# IDENTIFYING REAL OPTIONS TO IMPROVE THE DESIGN OF ENGINEERING SYSTEMS

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## Summary

This chapter is part of the developing literature on the use of real options in the design and development of major projects – more generally, of engineering systems. The chapters by Kazakidis and Kalligeros in this book are part of the same stream. This work differs substantially from the bulk of the real option literature. It focuses on improving the overall performance of technological projects by incorporating flexibility into their design.

The field is growing rapidly because engineering projects are expanding in scope and complexity while their environment is becoming increasingly uncertain in terms of stakeholder requirements, resource availability, market demand, and other aspects. Traditional engineering design methodology is deficient in dealing with such uncertainty. Practitioners in the field thus need new approaches.

Research in real options is leading to significant practical results. Many applications demonstrate that flexible designs can greatly increase expected overall performance compared to traditional rigid designs optimized for specific conditions. Flexible designs can deliver these benefits because their underlying architecture enables managers to adapt projects to circumstances that develop. Owners can thus cut losses by avoiding undesirable outcomes, and increase gains by taking advantage of new opportunities.

Part 1 describes the concept of this developing literature. It situates design flexibility in the spectrum between the standard use of real options and traditional engineering design. As indicated below, the focus on flexible design involves deep reframing of the way we think about both design and the

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use of real options. The focus on flexibility in design involves important changes in paradigm and practice. In a nutshell, our work is located midway between standard engineering practice (which does not deal systematically with design flexibility) and financial real options analysis (which does not deal with system design).

Part 2 deals with a core issue in the development of flexible designs: the problem of identifying the most desirable sources of flexibility. This topic is novel from the perspective of the standard literature on real options, which assumes that the sources of flexibility, the options, are either known or obvious. Specifically, this section presents an efficient procedure for identifying desirable real options for engineering systems. It uses screening models, that is, relatively simple representations of the system that are computationally efficient. It couples these models with simulations of the distribution of the possible future outcomes in terms of the range of values of factors that influence the performance of the system. By scanning a range of possible flexible designs, it thus identifies those that are most promising. The presentation illustrates the use of screening models using a case study concerning the development of a hypothetical deep-water oil field under uncertainty.

## PART 1: THE CONCEPT OF FLEXIBILITY IN DESIGN

### Theme: Focus on Flexibility

The work on flexibility in design aims to improve the overall value of projects. The motivation for this effort lies in the fact that flexibility can provide truly significant increases in overall expected value, as much as 30% or more in several instances, compared to standard designs that do not incorporate flexibility. By value we refer to output of the system, along whatever metric is relevant to its managers; this may be profit or net present value for a commercial company, lives saved for a health care enterprise, or pollution reduction for an environmental agency. Conversely, we are not referring to the technical excellence of a system whose performance is considered a sine qua non.

Additionally, flexible designs can provide substantial valuable insurance against downside risks, as well as enable system managers to take advantage of new opportunities. In general, flexibility in design shifts the distribution of outcomes from the less desirable to the more favorable. Both the case study presented in Part 2 and numerous examples demonstrate these possibilities. See for example: de Neufville et al (2006), de Weck et al (2004); and Hassan and de Neufville (2006).

Flexibility is most valuable when uncertainty is high, as is well known from the financial literature on options. Flexibility in fact derives its value from uncertainty. If there were none, if we knew what would happen, there would be no point in having contingency plans or insurance. Conversely, the greater the risks, the more valuable insurance policies become. De Weck et al. (2007) indicate how this plays out in product design.

Flexibility is therefore most valuable for longer term projects. This is for two reasons. First, the future is most uncertain for longer term projects. As many studies consistently demonstrate, forecasts are “always wrong” in that the actual demands for services or prices of goods may easily be less than half or more than twice as much as anticipated (See Flyvjberg et al, 2003 and 2005 for example). There is thus great virtue in waiting to find out what is necessary and to design accordingly.

Flexibility in design is further valuable because activities that last a long time give the system managers considerable scope to decide on the size and timing of investments, and thus to modify the cash flow to increase the net present value. The ability to expand a project easily, and as needed, makes it possible to defer investments and thus to discount their negative impact on present values, or to avoid investments altogether if future circumstances turn out to be unfavorable for expansion. If it is possible to expand both when and how necessary, then it is possible to avoid creating an initial project that embodies the capability to meet possible future “needs” -- that may not ultimately be required.

Flexibility is thus valuable for all kinds of projects in which the designers can influence the size and timing of projects. It adds value to all kinds of large-scale infrastructure projects, such as highways (de Neufville et al, 2008), railroads (Petkova, 2007), airports (Chambers, 2007) and communications networks (de Weck et al, 2004; Hassan and de Neufville, 2006). Equally, it applies to projects in many different areas, such as the extractive industries (Bababidje, 2007), manufacturing and product platforms (Suh and de Weck, 2007), and hospital services (Lee, 2007, de Neufville et al, 2008). As shorthand for this range of interest, we usually refer to flexibility in system design.

Creating flexibility in design is equivalent to creating real options. For example, designing an aircraft so that the fuselage can easily be stretched to accommodate more passengers or cargo gives the manufacturer the “right, but not the obligation” to produce larger models. However, these options created in the design of the system differ from real options as commonly understood.

We refer to options that involve design features as “real options **in** systems” to distinguish them from real options that treat the technology as a ‘black box’ and that can be thought of as “real options **on** systems” (Wang, 2005). The option to acquire or open a mine, for example, does not involve any design issues. Most of the literature on real options refers to those "**on**” systems. The distinction between options “**on**” and “**in**” systems has important conceptual and analytic consequences, as discussed below.

**Real Options “in” System Design: A Paradigm Change**

It is important to understand that the explicit consideration of flexibility in system design represents a considerable departure from current engineering practice. Although designers often promote the idea of flexibility, the fact is that the recognition of the need for and value of flexibility in design represents a paradigm change for many practitioners.

The focus on flexibility in system design represents a paradigm change because it presumes that the major requirements of the system are – at least partially - unknown, indeed, unknowable in advance. The rationale for flexibility in design, for options in general, is precisely that the future is uncertain and that there is value in having the “right, but not the obligation” to react to future developments. The options to exit from a bad situation, or to take advantage of new opportunities, only make sense to the extent that one recognizes in advance that such situations may occur. However, the practice of engineering design routinely assumes that unknowable future uses of the system can and are in fact known! To shift from the assumption that major design factors are known, to the reality that they are not, may entail a difficult conceptual and organizational break.

The empirical fact is that the design of important engineering systems routinely proceeds on the basis of fixed assumptions. For example:

- The design of the $5 billion Iridium system of communication satellites was based on the assumption made around 1990 that the system would have a subscriber base of 3 million customers once deployed in 1998. This was done despite the reality that the future demand for a new technology a decade hence is highly uncertain – and in this case the customer base at the time of bankruptcy of the system was only about 50,000. (de Weck et al, 2004)
- It is common practice in the extractive industries (petroleum and mining) to assume that the future price of the output product is fixed. Thus Codelco, the Chilean national copper company, assumed a

long-term price for copper of about $1 a pound, when the actual price had fluctuated between $ 0.70 and $ 4.00 a pound within the previous 5 years (de Neufville, 2006). Likewise, the major oil companies were in 2007 basing investment decisions on the notion that future prices were fixed at about $35 a barrel (the exact assumed amount varies between companies and is highly confidential) in the context of actual prices varying by over a factor of 2 either way.

- The design of US military systems is typically based on “requirements”, despite the continuing experience that the actual role of military systems once deployed often differs greatly from that originally anticipated (Bartolomei, 2007).

The engineering tradition of assuming that major design requirements can be known appears to have evolved from two complementary forces:

1. The notion that many important drivers of value – such as the demand for satellite communications services or the future price of oil or copper – are social factors outside of the purview of engineering; and.
2. The very complexity of design, which impels designers to make simplifying assumptions, to be able to execute the kind of detailed design which they ultimately have to make in order to ensure technical feasibility.

It certainly is true that in the extractive industries the financial sides of companies insist on setting the price of the product (oil, copper, etc) that designers will use when they evaluate alternative designs. An important rationale for this approach is to establish a level playing field for the promoters of projects throughout the company. The downside of this approach is of course that if you assume that the price of oil will be $35 a barrel for the life of the project; you will not make any provisions for extracting oil from fields that only make sense when the price is higher than $35 a barrel, such as the $100 price reached in 2008. By making such deterministic assumptions one may thus leave considerable value unexploited.

In any case, the practice of disregarding variability in future prices of products is firmly embedded in many corporate cultures. Many engineers feel that this situation is in the natural order of things, as they should stick to technology and leave economics to others. Many senior engineers in these companies also consider that it is taboo to consider price variability in design analyses. Even when designers accept the desirability of recognizing the variability of price and exploring how this can lead to improved designs, they face tough organizational battles with the financial side of the company, which naturally does not want to give up the power it has been exercising over the designers.

Purely within the context of engineering practice, moreover, it has traditionally been felt necessary to simplify the design problem by assuming that important parameters are fixed. To appreciate this, consider Figure 1. It first lays out the full scope of what it would take to analyze the entire planning, design, and operational management of a system. A complete examination of all the possibilities would consider:

- all the combinations of the design,
- crossed with all the ways that outside factors (such as price and level of demand) would influence its performance,
- further crossed with all the possible ways that managers might react to situational variations, and
- considering a wide range of metrics of interest to the several stakeholders for the system.

This problem is computationally intractable at present, and will be so for some time to come. For example, if we conservatively assume that the design space for a major system allows for 1,000,000 different combinations of the settings of the design variables, that there are 10,000 different demand scenarios, 100 different decision rules and 10 metrics of interest, then this leads to a combinatorial space of order $O(10^{13})$. In order to make progress, the design problem must be simplified.

Current practice only examines a portion of the total design problem. As Figure 1 indicates, the analysis process:

- typically assumes fixed values for important factors.
- The logic of the situation is then that it considers one implementation plan, and makes no allowance for the reality that the system owners will manage the asset intelligently and react to circumstances as they evolve – an assumption that of course is contrary to what actually happens.
- Finally, this analysis leads to a single cash flow associated with any design and a single set of equivalent measures of the discounted value of that unique cash flow (such as Net Present Value or Internal Rate of Return or Return on Investment).

**[Figures 1 and 2 about here]**

Carrying out this analysis properly in detail for any major system (such as for a fleet of satellites, a hospital or an oil platform) is a major project. Engineers who have spent years on this kind of evaluation are naturally reluctant to consider expanding their large task. Yet the gap between current practice and the reality of system planning, design and management is great, as Figure 2 indicates. Bridging this gap across engineering practice will indeed be a paradigm change in engineering.

**Theme: Focus on Improved Design not on Price of Option**

The root issue in creating a flexible design is to determine which part of the system should be flexible? Which parts should be configured to provide the real options that will give the system managers the "right, but not the obligation" to change the size or function of a system?

Determining where flexibility should be embedded in a design is an immense issue. Even fairly simple systems involve many different elements that could be designed to be adjustable. Consider the design of unmanned aerial vehicles (UAV). These are bigger, more sophisticated versions of radio-controlled model aircraft. They have 6 major parts: the wings, the fuselage, the tail, the motor, the control element and a payload. Flexibility could be designed into each of these elements, and could be useful in different circumstances depending on the future possible use of the UAV. Identifying where to embed flexibility in the UAV is not obvious, and requires careful analysis (Bartolomei, 2007). For larger systems, such as a communications network, an automobile production process, or a refinery, the number of combinations of design parameters can be astronomical. Further complicating the problem, the determination of what real options should be developed requires that we consider how the many possible designs perform under a range of possible scenarios. The total number of possibilities can be staggering. For example, Hassan (2006) estimated that the design space for her very simplified model of the exploitation of an oilfield involved $10^{60}$ possibilities.

The size of the problem involved in determining which real options should be built in has important consequences for the valuation of the options. It means that the valuation process used in this analysis cannot be fully exhaustive and accurate. Refined, final valuations have to be done in a different process.

The logic behind this conclusion is straightforward:

- The size of the problem involved in determining what flexibility should be involved in a design is so large that
- simplified methods need to be used in order to explore the possibilities, and
- thus the associated estimates of the value of the possible design cannot be expected to be precise – they are indicative, they represent a sample taken from a larger set, they are not final.

It is to be stressed that the analysis to determine design flexibility is aimed at only the upfront stage of the design process. Indeed, the process of identifying the design elements whose flexibility most strongly increases expected value is not the same as the process of designing the system in detail. On the contrary, the overall design process inherently involves 2 stages:

1. Some process for defining candidate overall configurations of the system and the extent and nature of their design flexibility. This stage is typically referred to as "conceptual design" or "systems architecting"; and then
2. Detailed analyses of these architectures to determine their exact designs and to evaluate them in detail to select one for implementation. This is the "detailed design" or "define" stage.

An example illustrates the point. In designing parking garages for a growing area, a critical question is: How many levels should it have? An analysis of design flexibility for a particular location – only possible using an approximate model of the construction costs and prospective revenues – indicates convincingly that it is desirable to have the flexibility to increase the number of floors, in case demand grows to justify them. The flexible design in this case increases expected value by about 25%, reduces initial capital expenditures by about 20%, and both reduces the value-at-risk and increases the maximum possible benefits (de Neufville et al, 2006). The valuation process used was crude, but sufficient to produce the result. The numbers generated to achieve this useful result are not however sufficient to provide the kind of refined, final valuation that will ultimately be needed to justify the financing of the project.

In short, the role and tasks of system designers are different from those of financial and real options analysts. Systems designers identify which architectures offer the greatest possibilities and can use simple, approximate valuations to achieve good results. This phase defines a few possible designs with varying degrees of flexibility (real options content). Economic analysts justifying budget allocations to a final design need the much more detailed designs developed from the optimal overall architectures.

Overall, as the two preceding sections indicate, this work on design flexibility lies between

- financial real options analysis -- which does not deal with system design; and
- standard engineering practice -- which does not deal systematically with design flexibility.

As a practical matter, dealing effectively with design flexibility involves a much larger view of the design process, but a simplified, more approximate take on the valuation of the options.

### Identifying the Best Opportunities for Flexibility

The identification of the best opportunities for flexibility requires us to apply new measures of value. Just as the work is situated between standard engineering practice and financial real options analysis, so must our metrics be. Thus:

- From the perspective of standard engineering, the metrics need to reflect the reality that future performance is a distribution of possibilities, and cannot be fairly encapsulated by any single deterministic measure such a Net Present Value;
- From the perspective of financial real options analysis, it is unrealistic to assume that the measures of value that can be generated from analysis of a design can in any way reflect a proper risk-balanced market price, enforced by the possibility of arbitrage pricing.

In short, our measures of value need to be more complete than those commonly used in engineering, and more practical, less theoretical than those appropriate to sophisticated options analysis rooted in the financial derivative markets.

Once we recognize that there is uncertainty and a distribution of possibilities, it is no longer meaningful to think of a deterministic measure of the discounted cash flow or value of a system, such as Net Present Value (NPV). At the very least, we need to consider some comprehensive view of the possible values associated with a design. The Expected Net Present Value (ENPV) is the more obvious of the possible summary measures, and probably the easiest to understand. As the name implies, the ENPV is simply the average discounted value of a design.

A single measure is not enough however. It is easy to imagine two sets of distributions that share one measure but differ markedly from each other. For example, two distributions might have the same

ENPV, but one could have a much narrower standard deviation. A person or organization might then prefer the distribution with the narrower distribution – and less risk. Thus, a single measure does not fully inform the decision-making process.

Nor can we reasonably argue that one measure is necessarily better than others. Although it might be tempting to think of ENPV as the primary measure of value – by analogy with NPV -- it could easily be misleading. Decision-makers might prefer a design with a smaller standard deviation (taking it to be less risky) even though it has a lower ENPV. In short, we need to think of various ways to consider the whole distribution of possible outcomes.

The Value-and-Risk-and-Gain (VARG) diagram is a convenient way to display the distribution of possible results. It graphs the cumulative value associated with any possible design. It builds upon the Value-at-Risk (VAR) concept used by bankers to identify the risk of the losses they might incur. As might be expected, lenders focus on the likelihood that they might not recover their loans. Investors, however, are concerned not only with possible losses but also and most importantly with the amounts they might gain. Thus the VARG curve displays the entire range, as Hassan et al (2006) indicate.

**[Figures 3 and 4 about here]**

We arrive at the VARG in two steps:

1. For each potential design (with or without embedded flexibility), uncertain future scenario and managerial decision making we evaluate the outcomes over time. If our metric is profits, we consider possible future cash flow, as in Figure 3, and develop a Net Present Value (NPV).
2. We then consider the distribution of possible scenarios, each representing different demands scenario and managerial responses, to obtain a distribution of NPVs. This is conventionally shown in the form of a cumulative distribution function as in Figure. 4.

Many metrics can be read from a VARG curve. The ones that seem most useful to decision-makers are the expected NPV (EPNV), and the maximum and minimum results. It is also possible to calculate the standard deviation (SNPV) which measures the spread of the distribution. Many designers use this measure to calculate the “robustness” of a system, that is, the degree to which its performance is affected by uncertainties. In some cases (such as the tuning of a radio) this is a good feature. In general, however managers prefer designs skewed towards upside gains, thus with high upside spreads.

Initial CAPEX (Capital Expenditure) is another useful measure of performance in addition to the ENPV and the VARG. Initial CAPEX is a particularly interesting metric because it is often a main element distinguishing a conventional inflexible design and one with options. This is because designs with options are generally staged (representing an initial implementation followed by later stages in which options are possibly implemented). Staged developments correspondingly are cheaper initially than conventional designs, because they defer some build-outs until future events demonstrate the need for expansion. As can easily be appreciated, a design with a lower level of Initial CAPEX leads to higher returns on investment for the same amount of EPNV as a design with a higher Initial CAPEX. Thus, the level of Initial CAPEX is often a primary distinction between designs with various levels or forms of flexibility.

Decision-makers may be interested in the probability of levels of Minimum and Maximum returns from a project. For example, one might want to know the possible downside with a 10% chance of occurrence, which is known as the “10% the Value at Risk” (VAR). In Figure 4 this is -90 million dollars. Conversely, one might focus on the upside potential or “Value at Gain” (VAG). For example, the 10% VAG (corresponding to the complementary 90% VAR) is read at 90% level of the vertical axis. In Figure 4 there is thus a 10% chance that the gains from the system will be greater than 290 million dollars,

Other measures are also possible. The important point is that once we deal with distributions of outcomes, we need a range of measures of the value that a system may deliver. As indicated in the case study presented in Part 2, a combination of graphs and tables provides a convenient way to represent the measures of value for system with various degrees of flexibility and to identify those that should be examined in detail.

Overall, we use the VARG graphs, complemented by a table summarizing the several metrics of value, to help identify which design architectures are most attractive for detailed design. When higher values are toward the right, as in Figure 4, then configurations with curves and ENPV toward the right are better. The better alternative is obvious if its curve lies entirely to the right of another. In general however, tradeoffs have to be made as it is rare that one design absolutely dominates all others.

A key point is that as system designers we have the ability to improve designs that have uncertain outcomes. We do this by shifting the VARG curves to the right as much as possible. By intelligently screening for, designing in and exercising flexibility in the form of real options throughout a system’s lifecycle we may in fact "design" or at least influence the shape of the NPV distributions given a set of exogenous uncertainties. We do this typically by two complementary types of actions: one set reduces the downside tail (acting as "puts" for the system), and the other set extends the upside tail (acting as "calls"). Overall, we want to make the Expected Net Present Value higher.

## PART 2: USING SCREENING MODELS TO IDENTIFY VALUABLE FLEXIBILITY

### Analytic Approach: Screening Models

A proper search for the best configuration of a system cannot be done in great detail. Explicitly or implicitly, the investigation needs to consider many thousands of possibilities, as Figure 1 suggests. Whether the focus is on a network of communications satellites, a deep-water platform for exploiting petroleum reservoirs or on a hospital, the range of possible design elements and the way they can be combined is very large.

The standard engineering approach to design focuses on the detailed definition of the possibilities. This is natural, since the engineering team ultimately has to specify the design in great detail. The design process thus revolves around one or more very detailed – "high fidelity" – models of the technical aspects of the systems. Using these high-fidelity models to create a single design can easily take months – a single run of a detailed model of a system may take a day or more.

It is simply not practical to use fully detailed, high-fidelity models to determine the best configuration of a system in the context of major uncertainties. Any proper analysis of possible scenarios necessitates the examination of a large number of possible designs: 500 is a standard number at present. Exploratory analyses of alternative configurations for a system cannot afford to carry out 500 trials that each take a day or a week.

To conduct a proper search for the best configuration of a system, it is necessary to use models that can be run very much faster than the detailed, high-fidelity models. To achieve this speed, it is necessary to sacrifice some of the detail. As Figure 5 suggests, the analysis needs to trade details for speed. As indicated in the case study presented later on, it is frequently possible to define reasonable mid-fidelity models of a system that run on the order of a 1000 times faster than the completely detailed high-fidelity models. Correspondingly, this permits the consideration of about a 1000 cases instead of just one within the same time.

**[Figure 5 about here]**

Mid-fidelity models used for the rapid exploration of a complex system are known as "screening models". The name indicates their use. Screening models examine many different designs to identify – to screen out – the smaller number that deserve detailed configuration. Screening models have long been used in system design. They became common shortly after optimization techniques first became prevalent in the design of infrastructure systems. Jacoby and Loucks (1972) provide a classic example of the use of screening models, and de Neufville and Marks (1974) compile others. Wang and de Neufville (2005, 2006) extended the use of screening models to the analysis of flexibility in systems design.

Screening models identify system configurations that are most worthy of detailed analysis and evaluation. They are properly used in early parts of the analysis, as Figure 6 suggests. Screening models enable the designers to sort through the universe of possible system architectures rapidly, and to define top designs.

Screening models provide an analytic process for determining which system configurations are potentially most valuable. They complement the often intuitive ways that engineers now use to fix on the architectures they will examine in detail. Indeed, it is often the case that the design team fixes on possible system architectures based on the intuition or experience of the lead engineers, on what some competitors have recently done, or on what it perceives to be good practice. Screening models provide a much more rigorous, more analytical – and in the end more of an engineering approach -- to the definition of which designs the team should analyze in detail. As Figure 6 suggests, they provide a transition between the large universe of possibilities and the narrow focus on a few possible designs.

Note that the use of screening models does not have to be fully automated. In some cases, the range of designs can be fully described analytically and can be fully explored thought some automated process. Alternatively, as in our case study, the process is hand-tailored by the analyst. In this case, the systems designer – guided by experience, intuition or direction of the client – picks a few trial configurations to be explored and tries them out. The initial results guide the subsequent choice of trial configurations.

Screening models work in combination with detailed design models. Each type fulfills its distinct role. The screening models operate at the first stage of the design process; they identify overall design configurations for detailed design. Complementarily, the detailed design models refine the configurations suggested by the screening models. As such, each type needs to be judged on its own merits for fulfilling its role. The screening models should not be judged on the basis of their deficiencies compared to the detailed models, and vice-versa.

**[Figure 6 about here]**

Screening models need to be judged on the basis of their effectiveness in correctly identifying interesting configurations for detailed consideration. Not just any simplified model constitutes an effective screening model. A priori, it is never obvious which simplifications of the detailed models are appropriate and useful. Proposed screening models need to be validated. Generally speaking, screening models should be accurate enough to properly reflect the *relative* NPV ranking of different designs under uncertainty. Detailed models on the other hand focus on producing answers that are accurate on an *absolute* scale.

**Screening for Real Options**

Screening models enable the transition from current practice to a more comprehensive analysis of projects. Because these mid-fidelity models are faster than the high-fidelity models used for design, they reduce the computation effort required for the consideration of the initial design, and allow for a larger analysis of the effect of outside factors, such as variations in the price of or demand for the product. Figure 7 illustrates the possibility.

Of course, we want to make sure that the use of the mid-fidelity models is effective, that is, that they guide us correctly to interesting designs, with a minimum number of false positives. Thus we need to make sure that we test the mid-fidelity models. Most basically, we need to verify that they correctly describe the physical realities, both as regards the detailed elements (the “trees”) but also the overall features, such as the existence and degree of economies of scale (the “forest”). Functionally, we need to see to what extent they correctly rank alternative designs – even when the absolute values they assign to alternatives are approximate.

Using screening models to identify real options is novel. Known previous applications of screening models have assumed that the major specifications for the system were fixed, and the screening models were directed toward breaking down the analysis of the design into computationally manageable bites. The Wang/de Neufville work cited above possibly represents the first application of screening models to the identification and definition of opportunities for flexibility and real options.

The use of screening models for identifying real options requires a major intellectual jump for many engineers. Because options are only valuable when there is uncertainty, the screening models used to identify real options must explore the uncertainties that surround a system, such as the future price or quality of a product, the demand for it compared to new technologies, and the regulatory or political context. The analysis has to consider the distribution of these uncertainties and outcomes. This fact naturally complicates the analysis compared to the conventional deterministic analysis: each run of the model must consider and compare many possible outcomes instead of just one. This complicates the evaluation and comparison of the choices: we require a new set of criteria and procedures for choosing the best designs.

From a purely analytic perspective however, using screening models to identify real options is straightforward. It consists of applying the range of possible outside factors to the screening model, the simpler, mid-fidelity representation of an initial design. This process can be automated by simulating the assumed distributions of the outside factors. Such a simulation is easily implemented as an add-in to a spreadsheet, or can be executed using any of a number of commercial packages, such as Crystal Ball ®.

**[Figure 7 about here]**

**The Example Problem**

The case study presented in this analysis was inspired by the issues concerning the design of deep-sea platforms for the exploitation of oil fields. These are massive, highly expensive long-term projects. The platforms themselves easily cost from $300 million to $1 billion each, even when in relatively easy conditions (such as off-shore of Angola) and easily much more when they have to deal with especially challenging conditions (such as those created by sea ice off of Sakhalin in Russia).

These projects exist in highly uncertain environments. Great uncertainty inevitably surrounds the:

- quantity of oil that may be extracted – this depends on the detailed geological characteristics of the substructure, which will not be fully known until long after the project starts (see Bababidje, 2007) ;
- quality of the oil – that is, the degree of oil and gas, the hydrocarbon composition including sulfur and water contents, etc.; and

- value of the oil to the investor -- determined globally by the highly volatile world markets, and further by the revenue-sharing agreements with the owners of the oil fields. As a matter of record, the price of oil ranged from 15 to over 125$/barrel between 1990 and mid 2008.

Given the great uncertainty inherent in these projects, they are prime candidates for the use of flexibility in design, whose value is greatest when the uncertainties are highest.

### Developing the Screening Model

The designers of oil platforms use highly sophisticated models for each of the major portions of the platform system. Generally, as Figure 8 indicates, systems consist of models of the:

- Inputs – the nature of the oil field;
- Production – the possible physical design of the platform, its wells, and the connections between them; and
- Output, immediately in terms of the oil and gas produced, but most significantly in terms of economic value, which places a premium on immediate gains and discounts future revenues.

Complex feed forward and feedback mechanisms connect these major elements. They relate to the:

- physical flows of materials (oil, gas, water…) going through the system;
- logical flows that capture the control logic that regulate the physical flows, such as the rates, timing, and capacity constraints on physical flows; and
- financial flows, generally driven by the physical flows in terms of revenues, and by the investments and operations in terms of costs.

For example, the design of the production system affects the output, but the output over time defines what kinds of inputs – such as water or gas injections to sustain pressure – will be needed.

The high-fidelity versions of these models are generally distinct and separate. This is because they are usually developed by quite different groups of professionals, ranging from the petroleum geologists who characterize the oil field, through the engineers who design the platform and wells, to the economists who model the financial performance. In the context of high-fidelity design, these models are run separately, and do not exchange data or “talk” to each other each time they are run. This arrangement is quite satisfactory in the context of detailed design.

A screening model must be integrated. It needs to bring together the distinct phases of the detailed design. This is because we will use it to analyze thousands of situations, defined by the crossing of various trial designs with a wide range of possible scenarios. Developing an integrated, mid-fidelity model from the high-fidelity versions thus requires considerable effort – easily on the order of 6 person-months of direct effort.

Screening models also need to be perfected and validated for use without overburdening them with excessive detail. What does and does not represent necessary detail in a screening model is not an easy question to answer. In general, the screening model should include specific factors that may significantly affect the value metrics (such as NPV and VARG elements) and the rank order of the alternative system architectures. But since screening models are needed to produce VARG estimates for designs, there is a chicken-and-egg problem with respect to their fidelity. The issue can be resolved by taking an iterative approach. A screening model will have sufficient fidelity when it meets acceptable criteria, for example when the iterations rank designs (with varying degrees of flexibility) consistently and the VARG estimates stabilize to within 5-10% compared to earlier estimations. The specific details to be included in a screening model will depend on the application.

**[Figure 8 about here]**

Offshore oil and gas projects face both large business risks and significant opportunities. A major source of uncertainty concerns the volumes and composition of the hydrocarbon reservoirs in a field. Another relates to the market environment, particularly the oil and gas prices. Both these internal and external uncertainties have significant impact on the success of projects and need to be taken into account when defining the strategies for developing a project, most specifically by building in the flexibility to deal with the alternative scenarios they may present.

Estimates of the size of an oil field may vary greatly. The oil industry usually defines this in terms of its STOOIP, the stock tank original oil in place. From one perspective, this is a fixed number determined by long-term geologic conditions. However, as a practical matter it is an estimate likely to have a wide distribution. The STOOIP for a field normally changes considerably over the life of a project, as further exploration and then exploitation of the field proceeds, and as more information about its details emerge. Moreover, the estimated STOOIP may not converge to a single number. New discoveries of reservoir conditions, such as its degree of fragmentation, may disruptively change the estimate. As the STOOIP is a main driver of many design decisions, it is very important for decision makers to recognize the Reservoir Uncertainty and take it into account in their design of field development strategies.

As the historical record clearly demonstrates, the demand and prices for crude oil and gas are highly volatile. These variations strongly affect the success of field development and operations. For example, when oil prices and demand are high, early oil to market in the field will take advantage of the favorable market conditions; and thus a flexible design that can rapidly expand the capacity of a platform would be desirable. Decision makers need to consider the Market Uncertainties in defining their strategies for developing oil fields.

**Flexibility in Petroleum Projects**

Real options can be created at three levels of offshore petroleum projects. The flexibility can be:

- inter-facility – considering how the major elements or facilities in a field might be linked. This is the highest level of flexibility, which considers that platforms and major subsurface elements can be added, moved or retired from the field, or new reservoirs are connected to existing facilities over time. This kind of flexibility defines the topology choices between reservoirs and platforms. Typical examples are flexible staged development for a single large oil field or tie-back of a new reservoir to an existing platform.
- intra-facility – applies within one field or one facility. It defines the design options of individual platforms, wells, etc. Examples of such flexibility are adding extra space in the production, drilling or cellar deck allowing later addition of modules, such as the addition of more water injection pumps, compression trains, or the decommissioning of a flare tower once gas export via pipeline to an onshore LNG facility begins
- operational -- does not require changes to the physical system. For example, to achieve higher oil recovery rates from a reservoir, field operators can actively manage production by increasing water and gas injection rates, changing the mix of incoming fluids from different reservoirs, switching between production and injection wells, or temporarily shutting down wells.

**Step-wise Development of the Analysis**

The analysis for the example oil field was carried out in steps, as Figure 9 indicates. This was done to help explain the use and value of screening models to identify opportunities to improve the design of the oil platforms significantly. Once the use of screening models is widely understood, it will not be necessary to break the analysis out into these steps.

Step (1) represents traditional practice. It applies the screening model to a conventional design that optimizes project value based on a deterministic "best guess" estimation of reservoir volumes and fixed oil and gas prices. It estimates a single Net Present Value (NPV).

Step (2) evaluates the conventional design recognizing both reservoir and market uncertainty. It simulates the joint distribution of these factors and calculates the NPV associated with each sample and then the average or expected net present value, (EPNV). Note carefully that the ENPV in general differs from the deterministic NPV. This is due to Jensen's Inequality (Wikipedia, 2008), which is simply that the value calculated from an expected value of a parameter only exceptionally gives the true value given by the expectation over the possible states:

$$ENPV = EV\,[f\,(x)] \neq f[\,EV(x)] \quad \text{unless all functions are linear}$$

Step (2) presents results both in a table and using the Value-at-Risk-and-Gain (VARG) curve, which gives a more comprehensive evaluation of the project under uncertain factors. This step makes two points:

- Ignoring the distribution of uncertain variables leads to an incorrect assessment of the NPV; and
- A project leads to a distribution of possible outcomes.

Steps (3) and (4) represent the screening model in action. They consider different kinds of flexibility in field development. Each possibility leads to a set of metrics as in Step (2) that can be used to rank the possible developments, most importantly in comparison with the conventional design as evaluated in Step (2). The end result of this process is a short list of the best candidates for detailed design. The process thus identifies the kinds of flexibility – the real options – that seem to improve the overall performance of the design most significantly. This is the objective of the screening process.

### Alternatives Considered

The analysis focused on the concept of modular design, the idea of building a complex system as a series of equal modules. This approach to system design is now being widely developed in the oil and gas industry, where it goes by the name of “Design One, Build Many” (See for example: ExxonMobil 2008; The Peninsula, 2007; Shell, 2008).

The three alternative designs considered were:

1. A big monolithic facility. This represents conventional design – a facility optimized to deal with the best estimates of the size of the field and predefined oil prices. Due to economies of scale, this strategy might gain benefits due to big batch size orders of equipment and facilities from supplier. However, this design might lead to oversized capacity if the reservoir and market conditions were not favorable.

2. Pre-determined staged development: This strategy develops the facility in pre-determined stages over time. One advantage of this strategy is that following stages can benefit from learning. Another is that major capital investments are phased over time

3. Flexible staged development: This strategy allows the number and timing of stages to be flexible. The number of stages depends on the time-varying estimate of STOOIP. To analyze this case it is necessary to posit a decision rule, that is, criteria that determine the timing and size of additional stages.

**[Figure 9 about here]**

**Example Calculations**

The analysis evaluated the three field development strategies under reservoir uncertainty. It used hypothetical but generally representative numbers. The results are purely illustrative. A Monte Carlo simulation of 600 samples represented the distribution of the STOOIP. Using a mid-fidelity integrated screening model, each run only took about 1.2 seconds. We could thus simulate hundreds of runs quickly. In contrast, the applicable high-fidelity reservoir models can take a couple hours for a single run.

Figure 10 and Table 1 display the simulation results. They illustrate several important conclusions:

- The conventional design has considerable risks. It is attractive overall (Expected Net Present Value = $6.15 billion). However, it has considerable downside risk if the quantity of oil and gas is low (Minimum NPV ~ $1.3 billion loss). Moreover, it is limited on the upside in that it cannot expand capacity should this be desirable. Thus, the conventional design is neither protected on the downside nor can seize upside opportunities.

**[Figure 10 and Table 1 about here]**

- The inflexible staged development has no overall benefit in this example. It reduces the present value of costs by deferring some investments and incorporating learning into subsequent stages. However, it increases costs by foregoing the economies of scale associated with a single large facility. Moreover, by postponing investments it also delays revenues and thus their present value. The overall effect in this hypothetical case is to reduce the expected net present value. Such an alternative offering no additional value should be "screened out" of further consideration.

- The flexible staged strategy offers significant improvements in this case. Because it only adds stages when the STOOIP is proven, it avoids potentially big loses. Thus its minimum Net Present Value is much greater than that of a single monolithic facility. As it can be expanded beyond the capability of the single large facility, it can accelerate the recovery of revenues and achieve much higher Net Present Values if the amount of oil is particularly high. These effects combine to create an Expected Net Present Value of $ 7.86 billion or over 25% better than the conventional design. This strategy should thus be retained for detailed analysis.

Overall, this analysis supports the "Design One, Build Many" strategy promoted by some companies.

The display of the several metrics (Table 1) and the Value-at-Risk-and-Gain curves (Figure 10) provide interesting insights into the benefits of suitable flexibility:

- They display the significant gains to be obtained by being ready to take advantage of upside opportunities. The flexible staged approach makes it possible to achieve great returns in this particular example – more than double the average value of the conventional design – under favorable circumstances.

- Conversely, as especially obvious in Table 1 but masked in the VARG graph, the flexible staged design avoids downside losses. This full implementation of this project can be stopped under unfavorable circumstances, and the potential $1.77 billion loss of the conventional design is essentially avoided.

- The flexible staged design essentially more than doubles the rate of return, in that it only requires an initial investment of $1.38 billion to get an ENPV of $ 7.86 billion, whereas the conventional design requires a more than double up front commitment of $ 3.12 billion to obtain a lower overall ENPV of only $ 6.15 billion.

In short, the example analysis shows how using a screening model can identify design flexibility – real options embedded in the design – that can significantly improve the expected value of the project. The example shows the principle – it does not pretend to have considered anywhere near all the possibilities for flexible design, and thus does not pretend to have identified the absolute best.

Further, the example shows that even a relatively simple first pass analysis that recognizes uncertainty can lead to flexible designs that offer impressive – in this case more than 25% -- improvements in value over conventional approaches.

**Summary and Future Work**

This chapter focuses on the development of valuable flexibility in designs. It is part of a growing field of practice that promises – and so far demonstrates – great potential for significantly improving design practice. To give it a name, it is about “flexibility or real options **in** systems”.

Conceptually and professionally, this work lies midway between standard engineering (which does not consider design flexibility in any detail) and financial real options analysis (which does not look at design). This position requires a consider professional jump for engineering practitioners on the one hand – who need to engage explicitly with uncertainties in the design requirements; and for economic analysts – who correspondingly need to consider a broader measures of valuation metrics in this context and need to work more closely with their engineering counterparts.

The chapter specifically presents the “screening model” approach to the core problem of identifying the system elements that should be flexible in order to increase value. Screening models are mid-fidelity models that run much faster than standard detailed design models. They can examine the performance of many designs across great ranges of scenarios, and can thus identify system architectures that are most attractive as prospects for detailed design.

The case study illustrating the use of screening models to identify desirable flexible designs also suggests how these can be enormously valuable. In this case, the possible increase in Expected Net Present Value is about 25%! This benefit is furthermore accompanied by a decrease in the risk of losses, and increase in the possible gains!! It furthermore reduces the initial CAPEX investment, and thus substantially boosts the return on this investment!!!

A case study also suggests two areas of future work:

1. It is important to develop criteria for the scope and level of detail in the screening model required to produce reliable results. What level of detail should be included in the different input, output and production system components of the screening model? How should it account for the various economic feed-forward and feedback mechanisms? These can be significant as experience between 2006 and 2008 indicated. As the oil price jumped (from $30 to over $100 per barrel), so did the costs of raw materials, equipment and contractor services. The cost of drilling wells more than doubled. Feedback between oil price and the cost of contractor services and equipment eventually impacts the capital and operating expenditures. When such phenomena affect the rank order of alternative designs they should be included in the screening model. The issues of concerning the fidelity of screening models need to be formalized in the future.

2. We also need to deepen our understanding of how and why changes to existing engineering systems happen. How are changes initiated and how do they propagate through the system and cause other "knock-on" changes (Giffin et al. 2007)? The case study assumed that managers would be entirely "locked in" to the single facility even if the amount of oil was much larger than anticipated. In reality, this is not so. At some point, managers would expand the monolithic platform, albeit in a reactive mode – slower and more expensive than if the possibility of expansion had been designed into the system. A more refined screening model may therefore include the possibility and cost of making such reactive changes and might consist of an ensemble of discrete change cost reducers (Silver and de Weck 2007). Since designers and engineers are intimately familiar with the need and difficulty of making changes to their configurations, this interpretation of real options may help to further anchor the concept of flexibility in system design in modern engineering practice.

**ACKNOWLEDGEMENTS**

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## LIST OF TABLE AND FIGURE CAPTIONS

| Situation | Initial Design | Outside Factors | Managers Adjust | Metrics Used |
|---|---|---|---|---|
| Complete Process for Development of a Complex System | Physical infrastructure<br><br>(Many possibilities) | Price, demand for services<br><br>(Many possibilities) | Best use of existing facilities; development of additional facilities<br><br>(Many possibilities) | Net Present Value, Rate of Return, Initial Capital Expenditure, etc.<br><br>(Many possibilities) |
| Current Practice | Physical infrastructure<br><br>(A few possibilities) | Price, demand for services<br><br>(1 value for each) | Best use of existing facilities; development of additional facilities<br><br>(1 plan) | Net Present Value, Rate of Return, etc.<br><br>(1 Cash Flow) |

**Fig. 1: Detailed Contrast between Real Situation and Current Design Practice**

| | Initial Design | Outside Factors | Managers Adjust | Performance |
|---|---|---|---|---|
| Actual Situation | Many possibilities | Many possibilities | Many possibilities | Many possibilities |
| Current Practice | A few possibilities | 1 value for each | 1 plan | 1 Cash Flow |

**Fig. 2: Summary Contrast between Real Situation and Current Design Practice**

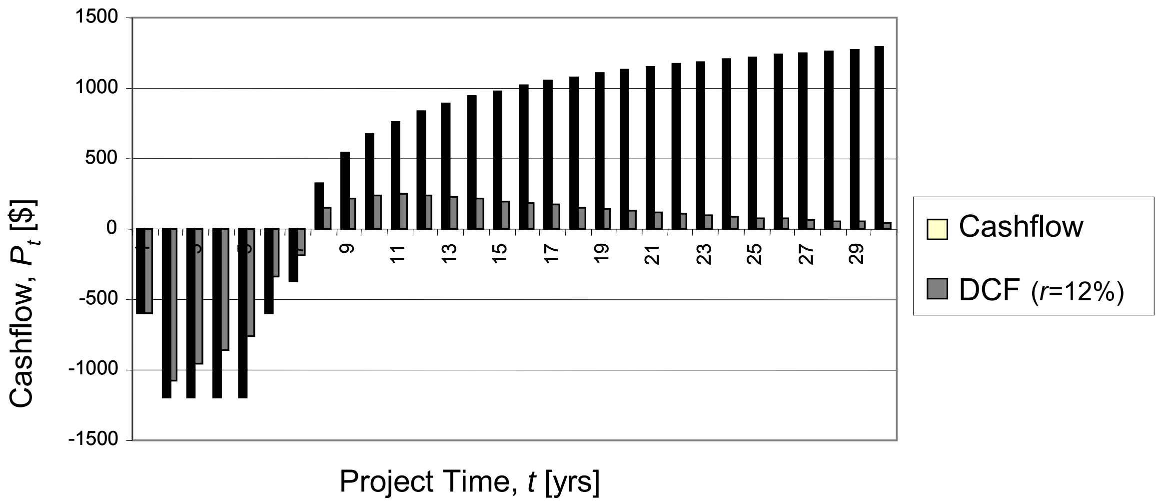


**Fig. 3: Cash Flow and Discounted Cash Flow for a Hypothetical 30 Year Project**

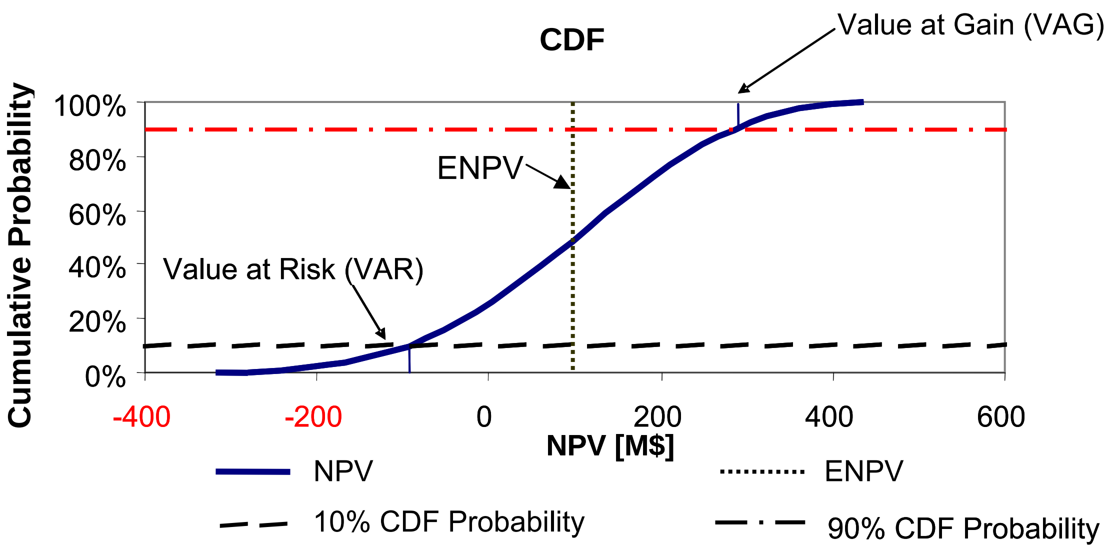


**Fig. 4: Value at Risk and Gain (VARG) curves a hypothetical project**

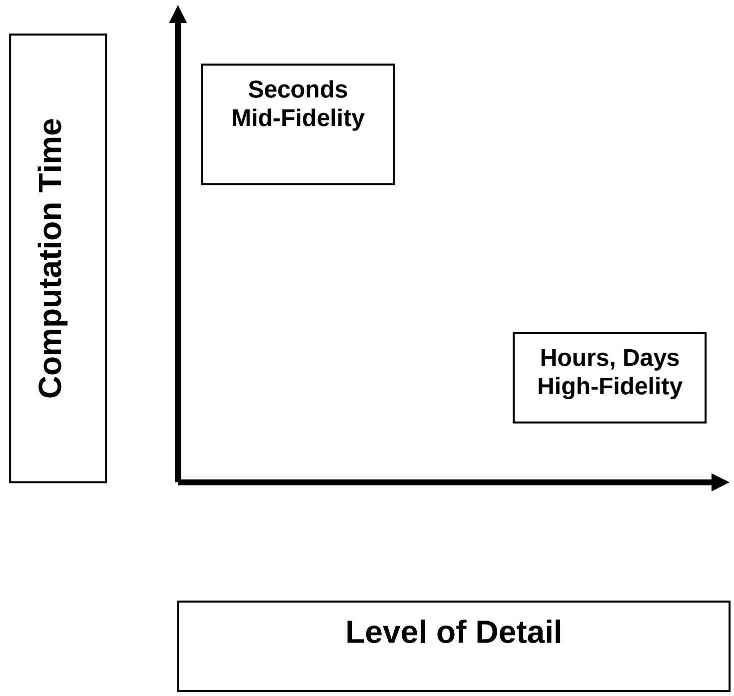


**Fig. 5: Trade-off between High-Fidelity Models taking days or weeks to run, and Mid-Fidelity Models that run in seconds or a few minutes.**

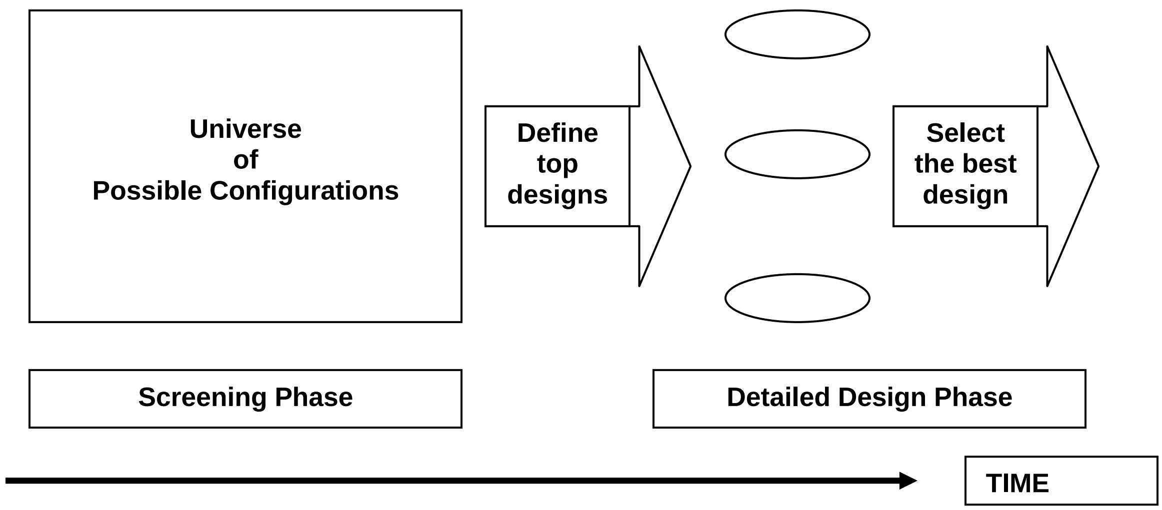


**Fig. 6: Screening Models Help Define Top Designs for Detailed Analysis and Design**

| | Initial Design | Outside Factors | Managers Adjust | Performance |
|---|---|---|---|---|
| Actual Situation | Many possibilities | Many possibilities | Many possibilities | Many possibilities |
| Using Screening Models | Many possibilities | Some important possibilities | Some possibilities | Many Cash Flows |
| Current Practice | A few possibilities | 1 value for each | 1 plan | 1 Cash Flow |

**Fig. 7: Contrast between Possibilities Using Screening Models and Current Design Practice**

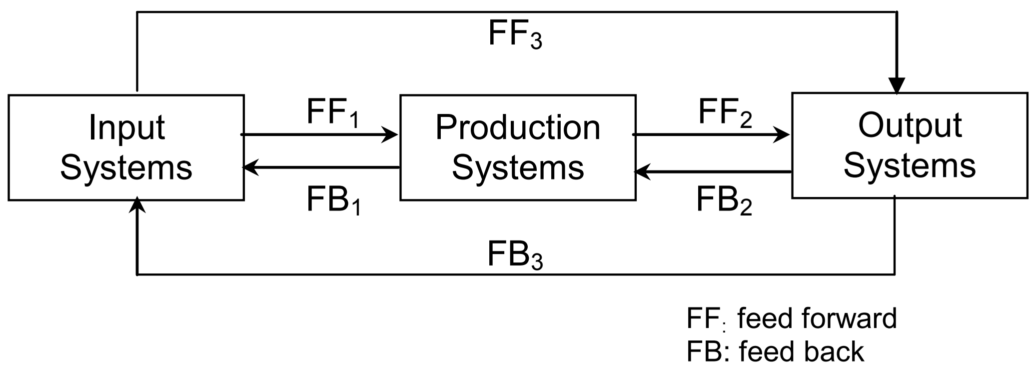


**Fig. 8: A generic integrated systems model of Uncertainty in Petroleum Projects**

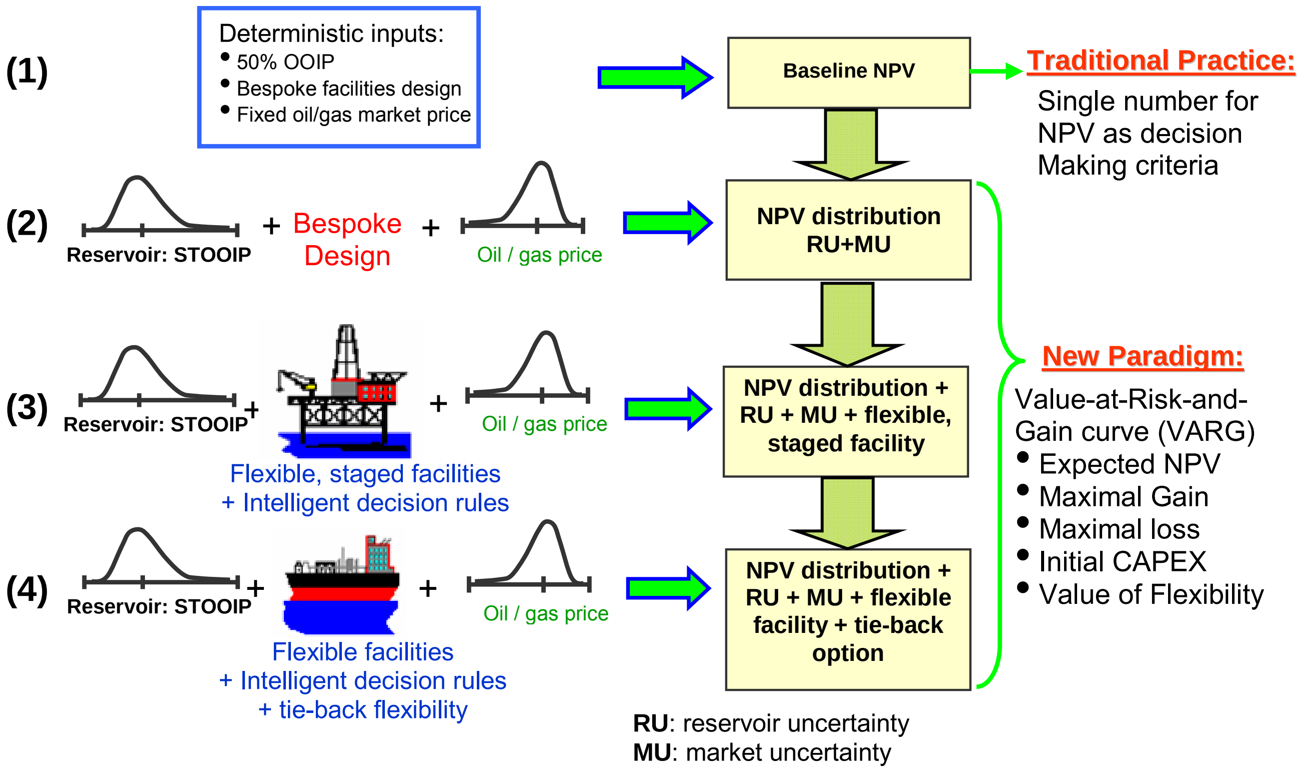


**Fig. 9: Applications of the integrated screening model to oil and gas field development**

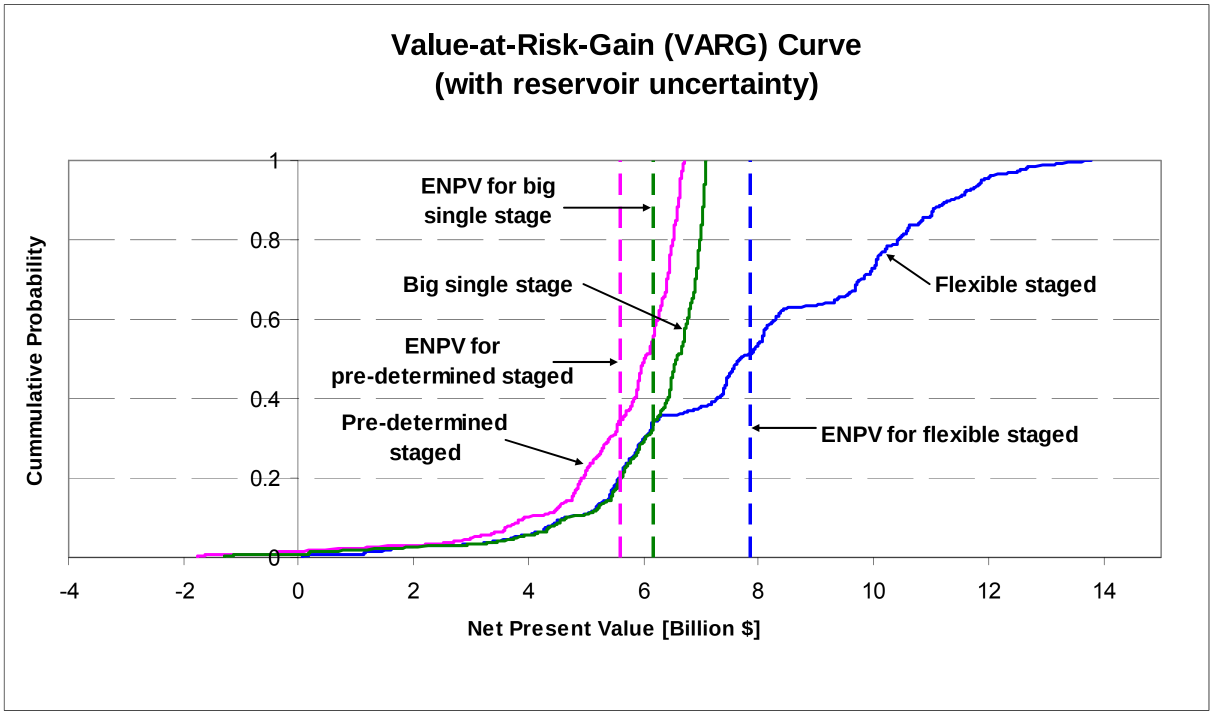


**Fig. 10: Value-at-Risk-and- Gain (VARG) curves for three field development strategies**

**Table 1: Measures of value for development strategies ($, Billions)**

| DEVELOPMENT TYPE | NPV | | | CAPEX | |
|---|---|---|---|---|---|
| | Expected | Minimum | Maximum | Initial | Possible Maximum |
| **Flexible Staged** | 7.86 | 0.05 | 13.87 | 1.38 | 3.08 |
| **Pre-determined Stage** | 5.60 | -1.77 | 6.72 | 1.40 | 1.40 |
| **Big Single Stage** | 6.15 | -1.29 | 7.08 | 3.12 | 3.12 |