 ⊢ 0.9</td><td rowspan="5">Very Low Risk</td><td>Virtual Certainty</td></tr>
<tr><td>0.9 ⊢ 0.8</td><td>Reasonable Geological Confidence</td></tr>
<tr><td>0.8 ⊢ 0.7</td><td rowspan="2">Occurrence Probable</td></tr>
<tr><td>0.7 ⊢ 0.6</td></tr>
<tr><td>0.6 ⊢ 0.5</td><td rowspan="2">Significant Uncertainty</td></tr>
<tr><td>0.5 ⊢ 0.4</td><td rowspan="3">Low Risk</td></tr>
<tr><td>0.4 ⊢ 0.3</td><td rowspan="3">Higher Probability of Absence</td></tr>
<tr><td rowspan="2">0.3 ⊢ 0.2</td></tr>
<tr><td rowspan="2">Moderate Risk</td></tr>
<tr><td rowspan="2">0.2 ⊢ 0.1</td><td rowspan="2">Geological Factor of High Risk</td></tr>
<tr><td rowspan="2">High Risk</td></tr>
<tr><td rowspan="2">0.1 ⊢ 0.0</td><td rowspan="2">Impossible to Occur</td></tr>
<tr><td>Very High Risk</td></tr>
</table>

Source: Otis and Scheneidermann (1997) and Rose (2004)

Incompatibilities in these models can occur when there is a large difference between the probabilities of the factors since the model (2) strictly considers the lowest probability of occurrence among the geological factors.

The following section presents an alternative approach to the calculation of Pg, based on the principles of Bayesian statistics.

3. Bayesian Approach to the Definition of Geological Risk

Before presenting the Bayesian approach, it is important to verify some assumptions used about the geological risk. (1) The geological risk depends on predetermined geological factors; (2) the mathematical expression that relates the probabilities of occurrence of these factors is not important for the application of the Bayesian model; (3) some information about past events (analogous fields in the case of undiscovered oil resources) is necessary for the model to perform well; (4) the probabilities of occurrence of the geological factors are considered to be uncorrelated (which is an approximation). Also, the determination of the qualitative description of the geological factor remains subject to the process presented in table 5. However, the combination of these factors starts to be performed using the well-known Bayes 'theorem (3) presented as follows:

$$P(\boldsymbol{\theta} \mid F_1 = Q_1, F_2 = Q_2, F_3 = Q_3, F_4 = Q_4) = \frac{P(F_1 = Q_1, F_2 = Q_2, F_3 = Q_3, F_4 = Q_4 \mid \boldsymbol{\theta}).P(\boldsymbol{\theta})}{P(F_1 = Q_1, F_2 = Q_2, F_3 = Q_3, F_4 = Q_4)} \tag{3}$$

With,

$P(\theta) -$ Probability of hydrocarbons occurring

$F_i -$ i-th geological factor

$Q_k -$ the expression that qualifies the i-th factor, e.g. (favorable, neutral, unfavorable, etc.).

This update scheme can be used for numerous types of information (Clemen & Winkler, 1999). The Bayesian approach presents the difficult task of obtaining the joint probability of the geological factors conditionally on the occurrence of the event, $P(F_1 = Q_1, F_2 = Q_2, F_3 = Q_3, F_4 = Q_4 \mid \theta)$, which is necessary to obtain the relationship between the event and the geological factors. As we consider the occurrences of independent geological factors, we can perform the following transformation:

$$P(\theta \mid F_1 = Quali_k; \cdots; F_n = Quali_k) = \frac{\prod_{i=1}^{n} P(F_i = Quali_k \mid \theta)}{\prod_{i=1}^{n} P(F_i = Quali_k \mid \theta) + \prod_{i=1}^{n} P(F_i = Quali_k \mid \overline{\theta})} \quad (4)$$

For the Bayesian approach to have a satisfactory result, there must be a reasonable history of observed events. The example presented in table 5 supposes a history for the occurrence of each geological factor, in past geological explorations, in three qualitative classes: unfavorable, neutral, and favorable.

Table 5. History of Occurrence of Geological Factors (example)

Factor A	$\boldsymbol{\theta}$	$\boldsymbol{\overline{\theta}}$	**Factor B**	$\boldsymbol{\theta}$	$\boldsymbol{\overline{\theta}}$	**Factor C**	$\boldsymbol{\theta}$	$\boldsymbol{\overline{\theta}}$	**Factor D**	$\boldsymbol{\theta}$	$\boldsymbol{\overline{\theta}}$
Unfavorable	5	25	Unfavorable	6	23	Unfavorable	7	25	Unfavorable	6	24
Neutral	20	20	Neutral	22	18	Neutral	22	20	Neutral	24	18
Favorable	30	18	Favorable	31	20	Favorable	27	17	Favorable	29	18
Totals	**55**	**63**		**59**	**61**		**56**	**62**		**59**	**60**

Source: Authors

In terms of probability we have those presented in table 6:

Table 6. Probability of Occurrence of Geological Factors (example)

Factor A	$\boldsymbol{\theta}$	$\boldsymbol{\overline{\theta}}$	**Factor B**	$\boldsymbol{\theta}$	$\boldsymbol{\overline{\theta}}$	**Factor C**	$\boldsymbol{\theta}$	$\boldsymbol{\overline{\theta}}$	**Factor D**	$\boldsymbol{\theta}$	$\boldsymbol{\overline{\theta}}$
Unfavorable	0.09	0.39	Unfavorable	0.10	0.37	Unfavorable	0.12	0.40	Unfavorable	0.10	0.40
Neutral	0.36	0.31	Neutral	0.37	0.29	Neutral	0.39	0.32	Neutral	0.40	0.30
Favorable	0.54	0.28	Favorable	0.52	0.32	Favorable	0.48	0.27	Favorable	0.49	0.30
Totals	**1**	**1**		**1**	**1**		**1**	**1**		**1**	**1**

Source: Authors

Using the above historical data, if we calculate the probability of hydrocarbon discovery using expression 3, given that the geological factors were evaluated as A = Favorable, B = Neutral, C = Favorable and D = Neutral, using 4, we express by:

$$P(\theta \mid A = F; B = N; C = F; D = N) = \frac{0{,}545 \cdot 0{,}373 \cdot 0{,}482 \cdot 0{,}407}{0{,}545 \cdot 0{,}373 \cdot 0{,}482 \cdot 0{,}407 + 0{,}285 \cdot 0{,}295 \cdot 0{,}274 \cdot 0{,}300} = 0{,}85$$

In this example, the probability of hydrocarbons occurs given the historical data is 85%. The main virtues of the Bayesian approach are to avoid biases, despite (in the same way as the others) considering the factors as probabilistically independent (when, in fact, they are not) and also making it possible to adjust the final probability for a coherent solution, even that experts have been systematically biased in their assessments of geological factors.

The main problem with using this approach in the oil exploration activity is the difficulty of generating reliable historical data since the formation of a play does not necessarily have to do with others evaluated by the team. However, the use of this methodology in a field already under development or with existing analogous fields can bring more satisfactory results than the subjective incorporation of analogies.

In recent years, the application of the Bayesian approach has been growing, mainly in areas where subjective probability is used, but in real applications for the calculation of geological risk, the approximate classical approach is still much more present, mainly due to its practicality. However, it is intuitively perceived that the Bayesian approach is more adequate to deal with the biases of specialists and its complexity is very reduced if it is properly implemented on a computer.

4. Conclusions

The estimation of geological risk in the process of assessing undiscovered oil resources plays a fundamental role in the composition of the oilfield exploration project portfolio. Over the years, new methodologies and procedures have been developed to increase the credibility of this type of assessment. This article aims to contribute to stimulating research on this subject.

Many oil companies today develop their methods and algorithms for carrying out risk analysis, seeking to maximize the value of their exploration and production portfolio. However, the competitive advantage that such methods can provide makes them little known.

Most of the known and adopted methods for risk assessment have important limitations. The methods described as classic, do not take into account the bias of expert evaluators that are already reflected in data from previous evaluations of analogous situations. The Bayesian approach presupposes the existence of a history of assessments, which is not always possible to obtain, but which can exist, or be accumulated, for large oil basins. In it, the specialist has as the main concern the evaluation of certain geological characteristics, and the model conveniently combines these evaluations with the information present in the evaluation history of geologically similar areas.

5. References

Clemen, R., & Winkler, R. (1999). Combining Probability Distributions From Experts in Risk Analysis. *Risk Analysis, 19*(2), 187-203.

Daneshkhah, A. (2004). *Psychological Aspects Influencing Elicitation of Subjective Probability.* Technical Report, The University of Sheffield, Sheffield. Access in 05/052020, available on https://www.researchgate.net/profile/Alireza_Daneshkhah/publication/255574139_Psychological_Aspects_Influencing_Elicitation_of_Subjective_Probability/links/0046353b6c3434cf93000000/Psychological-Aspects-Influencing-Elicitation-of-Subjective-Probability.pd

Hora, S. (May de 2004). Probability Judgments for Continuous Quantities: Linear Combinations and Calibration. *Management Science, 50*(5), 597-604.

Hyne, J. P. (2001). *Nontechnical Guide to Petroleum Geology, Exploration, Drilling, and Production* (2ª ed.). Tulsa: Pen Well Corporation.

Jones, C. (2018). The Oil e Gas Industry Must Break the Paradigm of Current Exploration Model. *Journal of Petroleum Exploration and Production Technology, 8*, 131-142.

Kahneman, D., Slovic, P., & Tversky, A. (1982). *Judgment under Uncertainty: Heuristics and Biases.* Cambridge: Cambridge University Press.

Li, J., Yun, P., Dufen, S., Jiexin, Y., & Tao, W. K. (2016). Deep Water Oil & Gas: New Opportunities and Suggestions for Chinese Oil Companies. *IOP Conf. Series: Earth and Environmental Science* (pp. 1-6). Chongqing: IOP Publish.

Lucena, B. R. (2006). *Avaliação de Recursos de Petróleo Não Descobertos: Metodologias e Métodos de Eliciação de Informações Subjetivas.* PUC-Rio, Rio de Janeiro.

Otis, R., & Schneiderman, N. (1997). A Process for Evaluating Exploration Process. *AAPG Bulletin, 81*(7), 1087-1109.

Ribeiro, C., Inacio Jr., E., Ly, Y., Furtado, A., & Gardin, N. (2020). The influence of user-supplier relationship on innovation dynamics of Oil & Gas industry. *Technology Analysis & Strategic Management, 32*(2), 119-132.

Rose, P. (2004). *Risk Analysis and Management of Petroleum Exploration Ventures* (Vol. 12). Tulsa: AAPG.

Rose, P. (2017). Evolution of E & P Risk Analysis (1960-2017)*. *AAPG 100th Annual Convention and Exhibition.* Houston: AAPG Datapages.

Schuenemeyer, J. (2002). A Framework for Expert Judgment to Assess Oil and Gas Resources. *Natural Resources Research, 11*(2), 97-107.

Spetzler, C., & Stäel von Holstein, C. (1975). Probability Encoding in Decision Analysis. *Management Science, 22*(3), 340-357.

Stabell, C., & Sheehan, N. (April de 2001). Competitive Advantage in Petroleum Exploration. *Oil & Gas Journal, 99*(17), 30-36. Access in April, 2020

Zhu, Z., Lin, C., Zhang, X., Wang, K., Xie, J., & Wei, S. (2018). Evaluation of Geological Risk of Hydrocarbon Favorability Using Logistic Regression Model with Case Study. *Marine and Petroleum Geology, 92*, 65-77.