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Value of Information in the Oil and Gas Industry: Past, Present, and Future

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Abstract

An important task that petroleum engineers and geoscientists undertake is to produce decision-relevant information. Some of the most important decisions we make concern what type and what quality of information to produce. When decisions are fraught with geologic and market uncertainties, this information gathering may take the form of seismic surveys, core and well test analyses, reservoir simulations, market analyses, price forecasts, etc., on which the industry spends billions of dollars each year. Yet, considerably less time and resources are expended on assessing the profitability or value of this information. Why is that?

This paper addresses how to make value-of-information (VOI) analysis more accessible and useful, by discussing its past, present, and future. Based on a survey of SPE publications, we provide an overview of the use of VOI in the oil and gas industry, with a focus on how the analysis was carried out and for which types of decisions VOI analysis has been performed. We highlight areas where VOI methods have been used successfully and identify important challenges.

We then identify and discuss the possible causes for the limited use of VOI methods and suggest ways to increase the use of this powerful analysis tool.

Introduction

One of the most useful features of decision analysis is its ability to distinguish between constructive and wasteful information gathering. Value-of-information (VOI) analysis evaluates the benefits of collecting additional information prior to making a decision. Such information gathering may be worthwhile *if* it holds the possibility of changing the decision that would be made without further information. VOI attributes no value to “uncertainty reduction” or “increased confidence” per se. Rather, value is added by enabling the decision maker to better “tune” his/her choice to the underlying uncertainty. Thus, information value is forever an

entanglement of uncertainty and decision making; one cannot value information outside of a particular decision context.

It has been almost 40 years since Grayson (1960) introduced the VOI concept to the oil and gas industry, yet very few real applications have been published. Although some operating company professionals report using it occasionally, VOI assessments do not seem to be used on a routine basis—not even for the largest information gathering investments such as 4D seismic or appraisal wells. Nor does the concept seem to be well known among petroleum engineers and geoscientists. In fact, engineers and scientists tend to believe that more information or data is always better, since, after all, uncertainty is bad and data reduces uncertainty.

This paper is organized as follows. The next section defines VOI analysis and discusses some of its basic properties. The third section discusses the history of VOI and provides the first comprehensive review of VOI papers published in the SPE literature. Through a content analysis of these papers, we characterize various attributes of VOI applications and illustrations and show the evolution of the methodology. In the fourth section, we discuss the current status of VOI use. The fifth section addresses the future of VOI and what we believe is required to increase the awareness, understanding, and use of the approach in making decisions on information gathering. In the sixth section, we clarify some aspects of VOI that are widely misunderstood. The final section of the paper contains concluding remarks.

Value-of-Information Analysis

Most of what petroleum engineers or geoscientists do involves “acquiring” information, with the aim of improving decision making. “Information” is used here in a broad sense to cover acquisition of data, performing technical studies, hiring consultants, performing diagnostic tests, etc. In fact, other than to meet applicable regulatory requirements, the main reason for collecting any information, or doing any technical analysis, should be to make better decisions. The fundamental question for any information-gathering process is then *whether the likely improvement in decision making is worth the cost of obtaining the information*. This is the question that the VOI technique is designed to answer.

The oil and gas literature includes a number of different, and sometimes erroneous, definitions of VOI. For example, the VOI is not defined as the difference between the value with information and the value without information (Coopersmith and Cunningham 2002). This is true in many

cases, but not in general. In the Appendix, we provide a rigorous definition of VOI. In the Misconceptions section of this paper, we have detailed several misunderstandings that are common in the SPE literature. These range from assuming that a test can only increase our chance of success (Head 1999; Waggoner 2002; Ballin et al. 2005; Steagall et al. 2005), to statements that information value is strictly increasing in our prior uncertainty (Coopersmith and Cunningham 2002), to claims that VOI can be negative (Waggoner 2002). In this section, we suppress the mathematical detail and present a simple framework which allows us to explain and illustrate the VOI concepts easily.

Modeling Information Gathering

In any information-gathering activity, we are concerned with two fundamental uncertainties: (1) the uncertainty we hope to learn about, but cannot directly observe, which we call the distinction (or event) of interest, and (2) the test result, which we refer to as the observable distinction (Howard 2005). For example, consider a medical test for a particular disease. We are uncertain as to whether or not we have the disease and cannot directly observe this (the distinction of interest). Our doctor, however, can perform a test for a particular antibody that is only present if we do in fact have the disease (the observable distinction). In an oil and gas setting, the distinction of interest might be the amount of oil in a particular reservoir and the observed distinction might be a seismic test result.

We can effectively represent and communicate this information structure through the use of a "relevance" or "influence" diagram (Howard 2005). **Fig. 1** displays a relevance diagram and an example probability tree for a simple information-gathering situation. We begin with a *prior* probability distribution over the distinction of interest. For example, the distinction of interest could be fault transmissibility, while the observed distinction is a test result such as production test. The arrow between the two nodes in Fig. 1 represents the relevance of (or the dependence between) the distinction of interest and the observed distinction. Returning to our example of fault transmissibility and production test results, the arrow would capture the fact that we believe the subsurface reality affects the production test results. The strength or accuracy of the relationship is codified by the *likelihood* function.

An example may make these concepts more clear. Suppose we have evaluated a development opportunity and now face the sanctioning decision. There is still a lot of uncertainty as to whether the field will be profitable and our analysis shows that one of the main drivers of the profitability is the time period we can keep the production at the plateau rate. Through sensitivity analysis we find that the fault transmissibility has the largest impact on the plateau length with a 25% chance of open faults resulting in a plateau period of 5 years or more and a 75% chance of tight faults which we believe will reduce the plateau period to less than 5 years. This information represents our prior beliefs and is displayed in the first part of the example probability tree in Fig. 1.

Now suppose, we can conduct a long-lasting production test including one observation well and one producer in a

neighboring segment to measure interference between the two wells, which again gives information about the fault communication. Based on past experience, combined with expert input, we believe the test will indicate that the faults are "Open" with probability 0.9 if they actually are open and "Tight" with probability 0.9 if the faults truly are tight. These metrics are not reported directly by the test itself but rather through the interpretation of the test results by the well test analysis experts. These probabilities need not be symmetric or equal. In fact, in real applications it would be surprising if they were. This assessment of the likelihood function is depicted in the second part of the tree in Fig. 1.

The bolded probabilities are the only inputs, since probabilities must sum to 1. These assessments imply that the chance the faults are Open and the test reports "Open" is 0.225 ($0.25 \cdot 0.90$). This probability is the product of two events and is referred to as a *joint probability*. The other joint probabilities are 0.025, 0.075, and 0.675. Notice that the joint probabilities sum to 1.

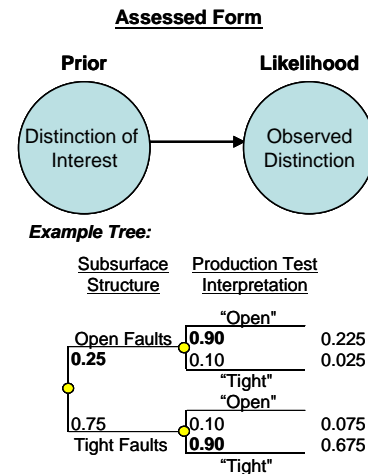


Fig. 1—Information Gathering Relevance Diagram in Assessed Form

The relevance diagram in Fig. 1 is in *assessed form*, which is generally how the reliability or accuracy of the testing procedure is assessed; we assess how likely the test is to report different outcomes for a known subsurface configuration. While the reliability of the test is assessed in this order, this is not the order in which the information will actually flow in the real world. In the actual testing situation we will first observe the test and then update our beliefs regarding the distinction of interest. For example, we would like to know the probability of Open Faults given that the production test has been interpreted as reporting "Open." This is depicted in the relevance diagram shown in **Fig. 2**, which is in *inferential form* because we are making an inference based on our observation. Note that while not required or common, we have drawn the relevance diagram and the corresponding tree in reverse order to facilitate comparison with Fig. 1.

The probabilities depicted in Fig. 2 are simply calculated from those in Fig. 1. For example, from Fig. 1 we know that the probability of an "Open" test result and Open Faults is still 0.225. The other joint probabilities are obtained similarly.

Once we know the joint probabilities the other probabilities follow directly. For example, the probability of an "Open" test result is $0.30 = 0.225 + 0.075$. The probability of Open Faults given an "Open" test result is $0.75 = 0.225 / 0.30$. It is important to note that once the relevance diagram in Fig. 1 has been fully specified and the probabilities assessed, the probabilities in Fig. 2 are a logical consequence, *not a matter of opinion*.

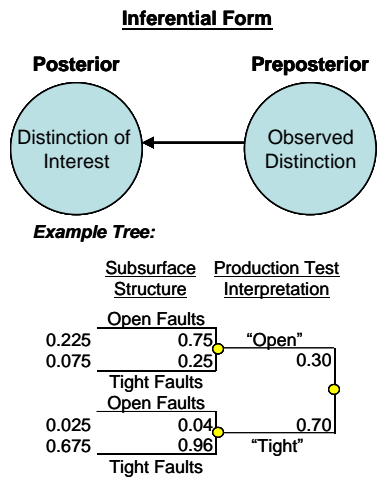


Fig. 2— Information Gathering Relevance Diagram in Inferential Form

Once our prior distribution has been updated based on the test result, we refer to it as the *posterior*. The *preposterior* (or predictive distribution) encodes the probability of observing different test results before the test is actually completed. The reversal of the arrow between the assessed and inferential forms represents the application of Bayes' theorem. For an introduction to Bayesian calculations see Clemen and Reilly (2001).

From the inferential form of the tree, we see that if the test result comes back "Open," then we would revise the probability of Open Faults from 0.25 to 0.75. On the other hand, if the test result comes back "Tight," then we would revise the probability of Open Faults from 0.25 to 0.04. All testing situations must include cases where the posterior probability is greater than or less than the prior. It is not possible for the probability of Open Faults (or geologic success, in an exploration setting) to always increase simply because a test was performed, as is sometimes assumed in the SPE literature.

One may wonder whether the analysis described above could be extended to other faults in the structure. The answer is yes, but this would require additional modeling and assessments. In particular, one would need to model the geologic dependence between faults. See Bickel et al. (2008) for a discussion of modeling information value in the case of geologic dependence.

Calculating the Value of Information

The VOI is *defined* as the most the decision maker should pay for additional information on the distinction of interest. If the decision maker is risk neutral, then

$$VOI = \left[\begin{array}{c} \text{Expected value with} \\ \text{additional information} \end{array} \right] - \left[\begin{array}{c} \text{Expected value without} \\ \text{additional information} \end{array} \right]$$

It is important to note that this is not the definition of VOI. It happens to be true in certain circumstances that may or may not hold in practice. Please see the Appendix for a more rigorous discussion of VOI.

If the additional information is perfect (that is; the information provides perfect knowledge of the state of the world), then we refer to the VOI as the value of perfect information (VOPI) or the value of clairvoyance (VOC), which places an upper bound on any information-gathering activity. No test, no matter how sophisticated, is worth more than the VOC.

Sometimes the value of perfect (imperfect) information is referred to as the Expected Value of Perfect (Imperfect) Information (EVPI/EVII). While common, these terms need to be used with care. First, as discussed above, they assume risk neutrality. Second, there is nothing "expected" about the EVPI or the EVII; the value of information (perfect or otherwise) is a deterministic buying price, as detailed in the Appendix. In the case of risk neutrality, this buying price is equal to the difference between two expected values. Finally, the expected value with information can only be greater than the value without information *if* some decision may be affected by the revelation of the information. If the decision maker would make the same decision no matter how the test comes back, then VOI = 0 and the test is worthless.

Any information-gathering activity must meet the following four criteria if it is to be value adding (Howard 2005):

- i. *Observable*: The test result must be observable. This may seem like an easy criterion to meet, but many VOI illustrations do not include an observable test result. For example, seismic tests do not report "big reservoir."
- ii. *Relevant*: The test result must have the ability to change our beliefs about the distinction of interest. For example, there must be a relationship between the observable seismic signal and the underlying reservoir properties.
- iii. *Material*: The test result must hold the possibility of changing a decision you would otherwise make. This seems to be the most confusing aspect of VOI analysis, but should not be. How much would you pay for a medical test that has no bearing on your treatment? Zero!
- iv. *Economic*: The cost of the test must be less than its value.

We illustrate these concepts by returning to our sanctioning example from above. If we sanction and the faults are open then we will earn \$400 million. On the other hand, if we sanction and the faults are tight we will lose \$40 million. The decision tree in the absence of additional information is shown in **Fig. 3**. The expected value of sanctioning is \$70 million ($0.25 \cdot \$400 - 0.75 \cdot \40).

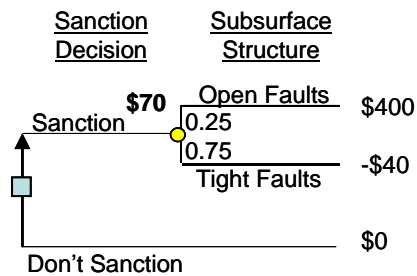


Fig. 3—Sanction Decision Tree

Now suppose we have access to the test detailed in Figs. 1 and 2. By assumption, this test is *observable* and therefore meets the first criterion of a value-adding test. The test is also *relevant* because the probability of Open Faults given the test reports "Open" does not equal the probability of Open Faults if the test reports "Tight" ($p(\text{Open Faults}|\text{"Open"}) = 0.75 \neq p(\text{Open Faults}|\text{"Tight"}) = 0.04$). Therefore, the test result has the ability to change our beliefs.¹ But, does it have the ability to change our decision making? That is; is the test *material*? If we are risk neutral, then we should sanction, as shown in Fig. 3. If the test reports "Open," then the probability of Open Faults is 0.75 and the expected value of sanctioning is \$290 million ($0.75 \cdot \$400 - 0.25 \cdot \40). Therefore, we should sanction, which is what we would have done without the information. However, if the test comes back "Tight," then the probability of Open Faults is only 0.04, the expected value of sanctioning is -\$22.4 million, and we would instead choose to walk away. Therefore, the test is material.

Could a test be relevant, but not material? Certainly. As long as the probability of Open Faults exceeds $40/440 = 1/11 \sim 0.09$, the expected value of sanctioning will exceed \$0. If the accuracy of the test is between 0.5 and 0.769, then $p(\text{Open Faults}|\text{"Tight"})$ will be greater than 0.09 and we will choose to sanction even though our test reported "Tight." In this case, the value with additional information will equal \$70 million and the test is worthless.

The final question is whether the test is *economic*. There is a 30% chance that the test will report "Open" (see Fig. 2), in which case we will sanction with an expected value of \$290 million. There is a 70% chance the test will report "Tight," in which case we will not sanction, gaining nothing but risking nothing. Therefore, the value with additional information is $0.30 \cdot \$290 \text{ million} = \87 million . The value without additional information was \$70 million. Therefore, the test is worth \$17 million. As long as its cost is less than this amount, it is economic.

How much would perfect information be worth? If we knew the faults were open, a 25% chance, we would sanction and earn \$400 million. If we knew they were tight, a 75% chance, we would walk away. Therefore, the value with perfect information is $0.25 \cdot \$400 \text{ million} = \100 million , and therefore perfect information is worth \$30 million. It might be surprising that a 90% accurate test is only worth slightly more than half the value of a perfect test, instead of 90%, but this

¹ In our particular example, only a 50-50; i.e., $p(\text{"Open"}|\text{Open Faults}) = p(\text{"Open"}|\text{Tight Faults}) = .5$, likelihood would be irrelevant.

result is typical. For example, Bickel (2008) demonstrates that the value of a test with correlation coefficient R is in many cases worth less than $R^2 \cdot 100\%$ of perfect information.

The Past

Schlaifer (1959) was the first to define VOI in the context of business decisions. His book, which is primarily focused on problems of statistical inference and sampling, not only provides the first decision-theoretic definition of VOI, but discusses the problem of decisions under uncertainty in a broad sense.

Only a year after Schlaifer defined the VOI concept in a business analytic context, Grayson (1960) introduced it to the oil and gas industry. In his book *Decisions under Uncertainty: Drilling Decisions by Oil and Gas Operators* Grayson presents "organization and procedures for decision making." His focus is on drilling decisions, and the chapter "Information Decisions" illustrates in detail how to use the VOI concept to aid decisions regarding the "purchase of information." Despite this strong start, it would be 23 years before the first SPE paper (Warren 1983) would use the term "value of information" in the title.

In the meantime, the decision-theoretic approach, including VOI, had been refined and several important publications had appeared outside the oil and gas industry. Schlaifer (1961) published a somewhat condensed and simplified version of his 1959 text, more suitable as an elementary text, on business decisions. The same year, a more advanced work was published by Raiffa and Schlaifer (1961). Both of these books discuss VOI and like Schlaifer's original book, are more focused on problems of statistical inference and sampling than decision analysis as we know it today.

Howard (1966a) coined the term "decision analysis" and Howard (1966b) detailed VOI's role in the decision-analysis cycle. Raiffa's (1968) book offered an excellent and practical introduction to decision analysis and VOI.

The publications discussed above formed the backbone for subsequent SPE papers (as well as for papers and books in other industries) on VOI analysis. We next review relevant papers in the SPE literature.

Review of VOI Literature

The search for SPE papers concerning VOI was conducted through the eLibrary on the spe.org website. We considered papers published through 2006. We searched for the phrases "value of information," "information value," "data worth," "worth of data," "value of seismic," "value of 3D seismic," "value of 4D seismic," "value of logs," "value of core," and "value of well," which would include well testing, etc. The results were screened for titles that indicated information gathering, and the abstracts of those titles were checked for an indication that VOI was being quantified. In addition to the search results, relevant papers listed in the references were also reviewed.

We decided that in order for a paper to be included in the survey, VOI had to play an important role. Papers that satisfied this requirement but were simply earlier versions (e.g., conference papers) of later published papers were not included.

We found 30 VOI papers published in the SPE literature between 1962 and 2006. They are listed in **Table 1** below.

**TABLE 1—SPE VOI PUBLICATIONS,
1962–2006**

| Year | Author(s) |
|------|----------------------------|
| 1962 | Grayson |
| 1971 | Dougherty |
| 1972 | Silbergh and Brons |
| 1972 | Hirakawa |
| 1983 | Warren |
| 1987 | Moras et al. |
| 1988 | Lohrenz |
| 1989 | Gerhardt and Haldorsen |
| 1992 | Dunn |
| 1993 | Stibolt and Lehman |
| 1996 | Demirmen |
| 1999 | Head |
| 2001 | Demirmen |
| 2001 | Koninx |
| 2002 | Coopersmith and Cunningham |
| 2002 | Waggoner |
| 2002 | Begg and Bratvold |
| 2002 | Raghuraman et al. |
| 2003 | Portella et al. |
| 2003 | Haskett |
| 2004 | Galli et al. |
| 2004 | Wills and Graves |
| 2005 | Branco et al. |
| 2005 | Steagall et al. |
| 2005 | Ballin et al. |
| 2005 | Kumar and Hara |
| 2006 | Coopersmith et al. |
| 2006 | Bickel et al. |
| 2006 | Prange et al. |
| 2006 | Aggrey et al. |

Fig. 4 displays the cumulative number of VOI papers published over this time, separated according to whether they appeared in refereed journals (e.g., the *Journal of Petroleum Technology* or *SPE Reservoir Evaluation and Engineering*) or conference proceedings. Several interesting points emerge. First, the uptake of VOI methods appears to have been particularly slow in the early years, with nine years passing between the publication of Grayson's "Bayesian Analysis—A New Approach to Statistical Decision Making" in 1962 and the next VOI related publication—Dougherty's (1971) "The Oilman's Primer on Statistical Decision Theory," which was never published and only resides in the SPE Library. Second, it was not until 1983, over 20 years after Grayson's book, that the term "value of information" appeared in the title of an SPE publication: Warren's "Development Decision: Value of Information" presented at the Hydrocarbon Economics and Evaluation Symposium. Third, very few VOI-focused articles have been published in SPE's peer-reviewed journals. Finally, there has been a relative explosion of VOI articles in the last 10 years, but again these are papers which are primarily included in SPE conference proceedings.

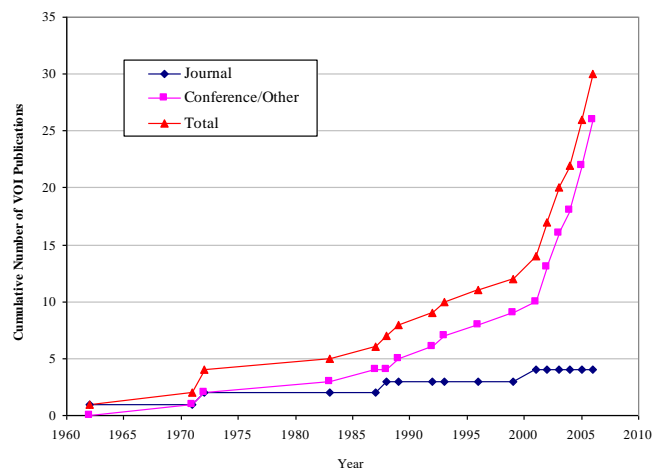


Fig. 4—Cumulative Total of SPE VOI Papers

Paper Type: We categorized each paper as illustration, application, or theoretical regarding VOI. We defined illustration papers as those that present the VOI methodology and demonstrate its use in a simple, but perhaps real, example. Application papers were those that primarily discussed the use of VOI in a real decision. Theoretic papers were those that extended VOI techniques in important ways or introduced new methods to the oil and gas literature. Of the 30 papers we surveyed, we classified 17 as illustrations, 7 as applications, and 6 as theoretical. The low number of papers dealing with theory is not surprising given that VOI is a relatively mature topic. What is a bit surprising and disappointing is the very low number of published applications. The literature is awash in illustrations, many repeating previously published ideas, but lacks clear guidance and direction for how to actually use VOI to create value.

Two of the theoretical papers are worth discussing here. In an early paper that is part of the SPE Library, but was never published, Moras et al. (1987) used the concept of VOI to design an optimal monitoring system for a gas storage facility. Their methodology was quite advanced for its time, but ultimately relied on heuristics to place monitoring wells. Recent advances in computational ability and algorithms may enable new solutions to this problem. This problem is timely as the sequestration of CO₂ may be on the horizon. Very recently, Aggrey et al. (2006) have merged concepts of VOI and system reliability to quantify the value of perhaps better (in an information sense), but less reliable, down-hole sensors.

Reliability: A critical input into any VOI analysis is the assessment of the information's reliability. Five papers illustrate perfect information, which does not require any additional assessment. The remaining papers are concerned with imperfect information. Unfortunately, only 13 of the remaining 25 papers address reliability. Of these, 11 assess reliability or the likelihood function via expert assessment. While we personally support the use of expert assessment, many view this "subjective" step as a significant weakness of VOI analyses. Only two papers (Branco et al. 2005; Bickel et al. 2006) attempt to go beyond expert assessments and tie the likelihood function to some form of model (e.g., geophysical).

Bayesian Model: Any VOI analysis requires a Bayesian calculation. In the simplest situation, one constructs a discrete

probability tree, assesses the probabilities, and "flips the tree" to perform the Bayesian calculation. This technique is used in almost every SPE paper dealing with imperfect information. However, this technique does not work well if one wants to model learning about continuous reservoir properties such as porosity. To handle continuous uncertainties, one could use a conjugate prior distribution to match the sampling process (Winkler 2003). This method is applied by Bickel et al. (2006). For more complicated situations where no conjugate prior is available, methods such as Markov Chain Monte Carlo (MCMC) must be used. We are unaware of any SPE papers employing this method in a VOI context.

Information Source: The majority of VOI papers we reviewed are focused on valuing seismic information. Only one paper (Wills and Graves 2004) quantifies the value of taking a core sample. Most papers consider only one source of information when conducting the VOI analysis. Only two papers (Dougherty 1971; Wills and Graves 2004) consider the ability to choose between different information sources or sequentially acquire information from multiple sources.

Decision Modeling: As discussed above and detailed in the Appendix, information has to offer the possibility of changing a decision if it is to have value. This generally requires explicitly modeling the decision(s) affected by the information. Yet, many of the papers we reviewed do not do this. Instead they assume things will only get better after gathering information, for example, that the chance of geologic success will only increase. While this may be true in most cases because a better location will be selected, we believe that the modeling of how the information changes our beliefs should be separated from how it changes decision making. Combining the two makes it impossible to separate the accuracy of the information from the context of the decision problem, which limits the ability to apply the results in different settings.

Degree of Interpretation: Many papers model the observable test result at a high level of interpretation. For example, most papers discussing seismic use terms such "big reservoir" or "oil present." These are interpretations, since seismic does not actually produce these results. A high level of interpretation makes it difficult to separate the accuracy of the test procedure or the technology from the accuracy of the interpretation.

The Present

Based on our experience, VOI analysis is not routinely used in the oil and gas industry. Even for information-gathering activities that cost in excess of \$10 million, such as appraisal wells or seismic surveys, the information-collection decision is typically made based on some sense of "reducing uncertainty will always have value." As discussed earlier, this is a misconception.

Having said that, many operators will argue that they are assessing the value of information when they collect data. What they typically mean by this is a qualitative assessment along the lines of "this information will increase our confidence in our decision." As argued earlier, this is a misconception because increasing confidence, or reducing uncertainty, has no value by itself. Another common practice is to assess the information value after the fact, for example, in

the form of historical look-backs to document the impact of the information (Aylor 1999; Waggoner 2000). This introduces a bias for two reasons. First, there is a strong incentive not to publish unsuccessful information gathering activities. Second, it ignores cases where information was not gathered, but should have been.

The Future

Because VOI focuses the analysis on the most critical pieces of information and modeling, increased use of VOI methodologies would speed analyses, reduce cycle times, and produce greater insights. Based on our experience, the industry spends ever increasing amounts on data gathering, modeling, etc., with very little understanding of the value of these activities.

The "Digital Oil Field" (Jacobs and Ward 2006), sometimes called "Integrated Operations" or "eFields," is a case in point. The oil and gas industry has invested heavily in this concept for the past several years and will continue to do so in the future. CERA has estimated increased production in the range of 125 billion barrels—roughly equivalent to the current estimates for the entire producible reserves of Iraq (Jacobs and Ward 2006). A central element in the Digital Oil Field paradigm is that the decision maker will have "real time" access to a continuous flow of data and information. Although estimates have been made as to the value of the digital oil field revolution, we are aware of no rigorous effort to calculate the value of more data in real time for a specific decision situation. The VOI approach is ideally suited not only to assess the value of a digital oil field operation, but to support and guide strategic management decisions for introducing and implementing the new paradigm across a company's assets.

There are a number of barriers that need to be removed in order to increase uptake of the VOI methodology. The most important are summarized below.

Education and Training: There is obviously a need for education and training. Training is required to ensure that current management and professional staff develop a level of comfort and familiarity that should both increase and improve the use of the VOI methodology. This includes training to develop a deep understanding of and comfort with relevant probability aspects such as subjective probability assessments and Bayesian analysis. We believe that in addition to professional training, the industry should encourage academia to better train engineers, particularly undergraduates, in decision making. Engineering is a decision-making discipline (called design), but we simply do not train engineers in decision making. In fact, we spend more time teaching them to manipulate seldom-used mathematical formulas or to write computer programs in soon to be outdated languages than we do teaching them how to make high-quality decisions. While this is true in all engineering disciplines, it appears to be particularly acute in petroleum engineering (Bratvold and Begg 2006).

Real-World Decision-Making Applications: As illustrated by the literature review, a relatively small number of the published papers deal with real decision-making applications. More real-world applications are needed to communicate and illustrate the VOI principles as well as to convince the oil and gas community that this is a viable and

valuable tool. More real-world applications of VOI will also require methodologies and tools that can handle realistic, and often more complex, decision situations. There must be tools available for the analyst to identify and structure the decision as well as to structure and support the assessment of the relevant parameters. The analyst must, for example, be allowed to use multiple, potentially-correlated information sources as well as any type of probability distribution for the prior and the likelihood.

Assessing Information Reliability: At a minimum, VOI analysis requires the identification of the available decision alternatives with payoffs and the assessment of prior and likelihood probabilities. If several information sources are being used, the analysis may also require the assessment of correlated likelihood distributions. None of these parameters is easy to derive and most engineers are struggling to estimate them.

The most difficult, and uncommon, parameter to assess may be the likelihood function, as there is no tradition to even think about information-gathering devices in that context. We generally do not try to quantify the accuracy or reliability of the appraisal well, reservoir simulation study, or log interpretation. This quantification is, however, required for VOI analysis. Hence we need to learn how to do it. When we have access to relevant historical (or other) data, we should use it in our assessments. For example, in judging the quality of the information from seismic surveys or core analysis, relevant historical data may exist. Unfortunately, although most oil and gas companies have a long history of collecting this type of information, very few have developed suitable knowledge bases on the reliability of the information they are gathering. Such databases will not only make it easier to start applying the methodology, but will also contribute to ensuring consistency across multiple VOI analyses.

The likelihood function can also be assessed through models as discussed in Bickel et al. (2006) and Branco et al. (2005). More work is required to develop suitable models for many information-gathering activities. Although there will always be subjective expert judgment involved in assessing the likelihoods, these models will also support increased consistency in the assessments.

It should also be noted that assessing the accuracy of the information is not limited to the cases where we want to do a VOI analysis. It would, in general, be hard to justify spending precious resources to gather any type of information if we have no idea of or are unwilling to assess the quality (accuracy) of the information.

Implementation and Software Applications: Many of the papers surveyed use simple Excel-based models for the VOI calculations. This works well for relatively simple decision situations when the analyst is experienced in developing VOI models. A broad and consistent use of the VOI concept will require improved software applications targeted at VOI and decision analysis. Such an application should focus on the ease of structuring the decision problem. It must also include more sophisticated Bayesian inversion techniques such as Markov Chain Monte Carlo simulation, to allow the user to freely select the form of the input distributions. Finally, like any decision supporting application, it must include the possibility of investigating the robustness

of the decision choices as a function of variations in the input parameters including the prior and the likelihood.

Journal Publications: Finally, we would like to see the SPE offer a journal with a decision-making focus. As argued above, petroleum engineering, like any other engineering discipline, is fundamentally about decision making, and yet SPE does not currently offer a journal for this type of research and application. This should not primarily be a journal on quantification of uncertainty and risk. Although uncertainty assessment is often an element of high-quality decision making, it is not, in and of itself, value-adding (Bickel and Bratvold 2008). Such a journal would not focus solely on VOI papers. As such, we believe an adequate pool of paper exists to publish a journal on at least a quarterly basis.

VOI Misconceptions

The SPE literature contains many misconceptions regarding information value. In this section, we clarify some of the widely misunderstood aspects of VOI.

Decision Change: Information that does not hold the possibility of changing a decision is worthless. Simply reducing uncertainty creates no value. This has been discussed in detail, but is worth emphasizing. Many VOI papers in the SPE literature simply assume that the probability of success can only increase after conducting a test (Head 1999; Waggoner 2002; Ballin et al. 2005; Steagall et al. 2005). This clearly cannot be the case since the test itself does not change anything. Only our decisions can increase the chance of success and these decision changes should be modeled explicitly.

Uncertainty: Increasing uncertainty in the prior distribution *does not* necessarily lead to larger valuations of information (Gould 1974). For example, increasing uncertainty regarding geologic success does not necessarily lead to greater information value. Such a result may hold in specific cases, but not in general. This point is not appreciated in the SPE VOI literature with some (Coopersmith and Cunningham 2002) claiming that VOI must increase with uncertainty in the prior distribution. For examples to the contrary see Bickel (2008).

Reliability Limits: Suppose we are performing a test with two possible outcomes: "Open" and "Tight." If $p(\text{"Open"}|\text{Open}) = p(\text{"Tight"}|\text{Tight}) = 1$, then the test is said to be perfect and *may* be quite valuable. Is 0 the worst possible reliability? No, that would still be perfect; a test that always reads out the opposite just needs to be relabeled. In this case, the lowest possible reliability is 0.5. That would be just as futile as flipping a coin. Such a test would fail the "relevant" criterion we discussed above. This point, while subtle, is quite important, as the view that reliabilities can be worse than 0.5 might lead one to believe that VOI can be negative (Waggoner 2002), which it cannot.

Relationship between EVPI and EVII: Information value is highly sensitive to information reliability. In the example discussed above, a test with a reliability of 1 is perfect. A reliability of 50% is guaranteed to have no value because it fails the relevancy criterion. Information value goes from perfect to zero somewhere between reliabilities of 1 and .5—not 1 and 0. Therefore, one needs to be very careful in assuming that a high EVPI ensures that EVII will be high

enough to justify a particular test. Some SPE VOI papers assume that imperfect information must be valuable simply because the EVPI is high (Portella et al. 2003). This is a risky assumption. Rather than making such an assumption, the specifics should be modeled directly—there are rarely any shortcuts. See Bickel (2008) for a more detailed discussion of this point.

Accuracy of Information: The VOI is non-decreasing in information accuracy, as codified by the likelihood function (Blackwell 1953). This finding has been demonstrated by several authors in a variety of contexts (Kihlstrom 1974; Wilson 1975; Hilton 1979). Clemen and Winkler (1985) have studied the effect of dependence between information sources and found that even modest degrees of correlation between information sources can significantly lower the VOI. This is critical when evaluating sequential-testing programs. In order to value a sequence of tests, the dependence between the test results must be addressed. This is not always done in the examples one finds in the SPE literature (Coopersmith et al. 2006).

Superadditivity/Subadditivity: The VOI is not additive across independent sources of uncertainty (Samson et al. 1989). For example, the VOI on uncertainties X and Y together may be greater than (superadditive), less than (subadditive), or equal to the VOI on X plus the VOI on Y .

Flexibility: Hilton (1981) proves that there is no general monotonic relationship between degree of flexibility and information value. That is, adding (removing) alternatives to (from) the decision problem does not necessarily increase (decrease) information value.

Risk Attitude: There is no general monotonic relationship between degree of risk aversion and information value (Hilton 1981). A risk-neutral decision maker could value information more or less highly than a risk-averse decision maker in a particular situation.

Summary and Conclusions

VOI analysis represents an important and powerful tool for all decision makers in the oil and gas industry. The methodology can help determine the potential value of any information-gathering activity, as well as the value of improved acquisition technologies, prior to actually gathering the information.

This paper provides a comprehensive review and reference for analysts and decision makers that may aid in the efforts to move past the demonstration phase of VOI and into its real use as a tool to improve the quality of oil-field decision making. The review of the SPE VOI literature shows that the uptake of the concept has been slow and the industry has not made VOI analysis an integral part of its decision-making process. There are a number of reasons for this, including lack of basic decision-analysis skills and the inexperience of petroleum engineers and managers with applying the VOI methodology. In reviewing the literature, we also noticed that there are a number of misconceptions regarding information value. This can only create confusion and further delay the uptake of the methodology.

Although a number of issues remain in the context of developing a broad and deep understanding and routine application of the concept, we remain optimistic about the value of the VOI methodology for the oil and gas industry.

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Nomenclature

$p(A)$ = marginal probability of event A

$p(A|B)$ = conditional probability of event A given event B

VOI = Value of Information

VOC = Value of Clairvoyance

VOPI = Value of Perfect Information

EVPI = Expected Value of Perfect Information

EVII = Expected Value of Imperfect Information

Appendix

Suppose a decision maker (DM) faces an uncertain state of nature defined by random variable X , with specific outcome x_i , and must select an alternative a from a set of feasible alternatives Ω . $v(a, x_i)$ is a value function that assigns a value to each alternative-outcome pair. The DM's optimal alternative is the a^* that solves

$$\max_{a \in \Omega} \sum_i u(v(a, x_i)) p(x_i) = \max_{a \in \Omega} E[u(a, x)],$$

where u is the DM's von Neumann-Morgenstern utility function (von Neumann and Morgenstern 1947; Savage 1954), $p(x_i)$ is the probability of x_i , and E is the expectation operator. The DM's maximum expected utility is

$$\bar{u}^* = E[u(a^*, x)].$$

Assuming the DM's utility function has an inverse, his/her certain equivalent, CE , is the amount given with certainty that has the same expected utility as the optimal action, which can be found by solving $CE(u^*) = u^{-1}(\bar{u}^*)$. If the DM is risk-neutral, then his/her utility function is linear and his/her certain equivalent is equal to the expected value.

Now suppose that for an amount b , the DM is able to purchase an information system or test Θ that yields a signal θ_j regarding the state of nature x_i . According to Bayes' theorem, the probability of x_i given θ_j is

$$p(x_i | \theta_j) = p(x_i) p(\theta_j | x_i) / p(\theta_j),$$

where $p(\theta_j | x_i)$ is the likelihood function, which encodes the accuracy of the information system, and

$$p(\theta_j) = \sum_i p(x_i) p(\theta_j | x_i)$$

is the probability of observing signal θ_j before conducting the test. The DM's expected utility conditional on a particular signal θ_j and cost b is

$$\begin{aligned} \bar{u}^*(\theta_j, b) &= \max_{a \in \Omega} \sum_i u(v(a, x_i) - b) p(x_i | \theta_j) \\ &= \sum_i u(v(a_j^*, x_i) - b) p(x_i | \theta_j), \end{aligned}$$

where a_j^* is the optimal action given signal θ_j . The DM's expected utility for the system Θ is

$$\bar{u}(\Theta, b) = \sum_j \bar{u}^*(\theta_j, b) p(\theta_j)$$

The most the DM should be willing to pay for Θ , the value of information (VOI), is the value b' that solves

$$\bar{u}^*(\Theta, b') = \bar{u}^*$$

Or, when

$$CE(\bar{u}^*(\Theta, b')) = CE(\bar{u}^*)$$

If the DM's utility function exhibits constant risk aversion (i.e., it is linear or exponential), then

$$CE(\bar{u}^*(\Theta, b')) = CE(\bar{u}^*(\Theta, 0)) - b'$$

and therefore

$$b' = CE(\bar{u}^*(\Theta, 0)) - CE(\bar{u}^*)$$

In other words, the value of the information system, defined as the most the DM would pay for it, is equal to the certain equivalent with free information, less the certain equivalent without information. If the DM is risk neutral, then the certain equivalents are equal to expected values and the value of information is equal to the expected value with information, less the expected value without. Thus, the definition of VOI commonly used in the oil and gas industry is only correct in special circumstances. Fortunately, one of these is risk neutrality, which is a robust practical assumption.

Note that b' is not an expected value; it is not the mean of a distribution. Rather, it is the deterministic amount that equates the value with information to the value without.

What if the decision maker's preferred alternative is independent of the information signal? Assume for the moment that the information is free. If the DM chooses the same optimal action for any θ_i then

$$\begin{aligned} \sum_j \sum_i u(v(a^*, x_i) - b) p(x_i | \theta_j) p(\theta_j) = \\ \sum_i u(v(a^*, x_i) - b) p(x_i) = \bar{u}^* \end{aligned}$$

and therefore $b' = 0$ —the information system is worthless.

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