Value-at-Risk Analysis for Real Options in Complex Engineered Systems

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Abstract – *This paper presents a simple but powerful Real Options Valuation methodology suitable for valuing flexibility in complex engineered systems. It is based on value-at-risk analysis and relies on a standard discounted cash flow approach. A case study on the architecting of flexible satellite fleets is presented. The architecting framework integrates spacecraft engineering design with economic analysis for the purpose of maximizing the financial value of a fleet to the operator under uncertain, evolving market conditions. The investigation considers the forecasted demand evolution for a satellite service in two distant geographical markets simultaneously and provides flexible fleet architectures that significantly improve various aspects of the value-at-risk distributions compared to those of a traditional, rigid fleet architecture. It is shown that the flexible architectures are able to capture more revenue, mitigate more risk and/or reduce overall required investment. The suggested Real Options "in" the system, rather than "on" the system, approach allows engineers, strategists, or decision makers in engineering establishments to embed flexibility in the design of complex systems for the purpose of maximizing their total lifetime value.*

Keywords: Real Options, Flexibility, Spacecraft Design, Fleet Architecture, Genetic Algorithm.

1 Introduction

The topic of "designing for flexibility in engineering systems" is of much interest at the Engineering Systems Division at MIT. In financial markets, options and derivatives on securities have been adopted as proven mechanisms of coping with uncertainty [1]. A financial option gives its owner the right, but not the obligation, to take a particular course of action in the future, thus provides flexibility in the decision making process with the objective of limiting downside losses while capitalizing on upside potential opportunities. Building on financial options valuation approaches, Real Options Valuation (ROV) has been emerging in the past few years as a set of tools, or perhaps a discipline, that applies ideas from quantitative finance to engineering projects. Real Options analysis is used in strategic planning to cope with uncertainty in engineering projects by embedding flexibility and allowing for adaptive and staged deployment.

This paper presents a transparent ROV approach that is appropriate for engineering applications and use by engineers that are interested in embedding flexibility in the technical design of systems for which the assumptions behind sophisticated and exotic financial options valuation approaches are invalid. Additionally, the suggested approach allows direct comparison between flexible and rigid architectures or system configurations. This value-at-risk analysis-based ROV approach was formulated by de Neufville et al [2] in an effort to propagate systems thinking and flexibility *in* engineering design.

This approach is called "Real Options *in* Systems" to indicate that the approach encourages engineers to explore technical flexibility levers that maximize systems' value as opposed to performing Real Options analysis *on* the system without investigating how to design for flexibility in engineered systems. The value-at-risk ROV approach is described through an application to a case study involving the architecting of flexible satellite fleets and comparing them to a rigid baseline architecture.

2 Case Study: Satellite Fleet Design

This investigation applies value-at-risk analysis to rigid and flexible designs for a satellite fleet. It demonstrates how the analysis both quantifies the value of flexibility and demonstrates how flexible designs manage uncertainty by shifting the distribution of possible outcomes to the right and, most specifically, by slashing the range of possible losses.

Like many complex systems, commercial communication satellites are designed for long lifetimes; in this case, 15 or more years of service. It is difficult to forecast accurately the demand for satellite services. Thus it is also difficult to identify properly a satellite's optimal set of design requirements in terms of geographical coverage, service type and required traffic capacity over this long operational lifetime in order to maximize its profitability. Identification of design requirements is even more problematic because of the evolutionary nature of the demand, i.e. that demand is a function of time and could change rather than remain constant over a satellite lifetime because of demographics, competition from terrestrial services, political, economic or other factors.

When a satellite system is designed to satisfy a rigid set of requirements, i.e. provide a certain service type with a specific bandwidth capacity and geographical coverage, the operator risks large losses if the market the satellite system is designed to serve does not emerge as forecast. On the other hand, if the market under consideration indeed materializes but, for example, ends up requiring more capacity than anticipated, the operator might not be able to capture this additional revenue. Furthermore, when a market is dynamic, i.e. changes over time, ambiguity is encountered in requirement specification as related to the appropriate mix of services and their associated capacity and coverage.

A central question is how to embed architectural flexibility in a communication satellite fleet such that the expected economic value is maximized. In engineering projects, flexibility could be built in via a staged deployment approach; i.e., an architecture could be configured into multiple stages that are built and brought to service over time based on market development. Using staged deployment to design for flexibility in individual commercial communication Geosynchronous spacecraft means that the spacecraft design itself has to be altered over its lifetime to adapt to emerging market conditions. This is especially hard because commercial communication satellites are typically inaccessible after launch.

One solution to provide flexibility is by on-orbit servicing. Researchers [3] have investigated the feasibility of various concepts of doing this. It remains to be seen whether this proves to be economically feasible. Moreover, in order for on-orbit servicing to materialize, some technical challenges must be overcome first, which perhaps classify on-orbit servicing as a possible future solution.

In contrast, the objective of the research presented in this paper is to embed flexibility in the design of commercial communication satellites using "current technology", assuming the unavailability of any kind of on-orbit servicing. This approach provides solutions that could be implemented in the design of today's commercial communication satellite systems. Hassan et al [4, 5] provide more information on the detailed technical implementation of this approach.

The analysis presented in this paper assumes that the impact of design flexibility, which is provided on the spacecraft level, is valued on the fleet level in a system-of-systems (SoS) context. That is, the ability of the spacecraft to provide different and/or similar communication services to multiple disconnected geographical markets at different stages during its lifetime provides flexibility on the operational level of a fleet such that losses could be minimized and revenue could be maximized. In that sense, the framework presented in this paper couples vehicle-centric design and operations-centric (fleet) architecting.

3 Demand Dynamic Uncertainty

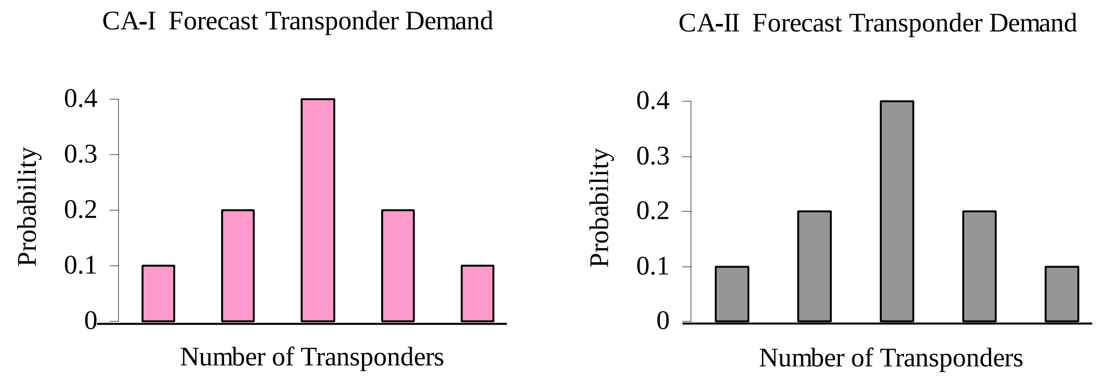
The sample case study considers the demand evolution for a single satellite service in two geographically disconnected regions. This is a Ku-band fixed satellite service. The two regional markets under consideration have coverage area requirements of 40 and 52 deg^2 as viewed from Geosynchronous Earth Orbit (GEO). These coverages define regions with areas similar to those of Continental Europe and Latin America. These areas will be referred to as: Coverage Area I (CA-I) and Coverage Area II (CA-II) respectively. The analysis assumes that the two coverage areas are disconnected and are sufficiently distant that they could only be served from different orbital locations.

The demand in the two regions is assumed to follow the discrete distributions described in Figure 1. A 20 year timeline is considered for the demand distributions and is divided into four five-year stages: the first stage spans year 1 (Y1) to year 5 (Y5); the second stage spans year 6 (Y6) to year 7 (Y7), and so on. The demand in each region or coverage area is assumed to have five discrete possibilities that are referred to as scenarios 1, 2, … 5 ($S_1, S_2, \ldots\ S_5$). The analysis assumes that there is no cross-strapping between the scenarios across the four stages.

Figure 1 shows that the transponder demand is decreasing in CA-I over a period of 20 years while the demand in CA-II is increasing. There are 25 possible scenario combinations of transponder demand levels in the two markets or coverage areas under consideration.

4 Fleet Architecting Framework

The fleet architecting framework is meant to tackle strategic planning problems as exemplified in the challenges presented in the demand evolution section. In its current version, this framework is intended to answer



	S_1	S_2	S_3	S_4	S_5
Y1:Y5	40	50	60	70	80
Y6:Y10	10	20	30	40	50
Y11:Y15	5	10	15	20	25
Y16:Y20	0	0	0	0	0

	S_1	S_2	S_3	S_4	S_5
Y1:Y5	0	0	0	0	0
Y6:Y10	5	10	15	20	25
Y11:Y15	10	20	30	40	50
Y16:Y20	40	50	60	70	80

Figure 1. Forecast transponder demand distributions for a fixed satellite service in two hypothetical markets over 20 years

questions related to the number of satellites in a fleet, satellite payload design as related to demand models, and amount of required payload flexibility. The main building blocks this framework are schematically depicted in Figure 2. The framework is organized to couple economic and technical domains. The economic domain houses the forecasted market demand models for satellite services, which are uncertain and dynamic, and the ROV model, which probabilistically evaluates the Net Present Value (NPV) of a fleet and constructs the value-at-risk cumulative density function of an architecture. The technical domain houses the spacecraft (S/C) sizing and reliability models that are coupled with a Genetic Algorithm (GA), a heuristic optimization approach based on Darwin's Theory of Natural Selection, to find optimal spacecraft designs.

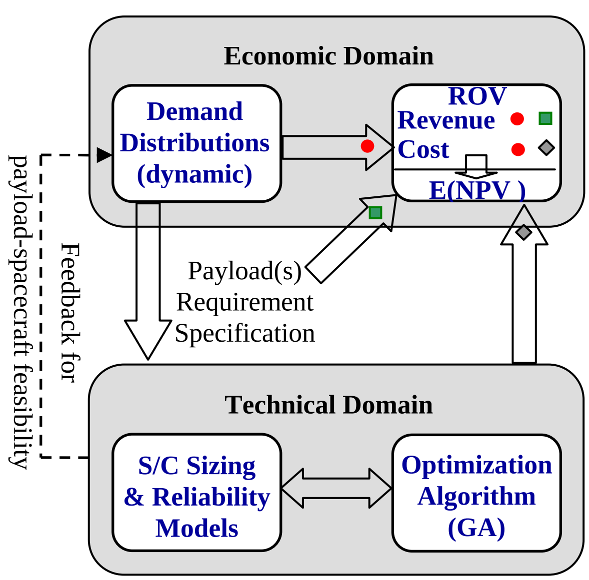


Figure 2. Satellite fleet architecting framework

4.1 Step I: Fleet Architecting Using Demand Models

Fleet architecting starts and ends in the economic domain and constitutes an iterative process between the economic and technical domains. A single iteration starts by investigating the demand models for satellite services over a number of potential geographical markets. A fleet architecture is then generated to satisfy parts of or all the demand predicted in the different geographical markets under consideration. Four operational parameters related to the fleet architecture are decided upon at this stage of the design process and are passed to the next stage of the analysis. The four parameters are: the number of coverage areas (geographical markets) that the fleet is going to serve, the mix of services the fleet will provide in each coverage area, the number of spacecraft in the fleet, and the allocation of each spacecraft to serve one or more coverage areas. Those parameters are determined for each stage.

The determination of the four fleet parameters maps the multistage operational strategy of the fleet and lays down the payload requirements for each spacecraft in the fleet. Spacecraft payload requirements may or may not include operational level flexibility requirements. For example, a rigid fleet architecture could correspond to two spacecraft, each of which is designed to exclusively serve one of the two independent coverage areas during all four stages in the 20-year time. On the other hand, a flexible fleet architecture may include a single spacecraft that incorporates payload capabilities (antenna size and transponder design) to serve CA-I or CA-II at different stages in the 20-year time span depending on demand materialization. The flexible spacecraft must also have the capability of moving itself to another orbital location when switching coverage areas.

4.2 Step II: Spacecraft Design

The payload design requirements for each spacecraft in the fleet are passed from the economic to the technical domain. In the technical domain, the GA is coupled with the spacecraft sizing and reliability estimation models to find optimal spacecraft designs that satisfy the given payload requirements. The GA generates spacecraft designs with optimal combinations of technology choices and redundancy levels that minimize spacecraft launch mass (surrogate for cost) and satisfy reliability constraints.

4.3 Step III: Revenue Estimation

After the technical domain generates optimal, feasible designs for the spacecraft systems in a given fleet architecture, the ROV module probabilistically evaluates revenue and cost, hence its net present value. Revenue estimation requires two inputs: the forecasted, uncertain, dynamic demand models similar to the distributions in Figure 1, and the payload design parameters of the spacecraft in the fleet, including the number of available transponders designated to each service type and all the coverage areas those transponders are designed to serve at any stage in the 20-year time span.

4.4 Step IV: Cost Estimation

The last step in an iteration in the fleet architecting framework is the cost estimation of the generated fleet architecture. The cost of a fleet is divided into spacecraft acquisition, launch, insurance and operating costs. The spacecraft cost is determined by the spacecraft payload design and the bus design, which is information passed onto the ROV model from the technical domain. For the same number of available transponders, a flexible spacecraft (one that could serve multiple coverage areas at different stages or provide multiple services) is more expensive than a rigid spacecraft. The launch cost is determined mainly based on the total wet mass of the spacecraft in the fleet, which again is information passed onto the ROV model from the technical domain. Finally, the operating cost is a function of the size of the spacecraft, but also varies with the operational strategy. The operating cost increases when two spacecraft are co-located in the same orbital position. For example, the operating cost of a 60 transponder spacecraft system is less than that of two 30 transponder spacecraft systems that are co-located in the same orbital position to serve a single coverage area.

5 System Architectures

The framework described in Figure 2 was employed to generate a rigid and three flexible fleet architectures along with their associated optimal spacecraft designs as solutions meeting the requirements in Figure 1. The rigid architecture includes two spacecraft; each is dedicated to serve only one of the coverage areas for 15 years. The CA-I spacecraft provides services in the first, second, and third stages. This spacecraft has 60 active transponders, which is the average transponder demand in the first stage (forecast peak). The CA-II spacecraft provides services in the second, third, and fourth stages. This spacecraft has 60 active transponders, which is the average transponder demand in the fourth stage (forecast peak).

The three flexible fleets have different architectural configurations and use combinations of four levers to embed architectural flexibility. The first lever is the payload flexibility switch that allows a spacecraft to serve either of the two coverage areas. The second and third fleet levers are the number of spacecraft in a fleet and the payload size in each spacecraft. Finally, the fourth lever is the timing or relative sequencing of spacecraft deployment. Table 1 summarizes the architectural configurations. Note that flexible fleets II and III have the same configuration except that the second spacecraft in flexible fleet II is deployed at the beginning of the first stage while in flexible fleet III, it is deployed at the beginning of the second stage.

The GA, coupled with the spacecraft technical models, found optimal designs for each of the spacecraft in the four fleet architectures. Table 2 compares selected spacecraft design parameters that the GA produced are and demonstrates the effect of change in payload requirements on the optimal design of the spacecraft.

Two facets of Table 2 are worth highlighting. First, in the rigid fleet architecture, although S/C I and S/C II have the same transponder design, the mass of S/C II is larger because CA-II is 12 deg^2 larger than CA-I. It thus requires a larger antenna to provide full coverage, which increases the structural mass of the spacecraft. Second, the single flexible S/C in flexible fleet I also has the same number of active transponders as S/C I and S/C II in the rigid fleet architecture. However, the flexibility requirements in the transponder design adds the mass of extra pairs of frequency filters for each transponder and decreases the HPA efficiency. This increases payload power requirements that in turn require more capabilities from the bus subsystems as shown in the design of the solar array, batteries and thermal radiator in Table 2.

6 Value-at-Risk Analysis

A value-at-risk (VaR) analyses display the cumulative distribution function (CDF) of the possible outcomes of a design. The VaR itself is the minimum loss that might exist at any probability. A comparison of the VaR curves of two architectures or design solutions shows the differences both in maximum possible loss and gain between them.

Table 1. Architectural configuration of fleet solutions

Architectural Parameters	Rigid Fleet	Flexible Fleet I	Flexible Fleet II	Flexible Fleet III
Number of spacecraft	2	1	2	2
Active transponders	S/C I in CA-I: 60 S/C II in CA-II: 60	60	S/C I: 30 S/C II: 30	S/C I: 30 S/C II: 30
Payload flexibility	none	yes	both yes	both yes
Deployment stage	S/C I in CA-I: stage I S/C II in CA-II: stage II	stage I	S/C I: stage I S/C II: stage I	S/C I: stage I S/C II: stage II

Table 2. Selected parameters of optimal spacecraft designs for the fleet architectures in Table 1

Optimized Design Parameter	Rigid Fleet		Flexible Fleet I	Flexible Fleet II		Flexible Fleet III	
	S/C I in CA-I	S/C II in CA-II	Flexible S/C	Flexible S/C I	Flexible S/C II	Flexible S/C I	Flexible S/C II
Total Launch Mass (kg)	4,541	4,888	5,962	2,725	2,725	2,725	2,725
Payload							
Active HPAs*	60	60	60	30	30	30	30
Available HPAs	72	72	72	36	36	36	36
HPA efficiency (%)	58	58	55	55	55	55	55
Payload Power (W)	6,960	6,960	7,326	3,663	3,663	3,663	3,663
Bus							
Solar Array Area (m^2)	69.7	69.7	73.3	36.7	36.7	36.7	36.7
Battery Mass (kg)	240	240	338	127	127	127	127
Radiator Area (m^2)	9.9	9.9	10.7	5.5	5.5	5.5	5.5

*HPA: High Power Amplifier, S/C: Spacecraft, CA: Coverage Area

VaR calculations also lead to valuation of the flexibility provided by the different architectures. This is the difference between the expected net present value, E(NPV), of a flexible and a rigid design as shown in Equation 1.

$$flexibility\ value = E(NPV)_{flexible} - E(NPV)_{rigid} \qquad (1)$$

The E(NPV) themselves can be calculated from present values of the revenues and costs of any design, as provided by the revenue and cost estimation models of the fleet architecting framework. For the purpose of the graphical comparison of the NPV distributions of the flexible fleet architectures against that of the rigid architecture, continuous approximations of the discrete CDF's of the four fleet architectures were implemented.

Figure 3 and Table 3 summarize the VaR analysis of the four fleet architectures. The next four subsections analyze these results in detail.

6.1 Valuation of the Rigid Fleet Architecture

The rigid architecture is representative of a traditional fleet design approach where demand evolution and uncertainties are ignored and payload requirements are determined based on forecast peak demand. This rigid fleet architecture cannot respond to changes in market demand. On the other hand, it offers the best possible use of spacecraft resources from a narrow technical perspective. For example, the HPA can be operated at a maximum efficiency of 58%, which minimizes payload power requirements. This usually leads to lighter, less expensive spacecraft systems. Note, however, that the objective of designing the spacecraft is not to maximize technical performance but overall economic efficiency.

The mean of the distribution in Figure 3 is equivalent to the E(NPV). For this rigid architecture, E(NPV) is $ 49.94 million with a standard deviation is $ 3.69 million. It should be noted that the probabilistic analysis used to value the NPV distributions provides a realistic estimate of the fleet value by accounting for the uncertainties associated with the evolution of the market demand. Deterministic NPV calculations would have led strategists to overestimate the value of the rigid fleet architecture. This is because, in a deterministic approach, the demand is assumed to stay constant at the payload size that the spacecraft in the fleet is designed to support. In the rigid fleet architecture and in a deterministic NPV calculation approach, the demand would be assumed to stay constant at 60 transponders in each of the coverage areas over the life of the system. This invalid and unrealistic assumption leads to an NPV value of $ 73.21 million, a $ 23.27 million overestimate of the true value. This calculation shows that probabilistic analysis should always be implemented to realistically estimate the value of a project.

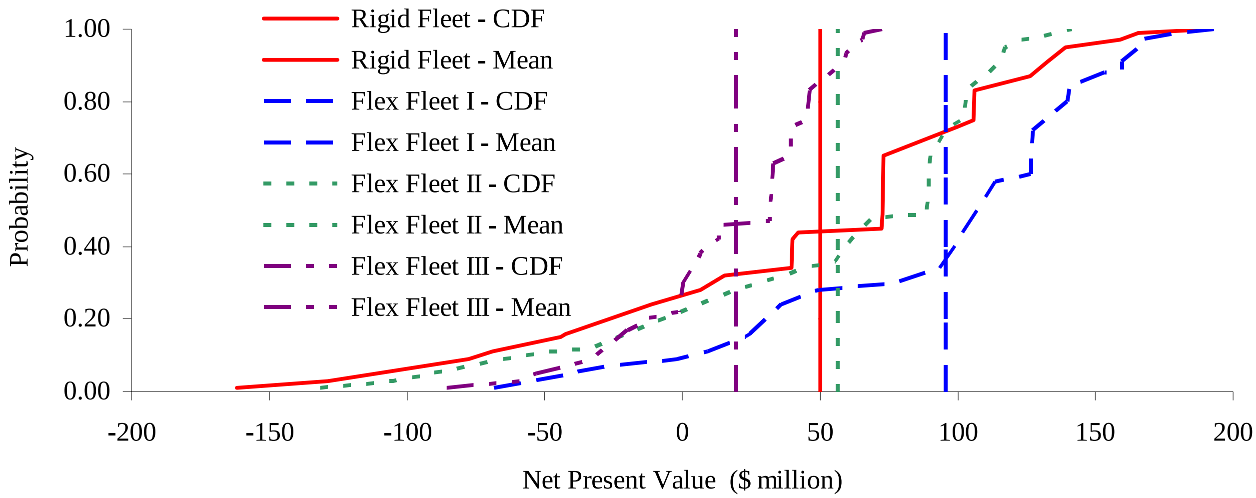


Figure 3. Value-at-risk distributions (cumulative density functions) for the four satellite fleet architectures

Table 3. Comparison of economic values of the four satellite fleet architectures

Architectural Value Parameter ($ million)	Rigid Fleet	Flexible Fleet I	Flexible Fleet II	Flexible Fleet III
E(NPV)	49.94	95.81	56.20	19.40
Std(NPV)	3.69	4.63	3.74	1.63
Flexibility Value	-	45.86	6.26	-30.55
Fixed cost, pay year 1	242	275	341	170
Fixed cost, pay year 6	242	-	-	170
PV(fixed cost) at year 1	392	275	341	276
Maximum possible gain	192	193	142	73
Maximum possible loss	162	68	131	86

As Figure 3 shows, The VaR provides decision makers with an idea about the maximum possible losses or gains their project could realize. For the rigid fleet architecture, the maximum possible loss is $ 162 million and the maximum possible profit is $ 192 million.

An important piece of information for the decision making process that can be obtained from the cost analysis is the initial capital investment required for a fleet architecture. A general good investment strategy is to choose projects with lowest initial investments to minimize the possibility of early losses. In the space industry, this strategy is hard to achieve because most of the fixed cost of a fleet, including spacecraft acquisition, launch and insurance, must be invested before generating any revenue from the fleet's services. The initial capital investment can be used to compare the value of flexible fleet architectures against that of the rigid fleet architecture. For the rigid fleet architecture, the initial capital investment is $ 242 million, which includes the cost of acquiring, launching and insuring S/C I that serves CA-I. At the beginning of the second stage, an additional $ 242 million must be paid to acquire, launch and insure S/C II that serves CA-II. Using a yearly discount rate of 10% and ignoring inflation, the present value of the total fixed cost invested in the rigid architecture is estimated as $ 392 million.

6.2 Valuation of the Flexible Fleet Architecture I

Flexible fleet architecture I comprises a single large flexible spacecraft with 60 active transponders and can serve either coverage area at a time. This single spacecraft fleet configuration is inspired by the fact that a major cost element in the fixed cost of a satellite system is the launch cost. Therefore, it is intuitive to think that the fewer the launches, the less costly the fleet, and the larger financial fleet value. Figure 3 shows that the E(NPV) of flexible fleet architecture I is $ 95.81 million (compared to $ 49.94 million for the rigid architecture) with a standard deviation of $ 4.36 million (compared to $ 3.96 million for the rigid architecture). The maximum possible loss and gain for flexible fleet architecture I is $ 68 and $ 193 million (compared to $ 162 and $ 192 million for the rigid fleet architecture).

Figure 3 shows that flexible fleet architecture I offers a huge improvement in economic value over that of the rigid fleet architecture with an increase in the E(NPV) of almost 92% corresponding to a flexibility value of $ 45.86 million. Flexible fleet architecture I offers this large increase in fleet value via risk minimization rather than revenue maximization. This becomes clear by comparing the CDFs' lower end tails, which represent maximum possible losses, and CDFs' upper end tails, which represent maximum possible gains. The maximum possible gain that flexible fleet architecture I could obtain is nearly the same as that of the rigid architecture; however, the maximum possible loss flexible fleet architecture I could incur is limited to only 41% of the maximum possible loss that the rigid architecture could incur. Fleet architecture I offers risk minimization through its low fixed cost, whose present value is only 70% of that of the rigid architecture.

6.3 Valuation of the Flexible Fleet Architecture II

Flexible fleet architecture II comprises two small spacecraft, each of which operates 30 active transponders and can serve either coverage area at a time. The two small spacecraft are deployed at the beginning of the first stage. This configuration is inspired by a relatively new trend in the commercial communication satellite industry towards acquisition of small to medium size spacecraft. Because the fleet is flexible, at any of the four stages, depending upon how demand materializes, the two spacecraft may need to be co-located in a single orbital spot to serve the same coverage area. Operating two spacecraft in one orbital location complicates the operational processes, which increases the operating cost.

The E(NPV) of flexible fleet architecture II is $ 56.20 million (compared to $ 49.94 million for the rigid architecture) with a standard deviation of $ 3.74 million (compared to $ 3.96 million for the rigid architecture). The maximum possible loss and gain for flexible fleet architecture II is $ 131 and $ 142 million respectively (compared to a maximum possible loss and gain of $ 162 or $ 192 million for the rigid fleet architecture). The economic value of flexible fleet architecture II is close to that of the rigid architecture. Although flexible fleet architecture II decreases the maximum possible loss of the rigid architecture by $ 31 million, it also decreases the maximum possible gain by $ 50 million. Therefore, the advantage of cutting maximum losses is partially reduced by the disadvantage of decreasing the maximum possible gain. Additionally, the value that the flexibility of the architecture offers is only $ 6.26 million. However, the true advantage of flexible fleet architecture II over the rigid fleet architecture is that flexible fleet architecture II requires a total fixed cost of $ 341 million (paid upfront at the beginning of the first stage), only 87% of the present value of the total fixed cost required for the rigid fleet architecture.

6.4 Valuation of Flexible Fleet Architecture III

Flexible fleet architecture III has two small flexible spacecraft similar to flexible fleet architecture II. However, it deploys S/C II at the beginning of the second stage, whereas in flexible fleet architecture II, both spacecraft are deployed at the beginning of the first stage. This architecture is studied to investigate the effect of sequencing, which is considered one of the flexibility levers, on the financial performance of a fleet. The advantage of a delayed deployment of S/C II decreases the present value of its cost and the upfront investment. However, having only one spacecraft in stage one eliminates the fleet's ability to capture large amount of revenue from CA-I early on.

The E(NPV) of flexible fleet architecture III is $ 19.40 million (compared to $ 49.94 million for the rigid architecture) with a standard deviation of $ 1.63 million (compared to $ 3.96 million for the rigid architecture). The maximum possible loss and gain for flexible fleet architecture III are $ 86 and $ 73 million respectively (compared to $ 162 and $ 192 million respectively for the rigid fleet architecture). The only advantage that flexible fleet architecture III offers is that its NPV distribution has a small standard deviation and a tight NPV range. The NPV range for flexible fleet architecture III is only 45% of that of the rigid architecture and is 58% of that of flexible fleet architecture II. This small spread might be preferred by a conservative satellite operator willing to sacrifice possible large gains in order to significantly minimize risk. In other words, the "value of flexibility" is now negative. The cost of flexibility for flexible fleet architecture III is $ 33.55 million. This cost could be considered as an insurance premium that a risk averse satellite operator might be willing to pay.

7 Conclusions

The case study presented in this paper shows how the value-at-risk analysis can calculate the value of flexibility as regards increases in expected net present value and changes in maximum capital investment and losses. This approach to Real Options provides a simple, but powerful, economic framework that allows for the valuation of flexibility in complex systems using a discounted cash flow approach that is well known to engineers, project mangers, and strategic decision makers.

The suggested value-at-risk analysis was applied to the architecting of commercial communication satellite fleets. The fleet architecting framework integrates economic valuation with spacecraft technical design to maximize the financial value of a fleet under uncertain, dynamic market conditions. A sample case study is presented where the demand evolution in two geographically disconnected markets is considered simultaneously over a 20 year time span. The forecast demand models show that while the demand is at a peak in one market and is rapidly vanishing, the demand in the other market is nonexistent at present but quickly picks up and reaches a peak towards the end of the time window of the problem.

The fleet architecting framework comprises an economic and a technical domain. The economic domain includes uncertain, dynamic demand models, parametric cost and revenue models, and the value-at-risk Real Options valuation. The technical domain includes a spacecraft sizing model and a spacecraft reliability estimation model that are coupled with a Genetic Algorithm to generate optimal spacecraft designs. The inputs to the technical domain are payload requirements and flexibility requirements that are generated and passed down from the economic domain based on forecast demand.

Four fleet configurations along with their optimal spacecraft designs were generated. One configuration is a traditional, rigid fleet architecture where each spacecraft is tuned to serve only one geographical market. Four flexibility levers are combined at different levels to generate three flexible fleet architectures. The first lever is flexible payload design that allows a spacecraft to serve either market at a time. The second and third levers are the number of spacecraft in a fleet and the size of the payload on each spacecraft. The fourth flexibility lever is the sequencing or deployment plan of the spacecraft over the 20 year period under consideration. The value-at-risk analysis proves that flexible fleet architectures provide significant economic value over that of the rigid fleet architecture.

Readers interested in Real Options should appreciate that the value-at-risk analysis provides much more information than a conventional Real Options analysis that only calculates the value of flexibility. As the results and discussion show, the value-at-risk analysis generates a range of information that may be useful to decision makers.

Designers should carefully note that the architectures that maximize the value of the system are often far different from those that maximize narrow technical efficiency. Indeed, in this case study, the rigid architecture that maximizes technical efficiency provides the most risky system of far lower expected net present value than flexible architecture alternatives.

We believe that the power of the suggested "Real Options *in* the system" analysis lies in its ability to empower engineers to find approaches that embed flexibility in complex systems and observe the value of flexibility using value-at-risk distributions. Being able to perform this simple economic analysis will allow engineers to change their designs to manipulate the value-at-risk distributions in ways that are favorable to the stakeholders of the systems.

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References

[1] Dixit, A., and Pindyck, R., *Investment under Uncertainty*, Princeton University Press, Princeton, N.J., 1994.

[2] de Neufville, R., Scholtes, S., and Wang, T., "Real Options by Spread Sheet, Parking Garage Case Example," *Journal of Infrastructure*, ASCE, in press.

[3] Saleh, J., Lamassoure, E., and Hastings, D., "Space Systems Flexibility Provided by On-Orbit Servicing: Part 1," *J. of Spacecraft and Rockets*, Vol. 39, No. 4, 2002, pp. 551-560.

[4] Hassan, R., de Weck, O., de Neufville, R., Hastings, D., and Mckinnon, D., "Embedding Architectural Flexibility in Communication Satellite Fleets Using Real Options Analysis and System Optimization Methods," in preparation for the *AIAA Journal*, AIAA.

[5] Hassan, R., and Crossley, W., "Multi-Objective Optimization of Communication Satellites with Two-Branch Tournament Genetic Algorithm," *Journal of Spacecraft & Rockets*, AIAA, Vol. 40, No. 2, 2003, pp. 266-272.