Integrated Method for Designing Valuable Flexibility in Oil Development Projects

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Summary

This paper presents an integrated method for identifying and inserting valuable flexibility into major projects. It builds upon recent work that (1) documents how errors in estimates can bias the selection of design concepts, (2) shows how concept flexibility can improve the project performance, and (3) usefully illustrates the probability distribution of outcomes. It involves: (1) developing and evaluating a base case design, (2) exploring the outcomes this design might generate, (3) identifying opportunities for flexible design, and (4) evaluating and selecting the most valuable flexibility to incorporate into the design. It embodies a paradigmatic change in the way designers deal with uncertainty: instead of basing a design on fixed assumptions and then testing its sensitivity to risks, the approach recognizes risks in the design process and thereby develops valuable flexibility that increases the expected value of projects. A case study of an oil platform development in the Gulf of Mexico demonstrates the method.

Introduction

Standard Design Process Leads to Losses. As observed in practice, the standard approach to the design of major development projects is a deeply technical process that focuses on the highly complex physical arrangement of the system. Indeed, the major elements of the platform, the risers, the tiebacks, and so on can be combined in literally millions of ways, sizes, and locations at different times. Both to simplify this process, and because physical design focuses on engineering, the usual approach assumes that major parameters are known. Most obviously, the design process normally takes the price of oil as given; in fact, senior management typically requires that designers across the company all use the same value for oil in their evaluations. Equally important, the design process typically works with a best estimate of the original oil in place (OOIP). In short, the standard approach to design is a technical process that generally does not explore in detail the consequences of the major variations in two of the prime drivers of value of any project.

The actual conditions that prevail, however, almost never equal point forecasts that have been assumed for design, whether one refers to the price of oil, the amount in the reservoir, the time and cost of construction, etc. The general rule, as demonstrated by experience in many fields of design, is that the "forecast is 'always' wrong" as demonstrated by observation of the discrepancies between prior point estimates and subsequent reality (de Neufville and Odoni 2003). Note that this fact is not inconsistent with the notion of a most likely estimate, which represents a balance between the possible upside and downside values of a parameter. A 'most likely' set of parameters may correctly represent some middle or average value and yet be unlikely to occur in practice.

Flexibility Has Value. As Begg et al. (2002) demonstrate for the case of oil and gas investments, we can improve significantly on the standard process by building flexibility into the system. We can do this by proactively managing the uncertainties in the process, specifically by designing in the appropriate opportunities to react appropriately to the actual circumstances that develop. For example, if we build a platform that is designed to enable the use of additional wells, then we can expand production–and increase value significantly–if the field proves to be richer than anticipated. This flexibility has the further advantage of permitting the design to be initially smaller (and thus less expensive and less vulnerable to losses) than it might otherwise be if it were initially built to exploit a possible, but not definite, larger field.

The recognition of uncertainty in the values of important design variables is key to the understanding and obtaining the value of flexibility. The core idea is that if the design process recognizes up front that the future is uncertain, then it can incorporate the ability to adapt to different scenarios, so that system operators can manage uncertainty effectively. Flexibility permits both the expeditious exploitation of new opportunities, the adjustment of functions to new kinds of needs (such as handling different proportions of fluids or gas), and the economical scaling back of unproductive facilities. In short, to get the most out of our projects, we need to incorporate uncertainty into the design process itself: this is what motivates the inclusion of flexibility and allows us to increase the value of projects.

The demonstration that flexibility has value (Begg et al. 2002) has been replicated in many other fields. Examples abound, both in petroleum developments (Hassan et al. 2006; de Neufville et al. 2008), and many other projects (see http://ardent.mit.edu/real_options/Common_course_materials/papers.html). In short, many studies demonstrate that properly conceived flexibility can have great net value–beyond its cost–when designed into projects with long-term, uncertain futures.

Graphs of Cumulative Distributions and Value-At-Risk-and-Gain (VARG). Visual representations of the range of uncertainties associated with important parameters are most useful in developing the recognition of the nature and extent of uncertainty. Plots of cumulative distributions of outcomes may provide particularly effective means of communication because they specifically present the net effect–the integral–of a specific level of uncertainty. That is, a cumulative plot directly indicates the percent of a phenomenon or outcome that is above or below any specified cut-off level.

Cumulative distribution curves are widely used in the financial community, where they are called Value-at-Risk (VAR) curves. The practice is to highlight the cumulative amount less than a reference value–that is, to emphasize the possible losses, the Value-At-Risk. As can be imagined, bankers are mostly concerned with getting their money back and hence focus on possible losses. The VAR curves thus slope from bottom left up to the upper right. The curves used by Hayashi et al. (2007), in keeping with practice among petroleum geologists, implicitly emphasize possible gains, and thus slope from upper left to lower right; otherwise the curves are identical in concept. Jablonowski et al. (2008) use VAR curves without using that name.

In design practice, it is becoming increasingly common to think about these curves in terms of Value-At-Risk-and-Gain (VARG). This is because system designers are interested not just in the possible losses, but also the possible gains. Thus, they want to develop design strategies that lessen the possibility of losses and complementary ones that increase the possibilities of gains (see de Neufville et al. 2008). Apart from the difference in name–and the associated increased focus on gains–the curves are identical.

VARG curves can be design aids, in addition to being representations of results. Designers now use them to identify design

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Original SPE manuscript received for review 10 November 2008. Revised manuscript received 24 December 2008. Paper SPE 122710 peer approved 3 January 2009.

elements that might be changed to provide greater expected value. Specifically, we can investigate in detail the tails of the curves–those with the possibility of greatest loss or gain–to develop design concepts that would decrease or even prevent possible losses, and others that could enhance the maximum gains if the right circumstances occur. As an example, if it appears that the project might incur great losses if the reservoir were fractured and could not be exploited efficiently with a proposed design, then that design might be altered to give it the flexibility of easily expanding the number of wells, and thus avoid the major losses. In short, the identification of a possible problem indicates the kind of flexibility that would enable intelligent, effective management of the uncertainty. Similarly, examination of the circumstances that might lead to greater gains can help identify other kinds of flexibility that would enable managers to get the most value from the field.

Proposed Method

The proposed approach is an outcome of long-term work on the improvement of design methods. Building on both the developments outlined in the preceding section and parallel work in other fields in real options aimed principally at financial considerations, it embodies a paradigmatic change in the way *designers* deal with uncertainty. Instead of creating designs based on fixed assumptions and then testing their sensitivity to risks, the proposed process recognizes risks in the design process, and thereby develops valuable flexibility that increases the expected value of development projects.

The proposed method involves four complementary steps:

1. **Development and Validation of Basic Economic Model.** The economic valuation of alternative designs requires a model that captures the logic of the value generation for possible designs: $V = f(x_t, y)$, where y is the initial design variables and the x_t is the uncertainties that unfold over time, such as fluctuation in oil price and the different realizations for the amount of OOIP. If such a model is not available, it needs to be developed, generally from a combination of an "oil and gas" technical model, an economic model, and simulation procedures that can factor in the evolution of the uncertainties x_t. The model also needs to be validated. This may most easily be done with respect to a base possible design for a project.

2. **Exploration of the Range of Outcomes Base Design Might Generate.** The idea here is to calculate the distribution of the outcomes that could develop from a range of possible uncertainties. The essential point is to develop sensible distributions of the uncertainties x_t. Pragmatically, some of the uncertainties will have little effect on value and can be dealt with as averages, whereas others will affect value significantly and should be handled probabilistically. The uncertainties might include, in addition to obvious factors such as the price and quantity of oil, other parameters such as expected watercuts, construction costs, etc. This step produces a distribution of performance of economic value for any chosen set of design parameters and evolution of uncertainties. The results can then be plotted in cumulative distribution curves such as the VARG.

3. **Identification of Opportunities for Flexible Design.** The analysis of the VARG or other cumulative distribution curves, coupled with expert knowledge of the system, can be used to identify possible design combinations that offer means either to mitigate downside risks, or to take advantage of upside opportunities. These flexible design combinations can then be valued. To do so, it is necessary to modify the basic model of value to include effect $z_t(x_t)$ of exercising, making use of the flexibility at appropriate times–for example when the price of oil is high. This model can be thought of as $g(x_t, z_t(x_t), y)$. Note that this step requires the specification of the decision rules for exercising the design option, and that these presumably vary over time—for example, the decision to develop additional wells when the price of oil is high is likely to depend on how long a field has been in production and how much oil is left.

4. **Selection of the Most Valuable Flexibilities.** The design team will need to make design choices based on multiple criteria. Expected or average economic performance is unlikely to be a sufficient criterion of selection, because projects with similar Expected Net Present Value (ENPV) can have quite different risk profiles and levels of original capital expenditure (CAPEX). Because the analysis explicitly considers uncertainties from the start, the evaluation can and should consider the measures of value associated with these distributions. Indeed, the VARG or similar distribution curves not only embody estimates of the ENPV of a project, but also measures such as the minimum and maximum values for the project (which will be of interest to risk-averse financing groups and investors). The analysis can compare these returns to the different amounts of CAPEX and obtain the resulting benefit-cost ratios associated with each design.

This 4-step process provides designers with a practical procedure for incorporating the greater understanding that researchers and practitioners have been developing about the costs of designs based on fixed (and inevitably inaccurate) assumptions, the value of flexibility, and the desirability of presenting evaluation in the form of distributions. As we collectively gain more experience in working with these issues, we can expect that practice will indicate many improvements that should be made to the process.

The goal is both to increase the expected value of the design through the incorporation of flexibility and to reduce the risk of a project, particularly against catastrophic or unacceptable losses. This definition of the vision embodies two points that deserve emphasis. The first recognizes that we operate in an uncertain world, and that the outcomes of designs are probabilistic. In that context we can only properly speak of expected values of distributions, hence the stress on "expected value of the design". The second point is that flexibility is the way that system managers can manage uncertainties effectively over time, and that incorporating the right kinds of flexibilities is the key to increasing the value we can deliver through project design.

The procedure also seeks to improve the decision-making process by transparently revealing the implications of uncertainties. This process, and the associated VARG and other devices, make the choices clearer and thus help designers better understand their choices and associated risks.

To describe and validate the proposed procedure, we present a specific development of platforms in the Gulf of Mexico. To protect corporate confidentiality, the specific details are masked. However, the overall presentation accurately represents the essential features of the project.

Case Study

Background. The case concerns two oil fields in over 100 meters of water in the Gulf of Mexico. We refer to them as "Sample" and "Rother." A seismic survey discovered them in the initial exploration phase. The company drilled an exploration well four years later and appraisal wells seven and nine years after that.

As could be expected, the results from the appraisal wells were ambiguous. The first exploration well at Sample put the oil reserves in place at approximately 80 million barrels (MMBO); the second increased the estimate to 200 MMBO. Conversely, the first Rother exploration well generated an estimate of approximately 220 MMBO, which the second well dropped to approximately 100 MMBO. The major technical issue revolved around reservoir continuity and connectivity. Possible fault blocks that compartmentalized the reservoirs and sub seismic barriers/baffles provided some explanation of the large variations in estimated reserves. The design of the exploitation thus had to proceed with great uncertainty about the actual amount of OOIP in both fields. **Fig. 1** shows the estimated probability mass functions for each field.

The management team chose Sample as the primary development. Rother was the secondary development, produced through sub-sea (SS) wells to the hub at Sample. The design for the Sample extraction facility was a tension leg platform (TLP), with 8 direct vertical access (DVA) wells with 5 sub-sea tiebacks. The daily production capacity for the platform was 100,000 barrels oil (BOPD) and 150 million standard cubic feet of natural gas (MMSCF/D).

Analysts evaluated the net present value (NPV) of the project using a 32% expected ultimate recovery (EUR) factor for a "most likely" estimate of OOIP and a fixed oil price forecast. [The price

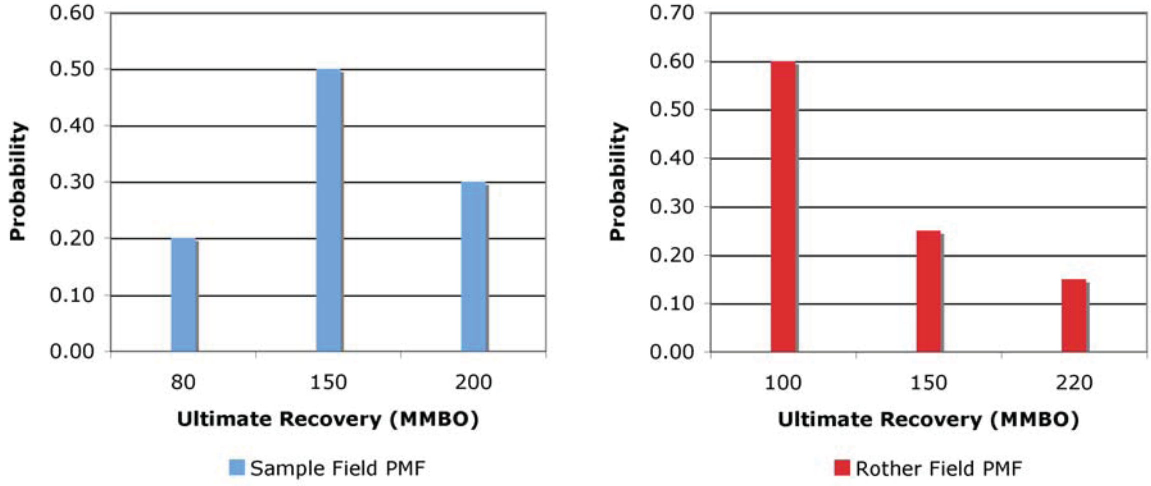

Fig. 1—Probability mass functions for Sample and Rother fields.

used is, of course, highly confidential, but the prices used in the analysis of the case are representative of those prevailing at the time of the development.] Five years after the project startup, the estimates of OOIP had shrunk 25%. The reservoir was not as vast and continuous as initially thought. Moreover, construction issues had delayed the time to first oil, and the compartmentalized nature of the reservoirs required additional wells and increased production costs.

Had oil prices been as originally forecast in project valuation, the actual NPV of the project would have been much lower given the combined effect of unexpected increased costs and lower production. The first post-project execution review showed a NPV reduction of approximately 25%. Fortunately, the forecasts of oil prices were wrong, and price increases during the production period enabled the project to attain its financial goals. Thus, even though the project turned out to be profitable, it was unsuccessful based on project valuation and expectation.

Scope of the Case Study. For the purpose of demonstrating and validating the proposed method, the analysis focuses on one main source of uncertainty: the total OOIP in the reservoirs. A more complete analysis would simultaneously consider possible variations in the price of oil, but adding this second dimension to the analysis confuses the presentation and adds nothing to the demonstration of concept. Uncertainty in the price of oil is included at the end by way of illustration. From a design perspective, the analysis considered a TLP platform designed with additional slots so that extra DVA sub-sea wells can be easily added if the reservoirs contain high quantities of oil, similar to what Begg et al. (2002) proposed. The analysis considers three cases:

- Sample developed alone,
- Rother developed alone, and
- Sample and Rother developed together.

For all three cases, the method estimated the value of flexibility in design by comparing the expected value of the inflexible, basic design with a flexible design allowing production expansion. The analysis also recognized that in this case if the flexibility to add wells were not included at the start, further expansion would not have been economically practical. To protect confidentiality, all numbers used for valuation are hypothetical. Babajide (2007) provides more details on specific assumptions.

Step 1: Development and Validation of Basic Economic Model. This step creates the economic model to value the standard, base case design (8 DVA wells with 5 subsea tie backs). A discounted cash flow analysis estimates the NPV. The model incorporates key design elements for cost, sources of uncertainty, and decisions to be made, as **Table 1** summarizes. As in standard design processes, the model uses single point estimates for OOIP and price. This base case analysis provides a starting point to ensure that everyone on the team agrees and is aware of what needs to be accomplished.

TABLE 1—KEY FACTS, SOURCES OF UNCERTAINTY, AND DECISIONS RELATED TO THE PROJECT

Category	Issues
Fact	Fields are offshore in 100+ meters of water
Uncertainty	Extent of reservoir compartmentalization, which affects the expected reserves in Sample, Rother, and both fields combined.
Uncertainty	Future oil price
Decision	What facility to put in place (TLP, floating production, storage and offloading (FPSO))?
Decision	How many wells to drill and complete?

As Fig. 1 shows, the most likely estimates of oil for the Sample and Rother fields are 150 and 100 MMBO, respectively, based on a 32% recovery factor. Using these amounts as the deterministic forecast for production capacity, and a price forecast of $15/barrel in the range acceptable at the time of the design, the basic economic model calculates the NPV of each field as $8,267M and $5,832M. Exploiting both fields with a common platform–instead of two as in the separated case, which reduces cost–and five sub-sea tiebacks leads to a total production of 250 MMBO and a project NPV of $20,639M. This assessment is unrealistic however, because it does not account for uncertainty in OOIP and price. As Jablonoswki et al. (2008) report, and as further shown below, investment decisions based on such deterministic valuations can be erroneous and value-destructive.

Fig. 2 shows the results in the form used for decision analysis, to provide an easy contrast between the deterministic analysis and those that incorporate uncertainty.

Step 2: Exploration of the Range of Outcomes Base Design Might Generate. This step develops probability distributions of the possible actual outcomes associated with uncertainties in the parameters being examined, using the best information available at the time of design. In this case, this consists of the probability mass functions of the oil in place ultimately recoverable (Fig. 1).

In general, it is necessary to develop probability mass functions that combine individual assessments of uncertainty. In this case, the analysis needs to combine the distinct information on each field. For simplicity, it is assumed that the OOIP in each field can be treated as an independent random variable, that is, that the reservoirs are not connected. The probability tree in **Fig. 3** shows the possible outcomes for production of both fields combined with associated probabilities. The numbers on the rightmost column

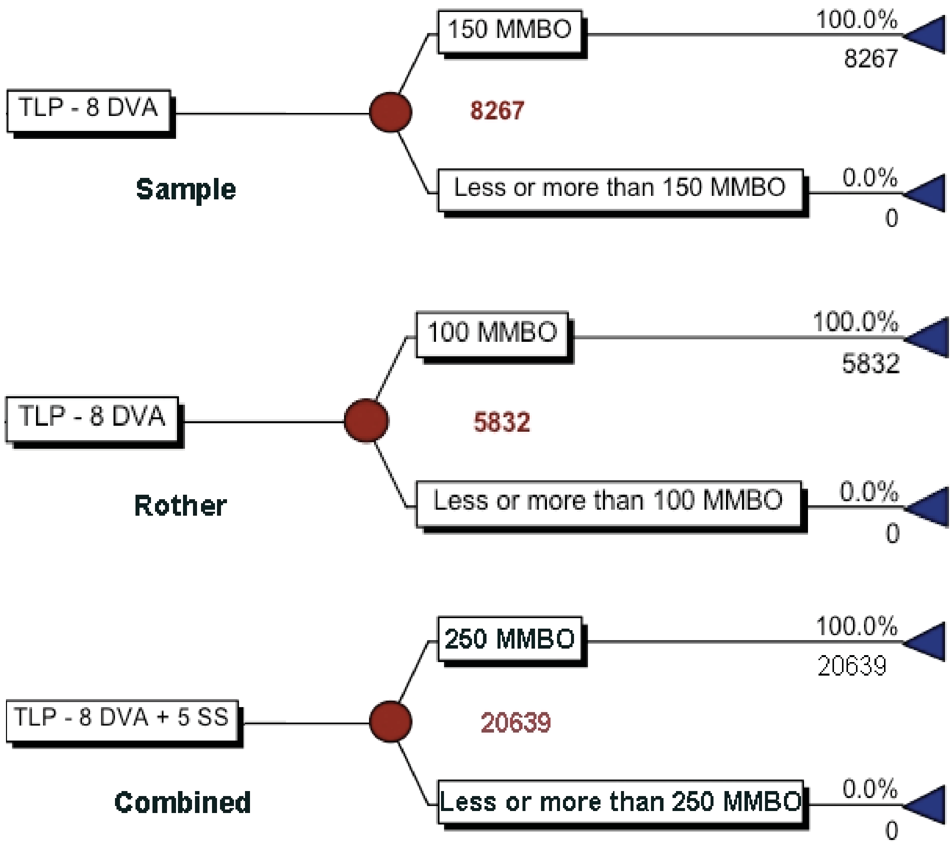

Fig. 2—Estimated NPV of development based on 100% probability of most likely reserves.

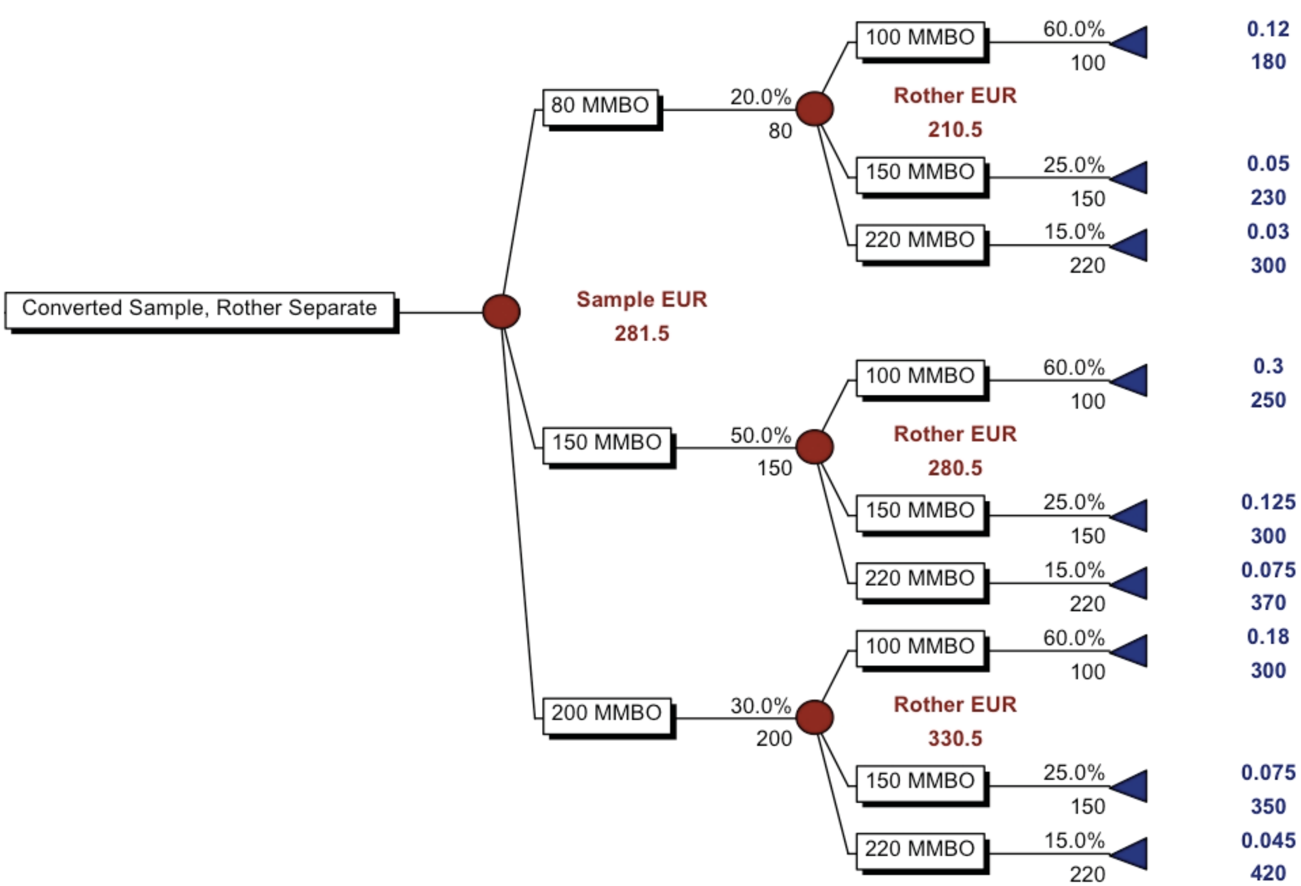

Fig. 3—Probability tree for the combined reserves in both fields.

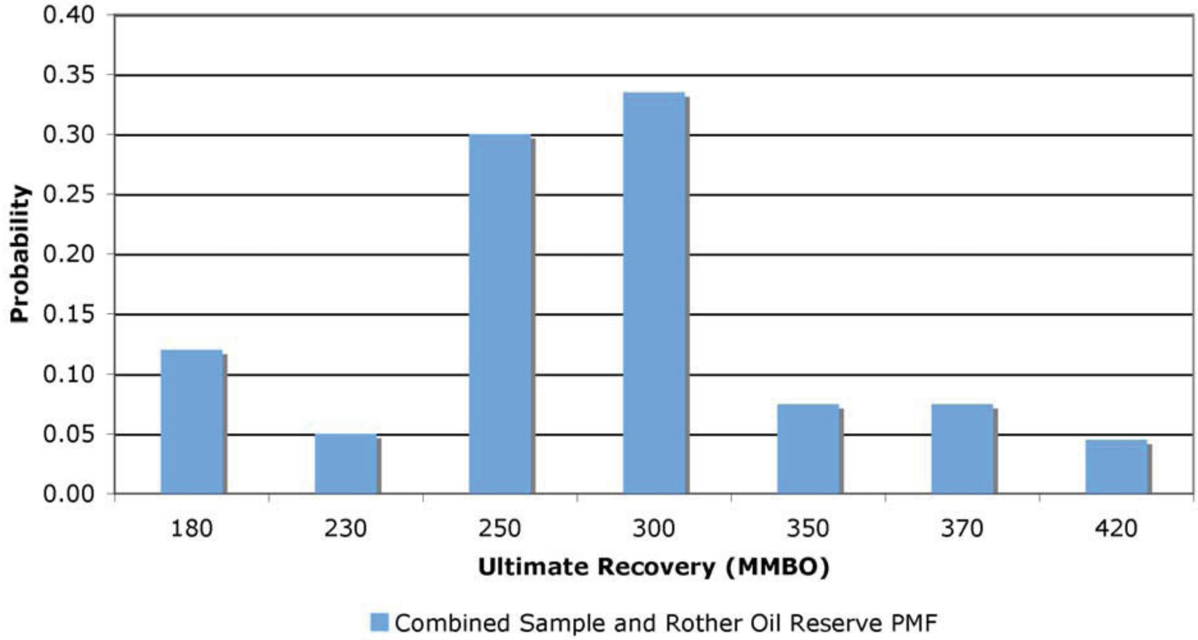

Fig. 4—Combined probability mass function for oil reserves in both fields.

show the probability of a particular outcome, and the associated total oil produced. For instance, the topmost path shows a 0.12 probability of producing 80 MMBO from Sample, 100 MMBO from Rother, for a combined production of 180 MMBO. The probability mass function for the combined production consists of the sum of the probabilities of any particular outcome. For example, there are three combinations of OOIP in the Sample and Rother fields that lead to a combined production of 300 MMBO. The probability of that production is the sum of the individual probabilities of these combinations; that is, 0.335. **Fig. 4** displays the resulting probability mass function for the combined oil reserves.

Note that while the case deals with discrete probabilities, the approach can be extended to continuous probability distributions. Moreover, commercially available software facilitates the task of fitting distributions to desired ranges and parameters of the distributions.

The analysis recognizing uncertainly in the OOIP leads to a different valuation and expected production than the deterministic analysis. In this case, the analysis generates an ENPV, in the sense that it is the probabilistically weighted average of the outcomes, of $22,935M as **Fig. 5** illustrates, with an expected production of 281.5 MMBO for the basic inflexible design. This contrasts with the NPV of $20,639M and production of 250 MMBO generated by the deterministic analysis. These higher values are due to the fact in this case that the probability mass function is skewed towards higher values than the deterministic estimate of 250 MMBO.

Step 3: Identify Flexible Design Opportunities. Finding the most valuable potential sources of flexibility in complex projects can be difficult. In general, it is not clear where the flexibility should be inserted "in" design; thousands of interacting design components might have to be considered. How to do this is a major current topic for doctoral and other research. As regards the oil industry, Kalligeros (2006) and Lin (de Neufville et al. 2008) are exploring possibilities. Other research considers defense systems (Bartolomei 2007), car manufacturing (Suh 2005), and infrastructure generally (Wang 2005). These approaches are not yet ready for operational use.

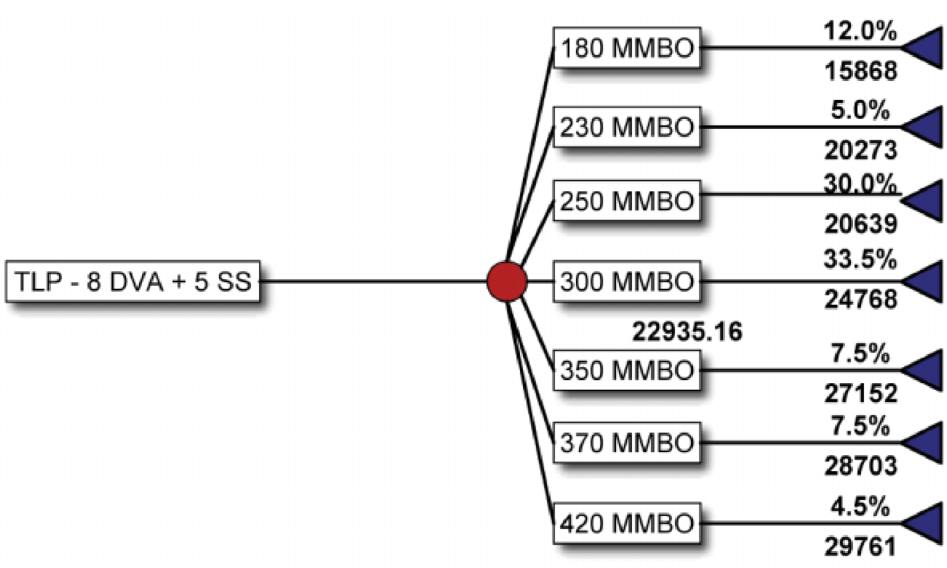

Fig. 5—Expected value of base case design of development with probabilities for OOIP.

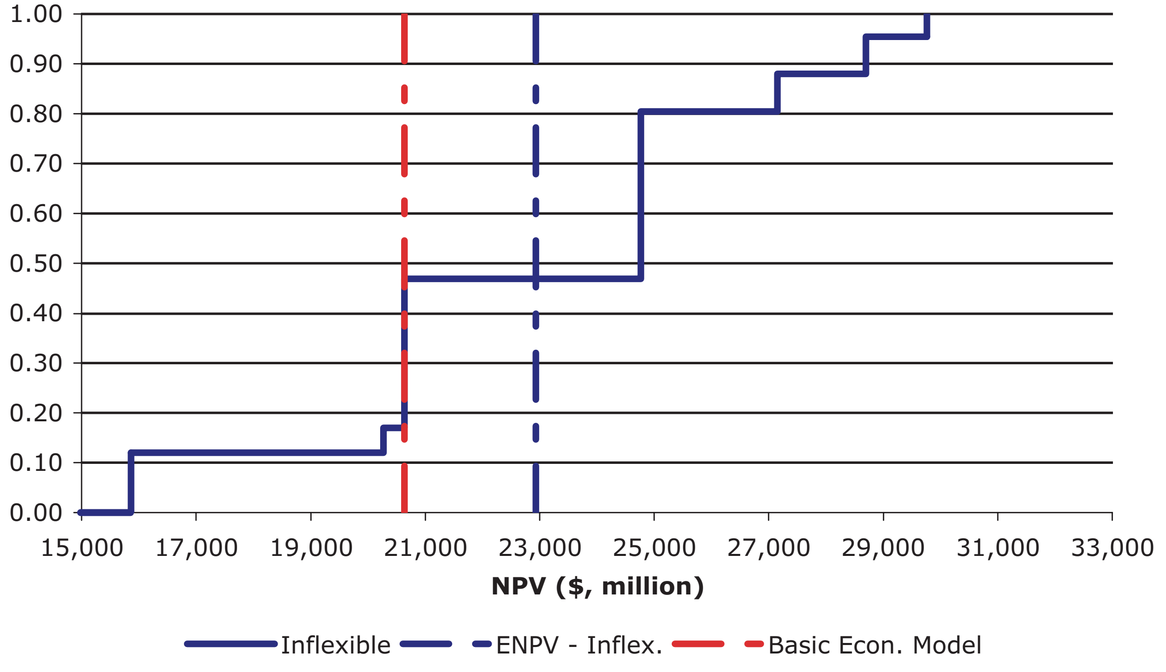

Fig. 6—VARG for base case (inflexible) design.

For current practice, it is instructive to consider the VARG diagram of the base case. This examination can indicate the available opportunities for flexibility. Thus **Fig. 6** shows that the outcomes for the inflexible design are skewed downwards, even though there is the potential for large upside opportunities. This observation suggests that flexibility that enables easy expansion of the production capability might be beneficial.

The capability to expand production easily can be obtained by designing extra DVA and SS well slots in the TLP so additional wells can be added when desirable. In general, the analysis would consider various combinations to find the optimum solution. It could also explore the possibility of exercising the option to expand production capacity at several different times and increments.

For brevity of presentation, this analysis proceeds directly to a much-improved design. The flexible design considered here adds two extra DVA and two extra SS well slots to the base case design. It also assumes that the decision to expand is only taken once (which seems realistic due to the cost of mobilization), five years after production operations start. The overall idea is that, as the uncertainty in OOIP gradually resolves over time, management may decide to exercise the option to add the direct vertical access and sub-sea wells. When conditions are suitable, this decision will increase production capacity, revenues, and hence the project ENPV.

Step 4: Selection of the Most Valuable Flexibilities. The flexibility in this case can be applied to each of the three possible production decisions: to develop either Sample, Rother, or both together. The immediate object is to find the arrangements that maximize the ENPV. Designers should however make use of the distributional information available through the VARG, for example the possible maximum or minimum values, which may be of interest to the ultimate decision-makers.

Decision-trees in **Fig. 7** set out the analysis for the development of the fields separately. The diagrams each lay out the choices that management can take about exercising the option to expand. On the rightmost column, a "True" statement means it is optimal to exercise the option. This is useful for management to determine what conditions are appropriate to exercise the flexibility. A "True" statement next to the chance node means it is worthwhile incorporating the flexibility in design.

The decision trees in Fig. 7 also give the results. First, it can be seen that flexibility improves the value of the project, as indicated by the "True" indications at the roots of each decision tree. Comparing these results with those in Fig. 2 shows that the value of each field developed separately has increased significantly: for Sample from $8,267M to $9,135M, and for Rother from $5,832 to $7,983M.

The decision-tree in **Fig. 8** summarizes the situation for flexibility in development of both fields together. It is more complicated than those in Fig. 7 because there are more possible combinations; otherwise, it is the same. Compared with the inflexible design, the ENPV is increased from $22,935M to $24,622M, with an approximate value of flexibility of $1,687M. This also indicates that designing in extra DVA and SS slots is worthwhile.

The VARG curves also help identify the most desirable design. In **Fig. 9,** the solid lines show the cumulative mass functions of possible outcomes, and dashed lines show the ENPV for both inflexible and flexible designs, as well as the deterministic analysis. The design with the flexibility to expand production clearly pushes the distribution of outcomes and ENPV to the right, expanding opportunities for gains.

Decision-makers do not decide on averages alone. They are also interested in the variation of returns. The VARG charts illustrate the range of outcomes. The data used to develop these curves also provide other valuation metrics, as **Table 2** shows. Decision-makers in the first instance might choose a design that limits downsides (minimum achievable NPV) or exploits the upsides (maximum NPV). They will also want to compare the initial capital expenditure (CAPEX) associated with alternative designs. Table 2 compares these metrics for the case study and indicates how each metric ranks the alternative designs. In general, as here, no design can be expected to be unambiguously better on all counts.

To account for oil price uncertainty, the 4-step analysis was repeated using different oil prices, specifically ± $5/barrel from that assumed, that is, prices of $10/barrel and $20/barrel. The ENPV for the inflexible and flexible designs were found for each price scenario, and the value of flexibility is the difference between the two. Using an assumed distribution of possible forward oil prices at the time of the initial evaluation in the 1990s, **Table 3** summarizes the expected values of the alternative designs and of the flexibility to add extra DVA and SS wells. Comparing the expected value of flexibility ($1,712M) with the cost of enabling the flexibility by adding the additional DVA and SS slots ($34M, the difference between the two initial CAPEX in Table 2), it is clear that the investment in flexibility is really worthwhile. This single flexibility increases overall expected value by approximately 7%

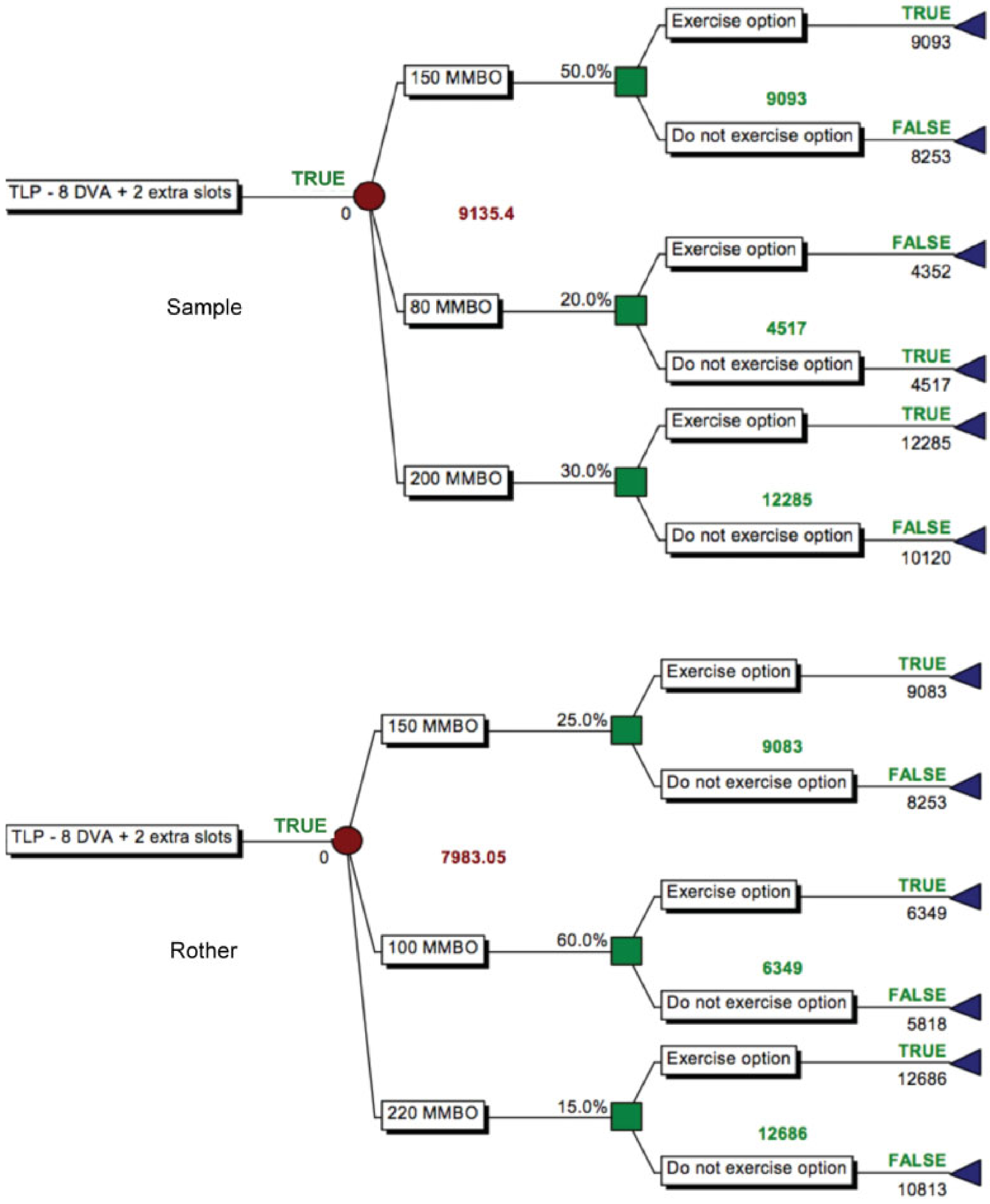

Fig. 7—Decision trees to analyze use of flexibility for Sample and Rother separately.

in this case. As **Table 4** shows, the ENPV value of the flexibility in this case is fifty times its cost!

Conclusion

This paper presents a practical integrated design method for increasing the ENPV of a project. The essence of this approach is that it provides a procedure to explore the impacts of the uncertainty of major variables *during* the design, not afterwards, as generally done. This process enables designers to identify valuable opportunities to manage uncertainty and increase the overall value of the project. These opportunities consist of flexibilities designed into the system.

As this case and other examples indicate, flexibility can increase value significantly. In this instance, a single kind of flexibility led to about 7% improvement. In other situations, involving more and more complex kinds of flexibilities, total improvements in value were in the range of 20% or more (Hassan et al. 2006; de Neufville et al. 2008). This potential should not be ignored.

The concept of systematically recognizing uncertainties early in the design and then of identifying and inserting flexibility in design

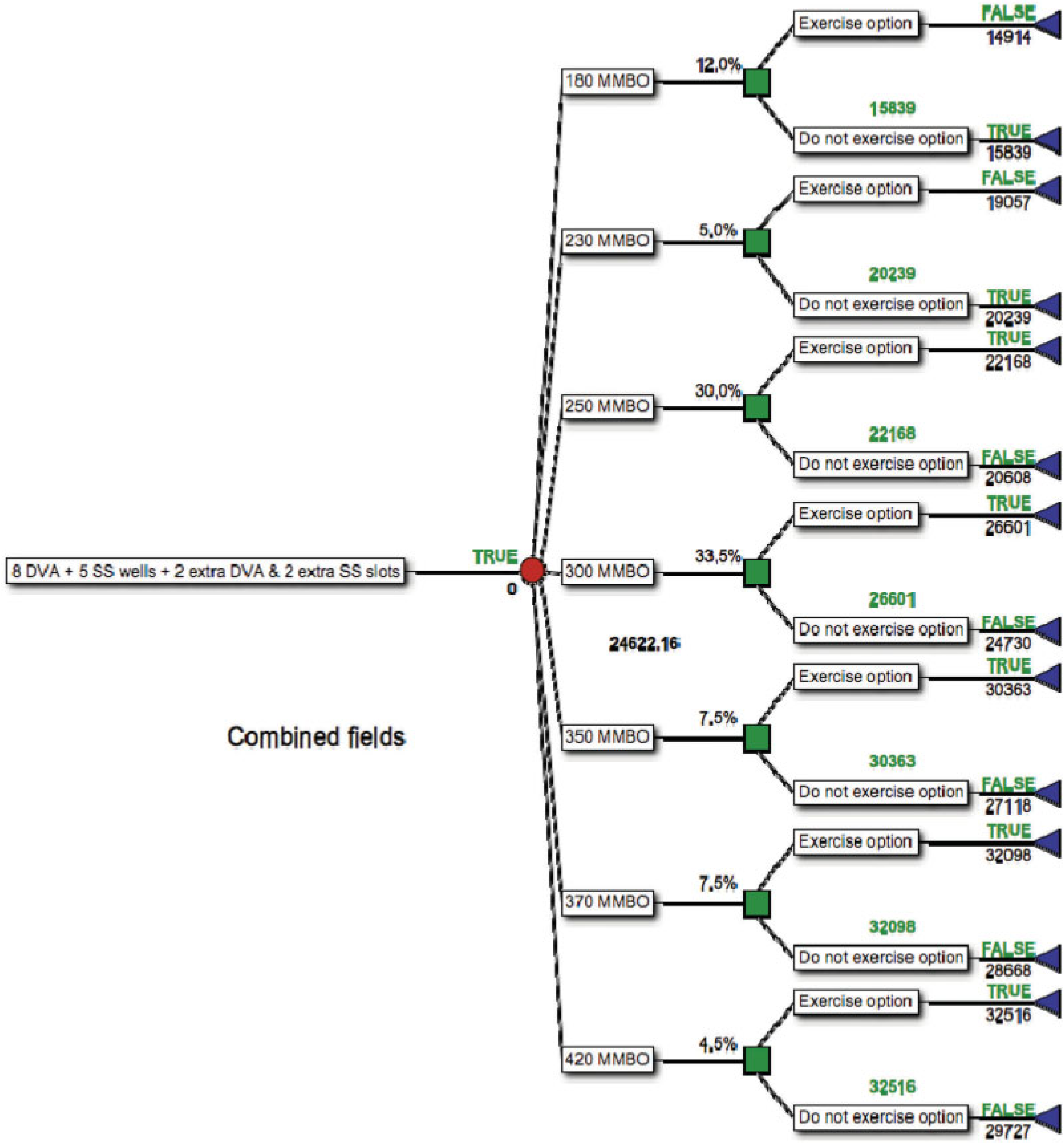

Fig. 8—Decision trees to analyze use of flexibility for both fields developed together.

thus needs to be adopted. This signals a paradigmatic change in the design process. As such, it will be difficult–old habits die slowly. However, companies and industries that adopt some version of this process will reap substantial benefits compared to their competitors who do not recognize the value of managing uncertainty through the use of flexibility designed into the system.

The process suggested in this paper can and certainly will be improved. We need practical, computationally efficient ways to identify desirable kinds of flexibilities in a system. Recent research, as suggested in the text, is promising but not yet operational. Practitioners also need to think about what metrics they should use in measuring the value of projects. Net present value by itself does not properly reflect the range of possible outcomes. Furthermore, in many cases such as health care, education, defense, and space exploration, monetary values are often not useful measures of performance.

The proposed process should be generally applicable to many fields of design. While this presentation and case study concerns the development of oil fields, there is nothing in the process that limits its applicability to a specific field. Designers in any field should be able to increase the value of their projects by considering future uncertainties early in the design, and by incorporating means of adapting to future realities early as they unfold.

As regards the development of oil fields in particular, researchers and practitioners need to develop computationally efficient procedures for carrying out the kind of analyses outlined above. The essential issue is that, when we consider distributions of parameters, we greatly expand the size of problem to be explored. To get around this problem, our team and others are working on the use of "screening models", that is, simplified models that can be used for preliminary explorations of possible designs.

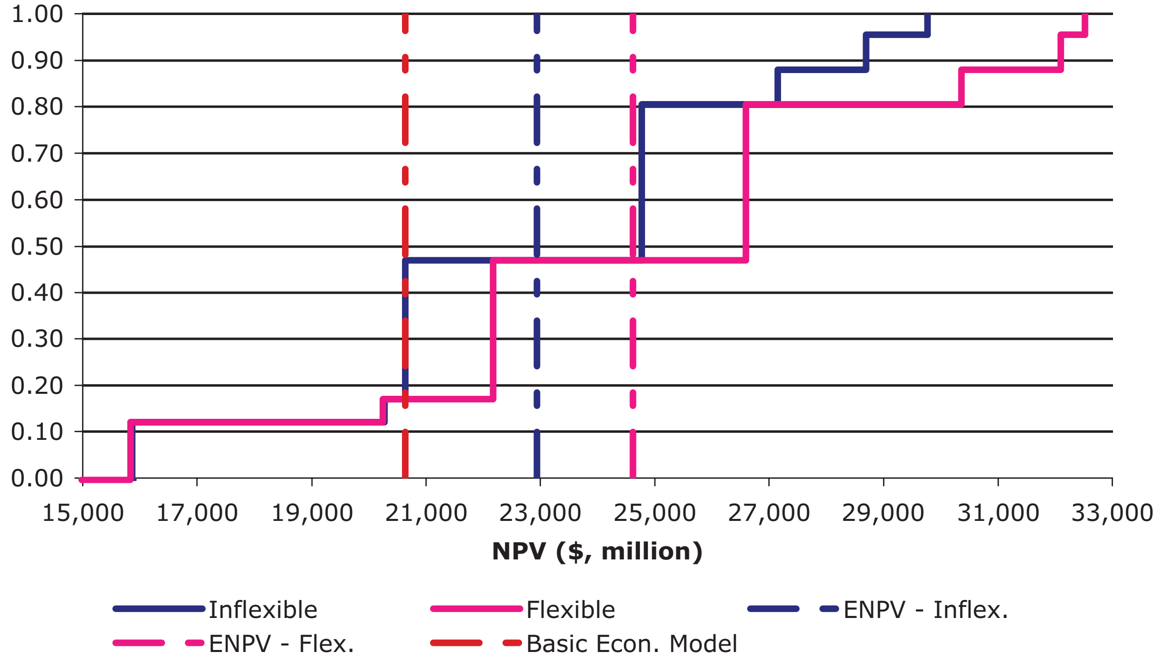

Fig. 9—VARG curves comparing the development of the combined fields with and without flexibility. Dashed lines show their ENPV.

TABLE 2—COMPARISON OF ECONOMIC METRICS FOR THE COMBINED DEVELOPMENT

($, million)	Designs			Which better?
	Deterministic	Inflexible	Flexible	
ENPV	20,639 (unrealistic)	22,935	24,622	Flexible
Minimum NPV	N/A	15,868	15,839	Same
Maximum NPV	N/A	29,761	32,516	Flexible
Initial CAPEX	956	956	990	Inflexible
NPV/CAPEX	22	24	25	Flexible

TABLE 3—ANALYSIS FOR EXPECTED VALUE OF FLEXIBILITY CONSIDERING THREE PRICE SCENARIOS: LOW, MEDIUM, AND HIGH PRICE

	Prices Per Oil Barrel			
	Low ($10/barrel)	Medium ($15/barrel)	High ($20/barrel)	Expected Values
Probability of scenario	0.15	0.65	0.20	–
ENPV inflexible ($, M)	15,137	22,935	30,504	23,279
ENPV flexible ($, M)	16,251	24,622	32,747	24,991
Value of flexibility ($, M)	1,113	1,687	2,244	1,712

TABLE 4—COMPARISON OF FLEXIBILITY VALUE TO ACQUISITION COST FOR INVESTMENT DECISION

Cost of flexibility ($, M)	34
Average value of flexibility ($, M)	1,712
Benefit-cost ratio	50

Nomenclature

$f(\ )$ = value as function of ( )
$g(\ )$ = value with exercise of flexibility
V = value of project
x = uncertain parameter
x_t = uncertain parameter varying over time
y = design variable
$z_t(\ )$ = effect of exercising flexibility over time

Acknowledgments

The authors thank the Shell team in New Orleans, in particular Rich Sears, Stuart Hara, and Fred Lerch for their time and advice. We also thank Jon Unwin, Ton van den Heuvel, Lisa Johnson, Frank Glaviano, and Andy Melancon for valuable support to this work. We deeply appreciate the thoughtful comments we have received from Steve Begg from the University of Adelaide, Christopher Jablonowski of the University of Texas, Stefan Scholtes from the University of Cambridge, and Denis Schiozer from the Universidade Estatal de Campinas. We are also grateful for the financial support provided by Shell, the Fonds Québécois de la Recherche sur la Nature et les Technologies, and the Natural Sciences and Engineering Research Council of Canada.

References

Babajide, A. 2007. Real options analysis as a decision tool in oil field developments. MS thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts (February 2007), http://ardent.mit.edu/real_options/Real_opts_papers/Babajide_Thesis_FINAL.pdf.

Bartolomei, J. 2007. Qualitative knowledge construction for engineering systems: Extending the design structure matrix methodology in scope and perspective. PhD dissertation, Massachusetts Institute of Technology, Cambridge, Massachusetts (June 2007), http://ardent.mit.edu/real_options/Real_opts_papers/Bartolomei%20Thesis.pdf

Begg, S., Bratvold, R., and Campbell, J. 2002. The Value of Flexibility in Managing Uncertainty in Oil and Gas Investments. Paper SPE 77586 presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, 29 September–2 October. DOI: 10.2118/77586-MS.

de Neufville, R., de Weck, O., Lin, J., and Scholtes, S. 2008. Identifying real options to improve the design of engineering systems. Revised draft (unpublished), http://ardent.mit.edu/real_options/Real_opts_papers/nembhard%20final%20draft.pdf

de Neufville, R. and Odoni, A.R. 2003. *Airport Systems: Planning, Design, and Management*. New York: McGraw-Hill.

Hassan, R. and de Neufville, R. 2006. Design of engineering systems under uncertainty via real options and heuristic optimization. *Proc*., 10th Annual Real Options Conference, New York City, 14–17 June, http://ardent.mit.edu/real_options/Real_opts_papers/Hassan_deN_ROG_submitted.pdf

Hayashi, S.H.D., Ligero, E.L., and Schiozer, D.J. 2007. Decision-Making Process in Development of Offshore Petroleum Fields. Paper SPE 107737 presented at the Latin American and Caribbean Petroleum Engineering Conference, Buenos Aires, 15–18 April. DOI: 10.2118/107737-MS.

Jablonowski, C., Wiboonkij-Arphakul, C., and Neuhold, M. 2008. Estimating the Cost of Errors in Estimates Used During Concept Selection. *SPEPFC* **3** (1): 1–6. SPE-110191-PA. DOI: 10.2118/110191-PA.

Kalligeros, K. 2006. Platforms and real options in large-scale engineering systems. PhD dissertation, Massachusetts Institute of Technology, Cambridge, Massachusetts (June 2006), http://ardent.mit.edu/real_options/Real_opts_papers/Kalligeros%20Dissertation.pdf

Suh, E.S. 2005. Flexible product platforms. PhD dissertation, Massachusetts Institute of Technology, Cambridge, Massachusetts (September 2005), http://esd.mit.edu/people/dissertations/eun_suk_suh.pdf

Wang, T. 2005. Real options “in” projects and systems design—Identification of options and solutions for path dependency. PhD dissertation, Massachusetts Institute of Technology, Cambridge, Massachusetts (May 2005), http://ardent.mit.edu/real_options/Real_opts_papers/tao%20dissertation.pdf

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