Designing Capital-Intensive Systems with Architectural and Operational Flexibility Using a Screening Model

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Abstract. Development of capital intensive systems, such as offshore oil platforms or other industrial infrastructure, generally requires a significant amount of capital investment under various resource, technical, and market uncertainties. It is a very challenging task for development co-owners or joint ventures because important decisions, such as system architectures, have to be made while uncertainty remains high. This paper develops a screening model and a simulation framework to quickly explore the design space for complex engineering systems under uncertainty allowing promising strategies or architectures to be identified. Flexibility in systems' design and operation is proposed as a proactive means to enable systems to adapt to future uncertainty. Architectural and operational flexibility can improve systems' lifecycle value by mitigating downside risks and capturing upside opportunities. In order to effectively explore different flexible strategies addressing a view of uncertainty which changes with time, a computational framework based on Monte Carlo simulation is proposed in this paper. This framework is applied to study flexible development strategies for a representative offshore petroleum project. The complexity of this problem comes from multi-domain uncertainties, large architectural design space, and structure of flexibility decision rules. The results demonstrate that architectural and operational flexibility can significantly improve projects' Expected Net Present Value (ENPV), reduce downside risks, and improve upside gains, compared to adopting an inflexible strategy appropriate to the view of uncertainty at the start of the project. In this particular case study, the most flexible strategy improves ENPV by 85% over an inflexible base case.

Keywords: screening model, capital-intensive systems, uncertainty, architectural flexibility, operational flexibility, Monte Carlo simulation.

1 Introduction

Capital-intensive projects, such as energy and transportation infrastructure, are complex engineering systems. They share similar characteristics which make the design and development planning very challenging.

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- *Long lifecycle*: The lifecycles of these systems (i.e., design, development, operation, and abandonment) easily span several decades.
- *Capital-intensive*: Design and development of these systems require hundreds of millions or billions of dollars of initial investment while future return is uncertain.
- *Evolving internal and external uncertainty*: These systems are being designed, developed, and operated in an uncertain environment (i.e., consumer demand, market conditions). Systems' internal characteristics and performance may also be uncertain over the long lifecycle.
- *Complex interactions among multiple domains*: Design and development of such systems involves multiple domains (i.e., engineering, natural science, economics, and management science) whose complex interactions can lead to unexpected outcomes.
- *Significant economic and societal impacts*: These systems are critical infrastructures whose success has large social and economic impacts due to people, capital, and other resources involved.

The practice of traditional engineering design focuses on optimizing systems' performances given deterministic assumptions of the future environment in which they will be operated. Deterministic optimization often leads to a point solution that is appropriate if the future is relatively stable. However, for capital-intensive systems to be deployed in uncertain environments, the deterministic assumptions for systems' internal and external factors are insufficient over systems' long lifecycle. In certain circumstances, such point-optimal designs without taking into account uncertainty may cause huge financial loss. For example, Iridium and Globalstar pioneered mobile space-based telephony in the late 1990s. Despite extraordinary technical breakthroughs, these systems were commercial failures, respectively resulting in losses of roughly $5 and $3.5 billion [1]. The proximate causes of these failures were deterministic forecasts of market demand (ground-based cellular telephony rose rapidly in the mid 90s) and inflexible system architectures that could not be easily downsized or switched to different types of service or coverage. In summary, traditional optimization-based engineering design approaches can not effectively deal with the challenges in capital-intensive systems' design and development.

In facing design under uncertainty, essentially there are two alternatives: one is *robust design*, which designs systems to perform adequately over a large range of future operating conditions. It is a passive approach desensitizing systems to noisy factors [10]. The other is *flexible design*, which designs systems to be easily be changed to adapt to uncertain future conditions. Flexible design deals proactively with uncertainty.

There is emerging literature on the flexible design and development of capital - intensive systems. A growing body of papers focuses on designing managerial or operational flexibility into infrastructures. de Weck *et al.* [1] propose a flexible staged deployment strategy for constellations of commercial communication satellites under customer demand uncertainty. Hassan *et al.* [2] develop a "Value-at-Risk-Gain (VARG)" approach for evaluating flexibility in architecting a fleet of satellites under demand uncertainty. Wang and de Neufville [3] propose a screening model approach to identify real options "on" engineering systems, and demonstrate the approach through the development of hydropower stations for a river basin. Zhao and Tseng [4] discuss the value of infrastructure expansion flexibility using an example of a parking garage, in which upfront investment on enhanced foundations and columns enables expansion flexibility if future demand for parking increases. Ford *et al.* [5] propose a real options approach for using strategic flexibility to recognize and capture project values hidden in dynamic uncertainty using a toll road project to demonstrate the proposed method. Ajah and Herder [6] propose a six-step process for integrating real options into the design of energy and industrial infrastructure. Lund [7] develops a stochastic dynamic programming model for evaluating flexibility over the lifecycle of offshore petroleum projects.

This paper extends the idea of using a screening model [3] and VARG curves [2] to explore and evaluate different flexibilities under uncertainty. A screening model is an integrated representation of a system at mid-fidelity level. It usually connects the input systems (reservoir), production systems (platforms, wells), and output systems (crude oil /gas export systems) through feedback and feed forward loops, which can take physical, logical, and financial forms. Because it connects sub-domains at mid-fidelity level, it requires much less computational and setup time (seconds or hours respectively) than traditional high-fidelity but disconnected models in each discipline (hours or weeks). A screening model thus enables more efficient exploration of the design space under uncertainty. It needs to include the essential details of a system, and produce a relatively stable ranking order for different strategies or design alternatives. Engineers' experience and quantitative methods (e.g., Design of Experiments for facility modeling) are utilized to determine its essential details. A screening model needs to be calibrated against existing systems or high fidelity models to achieve the errors within ±10%, as a rule of thumb. VARG curves are another important concept in this paper. They are essentially cumulative probability distributions for the NPV of a project. Compared to the "static" discounted cash flow or NPV methods, a VARG curve gives a holistic view of a project's outcomes showing both risks and opportunities. A good strategy or design alternative should "shape" the VARG curve towards favorable directions, such as cutting downside and extending upside tails and thus improving the mean. A VARG curve gives decision makers and system architects a quantitative way to design and compare different strategies under uncertainty. Using these concepts, this paper proposes a computational simulation framework and illustrates it through a case study of flexible development strategies in an offshore petroleum project.

This paper is organized as follows. Section 2 classifies different types of uncertainty and flexibility in capital-intensive systems. Section 3 proposes a generic computational framework for exploring flexibilities under multi-domain uncertainties. Section 4 applies the proposed approach to study flexible field development strategies in an offshore petroleum project. Section 5 concludes this paper.

2 Uncertainty and Flexibility in Capital-Intensive Systems

2.1 Uncertainty in the Lifecycle of Capital-Intensive Systems

Many types of uncertainty influence the technical and economic success of capital-intensive systems over their long lifecycle. In general, these fall into the following three categories:

- *Endogenous uncertainty*: Endogenous uncertainty, such as technical uncertainty, is embedded in systems. Decision makers and system architects can actively direct and manage its evolution by investing in projects, such as reducing subsurface uncertainty by drilling more appraisal wells. Modeling endogenous uncertainty requires domain knowledge. For example, the evolution of hydrocarbon volume estimates is endogenous uncertainty for an offshore petroleum project, and depends on human understanding of geological structures and hydrocarbon characteristics underground.
- *Exogenous uncertainty*: Exogenous uncertainty is independent of technical systems. It is outside the control or direct influence of system architects. Examples include market uncertainty, e.g. commodity prices, market demand. Stochastic models, such as Geometric Brownian Motion (GBM), or lattice models, have been developed to simulate the evolution of exogenous uncertainty.
- *Hybrid uncertainty*: Hybrid uncertainty can be partially influenced by system architects. Examples include development uncertainties, such as cost, schedule, and contracts, which generally depend not only on systems designs and development plans but also on market conditions.

2.2 Flexibility over the Lifecycle of Capital-Intensive Systems

In general, there are two types of flexibility over the lifecycle of systems: architectural and operational. Architectural flexibility is achieved by designs allowing a system's configurations to adapt to future uncertainty with relative ease. Operational flexibility is achieved by designs which enable changes in the mode of operations for systems to maximize value and it does not involve major configuration changes. This section uses the development of an offshore hydrocarbon basin to illustrate these two types. Fig. 1 shows a representation of the architecture of a hydrocarbon basin, where facilities (i.e., production or well platforms) and fields (i.e., hydrocarbon fields) are connected by flowlines for production, injection, service, and export.

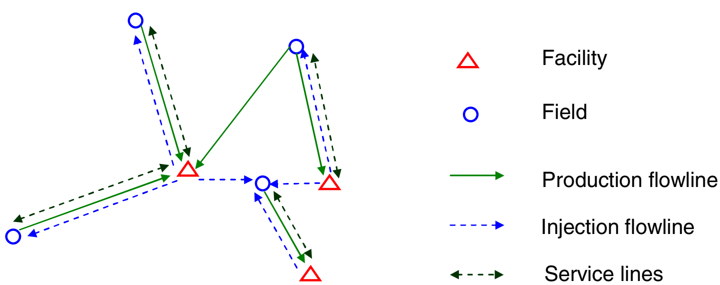

Fig. 1. Network representation for the architecture of a hydrocarbon basin

Architectural flexibility. Architecture flexibility means that it is possible to modify system configurations or layouts. Given the hydrocarbon basin in Figure 1, this is the ability to

- **Add, delete nodes or connections:** These can be easily added and abandoned over the lifecycle of projects. Exercising this type of flexibility changes the physical configurations (i.e., the number of fields developed, facilities and connections) in a hydrocarbon basin.
- **Modify connections among nodes:** To change the fields-facilities connections, such as tieback of a field to a facility using subsea development, as shown in the case study. This flexibility is commonly referred as system reconfigurability.
- **Modify the designs or properties of nodes or connections:** This flexibility changes the properties of nodes or connections in a network but not its configuration. . For example, *Capacity flexibility* allows easy expansion or contraction of the capacity of facilities or flowlines. If it is not initially planned or designed into systems, it may be prohibitively costly to change capacity afterwards. For an offshore oil platform, it may be impossible to add additional processing equipment due to limited space, buoyancy, or insufficient sub-structural support.

Operational flexibility. Operational flexibility allows easy modification of operating strategies without changing the system architecture, configuration or design. It allows, operators to change and fine-tune systems' operations to maximize their value according to current or near-term conditions. Given the long operating stage of capital-intensive projects, operational flexibility can add a lot of value. For example, *capacity allocation flexibility* is an operational flexibility, which allocates production capacity for multiple products or resources to maximize production under uncertainty. In petroleum projects, active reservoir management, such as changing fluid production and injection rates, is one type of operational flexibility.

Architectural flexibility has long term strategic impact. Operational flexibility focuses on near term. Architectural flexibility sometimes enables operational flexibility. For example, in the development of a deepwater hydrocarbon basin, tieback flexibility enables allocation of production capacity among multiple fields.

3 A Computational Framework

To explore flexibility under uncertainty, this paper proposes the computational framework shown in Fig. 2. There are two iteration loops. The outer loop represents a Monte Carlo simulation and each run includes one combinatorial sample from multi-domain uncertainty. The inner loop simulates the development and operation of engineering systems over their lifecycles. A decision making module is built into the inner loop, which observes the evolution of multi-domain uncertainty and then modifies the integrated screening model by exercising pre-defined flexible strategies.

Hence, because the screening models are time-variant, the resource systems and systems designs can be changed over the course of a project's lifecycle. After the completion of the simulation, flexibility strategies and their designs are compared in terms of the probability distributions of technical or economic metrics, such as a Value-at-Risk-Gain (VARG) curve for Net Present Value (NPV).

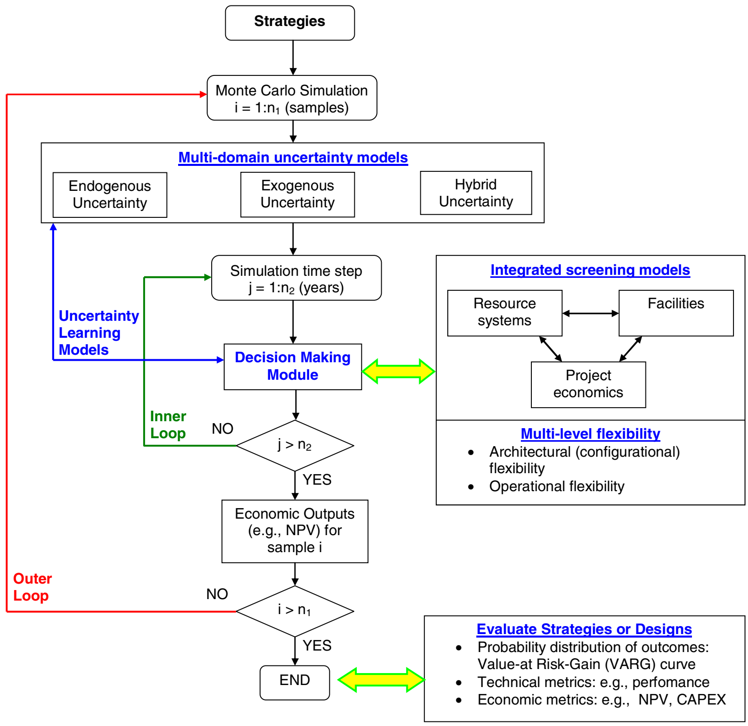

Fig. 2. A computational framework to explore flexibility under multi-domain uncertainty, i= sample in uncertainty space, j= time step index, n_1=number of Monte Carlo samples, n_2= number of total time steps

The key elements of this computational framework include:

- *Multi-domain uncertainty models*: Stochastic models need to be developed for simulating the evolutions of resource, technical and market uncertainty. Monte Carlo simulation samples multi-domain uncertainty, and then simulates different strategies under uncertainties.
- *An integrated screening model*: This is a simple representation of the technical-economic systems. It permits a large number of runs as it requires much less computational effort than high-fidelity models. It is used to select and evaluate promising strategies in the early stages of a project. In general, it connects resource systems, facilities, project economics, and their interactions.
- *Flexible strategies*: Architectural and operational flexibilities are embedded into systems' initial designs so that they can be exercised in the future when conditions are favorable.
- *Decision rules*: Decision rules are a set of heuristics, which set up the conditions for exercising flexibilities. In simulations, the decision rules determine when and how to exercise flexibilities according to unfolding uncertainties.

- *Probabilistic evaluation of strategies*: Value-at-Risk-Gain curves (VARG) are used as a probabilistic evaluation of systems' economic outcomes under multi-domain uncertainty. Statistics, such as projects' Expected NPV (ENPV), maximal NPV, minimal NPV, can be obtained from VARG curves.

4 A Case Study in an Offshore Petroleum Project

This section demonstrates the proposed framework by applying it to the development of an offshore hydrocarbon basin. The case study explores and compares different types of flexibilities during field development.

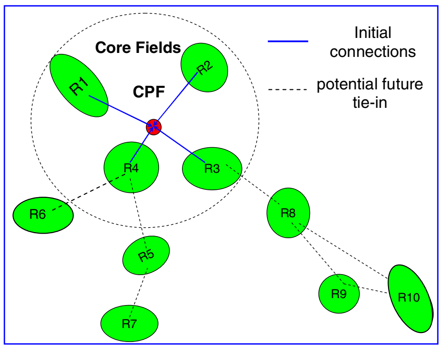

Fig. 3. Field layout for a hydrocarbon basin

The notional layout of a hydrocarbon basin is shown in Figure 3. It involves 10 small fields, some discoveries and some prospects, but none of them is individually large enough to justify the capital investment of a dedicated Central Processing Facility (CPF). Thus, a proposed development concept puts a CPF in the center of several core discoveries (i.e., R1~R4) and connects it to the core and potentially to the tieback fields (i.e., R5~R10) through subsea development. During the early stages of the project, recoverable hydrocarbon and market conditions are uncertain. However, important field development decisions have to be made regarding whether or not to embed flexibilities in systems design. This case study considers three types of flexibility:

- *Tieback flexibility*: This allows connection and exploitation of the other tieback fields through the CPF if the reserves in the core fields turn out to be smaller than initial estimates. Depending how the uncertainty for each tieback field evolves, tieback flexibility will result in different configurations, such as different connection schemes among selected fields and the CPF. It is enabled by initial systems design, such as flexible subsea architectures and production systems on the CPF, which allow connecting fluids from multiple fields.
- *Capacity expansion flexibility*: This is the ability to add production capacity (i.e., add additional decks and equipment) on the CPF to produce more hydrocarbons. It is also enabled by initial designs, such as allocating extra space on the platform or

building a stronger substructure for future expansion. In this study, capacity expansion flexibility is limited to a single expansion by a pre-defined increment.

- *Active Reservoir Management (ARM) flexibility*: With ARM flexibility, field operators can maximize hydrocarbon production rates by actively managing fluid streams from different wells. Allocation schemes may depend on reservoir characteristics (e.g. pressure, fraction of water in the fluids) or facilities (i.e., processing capabilities).

This case study developed an integrated screening model, which interconnects reservoir production, facility design and cost estimates, and project economics. A stochastic model was developed to simulate the evolution of reserve estimates and generate trajectories of reserve estimates over time. Key aspects of the model are:

- It assumes that the reserves estimate for each reservoir follows an independent lognormal distribution at any given point of time.
- The standard deviations (or the range defined by P10 and P90) of these distributions usually decrease exponentially over time.
- The median (or P50) follows a random walk and the magnitude of the random walk step exponentially decreases over time.
- With each successive time step, there is a chance that the median undergoes a disruptive change. The probability of such a change also exponentially decreases with time and when the disruptive change occurs, the standard deviation has a step increase.

The model was developed to reproduce qualitatively the behavior seen in two historical data sets and it has numerous parameters to tune the evolutionary behavior of reserve estimates. Unfortunately we have only located limited actual data [9] and so full validation of the reserve evolution model is not possible. The most important aspect which the model must reproduce is the appreciation factor (the ratio of the reserve estimates at times t and 0). To validate the predicted outcome for this quantity, a comparison between the model results and the data from [9] was made (see Figure 4). This shows that the model, if anything, underestimates the extent of reserves appreciation. To guard against the possibility that initial reserves estimates may now be better than ~20 years ago, the evolution model has been left untuned. It is likely that the properties (e.g. quality or hydrocarbon-water contact) of 10 nearby reservoirs in a basin may be correlated (rather than independent as assumed). As it is extremely difficult to quantify such a correlation, no attempt was made to do so. Ignoring the correlation will tend to decrease the range of basin reserve changes providing another reason why the model might underestimate the extent of reserve appreciation. So long as the model underestimates the reserve change, any benefits attributed to allowing flexibility are also expected to be underestimated.

A decision rule is embedded in the simulation to determine when and how to exercise the three types of flexibility depending on how reserve estimates evolve over time. A detailed description of these models and simulation procedures can be found in [8]. The decision rule is based on current reserve estimates in each individual field and the processing capacity for the topside facilities. In year 0, a CPF with a given processing capacity is developed for the four core fields. Starting from year 3, if the

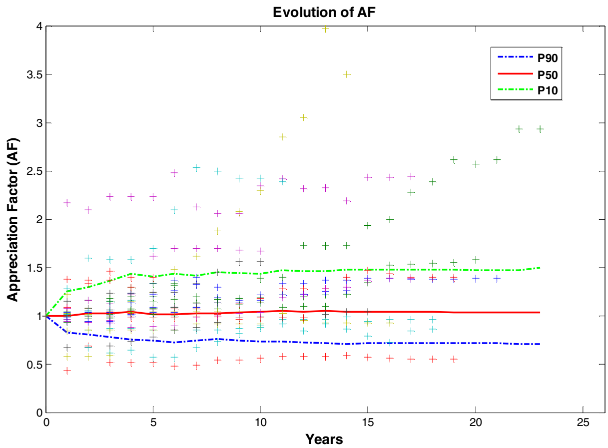

Fig. 4. Comparison of Appreciation Factors: P10, P50, and P90 are based on the simulation results of the reserve evolution model; points (+) are actual data for 126 North Sea fields [9]

total reserves of the core fields are lower than a certain threshold, other fields will be tied back. The decision rule selects the field with minimal development cost (per unit reserve) for tieback. When the total reserve of core fields and tieback fields exceeds a certain threshold, the decision rule exercises the defined processing capacity expansion increment. A capacity allocation subroutine determines how to allocate the platform capacity if potential production exceeds it. As a result, the actual timing and sequence of tieback also depends on platform capacity and different capacity allocation schemes. At each year, the reserve estimates are updated based on the evolution model. In order to allow flexibility options to be exercised, an up-front additional CAPEX is incurred which is assumed to be 10% of the CAPEX for the inflexible development.

A full factorial experimental design was used to study the effects of different flexibilities. Three types of flexibility, each either enabled (Y) or disabled (N), result in a total of eight strategies as shown in Table 1.

Table 1. Full Factorial Design of Experiments for Development Strategies

Strategy ID:	Tieback flexibility (Y/N)	Capacity expansion flexibility (Y/N)	ARM flexibility (Y/N)
Strategy 1	N	N	N
Strategy 2	N	N	Y
Strategy 3	N	Y	N
Strategy 4	N	Y	Y
Strategy 5	Y	N	N
Strategy 6	Y	N	Y
Strategy 7	Y	Y	N
Strategy 8	Y	Y	Y

For each strategy, two hundred Monte Carlo runs were performed with samples from the reservoir uncertainty model. The economic outcome (i.e., NPV) of each strategy is sorted and plotted as a cumulative probability distribution curve (or VARG curve). Figure 5 shows the VARG curves for the eight strategies. Table 2 shows the statistics for NPV and CAPEX. From Figure 5, we can see that the most flexible strategy (i.e., strategy 8 with all three types of flexibility enabled) significantly improves expected NPV, reduces downside risk, and extends upside gain.

Therefore, strategy 8 appears to be the best strategy among eight alternatives given the assumptions of the model. Compared to strategy 1 (without any flexibility), the three types of flexibility in strategy 8 improve the project's ENPV by 85%. From Table 2, we also find that the flexibility strategies do not require significant upfront investment (initial CAPEX only increases from 64% to 66%).

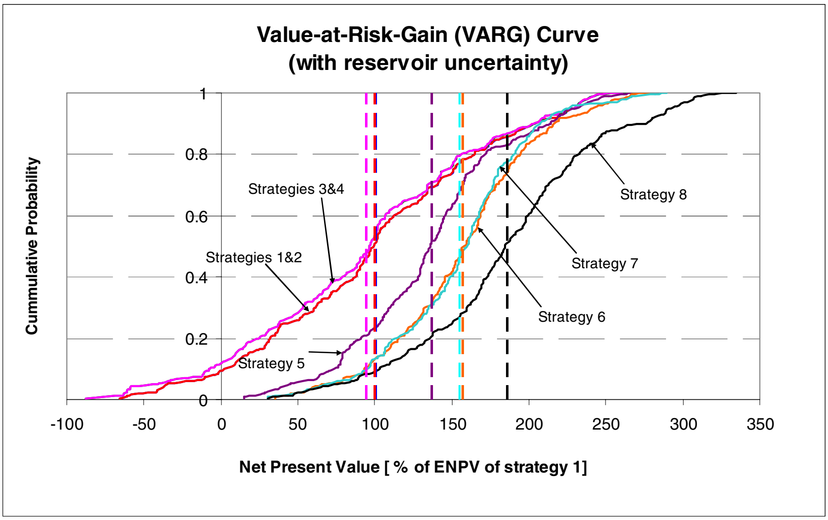

Fig. 5. VARG curves for eight strategies

Table 2. NPV and CAPEX statistics for eight strategies

	NPV (% of the ENPV for strategy 1)				CAPEX (% of the expected CAPEX for strategy 1)			
	ENPV	Min	Max	σ(NPV)	Expected	Min	Max	Initial
Strategy 1	100	-66	252	74	100	100	100	64
Strategy 2	100	-66	255	74	100	100	100	64
Strategy 3	94	-88	263	77	102	100	109	64
Strategy 4	94	-88	261	77	102	100	109	64
Strategy 5	136	15	267	52	137	104	168	66
Strategy 6	157	33	278	48	137	104	168	66
Strategy 7	155	30	289	47	173	136	200	66
Strategy 8	185	30	335	61	173	136	200	66

A regression model for ENPV[1] can be obtained by Design of Experiment (DOE) analysis:

$$ENPV(x_1,\ x_2,\ x_3) = 127.27 + 30.30x_1 + 40.40x_2 + 6.57x_3 + 7.07x_1x_2 + 6.57x_1x_3 + 1.52x_2x_3 \quad (1)$$

Where x_i takes value -1 (no flexibility) or 1 (with flexibility); x_1 tieback flexibility; x_2 : capacity expansion flexibility; x_3 : ARM flexibility. The main effects of the three factors represent the Value of Flexibility (VoF). Figure 6 shows the main effects and interaction effects for the three flexibilities on the project's ENPV.

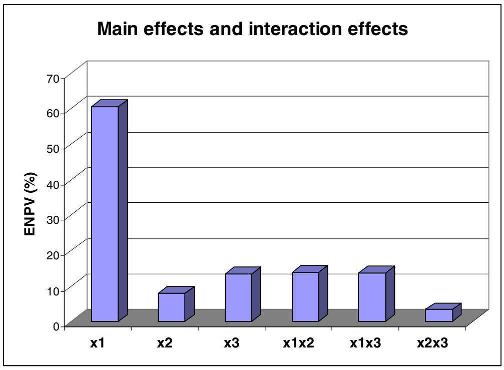

Fig. 6. Main effects and interaction effects of three flexibilities on ENPV

Figure 6, shows that all main effects and interaction effects are positive, which means that all three types of flexibility increase the project's ENPV and the benefits of pairwise combinations are more than additive. Tieback flexibility contributes most to ENPV. On average, tieback flexibility improved the project's ENPV by 60% in this case study. The second most important source of value is operational flexibility.

5 Summary and Discussion

This paper proposes a computational simulation framework to explore different flexibilities in systems' architectural designs and operations under multi-domain uncertainty. The proposed approach has been applied to the development planning of a deepwater hydrocarbon basin. Three types of flexibility: tieback flexibility, capacity expansion flexibility, and ARM flexibility have been studied through DOE analysis based on Monte Carlo simulation results. It has been shown that tieback flexibility significantly improves the project's ENPV under reservoir uncertainty. The proposed computational framework gives decision makers and system architects a formal way to explore different types of flexibility during the early stages of capital-intensive systems' design and development planning. It might be argued that the estimated

[1] ENPV and CAPEX are is normalized against their respective values for strategy 1 and expressed as percentages.

improvement in ENPV is based on an unfair reference case (Strategy 1) in that only the four core fields are developed and so the more flexible cases potentially exploit additional resources. However, as the four core fields are the most promising, it is unlikely that the satellite fields can be economically developed at all except as tiebacks requiring initial up-front investment. Nevertheless, a more rigorous estimate of ENPV improvement could include as part of the reference case the possibility that reserves evolution for R5~R7 or R8~R10 may result in either or both of these clusters being capable of development with a dedicated CPF.

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