VALUE-INFORMED SPACE SYSTEMS DESIGN AND ACQUISITION

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Joy Brathwaite

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VALUE-INFORMED SPACE SYSTEMS DESIGN AND ACQUISITION

Approved by:

Dr. Joseph Saleh, Advisor
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Daniel Schrage
School of Aerospace Engineering
Georgia Institute of Technology

Dr. John-Paul Clarke
School of Aerospace Engineering
Georgia Institute of Technology

Dr. William Belton
School of Economics
Georgia Institute of Technology

Dr. Ismael Fernandez
GE Energy
General Electric Co.

Date Approved: December 14, 2011

To my parents, Shaulton and Irma, and my sisters, Indira and Vicky

"Lives of great men all remind us
We can make our lives sublime,
And departing, leave behind us
Footprints on the sands of time"

H.W. Longfellow (1807-1882)

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"Nobody, but nobody
Can make it out here alone"

Maya Angelou

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LIST OF ABBREVIATIONS

a_l	Course of Action
C_{ioc}	Cost to Initial Operating Capability
C_{ops}	Operations Costs
CVaR	Conditional Value-at-Risk
D_j	Space System Design Vector
EVA	Economic Value Added
$E[\cdot]$	The Expectation Operator
IP	Information Product
LCC	Lifecycle Cost
NPV	Net Present Value
p.m.f	Probability Mass Function
p.d.f	Probability Density Function
R	Downside Risk
S_i	Environmental Scenario
T	Number of 36 MHz Equivalent Transponders
Tx	Unit of Measurement for 36 MHz Equivalent Transponders
UP	Upside Potential
VaR	Value-at-Risk
VOI	Value of Information
VOD	Value of Design
WACC	Weighted Average Cost of Capital
π	Pay-offs to Stakeholder

SUMMARY

Investments in space systems are substantial, indivisible, and irreversible, characteristics that make them high-risk, especially when coupled with an uncertain demand environment. Traditional approaches to system design and acquisition, derived from a performance- or cost-centric mindset, incorporate little information about the spacecraft in relation to its environment and its value to its stakeholders. These traditional approaches, while appropriate in stable environments, are ill-suited for the current, distinctly uncertain, and rapidly changing technical and economic conditions; as such, they have to be revisited and adapted to the present context. This thesis proposes that in uncertain environments, decision-making with respect to space system design and acquisition should be value-based, or at a minimum value-informed. This research advances the value-centric paradigm by providing the theoretical basis, foundational frameworks, and supporting analytical tools for value assessment of priced and unpriced space systems.

For priced systems, stochastic models of the market environment and financial models of stakeholder preferences are developed and integrated with a spacecraft-sizing tool to assess the system's net present value. The analytical framework is applied to a case study of a communications satellite, with market, financial, and technical data obtained from the satellite operator, Intelsat. The case study investigates the implications of the value-centric versus the cost-centric design and acquisition choices. Results identify the ways in which value-optimal spacecraft design choices are contingent on both technical and market conditions, and that larger spacecraft for example, which reap economies of scale benefits, as reflected by their decreasing cost-per-transponder, are not always the best (most valuable) choices. Market conditions and technical constraints for which convergence occurs between design choices under a cost-centric and a value-centric approach are identified and discussed. In addition, an innovative approach for characterizing value uncertainty through partial moments, a technique used in finance, is adapted to an engineering context and applied to priced space systems. Partial moments disaggregate uncertainty into upside potential and downside risk, and as such, they provide the decision-maker with additional insights for value-uncertainty management in design and acquisition.

For unpriced space systems, this research first posits that their value derives from, and can be assessed through, the value of information they provide. To this effect, a Bayesian framework is created to assess system value in which the system is viewed as an information provider and the stakeholder an information recipient. Information has value to stakeholders as it changes their rational beliefs enabling them to yield higher expected pay-offs. Based on this marginal increase in expected pay-offs, a new metric, *Value-of-Design (VoD),* is introduced to quantify the unpriced system's value. The Bayesian framework is applied to the case of an Earth Science satellite that provides hurricane information to oil rig operators using nested Monte Carlo modeling and simulation. Probability models of stakeholders' beliefs, and economic models of pay-offs are developed and integrated with a spacecraft payload generation tool. The case study investigates the information value generated by each payload, with results pointing to clusters of payload instruments that yielded higher information value, and minimum information thresholds below which it is difficult to justify the acquisition of the system.

In addition, an analytical decision tool, probabilistic Pareto fronts, is developed in the *Cost–VoD* trade space to provide the decision-maker with additional insights into the coupling of a system's probable value generation and its associated cost risk.

CHAPTER 1

INTRODUCTION

Following the heydays of the Apollo program, the space industry saw a change in the design and acquisition of space systems that emphasized financial responsibility and cost considerations; the latter were neither left as after-thoughts of design nor were they subordinate to system performance any longer. This shift from a performance-centric to a cost-centric mindset—more prominent for civilian and commercial systems than for certain national security assets—was brought about by budgetary constraints and increasingly competitive markets, and was facilitated by ever-more financially aware engineers and program managers. Unfortunately, too much emphasis on cost brought in its wake a host of systemic problems in government acquisition of space assets. Starting as early as the eighties, the Government Accountability Office (GAO) identified several structural flaws with such an approach including incentives to underestimate cost, poor oversight and the inadvertent promotion of increased mission risk [1-5]. As a result of these structural flaws, cost overruns and schedule slippages were not contained as desired, but instead continued to be a significant problem in aerospace system acquisitions. In a study by the RAND Corporation the average cost growth for a set of 68 Department of Defense programs between 1968 and 2003 was 46% (See Table 1) [6]. NASA also displayed a similar pattern in its cost management. In a set of 72 programs executed by NASA between 1977 and 2004, the Congressional Budget Office (CBO) found that these programs had an average cost overrun of 45% [7].

In 2003, a Joint Task Force consisting of the Defense Science Board and the Air Force Scientific Advisory Board was commissioned to identify the systemic problems emerging from a cost-centric mindset in the US national security space program acquisitions, and provide recommendations to address these problems. The resulting Joint Task Force report (also known as the Young's Panel Report) identified five key deficiencies, three of which are relevant to this thesis [8]. These deficiencies are shown in Figure 1.

Table 1. Cost Growth in DoD Programs between 1968 and 2008

Type of System	Average Cost Growth
Aircraft	35%
Cruise Missiles	64%
Electronic Aircraft	52%
Electronics	23%
Helicopters	76%
Launch Vehicles	130%
Missiles	52%
Satellites	55%
Vehicles	67%
Others	40%
Average of 68 programs	46%

Key Deficiencies

1. "Cost has replaced mission success as the primary driver in managing space development programs" (pp.2)
2. "The space acquisition system is strongly biased to produce unrealistically low cost estimates throughout the acquisition process. These estimates lead to unrealistic budgets and unexecutable programs" (pp. 2)
3. "Industry has failed to implement proven practices on some programs" (pp.4)
4. "Government capabilities to lead and manage the acquisition process have seriously eroded" (pp. 3)
5. "The space industrial base is adequate to support current programs, although there are long-term concerns" (pp. 4)

Source: T. Young et al., Report of the Defense Board/ Air Force Scientific Advisory Board Joint Task Force on Acquisition of National Security Space Programs, Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics, 2003

Figure 1. Key deficiencies identified by the Joint Task Force

Deficiency #1: Cost has replaced mission success as the primary driver in managing space development programs.

For space programs, the consequences of mission failures can be extremely costly. The Space Shuttle Columbia disaster provided an illustration of the impact of failure (the two year grounding of the Space Shuttle) on operations, costs and the overall advancement towards the program goals [9]. The shift in emphasis from mission success, exemplified in the high technical quality of space systems, to cost minimization has contributed to the deterioration in quality throughout the entire acquisition process. Despite the focus on cost, there has been excessive cost and schedule overruns, highlighting the failure in placing cost as the primary driver. In addition to cost growth, the Young Panel Report noted that excessive mission risk and poor investment strategies plague space acquisitions.

Deficiency #2: The space acquisition system is strongly biased to produce unrealistically low cost estimates throughout the acquisition process. These estimates lead to unrealistic budgets and unexecutable programs

A cost minimization framework has led competing contractors to submit proposals in which costs are severely underestimated. This phenomenon is known as “price to win”. The task force discovered this problem to be so pervasive that it was not unusual for cost growth to be within the range of 50 to 100 percent.

Deficiency #3: Industry has failed to implement proven practices on some programs

The Young Panel report found failure to follow best practice procedures in engineering and management has led to unproductive government actions, contract provisions, and fee structures. As such, an unintentional environment is created in which incentives exists to encourage cost and schedule overruns, and increase mission risk.

The Young panel report recommended as a remedy to these problems, a renewed focus on mission success and not performance. Mission success, like a balanced scorecard, is a holistic qualifier which encompasses the positive elements of both the cost-centric and performance-centric approaches. This balanced scorecard assesses the effectiveness with which the system achieves mission objectives, and in achieving mission objectives (partially or completely), create value for the stakeholders

Interestingly, a number of the problems that drives cost growth could be associated with a failure to properly couple cost considerations, performance, and the relevance of the latter to the customer, end-user, and/or other stakeholders. By focusing on cost estimation, contractors are motivated to provide the minimum performance level as defined in the requirements in order to ensure they submit the lowest bid while rarely accounting for or indicating the cost risk potential. As a side note, this constitutes an important flaw in the acquisition process, even within an agreed upon cost-centric mindset, since the various bids are not submitted at an iso-cost risk level. There is little incentive to exceed these requirements, or design a system with innovative attributes such as flexibility, which while they might be valuable to the customer, often come at a cost. As a result of the cost-centric mindset, system attributes which are initially costly but enhances the value of the system for the customer or stakeholder may be excluded from the design down-selection process.

By choosing to focus on and minimize cost, decision-makers and contractors may constrain the performance of the system, and more importantly they can inadvertently limit its value creation potential. If the design or acquisition of a system is (rightfully) conceived of as an investment, then an immediate question should be asked: is the return on this particular investment (here the system design) maximized? Or said differently, can we obtain a better return if the resources committed to this particular investment were spent differently, (e.g., on a different system design)? The reader can already see through these two questions that a cost-centric mindset in design and acquisition is myopic since it focuses on one characteristic of the investment, namely the resources committed; it should be self-evident however that an evaluation of an investment is meaningless if restricted to the resources committed (e.g., measured by cost) without an assessment of its return or its value (its value creation potential or its net value). As a result, a cost-centric approach to system design and acquisition is at best myopic. An adequate framework for conducting system trade-offs will couple both performance and cost in a meaningful way so as to allow the decision-maker to assess the value of the system to the stakeholder. It will identify two aspects of the engineering product. These are the resources utilized in system development and operation (proxied by cost), and the value generated by the system. It will decompose analysis into the fundamental components which drive trade-offs such that engineers are able to assess the design space in a more informed manner.

1.1 Problems with Assessing Value in Design and Acquisition

Engineering system design and acquisition is a critical segment in the development and acquisition of a space system, and to a certain degree, drives the value that stakeholders derive from the system. It is during this design process that user needs and requirements are transformed into an engineering solution or set of solutions, and limited resources are committed by the organization (e.g., corporation) to develop the most viable solution(s). Conceptually, Hazelrigg [1996] defined [systems] engineering as involving "the manipulation of nature to create systems for the benefit of at least some segment of mankind" [10]. Throughout the discipline of system design and acquisition, a number of methodologies has emerged in attempts to quantify the benefits or value of the system to the stakeholder. Examples of such methodologies include utility analysis, which maps the attributes of the system into a non-dimensional indicator of the appeal of the system to the stakeholder, and value engineering, which defines the value of the system as its functionality per cost [11-17]. However these methodologies, while widely advocated and commonly utilized, suffer from a number of weaknesses. First a number of these approaches view value as intrinsic to the system or as an absolute measure (i.e., dependent primarily on technical attributes, performance and cost of the system). As a result, strategies to improve value are geared towards increasing the cost effectiveness of the system or the performance to cost ratio. In other words, traditional approaches to system design and acquisition tend to be cost-centric or performance-centric in nature. While the intrinsic or technical attributes of a system are key drivers of the system's value, additional drivers exist which a cost-centric or performance-centric mindset does not capture adequately. For example, the system's environment plays a fundamental role in determining the value of a commercial system to the corporation. Intuitively, one might understand how the value of a commercial engineering system varies with the market environment. A greater demand for the flow of services provided by the system leads to a higher system value for investors. Conversely, lower demand may lead to lower system value. From this intuitive understanding of the relationship between the system and its environment, it is not difficult to extrapolate that volatility in the system's environment (e.g., market demand) may lead to volatility in the system's value. Thus, methodologies and metrics used to conduct value analysis in engineering system design and acquisition should account for such externalities and their impact on system value.

Second, some of the value methodologies focus on abstracting the technical attributes of the system to a single non-dimensional index which reflects the appeal of that system to the stakeholder. This index is used to rank the systems under consideration in order of preference to the relevant stakeholders. While such methodologies do incorporate preference information from the stakeholder within the construction of the index, at times the construction of the index may be non-transparent and unrepeatable if not properly documented. The potential for non-transparency occurs at two points in the index creation. The first point is the gathering of preference information for the system technical attributes from a sample of relevant stakeholders. Ideally, the preference information from this sample of stakeholders should represent the preference of the wider stakeholder population. However, in a number of cases, changes in the sample of stakeholders may lead to significant differences in the system rankings. The second point of non-transparency occurs in the methodology to combine the stakeholder preference information into a single index. One flaw identified in utility analysis, specifically expected utility analysis, is the ineffective consideration of risk preferences among probabilistic outcomes [18]. In the context of system design and acquisition, the value of the system is a probabilistic outcome. Thus, the application of utility indices and analysis may lead to a ranking of systems that is inconsistent with stakeholder preferences at times.

Finally, in addition to the above difficulties in what is referred to as value analysis, assessing the value of space systems is further compounded by the fact that space systems may serve multiple stakeholders in disparate fields. Each of these stakeholders receives a unique value flow from the space system depending on the environmental factors, the system technical attributes and the stakeholder's objectives. The above value methodologies often assume the preferences of the stakeholders are homogenous. The advantage of considering homogenous stakeholders is that each stakeholder receives identical benefits and costs. Thus optimizing the system for any given stakeholder optimizes the system for all stakeholders. In making this assumption, the stakeholder may select the most value efficient system from the systems under consideration. However, the benefits, costs and risks from the system are borne differently by different stakeholders. For example, consider a planetary mission to Venus. There are various stakeholder groups which may benefit from the space system. A science stakeholder group focusing on geomorphology would benefit significantly from a system with a lander component but not significantly from a balloon component. A science stakeholder group focusing on atmospheric properties would benefit significantly from a system with a balloon component but not from a system with a lander component. Thus, in considering multi-stakeholders it is also necessary to consider whether the benefits, costs and risks from the system are borne equitably across all stakeholders.

Currently, engineers are versed in assessing the space system from a technical perspective. Metrics and analytics which allow system engineers to analyze the cost and performance of the system are well developed. Thus, engineers are able to optimize system performance and cost given the appropriate metrics of interest. In contrast, metrics and analytics which allow engineers to rigorously assess the space system from a value perspective are limited [19-24]. As a consequence, there is a need for tools which would enable engineers to practically incorporate value analysis into space system design and acquisition. Unlike cost, value is not an intrinsic characteristic of a system, but a "networked" metric that characterizes a system in relation to its environment, the system's attributes and a set of stakeholders. As such, it is difficult to determine the impact of a design decision on the system's net value if decisions are implemented based on cost and performance metrics alone. It is possible, for example, that system engineers may compromise value despite improving cost effectiveness without the appropriate metrics and decision framework to measure value. In addition, by considering stakeholders as a homogenous group, engineers are unable to transparently assess the various benefits, costs and risks borne by the individual stakeholder groups. Thus a value framework should have the capability to characterize a system in relation to its environment and technical attributes as well as assess the value each distinct stakeholder or stakeholder group, ascribes to the system.

1.2 Research Objectives

To address these deficiencies, this thesis aims to provide operational frameworks for value assessment in space system design and acquisition which are grounded in an economic foundation. In particular, this thesis proposes an information-theoretic approach to value assessment which will be guided by three research objectives. The first research objective may be stated simply as follows:

R1. Develop a value-based framework for priced space systems that incorporates information flows deemed necessary for decision-making in the space system design and acquisition environment under a neo-classical economic formulation

One focus of this research is the development of an analytical value-based framework for priced systems. By definition, frameworks are conceptional structures for organizing and formalizing ideas and information [195]. Thus an analytical framework should by its nature capture the flows of information needed for decision-making, and the value consequences of design decisions to the stakeholder. This first research objective, although simple in formulation, enables complex and varied research avenues. One avenue is explored in this thesis. This avenue attempts to understand the value and design implications of a value-centric mindset versus a cost-centric mindset in space system design and acquisition. While it appears to be generally accepted that the value-centric approach is an improved design and acquisition approach relative to cost-centric approach, this hypothesis has not been tested quantitatively. Value analysis is specific to the relevant stakeholder and system. Thus, it is difficult if not virtually impossible to comprehensively test such a hypothesis. Instead, this study will focus on utilizing the value-based framework for priced systems to test the hypothesis for the case of a commercial communications satellite. This is done as the concept of value and accompanying metrics are well accepted in the commercial sector. Drawing on this portfolio of established metrics reduces the potential for ambiguity in the meaning of value during the analysis. The insights provided by the comparative analysis will either substantiate the qualitative arguments for value-centric design or lead to greater research on how best to incorporate stakeholder and environment information into the system design and acquisition process.

The second research objective emerging from the literature review and problem definition seeks to establish an analytical value framework for unpriced systems using a Bayesian update approach. It may be stated as follows:

> **R2. Formulate an analytical value-centric framework for unpriced space systems which estimates the value of the space system based on the value of information the space system provides stakeholders**

Space systems provide stakeholders with information. This information has value as the information increases the knowledge of the stakeholder (e.g. planetary missions), and in some cases, lead stakeholder to adjust operational decisions (e.g. earth science missions). Thus, under the second research objective, the space system is viewed as a provider of information, and the space system's value stems from the value of the information it provides stakeholders.

The final research objective lies in the value performance analysis of the system. In particular, this work will focus on one aspect of the value performance, the value uncertainty of a system. This third and final objective is stated as follows:

> **R3. Develop analytical tools which allow the decision-maker to 1) decompose value uncertainty into its constituents, upside potential and downside risk, and 2) identify Pareto optimal systems in a probabilistic environment**

The current dominant mindset in uncertainty analysis seeks to minimize uncertainty. Little emphasis is placed on understanding the composition of the uncertainty with respect to upside potential and downside risk. The value-centric mindset places an emphasis on unraveling uncertainty into it constituent parts, and understanding how the engineer may adjust the design attributes to allow the system to capitalize on opportunities that may evolve in the operating environment while limiting the system's exposure to risk. Second, current analytical tools that allow the decision-maker to identify Pareto optimal designs generally formulate objectives such that the objectives are deterministic. For value analysis, this thesis introduces a new analytical tool which allows the decision-maker to select Pareto optimal designs under probabilistic objectives. In all, the third research objective explores what additional analytical tools are needed to evaluate the value performance of a system in the context of uncertainty.

1.3 Summary of Research Flow

In order to address the research objectives given in the previous section, the outline of this thesis is presented in Figure 2**.** Chapter 2 reviews the current intellectual thought on value across the field of economics and the status of value-centric design in the aerospace industry. From the economic background, applicable principles are identified that can offer insight into value assessment in space systems design and acquisition. From the aerospace background, gaps that currently exist in value-centric design and acquisition in the aerospace industry are highlighted. Chapter 3 develops a value-centric framework for priced systems and demonstrates the ability of the framework to support a wide range of value-based decision-making tools. The framework and analytical tools are used to evaluate the design and value implications of a value-informed approach versus the dominant cost-centric approach to system design and acquisition. Chapter 4 focuses on value analysis for unpriced systems. In particular, in Chapter 4 it is posited that the value of the space system is derived from the value of the information it provides stakeholder. Based on this premise, a Bayesian framework is constructed to assess the value of the space system to stakeholders. Also, a new decision-making tool, probabilistic Pareto fronts, is introduced which identifies Pareto dominant designs in a probabilistic environment. Chapter 5 discusses the objective of value analysis in space system design and acquisition, and draws on the neo-classical economic concept of value, as well as common principles garnered from the creation of the priced and unpriced value frameworks, to formulate the concept of value in space system design and acquisition. Chapter 6 summarizes this work and discusses avenues for future work.

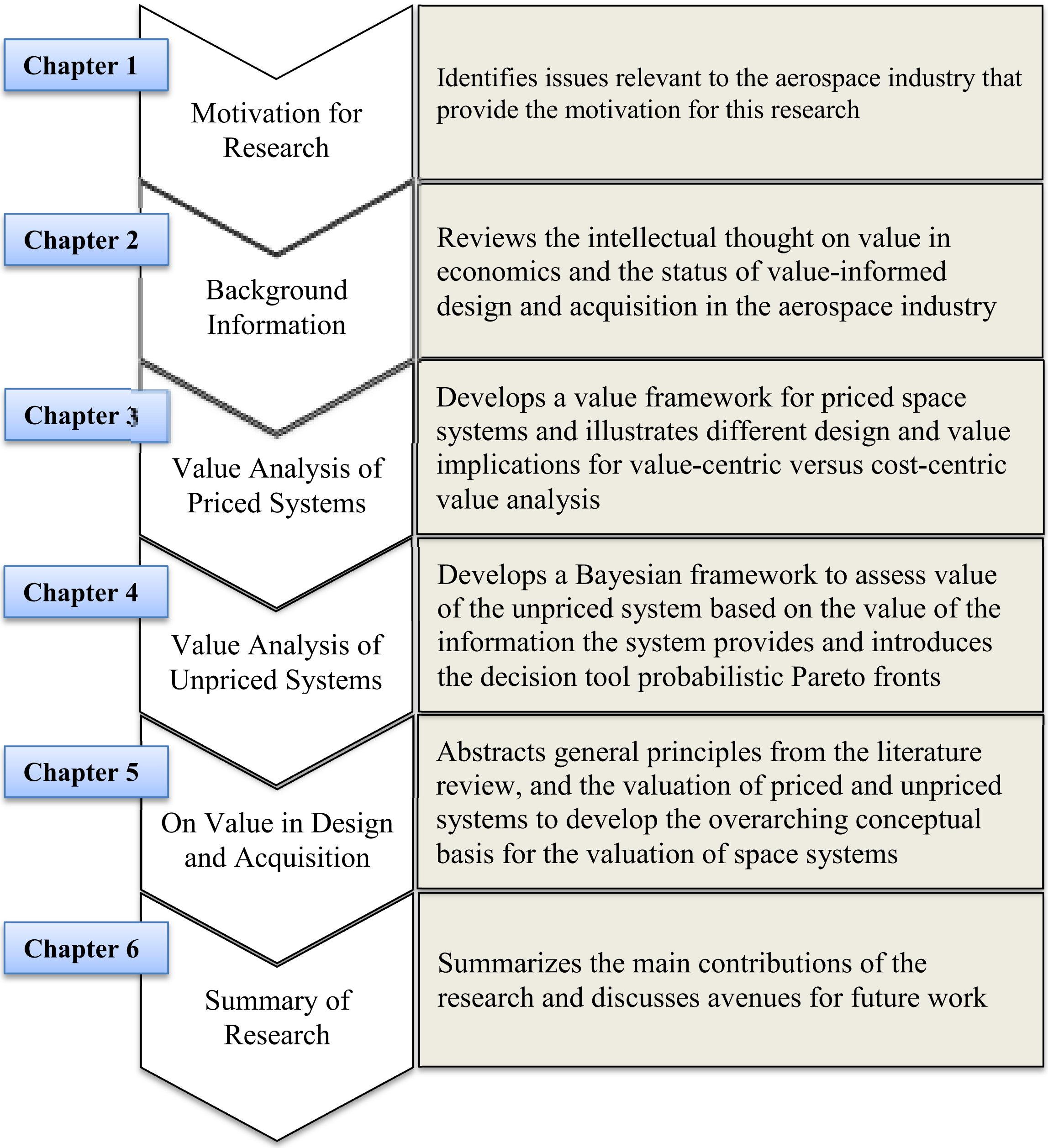


Figure 2. Research outline

CHAPTER 2

LITERATURE REVIEW

The background presented in this chapter reviews the concept of value and its importance to the aerospace industry. Specifically, this chapter has two objectives: 1) understand the intellectual thought on value in a general economic context and extract principles that are useful to value analysis in space system design and acquisition, and 2) understand value in the specific context of space system design and acquisition as well as the gaps and challenges that currently exists in value analysis in the space industry.

2.1 Origins of Value Quantification

Scholarly interest in the concept of value probably started in the second half of the 18th century with Adam Smith (1723–1790), and later became a source of heated disagreement among two groups of economists, those who believed value is an objective concept determined by the resources expended to acquire a commodity and those who believed value is subjective determined by the user satisfaction derived from the commodity. Similar to the current debates in the aerospace industry surrounding the definition and quantification of value, early economists struggled with differing perspectives on the nature of value, the definition of value and the primary components of value.

In one of the earliest studies of value, *An Inquiry Into the Nature and Causes of the Wealth of Nations* by Adam Smith, noted that [25]:

"The word value, it is to be observed had two different meanings, and sometimes expresses the utility of some particular object, and sometimes the power of purchasing other goods which the possession of that object conveys. The one may be called ***value in use;*** the other ***value in exchange.*** The things which have the greatest value in use have frequently little or no value in exchange; and, on the contrary, those which have the greatest value in exchange have frequently little or no value in use."

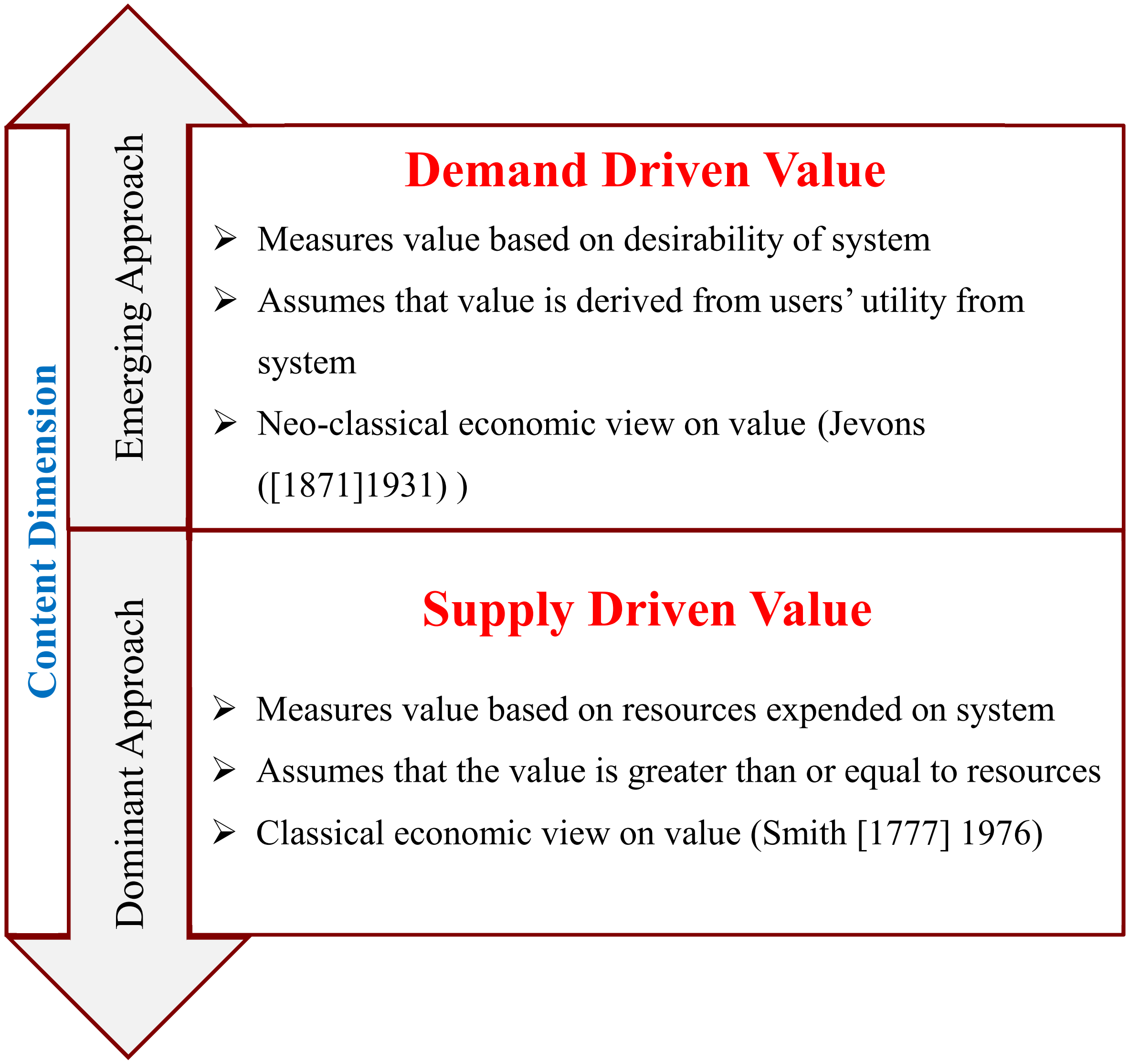
Note in this statement, Adam Smith already recognized the complexity and difficulty in attempting to generate a single encompassing approach to the assessment of value. Instead, Smith noted that there are least two categories of value, ***value in use*** and ***value in exchange***. By its nature value is multi-faceted, generated by various factors and needs. Consider the case of the value of air and the value of a Picasso painting. Air has little value in exchange, but great value in use. In contrast, a Picasso painting has substantial value in exchange but limited value in use. Myopically seeking to prescribe a single approach to the valuation of an object may lead to a biased understanding of the worth of that object. With this insight into the value, Smith delved further into the factors that determined value in exchange. He stated "Labor alone, therefore, never varying in its own value, is alone the ultimate and real standard by which the value of all commodities can be at all times and places estimated and compared. It is their real price; money is their nominal price only". Smith defined real price as the central price to which the price of all commodities continually gravitate [25]. Labor as a measure of value, was further advanced by Ricardo who argued that a theoretical invariable measure of value can be created by which the real value of objects can be compared; this invariable measure of value would not be affected by the same economic or environmental fluctuations as other measures. Scarcity, along with the factors of production (e.g., fixed capital, labor) drove the exchangeable value of a commodity, and each factor of production may be measured in terms of labor [26]. Together, these two economists defined what is known today as either the Labor Theory of Value or the Costs of Production Theory of Value.

While the Cost of Production Theory of Value contributed to the understanding of value by recognizing that suppliers desired to be compensated for resources expended on the system (i.e., supply-side), there was a number of challenges to this theory from other prominent economists at the time. Opponents pointed to the absence of demand-side factors as a major deficiency in the Cost Production Theory of Value [27]. Particularly, Jevons ([1871]1931) and Marshall ([1923]2009) identified the inability of the supply-side theories to predict the aggregate consumer behavior as reflected in the market prices [28,29]. Unlike the absolute intrinsic measure of value put forward by the Cost of Production Theory of Value, the value of an object must always be expressed in something and not stand alone as an absolute measure. The conceptual divide between the proponents and opponents of the Cost of Production Theory of Value is easily illustrated by considering the application of this value theory to the aerospace industry. Applying a Cost of Production Theory of Value to system design suggests that any system requiring a great input of labor (as measured by wages or manpower hours) is more valuable than systems requiring a low input of labor. There is limited consideration for the effectiveness with which the systems fulfill the intended objectives of the stakeholder. This failure to link the value of the system to the stakeholders' needs led a number of economists to reject the Cost of Production Theory of Value and instead develop a more subjective theory of value.

The formulation of the subjective theory of value is based on three fundamental ideas. The first is, at its core, an antithesis to the Cost of Production Theory of Value. It states that value is a relative concept and must be expressed in relation to the stakeholder and other objects [29,30]. Essentially, this relative notion of value suggests that the concept of intrinsic value as suggested by Ricardo ([1817],1963) was a fallacy as value was not imbued into an object based solely on the inputs required to produce that object [27]. The second idea of the subjective theory of value posited that consumers desire to maximize the utility derived from consuming goods or services [29]. Specifically, Jevons ([1871],1931) noted that value is measurable in marginal utility. This posit reflected the influence of demand-side factors on the value of an object, and in doing so, indicated that an understanding of consumers preferences and behaviors were necessary components in determining value. The final fundamental idea in the subjective theory of value was a synthesis which incorporated both supply-side factors and demand-side factors. Marshall ([1923]2009) postulated that in a competitive market, the revealed value of an object occurs at the equilibrium point where the marginal utility of the object equals its marginal cost [28]. Interestingly, formulating a theory of value based on the interaction between marginal utility and marginal cost eventually led to the term "value" being used synonymously with "price". Indeed, several seminal works on value to follow (e.g. A Theory of Value (Debreu 1959)), did not defined value but simply assumed the value was identical to price [31].

The two competing theories of value advanced the understanding of value substantially. The Cost of Production Theory of Value highlighted the importance of the supply-side in value determination, and recognized that suppliers desired to be compensated for resources expended. However, this theory of value was incomplete. Although Ricardo noted that value in exchange is driven in part by the utility of an object, the Cost of Production Theory of Value did not account for the utility consumers derived from acquiring the object. The subjective value of theory built on the Cost of Production Theory of Value by positing that consumer preferences and utility were important factors in value determination. The foundations laid out by Marshall ([1923]2009), Jevons ([1871],1931) and others became known as neo-classical economics, and is today the dominant school on value from an economic perspective [28,29,32].

Ultimately the difference between these two perspectives on value lies in the content or the types of information required for the value analysis and is summarized in Figure 3. The classical economic view of value assumes that the stakeholder will only expend resources less than or equal to the value gained from the system. Thus, a measure of the resources expended to create the system forms a lower bound for the value of the system. This classical economic perspective of value is the basis of the cost-centric mindset, the dominant approach to value analysis in space system design and acquisition. The neo-classical economic view on value analysis assumes that information about the stakeholder's desirability for the system is the primary type of information needed for value analysis. The neo-classical economic perspective on value analysis forms the basis of the value-centric approaches emerging in space system design and acquisition. This latter perspective will be the focus in the remaining sections of the literature review.



Demand Driven Value

- Measures value based on desirability of system
- Assumes that value is derived from users' utility from system
- Neo-classical economic view on value (Jevons ([1871]1931))

Supply Driven Value

- Measures value based on resources expended on system
- Assumes that the value is greater than or equal to resources
- Classical economic view on value (Smith [1777] 1976)

Figure 3. Content dimension of value

2.2 Assumptions of Neo-Classical Economic Value Assessment

The foundation of neo-classical economic value analysis may be described as an approach to the allocation of scare resources [32]. In a design and acquisition context, decisions may be considered analogous to the allocation of scarce resources (e.g. funding, labor) as the program manager is resource-constrained and can only select a subset of all system alternatives under consideration. Under the neo-classical value perspective, quantitative modeling of the decision process is enabled by a number of behavioral assumptions about the system stakeholder. These assumptions are formulated into a theory of preference and define the behavior of a rational stakeholder [33]. The first assumption is termed the completeness property and can be stated as follows:

> *When facing a choice between two designs, $\boldsymbol{D_A}$ and $\boldsymbol{D_B}$, the decision-maker can rank these systems such that one of the three relationships is true: design $\boldsymbol{D_A}$ is preferred to design $\boldsymbol{D_B}$, design $\boldsymbol{D_B}$ is preferred to design $\boldsymbol{D_A}$, or the decision-maker is indifferent between design $\boldsymbol{D_A}$ and design $\boldsymbol{D_B}$.*

The purpose of this property is to eliminate the possibility that the system stakeholder is unable to define the preference for a system relative to another system. In effect, this property states that a given system can always be ranked relative to another. The second assumption is known as the transitive property and can be stated as follows:

> *If design $\boldsymbol{D_A}$ is preferred to design $\boldsymbol{D_B}$, and design $\boldsymbol{D_B}$ is preferred to design $\boldsymbol{D_C}$, then design $\boldsymbol{D_A}$ is preferred to $\boldsymbol{D_C}$.*

It would be difficult to model the preferences of the system stakeholder if the stakeholder's rankings of the systems are not logically consistent. The transitive property is important as it eliminates the possibility of certain types of behavioral inconsistencies and facilitates the modeling of the stakeholder's desirability for each system. Together the completeness property and the transitive property describe a decision-maker with a well-defined set of preferences. The third property is often added to the set of assumptions to complete the description of a rational decision-maker, and is called the monotonicity property. This property states:

> *All other attributes being equal, if design* $\boldsymbol{D_A}$ *provides greater benefit (or lower costs) for a given attribute than design* $\boldsymbol{D_B}$*, design* $\boldsymbol{D_A}$ *is preferred to design* $\boldsymbol{D_B}$*.*

Unlike the first two properties which are considered critical in value analysis this third property, monotonicity, is often included to simplify the analysis, as it implies that value increases monotonically with increasing benefits and decreases monotonically with increasing costs [33].

In a value-centric framework, an assessment of the stakeholder's desirability for the engineering system is built on these properties of well-defined preferences. Often, the output of the value-centric framework is a ranking or pseudo-ranking of the system candidates under consideration. Thus in order to ensure consistent and completeness in the ranking, value models adhere to the assumptions of a rational decision-maker either implicitly or explicitly.

The types of value assessments which are built on these assumptions, and utilized to create rankings may be divided into two groups, priced and unpriced. Priced assessments are those in which the goods (or services) may be bought or sold in markets [34]. As such, the value of the goods (or services) is said to be revealed by the action of the stakeholders as the goods (or services) directly generate revenues [35]. In contrast, unpriced assessments are those in which the goods (or services) are not brought or sold directly in markets, and the value of the goods (or services) are not readily revealed. This difference in priced and unpriced value engenders different value assessment approaches. An overview of the various valuation methodologies for each type of value assessment is provided.

2.3 Priced Valuation Methodologies

Traditionally, priced value is explored in a business context in which valuation issues arise in three basic manners, project valuation, security valuation and firm valuation [36].The purpose of the valuation is to determine whether the project, security or firm is a worthwhile investment. There are three general (though not necessarily mutually exclusive) approaches which may be employed for the valuation. These are discounted cashflow (DCF) valuation, relative valuation and contingent claim valuation [37]. DCF valuation relates the value of system to the present value of future cash flows, relative valuation relates the value of the system to the pricing of comparable assets, and contingent claim valuation uses option pricing models to assess the value of the assets that share option characteristics. Of these three general valuation approaches, discounted cashflow valuation and option pricing models have found greater applicability to engineering systems.

2.3.1 Discounted Cashflows Valuation

One seminal contribution to the concept of priced value is the idea of investment value, first articulated by John Burr Williams in 1938, and upon which most project valuations (or priced value quantification) are based. In 1938, John Burr Williams (1899–1989) promoted the valuation of investments through a methodology known as discounted cash flow (DCF) in his book *The Theory of Investment Value* [38]. Williams defined the investment value of a stock as the present worth of all dividends to be paid upon it in the future, and the investment value of a bond as the present worth of its future coupons and principal. The underlying assumption of the present worth is that people have *present-biased preferences*, that is, people place more weight on receiving benefits in the present than receiving those same benefits at some point in the future [33]. In the case of an investment, the decision-maker will exponentially discount the expected future cashflows relative to the expected present cashflows [37,39]. The analog of Williams' concept of investment value for an engineering system, say a commercial communication satellite, is the following: consider the services provided by the spacecraft over its operational life. The present value of the revenues provided by these services determines the value of the spacecraft for its owner. In addition, when all the costs associated with acquiring, launching, insuring, and operating the satellite are accounted for (and discounted appropriately), we would obtain the Net Present Value of the spacecraft. It is useful to remember that the acquisition of a satellite, or any other engineering system for that matter, constitutes an important investment for the owner, and as such, assessing its value based on the concept of "investment value" is justifiable. The value of an investment in a commercial context is sometimes referred to as "priced value", although the qualifier "priced" is often implicitly assumed and dropped. For our purposes, the "priced value" of an engineering system can be assessed if there exists a market for the services provided by said system. For instance, the lease price of on-orbit transponders provides a major input in determining the “priced” value of a communications satellite.

2.3.2 Contingent Claim Valuation

Contingent claim valuation provided an important contribution to the valuation of projects, firms and securities by recognizing that the value of an asset may be greater than the present value of the expected cash flows if the cash flows are contingent on the occurrence of an event [37]. In effect, this valuation technique recognizes that the decision-maker has the option but not the obligation of taking an action in the future and this option has value [40]. Analyzing the value of this option represented an important advancement to traditional DCF as option pricing accounted for uncertainties in the operating environment that are difficult to incorporate into traditional DCF. Furthermore, contingent claim valuation has become a powerful tool for capital budgeting in which operating environments are dynamic and management has the flexibility to adjust the initial project strategy as information is gathered [41]. Over the last four decades, a number of contingent claim valuation methods have been developed to quantify the value of the option. More prominent among these methods are Black-Scholes model, the binomial model and real options [37,40,42]. The analog of contingent claim valuation for an engineering system, say a supersonic business jet, is the following: consider that case whereby the decision-maker has to select between two investment strategies in regards to a supersonic business jet [43]. The first strategy is to invest in a long range jet and the second strategy is to invest in a long range jet with the option to adapt to low sonic boom design should market preferences change. In traditional DCF, by accounting for all the discounted costs associated with developing, manufacturing, insuring, and operating the ong range jet, and the discounted revenues generated from operating the jet, we would obtain the Net Present Value of the jet. Incidentally, simply using traditional DCF would yield the same value for the two strategies as traditional DCF does not account for the option to adapt. However, by assuming a level of preference volatility and utilizing a binomial pricing option, it becomes possible to differentiate between the two strategies in terms of value, with the second strategy yielding a higher value to the jet operator due to the attached option.

2.3.3 Common Metrics in Priced Valuation

A number of metrics based on the idea of discounted cash flows have been developed to quantify the value of an investment. Some of these metrics such as the Return on Equity, Return on Assets and profit are not considered suitable proxies for the value of engineering systems as these types of metric do not adequately discount future benefits and costs, or may only applicable to a single time period. However, three metrics are recognized as good proxies for value or value creation, and as such, are often used to guide investment decisions. These are the Net Present Value (NPV), Economic Value Added (EVA), and Value-at-Risk. If properly adapted, these metrics offer the most promise for quantifying the value of engineering systems.

2.3.3.1 Net Present Value

Consider an investment with present and future costs and income streams. The NPV of this investment (e.g. an engineering system) accounts for the time value of money, including the risk and opportunity cost, by appropriately discounting the associated costs and revenues. For an investment with cash flows accounted for or occurring at discrete points in time, its NPV is written as follows:

$$NPV = \sum_{t=0}^{n} CF_t / (1+r)^t \qquad \textbf{Eqn. 1}$$

where r represents a measure of risk, the risk-adjusted discount rate, t is the time period and CF_t is the cashflow (paid or received) at each time period. NPV discounts all payments to the current period, thereby allowing investors or decision-makers to compare projects over varying time frames and with different cashflow patterns. The NPV is considered a good proxy of value creation for the resources (to be invested), and as such, a simple rule follows: projects with negative NPV destroy value and should not be funded. The corollary of this rule is generally accepted (when only expected values are calculated): projects with positive NPV create value and can be accepted [44].

Furthermore, system A is considered a better investment than system B if it has a greater NPV. NPV calculation is relatively simple if cash flows can be accurately projected and the risk associated with the project is transparent [37]. However, in most cases there is a large degree of uncertainty associated with future cash flows and risk. Thus, deterministic calculations of NPV can convey a false sense of accuracy and may lead to wrong investment decisions. One way for dealing with this limitation is to consider the NPV a random variable and run Monte Carlo simulations with the various uncertainties accounted for in the inputs. The output of the simulations will be a probability density function of the NPV, which, unlike a single point estimate, can contributes to better value and risk informed decision-making. Caution should also be applied in using NPV when considering investment choices involving not a single project but a portfolio of projects, as attempting to maximize the NPV of each project does not necessarily lead to maximizing the NPV of the total portfolio[44].

2.3.3.2 Economic Value Added

It is desirable that decision-makers choose projects which produce the more efficient level of investment for stakeholders. This does not suggest the least expensive system but the one which creates the greatest investment value over the course of its lifetime with the more efficient utilization of resources [45]. The Economic Value Added (EVA) is a measure of the dollar surplus or the residual value created by an investment in an system or portfolio of systems [37]. Developed by US-based business consultants Stern Stewart and Co., Economic Value Added is premised on the fact that enterprises, or in our case engineering systems, should return more to their stakeholders than they consume in resources [46]. As such EVA is computed as the product of the excess return on the investment in the system and the capital investment in the system [37].

$$EVA = CapitalUsed \times (ROIC - WACC) \qquad \textbf{Eqn. 2}$$

This equation requires the assessment of two parameters, the total returns to the stakeholder from the engineering system as measured by the return on invested capital ($ROIC$) and the cost of the required resources as measured by the weight average cost of capital ($WACC$). Focusing on one parameter will cause the organization to either over-invest or under-invest its capital, thereby destroying value. For example, attempting to minimize cost will result in a decrease in the costs incurred. However, it may cause revenues to fall at an even greater rate leading to destruction in value. The Economic

Value Added compares the cost of acquiring the capital to the return from investing the capital to determine whether to embark on the project.

2.3.3.3 Value-at-Risk

Value-at-Risk (VaR) is a common risk measure used in financial risk management. It is defined as the possible maximum value loss over a given holding period within a fixed confidence level [47-49]. Mathematically, this may be written as follows:

$$VaR_{\alpha}(VL) = \sup\left\{vl \middle| P[VL \geq vl] > \alpha\right\} \qquad \textbf{Eqn. 3}$$

where *VL* is the random variable value loss and *100(1-α)*% is the confidence level. Given the value loss probability density function, the VaR identifies the percentile value for a given confidence level. The conceptual simplicity and ease of computation enables VaR to be readily adaptable to several applications including engineering system design[50,51]. For example, consider an engineering system which has a VaR of $20M at the 95% confidence level. The stakeholder may interpret this information in two ways. These are 1) there is a 5% likelihood that the value loss will exceed $20M or 2) the stakeholder can be 95% confident that the value loss will be less than $20M. Thus the VaR provides insight into the value risk associated with an engineering system.

Despite its simplicity, the VaR is charged with a number of conceptual issues, namely it disregards losses beyond the VaR level. The implication of measuring only percentiles results in the underestimation of risk for distributions with low kurtosis (i.e. fat tails) or a high potential for large losses [47,49,52]. As such the VaR is at times modified to address this issue. The conditional value-at-risk (CVaR) seeks to address this issue by incorporating information about the tail of the value distribution. CVaR is defined as the conditional expectation of the value losses for losses beyond the VaR level [47,52]. Mathematically, it is defined as follows:

$$CVaR_{\alpha}(VL) = E\left[VL \middle| VL \geq VaR_{\alpha}(VL)\right] \qquad \textbf{Eqn. 4}$$

CVaR, in drawing on information from the tail of the distribution, provides a better measure of the risk of value losses than VaR.

2.3.4 Limitation of Priced Valuation to Space System Design and Acquisition

The previous sections dealt with the "priced" value of investments, or projects that provide a revenue stream (i.e., a market exists for the services provided by these systems). A number of engineering systems however, national security or scientific spacecraft for example, do not meet this criterion. As such, it is difficult to observe the desirability of the system to stakeholder through a market mechanism. Several valuation approaches have been developed in an attempt to deal with the challenging but important issue of unpriced value assessment. In the next section, the concept of the unpriced valuation is explored. In particular, focus is given to those methodologies which are more applicable to space systems design and acquisition.

2.4 Unpriced Valuation Methodologies

The issue of practical methods for the valuation of systems with unpriced values has been explored in several fields, particularly in support of policy-making. As with the

Department of Defense and NASA, all government agencies are faced with limited resources. Thus it is impossible for the policy-maker to choose all alternatives under consideration. Trade-offs must be made. It is essential that the policy-maker understands the impact of each policy alternative on affected parties. As such, in policy analysis, costs and benefits may be monetized to enable a substantive comparative analysis. A secondary reason for the need to value unpriced resources is the determination of legal liabilities incurred as a result of policy action. For example, the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) has extended professional industry interest in Natural Resource Damage Assessments (NRDA) values [53]. Federal agencies are seeking the ability to assess the damages sustained and compensatory costs incurred during the exploitation of natural resources. Thus, it is essential that systematic methods of valuing these resources are developed and utilized. Three categories of valuation methodologies for resources, which may have a potential applicability to space systems, are provided in greater detail. These are expected utility theory, contingent valuation and hedonic pricing.

2.4.1 Expected Utility Theory

In neo-classical economics, economists rely on the basic premise that people select goods or services they value most highly. Similarly, in engineering system design and acquisition, engineers attempt to select systems for development and acquisition that they believe stakeholders value most highly. One economic construct often employed to articulate these preference relations (e.g. the preference for one system over another) is utility. The notion of utility and its resulting functions reflect a correlative to desire or want, that is, utility reflects the satisfaction a stakeholder receives from an engineering system relative to another system [54,55]. When choosing between riskless alternatives the objective of the decision-maker is to select the alternative (e.g. engineering system) which maximizes the utility [56]. However, as one might recognize decisions are often made under uncertainty. Expected utility theory takes the notion of utility a step further, by attempting to capture the behavioral idiosyncrasies of stakeholders when making decisions under risk. In particular, the expected utility theory proposed that in the presence of uncertainty rational stakeholders weight the utility of each outcome (μ_i) by the probability of that outcome (p_i) occurring as shown [35]:

$$E[\mu] \equiv \sum_i p_i \mu_i \qquad \textbf{Eqn. 5}$$

Furthermore, under the theory of expected utility it can be shown that stakeholder maximize the expected utility when making decisions [57]. In the context of space system design and acquisition, the objective of the decision-maker is to identify the engineering system for acquisition which maximizes the expected utility.

While expected utility theory is adopted as one of the pre-eminent paradigms in rational decision-making, there is a number of critiques about it underlying assumptions [58]. Most notable among these critics are Kahneman and Tversky [18]. These economists highlighted there were classes of decision under risk problems which routinely violated the assumptions of expected utility theory. In particular, it was noted that decision-makers do not necessarily conform to the expected utility rule put forward by von Neumann and Morgenstern and as given in Eqn. 5, but rather decision-makers tend to overweight outcomes that are considered certain relative to outcomes which are less probable. This alternative model of decision-making under risk was formulated into a descriptive model of rational choice known as prospect theory. Despite the fact it is generally accepted that expected utility theory may provide misleading inferences about how stakeholders make decisions, it continues to be a dominant paradigm in modeling decisions under uncertainty due to its “attractive consistency properties” [59] .

2.4.2 Contingent Valuation

Contingent valuation is a direct nonmarket valuation model. In the absence of a market for the flow of services the system provides, the contingent valuation methodology seeks to create a hypothetical market by asking stakeholders how much they are willing to pay for a system [60,61]. It is a survey based approach, which utilizes questionnaires to extract information about the preferences and value placed on system attributes from the stakeholders [62]. Data collected from the survey can be analyzed statistically to create a value profile of each attribute.

This methodology has the advantage of providing an economic valuation of the space system when compared to the expected utility method. However, contingent valuation methodologies can be expensive to administer, and they involve numerous technical challenges. The development and mechanism through which a survey is delivered to the sample of stakeholders plays a critical role in ensuring the integrity of its results. The structure of the questions should directly reflect a hypothetical market which mirrors the actual market being examined. Thus it is important that the analyst understands the way stakeholders think about the value of the system [62,61]. This will drive the structure and type of the questions presented and helps to eliminate possible biases in the survey. In addition, the survey should not be administered in an environment that influences the stakeholder’s responses. Finally, the value profile created is hypothesized as a true market cannot be fully estimated based on intentional behavior as opposed to actual behavior [62,60].

2.4.3 Hedonic Pricing Methods

Hedonic techniques are a set of regression methods employed to measure the value assigned to attributes of the system by the stakeholder. It is premised on the idea that the engineering system has a number of attributes which individually constitutes its value to the stakeholder. The price the stakeholder is willing to pay for the system is assumed to be a function of the value placed on the characteristics. More practically, hedonic pricing techniques utilizes the systematic variation in the price between two or more systems due to heterogeneity in the systems’ attributes to infer the stakeholder’s willingness to pay for a given attribute [63,64]. A common functional form that links the variation in price to the variation in attributes is given as:

$$P_k = \beta_0 + \sum_{j=1}^{m} \beta_j X_{kj} + \varepsilon_k \qquad \textbf{Eqn. 6}$$

In this linear relationship X_{kj} is the j^{th} attribute of system k, and the coefficient β_j is the per unit value which the stakeholder places on attribute X_j. Linearly combining the marginal value for each attribute provides the price, P_k , for the engineering system.

2.4.4 Limited Use of Unpriced Valuation Methods

With the exception of utility theory, unpriced valuation techniques have found limited implementation in space system design and acquisition. It is not entirely clear why this is the case. However, there are a number of possible factors that may have contributed to their limited use. First, there is the lack of data available on passed missions. It is noted that no comprehensive database exists as the history of projects are often not recorded[1] [65]. As a result, data on space missions which would allow the engineer to dissect the success (or failure) of a mission and relate this success (or failure) to the technical parameters of the system and programmatic characteristics are limited. Second, while a number of unpriced valuation techniques have been created in the areas of policy-making, these techniques have limited visibility in system design and acquisition. As such, utility theory is often the value assessment approach of choice as it requires little data beyond that intrinsic to the mission under consideration.

2.5 Value in Aerospace Systems Design and Acquisition

Unlike the concept of value in economics which has been discussed for over three hundred years, the concept of value in aerospace systems design and acquisition is less mature. Arguably, the desire for analytical value assessment in the field of aerospace systems design and acquisition may be traced to the 1960s. Following the end of World War II, then Secretary of Defense Robert McNamara noted that the U.S. government could no longer extend an unlimited budget to the military. Instead, the Department of Defense must select a portfolio of systems that offers the highest return on public investment given its operational need [66]. He employed two economists to structure the acquisition of weapons systems based on a quantitative economic approach. These

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[1] although there are currently attempts at building a mission database

economists postulated that the acquisition of weapons systems is an economic problem in the allocation of resources and the criterion for the acquisition of the systems should be the "the maximization of gains-minus-cost if the two are commensurable…or, if they are not, the maximization of gain for a given cost or the achievement of given objectives at minimum cost" [67,68]. Following this contribution to defense economics, a number of practitioners attempted to quantify the value of the aerospace system by examining its functionality per cost or cost per functionality [69,70,22]. While these approaches represent a step in the right direction, they relied on a faulty assumption, that is, these approaches assumed that there exists a monotonic relationship between functionality per cost and value. Specifically, it is assumed that the benefits resulting from economies of scale (i.e. increased functionality per cost) translate into more valuable satellites, and is what has been noted in the previous chapter as a cost-centric mindset to acquisition and design.

2.6 Use of Value Models in Space Systems Design and Acquisition

Despite the fact that initial attempts at value analysis were primarily cost-centric and limited in their ability to assess value (See Chapter 1), value models continue to be essential in aerospace system design and acquisition. These models are important in system design and acquisition in that they are vehicles through which engineers map system attributes to the satisfaction level of the stakeholder. Ideally, the value model is a quantitative encapsulation of stakeholder preferences and provides engineers with insight about the impact of design choices on the satisfaction level of the stakeholder [71-73]. Motivating the development of value models is the complexity of the engineering systems design problem in which objectives are often conflicting and the implications of technical trade-offs to user satisfaction is not immediately obvious. Thus value models are used in diverse capacities depending on the analysis being conducted by engineers. Collopy (2009) identifies four such capacities [73].

C1. Value models may be used in trade studies to rank designs under consideration

C2. Value models may be used in design problems as an objective function to select the optimal design for stakeholder satisfaction

C3. Value models may be used for technology evaluation and to derive the value of a particular system attribute

C4. Value models may be used to evaluate the design space and determine regions (if any) where the best designs are clustered.

These four categories point to the potential applicability of value models in aerospace systems design and acquisition.

2.7 Value Assessment of Priced Aerospace Systems

For the purposes of value analysis, space systems may be divided into two categories, priced and unpriced systems. A priced space system is defined as one in which the operator of the system receives rent or quasi-rent for the flow of services provided by space system and/or one in which the user of the system purchases unsubsidized services of the space system [33,35]. This rent or quasi-rent is often allocated through a competitive market mechanism. For priced systems, stakeholders' preferences for the services of the system are revealed through their market behavior, and these preferences are aggregated (to a certain extent) into cashflow streams. These cashflow streams may be used to directly assess the value of the system to said stakeholders. Thus, the value of a priced space system to stakeholders may be proxied by discounting 1) the generated cashflows to stakeholders (e.g. satellite operator) from the space system or 2) the expended cashflows by the stakeholders (e.g. end-users) for the services of the space system. Priced space systems are primarily found in the commercial space market.

In recent years, a number of papers has emerged to quantify priced value in aerospace systems engineering and design. In 2003, Saleh et. al developed a new methodology to determine the value of flexibility provided by on-orbiting servicing in space systems by accounting for a time variant flow of services relative to an expected flow of services over the operating life of the spacecraft using Decision Tree Analysis [74]. Peoples and Wilcox (2004) utilized a stochastic NPV method to understand the financial implications of design choices for a commercial aircraft, Shockley (2007) examined the value of Jet Engine Maintenance Contracts using Real Options, Long et al. (2007) estimated the service price a satellite operator would be willing to pay for an upgradable commercial communication satellite and the list goes on [23,75-79,186]. In 2008, Fernandez proposed that all project information can be aggregated into two parameters, risk and return, once a suitable robust method has been developed. In this analysis, the return may be measured by extended NPV and risk by the range of extended NPV under different conditions. From there, it is possible for a stakeholder to identify solutions or alternatives which maximizes the value extracted from the system for a given level of risk.

As the highlighted studies indicate, value methodologies and metrics for priced aerospace systems tend to more prevalent in non-space systems than in space systems. Value studies for non-space systems are often used in diverse applications such as engine maintenance, aircraft speed selection, aircraft structures analysis, and general aircraft maintenance operations. In contrast, value studies for space systems tend to be focus on system flexibility and in some cases, on orbit servicing.

2.8 Value Assessment of Unpriced Aerospace Systems

Unlike priced aerospace systems, in which attributes may be mapped directly to a monetary value, a large number of systems in the aerospace industry are termed upriced, and vary from priced systems in a number of ways. First, unpriced systems do not directly generate cash inflows from the end-users, and consequently, stakeholder preferences are not readily revealed and monetized [34]. Second, the costs and benefits associated with unpriced systems are often incommensurable and are difficult to aggregate into a single useful metric [67,68]. Third, unlike priced systems in which the space system's services are allocated through a competitive or quasi-competitive market, the market mechanism for unpriced systems is generally a monopsony (monopoly) in which there is a single demander (supplier) of the services provided by the space system. Thus, the space system operator does not receive rent or quasi-rent for the services of the system, and the value of these types of systems must be determined using a number of indirect valuation approaches. Examples of unpriced space systems include military intelligence, surveillance and reconnaissance satellites, and earth science, heliophysics and interplanetary spacecraft. In order to overcome this difficulty, unpriced value assessment is generally implemented in two manners within the aerospace system design and acquisition community. These are multi-attribute utility theory and multi-criteria decision making.

2.8.1 Multi-Attribute Utility Theory

Multi-Attribute utility theory (MAUT) has proved useful in aerospace systems design and acquisition as engineers are often faced with the problem of determining the value of systems based on multiple attributes, the measures of which are incommensurate [16,80-83]. By developing a utility function for the system based on the attributes of the system and stakeholder preferences, the engineer encapsulates the “goodness” of the system relative to the stakeholder. MAUT is based on the economic theory of utility theory [84,85]. The parameters of the multi-attribute function are determined through an assessment of equivalent lotteries based on the system attributes [86,87]. Relevant stakeholders are surveyed to determine their indifference between a lottery with a certain outcome and a lottery with uncertain outcomes, by varying the likelihood of the each outcome in the latter. The utility function is then specified based on the outcome of the equivalent lottery and commonly range from 0 (lowest level of utility) to 1(highest level of utility). MAUT is based on a number of axioms, which if not satisfied by the decision-maker preferences, may invalidate the utility analysis [87,89]. The axioms are completeness, transitivity, monotonicity and continuity. Satisfying these axioms ensures that the stakeholder’s preferences are well defined and consistent.

While MAUT offers a way to quantify the benefit of the system to the stakeholder, a number of weaknesses exists. First, stakeholders’ behavioral inconsistencies may emerge, which results in violations of the four axioms. In practice, stakeholders often deviate from the expected behavior as defined by the axioms [18,58].

As such, engineers may run into difficulties with creating the utility curve. Second, even if the behavior of stakeholders is consistent when the four axioms of expected utility theory, gathering survey information may be costly and operationally difficult. Questions must be structured so as not to unintentionally bias the stakeholders and the survey should not be administered in an environment which influences the responses of the stakeholders. If engineers do not adequately account for these weaknesses, utilizing a MAUT methodology may produce a ranking of design alternatives that is inconsistent with stakeholder preferences.

2.8.2 Multi-Criteria Decision-Making

Frequently, engineering system design is characterized by a multi-objective criterion space in which trade-offs must be made between conflicting objectives. System engineers are tasked with identifying a set of optimal design vectors which satisfies each objective simultaneously. The practice of systematically pinpointing this optimal set is known as vectorial optimization, and a wide array of concepts and methodologies have been developed which enables engineers to solve such optimization problems. Examples of these methodologies include weighted global criterion method, lexicographic methods and the weighted sum method among others [88-90]. Two vectorial optimization approaches commonly used in aerospace systems design and acquisition are discussed in more detail in the following sections.

2.8.2.1 Pareto Optimality

Formally, a vectorial optimization problem may be defined as follows [88]:

$$\underset{\mathbf{D}}{\textbf{Minimize}}\ \mathbf{F(D)} = [\mathbf{F_1(D), F_2(D), \ldots\ldots\ldots, F_n(D)}]^{\mathbf{T}}$$

Eqn. 7

$$\textit{subject to}\ g_k(\mathbf{D}) \le 0, \qquad k = 1,2,3,\ldots,l$$
$$h_u(\mathbf{D}) = 0 \qquad u = 1,2,3\ldots,w$$

where ***D*** is the design vector, *n* is the number of objective functions, *l* is the number of inequality constraints and *w* is the number of equality constraints. ***F(D)*** is the objective function vector, and $g_k(\mathbf{D})$ and $h_u(\mathbf{D})$ are inequality and equality constraints respectively. Unlike a single-objective space in which it is possible to identify a unique design vector which optimizes the objective, multi-objective criteria spaces are more complex producing a set of optimal designs. The concept of Pareto optimality deals directly with multi-objective optimization and formalizes the trade-off between a set of contradicting objectives. Under Pareto optimality, each feasible design vector in the design space is mapped to a criterion vector in the criterion space. Ideally, the criterion vector is a representation of the design value to the stakeholder. If objectives are formulated such that minimizing each objective is desirable, a Pareto optimal design may be defined as follows [88]:

> *A design,* $\mathbf{D}^* \in \mathbf{D}^{\mathbf{m}}$, *is Pareto optimal iff there does not exist another design,* $\mathbf{D}_j \in \mathbf{D}^{\mathbf{m}}$, *such that* $\mathbf{F}\,(\mathbf{D_j}) \le \mathbf{F}\,(\mathbf{D^*})$ *and* $F_i\,(\mathbf{D_j}) < F_i\,(\mathbf{D^*})$ *for at least one objective function.*

In other words, a design is considered Pareto optimal if there is no other design that can improve at least one objective without causing deterioration in at least one of the remaining objective functions. The locus of Pareto optimal points is known as the Pareto frontier. All points on the Pareto frontier are non-dominated designs. Visually, the concept of the Pareto frontier is illustrated in Figure 4 for the case of two objective functions. Each dot on the figure represents a design mapped to the criterion space. The red curve indicates the Pareto frontier formed by Pareto optimal designs. While the concept of Pareto optimality offers a systematic approach to reducing the number of design alternatives under consideration, in reality it is often necessary to select a single final design due to resource constraints. Thus engineers must find the best compromised design solution based on stakeholder preferences [91].

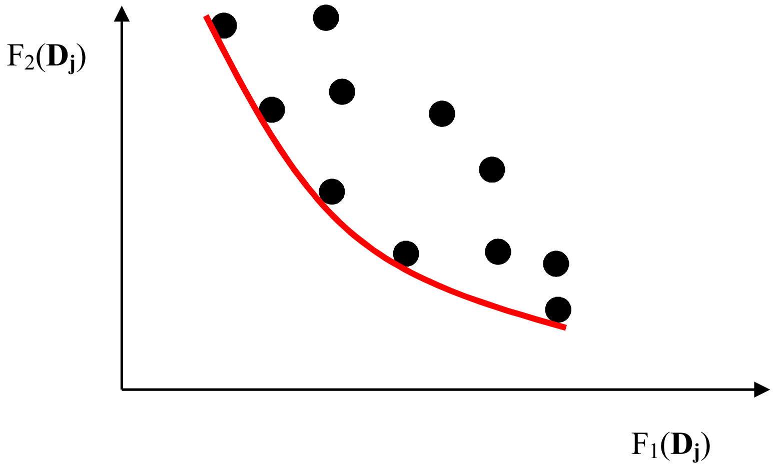


Figure 4. Illustration of a pareto frontier

2.8.2.2 Compromised Designs

A second conceptual approach to vectorial optimization is a compromise solution. Unlike Pareto optimality which yields a set of design solutions for consideration, a compromise solution yields a single design solution based on its Euclidean distance from an ideal point [88,91,92]. Under the compromise design approach, an ideal point (**F***) is defined which is the theoretical best solution in the criterion space and does not compromise any criteria. In other words, assuming that each objective function can be optimized individually, the elements of the ideal point consist of all the individual objective optima in the criteria space. Next a new function, $F_d(\boldsymbol{D}_j)$, is defined that is the sum of the Euclidean norms of each objective function from the ideal point. This function is shown in Eqn. 8.

$$F_d\left(\mathbf{D_j}\right) = \left\{ \sum_{i=1}^{n} w_i \left[F_i(\mathbf{D_j}) - F_i^* \right]^2 \right\}^{1/2} \qquad \textbf{Eqn. 8}$$

where w_i is the weight associated with each objective function and is a reflection of the stakeholder preference for optimizing that objective relative to the other objectives. In constructing a new scalar function, the multi-objective criteria space is collapsed into a single objective criterion space in which minimizing the objective function, $F_d(\boldsymbol{D}_j)$, provides the best compromised solution. Figure 5 illustrates the concept of the compromise solution with two conflicting criteria. The figure shows an identical criteria space to that in Figure 4. The green dot represents the ideal solution, while the blue lines are Euclidean norms from a specific design alternative to the ideal point. Designs which are least likely to satisfy the stakeholder's objectives tend to be furthest from the ideal solution. Note also that once the Euclidean norm is minimized, the best compromise design will also be a Pareto optimal design.

There are a number of issues which should be addressed when using the concept of the compromised solution. First, the function, $F_d(\mathbf{D}_j)$, will produce questionable results if each function is in different units. Thus it is necessary to transform each objective function, so as not to inadvertently bias the design solution towards fulfilling a particular objective [88]. Second, the process of quantifying preferences into a weighting scheme may be difficult, resulting in questionable schemes at best and non-transparent schemes at worst.

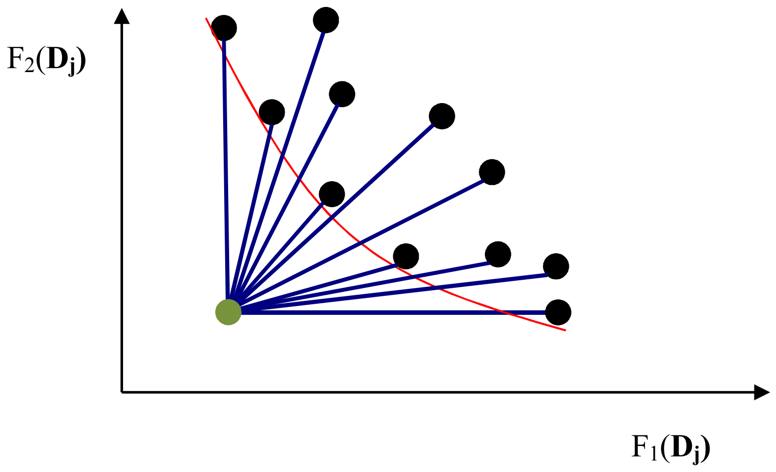


Figure 5. Compromised solution

2.9 Examples of Unpriced Value Models in Industry

In 2006, the American Institute of Aeronautics and Astronautics signaled the potential importance of value-centric design and acquisition to the aerospace industry with the formation of the Value-Driven Design (VDD) Program Committee. The official purpose of this committee is "to develop, mature, document, and release a design method that identifies and optimizes the attributes of the product or system of highest value to its stakeholders" [93]. The formation of this committee was followed by the issuance of a Broad Agency Announcement for the F6 program by the Defense Advanced Research Project Agency (DARPA) in July 2007 [94]. This program provided resources for academia and industry to conduct value driven system development and create analytical value tools with which to conduct value analyses. Spurred by the DARPA F6 program, a number of value analyses in the context of non-revenue generating space systems started emerge. For example, Orbital Sciences Corporation developed a benefit model based on the comparative pricing of the data feed [95]. Given this pricing structure, Orbital calculated the expected net present value of the satellite services. Furthermore, by translating the various uncertainties in the model to uncertainty in the net present value, the value risk of the satellite was determined. Lockheed Martin created a constant pricing structure per megabyte for the data feed based on the desire to ensure a reasonable profit margin [17]. Boeing created a value-centric design methodology tool called RAFTIMATE which determined the value of fractionated satellite architectures using utility analysis and cost [96]. Northrop Grumman developed a multi-attribute utility model to assess the value of the satellite services [17].

2.10 Uncertainty and Risk in Value Analysis

Investments in engineering systems are characterized by decision-making under uncertainty. This uncertainty arises from several factors, among which are technical and economic, and translates into imprecision in the expected value of the system to the stakeholder. It may be argued that from a stakeholder’s perspective an engineering system is an investment, and the decision to acquire said system is value based. Therefore, it is imperative that engineers understand the potential impact of uncertainty on the system value when making design choices.

Uncertainty may be defined indirectly based on the definition of certainty. Certainty is “a condition in which a decision-maker knows everything needed in order to select the action with the most desirable outcome” [97]. Under this condition, the decision-maker is assured that the selected design vector will maximize the final value of the system. Uncertainty is therefore a condition in which the decision-maker does not know everything needed to select the most desirable outcome. Numerous taxonomies of uncertainty exist with perhaps the most common classification being aleatoric uncertainty, which arises from variability in some aspect of the system under study, and epistemic uncertainty, which is due to ignorance about some aspect of the system under study [98,99,100].

For the purposes of value analysis, uncertainty falls into two distinct categories. The first category involves the lack of knowledge about the possible opportunities to enhance system performance or system value. The consequence of this type of uncertainty is that while the system delivers the expected system value, the system value may be sub-optimal. Obtaining additional information about the system in its environment, such that this type of uncertainty is reduced, may lead to greater system value for the stakeholder. The second category involves the lack of knowledge about the adverse events which compromises system value. In the presence of this uncertainty, the system may experience performance shortfalls and is unable to meet the defined performance or value expectations. Incorporating information about adverse events may lead to a more robust system, or systems that are more likely to maintain performance over a wider range of environmental variability.

Risk, while it emerges in part due to uncertainty, differs from uncertainty in that it involves not only the lack of knowledge about the occurrence of events, but also considers the consequences of an event or scenario should it occur. In other words, a consideration of risk involves answering three key questions [101]:

Q1. What are the negative scenarios that may occur?

Q2. What are the likelihoods that these scenarios occur?

Q3. What are the consequences of these scenarios occurring?

These three questions imply that risk is defined as a triplet in which engineers should possess information relating to the type of negative scenarios that may occur, the likelihood of these negative scenarios occurring and the consequences should the adverse events occurs. This definition of risk is codified as:

$$R_i = \left\langle S_{i,} p_i, C_i \right\rangle \qquad \textbf{Eqn. 9}$$

where *i* in the index of scenarios, S_i is scenario *i*, p_i is the likelihood of scenario *i* occurring and C_i is the consequence of S_i occurring.

Traditionally, managing uncertainty in system design has focused on managing risks, with a number of risk assessment methodologies or techniques being developed by various organizations [102-106]. However, as has been discussed, risk is but one element of uncertainty and simply managing risk offers a myopic perspective of value uncertainty analysis in system design and acquisition.

2.11 Ex-Ante Value Analysis versus Ex-Post Value Analysis

Before concluding the discussion on value analysis in space system design and acquisition, one important issue must be addressed, that is, the issue of ex-post value assessment and ex-ante value assessment. Value assessment may be either ex-post or ex-ante. An ex-post analysis is an assessment of the system value after the space system has been fielded. Benefits to various stakeholders have been realized and value assessed reflects the actual benefits of the system to stakeholder(s). Therefore, the ex-post value assessment may be described as backward looking and is important in determining whether a system achieved its expected value.

An ex-ante analysis of system value occurs before the system has been fielded and the benefits to the stakeholder(s) are unrealized. Fundamentally, one difference between an ex-post analysis and an ex-ante analysis is the incorporation of uncertainty about the future. Decision-makers are rarely, if ever, faced with a certain future. Ex-ante value analysis incorporates information about future events. It is an attempt to determine how the future will unfold, and in doing so, forecast the benefits the system provides to its various stakeholders. Thus ex-ante value assessments may be considered forward looking and are often conducted in the system design and engineering phase, where systems are not yet fielded. These two concepts are illustrated in Figure 6.

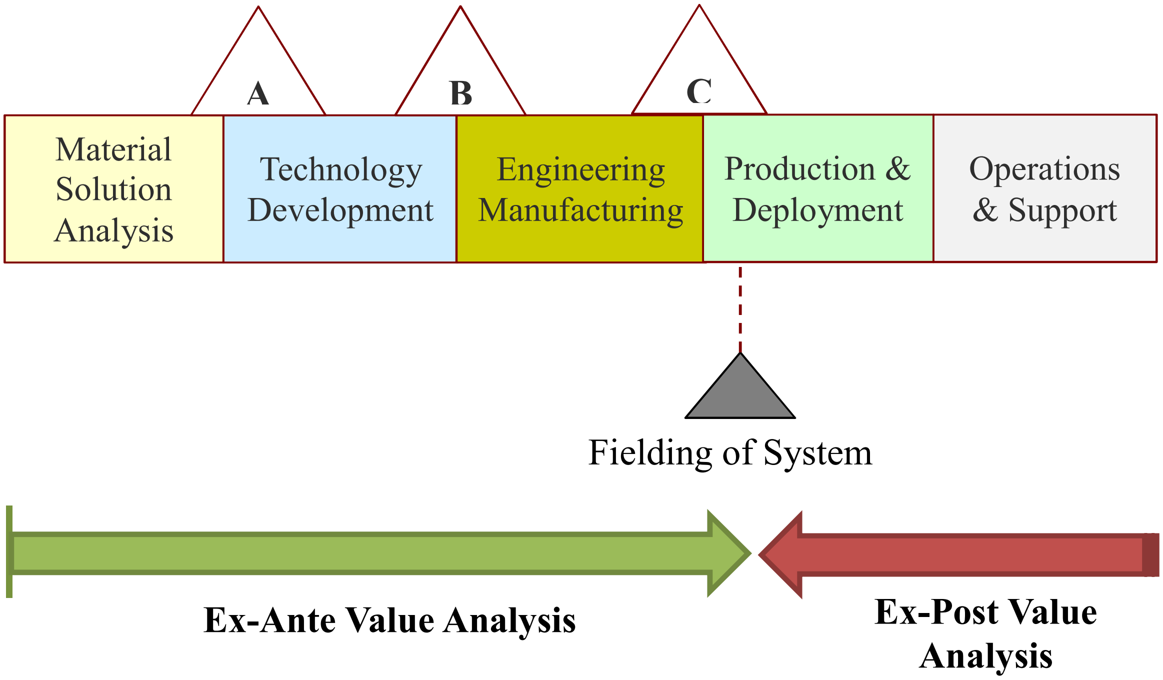


Figure 6. Temporal dimension of value analysis

Value-centric methodologies focus on assessing the value of the system to aid in design and acquisition decisions before the fielding of the space system. As such, the relevant category of the temporal dimension for design and acquisition is ex-ante value analysis. Combining both the temporal and content dimension (See Figure 3) indicates that in the context of space system design and acquisition, value is a viewed as a ***forward looking utility driven concept*** incorporating information about stakeholder preferences and environment.

2.12 Gaps in Value-Informed Space Systems Design and Acquisition

On an intuitive level, it is possible to understand why there is a slow shift in the space industry from the dominant cost- and performance mindset towards a value-centric design and acquisition mindset as value-centric approaches are more information-intensive. However as the literature review indicates, there are a number of gaps that currently exists in value-centric analysis. The first gap points to the inconsistency in value-centric approaches in priced system design and acquisition. The cadre of value-based metrics is neither extensive nor well accepted. Although there is an effort to develop such tools, further exploration is needed to identify suitable value-centric frameworks which extensively incorporates information about the preferences of the stakeholder and the relevant environments for decision-making in space system design and acquisition.

The second gap focuses on the argument that value-centric approaches to system design and acquisition result in improved decision-making (due to the additional environment and preference information embedded) over cost-centric approaches. This information argument has been well articulated qualitatively. However, to date, there appears to be little quantitative analysis to test such a hypothesis. There are no apparent analyses indicating that value-centric methodologies and metrics potentially offer stakeholders greater insight into the system value performance relative to traditional cost-centric metrics as has been proposed.

The third gap involves a strong bias in the valuation of unpriced systems towards multi-attribute utility theory and vectorial optimization. In some cases such methodologies may be operationally costly to administer and often involve trade-offs between non-commensurate metrics. While these techniques enable the stakeholder to map a multi-dimensional attribute (or criteria) space into a single non-dimension metric (or single dimension criterion space), resulting metrics may be non-intuitive, non-transparent, and if the analysis is not rigorously documented, may be difficult to reconstruct. Alternative frameworks are needed for assessing unpriced value in space systems which transparently links the system's attributes to the benefits received by the stakeholders.

The fourth gap revolves around value uncertainty analysis. In space system design and acquisition, the traditional dominant mindset in uncertainty analysis focuses on minimizing risk. However, focusing on risk is myopic as it de-emphasizes the potential benefits of uncertainty offered through the upside potential. Thus, it is essential to uncouple the two constituents of uncertainty, upside potential and downside risk, to fully understand the implications of uncertainty.

To aid in addressing these gaps highlighted in the literature review, the remaining chapters of this dissertation presents: 1) the conceptual basis for understanding value 2) information-theoretic value frameworks for priced and unpriced systems, and 3) applicable metrics and analytical tools for value-centric analysis.

CHAPTER 3

PRICED VALUE IN SPACE SYSTEMS DESIGN AND ACQUISITION

This chapter has two objectives: 1) to develop a value-centric framework and the corresponding analytical tools for the design and acquisition of a priced space system, and 2) to demonstrate, both qualitatively and quantitatively, the assumption that the additional information embedded in the value-centric framework leads to higher valued space systems for the stakeholder.

3.1 Value of Additional Information

It is often presumed that information has some forecasting and economic value, in that information enables a greater understanding about the expected performance of the system in its environment. Therefore, engineers may select design options which yield greater expected pay-offs in the presence of the information than had the engineers selected design options in the absence of that information [107]. Thus one of the primary underpinnings of a value-centric framework is that information has value, and appropriately incorporating this information into system design and acquisition leads to higher valued space systems for a stakeholder than systems selected in a cost- or performance-centric framework. But is the assumption that information has value valid?

The value of information is often measured as the difference in expected pay-off of a decision made in the presence of information relative to one made in the absence of information [108-110]. Stated mathematically, the value of information (*VOI)* may be defined as follows [108,109]:

$$VOI = \int \pi(\alpha, D_\alpha^*) dF(\alpha) - \int \pi(\alpha, D) dF(\alpha) \qquad \textbf{Eqn. 10}$$

The first variable, *D*, represents the design vector controlled by engineers. The second variable, α, may be stochastic in nature and is beyond the control of engineers. This variable is a quantification of the environmental factors which affect schedule, performance, cost and value. Together, the design vector and environmental factors determines the pay-off, $\pi(\alpha, D)$ of the system to its stakeholders. As the occurrence of environmental factors is uncertain, the pay-off is uncertain. Thus integrating over the range of environment factors produces an expected pay-off to the stakeholder as shown:

$$E_\alpha[\pi] = \int \pi(\alpha, D) dF(\alpha) \qquad \textbf{Eqn. 11}$$

Next assume that the objective of the stakeholder is to maximize the expected pay-off. If engineers possess full information about the environment, that is α is known before the design vector is chosen, engineers will select the design vector which maximizes the expected pay-off. An upper limit for the expected pay-off is given as:

$$\sup E_\alpha[\pi] = \int \pi(\alpha, D_\alpha^*) dF(\alpha) \qquad \textbf{Eqn. 12}$$

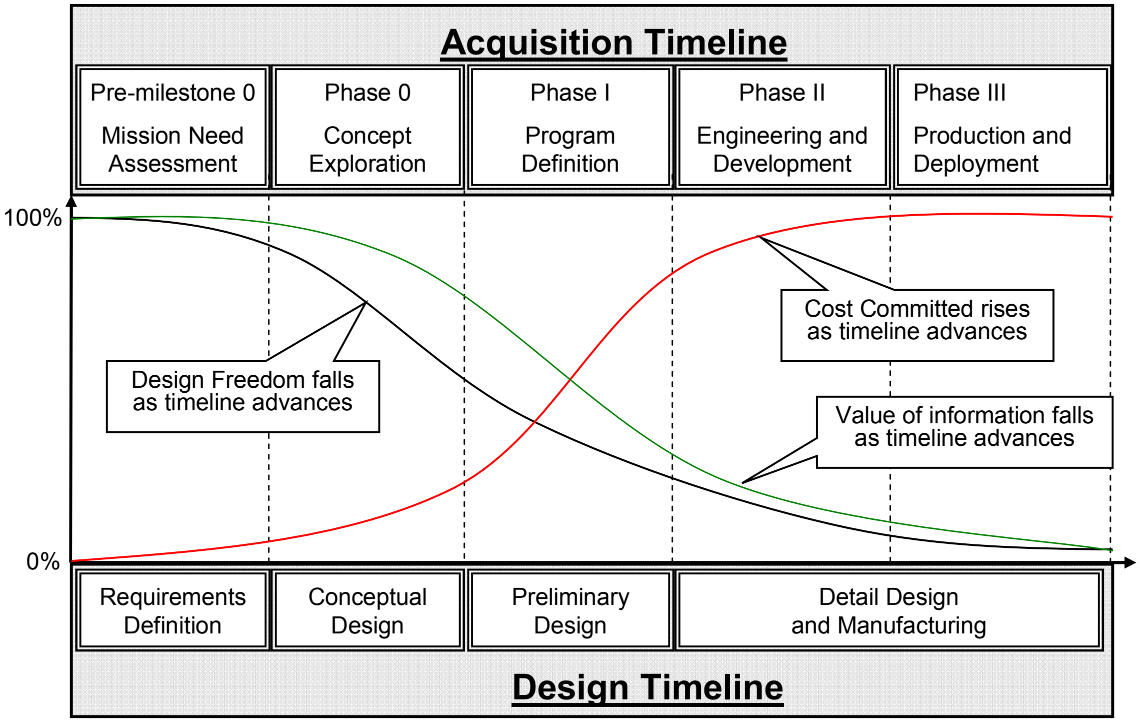
Thus, the value of perfect information is quantitatively described as the difference between the expected pay-off of the space system when all relevant information is embedded into the design and acquisition process and that only when partial information is embedded. The difference is given by Eqn. 10 which is always greater than or equal to zero. This formulation of the value of the additional information has two implications for system design and acquisition.

Implication 1: The value of information is minimal in well-characterized environments

If α is known then engineers will select the design vector that maximizes the expected pay-off. Therefore, from Eqn. 10, there is no value to obtaining additional information about the system in its environment [111]. This scenario reflects the case of a well characterized environment. Under such circumstances, cost-centric approaches may be appropriate. In contrast, for environments that are distinctly uncertain having additional information about the system in its environments is valuable to engineers. As such, value-centric approaches are more appropriate in uncertain environments. The additional implication is noted by Macauley (2005), and Letson, Sutter and Lazo (2007) [112,113].

Implication 2: Information has little value if decision-makers cannot act on the information

From a system design and acquisition perspective, incorporating as much information as possible is more critical at the conceptual phase than subsequent phases. In this phase, the system design is fluid and engineers may adjust numerous technical parameters to optimize performance or improve robustness in the presence of environmental factors. In addition, as design freedom is greater at the conceptual phase (i.e. design is not yet fixed), the cost committed by the stakeholder is still relatively low. Beyond the conceptual phase, design changes become increasingly restricted and costly. In these latter phases, fewer design actions are available to engineers and decisions in the presence of information are unlikely to differ substantially from those in the absence of information (i.e., the engineers are unlikely to make major changes to the system design). Thus the value of the additional information declines as the system design moves from the conceptual design phase to the detailed design phase to the production, deployment and operation support phase. This is illustrated in Figure 7.



Adapted from Porter, A.L., Read, W.H., The Information Revolution: Current and Future Consequences, Ablex Publishing Corporation, London England, Ch. 3

Figure 7. Value of information as design and acquisition timeline advances

It is therefore desirable to incorporate as much information as possible into the conceptual design phase. In these early phases, value-centric design approaches may be advantageous over cost-centric and performance-centric approaches due to the broader information set value driven approaches utilize.

3.1.1 Value of Additional Information in a Strategic Capacity

In a number of industries, studies have demonstrated the economic value of additional information in helping stakeholders to manage investments. While in some cases, the investment is not necessarily in engineering systems, there are certain insights which may be gleaned from considering a number of these studies that are applicable to aerospace systems. Consider the insights drawn from these industries in relation to the value of information in managing risks. Complex aerospace systems are often characterized by a high degree of risk due to the fact that investment in these systems is substantial and irreversible. These risks, which may be programmatic, technical, operational or environmental in nature, represent challenges to engineers and program managers. One proposed benefit of the value-centric approach to design and acquisition is that the additional information incorporated into the design and acquisition process enables better characterization, and therefore management, of the various risks the system may experience in its operational environment. This particular value of additional information has been demonstrated in a number of industries outside of the aerospace industry. For example in the climate and weather, Kaiser and Pulsipher (2006), Considine et al. (2004) indicated that incorporating more information about weather patterns in designing operating procedures may lead to longer operating times and lower opportunity costs for oil companies[110,114]. Lave (1963) and Wilks and Wolfe (1998) suggest that there is forecasting value in having more accurate information about weather patterns which may place harvest yields at risk [115,116]. In operations research, studies show that incorporating additional demand and supply information into the design of supply chains leads to lower risks of inventory excess or shortfalls [117]. Overall, these studies indicate that there is value to having additional information when managing risks. The corollary to system acquisition and design is that having additional information about the system in its environment may - in addition to increasing the benefits the stakeholder derives from the system - lead to better risk management.

From this qualitative discussion, it is clear that there is validity to the argument for embedding additional information about stakeholder preferences and the system's environment in space system design and acquisition. The following sections present a value-centric framework for priced space systems and supporting analytical tools, as well as quantitatively explore the implications of having this additional information.

3.2 Value-Centric Framework for Priced Space Systems

Value assessment is intrinsically a multi-disciplinary effort, and a value-centric framework for the design and acquisition of space systems is a "hub" for contributions from multiple functions within a company or agency. For example, in the case of a corporation, value assessment of a space system should include the traditional contributions from Engineering as well as analyses from Marketing, Sales, and Finance. The objective of the value-centric framework is to help engineers understand the value implications of design choices, and in doing so, make value-based or, at a minimum, value-informed design and acquisition choices. Brathwaite and Saleh (2009) developed a value-centric framework for commercial communication satellites [118]. A modified version of this value-centric framework is presented for priced space systems in Figure 8; shown on Figure 8 are the various modules or analyses required for value assessment, and how these modules relate and feed into each other. The framework consists of the following three key analyses blocks and their constituent modules:

B1. Traditional Engineering Analysis, which consists of the System Design Module and the Lifecycle Cost Analysis Module. The System Design Module generates the set of feasible technical parameters and the Lifecycle Cost Analysis Module estimates the cash outflows of the system.

B2. Traditional Business Analysis, which comprises of the Market Analysis Module and the Revenue Analysis Module. The Market Analysis Module assesses the market demand and pricing for the services of the proposed system as well as the associated demand and pricing volatilities, while the Revenue Analysis Module estimates the cash inflows per unit time that the system can generate in a given market environment.

B3. Value Based Decision Analysis Module, which encompasses the Value Analysis Module and the Decision Analysis Module. The Value

> Analysis Module integrates inputs from the Lifecycle Cost Analysis and Revenue Analysis modules and calculates the net value of a system as a random variable, while the Decision Analysis Module identifies the final system or portfolio of systems for further analysis and development.

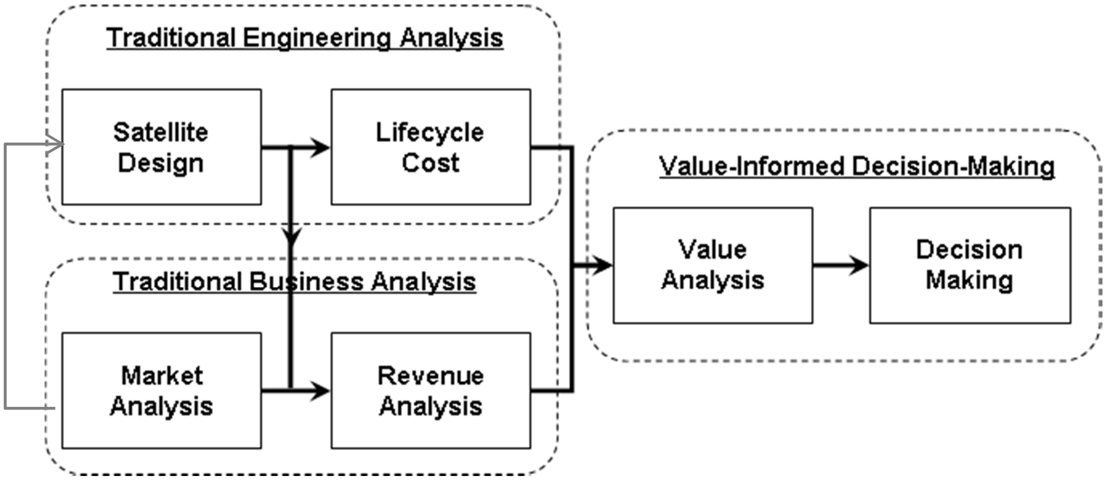


Figure 8. Value-Centric framework for commercial engineering systems

The value-centric design framework is applied to the case of a satellite operator faced with the decision of selecting the payload size of a satellite. The payload size is measured by the number of 36 MHz Equivalent transponders. The satellite operator first identifies a market need, as indicated by the arrow connecting the market analysis module to the satellite design module, and then considers a number of factors in making the design decision. Among these factors are: What is the value to be gained for a given payload size of the system? How robust is the system to a loss in value from adverse market conditions? The value-centric framework enables the direct consideration of these issues within the engineering environment. In doing so, it allows the satellite operator, in conjunction with the engineer, to make design choices which are value-informed. To begin demonstrating this decision process, the implementation of each module is provided.

3.2.1 Traditional Engineering Analysis

The objective of the Traditional Engineering Analysis Block is to generate a set of technically feasible design vectors, as well as estimate the resource expenditures to develop, manufacture, operate and retire the satellite. These resource expenditures, measured by costs, are assessed over the lifetime of the satellite.

3.2.1.1 Satellite Design Module

The engineering analysis considered several technical factors which are important to the satellite design analysis. Among these technical factors are the payload size, the bit error rate (BER), and the beamwidth. The payload size, or the number of 36 MHz Equivalent transponders (Tx)[2] on-board, measures the on-orbit service capacity supplied by the satellite. In the commercial communication industry, transponders are the value-generating components of the satellite, acting as conduits for information transfer between two terrestrial entities. All other factors held constant, increasing the number of transponders increases the quantity of information that may be transferred and consequently, the percentage of the satellite services market which may be captured. The

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[2] One unit of 36 MHz Equivalent Transponders is a unit of measurement of satellite capacity. For brevity, it is given the designation Tx.

BER addresses the reliability with which the information is transmitted. A lower BER suggests a lower probability that errors occur in the received message during transmission, while a higher BER suggests a greater likelihood the received message has been corrupted. The level of the BER is important to customers as it indicates the accuracy with which transmitted messages will be received. The beamwidth of the satellite antenna plays an integral part in determining the terrestrial footprint of the satellite. A wider beamwidth allows greater coverage of the targeted market but may be subject to greater pointing losses and greater e*quivalent isotropically radiated power* (EIRP) requirements. Thus, the satellite operator must select an appropriate beamwidth that balances coverage with losses and power requirements. The design values for each of these factors are set based on common values within the commercial space industry [119,120]. The design range for the payload size is set based on the approximate range of observed values in the annual financial statements of Intelsat between 2003 and 2009, as well as other sources [121]. These values are shown in Table 2 and are outputted to the Lifecycle Cost Module to estimate the resource expenditures associated with the satellite system.

Table 2. Design Parameters

Inputs	
Beamwidth (deg)	2
BER	1E-04
Transponder Bandwidth (MHz)	36
Type of Modulation	BPSK
Downlink Frequency (GHz)	12.5
Uplink Frequency (GHz)	14.5
Earth Antenna Diameter (m)	10
Number of Transponders (Tx)	25 - 89
Margin (dB)	15
Noise Temperature (K)	145

3.2.1.2 Lifecycle Cost Module

Once a satellite design is generated, the next step is an estimation of the lifecycle cost of the particular satellite based on the system design variables. This is the purpose of the Lifecycle Cost Module. The lifecycle costs are divided in two categories, the cost to initial operating capability (C_{ioc}) and the operating costs. The operating costs per satellite assess the annual costs to operate a satellite once it is in on orbit, and are determined by examining the cash components of the operating expenditures located in the annual income statements of a top satellite operator, Intelsat, as well as Intelsat's fleet size. These operating costs and the fleet size are shown in Table 3. It is interesting to note the operating costs per satellite are, for all intent and purpose, independent of the satellite design and relatively constant between 2003 and 2010 at approximately $11.5M. Estimating the costs to initial operating capability is a bit more complex. Each technical factor listed in Table 2 impacted the C_{ioc} and has to be accounted for in any cost estimate. For the cost estimation, a parametric model is chosen [119]. Parametric models, although not as accurate as bottom-up models, can be easily automated in analysis while still providing an acceptable level of fidelity for the purposes of this analysis. The cost estimation relationships are mass based, with the mass depending on the power requirements of the payload sub-system and consequently the power requirements of the satellite. Thus, the technical factors impacted the costs indirectly through the power requirements. These cost estimates are outputted to the Value Analysis Module. Based on the parametric cost models, the impact of changes in the design variables on changes in the cost to initial operating capability are assessed using the metric, design elasticity of cost. This design elasticity metric (ε_i) estimates the percentage change in C_{ioc} in response to a percentage change in the design variable (X_i) using the following equation [33]:

$$\varepsilon_i = \frac{d\ln(C_{IOC})}{d\ln(X_i)} \qquad \textbf{Eqn. 13}$$

The results are shown in Figure 9. The figure indicates that the payload size has the greatest impact on the cost to initial operating capability, with a 1% in the payload size resulting in just over a 40% change in the C_{ioc}. The impact on C_{ioc} generated from changing the payload size is significantly greater than the impact experienced from changes in the other design variables. This is evident by the fact that a 1% change in the

Satellite Antenna Mass, the design variable with the second largest impact, only led to a 3% change in C_{ioc}. On the opposite end of the scale, changing the BER rate has the lowest impact on the C_{ioc}, with a 1% change in the BER leading to less than a 1% change in C_{ioc}. As such, from a cost perspective the payload size is considered the dominant design variable.

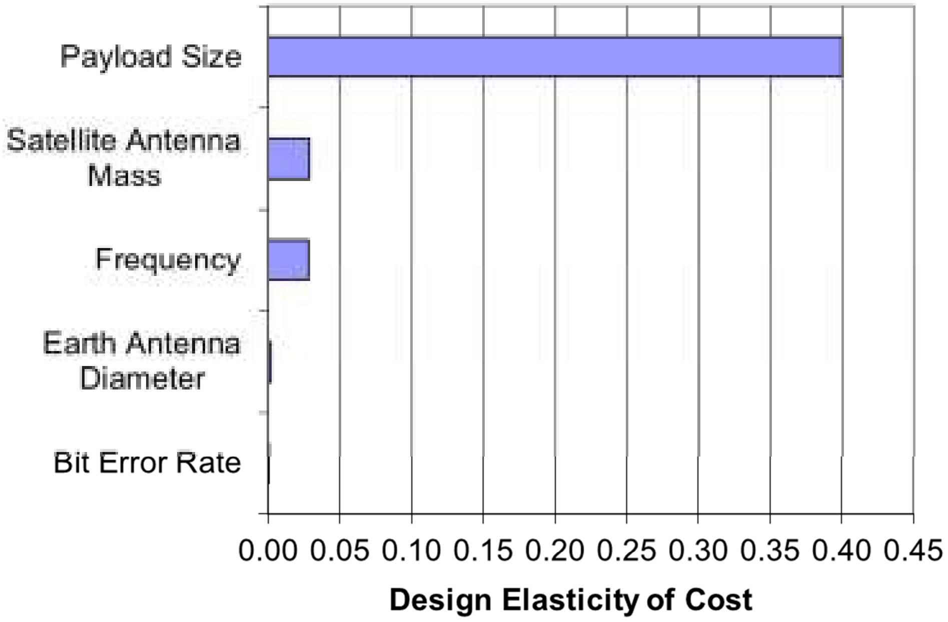

Figure 9. Design elasticity of cost

Together, the Satellite Design Module and the Lifecycle Cost Module comprise the engineering analysis. The previous discussion provided the implementation of each of these modules, illustrating how the feasible set of satellite designs is generated as well as the type of lifecycle cost modeling performed. Note thus far, there is no accounting for factors exogenous to the system in the design process. In other words, only the portion of the value-centric framework which is system-centric and does not incorporate considerations of end-user demand and pricing have been presented. Recall that the external environment is an important consideration in determining the value of an engineering system and should be included in the system analysis. In the next section, the modeling of market demand and pricing dynamics will be presented to complete the flow of the value-centric framework.

3.2.2 Traditional Business Analysis

The underlying dynamics of the market scenarios are constructed from actual data extracted from a satellite operator, Intelsat, financial statements between 2003 and 2010. In particular, information gathered provided an indication of the demand and supply dynamics within the satellite services industry, the pricing of such services and the cost of operations. The data obtained from these annual 10-K statements is shown in Table 3.

Table 3. Raw Market Data Taken from Intelsat Financial Statements

Year	Revenue ($Mil)	On Network Service %	Utilization Rate	Avail. Cap. (36 MHz)	Operations Cost ($Mil)	Satellites on Orbit
2010	2533	0.89	0.81	2120	596	53
2009	2513	0.95	0.83	2029	662	54
2008	2365	0.95	0.83	2127	565	53
2007	2183	0.95	0.76	2218	562	53
2006	1663	0.96	0.70	2238	472	51
2005	1171	0.93	0.63	1516	441	28
2004	1044	1.00	0.63	1481	330	29
2003	979	1.00	0.60	1369	262	25

*2010 data estimated from the first three 2010 quarterly statements

The information in Table 3 is as follows:

- Revenue is the total revenue collected by the satellite operator over the course of the year
- On Network Service percentage provides the approximate potion of the revenue collected that is due to on-orbit satellite services
- Available Capacity is the on-orbit supply measured in 36 MHz Equivalent transponders
- Utilization Rate indicates the percentage of on-orbit or available capacity sold

- Operations Cost is the cash component of the operating expenses incurred in providing satellite services over the course of the year
- Satellites on Orbit reflect the size of the Intelsat fleet.

Based on this raw data, an estimation of various market parameters is determined. The market parameters of interest and the details of the relevant estimations are given in the subsequent sections.

3.3.2.1 Market Analysis Module

The overarching objective of the Traditional Business Analysis Block is to enable an assessment of the cash inflows a satellite will generate over its lifetime. To do this, an adequate understanding of the demand and pricing dynamics faced by the satellite operator is desired. The demand and pricing dynamics are evaluated in the Market Analysis Module located in the Traditional Business Analysis Block.

The first step in understanding the demand dynamics of the satellite services market is to identify the demand parameters of interest to the satellite operator. These parameters are drivers of value and may be used to define a specific market demand scenario. The parameters identified are the market demand per satellite on initial operation of the satellite (d_i), the average annual growth rate of the market demand (g_i), and the market demand volatility (σ_i). Thus, the market demand scenario (S_i) is mathematically defined as:

$$S_i = < d_i, g_i, \sigma_i > \qquad \textbf{Eqn. 14}$$

After identifying the key demand value drivers the second step in understanding market dynamics is to determine reasonable values for each of these drivers (i.e., market demand per satellite on initial operation, average annual demand growth rate and demand volatility). The market parameters are estimated based on the data collected from the Intelsat financial statements. The initial total demand per satellite in the market is taken to be that at the end of the year 2010 as measured by the proportion of available capacity sold per satellite, that is, an approximate initial demand per satellite of 30 Tx. The next parameter, the average annual growth rate for the total market demand[3] is the arithmetic mean of the annual growth rate between 2003 and 2010. This is expressed as follows:

$$\overline{g} = \frac{1}{n}\sum_{i=1}^{n} g_i \qquad \textbf{Eqn. 15}$$

where g_i represents the annual growth rate between two years, n is the number of growth periods considered and $\overline{g}$ is the average annual growth rate. The average annual growth rate for the total market demand between 2003 and 2010 is calculated as 4.7%. In the absence of additional data, it is assumed that the average growth rate in demand for a single satellite is also 4.7%. The final parameter, the total market demand volatility, is taken to be the estimator:

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[3] The PamAmSat acquisition between 2005 and 2006 led to a sudden jump in available capacity between 2005 and 2006. To prevent a distortion in growth rates, the available capacity for the year 2003, 2004, 2005 was adjusted upwards by 722 Tx. (i.e., the difference in the available capacity between 2005 and 2006).

$$\hat{\sigma}_g^2 = \frac{1}{n-1}\sum_{i=1}^{n}(g_i - \bar{g}) \qquad \textbf{Eqn. 16}$$

where $\hat{\sigma}_g^2$ is the total market demand volatility. Similar to the average annual demand growth rate, the total market demand volatility of 5.3% is taken to be the demand volatility experienced by a single satellite. Based on these three parameters, the demand dynamics of the market over the lifetime of the satellite is modeled as a Weiner process, specifically as geometric Brownian motion.

After assessing the market demand dynamics faced by the satellite operator, the corresponding pricing dynamics were modeled. The price estimated in this analysis is the price per transponder utilized. Similar to the demand dynamics, the parameters price per transponder on initial operation of the satellite, the average annual growth in price per transponder and the price per transponder volatility are estimated. The price per transponder is proxied by the total revenue collected by the satellite operator from on orbit services in a given year divided by the utilized capacity in that year. This led to an initial price per transponder of \$1.5M, an average annual growth rate of 2.0% and a price per transponder volatility of 11.5%. The pricing dynamics are modeled based on geometric Brownian motion.

3.2.2.2 Revenue Analysis Module

The objective of the Revenue Analysis Module is to estimate the annual cash inflows of the satellite based on input received from the Market Analysis Module. However, an evaluation of the revenues is based on two aggregate pieces of information, the pricing of satellite services and the satellite utilized capacity. Therefore, in addition to the input provided by the Market Analysis Module, the Revenue Analysis Module also requires information from the Satellite Design Module. This is represented by the link connecting the Traditional Engineering Analysis Block and the Traditional Business Analysis Block in Figure 8.

The cash inflow analysis is concerned with the utilized capacity of the satellite as only utilized capacity generates revenue. For each year of operation of the satellite, the market demand will fluctuate leading to variations in the utilized capacity of the satellite. Given the level of market demand per satellite it may be possible for the satellite to capture all of the demand or only a portion of the demand. The proportion of demand that the satellite captures is dependent on its design, most prominently the size of its payload. In any given year, if the demand exceeds the payload size, the satellite has captured less than 100% of the demand per satellite and its capacity is fully utilized. Likewise, if the demand falls below the payload size, the satellite has captured 100% of the market but is partially utilized. This led to a definition of satellite utilized capacity for any given year as:

$$uc_j^t = \min\{d^t, ps_j\} \qquad \textbf{Eqn. 17}$$

where ps_j is the payload size of satellite j and d^t is the market demand per satellite in a given year t. Combining the price per transponder for a given year, p^t, with the utilized capacity for that year produces an annual revenue, R_j^t, from satellite j of

$$R_j^t = p^t \min\{d^t, ps_j\} \qquad \textbf{Eqn. 18}$$

The market analysis and the revenue analysis are the constituent analyses of the Traditional Business Analysis Block. For each of these two modules, a detailed overview of the implementation is provided, demonstrating how the market demand and pricing dynamics are modeled, and the annual revenues are calculated. The output of the Revenue Analysis Module, that is the annual revenues over the lifetime of the satellite, coupled with the output of the Lifecycle Cost Module, the cost to initial operating capability and the operating cost per satellite, enables an analysis of the value of the satellite to the satellite operator.

3.2.3 Value Based Decision Making

In the commercial communication satellite industry, satellites are value generating artifacts to the satellite operator. In fact, one may view the satellite as an investment, in which the operator expends resources in the development, manufacturing, launching and operation of the satellite on the expectation of a sufficient compensatory return. Therefore, it is important for the operator to quantify net value of the satellite prior to launch.

3.2.3.1 Value Analysis Module

The Value Analysis Module determines the net value of the satellite given its annual revenues as estimated by the Revenue Analysis Module and its associated costs as outputted by the Lifecycle Cost Analysis Module over the operational lifetime. The net value is measured by the Net Present Value of the system. As a discounted cash flow approach to the valuation of the satellite will be used, additional information is needed to assess the net value. In particular, knowledge about the discount rate is required to account for the time value of money, as well as any other risks associated with the cash flows. The discount rate may be proxied by the Weighted Average Cost of Capital (WACC), or the cost to the firm of securing the investment capital. The discount rate was determined to be 10% based on information in Intelsat financial statements. In addition to the discount rate, information on the expected lifetime of the satellite is required. This was taken to be 15 years. Given these three pieces of information, the cash flows (i.e., revenues and costs), the discount rate (i.e, WACC) and the lifetime of the satellite, it is now possible to estimate the Net Present Value of the satellite. If cash flows are discretized over the lifetime of the system (t_{life}) into time bins of width one year, and the revenue and operating costs (c_{ops}^{t}) are book kept at the end of the year, the Net Present Value of the system may be calculated as follows:

$$NPV_j = \sum_{t=1}^{t=t_{life}} \frac{R_j^t - c_{ops}^t}{(1+r)^t} - C_{ioc} \qquad \textbf{Eqn. 19}$$

where r is the discount rate. The NPV_j calculation is relatively simple if cash flows can be accurately projected and the risk associated with the project is transparent. However, in practice, there is always a degree of uncertainty associated with future cash flows. Thus, deterministic calculations of NPV_j can convey a false sense of accuracy and may lead to wrong investment decisions. It is therefore essential that any value analysis incorporate the uncertainties associated with the inputs of the value analysis (from the cost and revenue sides in Figure 8). Uncertainty in value analysis emerges because of uncertainties in the cost estimates, demand for the system services, lease price, or market conditions in general. For this analysis, the uncertainties in the market demand as well as the lease price are considered. Based on the geometric Brownian Motion model, uncertainties in the market demand and pricing are propagated to uncertainty in revenues, and consequently uncertainty in the system's NPV_j, using Monte Carlo analysis. Specifically, 5000 projected demand and pricing trajectories are considered for a given market scenario. Each demand and pricing trajectory provided a unique revenue profile for the system. Thus 5000 trajectories provided 5000 possible revenue profiles for the satellite, and likewise, 5000 possible NPV_j estimates. Based on the consideration of the several trajectories and the resulting system's NPV under each trajectory, a probability mass function (p.m.f) is established for each system under a given market scenario.

3.2.3.2 Decision Analysis Module

The Decision Analysis Module identifies the final system or portfolio of systems for further analysis and development based on the value analysis conducted in the Value Analysis Module. A wide selection of decision-making tools is enabled by the wealth of value information provided by the Value Analysis Module in the form of the NPV_j p.m.f. Some examples of these tools are Pareto Optimality, Value-at-Risk Analysis and Upside Potential/Downside Risk Analysis [52,118,122,123]. The specific tool selected is dependent on the stakeholder. This application is primarily concerned with value optimization of the system, in particular expected NPV_j maximization under a given market demand scenario (S_i). First the design and value implications of system selection is evaluated under a given market demand scenario. From there, the analysis is extended to various market demand scenarios in order to understand the design and value implications of changing market conditions. Finally, the analysis concludes by asking the question, what if there is uncertainty in the parameters which define the market demand scenario, that is, the initial market demand per satellite, the market demand volatility and the demand growth rate. Under this type of uncertainty, how should the satellite operator select designs such that they are robust to value loss?

3.3 Design Selection and Value Implications

The primary purpose of this section is to illustrate how value-informed decision-making is enabled by the framework in Figure 8, and consequently, the importance of incorporating information exogenous to the system in a design environment. However, before delving into the value-centric analysis, system design selection under the traditional cost-centric approach is analyzed. Presenting design selection under a cost-centric mindset serves to highlight the difference in design and value implications of the two mindsets (i.e. cost-centric and value-centric). Furthermore, the comparison emphasizes the importance of systematically infusing environmental information into system design and acquisition.

3.3.1 Design Selection

As mentioned previously, the cost-centric approach to system design and acquisition is based primarily on information endogenous to the system, such as the payload size, the carrier to noise ratio or the datarate. Thus in the engineering environment, cost-centric metrics employed to evaluate and rank design options are often of the form functionality per cost or cost per functionality. For this analysis, the common metric, C_{ioc} per transponder, is used to select the system design[4] [124]. The results of the C_{ioc} per transponder analysis are displayed in Figure 10.

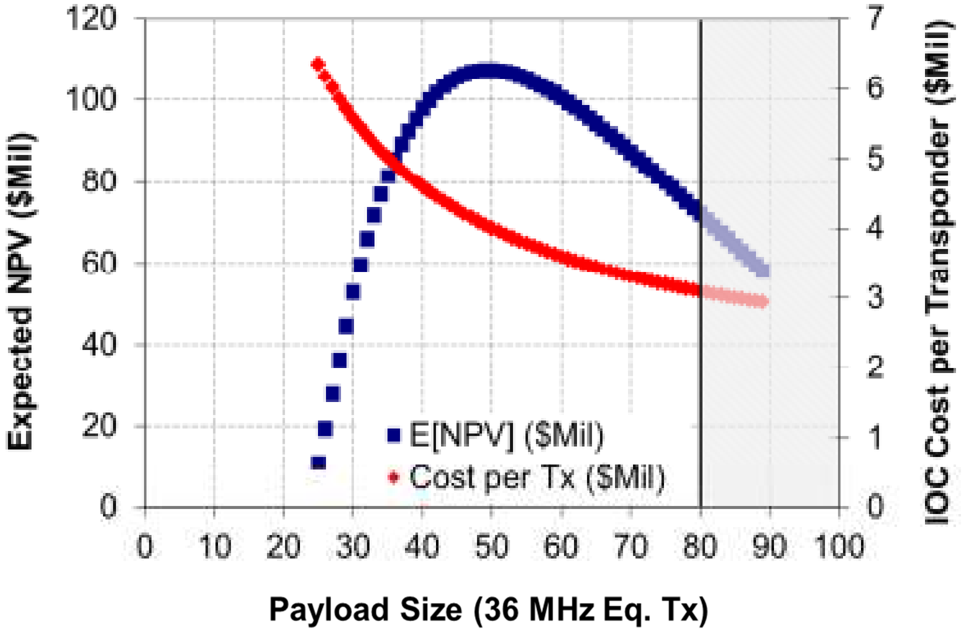

Figure 10. Comparison of value-centric vs. cost-centric design choices

The graph indicates that the C_{ioc} per transponder decreases monotonically with payload size, thereby exhibiting economies of scale with increasing payload size. Thus from a cost-centric perspective, engineers are inclined to select designs with larger payload sizes due to the increased functionality of the system for a given cost. This

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[4] Note it is irrelevant whether the C_{ioc} per transponder or the lifecycle cost per transponder is used for the design decision as the C_{ops} is independent of the payload size.

economies of scale argument may form the basis for decision-making in the commercial satellite industry, and the observed trend towards larger payload sizes on communications satellites in past years [124]. However, it is reasonable to expect that the satellite operator cannot capitalize on economies of scale regardless of the payload size. A maximum payload size exists beyond which the satellite may be infeasible or the design choice not prudent. These limitations on the payload size of the satellites may arise from cost constraints imposed by the satellite operator or hard design constraints imposed by the satellite manufacturer. In Figure 10, this maximum payload size constraint is marked by the black line, and is taken to be 80Tx. The shaded area to the right of the constraint on the figure indicates design alternatives which violate this constraint and should be eliminated from consideration. Therefore, considering the monotonically decreasing nature of the C_{ioc} per transponder with payload size and the imposed design constraint, design choices tend towards the edge of the design space or the maximum payload size possible. The payload size selected under the cost-centric framework will be 80Tx.

Now that the design selection under that cost-centric framework has been reviewed, the reader may now turn their attention to design selection under the value-centric framework. Recall that the fundamental difference between the cost-centric and the value-centric approaches to system design and acquisition lies in the information utilized in decision-making. Cost-centric design approaches base design decisions primarily on system-centric information, that is, information primarily related to system attributes such as datarate, carrier to noise ratio, etc. While this type of endogenous system information is essential to decision-making, it is not complete. Other data exogenous to the system should be considered. Value-centric system design and acquisition addresses this deficiency in the information set by accounting for external factors (e.g. demand growth, demand volatility) which are important to the stakeholder when making the design choices. For the value-centric analysis, suppose the satellite operator is interested in maximizing the expected NPV_j under a given market scenario or E[NPV_j| S_i]. As design selection under the value-centric mindset is dependent on external market conditions (i.e. context for valuation), it is necessary to state the values of the parameters which define the market demand scenario. The demand per satellite on initial operation or the initial market demand per satellite is 30Tx. The demand growth is 4.7% and the market volatility is 5.3%, values based on Intelsat financial data. Thus the scenario is given as follows:

$$S_1 = < 30Tx, 4.7\%, 5.3\% > \qquad \textbf{Eqn. 20}$$

As with the C_{ioc} per transponder, the results of E[NPV_j| S_1] analysis is displayed in Figure 10. There are several aspects of the variation in E[NPV_j| S_1] with payload size which may be noted. The E[NPV_j| S_1] increases initially with increasing payload size. One reason which may explain this trend is that small payloads sizes are unable to capture a significant portion of the market demand thereby constraining the expected Net Present Value the satellite operator receives. In other words, small payload sizes create excess demand leading to value forgone by the satellite operator. Within this design region, the marginal value gained outweighs the marginal lifecycle cost incurred from increasing the payload size. This leads to an overall rise in E[NPV_j| S_1]. On the other extreme, for payload sizes greater than approximately 47 Tx, the supply capacity exceeds the market demand, and no additional net value is gained from increasing the payload size. The marginal cost of adding an additional transponder outweighs the marginal value gained from that transponder. This difference in marginal cost and marginal value leads to decreases in E[$NPV_j | S_1$]. At the point where the marginal value of the satellite just equals the marginal lifecycle cost of the satellite, the payload size that maximizes the E[$NPV_j | S_1$] occurs. In a value-centric mindset, the decision-maker will be inclined to choose this value optimal payload size. For the market demand scenario listed in Eqn. 20, this value-optimal design has a payload size of 49Tx, and an optimal E[$NPV_j | S_1$] of \$107M.

In summary, the value-centric framework identifies design choices which maximizes net investment value for a given set of market conditions, or the E[$NPV_j | S_1$]. In contrast, the cost-centric design choices focus on minimizing the amount of cost per unit functionality, and may not lead to value-optimal design choices for the satellite operator. However, the importance of design frameworks lies not in the actual design selection, but rather in understanding the value implications of these design selections to the stakeholder.

3.3.2 Value Implications

In order to investigate the value implications, a new metric called the value loss is defined. The value loss determines the net value the satellite operator foregoes by not selecting the design which generates the maximum E[NPV_j] under the given market scenario. In other words, it is the value of the information exogenous to the system (i.e. market information) which is not incorporated into the system design and acquisition environment. Mathematically, the value loss is given as:

$$\Delta E[NPV_{jC} \mid S_i] = E[NPV_j \mid S_i]^* - E[NPV_C] \qquad \textbf{Eqn. 21}$$

where $E[NPV_j| S_i]^*$ is the expected Net Present Value of the optimal value-centric design for the given market scenario, S_i, and $E[NPV_C]$ is the expected Net Present Value of the cost-centric selected design. For the scenario in Eqn. 20, the cost-centric selected design of 80Tx has an $E[NPV_C]$ of \$72M. This cost-centric design results in a value loss of \$35M. Thus, selecting designs under the cost-centric mindset has the potential to lead to value losses for the satellite operator. In fact, one might amusingly note that the satellite operator pays an additional cost to incur value losses when selecting designs in a cost-centric framework.

3.3.3 Changes in Market Parameters

Two important questions that may emerge in comparing these two approaches to system design and acquisition are: 1) under what conditions do the design choices differ? and 2) what are the resulting value implications to the stakeholder? To investigate how design choices vary under changing market conditions, the initial market demand is perturbed in order to observe how the optimal payload size changes. In particular, three different market scenarios are investigated, the nominal market scenario, a second scenario in which the initial market demand is 20Tx and a third market scenario with an initial market demand of 40Tx. All other parameters (the market volatility and the market demand growth) which define the market scenario remain consistent with the first market scenario given in Eqn. 20. Figure 11 shows the three value analyses conducted when the initial demand parameter defining the market scenario is perturbed.

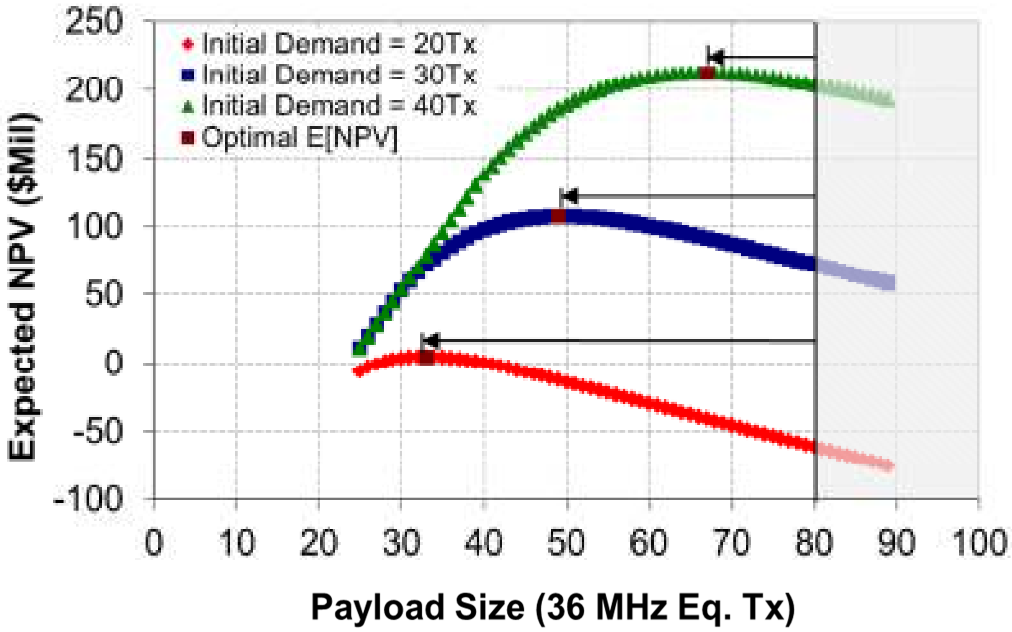

Figure 11. Design variable convergence in value-centric analysis

There are a number of key points which may be inferred from Figure 11. First, consider the design implications of perturbing the initial market demand. In value-centric analysis, the optimal payload under each market scenario is given by the brown block on each curve. Notice as the initial market demand increases, the payload size which maximizes the E[NPV_j| S_i] also increases. This matches intuition as the satellite operator must provide greater on-orbit capacity to meet the increased demand. Second, it is important to realize that while value-centric design selection is dependent on market conditions cost-centric design selection is relatively independent of market conditions. The cost-centric design framework incorporates primarily endogenous information about the system. Therefore changing the initial market demand has little effect on the design selection in a cost-centric framework, and design choice remains similar across the various market scenarios examined. Finally, the presence of the design (cost) constraint leads to convergence between value-centric and cost-centric design choices as the initial market demand per satellite increases. This is due to the fact that the design (cost) constraint is not only applicable in cost-centric analysis, but valid in the value-centric framework as well. Raising the initial market demand pushes the value optimal payload size towards the design constraint. As a result, the upper bound of the payload size in value-centric design is equivalent to the selected payload size from the cost-centric analysis.

As for the value implications of the value-centric design choices, it is observed that increasing the initial market demand leads to a significant increase in the optimal $E[NPV_j | S_i]$. Relative to the value optimal design under each market scenario, value losses of the cost-centric selected design (i.e. the value of the information not included in the cost-centric design decision-making) diminishes as the initial market demand per satellite increases. For example, in the case where the initial market demand is 20Tx, the satellite operator incurs approximately $65M in value losses if the design is selected under the cost-centric framework. Should the initial demand be 40Tx, the forgone value in choosing a cost-centric design is approximately $15M. For scenarios in which design convergence has occurred, the value implications of both approaches are equivalent.

A simple comparison of the value-centric mindset and the cost-centric mindset to system design highlights a number of differences. First, unlike value-centric design selection which is highly dependent on market conditions, cost-centric design selection is relatively independent of market conditions. Thus, while the cost-centric design selections lead to the largest payload size which satisfies the design (or cost) constraint, an optimal design may emerge from the value-centric framework for the market scenario considered. Second, the design (cost) constraint is not only applicable in the cost-centric framework, but valid in the value-centric framework as well. The presence of this constraint implies a set of market scenarios exists for which design convergence occurs between these two frameworks, and more importantly, comparable value implications. Finally, in cases where convergence does not occur and the satellite operator desires to maximize the expected net present value, designs selected under a cost-centric mindset are sub-optimal and results in value losses for the operator, that is, the engineer may forego value to the satellite operator by not utilizing information exogenous to the system when selecting the system design.

Thus far, the design and value implications of the value-centric mindset relative to the cost-centric mindset have been examined under the assumption that market parameters are certain. In the next set of analysis, uncertainty in the market parameters is incorporated into the value informed design framework, and the resulting design decisions and the value implications of these decisions are explored.

3.3.4 Parameter Uncertainty, Design Selection and Value Implications

The market parameters, initial demand per satellite, demand growth and demand volatility define the market demand scenario, and are the inputs to the geometric Brownian motion demand model. In the previous analyses, it is assumed that these parameters are well characterized. In reality, uncertainty exists in each of these parameters as the satellite operator is unable to fully account for all factors which impact these parameters. As the value optimal payload size is dependent on market conditions, a change in any of these parameters potentially leads to a change in the optimal payload size. This is illustrated in Figure 12 for a change in the market parameter initial demand per satellite. All other market parameters remain consistent with those in the first scenario.

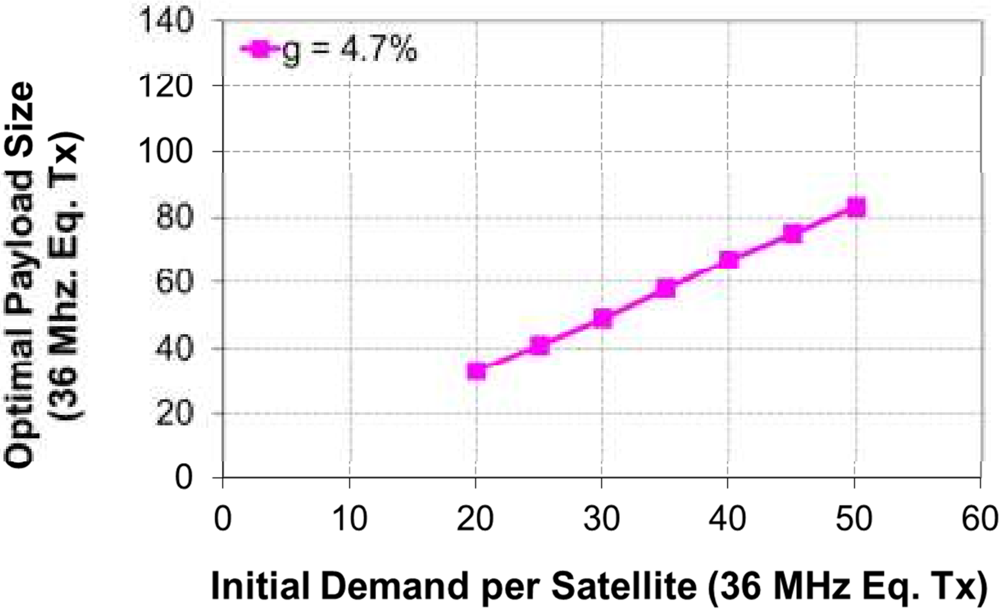

Figure 12. Value optimal payload size given initial demand per satellite

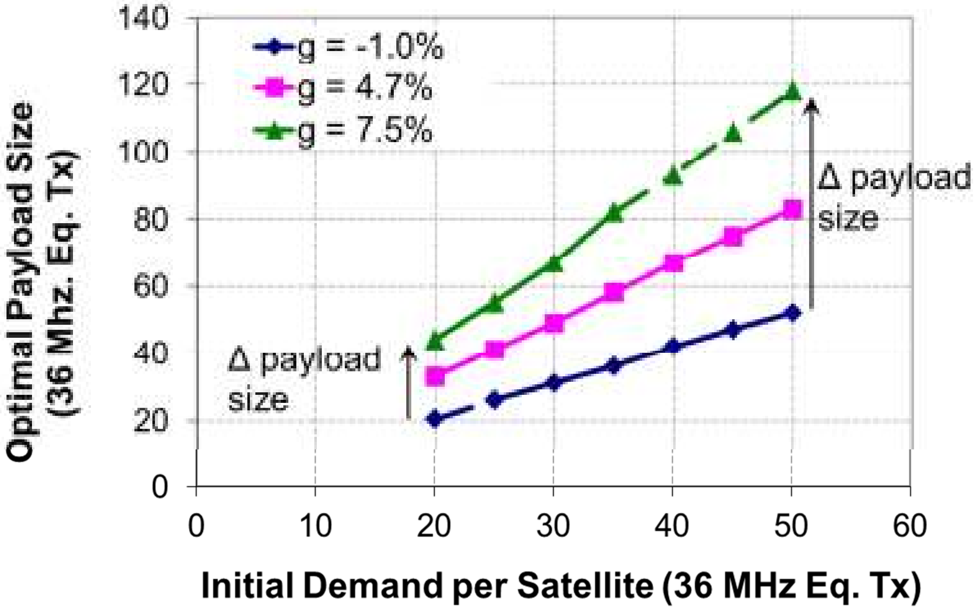

Figure 13. Value optimal payload size given initial demand and demand growth

The data given in Figure 12 indicates that the value optimal payload moves positively with the initial demand per satellite. As the initial demand rises from 20Tx to 50Tx, the optimal payload size also increases from 32TX to 83Tx. If in addition to uncertainty in the initial demand per satellite, uncertainty in the demand growth rate is also considered, a similar trend is displayed. Figure 13 indicates that increases in the growth rate lead to increases in the optimal payload size. As mentioned previously, such behavior in the optimal payload size matches intuition as the satellite operators would need to supply greater on-orbit capacity to meet the rise in demand and demand growth.

In order to understand the value implications of uncertainty in the market parameters to the stakeholder, the analysis starts by focusing on the initial market demand per satellite parameter. From Figure 12 and Figure 13, it is clear that selecting the value optimal designs which occur at the extrema of the uncertain market parameters may yield appropriate bounds on the design space. Within these bounds, the optimal payload size will occur. For example, assume the satellite operator estimates the initial demand for the satellite services will range between 30 Tx and 40 Tx but lacks additional knowledge for a more precise estimate. Based on the extrema approach, payload sizes between the ranges of 47Tx to 67Tx would be included in the portfolio of selected designs as the optimal design will be included in this range. This is illustrated in Figure 12. Now assume that uncertainty exists in both the initial demand per satellite and the demand growth, with estimates of the demand growth ranging between -1% and 4.7%. According to the extrema approach, selected design choices would range between 49Tx and 80Tx as shown in Figure 13.

While the extrema approach may guide engineers in selecting the design region in which the optimal occurs, it does not account for the value implications of the uncertainty to the operator. For example, suppose the satellite operator believes the initial market demand to be 30Tx. Based on a value assessment, the satellite operator will select an optimal payload size of 47Tx. This system would enable the operator to attain the largest expected net value given the market conditions. Now suppose the initial market demand turns out be 40Tx and not 30Tx as predicted. Under these market conditions the optimal payload size is 67Tx. Thus, the satellite operator would have selected a value sub-optimal design. More importantly, recall that sub-optimal value designs lead to value losses. Thus, in selecting a payload size of 47Tx, the satellite operator will incur value losses. It is therefore important that engineers not only identify a set of design bounds within which the optimal occurs, but refined these bounds to identify the designs which are robust to value losses under uncertainty about the market parameters.

The precision on these design bounds can be improved by considering the potential value losses the satellite operator can incur under market parameter uncertainty. Consider the case where the satellite operator is uncertain about the exact value of the initial market demand. He knows it will fall somewhere between 30Tx and 40Tx inclusive. If a single satellite design is considered, for example a satellite design with a payload of 80Tx, there will be a value loss if the market conditions are not such that this payload size is the value optimal payload size. Figure 14 illustrates this concept.

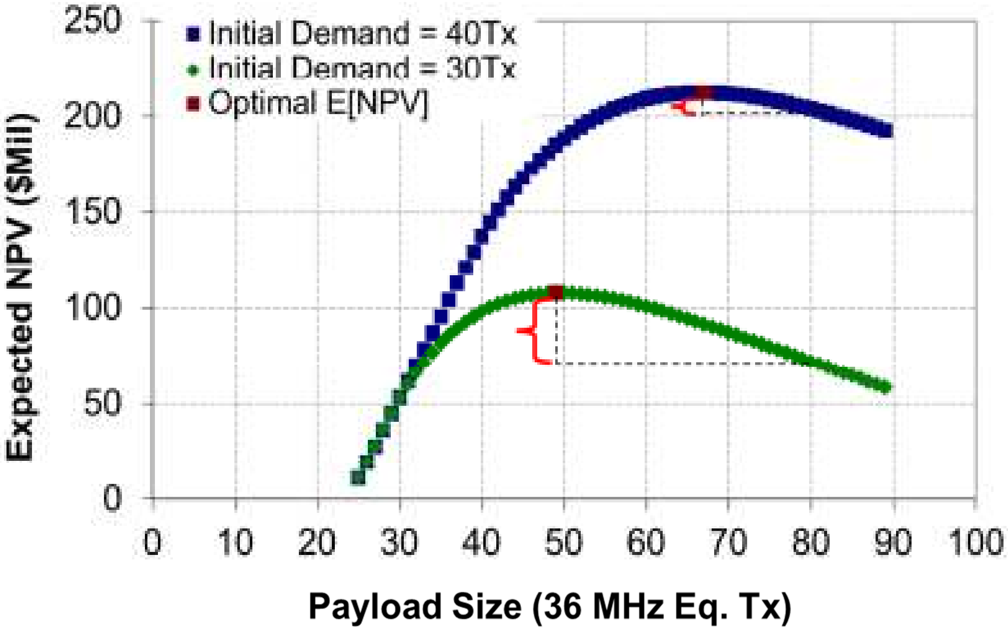

Figure 14. Value loss under uncertainty in market demand parameters

If the initial market demand is 30Tx, the example satellite will have a value loss of \$80M. Likewise, if the initial market demand is 40Tx, the example satellite will have a value loss of \$15M. More formally, this value loss is defined as follows:

$$\Delta E[NPV \mid T_j, S_i] = E[NPV \mid T^*, S_i] - E[NPV \mid T_j, S_i] \qquad \textbf{Eqn. 22}$$

where T_j is the payload size and T^* is the value optimal payload size for the scenario S_i. Now, if in addition to considering the scenarios of 30Tx and 40Tx, all possible scenarios within these uncertainty limits are considered, a set of value losses may be ascribed to the example satellite. Each of these value losses corresponds to a particular market demand scenario. Furthermore, if the satellite operator has no knowledge about whether there is a tendency to one particular value in the range between 30Tx and 40Tx, it may be assumed that the initial market demand per satellite is uniformly distributed over this range. As the scenarios are all equally likely to occur, the value losses for the example satellite will be uniformly distributed. This enables the creation of a probability mass function (p.m.f) of the value losses for a given payload size. Repeating this process for all payload sizes gives a set of p.m.f with each p.m.f corresponding to a particular payload size. The information from the p.m.f, is used to plot contours representing the probability that the satellite will exceed a certain value loss or

$$\Pr\{\Delta E[NPV \mid T_j, S_i] \geq l\} \qquad \textbf{Eqn. 23}$$

where l is the level of value loss. These probability contours are shown in Figure 15.

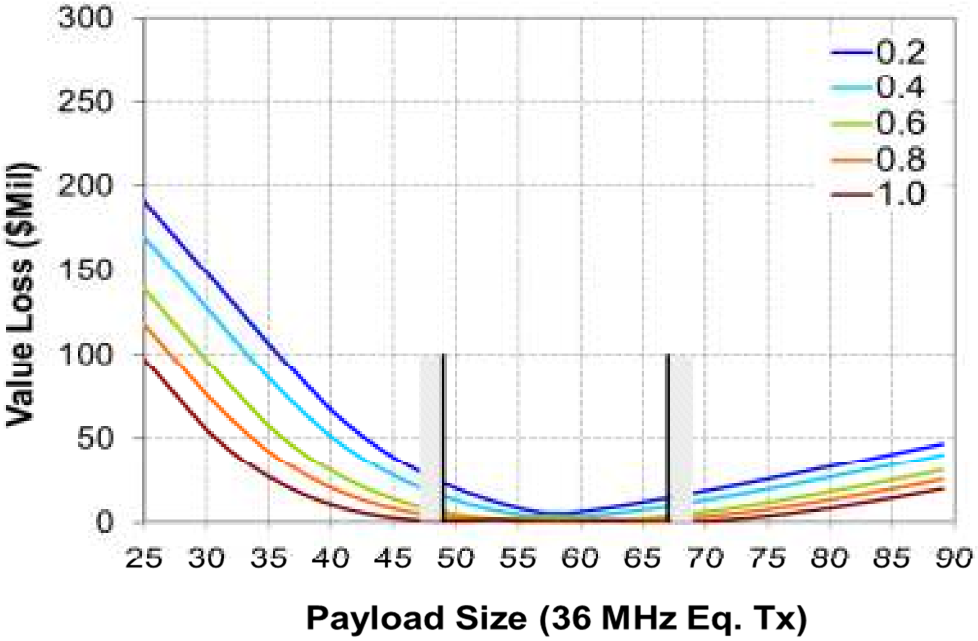

Figure 15. Probability contours of value loss under demand parameter uncertainty

The contour plots enable engineers to quantify the value loss associated with each payload size under uncertainty about market parameters. Consider a satellite system with a payload size of 40Tx. Figure 15 indicates that there is a 0.4 probability that the value loss from a satellite of this payload size will exceed $50M. Likewise, a satellite with a payload size of 30Tx is almost certain to experience value losses of $50M or more. Using these contour plots, engineers can identify design regions which are robust to value loss, that is, regions in which the designs have a high likelihood of experiencing low value losses. For this analysis, this design region lies between 51Tx and 61Tx. Within this region, designs have less than a 0.1 probability of exceeding $9M in value losses. On

Figure 15, the design bounds from the extrema approach are indicated by the two vertical black lines. Note the robust designs lie within the bounded region provided by the extrema approach.

Alternatively, the satellite operator may stipulate the tolerable value losses. For example, the satellite operator may desired not to incur value losses greater than \$10M with a 0.8 probability. These requirements may be formally stated as follow:

$$\Pr\left\{\Delta E[NPV \mid T_j] \geq \$10M\right\} = 0.2 \qquad \textbf{Eqn. 24}$$

From Figure 15, it is clear that payload sizes between 25Tx and 40Tx, and 82Tx and 87Tx do not fulfill this requirement as these payloads sizes almost certainly produce value losses greater than \$10M. In contrast, there is a likelihood that value losses associated with payload sizes between 40Tx and 82Tx may not exceed \$10M. Within this range only payload sizes between 55Tx and 63Tx have a 0.2 chance of producing losses greater than \$10M (i.e. 0.8 probability of incurring value losses less than \$10M). Thus payload sizes between 55Tx and 63TX satisfy the satellite operator's requirements.

3.4 Other Types of Value Analyses

Although the above analysis focused on the expected net present value of the system and quantifying the value loss from not including certain types of information, the wealth of value information that becomes available by the generation of the p.m.f of the net present value of the system under a given set of market conditions also enables other types of analysis. Examples of two types of analysis briefly presented in this section are the Pareto Optimality and Upside Potential/ Downside Risk.

3.4.1 Pareto Optimality

Significant research has been done over the past several decades on the centrality of uncertainty in decision-making in general, and investment decisions in particular [125-127]. Seasoned decision-makers rarely, if ever, use expected values alone. Since the purpose of a value-centric framework is to support decision-making (in the context engineering system design and acquisition), it may be essential at times that such a framework provide decision-makers not only with the expected NPV of various design alternatives under considerations, but also with a measure of the value uncertainty that these alternatives carry with them. The measure for NPV uncertainty used herein is the standard deviation of the system's NPV p.m.f.

Suppose the stakeholder is interested in knowing the net present value that may be expected from a given system, and the uncertainty associated with achieving that expected net present value. For this case, the Decision-Making Module in the Value-Informed Decision-Making Block would present the doublet, expected NPV and NPV uncertainty, for the set of designs under consideration. In addition, let's assume the satellite operator has two optimization objectives. These are 1) to maximize a system's expected NPV and 2) to minimize its value uncertainty. This is a vectorial or multi-objective optimization problem for which not just one optimal solution exists but a set of Pareto optimal design alternatives. As a consequence, the Decision-Making Module in the value-centric framework would present the decision-maker with the Pareto front or the set of Pareto optimal satellite designs (given the two objective functions). For the market condition given in Eqn. 20, the expected NPV and NPV uncertainty for all system designs under consideration is given in Figure 16. The Pareto front is given by the red line.

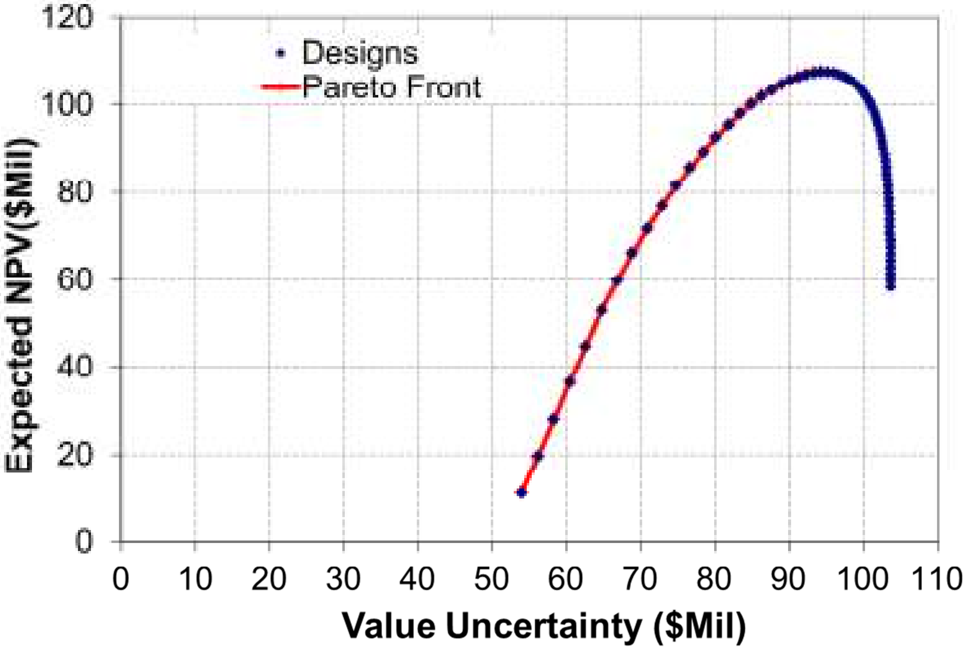

Figure 16. Pareto front of designs

All payload sizes in the range of 25Tx to 49Tx are on the Pareto Front. For these payload sizes, the satellite operator is almost assured of having 100% utilized on-orbit capacity (i.e. the satellite is 100% utilized). As such, there is minimal uncertainty associated with the NPV the satellite operator expects to receive for payload sizes within this range. Payloads sizes between 50Tx and 89Tx are Pareto sub-optimal designs. The on-orbit capacity offered by these larger payload sizes often exceeds the on-orbit demand. As such, the excess on-orbit supply created by the larger payload sizes leads to higher levels of NPV uncertainty.

Although value-centric framework identifies a set of Pareto optimal design alternatives, the final down-selection is left to the decision-makers. These decision-makers may have different preferences and tolerance for uncertainty, and as a result, they may set different constraints on the Pareto front. For example, one decision-maker may set a minimum threshold of expected NPV for a system to be considered, which translates into a horizontal line on Figure 16, and only the Pareto optimal design alternatives above this threshold would be considered. A different decision-maker may set another constraint for example in the form of a maximum tolerable value uncertainty, which translates into a vertical line on Figure 16. In this case, only the Pareto optimal design alternatives to the left of this threshold would be considered. A combination of these two constraints can also be conceived. In short, the final design down-selection is stakeholder-dependent; our value-centric framework simply provides the decision-maker with the value implications (expected NPV, and value uncertainty) of design alternatives and it identifies the Pareto optimal designs. In doing so, the Pareto front helps decision-makers interested in the two objectives expected NPV and NPV uncertainty, avoid selecting sub-optimal designs

3.4.2 Uncertainty: Upside Potential and Downside Risk

Aerospace systems engineering and program management are plagued with various types of uncertainty, among which are programmatic, operational and technical [102-104]. Understanding and managing these uncertainties is critical in order for engineers to develop a system which increases the probability (or at a minimum do not decrease the probability) of achieving project objectives. Traditionally, managing uncertainty in system design has focused on managing risks, with a number of risk assessment methodologies or techniques developed by various organizations [103-106]. However, risk is but one element of uncertainty, and simply managing risk offers a myopic perspective of uncertainty analysis in system design and acquisition.

Uncertainty in the space system design and acquisition has two components: 1) the upside potential that assesses the system's capability to take advantage of possible opportunities to enhance system value and performance and 2) the downside risk which assesses the system's vulnerability to adverse events and subsequently to performance and value reduction. Each of the components has different implications for system design. Design choices that augment the upside potential, and therefore the system value to the stakeholder, are desirable. In contrast, design choices which increase downside risk are discouraged and should be avoided [128]. Given the differing effects of upside potential and downside risk on engineering system design, it is imperative that the decision-maker is able to determine the proportion of the uncertainty attributed to upside potential and that attributed to downside risk for informed design down-selection.

The risk-centric mindset in managing uncertainty in aerospace system design has resulted in the development of few, if any, quantitative techniques for capturing upside potential and downside risk separately. In the field of finance, the concept of upside potential and downside risk has been studied extensively. In particular, investors and other practitioners in the finance field have employed the concept of partial moments to characterize uncertainty, manage risk and exploit opportunities [123,129-132].

The concept of partial moments stems from the general concept of moments. The α^{th} moment of a real valued function is given by the following equation:

$$M_{\alpha}(\tau;v) \equiv \int_{-\infty}^{+\infty} (v-\tau)^{\alpha} f(v)dv \qquad \textbf{Eqn. 25}$$

where M_{α} is the α^{th} moment, τ is the pivot and *f(x)* is the probability density function (p.d.f) of a random variable *v*. This general formula can be used to characterize the behavior of the random variable, *v,* and provide insightful information to engineers. Suppose engineers are concerned with achieving a desired level of system value. This desired level of value may be denoted by τ. The consequences of not achieving this desired value may be quantified by modifying the moment equation as follows:

$$R_{\alpha}(\tau;v) \equiv \int_{-\infty}^{v} (\tau-v)^{\alpha} f(v)dv \qquad \textbf{Eqn. 26}$$

where *R* is the downside risk of the system, the pivot, τ, is the desired level of system value and the random variable, *v*, is the system value. This metric is the lower partial moment and is described as the α-τ model in finance [130,133]. It reflects the expected value shortfall the satellite operator will incur from the system conditioned on the desired target value. In a similar vein, the consequences of exceeding the desired value may be quantified by modifying the moment equation as follows:

$$UP_{\beta}(\tau;v) \equiv \int_{v}^{+\infty} (v-\tau)^{\beta} f(v)d(v) \qquad \textbf{Eqn. 27}$$

This metric of upside potential (*UP*) is the upper partial moment of the distribution given the βth moment and the desired level of value, τ. It reflects the expected excess value the satellite will gain from the system conditioned on the desired target value. Pictorially, the concept of the lower partial moment and upper partial moment is depicted in Figure 17.

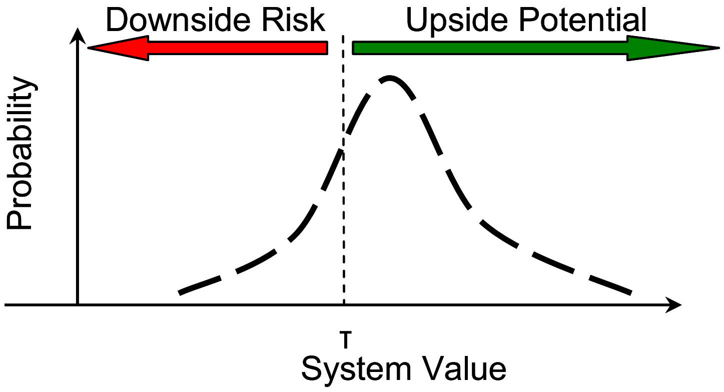

Figure 17. Notional p.d.f of system value depicting risk and upside potential

In the partial moment equations, the three parameters (τ, α, β) enable system engineers to capture the stakeholders' preferences and risk tolerance. The first parameter, τ, the desired level is defined by the stakeholder. At a minimum, τ should be set at a level which allows the stakeholder to recover resources expended on the system development and operation. The second parameter, α, is a weighting factor which captures the stakeholder's risk profile. The weighting factor for the upside potential, β, captures the stakeholders' desire for excess value gain. For a given τ , a higher α suggests a greater aversion to losses while a lower α suggests a more benign aversion to losses. For a given τ , a higher β suggests a more aggressive stakeholder who "chases" big pay-offs, while a lower β points to a conservative stakeholder. Common values of α and β used in the financial field are two and one respectively [134].

Based on the p.d.f of each system's NPV generated under the conditions listed in Eqn. 20, and using an α of two, a β of one and a target value of $0Mil, the upside potential and the downside risk is determined for each system design under consideration. These results are shown in Figure 18[5].

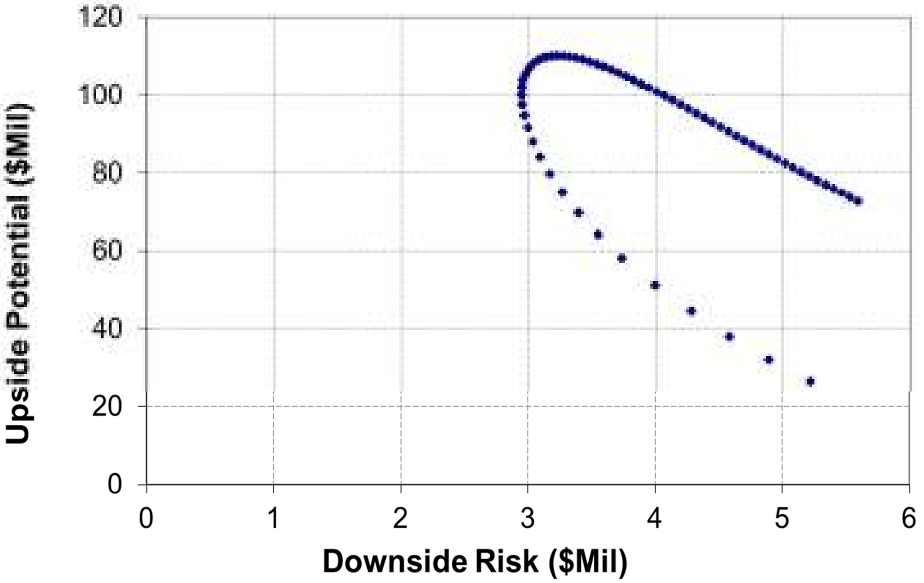

Figure 18. Upside potential and downside risk of designs

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[5] The root of the downside risk is plotted in Figure 18

From Figure 18, it is clear that a sub-set of the design space may be eliminated. The systems designs in this subset fall into two categories. The first category consists of those designs which offer the satellite operator a lower level of upside potential for the same level of downside risk when compared to other designs. The second category consists of those system designs which offer the satellite operator a higher level of downside risk **and** a lower level of upside potential when compared to other system designs. After eliminating these two categories of system design, the final portfolio of system designs presented to the decision-makers consisted of a single system design for this example, that of a payload size of 41Tx with an upside potential of $107M and a downside risk of $2.9M

3.5 Summary of Priced Value in Space Systems Design and Acquisition

Value-informed space system design and acquisition is receiving greater than ever attention in the space acquisition community. It is increasingly recognized that the traditional cost- and performance-centric approaches to design and acquisition are myopic in their consideration of the benefits and costs a system provides to the stakeholder. These traditional approaches rely primarily on system-centric information (e.g. data rate, modulation, instrument resolution) and incorporate limited information about factors exogenous to the system but are important to value generation. In contrast, a value-centric approach to system design and acquisition is a more information intensive approach as it equally incorporates information about factors both exogenous and endogenous to the system which are critical for the value generation of the space system.

This chapter furthered the current intellectual thought on value-centric design and acquisition through three critical discussions. The first discussion revolves around the implementation of a value-centric approach to system design and acquisition. In particular, it presented a value-centric framework for priced space systems. Within this framework are three analyses blocks needed for value assessment of the system. The first block, Traditional Engineering Analysis, utilizes information endogenous to the system and evaluates the technical performance and cost of the system, that is, the types of analyses traditionally completed in an engineering environment. The second block, Traditional Business Analysis, evaluates factors exogenous to the system such as the market demand and pricing dynamics, or analyses traditionally completed by the Sales and Marketing units of an organization. The third block evaluates the value of the space system to the stakeholder and is labeled Value-Informed Decision-Making.

The second discussion focuses on the importance of information exogenous to system in guiding engineering decisions. In particular, it highlighted the importance of this type of information in managing risks (e.g. programmatic, technical), and leading to higher valued systems for the stakeholder. Using the application of the acquisition of a satellite by a satellite operator proved insightful as it enabled a comparison of a traditional cost-centric approach and a value-centric approach to system design and acquisition. The results of this comparison indicate that the traditional economies of scale argument applied to the acquisition of commercial communication satellites is flawed as larger satellites do not necessarily equate to higher valued satellite to the satellite operator. Furthermore, not incorporating information exogenous to the system generally leads to value losses incurred by the satellite operator.

The third discussion demonstrated the usefulness of the decision information provided through the generation of the probability density function of the NPV of each system. First, it highlighted how engineers may incorporate uncertainty into decision making by evaluating system designs based on the expected NPV and NPV uncertainty. Secondly, and perhaps more importantly, it presented a methodology for better characterizing NPV uncertainty associated with each system design using the method of partial moments. This method allows decision-makers to decompose uncertainty into it two constituents, upside potential and downside risk. It is intended that by separating uncertainty into its two constituents, engineers will be better positioned to manage uncertainty.

CHAPTER 4

BAYESIAN VALUATION OF UNPRICED SPACE SYSTEMS

This chapter has two objectives: 1) to develop a value-centric framework for ex-ante value analysis of unpriced space systems which provides a linkage between the technical parameters of the system and the unique set of benefits (in terms of type, quality and quantity) the space system offers the stakeholder and 2) to develop an analytical tool that allows engineers to evaluate the coupled cost and value uncertainty associated with the space system.

4.1 Motivating Value Assessment of Unpriced Space Systems

In 1958, the National Aeronautics and Space Act established the National Aeronautics and Space Administration (NASA) to conduct the civil space program. Under this Act, the newly established agency was directed to focus on the "expansion of human knowledge of the Earth and of phenomena in the atmosphere and in space" [135]. The agency is tasked with identifying and executing space missions based on scientific merit so as to increase the knowledge of the scientific community. The idea here being, that by increasing the knowledge of the scientific community a trickled down effect occurs, and the knowledge of the society at large increases. However, limited, if any, formal consideration was paid to linkages between knowledge generation in the scientific community and creation of applications to the society at large.

In recent years, political and economic conditions led to calls for providing a sharper definition to this linkage. Ascribing social benefits to the data collected by spaceborne scientific instruments is receiving greater prominence as program managers are asked to partially justified space missions based on the potential applications enabled to the wider society. In fact, as early as 1992, the imperative to provide a definitive link between the generation of scientific knowledge and the societal applications is evident in reports on setting priorities in space-based research. In 1992, the National Academies Space Studies Board, the body responsible for compiling the list of priorities for the national space policy noted "the collection of data, the creation of information through its analysis, and the subsequent development of insight and understanding should be key governing objectives for scientific research in space" [136]. In this statement, the Space Studies Board referred to the information created for society as a whole and not just the scientific community. More recently in 2007, NASA, the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey (USGS) commissioned a report to identify flight missions which should be deemed high priority over the next decade [137]. Part of the impetus for this report is the desire to create a strategic plan for space missions that supported national needs for research and monitoring of Earth's ecological, atmospheric and geological systems. Eight criteria are identified as being critical to executing a successful space-based national strategy in earth science. Two of the criteria applicable to this research are the "contribution to applications and policy making" and "affordability (cost considerations, either total costs for missions or costs per year)". The first criterion explicitly called for identifying the linkage between advancements in scientific knowledge and societal benefits, while the second criterion recognizes the need for fiscal responsibility.

Over the last decade a number of studies has attempted to identify and quantify the societal benefits of observational data obtained from earth science satellites. For example, Centrec Consulting (2005) assessed the economic value of selected NOAA climate products within the railroad sector by comparing the cost to the railroad sector of acquiring the NOAA data from the National Climatic Data Center to the cost to railroad sector of acquiring the data on their own [138]. Hagan et al (2010) estimated the value of ocean observing systems in fisheries using a Bayesian approach [139]. Cohen and Goward qualitatively highlighted Landsat's role in the development of a number of ecological applications [140]. And the list goes on [141-145]. While these studies have successfully indicated the value of space missions to various elements of society, the type of analysis conducted in each study generally suffers from one limitation from a system design and acquisition perspective. Each study is an ex-post value analysis, that is, each study is performed after the system has been fielded, the mission has been completed, and the benefits of the system are realized. In contrast, one of the impetuses from the decadal survey is to assess the mission benefits a priori, or before the mission is executed. Thus a framework for ex-ante value analysis is needed, that is, a value analysis performed before the system is fielded, the mission is selected, and the benefits are realized. The first step in developing this value framework for the unpriced space system is to understand the various value flows that the system provides stakeholders.

4.2 Value Flows of Unpriced Space Systems

The earth science and applications decadal survey called for a stronger emphasis on how scientific knowledge generated by the space system may be leveraged by the greater society. In doing so, the survey implicitly advocated for a change in the current system-centric paradigm in system design and acquisition to a more novel stakeholder-centric paradigm. Under a system-centric paradigm, the role of the spacecraft is restricted to the potential scientific contributions which may emerge from its operation. It is assumed, and rightfully so, that the basic research conducted during the mission forms a critical component in broader knowledge generation [146]. As it is not obvious initially what applications will emerge from this basic research, the objective in a system-centric paradigm is to generate as much scientific knowledge as possible given cost, technical and schedule constraints, with the hope that useful applications may emerge. In other words, the system-centric paradigm employs a passive strategy in the management of applications generated to the broader society, and subsequently, to returns on the public investment in the space system. For system design and acquisition problems within the system-centric paradigm, the program manager and engineers attempt to optimize technical parameters of the space system to fulfill the data requirements of the scientific community - the principal users of the system's data. The primary type of information utilized in the space system design and acquisition decision problem within this paradigm is system intrinsic. As such, the program manager and engineers draw on cost- and performance-centric frameworks to facilitate design and acquisition decisions.

In contrast to the system-centric paradigm, the stakeholder-centric approach employs more of a proactive strategy in the management of societal applications enabled by the spacecraft. Under this new paradigm, simply assessing the scientific merit of the system is considered myopic as it limits the value assessment to the type, quantity and quality of data collected by the spacecraft with little consideration for the broader usefulness of the data. In fact, if one peers outside the system-centric paradigm it becomes obvious that the value generation of the space system is more complex than the basic science created [147]. Figure 19 illustrates the complexity of the space system value generation.

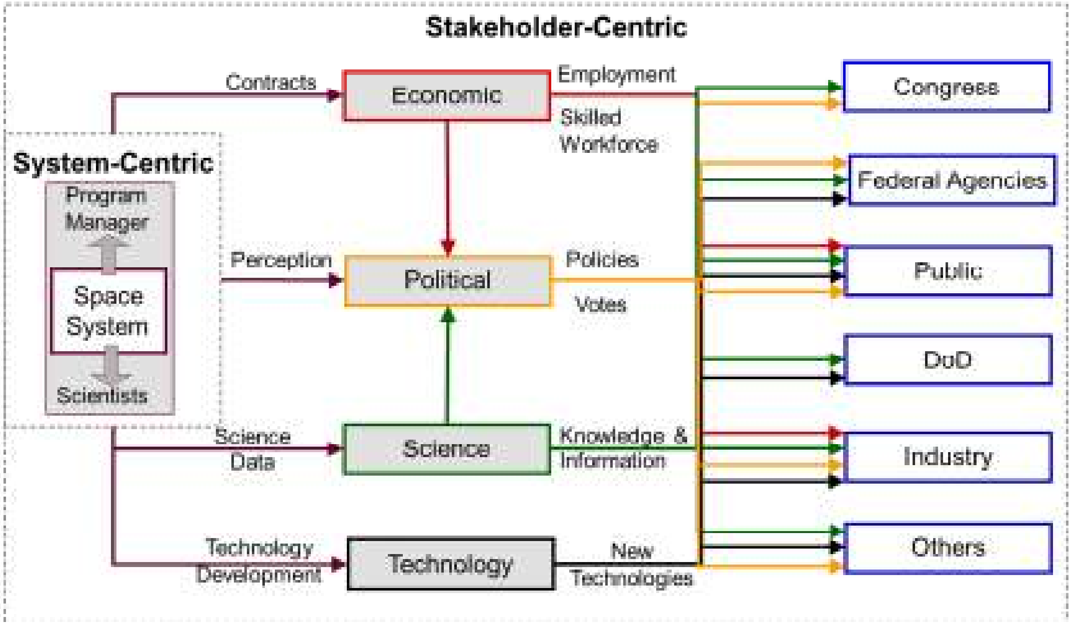


Figure 19. Examples of value flows from space system to stakeholders

As Figure 19 indicates, the system-centric paradigm is concerned with actively fulfilling the needs of mainly one cohort of stakeholders, the scientific community. However, from the figure, it should be clear that there are diverse stakeholder cohorts external to the system design and acquisition environment that receive value flows from the space system either directly or indirectly. Some of these value flows are illustrated in Figure 19. For example, the industrial base may receive an economic value flow through employment; the Executive Branch may receive a political value flow (i.e., political support) based on intelligence, surveillance and reconnaissance data gathered from space based assets; federal agencies (e.g. environmental protection agency) may receive a climate and ecological science value flow that increases knowledge about terrestrial phenomena; and the public may receive a technology value flow through technology spin-offs. These value flows are propagated through a number of mechanisms, among that are contractual agreements that provide economic incentives to maintain a skilled workforce, the crafting of public perception which increases public support for policies, scientific data collection which may be converted to information for decision-making, and the development of new technologies [147,148].

While it is recognized that each value flow is an important component in the value generation of the space system, this thesis will only focus on one of these value flows, the information value flow. This is done for two reasons. First, an assessment of the complete set of value flows to the complete set of stakeholders is onerous, and maybe even intractable. To solve such complex issues, it is sometimes necessary to tackle a small but important step in the larger problem. An assessment of the information value flow represents this small but important step to understanding the full value profile of the space system. Second, this thesis focuses on the information value flow as given the recent thrust emanating from the decadal survey, a number of program managers often justify missions based on the data products provided and the information products enabled [149-152]. In addition, in a number of beneficiary sectors the value assessment of the space system is often linked to the data provided [142,144,145,153]. For unpriced space systems, this research will posit that their value derives from and can be assessed through the value of information they provide. As such, a value-centric framework for the value analysis of the unpriced space system will be formulated based on the value of the information the system provides stakeholders.

4.3 Definitions of Information

In order to develop an information-centric framework for the valuation of unpriced systems, it is necessary to define information. Like value, information is an important concept in numerous fields. In each of these fields information is defined in a manner that supports its intended purpose in that field. There are two main (though not necessarily distinct) categories of information definitions, statistical and pragmatic definitions [155].

4.3.1 Statistical Definitions of Information

There are two distinctive characteristics of the statistical definitions of information. The first is the separation of the information content from the meaning of the message. For engineering applications, incorporation of the meaning of information is considered “irrelevant to the engineering problem” [154,156]. Furthermore, it is thought that incorporating the meaning of information into the definition reduces the tractability of quantifying information [157]. Thus from an engineering and natural science perspective, the semantic properties of information are considered to be independent of the information itself for definitional purposes. Second, statistical definitions of information utilize a mathematical approach and their resulting metrics are concerned with attributes of the data distribution such as coherence and accuracy than the pragmatic or semantic properties of the information [155]. Thus, when statistical information metrics are used to assess the value of the information to the stakeholder, the fundamental assumption imposed is that the level of information content is a latent measure of the pragmatic (i.e. useful) information value to the stakeholder. These measures while not direct indicators of information value may act as proxies for information value when obtaining data on the usefulness of the information may be tedious. Notable statistical definitions include the Shannon entropy definition, Fisher information definition, Blackwell informativeness and Kullback-Leibler divergence definition [158-160].

4.3.2 Pragmatic Definitions of Information

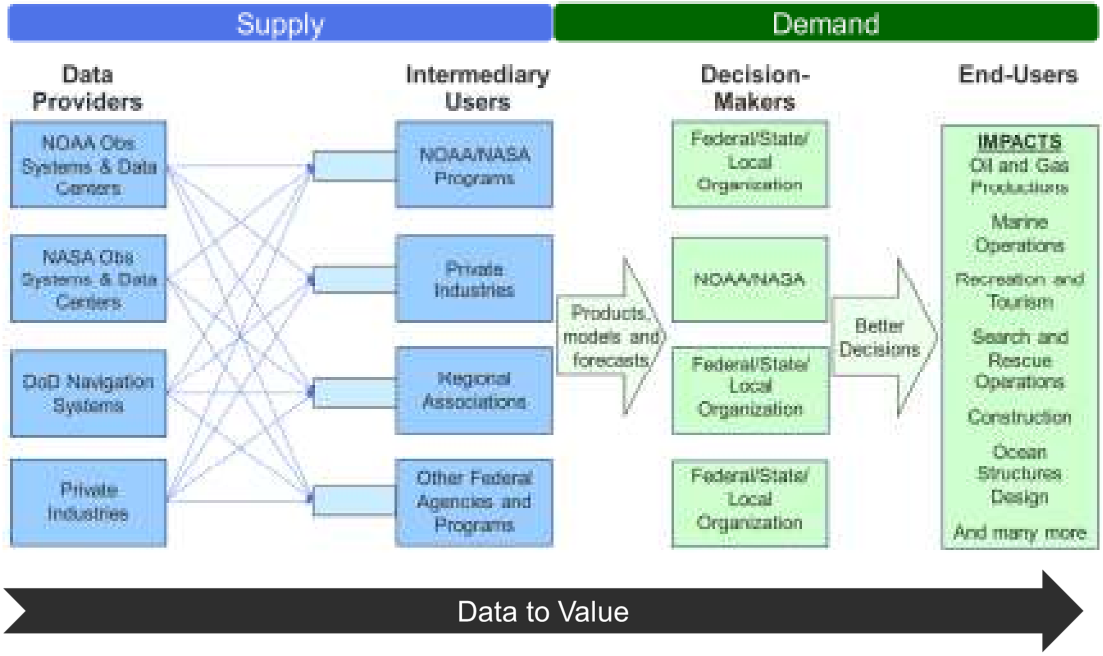
There are three distinctive characteristics of pragmatic definitions which separates them from statistical definitions. The first is the connectivity of information to its recipient. These definitions are semantic in nature and states that information is dependent on the receiver, that is, information stems from the interpretation and meaning of the message to the recipient [161,162]. In cases where the meaning of the message is a “complete novelty”, or the messages cannot be understood, the message is said to contain no pragmatic information [161]. Thus the message must have some meaning to the receiver for information to exist. The second characteristic captures the linkage between information and the impact on decision-making. Pragmatic information increases the knowledge of the receiver, and in doing so, results in the receiver selecting the desired course of action. For the third characteristic, pragmatic definitions view information as being subjective. Unlike statistical definitions which are concerned with only the mathematical properties of the message containing the information, pragmatic definitions are concerned with properties of the information such as timeliness and relevance to the receiver [155]. Thus, when pragmatic information metrics are used to assess the value of the information to the stakeholder, the fundamental assumption imposed is that information leads the decision-maker to select the desired course of action. This course of action yields a pay-off to the decision-maker which drives the value of the information.

4.3.3 Defining Information in Space Systems Design and Acquisition

It is important to note that although no definition is wrong, some definitions are more useful than others. Thus for the purposes of this work, the second category of definition is considered to be more relevant. However, as one may surmised from the discussion on the pragmatic definitions of information, obtaining a functional definition may be quite difficult. For example, how does one quantify the meaning of the message to different receivers? For this reason, the pragmatic definitions of information are augmented by a Bayesian construct. The primary purpose of information is the transformation of the knowledge base of the stakeholder. Suppose, at any moment the stakeholder has a certain belief about the occurrence of states of the relevant environment. For example, the stakeholder will have a certain belief about whether it will rain on a given day. By obtaining information, the stakeholder is able to update their beliefs about the occurrence of these states. From a Bayesian construct, probability is used to quantify rational degrees of belief [163]. Thus, this thesis will define information as "any stimulus that has changed the recipient knowledge, that is, that has changed the recipient's probability distribution over a well-described set of states."[188]. This definition will form the basis of the valuation methodology for unpriced space systems

4.4 Characterizing the Space System Information Value Flow

After defining information in the context of space system design and acquisition, the next step in developing the valuation framework for unpriced system is to articulate how the stakeholder derives information value from the space system. The formulation of the information value flow will be done through an information value chain. A value chain is a chain of successive activities in which each activity enhances the value of the information [198,199]. An illustration of the information value chain that emanates from the space system is provided in Figure 20 .



Adapted from Willis 2009 [166]

Figure 20. The information value chain

The value creation chain is divided into two categories, supply and demand. The first category, supply, is comprised the data providers such as the spacecraft operators like NASA and NOAA, and the scientists which collect, analyze and transform the data. Within the supply category are two types of stakeholders. The first set of stakeholders is the data providers. The main activity of these stakeholders is the collection of sensor data from the scientific instruments on the space system. This sensor data may be in situ or remote data observations. At this stage, the sensor data from the spacecraft is in its raw form and it not particularly useful to the end-user. The second set of stakeholders within the supply category is the intermediary users. These stakeholders may be scientists within private industries, federal agencies or a department within NOAA or NASA. In each case, such stakeholders play a critical role in the value creation chain as they utilize the raw data from the spacecraft to create or improve navigation algorithms or scientific models of geological, environmental, oceanic or space-based phenomena. Thus a scientific conversion is performed in which raw sensor data from the space system is transformed into information products. The scientific conversion adds value to the collected data, as the data is placed in a useful form for decision-making.

The activities conducted in the first segment, supply, creates an information product which fulfills a need in the second segment, demand. As information products, the data from the space system are in demand by a number of decision-makers. Among these decision-makers are federal and local agencies, private industries and other organizations. It may be stated that information products have value to the stakeholder as they allow the stakeholder to adjust or confirm operational decisions. In so doing, the information products allow decision-makers to make choices which may yield higher expected pay-offs than in the absence of that information [108,112,113]. Herein lies the value of the information products, and consequently the value of the data products supplied by the space system. Thus, at every stage from the data provision to the scientific conversion to decision-making to pay-off, the information value chain emanating from the space system creates a value-added product.

4.5 A Bayesian Valuation Framework for Unpriced Space Systems

Now that information is defined and the information value chain constructed, it is possible to develop the Bayesian framework for assessing the value of the information the space system provides to the stakeholder. For the stakeholder, a decision is usually expressed as problem of selecting a single course of action from a set of possible courses of action which may be taken. Intuitively, one might understand why information is important to solving this decision problem. From modern economic theory, information is viewed as a factor in decision-making which reduces uncertainty or aids in correcting misconceptions about the possible states of the stakeholder's environment [167]. For this analysis, the environment may be defined as a set of factors that are beyond the control of the stakeholder but impacts the pay-off of any decision made by the stakeholder [168]. These factors are termed state variables. In addition to the environmental state variables, an additional set of variables is needed to solve the decision problem. These variables are the possible outcomes or pay-offs from taking a particular course of action. The outcome variables provide the incentive for the stakeholder to select a course of action and are critical factors in solving the decision problem. The Bayesian framework incorporate these three pieces of data (set of actions, set of state variables, and set of outcomes) to assess the value of the space system.

Finally, before presenting the Bayesian framework for assessing the value of the system, one topic remains to be discussed, the premise of the Bayesian framework. The premise of the Bayesian valuation framework states that the space system is an information provider and the stakeholder an information recipients. Thus, the value of the space system stems from the value of the information it provides the stakeholder. Engineers can therefore assess the value of the space system to stakeholders based on the value of its information. Formally, the Bayesian framework is given in Figure 21 and may be described in the following manner.

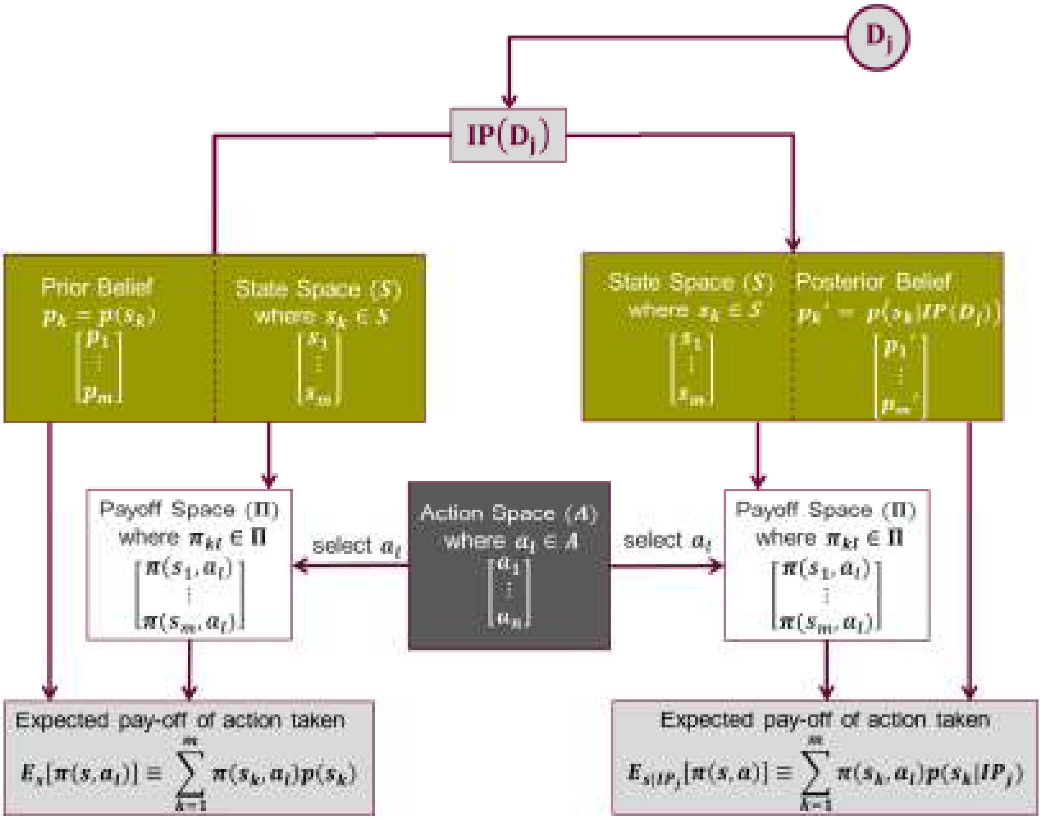


Figure 21. Bayesian framework for the valuation of unpriced space systems

Assume there exists a stakeholder faced with the dilemma of selecting a course of action from within an action space, **A**. This action space is represented by the dark grey central box in Figure 21. For simplicity, it is assumed that the action space contains the complete set of actions which the stakeholder may take, and these actions are both discrete and countable. Next, suppose that the stakeholder exists in a world of uncertainty. In this world, there are a number of scenarios or environmental states ($s_1, s_2, s_3, \ldots\ldots, s_m$) which may occur. For simplicity, these states are also assumed to be both discrete and countable. The stakeholder will select a course of action based on his belief about the probable occurrence of these states. The stakeholder's belief about the occurrence of each state may be represented by a probability mass function ($p_1, p_2, p_3, \ldots\ldots, p_m$) where

$$p_k = p(s_k) \qquad \textbf{Eqn. 28}$$

The state space and probability mass function are represented by the left green box in Figure 21. The stakeholder will make a decision by selecting a course of action ($a_l \in \mathbf{A}$). If state s_k occurs, the stakeholder will desire to select an action such that he maximizes his pay-off (or minimizes his cost) (π):

$$\pi(a^* \mid s_k) = \max_a \pi(a \mid s_k) \qquad \textbf{Eqn. 29}$$

However, the stakeholder does not know with certainty which state will occur before selecting the course of action. In other words, the stakeholder is faced with making a decision under certainty. For any given course of action ($a_l \in \mathbf{A}$), there are a number of possible pay-offs to the stakeholder depending on which scenario materializes. The set of possible pay-offs for the selected action as shown in Figure 21 may be represented as

$$\pi_l = \begin{bmatrix} \pi(s_1, a_l) \\ \vdots \\ \pi(s_m, a_l) \end{bmatrix} \qquad \textbf{Eqn. 30}$$

Under uncertainty, the stakeholder requires an objective function by which to evaluate alternative courses of action. The objective function will enable the stakeholder to rank the courses of action and select the optimal or best course of action. A number of objective functions are available for this type of analysis. One common objective function is the expected pay-off. For each course of action, the expected value weights each possible payoff by the probability that the pay-off occurs. For example, the expected pay-off from choosing the course of action a_l is given by[6]:

$$E_s[\pi(s, a_l)] \equiv \sum_{k=1}^{m} \pi(s_k, a_l) p(s_k) \qquad \textbf{Eqn. 31}$$

Defining the objective function as the expected pay-off allows the definition of an action rule for the stakeholder. The action rule will govern the stakeholder's decision as

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[6] This concept may be extended to the case where the state space is uncountable and $\boldsymbol{Pr}(s_k)$ is continuous as follows:

$$E_s[\pi(s, a_l)] \equiv \int_s \pi(s, a_l) p(s)$$

to which course of action to select. If it is assumed that the stakeholder wishes to maximize the expected pay-off, then the action rule will be to select the course of action which maximizes the expected pay-off:

$$\max_a E_s[\pi(s,a)] \equiv \max_a \sum_{k=1}^{m} \pi(s_k, a) p(s_k) \qquad \textbf{Eqn. 32}$$

Now suppose that there exists a space system (D_j). This space system acts as an information source to the stakeholder by enabling a set of information products which the stakeholder utilizes to update his current beliefs. For example, an earth science space system may provide geomorphological information to scientists allowing them to update their belief about the occurrence of a volcanic explosion. Based on the set of information products (IP_j), the stakeholder possesses new beliefs about the occurrence of each environmental state as shown in the right green box in Figure 21. These updated beliefs may be represented by the probability mass function (p_1', p_2', p_3', ……, p_m') where

$$p_k' = p(s_k \mid IP_j) \qquad \textbf{Eqn. 33}$$

As the stakeholder will select a course of action based on his belief about the probable occurrence of these states, the expected pay-off for each course of action will also be updated:

$$E_{s|IP_j}[\pi(s,a_l)] \equiv \sum_{k=1}^{m} \pi(s_k, a_l) p(s_k \mid IP_j) \qquad \textbf{Eqn. 34}$$

In updating the expected pay-off for each course of action, the action rule is modified as follows:

$$\max_a E_{s|IP_j}\left[\pi(s,a)\right] \equiv \max_a \sum_{k=1}^{m} \pi(s_k, a) p(s_k \mid IP_j) \qquad \textbf{Eqn. 35}$$

In other words, the stakeholder selects the course of action that maximizes the expected pay-off based on information obtained from the space system. It is well accepted that information is important as decisions made in the presence of information increases the expected pay-off to stakeholders relative to decisions made in the absence of information [113,155]. Furthermore, the value of having that information is the difference in expected pay-offs between these two cases. As a result, the value of the information provided by the space system, or more succinctly the value of the design (VOD_j) may be defined as

$$VOD_j = \max_a E_{s|IP_j}\left[\pi(s,a)\right] - \max_a E_s\left[\pi(s,a)\right] \qquad \textbf{Eqn. 36}$$

4.5.1 Limitations of the Bayesian Valuation Framework

The Bayesian valuation framework offers engineers a quantitative methodology for assessing the benefits the unpriced space system provide stakeholders, and linking these benefits to the system design. However, there are a number of limitations to the framework as presented. These limitations are as follows:

L1. The Bayesian framework as described should not be applied to the valuation of information that simply increases the knowledge of the stakeholder with no immediate apparent pay-offs or costs.

L2. The implicit assumption in the Bayesian framework is that information reduces uncertainty. However, there may be cases in which information does not reduce uncertainty but rather results in a structural readjustment in the stakeholder's belief about the occurrence of the environmental states. For such cases, it is possible that having additional information will lead to increases in expected costs or reductions in expected pay-offs.

L3. The posterior probability distribution of the occurrence of the environmental states has to be derived a priori, that is, before the fielding of the system. In some cases it may be difficult to model expected changes in the stakeholder' rational beliefs beforehand, thus making a derivation of the posterior probability distribution problematic.

Despite these limitations, the Bayesian framework may be rigorously applied to the valuation of a number of unpriced space systems. One such application is developed in the next section.

4.6 Application of Bayesian Framework to Earth Science Satellite

The previous section developed the theoretical model for the valuation of the space system. In this section, the Bayesian framework is applied to a space system decision problem for a proposed environmental monitoring mission. It is expected that the data gathered from this mission, when integrated with current weather prediction models, will yield increased accuracy in forecasting severe weather events such as hurricanes and flash floods. The objective of engineers is to select a system design for the spacecraft based on the environmental information to be provided by the design. The Bayesian framework is operationalized and applied to the earth science application using the process given in Figure 22. Shown in Figure 22 are the four segments in the information value chain as applied to space systems.

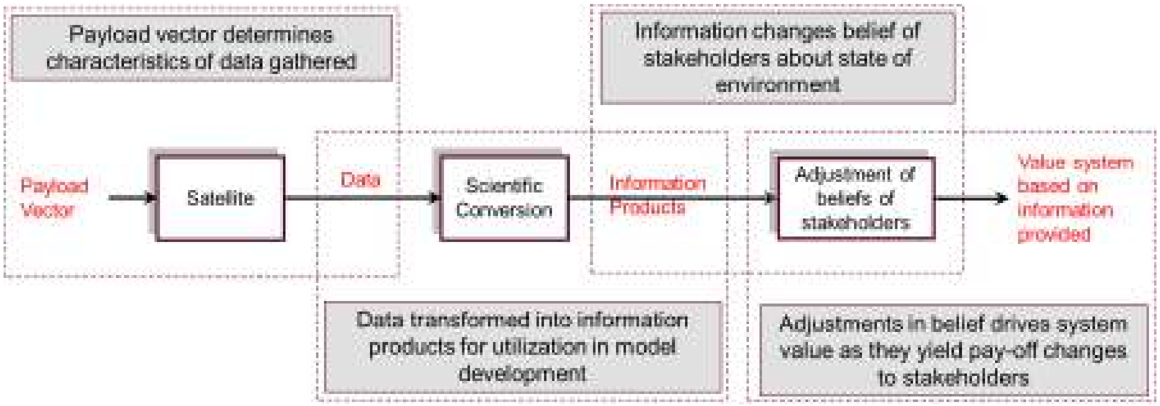

Figure 22. Operationalizing the Bayesian framework

Operationalizing the Bayesian framework involves four steps, data product generation, scientific conversion, adjustment in beliefs, and value of information estimation. These steps are based on the information value chain and are briefly summarized as follows:

Data Product Generation: The purpose of the data product generation is twofold. First, this step identifies a set of system design candidates which are capable of (or partially capable of) satisfying mission requirements. Second, after the set of system design candidates are determined, this step evaluates the type, quality and quantity of the data products provided by each design.

Scientific Conversion: The purpose of the scientific conversion is to convert the data products into useful information products for the stakeholder. More specifically, this step determines what information products or improvements in information products may be generated from the data products provided by each system design

Adjustment in Stakeholder's Beliefs: The purpose of this step is to assess how the stakeholder utilizes the new or improved information product to adjust his beliefs about the possible occurrence of the states of his environment. Specifically, this step assesses the change in the probability distribution of the occurrences of the environmental states.

Value of Information Estimation: The value of information estimation is the final step in operationalizing the Bayesian framework. This step involves four components. First, the set of possible actions the stakeholder may take in response to their environment has to be defined. Second, a pay-off scheme is devised which reflects the consequences of taking a particular course of action. Third, an action rule is constructed which

> guides the course of action taken. Finally, the value of the information provided by the space system may be determined based on the difference between the expected pay-off achieved in the presence of the new or improved information product and the expected pay-off achieved in the absence of the new or improved information product.

The steps for operationalization the value of information framework are briefly presented to orient the reader as the process is applied to the selection of an earth science satellite which aids in hurricane predictions. Greater detail is provided on each of these steps in the context of the example mission to assess the implications of the proposed Bayesian valuation framework for space system design and acquisition.

4.6.1 Data Product Generation

The generation of data products depends on the scientific instruments onboard the space system. For this analysis, the particular system parameter of interest is the selection of the instrument suite. The instrument suite is one of the key value drivers of the spacecraft, providing the stakeholder with the desired information, either directly or indirectly, to make operational decisions. As such, the instrument suite selected, and consequently the system design, is driven strongly by the mission. The environmental monitoring mission collects data about weather phenomena, specifically cloud imagery, atmospheric temperature profiles, wind speeds and atmospheric water vapor content. This particular mission considers three hypothetical instruments. These are instrument X_1, instrument X_2 and instrument X_3[7]. Given the three instruments, a set of seven system designs are considered with the instrument suite of each system design comprising some combination of the three instruments. The designs are defined as shown in Table 4.

Table 4. Candidate System Designs

		Candidate Designs						
		D_1	D_2	D_3	D_4	D_5	D_6	D_7
Instruments	X_1	1	0	0	1	1	0	1
	X_2	0	1	0	1	0	1	1
	X_3	0	0	1	0	1	1	1

In Table 4, X_i indicates the presence of a particular instrument in the payload vector of system design, D_j . For example, $X_1 = 1$ indicates the presence of instrument X_1 in the instrument suite of the design, $X_2 = 1$ indicates the presence of the instrument X_2, and $X_3 = 1$ indicates the presence of instrument X_3. From each of these instruments, a set of data products are generated. Instrument X_1 generates data about cloud imagery and near-surface wind vectors over global oceans. Instrument X_2 gathers data for the construction of atmospheric temperature profiles, as well as the temperature profiles of

---

[7] Examples instruments that these hypothetical instruments represent include Imagers, Sounders, Microwave Spectrometers and Microwave Scatterometers to name a few [169-173].

clouds. Instrument X_3 measures atmospheric water content, cloud liquid as well as provide cloud imagery. Based on the instrument suite, each system design is mapped to a set of data products. The mapping of the instrument suite to data products is assumed to be linear, that is, no data products emerged from the presence of an additional instrument on board which could not be obtained by at least one of the instruments in the instrument suite. Examples of the data products generated by each system are given in Table 5. Similar to Table 4, a value of one in the system design column indicates that system design generates the corresponding data product.

Table 5. Examples of Data Products

		Candidate Designs						
		D_1	D_2	D_3	D_4	D_5	D_6	D_7
Data Products	**Real Time Imagery**	1	0	1	1	1	1	1
	Temperature Profiles	0	1	0	1	0	1	1
	Moisture Profiles	0	0	1	0	1	1	1
	Sea Surface Temperature	0	1	0	1	0	1	1
	Wind Speed	1	0	0	1	1	0	1

4.6.2 Scientific Conversion of Data Products

The data products when integrated into weather prediction models may aid in improving the accuracy of those models. Examples of the information products related to hurricane forecasting that utilizes the generated data products include the forecast error, the hurricane intensity and the strike probability. This application focuses on the information product, Forecast Error.

The Forecast Error is defined based on the deviation of the hurricane from its predicted path at a given point in time. The National Hurricane Center utilizes the types of data products given in Table 5 to predict the position or track of the hurricane's center at 12-hours intervals up to 48 hours and 24-hour intervals up to 120 hours. The conversion of these data products to forecast hurricane tracks involves some degree of subjective judgment as well as quantitative analysis [174]. Thus, in addition to providing the forecast track of the hurricane at given points in time, the National Hurricane Center also provides the forecast error. Mathematically, the forecast error of a given hurricane computed using Cartesian coordinates is as follows [175]:

$$FE^{T} = \sqrt{\left[(x_a - x_p)^2 + (y_a - y_p)^2\right]} \quad \textbf{Eqn. 37}$$

where FE^T is the forecast error at a certain point in time (e.g. 48 hours), and $[x_{\mathrm{a}}, y_{\mathrm{a}}]$ and $[x_p, y_p]$ are the actual and forecast positions of the hurricane respectively at time T. The National Hurricane Center gathers data on the forecast errors and, based on five year time increments, provide this data in the form of a cumulative distribution [175]. For the 48 hour forecast, the cumulative distribution of the forecast error over the last five years (2006-2010) is shown in Figure 23.

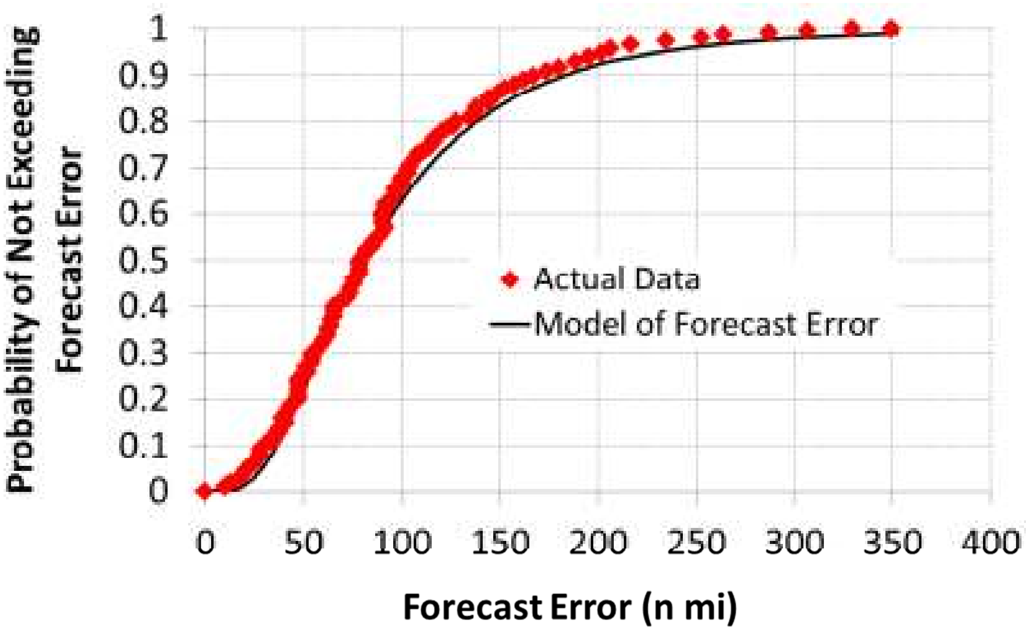

Figure 23. Cumulative distribution of 5-year forecast error (Atlantic Basin)

The cumulative distribution of the forecast error describes the percentage of forecast error which falls below a certain level. To facilitate automated analysis, a parametric model of the probability distribution of the forecast error is developed based on the raw data provided by the National Hurricane Center. In particular, the probability distribution of the forecast error is modeled using a lognormal distribution with parameters μ_0 and σ_0^2, where μ_o and σ_0^2 are the mean and variance of the natural logarithm of the forecast error ($ln(FE^{48})$), respectively. Using this distribution, the probability that a hurricane deviates from its path by a distance fe^{48} is given as:

$$p\left(fe^{48}\right) = \frac{1}{\sqrt[x]{2\pi\sigma_0^2}} e^{-\frac{\left(\ln\left(fe^{48}\right)-\mu_0\right)^2}{2\sigma_0^2}} \qquad \textbf{Eqn. 38}$$

where the parameters μ_0 and σ_0^2 of the lognormal distribution are related to the mean, m_0, and variance, v, of the forecast error (FE^{48}) as follows [176]:

$$\begin{aligned} m_0 &= e^{\mu_0 + \sigma_0^2/2} \\ v &= e^{2\mu_0 + \sigma_0^2}\left(e^{\sigma_0^2} - 1\right) \end{aligned} \qquad \textbf{Eqn. 39}$$

The mean forecast error, m, is determined to be approximately 99 nmi while the variance, v, of the forecast error is calculated to be approximately 69^2 nmi^2. This yielded parameter values of $\mu = 4.4$ and $\sigma_0^2 = 0.4$.

The definition and model of the forecast error provides a platform from which to assess possible improvements in the information product due to the data products generated by a given spacecraft. The type and magnitude of the improvements may be determined using subject matter experts who possess detailed knowledge of how the information products are generated from their data components. For this analysis, the improvement in the forecast error is modeled as a percentage reduction (r_j) in the mean forecast error, that is, the space system provides data which improves the accuracy of hurricane forecasting. The variance of the forecast error, v, is assumed to be unchanged. The resulting mean forecast error for a space system with design D_j is described as follows:

$$m_j = \left(1 - r_j\right) \times m_0 \qquad r_j \in [0,1] \qquad \textbf{Eqn. 40}$$

Determining the reduction in the mean forecast error is a complex process due the various uncertainties associated with converting data products into improvements in information products. Examples of these uncertainties include uncertainty in the quality of data products generated, and uncertainty in quantifying how the data products impact the information product. For each system design, the improvement in the information product is assumed to be uniformly distributed between the ranges as shown in Table 6.

Table 6. Reduction in Forecast Error

		Candidate Designs						
		D_1	D_2	D_3	D_4	D_5	D_6	D_7
Reduction (r_j)	**Mean**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**
	Max	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
	Min	**0.0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**

Once the mapping of the data product to improvements in the information is completed, the next step in operationalizing the Bayesian framework is to determine how these improvements affects the stakeholder's belief about the probable states of the environment.

4.6.3 Adjustment in Stakeholder's Beliefs

The stakeholder analysis is perhaps the more complex aspect of the Bayesian framework for unpriced space systems. The objectives of the decadal survey desired a system design and acquisition strategy in which consideration of societal benefits are integrated into mission selection, and system design and acquisition [136]. However, assessing societal benefits is somewhat difficult as the society consists of several non-homogenous stakeholders who utilize the hurricane forecasting information from the spacecraft in numerous applications. Any attempt to enumerate all stakeholders and subsequent usages of the spacecraft data by stakeholders would be onerous, if not impossible. One approach to addressing this issue with stakeholder analysis is to obtain a sampling of stakeholders who represent the primary users of information products enabled by the spacecraft [177]. This technique has been utilized to some degree by a number of the decadal selected missions [178,179]. This makes the problem of assessing benefits to stakeholders somewhat tractable. This analysis focuses on a single stakeholder. However, the process presented herein may be replicated for additional stakeholders.

For this application, the stakeholder of interest will be an oil rig operator in the Gulf of Mexico. There are two relevant environmental states to the oil rig operator as related to hurricane forecasting. These are 1) the oil rig is in the hurricane strike zone and 2) the oil rig is not in the hurricane strike zone. Based on the size of a typical hurricane, the strike zone is defined as an area swept out by a radial line of length 62.5 nmi with the center of the hurricane as the focus of the circular area [180]. Thus, if the hurricane passed within 62.5 nmi of the oil rig, the oil rig is considered in the strike zone. For a given hurricane, estimating the probability of the oil rig being in the strike zone is equivalent to estimating the probability of the hurricane deviating from its forecasted track such that it passed within 62.5 nmi or less of the oil rig. Figure 24 and Figure 25 illustrates the likelihood that the oil rig is in the strike zone given the hurricane's forecasted track is a distance (*d_i*) from the oil rig.

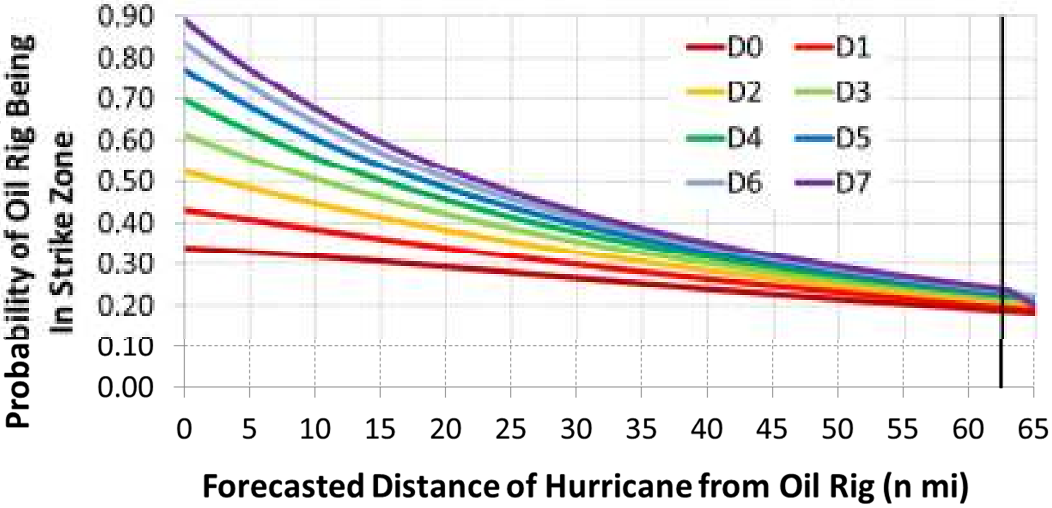

Figure 24. Probability of oil rig being in strike zone (strike zone distance)

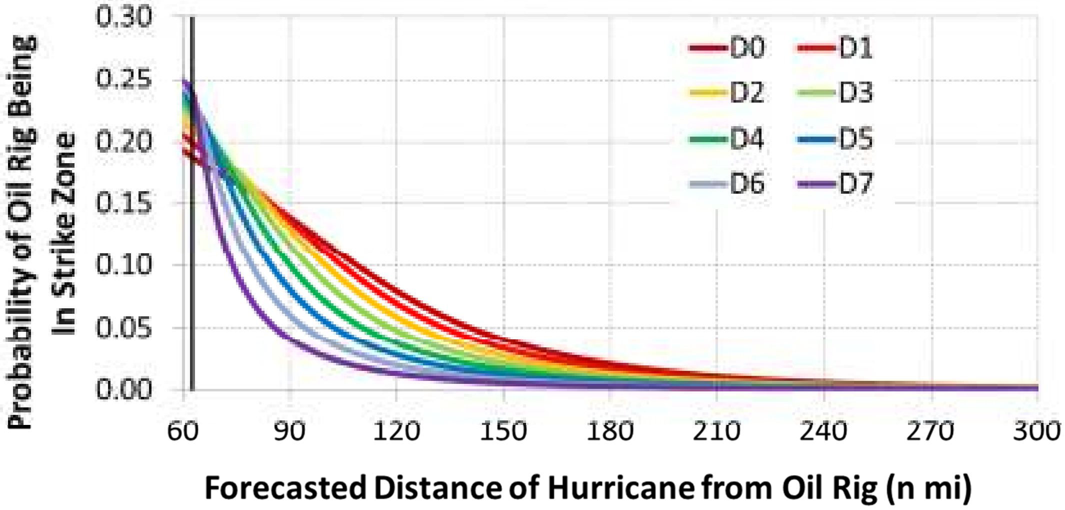

Figure 25. Probability of oil rig being in strike zone (non-strike zone distance)

In Figure 24 and Figure 25, the probability estimation based on the current data provided by National Hurricane Center is indicated by D_0, and the updated probability estimation given the information provided by the various system designs are given by D_1 through D_7. For example, if the hurricane is forecasted to pass a distance of 15 nmi from the oil rig, Figure 24 indicates that there is a 50% probability that the oil rig will actually be in the strike zone based on information obtained from system D_4. Likewise, if the hurricane is forecasted to pass a distance of 90 nmi from the oil rig, Figure 25 indicates there is a 10% probability that the oil rig will actually be in the strike zone based on information obtained from system D_4. In each figure, the black line demarcates 62.5 nmi from the oil rig.

4.6.4 Value of Information Estimation

To the oil rig operator, hurricane forecasts are important as forecasts guide decisions or actions, and these actions have consequences. For the oil rig operator, the action space consists of two possible actions. Once a hurricane is expected to be within the region of the oil rig, the operator must decide whether to shut down operations or to continue operations. This is not a trivial decision, as shutting down operations will lead to loss income and evacuation costs, while continued operations may lead to loss lives. In order to assess the consequence associated with each action, the decision problem is framed using a pay-off matrix as shown in Table 7.

Table 7. Pay-off Matrix for Oil Rig Operator

	In Strike Zone	Not In Strike Zone
Shut Down	Evacuation Costs Loss Income	Evacuation Costs Loss Income
Do Not Shut Down	Value of Lives Lost	None

For this analysis, the costs associated with shutting down operations consist of two components. The first component is the evacuation costs or the total costs to evacuate all personnel on the oil rig. The second component is the loss income or the income which the oil rig operator forfeited in shutting down operations. The possible cost associated with not shutting down operations is the value of lives loss. These costs would be incurred if the operator decided not to shut down operations and is struck by a hurricane. Data for these various costs are obtained from the a number of sources including the National Oceanic and Atmospheric Administration, Energy Information Administration, Bureau of Ocean Energy Management, Regulation and Enforcement, and National Ocean Industries Association. A summary of these costs is shown in Table 8.

Table 8. Summary of Costs

Cost Element	Cost
Evacuation Costs (C_e)	\$25,182
Loss Income (C_l)	\$266,047
Value of Lives Loss (C_v)	\$270,906,608

The action taken by the oil rig operator will be guided by some objective function. It is assumed that the objective of the operator is to minimize the expected costs associated with responding to the hurricane forecast. For example, should the operator decide to shut down operations in the event of a hurricane, he will incur an expected cost given by:

$$
\begin{aligned}
E\left[C_e + C_l \mid H, d_i, IP_j\right] = {} & \left[C_e + C_l\right]\Pr\left\{SZ \mid H, d_i, IP_j\right\} \\
& + \left[C_e + C_l\right]\left[1 - \Pr\left\{SZ \mid H, d_i, IP_j\right\}\right]
\end{aligned}
\qquad \textbf{Eqn. 41}
$$

where C_e and C_l indicates evacuation costs and loss incomes respectively, H indicates the expected presence of a hurricane in the Gulf of Mexico, d_i is the expected distance of the hurricane from the oil rig, SZ indicates the oil rig is in the strike zone and IP_j is the information product enabled by D_j upon which the probability estimates are based. In the event of a hurricane and the operator decides not to shut down operations, he can expect to incur costs of

$$
E\left[C_v \mid H, d_i, IP_j\right] = \left[C_v\right]\Pr\left\{SZ \mid H, d_i, IP_j\right\} \qquad \textbf{Eqn. 42}
$$

with C_v being the value of lives loss. The expected cost associated with each action is utilized to formulate an action rule. The decision to shut down ($a = 1$) is discrete and dependent on the relative magnitudes of the expected cost of shutting and the expected cost of continued operations:

$$\begin{aligned} a &= 0 \quad \text{if} \quad E[C_e + C_l \mid H, d_i, IP_j] > E[C_v \mid H, d_i, IP_j] \\ a &= 1 \quad \text{if} \quad E[C_e + C_l \mid H, d_i, IP_j] \leq E[C_v \mid H, d_i, IP_j] \end{aligned} \qquad \textbf{Eqn. 43}$$

The oil rig operator choses to shut down if the expected cost of shutting down does not exceed the expected cost of continued operations. Otherwise, the operator continues operating. The value of information provided by the system design, D_j, is the difference between the minimum expected cost the stakeholder expects to incur based on current data provided by the National Hurricane Center and the minimum expected cost the stakeholder incurs based on the updated information product provided by system design, D_j. Mathematically, this is given by:

$$\begin{aligned} VOI_j = {} & \min\{E[C_e + C_l \mid H, d_i, IP_0], E[C_v \mid H, d_i, IP_0]\} \\ & - \min\{E[C_e + C_l \mid H, d_i, IP_j], E[C_v \mid H, d_i, IP_j]\} \end{aligned} \qquad \textbf{Eqn. 44}$$

In other words, the value of information provided by a system design (VOI_j) is the expected costs savings to the oil rig operator of having the improved information (IP_j) relative to the current information (IP_0) provided by the National Hurricane Center.

4.6.5 Summary of Operationalizing the Bayesian Framework

Operationalizing the Bayesian framework involves four steps. These four steps as applied to the system design and acquisition problem for the environmental monitoring mission are briefly summarizes as follows:

Data Product Generation: For the hurricane forecasting application, seven system designs are identified, with each design having between one and three instruments in the payload. Next, based on the payload, a set of data products is assigned to each system. Examples of these data products include wind speed estimation, cloud imagery and temperature profiles.

Scientific Conversion: For the application, the information product of interest is the Forecast Error. This error is the deviation of the hurricane from its forecasted track and is generally measured in nautical miles. The improvement in the Forecast Error enabled by the various system designs, as well as the uncertainty in the improvement is provided in Table 6.

Adjustment in Stakeholder's Belief: For the example, the stakeholder of interest is the oil rig operator. For the oil rig operator, there are two mutual exclusive states of interest, being in the strike zone of a hurricane and not being in the strike zone of the hurricane. The likelihood of the oil rig being in the strike zone is estimated based on the information product, and the expected distance of the hurricane from the oil rig. This analysis is performed eight times, once for an estimation of the likelihood using current information from the National Hurricane Center, and seven additional times, once for each of the seven system designs.

Value of Information Estimation: For the oil rig operator, there are two possible actions to take in response to the expected presence of a hurricane. These are to shut down operations or to continue operations. The consequences of shutting down operations are loss income and incurrence of evacuation costs. The consequence of continued operations is the possibly of losing lives on the rig, measured by the value of lives lost. The decision rule governing the action taken is to shut down operations if the expected costs of shutting down did not exceed the expected costs of not shutting down. Otherwise, the oil rig operator continued operations. The value of the information is defined as expected cost savings from using improved information relative to using current information.

The current section presents the process for operationalizing the Bayesian framework, as well as provides details on the various quantitative models utilized in each step of the process. These models are fed into a simulation environment that outputted an estimate of the probability density function of the value of the design for each system design. In the next section, the simulation environment is discussed followed by the description of the data matrix outputted.

4.7 The Simulation Environment

The simulation environment utilizes a nested Monte Carlo approach to propagate the aforementioned uncertainties in the various models to uncertainty in the value of the design. The inputs to the simulation environment are 1) the set of system designs 2) the probability distribution of the improvement in the information products for each design candidate, and 3) the probability distribution of the forecasted distance (d_i) of the hurricane from the oil rig. This distance is assumed to be uniformly distributed between 0 nmi and 300 nmi. The nested simulation environment consists of two Monte Carlo analyses with each Monte Carlo analysis consisting of 2000 runs. The first Monte Carlo analysis propagated uncertainties about the improvement in the information product offered by a given design (See Table 6) and is termed the outer Monte Carlo process. The second Monte Carlo analysis is nested in the first Monte Carlo analysis and propagates uncertainties about the distance of the hurricane from the oil rig. This second analysis is termed the inner Monte Carlo process. An overview of the simulation environment is shown in Figure 26.

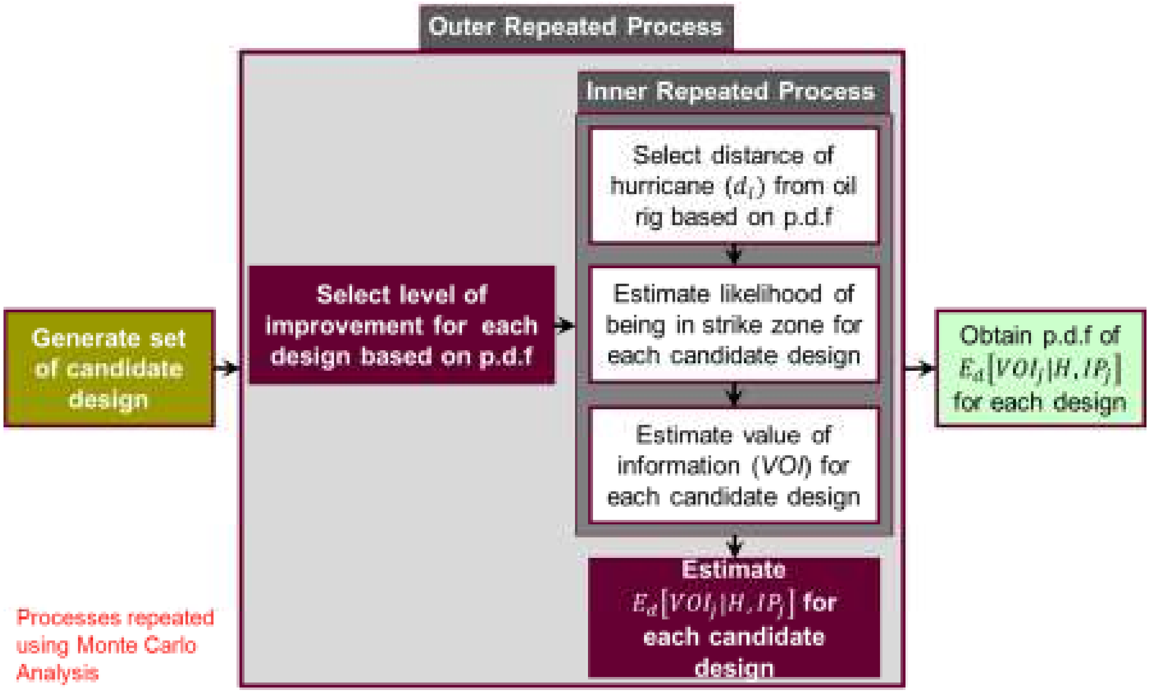

Figure 26. Simulation environment

The simulation consists of six modules. The first module generates a set feasible of system designs and maps the technical parameters of the design (D_j) to the information product (IP_j). The generated system designs and information products formed the inputs for the outer Monte Carlo process. The second module randomly selects an improvement level to estimate the information product (IP_j) enabled by each design candidate (D_j) based on the probability distributions in Table 6. This set of improvement levels is outputted to the inner Monte Carlo process. Within the inner Monte Carlo process are modules three through five. Module three within the inner Monte Carlo process randomly selects the expected distance of the hurricane from the oil rig based on a uniform distribution between 0 nmi and 300 nmi. Module four utilizes the distance information from module three as well as the information product to estimate the likelihood of the oil rig being in the strike zone for each system design. Based on these likelihood estimates, module five determines and stores the value of information provided by each design given the forecasted distance of the hurricane from the oil rig and the improved information product. The execution of modules three through five are repeated in the inner Monte Carlo process. The output of this inner Monte Carlo analysis is the expected value of information for each design over the forecasted distance of the hurricane from the oil rig given the presence of a hurricane (H) and the information product (IP_j). This expected value is termed the value of the design (VOD_j)

$$VOD_j = E_d\left\lfloor VOI_j \mid H, IP_j \right\rfloor \qquad \textbf{Eqn. 45}$$

After the value of the design is determined, another iteration of the outer Monte Carlo process occurs (i.e. another set of improvement levels is randomly selected) and the inner Monte Carlo analysis is repeated. The eventual output from the simulation environment is a probability mass function of the value of the design for each system design generated in the first module. The results from the simulation process are utilized to understand the design and value implications of each system design to the stakeholder. These value and design implication are discussed in the following sections.

4.8 Results and Analysis

The primary purpose of this section is to illustrate how value-informed decision-making for unpriced systems is enabled by the Bayesian framework. The results from the simulation environment are visualized and the system design and acquisition implications of the framework are analyzed.

4.8.1 Design Selection and Value Contours

The results from the simulation are displayed in Figure 27. For each system design considered, the annual value of the design to the stakeholder (i.e. the oil rig operator) is given in the form of a complementary cumulative distribution function, with the contours representing the probability that the annual value of the design meets or exceeds some level, *l*. Formally, the contours may be defined as:

$$\Pr\{VOD_j \geq l\} = pr \qquad \textbf{Eqn. 46}$$

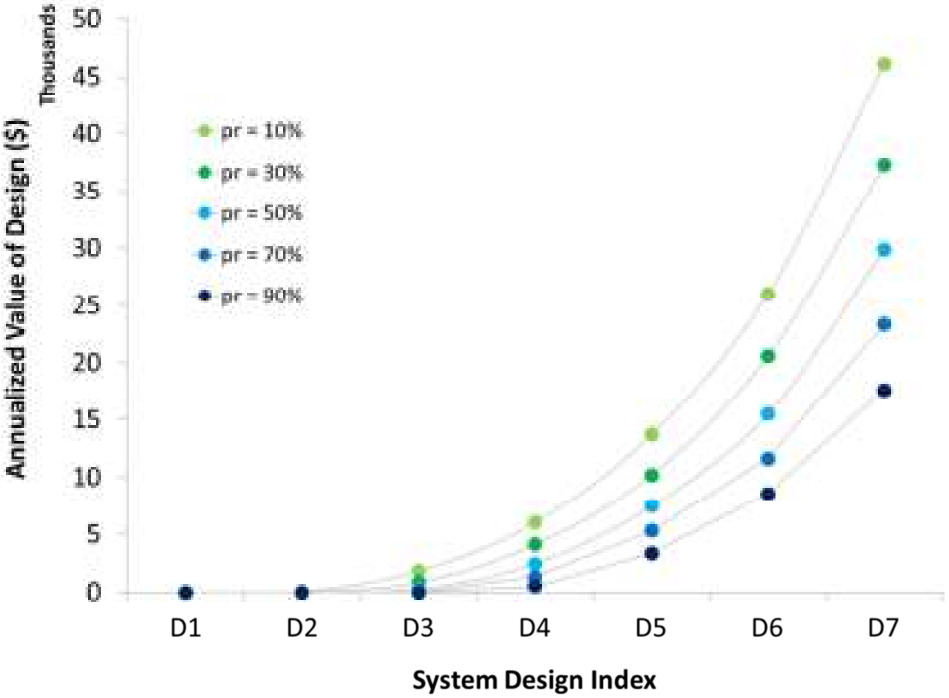

Figure 27. Annual value of information derived from system

Displayed as the complementary cumulative distribution function, the data provided in Figure 27 may be interpreted in a number of ways. First, the figure informs the engineer of the value generating capability of a given system. Consider system design five (D_5) and the probability contour:

$$\Pr\{VOD_j \geq l\} = 10\% \qquad \textbf{Eqn. 47}$$

The data from Figure 27 indicates that there is a 10% probability that value of information D_5 provides the oil rig operator is greater than or equal to $13,700. Phrased differently, the acquisition of system design D_5 has a 10% probability of providing a

$13,700 reduction in expected costs to one oil rig operator in the Gulf of Mexico on an annual basis. Alternatively, consider the probability contour:

$$\Pr\{VOD_j \geq l\} = 90\% \qquad \textbf{Eqn. 48}$$

Figure 27 indicates that there is a 90% probability that the cost savings to the oil rig operator from the acquisition of D_5 is $3,356. Thus, there is a high degree of certainty that the acquisition of D_5 will provide over $3,000 in savings per year to the oil rig operator. An alternative interpretation of the data in Figure 27 may be formulated in the context of multiple systems. Suppose engineers are interested in designing a system that meets or exceeds a certain value performance. For this illustration, assume that the value performance is $10 M or as shown in the equation:

$$\Pr\{VOD_j \geq \$10M\} = pr \qquad \textbf{Eqn. 49}$$

From the Figure 27, it is evident that system designs D_1 through D_4 are highly unlikely to meet the requirements, as the probability of these four designs meeting the requirements is less than 10%. While there is a greater probability of system design D_5 meeting these requirements, the probability is still relatively low at 30%. System design D_6 has the capability to meet the requirements with an 80% probability and system design D_7 with a probability greater than 90%. In this application, engineers are able to link the acquisition of the space system to the probable cost savings to the stakeholder. Motivated by the national imperatives for space-based earth science applications, these results indicate that this Bayesian framework provides a sharper definition of the linkage between the scientific data provided by the space system and the societal benefits provided to stakeholders.

Equally important to the interpretation of the data in Figure 27 are the design and value inferences which may be drawn. The first inference is technical in nature. The Bayesian framework indicates that there are system designs that provide information of no value to the oil rig operator. In particular, these are system designs D_1 and D_2, with system design D_3 providing information of marginal value to the oil rig operator. The ability of a system to generate valuable information products or valuable improvements in the information products is based primarily on its instrument suite. Recall from Table 4 that system design D_1 through system design D_3 has an instrument suite consisting of a single instrument. The low value of information provided by these three systems indicates that the data products generated by the individual instruments are not sufficient to result in valuable improvements in the information products. It is only when combined with other instruments that the pooled data products generated results in valuable improvements in information products. Thus the Bayesian framework allows the engineer to identify clusters of system designs or regions in the design space which offer the greatest value to stakeholders.

Perhaps even more important than this design implication emerging from the Bayesian framework is the insight into the differences between cost-centric and value-centric analysis. Cost-centric metrics are based primarily on information intrinsic to the system design and often utilizes metrics of the type, functionality per costs or cost per functionality. Such metrics are almost always never equal to zero, as the system performs some technical function and incurs a cost in doing so. As such, cost-centric metrics may erroneously indicate that the design provides value to the stakeholder (i.e., the oil rig operator). In contrast, the value-centric approach indicates that there are designs that do not; these designs being D_1 and D_2. It should be clear that by embedding the additional information about stakeholder's preferences and the environmental context into system decision-making (as in done in value-centric approaches), engineers can differentiate between systems that generate societal value and systems that do not.

4.8.2 Integrating Cost Risk Considerations

The previous section explored the information value the space system generates for a stakeholder. However, system designs are rarely selected based solely on value. Incorporating the cost risk into system decision-making is critical as program managers are constrained by budgets. It is important to understand the likelihood that a program manager will meet the budget constraint while acquiring a system that provides the required value performance.

For this analysis, the information value the space system generates to the stakeholder over a period of 15 years is considered. In measuring the 15 years, the clock is started at program initiation, in this case, at the start of Phase B in the design and acquisition process. The space system's development time is dependent on the space system's technical attributes. For example, space systems with larger instrument suites tend to have longer development times on average. Furthermore, these development times are probabilistic, and as a result, the time to launch is probabilistic. At some point after the system has been launched, the generation of information products begins. The time between launch and the generation of information products is assumed to be fixed at

2 years but may also be probabilistic. Once the space system generates information products, value accrues annually to the stakeholder. The annual information value is discounted to year zero at a rate of 7% and these discounted values are aggregated until the fifteen year time limit is reached. This process is shown in Figure 28.

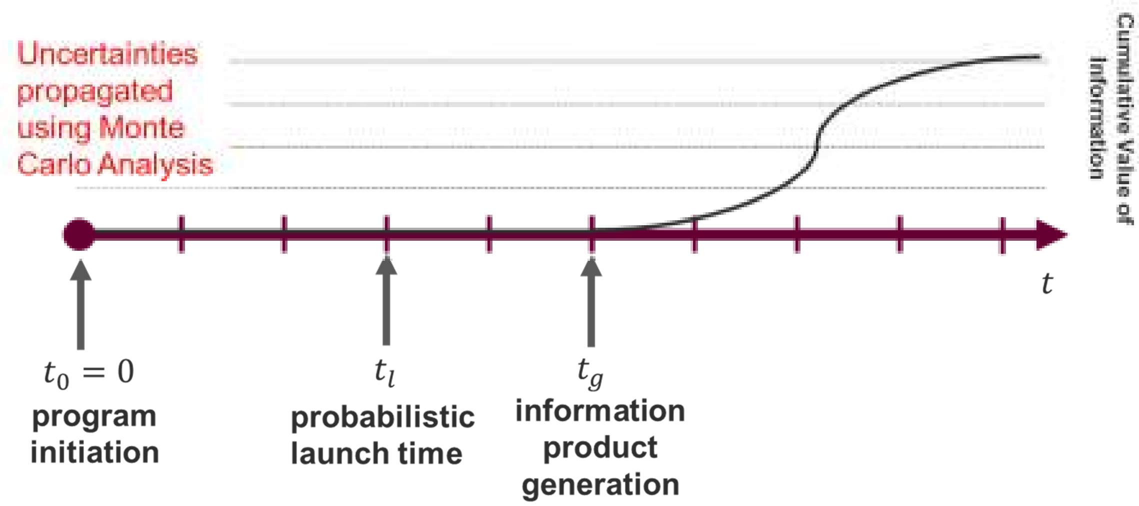

Figure 28. Timeline of system value generation

The uncertainty in the cumulative value of information is due to the uncertainty in the annual value of information as shown in Figure 27 and uncertainty associated with the schedule, particularly, the uncertainty associated with the time to launch as shown in Figure 28. Models for the mean launch time and the schedule risk which are dependent on the number of instruments in the payload suite are taken from Dubos and Saleh (2011) [181]. An empirical relationship between cost risk and schedule risk based on data from

18 NASA missions is developed to integrate the cost risk into the value-centric framework [182]. This relationship is shown in Figure 29.

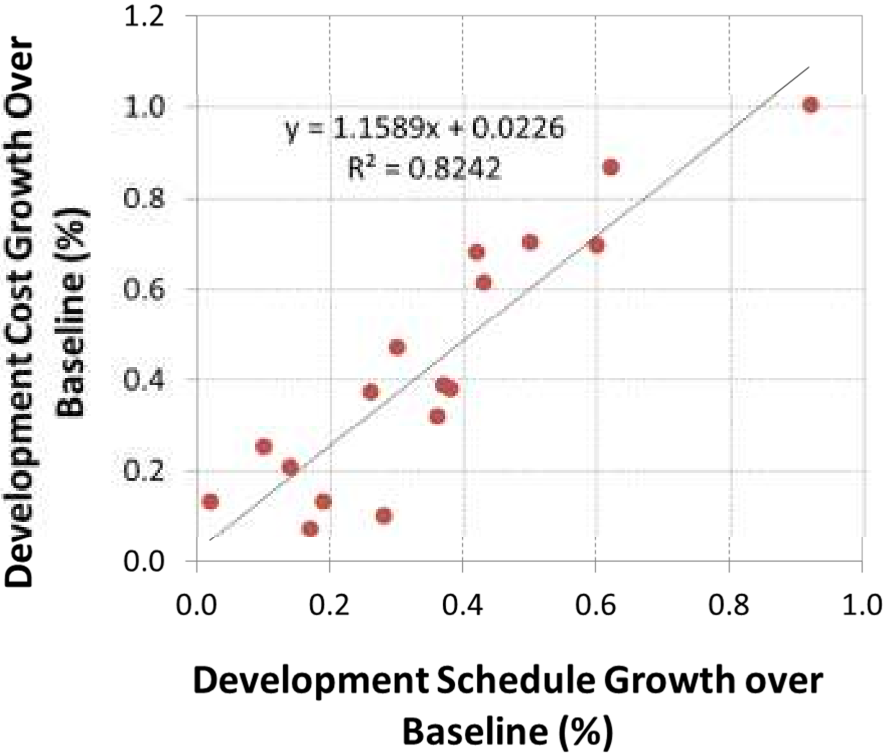

Figure 29. Empirical relationship between cost risk and schedule risk

In developing this empirical relationship, the cost risk is linked to the cumulative information value of the system over the 15 years. The process of integrating cost risk into value-centric decision-making is performed for all seven system designs with the results for D_7 shown in Figure 30.

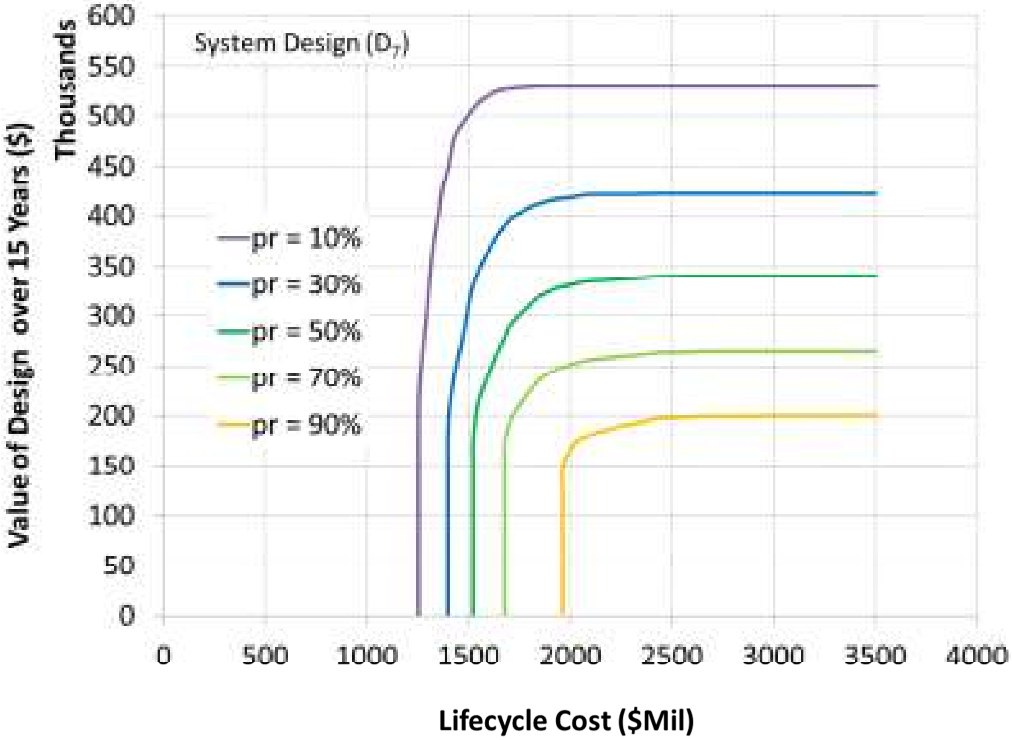

Figure 30. Joint value and cost probability contours

Displayed in Figure 30 are the joint probability contours between the cumulative information value to the stakeholder and the lifecycle cost of the system, LCC_j. Formally, the contours are defined as:

$$\Pr\{VOD_j \geq l; LCC_j \leq c\} = pr \qquad \textbf{Eqn. 50}$$

The contours indicate the probability that the space system will yield a certain level of information value, *l,* while simultaneously not exceeding a certain lifecycle cost, *c*. More intuitively, the probability contours may be interpreted as the likelihood of achieving a certain level of information value while remaining within a certain budget constraint. For example, the 90% contour indicates there is a 90% probability that the system will remain below a budget level of \$2.5B while simultaneously providing information value to the stakeholder of at least \$200,000 over the next fifteen years. These joint distributions of system value and cost risk provide useful insight to engineers of what might reasonably be expected from the system design at certain budget levels. For example, while there is a 90% probability of providing information value of \$200,000 to the stakeholder within a budget constraint of \$2.5B, it is highly unlikely the system will provide an information value of \$529,000 within a budget of \$2.5B. The probability of achieving \$529, 000 within the stated budget is 10%.

In addition to the insight offered by these probability contours about the value generation capability of a given system design under budget constraints, it is also desirable to compare the joint probability distributions across the various system designs. To do this, assume engineers are interested in examining the following contour across the seven system designs:

$$\Pr\{VOD_j \geq l; LCC_j \leq c\} = 70\% \qquad \textbf{Eqn. 51}$$

A graphical comparison of these system designs for the 70% contour is shown in Figure 31.

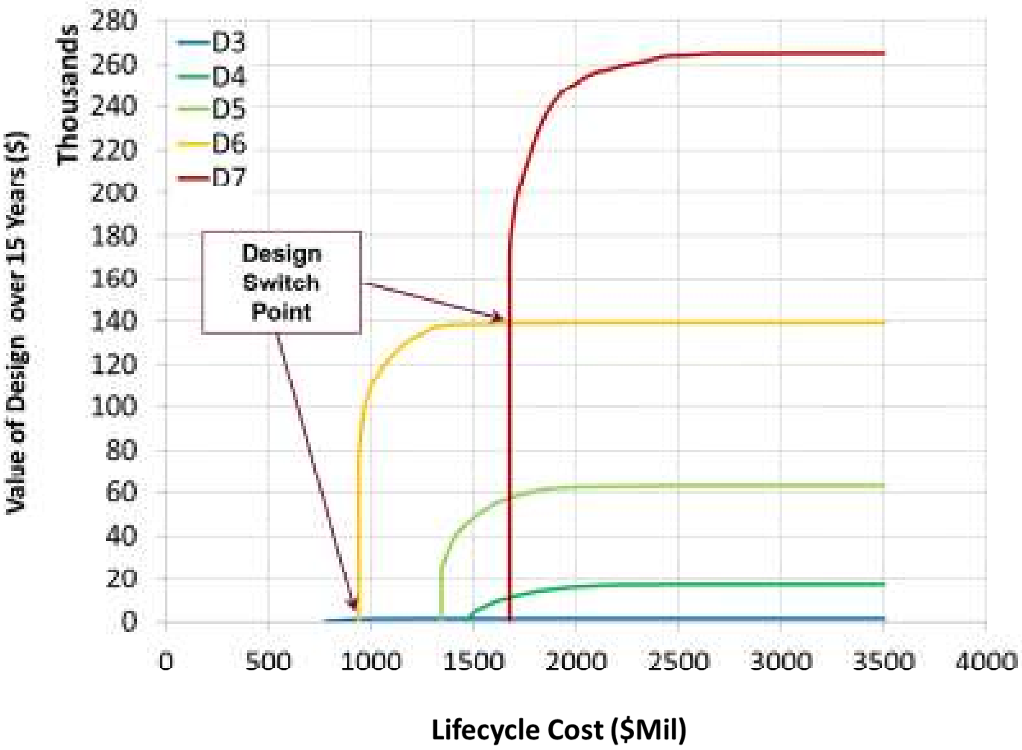

Figure 31. Integrated cost and value across system designs (70% Contour)

Shown in Figure 31 are iso-probability curves that indicate the cumulative information value for each system design given a budget constraint. For example, at a budget constraint of $2.0B, the graph indicates there is a 70% probability that system design D_5 will achieve a cumulative information value of $62,000. Likewise at the same budget constraint, there is a 70% probability that system design D_4 will achieve a cumulative information value of only $16,000 or about 25% of the value of D_5.

Using these types of observations from Figure 31, it should be clear that there are certain system designs that are dominated by other designs. For example, D_5 dominates D_4 as at a probability contour of 70% and any given budget constraint D_5 provides information that is of a higher value to the stakeholder than D_4. With the same reasoning,

D_6 can be said to dominate D_5. Conversely, there are a number of non-dominated designs which remain for further consideration. These are system designs D_3, D_6 and D_7.

Traditionally, in space system design and acquisition, the concept of a dominated or non-dominated design is formulated under deterministic objectives. Thus a system design is exclusively considered either dominated or non-dominated. However, such definitive statements cannot be made in a probabilistic environment in all cases. In a probabilistic environment, a design may be considered dominated or non-dominated depending on the budget constraint and probability contour of interest. In this analysis, Figure 31 shows the three system designs, D_3, D_6 and D_7, are non-dominated within certain budget constraints. For the probability contour of 70%, D_3 dominates all other system design for budget constraints that fall below \$940M. In fact, for this probability contour, D_6 and D_7 are unable to provide information of value to the stakeholder below budget levels of \$940M. This implies that unless the stakeholder has access to funds in excess of \$940M, system designs D_6 and D_7 should not be considered for development. However, once this budget constraint is reached, D_6 dominates all other designs. Likewise, at budget constraints greater than \$1.68B, D_6 becomes dominated and D_7 dominates all other design. The intersection of two probability contours at which a design switches from being non-dominated to dominated (or from dominated to non-dominated) is called the ***design switch point***.

4.8.3 Probabilistic Pareto Fronts

Based on the concepts of design switch points and non-dominated designs, it is possible to create a set of Pareto fronts in a probabilistic environment. These types of Pareto fronts, probabilistic Pareto fronts (*PPF*), may be defined in the following manner.

For simplicity, assume that there exist two probabilistic objectives of interest in the acquisition and design of the space system. One objective is a cost and the other objective is a benefit. The cost is defined such that the stakeholder desires to minimize cost and the benefit is defined such that the stakeholder desires to maximize benefit. Furthermore, assume that engineers are able to create a joint probability density function of the two random variables, cost (*C*) and benefit (*B*). Using the joint probability distribution, a modified cumulative distribution function for the pair of random variables may be formulated as follows:

$$G(c,b) = \Pr\{C(D_j) \le c \; ; B(D_j) \ge b\} \qquad \textbf{Eqn. 52}$$

This modified cumulative distribution may be interpreted as the probability of meeting or exceeding a level of benefits (*b*) while not exceeding a certain level of cost (*c*). Based on this distribution for each system design, a set of iso-probability contours may be defined as:

$$\begin{aligned} \Pr\{C(D_1) \le c_1 \, , B(D_1) \ge b_1\} &= \cdots\cdots = \Pr\{C(D_j) \le c_j \, , B(D_j) \ge b_j\} \\ &= \cdots\cdots = \Pr\{C(D_n) \le c_n \, , B(D_n) \ge b_n\} = pr \end{aligned} \qquad \textbf{Eqn. 53}$$

For each level of cost, *c*, a non-dominated system design (D^*) may be identified as

$$\begin{aligned} & B(D^*) \ge B(D_j) && \forall D_j \in D^n \\ s.t \quad & c = c_1 = \cdots\cdots = c_j = \cdots\cdots = c_n && \end{aligned} \qquad \textbf{Eqn. 54}$$

The *PPF* is described as the set of $B(D^*)$ across all cost levels. The *PPFs* for the 70% probability contour and the 30% probability contour are shown in Figure 32. The design switch points are also noted on the figure.

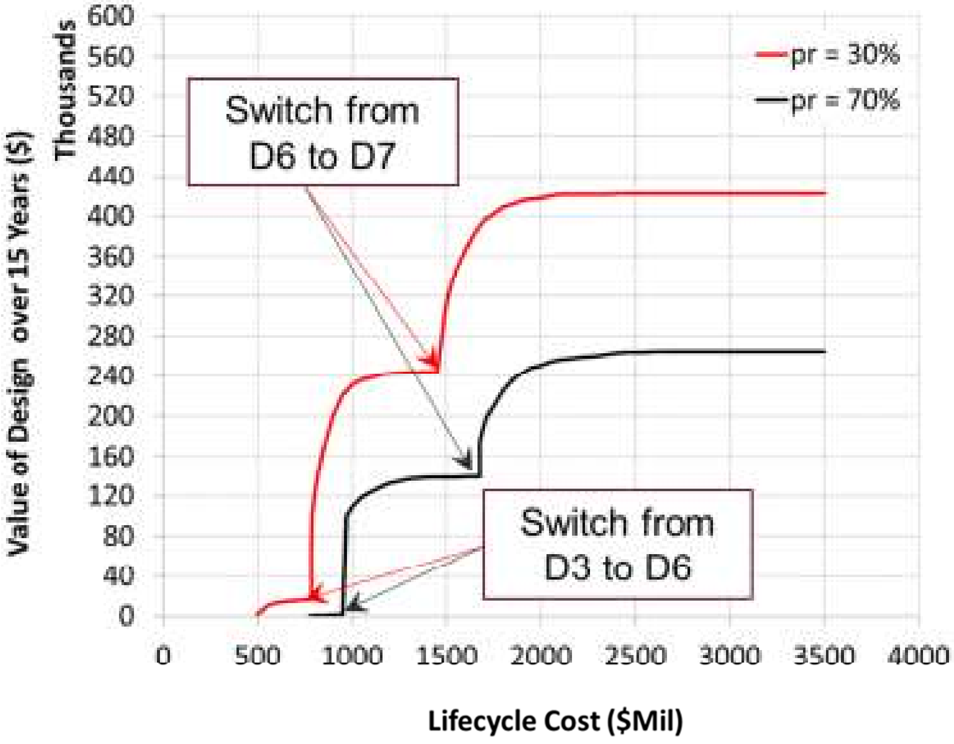

Figure 32. Probabilistic Pareto fronts

Beyond identifying dominant designs at a given budget constraint and probability contour, probabilistic Pareto fronts offer engineers other insights for decision-making. For example, consider a scenario in which program funding is highly uncertain. Using the *PPF*, engineers can identify the set of designs at the design switch point. By conducting further analyses, engineers can identify technical commonalities between designs within the set. In Figure 32, for the probability contour of 70%, there are two design switch points. The first design switch involves a switch from D_3 being the non-dominated system design to D_6 being the non-dominated system design. The second design switch point involves a switch from D_6 being the non-dominated system design. to D_7 being the non-dominated system design. In the first design switch point, the common instrument between D_3 and D_6 is instrument X_3. In the second design switch point, the common instruments between D_6 and D_7 are instruments X_2 and X_3. Under funding uncertainty, engineers can prioritize the instruments to keep in the instrument suite. Instrument X_3 will be marked as the primary payload instrument given this instrument is common to all system designs that yield the highest information value at a given budget constraint. Should the funding be reduced, engineers will be more inclined to eliminate instrument X_1 followed by instrument X_2 from the instrument suite. Thus, engineers are able to identify system designs that are flexible to funding instabilities.

Second, the *PPF* may guide funding decisions. Program managers can identify funding levels at which to initiate programs given a level of risk tolerance. For example, if the program manager desires to achieve a value of information of $125,000 over fifteen years with a probability of 70%, Figure 32 indicates an appropriate level of funding for program initiation would be $1,113M. Likewise, if the program manager desires to achieve a value of information of $125,000 over fifteen years with a probability of 30%, Figure 32 indicates an appropriate level of funding for program initiation would be $804M. Program managers may also justify requests for program budget increases by evaluating critical budget levels where a marginal increase in the budget leads to substantial increase in the level of information value provided. For example, assume that the program manager is given an initial budget of \$900M. A request for an additional \$100M may be supported using the *PPF*, as an 11% increase in the budget results in a 130% increase in the information value provided.

4.8.4 Robustness of Design Switch Points

To evaluate the robustness of the design switch points, the system designs defining the design switch points are identified for a number of iso-probability curves ranging between 10% and 90%. These are shown in Table 9.

Table 9. Similiarity of Design Switch Points

Iso-Probability Curve	Design Switch Point 1	Design Switch Point 2
10%	(D_6, D_7)	(D_3, D_6)
20%	(D_6, D_7)	(D_3, D_6)
30%	(D_6, D_7)	(D_3, D_6)
40%	(D_6, D_7)	(D_3, D_6)
50%	(D_6, D_7)	(D_3, D_6)
60%	(D_6, D_7)	(D_3, D_6)
70%	(D_6, D_7)	(D_3, D_6)
80%	(D_6, D_7)	(D_N, D_N)
90%	(D_6, D_7)	(D_N, D_N)
DSPSI	1.0	1.5
Max DSPSI	4.2	4.2
Min DSPSI	1.0	1.0

The design switch points are ordered based on the value level at which they occur for a given iso-probability curve, with design switch point one occurring at the highest value level and design switch point two occurring at the lower value level. The design switch point similarity index (DSPSI) measures the similarity between the set of designs defining each design switch point for the various iso-probability curves. Assuming that no co-dominance exists between two designs, the design switch point similarity index is defined as

$$DSPSI = -\sum_{i=1}^{Z} \frac{n_i}{2m} \log_2\left(\frac{n_i}{2m}\right) \qquad \textbf{Eqn. 55}$$

where m is the number of iso-probability curves considered, n is the number of times a particular design appears in the set of designs defining a particular design switch point (e.g. design switch point one), i indicates a distinct design in the set of designs defining a particular design switch point and Z represents the total number of distinct designs. The maximum numeric value of the DSPSI indicates no similarity between designs defining a particular design switch point for all iso-probability curves considered, that is, all designs are distinct. In such cases, the DSPSI is defined as

$$DSPSI = -\log_2\left(\frac{1}{2m}\right) \qquad \textbf{Eqn. 56}$$

The minimum numeric value indicates identical designs in the design switch point for all iso-probability curves considered, that is, there are only two distinct designs. In such cases, the DSPSI is defined as

$$DSPSI = -\log_2\left(\frac{1}{2}\right) \qquad \textbf{Eqn. 57}$$

Iso-Probability curves for which no pair of designs exists for a particular design switch point are given a place-holder pair (D_N,D_N) where D_N may be thought of as a null design. This null design is included in the calculation of the DSPSI as a distinct design. The DSPSI for the design switch point one is 1.0, while that for design switch point two is 1.5. The DSPSI indicates that designs consisting the design switch points are robust across the iso-probability curves considered with the system designs comprising the design switch point at the highest value level being identical, and designs defining the second design switch point showing high levels of similarities.

4.9 Summary of Bayesian Valuation of Unpriced Space Systems

In recent years, the space studies board advocated for a definitive linkage between the societal benefits of the space system and the technical attributes of the system. Motivated by the decadal survey, program managers often justify space missions based on the information the space system is expected to provide stakeholders. However, these justifications tend to be qualitative in nature. In this chapter, a Bayesian framework is developed for the valuation of the space system based on the value of the information the system provides stakeholders. In particular, the Bayesian framework is premised on the fact that information is important as decisions made in the presence of information yield higher expected pay-offs to stakeholders than decisions made in the absence of information. The Bayesian framework offers significant insight to engineers as the value and design implications garnered from this framework further highlighted the differences between cost-centric and value-centric approaches to space system design and acquisition. In addition, the Bayesian framework for the valuation of the space system aided in the formulation of probabilistic Pareto fronts. These types of Pareto fronts point to optimal system designs under probabilistic objectives, identify system flexibility characteristics, and support funding requests. Overall, the Bayesian valuation framework presented enables the valuation of unpriced space systems by creating quantitative links between scientific information provided by the space system and the broader societal applications engendered.

CHAPTER 5

ON VALUE IN SPACE SYSTEMS DESIGN AND ACQUISITION

This chapter brings together the general principles learned from the development of the value-centric frameworks as well as the literature review to formulate a conceptual basis for understanding the value of both priced and unpriced space systems. The chapter starts by discussing the ambiguity in the definition of value in the space industry and concludes by articulating a conceptual underpinning for the valuation of space systems in a multi-stakeholder environment.

5.1 The Problem of Defining Value

Colloquially, the oxford dictionary defined the value of an object as the regard that something is held to deserve, the importance, worth, or usefulness of something [183]. While this definition matches an intuitive understanding of the value of an object, it lacks the necessary precision for the implementation of value analysis in system design and acquisition. For example, how should importance be defined? To whom should the system be considered important? What is the worth of the system? Assuming the worth of the system can be defined, will the system be of the same worth to all stakeholders? This imprecision or nebulousness in the definition of value has persisted in aerospace system design and acquisition, and in doing so, created several challenges for various stakeholders in assessing system value. In fact, one may observe that there is no consensus on the definition of value in aerospace system design in general and space system design in particular. For example, AIAA Value Driven Design Program

Committee defined value driven design as “an improved design process that uses requirements flexibility, formal optimization and a mathematical value model to balance performance, cost, schedule, and other measures important to the stakeholders to produce the best outcome possible” [93]. Ross et al. (2010) took a more holistic approach and provided a non-functional definition of creating value as “balancing and increasing the net level of (1) satisfaction, with (2) available resources, while addressing (3) its degree of importance” [15]. Penn et al. (2010) described value-centric design as a “systems engineering process in which design alternatives are evaluated by a value model and the highest value alternative generally chosen” [184]. At the system level, Fernandez (2008) defined the value of a commercial engineering system as the price at which a customer would be indifferent between the purchase of such system for commercial purposes and investing the same amount in a risk-free interest bond [24]. While these definitions offer some direction on how to define value in system design and acquisition, there are a few points to note. First, AIAA VDDPC utilizes the qualifier "best" to describe the desired outcome without stating what qualifies a design as best. Thus, this definition lacks precise guidance in how engineers should determine value optimal designs. Second, Ross et al. (2010) noted that creating value should “address the degree of importance”, but fails to indicate importance to whom. There are various stakeholders in the design process, each with differing (and sometimes conflicting) objectives. Thus, the objectives of the design process that are important to one stakeholder may not be important to another. It is therefore necessary when talking about value to define it in the context of a stakeholder. Although, Penn et al. (2010) describes value-centric design, no reference is made to the definition of value. Finally, Fernandez's definition of value, while precise, applies to commercial systems only.

Such "fuzziness" in the concept of value in space system design and acquisition opens the door for skepticism among engineers and, in doing so, may inhibit the adoption of value-centric design and acquisition. Yet despite the fuzziness associated with the definition of value, there has been continued persistence in understanding the concept of value in space systems design and acquisition. As such, this first leads to the fundamental question: Why value value?

5.2 Three Pillars of a Value-Centric Approach

Intuitively, the concept of value can be understood as central to decision-making, whether the decision involves choosing between different engineering designs, or investing in a stock portfolio. In all cases, the goal is to allocate resources in such a way that the stakeholder is better off than had they not utilized the resources in that manner. A gain in value is used as the measure in determining the success of an investment and may be proxied by units such as dollars or another unit that is an agreed upon medium for acquiring or trading different products and services. The overarching objective of value-based design and acquisition is to aid stakeholders in determining the optimal allocation of their limited resources. In order to achieve this objective, it is necessary to identify the underlying drivers of a value-centric mindset. Three pillars support a value-centric approach to system design and acquisition. The first pillar is conceptual in nature and may be stated as follows:

P1. An engineering system in general (a spacecraft being one example of such a system) is a value delivery artifact. And the value of the system derives from the flow of service the system delivers over its lifetime to one or multiple stakeholders.

The core idea of a value-centric approach to system design and acquisition is that value deserves as much effort to quantify as the system's cost, and that value-based metrics make better guides for design optimization and alternatives selection than cost or performance related metrics. But why value "value" of engineering systems? The two remaining pillars address this question. An engineering system is an investment to its stakeholders, and as such, it is expected to provide value to said stakeholders. With this premise in mind, we can now state the second pillar of a value-centric approach to system design and acquisition. The second pillar has two versions; the pillar as formulated for a profit organization and the pillar as formulated for a public entity

P2a. A business or a corporation is a value-delivery entity providing goods and or services to its customers and value to its shareholders. An engineering system within such a corporation is one cog in the company's broader value-delivery machinery. The imperative to create shareholder value entails that any investment in a technical system be guided by its value creation potential or ability to contribute to shareholder value (not only by cost considerations).

P2b. A public entity acts as an agent to multiple stakeholders and is tasked with providing goods and or services which yield societal value. An engineering system within such an entity is one cog in that entity's broader value-delivery machinery. The imperative to create stakeholder value entails that any investment in a technical system be guided by its value creation potential or ability to contribute to stakeholder value (not only by cost considerations).

The third pillar of a value-centric approach to system design and acquisition is related to the concept of metrics in decision-making. Metrics pervade every aspect of our daily lives. The concept of a metric is a fundamental notion in human activities, and no work is actually ever done without an implicit or explicit consideration of a metric or a set of metrics to qualify said activity. A metric can be loosely defined as a standard of measurement. It can be measured directly, or estimated indirectly, qualitatively or quantitatively, or it can be calculated deterministically or probabilistically by combining different measurements [187]. Metrics are essential for decision-making. They allow us to characterize and rank different options, designs, performances, etc. and provide guidance in most of our actions and activities. In engineering design, metrics play a critical role in guiding the selection of the system architecture. System optimization for example hinges on the notion of a metric, or as is more familiar to the optimization community, on an objective function. These metrics or objective functions will guide design and acquisition choices by comparing how well each alternative fares on them. It is therefore essential that the metrics used to guide decision-making be the "right" metrics. The third pillar of a value-centric approach to system design and acquisition is related to the information content of value-related metrics. It is an information-theoretic argument and it can be stated as follows:

P3. Unlike cost or performance based metrics, which include only endogenous information about the system, value includes the most complete information about the system in its environment (i.e., both endogenous and exogenous information). As such, value allows for better, more transparent, and more relevant trade-offs for the decision-makers in system design and acquisition.

A number of financial metrics and methodologies have been adapted and applied to the valuation of engineering systems such as Net Present Value (NPV), real options valuation, and Economic Value Added (EVA). The reader is referred to Chapter 2 for a review of these metrics and their applications to engineering systems.

5.3 On Value in Space Systems Design and Acquisition

In the first pillar, the space system is conceived as a value delivery artifact providing services to one or multiple stakeholders. Traditionally stakeholders are defined as those entities which can affect or is affected by the achievement of an organization's objectives [188]. More specifically, in the context of space system engineering, a stakeholder may be defined as an entity which receives or is intended to receive some type of service from the space system. These services may take several forms, among which are informational, political or technical. It is in generating these services that the system generates value flows to the stakeholder. Conceptually, this is illustrated in Figure 33.

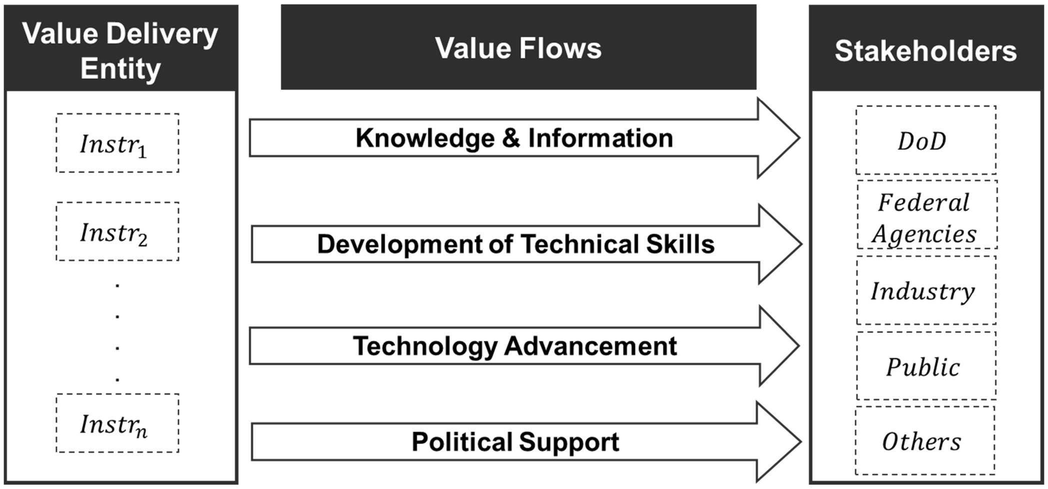

Figure 33. Space system as a value delivery artifact

As a value delivery entity, the space system provides value flows to the stakeholders based on its technical attributes (e.g. suite of scientific instruments, $Instr_i$). This is illustrated by the leftmost box in Figure 33. Also in Figure 33 are value flows indicated by the arrows. While the value flows provided in the diagram are not comprehensive, they are representative of the types of value flows provided by space systems [147,189]. For example, space systems are often information conduits transferring data and information from one entity to another. Intelligence, surveillance and reconnaissance satellites provide military stakeholders with information about enemy locations and movements. Space systems are workforce enablers, whose design and acquisition lead to the provision of funding for research and technology advancement, and consequently the development of a skilled workforce. In addition to creating a skilled workforce, technology spill-overs may occur leading to wider social benefits. The fielding of space systems may also provide a country with enhanced political prestige on the global arena. The right-most box represents various stakeholders to which the value flows. Broad categories of these stakeholders include government, industry and the public.

5.3.1 Importance of Value and Implications for the Concept of Value

Figure 33 provides an abstraction of the value mechanism of the space system, one that is important to grasp when articulating the concept of value of the space system to the stakeholder. However, to fully develop the concept of value it is also important to understand the intended usage of value analysis in the system design and acquisition environment. At its core, space system design and acquisition is a resource allocation problem. The program manager desires to allocate limited resources effectively through design and acquisition decisions. Value assessment is an attempt to resolve this resource allocation problem. In space systems design and acquisition, value is often thought of as a "conception of the preferable which influences choice and action" [190]. In other words, the more consistent usage of value in space systems design and acquisition is often to guide the selection of the more preferable design option given the resources available [15,24,79,186,191]. This preference-related concept of value stems from a neo-classical economic formulation. Under this formulation, a number of behavioral assumptions are made about the stakeholders [192-194]:

A1. Stakeholders have rational preferences among outcomes which may be identified and associated with a level of value

A2. Stakeholders are independent optimizers subject to constraints

A3. Stakeholders act on full and relevant information

These assumptions carry with them three implications relevant to conceptualizing the value of a space system to the stakeholder in a design and acquisition context.

Implication 1: Stakeholders are Originators of Value

The individual or group of individuals is the originator of preferences, and by extension, value. This is an important implication of a preference-related approach to value assessment in space system design and acquisition. First, as value is derived from the preference behavior of the stakeholder, stating the value of the space system without citing the stakeholder from whom the preference scheme is drawn, leads to an incomplete assessment of the system value. Different stakeholders may possess different preferences based on the attributes of the space system, and the stakeholders' objectives. As the system value is based on the preferences of the stakeholder, various stakeholders may assign a different value to the system. Identification of the stakeholder is therefore imperative in any value assessment of the space system.

Implication 2: Value of the Space System is a Relative to Alternative Investments

From the neo-classical economics framework, value arises in part from the preference of the stakeholder for one object relative to another. By definition, preference is a greater affinity for one outcome over another [195]. The stakeholder assesses the importance of each outcome in comparison to the other and, in doing so, assigns value to each outcome. In the context of space system design and acquisition, the idea of a reference may be extended beyond a design outcome (i.e. baseline system) to include alternative uses of the resources. To the stakeholder, the space system represents an investment of resources. Thus an assessment of the value of the space system may occur relative to any alternative investment of said resources. Value is not an intrinsic attribute of the system, but may only be defined based on an implicit or explicit comparison between two possible usages of the resources. To speak of the value of the space system without indicating the point of reference provides engineers with incomplete information with which to do a full value assessment.

Implication 3: Environment is the Context for System Valuation

The environment may be thought of as the context of the valuation. It is an encapsulation of scenarios exogenous to the system and beyond the control of the stakeholder which affect the flow of services provided by the system or the stakeholder's desire for said services. Environmental factors may encompass a wide variety of situations. For example, some may be operational in nature reflecting the physical conditions in which the system is to be operated. Others may be financial in nature as evident through funding instabilities experienced by numerous space programs. Yet still, some may be technology based as systems can become obsolete due to the introduction of disruptive technologies. Each scenario has the potential to either reduce/enhance the flow of services provided by the system or/and the stakeholder's desire for the services. The linkage between environmental factors and the value generation capabilities of the system indicates that such networked externalities are intricately tied to the functional concept of value. As environmental factors form the context of the valuation, it is not possible to define the value of the system independent of this encapsulation of scenarios.

5.3.2 Towards a Concept of Value in Space System Design and Acquisition

It is clear that value is not a simple concept. In fact, the value of the system to the stakeholder is a "networked" metric which changes based on three types of information: 1) information about the stakeholder 2) information about the environmental context 3) information about the reference resource allocation (e.g. baseline system). For these reasons, it is insufficient to define the value of the system as simply the worth of the system, or increasing the net level of satisfaction balanced against available resources [15,73]. In fact, in the system design, development, integration and testing phases (i.e. before system fielding has occurred) and for a given stakeholder, when one speaks of the value of the system, one is really asking four questions. These are:

Q1. What are possible scenarios which may occur (i.e. context for valuation)?

Q2. What is the likelihood of these scenarios occurring?

Q3. What are the benefits of the system to the stakeholder relative to the benefits of the alternative resource allocation (e.g., baseline system) under these scenarios?

Q4. What are the costs of the system to the stakeholder relative to the costs of the alternative resource allocation (e.g., baseline system) under these scenarios?

To understand how each question is essential to value assessment, consider the illustration given in Figure 34.

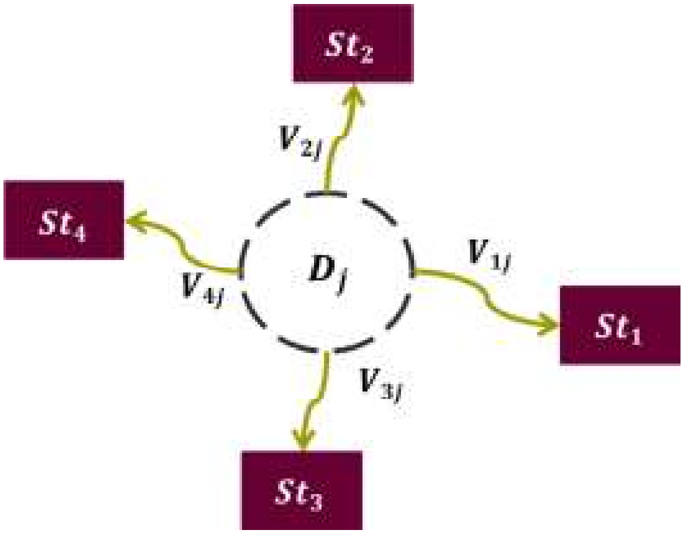

Figure 34. Value flows from system design to stakeholders

In Figure 34 is a system design D_j where D_j is defined as a vector of technical attributes (X_u) given by:

$$D_j = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ \vdots \\ X_k \end{bmatrix}$$ **Eqn. 58**

Based on these technical attributes, the system is capable of delivering value flows to a set of stakeholders. In Figure 34, the value flows are indicated by the arrows, V_{ij}, while the stakeholders are indicated by the boxes, St_i. Note that the value flow is defined based on the selected system design, D_j, and selected stakeholder, St_i. In order to assess the value of the system to a single stakeholder, the decision-maker will attempt to answer the four questions. For simplicity, the necessary information to address the questions is shown in Table 10.

Table 10. Notational Value Information for a Space System

Scenarios	Likelihood	Benefits	Costs
S_1	L_1	B_{ij1}	C_{ij1}
S_2	L_2	B_{ij2}	C_{ij2}
S_3	L_3	B_{ij3}	C_{ij3}
:	:	:	:
:	:	:	:
:	:	:	:
S_{n-2}	L_{n-2}	B_{ijn-2}	C_{ijn-2}
S_{n-1}	L_{n-1}	B_{ijn-1}	C_{ijn-1}
S_n	L_n	B_{ijn}	C_{ijn}

Contained in Table 10 is the value information for a notional space system relative to a given stakeholder. The first two columns of the table lists the set of scenarios that may affect the flow of the system services or the stakeholders' desire for the services and the likelihood of a particular scenario occurring. Recall from earlier that scenarios form the context for the valuation. Each scenario listed in the table offers a different possible context for the valuation. Columns three and four display the potential benefits and costs of the system to the stakeholder under each given scenario. The benefits and costs given in Table 10 are not absolute but are assessed relative to an alternative allocation of the resources (e.g., baseline system). For example, scenario one, S_1, occurs with likelihood, L_1. Under S_1, the stakeholder, St_i, will attain benefits, B_{ij1}, from system, D_j, but at a cost of C_{ij1}. Likewise, scenario two, S_2, occurs with likelihood, L_2. Under S_2, the stakeholder, St_i, will attain benefits, B_{ij2}, from system, D_j, but at a cost of C_{ij2}.

From this fundamental discussion of value, the reader will note that conceptualizing the value of the system to the stakeholder is rather complex as the concept should account for the four important factors, the environmental context or considered scenarios, the likelihood of the scenarios occurring, and the benefits and costs of the system to the stakeholder under each scenario relative to the benefits and costs of an alternative resource allocation. Thus, it is proposed that the value of the space system to the stakeholder be conceptualized as a set of quartets with each quartet containing information about the benefits and costs to the stakeholder under a given probable context, S_l. Formally, this value definition may be written as follows[8]:

$$V_{ij} = \left\{ \left\langle S_l, L_l, B_{ijl}, C_{ijl} \right\rangle \right\} \qquad \textbf{Eqn. 59}$$

where V_{ij} is the value flow stakeholder St_i receives from system design D_j , B_{ijl} and C_{ijl} are the respective benefits and costs of system design D_j to the stakeholder St_i under scenario S_l and L_l the likelihood of S_l occurring. Note that although the reference alternative resource allocation (e.g., baseline system) is not explicitly highlighted in the definition, it is implicitly utilized as a baseline from which to assess the benefits and costs of the system to the stakeholder.

5.3.3 A Few Points to Note about the Definition of Value

From a practical perspective, there are a few points that may be noted about the proposed definition. First, by defining the value flow from the system to the stakeholder in this manner, all possible value information about the system is captured and available for value analyses. However, depending on the type of value analyses conducted, it may be acceptable to extract certain pieces of value information (e.g. expected value, value at risk, maximum value) from the value set to conduct the system value assessments. While these pieces of extracted value information are useful and may provide insight into the system's value profile, it is essential to recognize that they do not reflect the full value

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[8] Those within the field of risk analysis may recognize that the concept of value follows a similar formulation to the concept of risk proposed by Kaplan and Garrick in their seminal paper Kaplan, S., Garrick, B.J., On the Quantitative Definition of Risk, *Risk Analysis*, 1(1981) pp. 11-27

information about the system, but are simply deemed acceptable characteristics of the value set for decision-making.

Second, no statement has been made about the form of B_{ijl} and C_{ijl}. The benefits and costs associated with the space system may take many forms. For example, in reality a stakeholder may receive multiple value flows from the system. These multiple value flows will be reflected in multiple benefits attained and multiple costs incurred from the system. Thus, under any given valuation context and depending on whether the criteria are commensurable, B_{ijl} and C_{ijl} may be quantified into a single metric or be described as a vector (i.e., benefits and costs are multi-dimensional). Likewise, if there is uncertainty associated with B_{ijl} and C_{ijl}, these two elements of the value concept may be represented as random variables or a vector of random variables. Thus, under any given context, the benefits and costs may be probabilistic and multidimensional, reflecting the multiple probable value flows received by a single stakeholder.

The third point revolves around ex-ante and ex-post value analysis. Although the proposed conception of value has been formulated for ex-ante value analysis, it is also applicable to ex-post value analysis. The phrasing of the four questions implies that the benefits of the system have not yet materialized and are appropriate for an ex-ante value definition. However, a simple rephrasing would also make these questions valid for systems in which the benefits and costs has materialized. For example:

Q1. Which scenario occurred (i.e. context for valuation)?

Q2. What is the likelihood the scenario occurred?

Q3. What were the benefits of the system to the stakeholder relative to the benefits of alternative resource allocation under this scenario?

Q4. What were the costs of the system to the stakeholder relative to the costs of the alternative resource allocation under this scenario?

From the rephrasing of the questions, it is clear that the ex-post case may be considered a special case in which the occurrence of a scenario is deterministic. As such, the ex-post value analysis may be defined as:

$$V_{ij} = \left\{ \left\langle S, 1, B_{ij}, C_{ij} \right\rangle \right\} \qquad \textbf{Eqn. 60}$$

The definition of value is easily adaptable to ex-post value by simply focusing on the emerged scenario and setting the likelihood to one, with stakeholder St_i receiving realized benefits of B_{ij} and incurring realized costs of C_{ij}.

5.4 Value Flows to Multiple Stakeholders

The definition provided in Eqn. 59 considers the value flows to a single stakeholder. At times engineers must assess the value of the system to numerous stakeholders simultaneously. This adds an additional layer of complexity to value analysis in space system design and acquisition. In a multi-stakeholder environment, the decision-maker is faced with the challenge of adequately balancing the costs and benefits of the system among several parties. In fact, if one un-bundles the concept of “benefit” and “cost”, it becomes clear that multiple stakeholders are affected differently by the design and acquisition of a complex engineering system, that is different (types of) costs, risks, and benefits are borne and reaped by different stakeholders. For this reason, in a multi-stakeholder context, it is appropriate not only to speak of the benefits and costs received by the individual stakeholders, but it is also imperative to speak of the value flow distribution of the space system. Formally, the value flow distribution may be defined as follows:

$$V_j = \lfloor V_{1j}, V_{2j}, V_{3j}, \cdots\cdots V_{mj} \rfloor \qquad \textbf{Eqn. 61}$$

where V_j is the value flow distribution for a given set of stakeholders St^m and a given system design, D_j. The value flow distribution is the mathematical compilation of the benefits and costs to the various stakeholders of the space system, and the likelihood of attaining these benefits or incurring these costs by each stakeholder in a given valuation context. By modeling the value of the system in a multi-stakeholder environment as a value flow distribution, engineers are able to fully and transparently assess the benefit/cost trade-offs for each stakeholder under various scenarios and as the technical parameters of the system are adjusted.

5.5 Summary of the Concept of Value

In recent years, the importance of value as a design metric has been gaining increased prominence in the space system design and acquisition community. Numerous papers and studies have emerged which promote value-based design methodologies, or techniques for quantifying the value of the space system. While these papers have aided in advancing the visibility of value informed decision-making, value still remains a nebulous concept in space system acquisition and design. This chapter sought to bring clarity to the concept the value of the space system to the stakeholder. In particular, it noted that the space system is a resource allocation problem in which engineers must commit limited resources (e.g. funding, labor) to the development and operation of space systems. In order to effectively allocate resources, three sets of information are essential for the value analysis. These sets of information are the stakeholder preferences, the alternative resource allocation (e.g., baseline system) and the environmental context. This chapter further expanded the value concept from a single stakeholder environment to a multi-stakeholder environment. In reality, the value of the system in a multi-stakeholder environment should be described as a value flow distribution, reflecting the distribution of benefits and costs amongst multiple stakeholders. This enables a transparent value assessment of the system to the various stakeholders.

CHAPTER 6

SUMMARY AND FUTURE AVENUES OF RESEARCH

Since the 1980s, a number of industry organizations and panels (e.g. Government Accountability Office, the Young's Panel, Congressional Budget Office, RAND) have identified significant and persistent problems with the acquisition of space systems [1-8]. Many of these problems are related to, or result in, inadequate cost controls, increased mission risk and performance shortfalls. Although the sources of a number of these issues are organizational in nature, it may be argued that several of these systemic problems result from a cost-centric mindset in design and acquisition that pervades the aerospace industry. This cost-centric mindset is characterized by an emphasis on the utilization of information intrinsic to the space system (e.g. data rate, cost, *EIRP*) for design and acquisition decisions. In particular, a cost-centric mindset focuses on the resources committed to develop and operate the space system with the idea being, that minimizing the cost per functionality or maximizing the functionality per cost yields higher valued space systems to the stakeholders. While these cost-centric approaches to space system design and acquisition allow engineers to be more fiscally aware, they have failed to achieve the leaps forward in the design and acquisition of space systems. In its stead, a slow shift towards a value-centric approach to system design and acquisition is occurring in the aerospace industry.

Value, as a concept, is intuitively understood in system design and acquisition but functionally difficult to articulate. It is a characteristic that the acquirer or user of the system (e.g. Department of Defense, NASA, commercial satellite operator) ascribes to the system and reflects a synthesis of the user's or acquirer's preferences for the given technical attributes of one system design over the technical attributes of another system design within the design space. The proposed shift in the industry from a cost-centric mindset to a value-centric mindset is an attempt to embed information about the acquirer's or user's desirability for the space system into the system design and acquisition environment, in addition to the traditional technical information (e.g. data rate).

Based on the essence of value-centric analysis, this thesis posits that an engineering system in general, and a space system in particular, is a value delivery artifact. And the value delivered, or the flow of service that the system is likely to deliver over its lifetime, whether tangible or intangible, deserves as much effort to quantify as the system's cost. Unlike cost or cost-based metrics, which include only endogenous information about engineering systems, value includes the most complete information about the system and its environment (i.e., both endogenous and exogenous information). As such, value allows for better, more transparent and more relevant trade-offs in system design and acquisition.

While the thrust towards value-centric design and acquisition is generally accepted as a step in the right direction, there is still a lack of consensus on the definition and theoretical foundations for value-centric design and acquisition. This thesis attempts to structure the consideration of value in space systems design and acquisition by exploring the concept of value in the field of economics, and extracting theories from the neo-classical economic paradigm to create a theoretically sound foundation for the development of value frameworks in the context of space systems design and acquisition. In particular, to advance the research on value-centric design and acquisition, this dissertation fulfilled three objectives. The first objective is stated as follows:

> **R1. Develop a value-based framework for priced space systems that incorporates information flows deemed necessary for decision-making in the space system design and acquisition environment under a neo-classical economic formulation**

For priced systems, stochastic models of the environment and financial models of stakeholder preferences are developed and integrated with a spacecraft-sizing tool to assess the system's value. The analytical framework is applied to a case study of a communications satellite, with market, financial, and technical data obtained from the satellite operator, Intelsat. This application investigates design and value implications of the value-centric versus the cost-centric approach to design and acquisition, with results indicating the ways in which value-optimal spacecraft design choices are contingent on both technical and market conditions, and that larger spacecraft for example, which reap economies of scale benefits, as reflected by their decreasing cost-per-transponder, are not always the best (most valuable) choices. While the design choices varied greatly between the two approaches depending on the market conditions, it is also observed that there are cases of convergence in a constrained design space.

In addition to the value of priced system, this thesis also explored the valuation of unpriced systems. The topic of unpriced system is the focus of the second research objective and is stated as follows:

R2. Formulate an analytical value-centric framework for unpriced space systems which estimates the value of the space system based on the value of information the space system provides stakeholders

For unpriced space systems, this research first posits that their value derives from and can be assessed through the value of information they provide. To this effect, a novel Bayesian framework is constructed to assess system value in which the system is viewed as an information provider and the stakeholder an information recipient. Information has value to stakeholders as it changes their rational beliefs, thereby enabling them to yield higher expected pay-offs (or incur lower expected costs). Based on this marginal increase (decrease) in expected pay-offs (expected costs), a new metric, *Value-of-Design (VoD),* is introduced to quantify the unpriced system's value. The Bayesian framework is applied to an example Earth Science satellite that provides hurricane information to oil rig operators in the Gulf of Mexico using nested Monte Carlo simulation and modeling. Probability models of stakeholders' beliefs, behavioral models of stakeholders' actions, and economic models of stakeholders' pay-offs are developed and integrated with a satellite payload generation tool, with economic, behavioral and technical data obtained from various sources (e.g., National Hurricane Center and NASA). The case study investigates the information value contours generated by each payload and the implications for system design and acquisition. Results indicated the probability with which each payload achieves a certain level of information value and pointed to clusters of payload instruments which yielded higher information value for these stakeholders. Minimum information thresholds below which it is difficult to justify the acquisition of the space system based on the information it provides are identified and discussed.

The third research objective focused on uncertainty analysis in value-centric design and acquisition. It was stated as follows:

> **R3. Develop analytical tools which allow the decision-maker to 1) decompose value uncertainty into its constituents, upside potential and downside risk, and 2) identify Pareto optimal systems in a probabilistic environment**

The final research objective is the development of analytical tools which allow engineers to 1) decompose value uncertainty into its constituents, upside potential and downside risk and 2) identify Pareto optimal systems in a probabilistic environment. In particular, this research characterized value uncertainty through partial moments, a technique commonly used in finance, and the introduction of probabilistic Pareto fronts. These two analytical tools developed in this research for space system design and acquisition enabled the coupling of value uncertainty and cost risk considerations as well as the disaggregation of value uncertainty into upside potential and downside risk. The tools are applied to value analysis for the commercial communication satellite and the

Earth Science satellite. These applications demonstrated the variety of insights which may be gained about the value uncertainty of the space system, and highlighted the resulting implications for uncertainty management in design and acquisition. For example, the analytical tools allowed engineers to identify system designs that are flexible to funding instabilities, and provides program managers with information that can support increased budget requests. Overall, these two analytical tools are constructed to allow engineers to dissect the anatomy of value uncertainty, and in doing so, enable better uncertainty management.

6.1 Future Avenues of Research

Value in space system design and acquisition is an interesting multi-faceted concept that has been under study for the last fifty years. In this dissertation, a slice of this concept is explored, but there remain a number of additional avenues for future research exploration. Two such avenues are discussed in this section.

The first avenue of research is a natural extension of this dissertation and considers the multi-stakeholder nature of space systems. Consideration of multiple stakeholders increases the complexity of system design and acquisition decisions as increases in benefits to one stakeholder may come at a cost to another stakeholder. Each stakeholder receives a unique value flow from the space system depending on the probable environmental factors, the system technical attributes and the stakeholder's objectives. Thus, in the multi-stakeholder space system design and acquisition environment an important question which arises is how should limited resources be allocated such that these resources are utilized effectively? Or phrased more colloquially, how should engineers make system design and acquisition choices such that the design and acquisition choice is satisfactory across a given set of stakeholders? Needless to say, the simple phrasing of this question does not belie its complexity. In fact, to evaluate the value flow distributions, engineers must rely on certain prior value judgments. These prior judgments fall into two broad categories and are stated as follows [197]:

J1. The preference for overall higher benefits relative to costs provided by the system

J2. The preference for a more equitable benefits and cost distributions among stakeholders

The first value judgment gives rise to efficiency considerations while the second value judgment gives rise to equity considerations. Efficiency and equity considerations directly impact how information about the value flows of the systems may be used to guide design selection and may at times result in different design and acquisition decisions. Greater research is needed in understanding the multi-stakeholder issues in the space system acquisition and design process and how the concept of equity and efficiency may be used to tackles such issues.

The second potential research avenue lies in the valuation of unpriced systems. As an engineering system the space system may be considered a provider of information for stakeholders. For inter-planetary and astronomy space system, the system provides information about the various characteristics of other bodies in our universe. For technology demonstrators, the space system provides information about the feasibility of potential uses of advanced technologies. For intelligence, surveillance and reconnaissance satellites, the space system provides information about enemy activities It is from this perspective, the provider of information, that a Bayesian framework is developed to assess the value of the unpriced system A key assumption in the Bayesian framework is that the information provided by the space system affects the actions of the stakeholder. However, there are cases in which the information provided by the space system does not affect the actions of the stakeholder. Instead the information simply leads to an increase in knowledge (e.g. astronomy space missions). Thus the underlying assumption in the Bayesian valuation framework for unpriced systems precludes the assessment of such space systems. The second avenue of future research focuses on extending the valuation model to assess not only the value of the pragmatic information (i.e. actionable information) provided by the system, but also the value of the statistical information, (i.e., information that only changes the rational beliefs or knowledge of the stakeholder) gained from the space system.

APPENDIX A

PROBABILITY MODEL OF BEING IN STRIKE ZONE

The probability of an oil rig being in the strike zone given a hurricane is expected to pass a certain distance from the oil rig is derived from information on the forecast error. The hurricane's forecast error is a random variable that indicates the probable deviation of the hurricane from its predicted track, and may be calculated using Cartesian coordinates as follows:

$$FE^T = \sqrt{\left[\left(x_a - x_p\right)^2 + \left(y_a - y_p\right)^2\right]} \qquad \textbf{Eqn. 62}$$

where FE^T is the forecast error at a certain point in time (e.g. 48 hours), and $[x_a, y_a]$ and $[x_p, y_p]$ are the actual and forecast positions of the hurricane respectively at time T. Annual forecast errors vary significantly due to the natural volatility of the hurricane track characteristics. As such the National Hurricane Center provides a five year sample data that describes the frequency of the forecast error [208]. This sample data is shown in Figure 35. The various data series on the chart represents the error associated with the forecast track prediction given the time frame of prediction, T. For example, the blue line indicates errors associated with a track prediction made 120 hours (5 days) before the hurricane is expected to reach the destination of interest. The green line indicates the green line indicates that errors associated with a track prediction made 48 hours (2 days) before the hurricane is expected to reach the destination of interest.

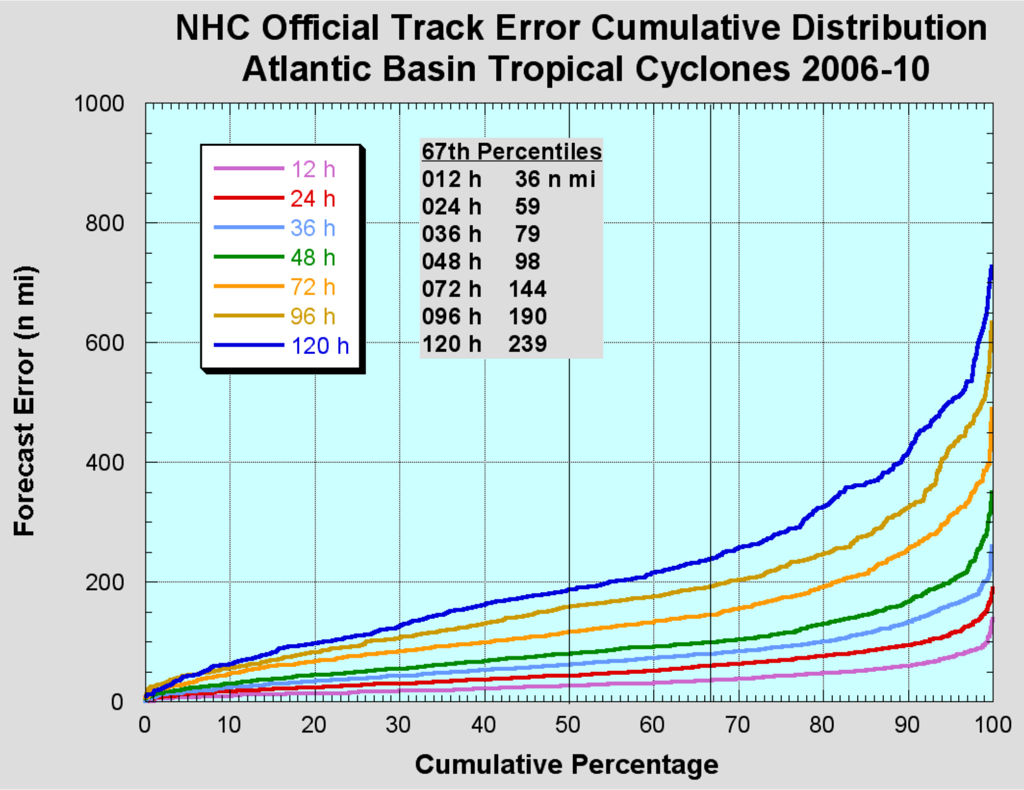

Figure 35. Cumulative distribution of forecast error

For each data series on Figure 35, the cumulative distribution functions of the forecast error may be mathematically interpreted as:

$$F_{FE^T}\left(fe^t\right) = \Pr\left\{FE^T \leq fe^T\right\}$$ **Eqn. 63**

If one considers the 67th percentile, the chart indicates that there is a 67% likelihood that the forecast error will be less than 239 nmi if the forecast is performed 120 hours before the hurricane hits. Likewise, there is a 67% likelihood that the forecast error will be less that 98 nmi if the forecast is performed 48 hours before the hurricane hits. Based on the data provided in Figure 35, the probability density function of the error associated with the 48-hr forecast is determined to be lognormally distributed with this distribution verified using a probability plot as shown in Figure 36. The corresponding parameters of the lognormal distribution are shown in Table 11.

Table 11. Parameters of the Probability Distribution

Parameter	FE^{48}	$ln(FE^{48})$
Mean	99.1 nmi	4.4
Variance	69.2^2 nmi^2	0.4

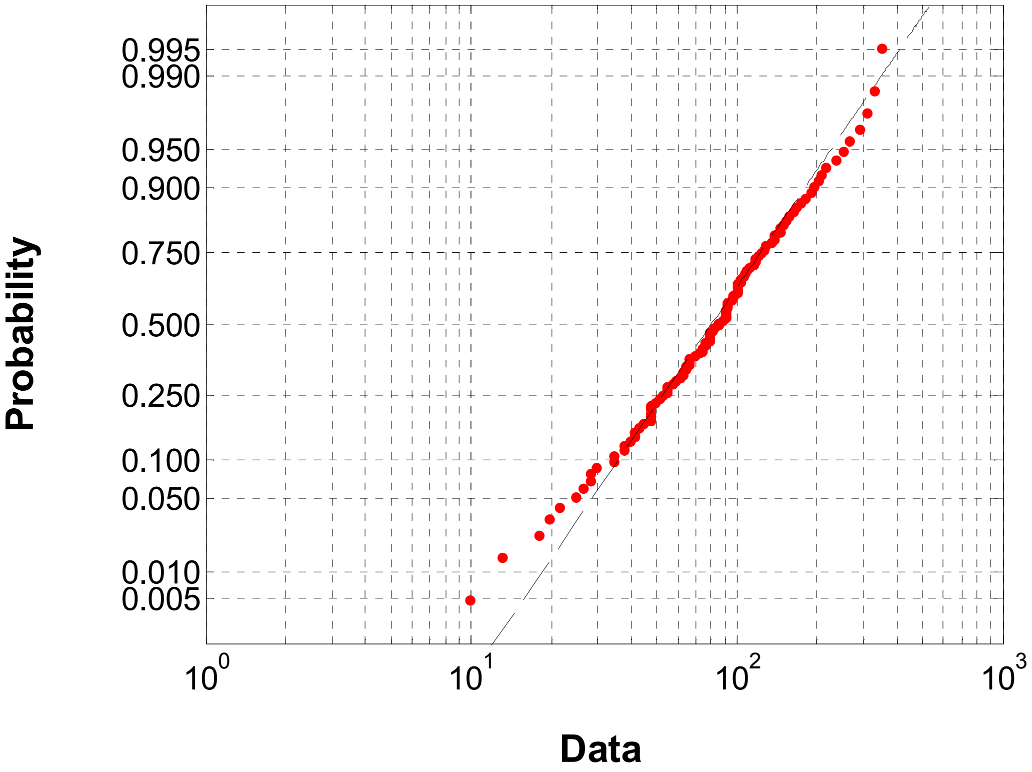

Figure 36. Probability plot of lognormal distribution

The strike zone is taken to be a circular area with a radius, *R*, of 62.5 nmi surrounding the center of hurricane [219]. For the oil rig to be in the strike zone, the actual track of the hurricane must pass within 62.5nmi of the oil rig. For the purposes of this analysis, this scenario may be stated as follows: given the distance of the hurricane from the oil rig is forecasted to be d_i, the oil rig will be in the strike zone if the hurricane deviates from its forecasted track such that it passes within 62.5nmi of the oil rig. This scenario is shown in Figure 37.

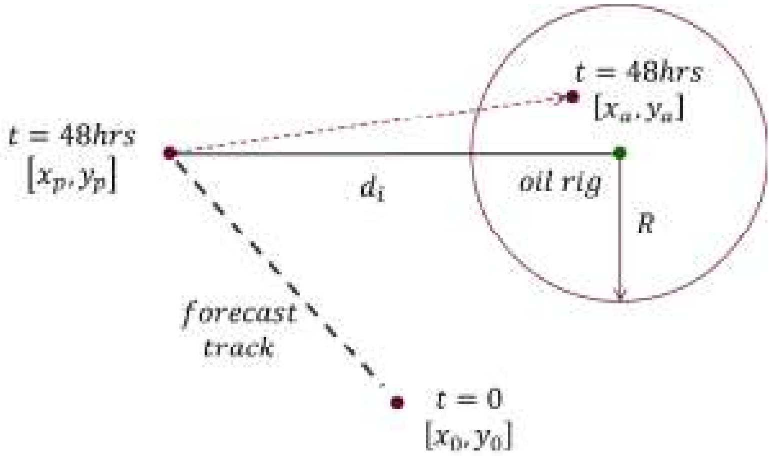

Figure 37. Oil rig in strike zone

From the formulation of this problem, it is possible to assess the probability of the oil rig being in the strike zone based on the probability distribution of the forecast error. The National Hurricane Center provided data about the absolute forecast error but did not indicate any directional tendency. As such, it is assumed that if the hurricane deviated by a distance fe_j from its original path, this deviation can occur randomly in any direction.

These possible directions in the deviation fe_j are represented by a red circle as shown in Figure 38. The red dot represents the location of the hurricane while the green dot represents the relative location of the oil rig. Therefore, the first step in computing the probability of being in the strike zone is to estimate the intersection of the red circle scribed by the radius fe_j and the green circle demarcating the possible strike zone area around the oil rig as shown in Figure 38. If the hurricane enters this area of intersection, the oil rig is considered in the strike zone. For the analysis, $2y$ is the common chord between the two circles and Δx is the closest distance from the hurricane's predicted location to the chord. Using these variables, the area of intersection (AI) is derived and given in Table 12.

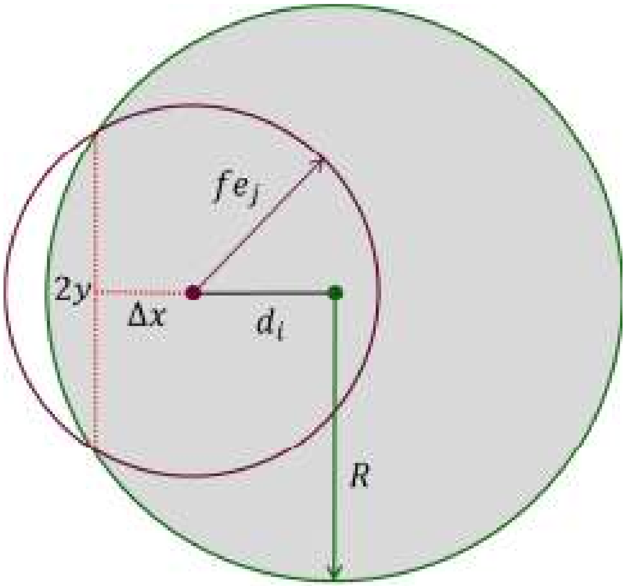

Figure 38. Diagram of hurricane predicted to be in strike zone

Table 12. Determining the Area of Intersection

Condition	Area (nmi^2)
$fe_j < R - d_i$	$AI(fe_j) = \pi fe_j^2$
$R - d_i \le fe_j < R^2 - d_i^2$	$\Delta x = \dfrac{R^2 - fe_j^2 - d_i^2}{-2d_i}$ $y = \sqrt{fe_j^2 - \Delta x^2}$ $AI(fe_j) = \left[\cos^{-1}\left(\dfrac{d_i + \Delta x}{R}\right)R^2\right] - (d_i + \Delta x)y + \left[\cos^{-1}\left(\dfrac{\Delta x}{fe_j}\right)fe_j^2\right] - \Delta xy$
$R^2 - d_i^2 \le fe_j < R^2 + d_i^2$	$\Delta x = \dfrac{fe_j^2 + d_i^2 - R^2}{2d_i}$ $y = \sqrt{fe_j^2 - \Delta x^2}$ $AI(fe_j) = \left[\cos^{-1}\left(\dfrac{d_i - \Delta x}{R}\right)R^2\right] - (d_i - \Delta x)y + \left[\cos^{-1}\left(\dfrac{\Delta x}{fe_j}\right)fe_j^2\right] - \Delta xy$
$fe_j \ge R^2 + d_i^2$	$\Delta x = \dfrac{fe_j^2 + d_i^2 - R^2}{2d_i}$ $y = \sqrt{fe_j^2 - \Delta x^2}$ $AI(fe_j) = \left[\cos^{-1}\left(\dfrac{\Delta x - d_i}{R}\right)R^2\right] - (\Delta x - d_i)y + \left[\cos^{-1}\left(\dfrac{\Delta x}{fe_j}\right)fe_j^2\right] - \Delta xy$

Based on the area of intersection, the probability of the oil rig being in the strike zone is given by:

$$\Pr\{SZ \mid H, d_i\} = \sum_{j=0}^{N} \frac{AI(fe_{j+1}) - AI(fe_j)}{2\pi(fe_{j+1}^2 - fe_j^2)} \left[erf\left(\frac{\ln(fe_{j+1}) - \mu}{\sqrt{2\sigma^2}} \right) - erf\left(\frac{\ln(fe_j) - \mu}{\sqrt{2\sigma^2}} \right) \right] \quad \textbf{Eqn. 64}$$

$$fe_0 = \begin{cases} 0 & d_i < R \\ d_i - R & d_i \geq R \end{cases} \quad \textbf{Eqn. 65}$$

$$fe_{j+1} = fe_j + \Delta d \quad \textbf{Eqn. 66}$$

$$N = \begin{cases} \dfrac{R + d_i}{\Delta d} & d_i < R \\ \dfrac{2R}{\Delta d} & d_i \geq R \end{cases} \quad \textbf{Eqn. 67}$$

where Δd is the incremental increase in the forecast track error, μ and σ are respectively the mean and variance of the lognormal random variable as given in Table 11.

APPENDIX B

COST MODELS

B1. Commercial Satellite Cost Model

The cost to initial operating capability (C_{ioc}) for the commercial communication satellites is dependent on the technical inputs listed in Table 2. Specifically, the technical inputs of the satellite determined the power requirements of the satellite, which in turn impacted C_{ioc}. For a set of inputs (i.e. each design), a link budget analysis is conducted to determine the power requirements of the satellite. The transmit power per satellite is calculated from the link budget equation given as [119]:

$$P_t = CN_o - G_r - G_t - L_a - L_p - L_s + N_o \quad (dBW) \qquad \textbf{Eqn. 68}$$

Each of the variables in the link budget equation is determined from the inputs as outlined:

1. Using BPSK modulation and Plus RS Viterbi Decoding, for a given bit error rate (BER), the required energy to noise ratio (E_bN_0) at the receiver is determined based on a derived empirical relationship with data taken from Wertz and Larson (1999) [119]:

$$E_b N_o = -0.0673 * \log(BER) + 1.945 \quad (dBW) \qquad \textbf{Eqn. 69}$$

2. Based on the bandwidth of a transponder (*BTx*), a guard (*bg*) of 4MHz and the number of transponders in the payload (*T*), the datarate (*DR*) for the satellite is estimated for the satellite as follows:

$$DR = 0.44 * (BTx - bg) * T \qquad \textbf{Eqn. 70}$$

3. Combining the data rate and the energy to noise ratio gives the carrier to noise (CN_0) as:

$$CN_0 = E_b N_0 + 10\log(DR) \qquad \textbf{Eqn. 71}$$

4. The system noise (N_0) is determined from the system noise temperature (T_s) and Boltzmann's constant (*k*) as:

$$N_0 = 10\log(kT_s) \qquad \textbf{Eqn. 72}$$

5. The attenuation losses (L_a), the pointing losses (L_p) and the space losses (L_s) are determined from the downlink frequency (f_d), the speed of light (*c*), the distance between the satellite and the ground station (*R*), the antenna half-power beamwidth (θ) and pointing losses (*e*) as follows:

$$L_a = 1\,dB \qquad \textbf{Eqn. 73}$$

$$L_s = 20\log\left(\frac{c}{4\pi fR}\right) \quad \textbf{Eqn. 74}$$

$$L_s = -12(e/\theta)^2 \quad \textbf{Eqn. 75}$$

6. The ground station and satellite antenna are assumed to be parabolic with the ground antenna gain (G_g) and the satellite antenna gain (G_s) calculated as follows:

$$G_g = 20\log\left(\frac{\sqrt{\eta}\pi Df}{c}\right) \quad \textbf{Eqn. 76}$$

where η is an efficiency factor of the antenna and the satellite antenna diameter is given by

$$D = \frac{21}{f_{GHz}\theta} \quad \textbf{Eqn. 77}$$

Finally, given the variables calculated in Eqn. 69 through Eqn. 77, the transmit power given in Eqn. 68 is computed. The transmit power accounted for about 60% of the operating power of the satellite [119]. The operating power determined the mass of the power system, with this mass consisted primarily of the mass of the solar arrays and the mass of the battery. The mass of the wiring is assumed to be incorporated into the mass of the arrays and the mass of the battery. The mass of the solar arrays depended on their required area. This area in turn depended on the spacecraft power requirements during eclipse (P_e) and during daytime (P_d), the efficiency of the solar arrays during these periods (X_e, X_d) and the length of the daytime and eclipse periods (T_d, T_e). The required power from the solar array during the daytime is given by:

$$P_{sa} = \left(\frac{\dfrac{P_e T_e}{X_e} + \dfrac{P_d T_d}{X_d}}{T_d} \right) \qquad \textbf{Eqn. 78}$$

To determine the area of the array, the end of life power requirements are also calculated. This is done through the following equations:

$$P_{BOLA} = P_0 I_d \cos\lambda \qquad \textbf{Eqn. 79}$$

$$P_{EOLA} = P_{BOLA} L_d \qquad \textbf{Eqn. 80}$$

where P_{BOLA} and P_{EOLA} are the beginning of life power and end of life power of the satellite per unit area of the solar array respectively, P_o is the power output of the array with a sun's incident angle (λ) normal to the solar panels, I_d is the inherent degradation of the solar array and L_d is the lifetime degradation. Once P_{EOLA} is determined, the area (Asa) and subsequently the mass of the solar array(M_a) is computed.

$$Asa = \frac{P_{sa}}{P_{EOLA}} \quad \textbf{Eqn. 81}$$

$$M_a = \frac{P_{EOLA} \times Asa}{66} \quad \textbf{Eqn. 82}$$

Based on the power requirement during eclipse, the length of the eclipse period and the specific energy density of the battery (*sed*), the mass of the battery (M_b) is defined as follows:

$$M_b = \frac{P_e T_e}{sed} \quad \textbf{Eqn. 83}$$

Using mass estimating relationships, the masses of the various subsystems are determined and used as inputs for the cost estimating relationships. The parameters for these mass estimating relationships are shown in Table 13.

Table 13. Subsystem Mass Fractions [119]

Subsystem	Percentage of Spacecraft Dry Mass
Payload	27.4
Structure	21.3
Thermal	3.6
Power	31.9
Telemetry, Tracking & Command	4.8
Attitude Determination & Control	6.9
Propulsion	3.8

The Research, Development, Testing & Evaluation (RDT&E) and production costs for each subsystem are modeled parametrically using a power relation. This parametric model is based on the mass of the subsystem (*X*) as shown:

$$C_{rdte} = hf \times cf \times \gamma X^{\rho} \qquad \textbf{Eqn. 84}$$

$$C_{prod} = \alpha X^{\beta} \qquad \textbf{Eqn. 85}$$

The values for parameters γ and ρ, and α and β are shown in Table 14 and Table 15 respectively. The parameter, *hf,* is a heritage factor reflecting the design maturity of the system and is taken to be 0.1[119]. The parameters γ and ρ are given for government systems. As suchis a commercial factor, *cf*, used to scale the RDT&E cost such that they are reflective of RDT&E costs for the commercial communications satellite sector. This factor is taken to be 0.8 [119].

Table 14. Parameter Values for RDT&E Costs of Subsystem [119]

Subsystem	γ	ρ
Payload	353.3	1
Structure	157	0.83
Thermal	394	0.635
Power	62.7	1
Telemetry, Tracking & Command	545	0.761
Attitude Determination & Control	464	0.867
Apogee Kick Motor	17.8	0.75

Table 15. Parameter Values for Production Costs of Subsystem[119]

Subsystem	α	β
Payload	140	1
Structure	13.1	1
Thermal	50.6	0.707
Power	112	0.763
Telemetry, Tracking & Command	635	0.568
Attitude Determination & Control	293	0.777
Apogee Kick Motor	4.97	0.823
Integration, Assembly & Testing (based on dry mass of satellite)	10.4	1

Additional costs associated with the acquisition of commercial communications satellites include the Insurance Costs (C_I) and the Launch Vehicle Costs (C_{LV}). Combining these cost gives the total the total costs to initial operating capability (C_{ioc}) as:

$$C_{ioc} = (1 + if) \times \left(\sum_{i=1}^{n} \left(hf \times cf \times \gamma_i X_i^{\rho_i} + \alpha_i X_i^{\beta_i} \right) + 10.4 \sum_{i=1}^{n} X_i + C_{LV} \right) \qquad \textbf{Eqn. 86}$$

where n is the number of subsystems and if is the insurance rate. This insurance rate is assumed to be 13% [198].

B2. Earth Science Spacecraft Cost Inputs

The lifecycle cost of the earth science spacecraft comprised the spacecraft development and production costs, launch vehicle and insurance costs, and the mission operations cost. Nominal values for these costs are estimated using the NASA Spacecraft Vehicle Level Cost Model and NASA Mission Operations cost model [199,200]. The former determines the cost of the spacecraft based on the spacecraft's dry mass while the latter determines the mission operations cost based on the investment costs in the spacecraft (i.e., the development and production, and launch and insurance costs). The final cost estimates for each system design is shown in Table 16.

Table 16. Nominal Cost Estimates

($FY10 Mil)	D_1	D_2	D_3	D_4	D_5	D_6	D_7
Total RDT&E Costs	504	376	217	154	649	336	489
Total Production Costs	212	149	76	99	201	131	170
Launch Vehicle and Insurance Costs	223	151	101	115	233	136	204
Missions Operations Costs	20	15	9	9	23	14	19
Total Costs	**959**	**690**	**402**	**376**	**1106**	**616**	**882**

APPENDIX C

PROBABILITY DISTRIBUTIONS AND CONTOURS

This appendix provides the joint probability distributions, the joint probability contours, and the iso-probability curves of the cumulative Value of the Design over fifteen years for each system design considered in Chapter 4.

C1. Joint Probability Distributions

The joint probability distributions between the value of information provided by the system design over 15 years and the lifecycle cost of the system are given in Figure 39 through Figure 44 where the probability level is indicated by the color gradation on the figures.

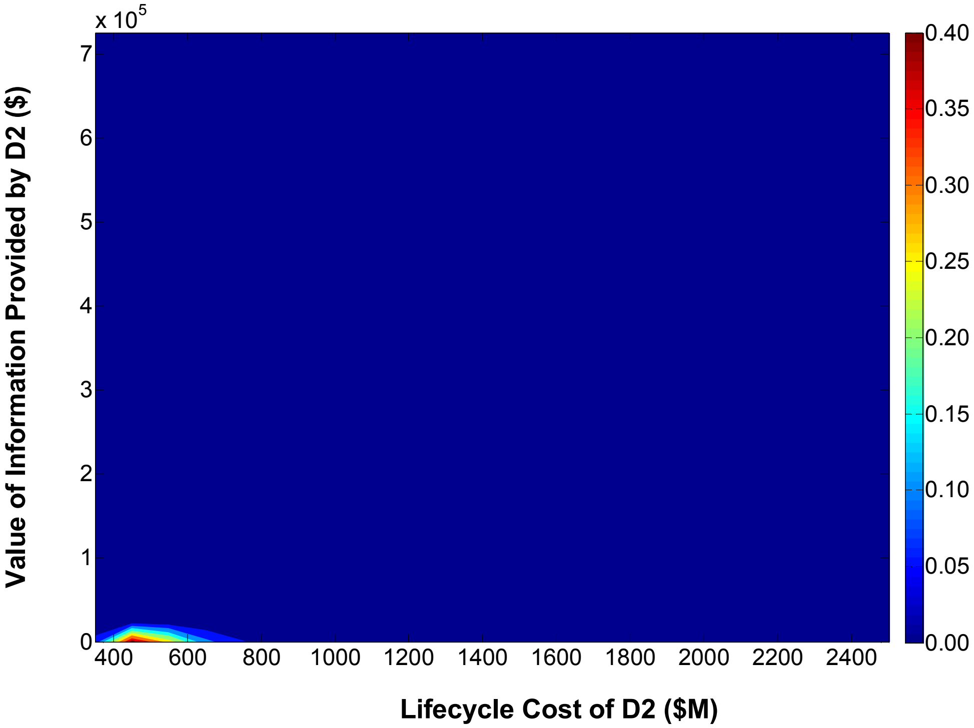

Figure 39. Joint probability distribution of D2

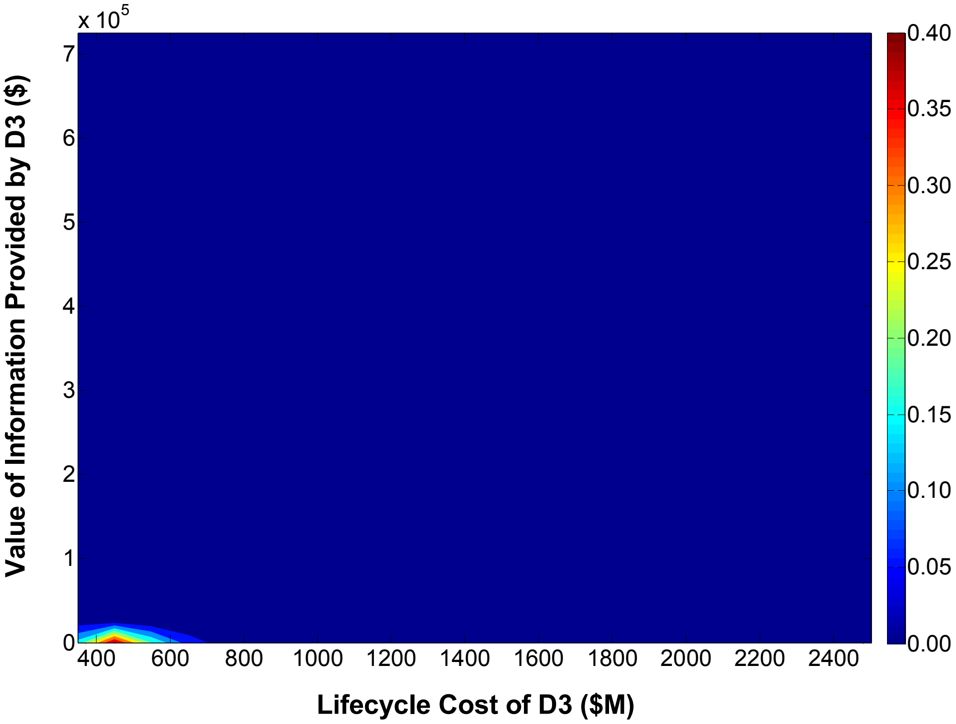

Figure 40. Joint probability distribution of D3

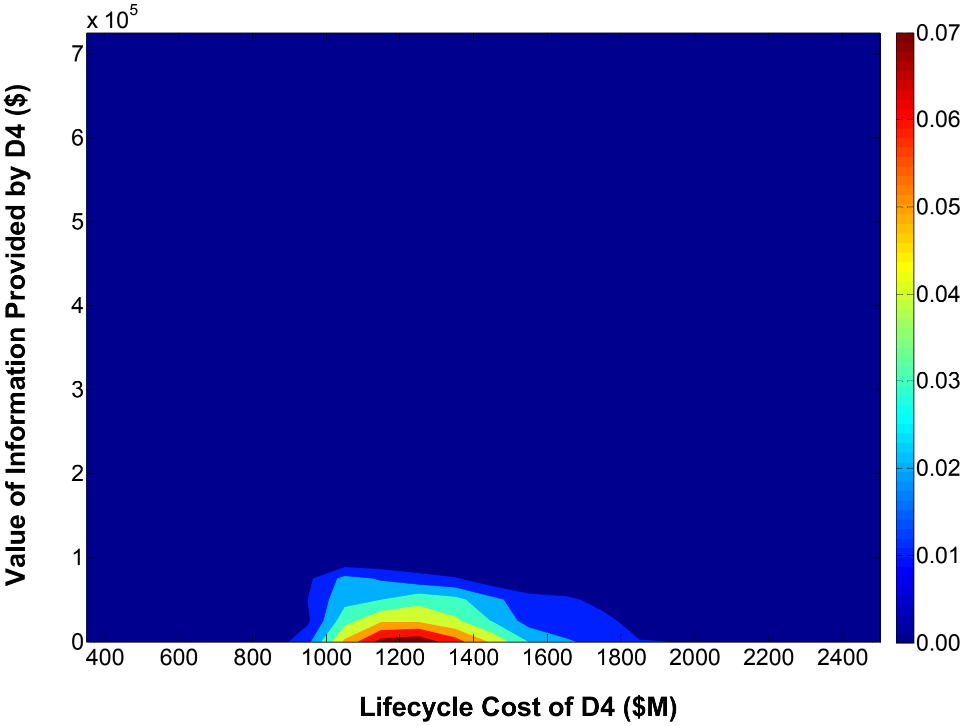

Figure 41. Joint probability distribution of D4

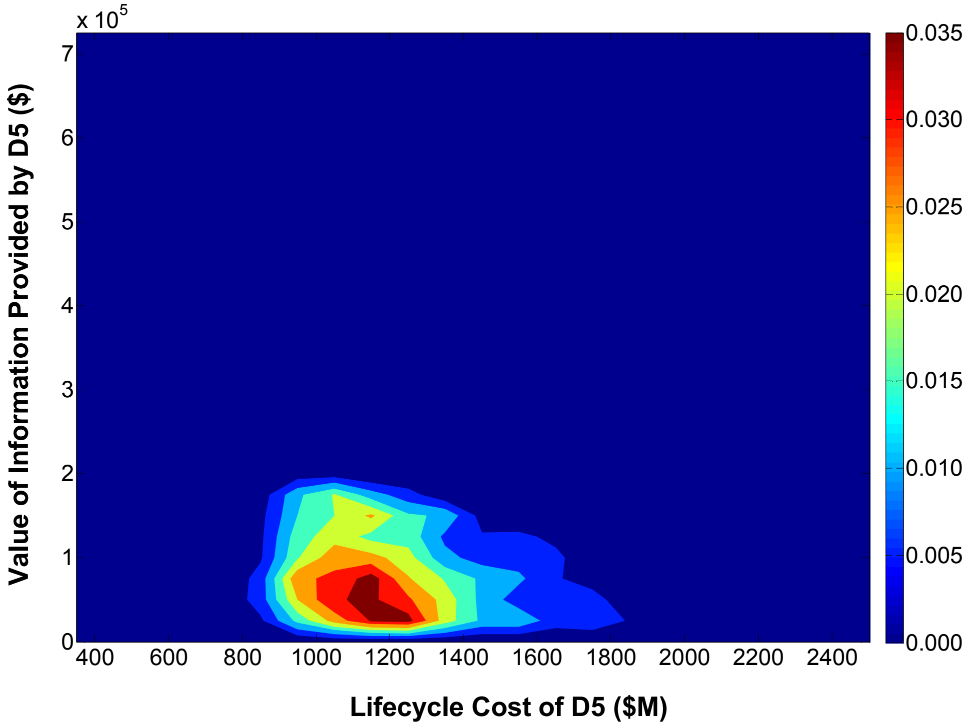

Figure 42. Joint probability distribution of D5

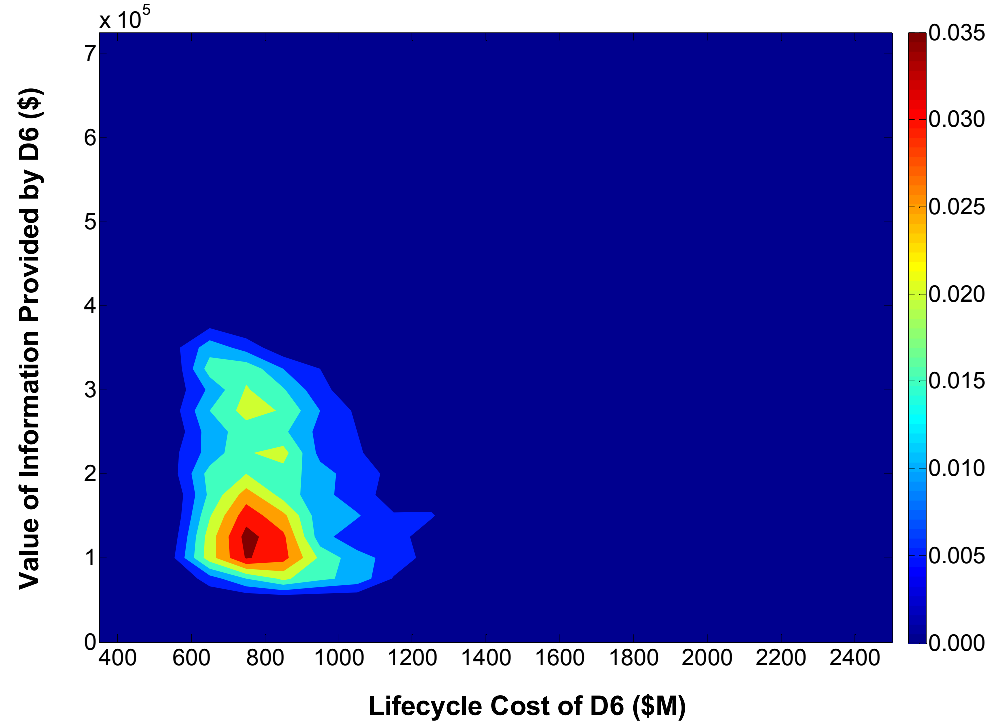

Figure 43. Joint probability distribution of D6

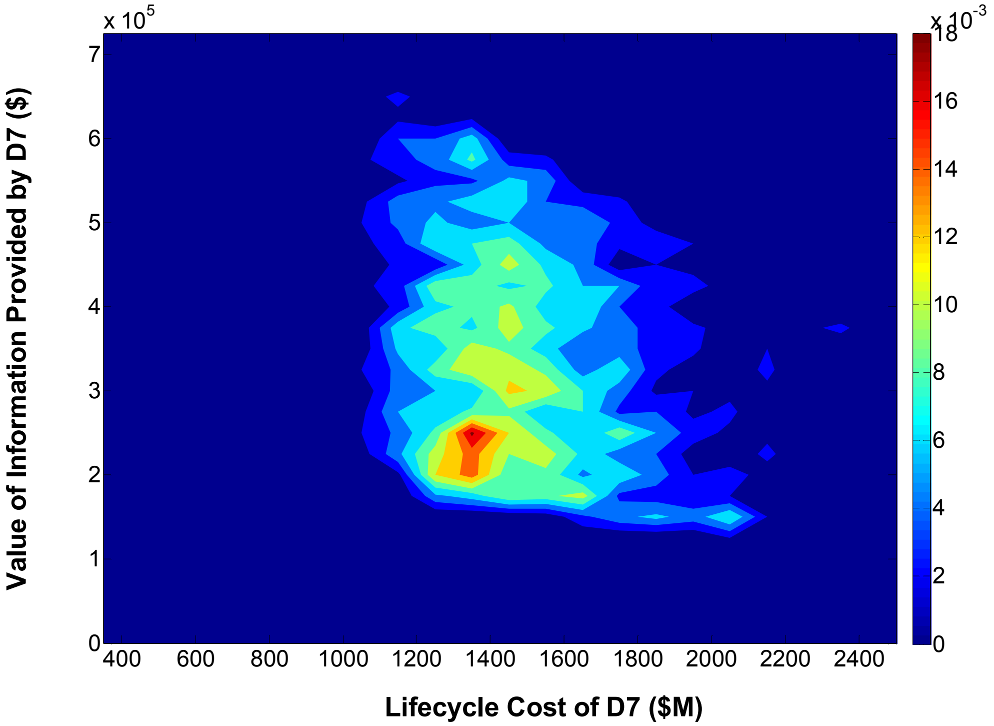

Figure 44. Joint probability distribution of D7

C2. Joint Probability Contours

The joint probability contours between the value of information provided by the system design over 15 years and the lifecycle cost of the system are given in Figure 45 through Figure 50 where the contour is defined as

$$\Pr\{VOD_j \geq l; LCC_j \leq c\} = pr \qquad \textbf{Eqn. 50}$$

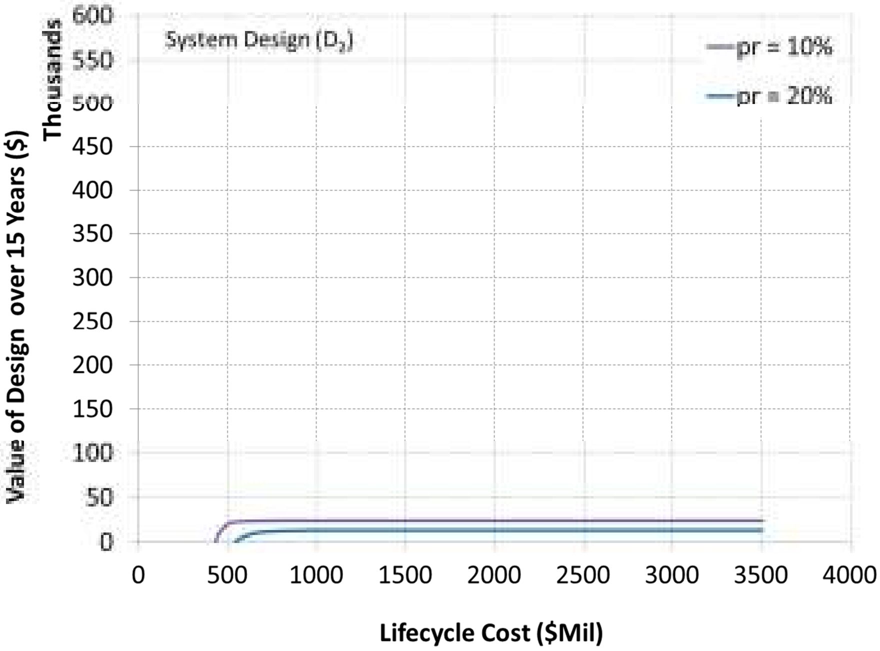

Figure 45. Joint probability contours of D2

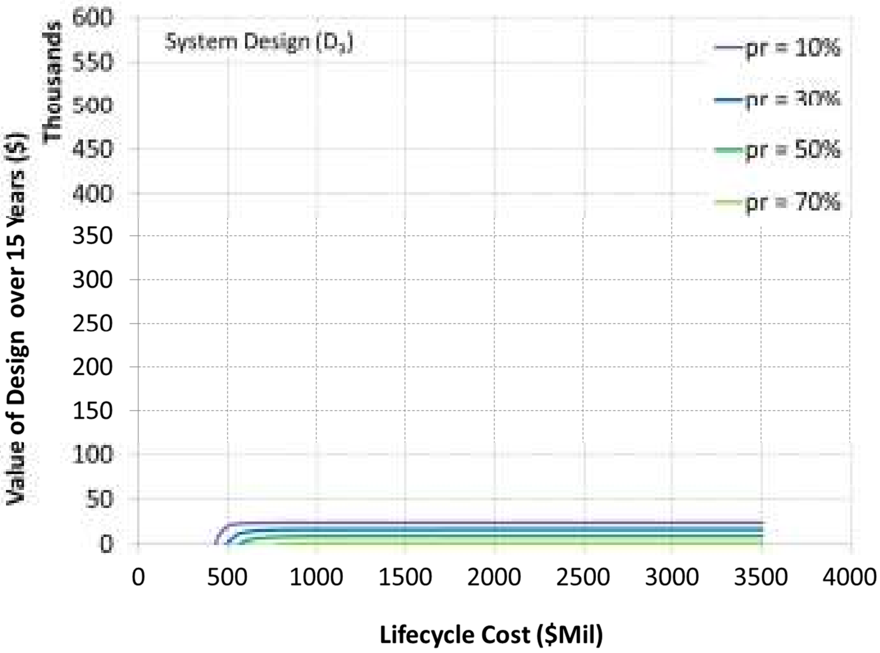

Figure 46. Joint probability contours of D3

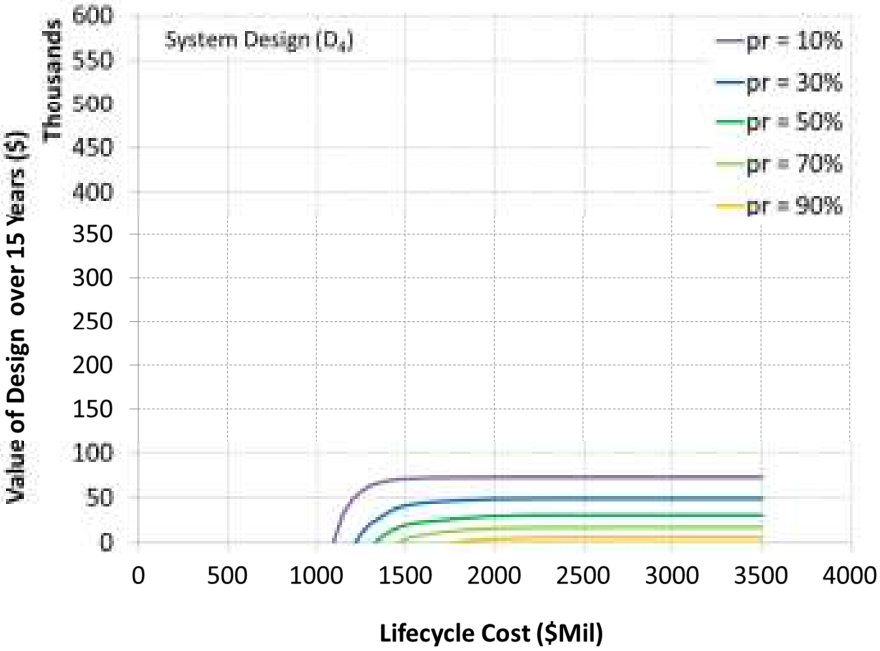

Figure 47. Joint probability contours of D4

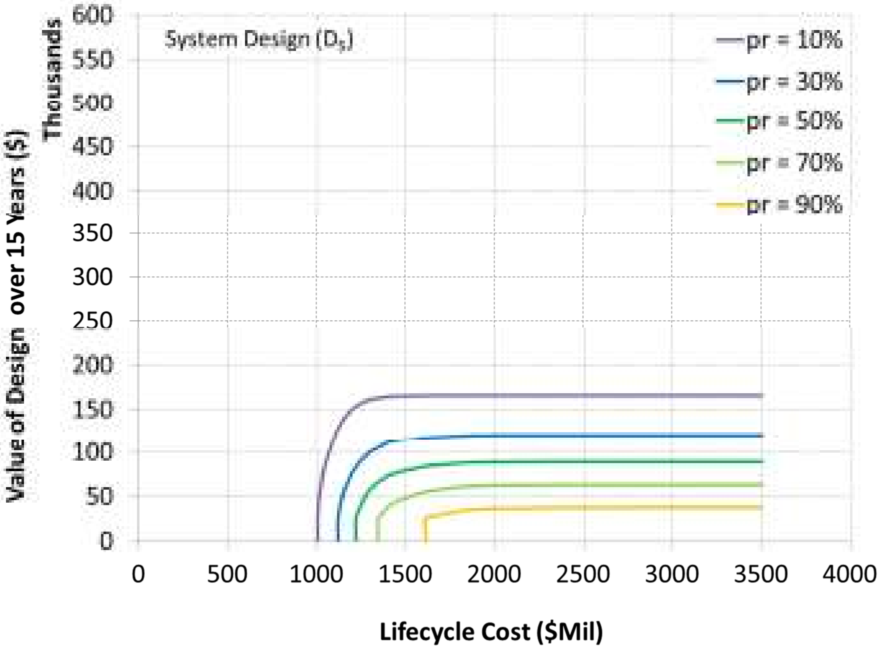

Figure 48. Joint probability contours of D5

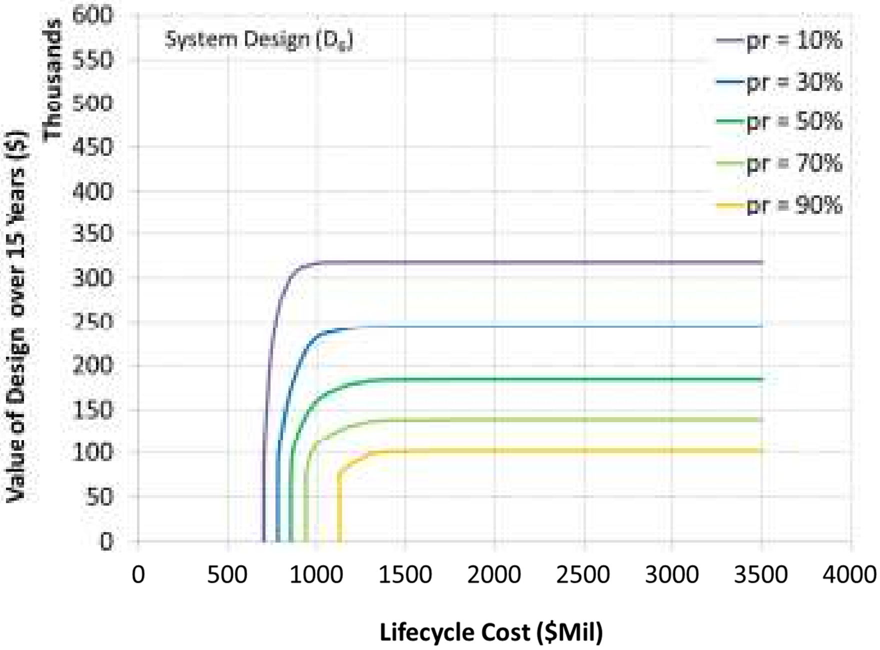

Figure 49. Joint probability contours of D6

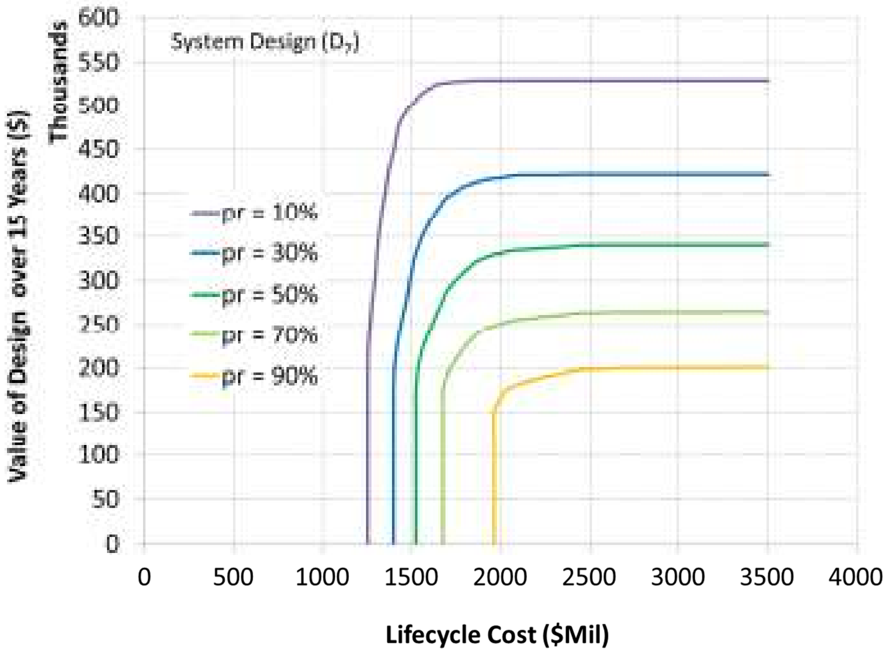

Figure 50. Joint probability contours of D7

C3. Iso-Probability Curves

The iso-probability curves between the value of information provided by the system design over 15 years and the lifecycle cost of the system are given in Figure 51 through Figure 59 where *pr* indicates the probability level.

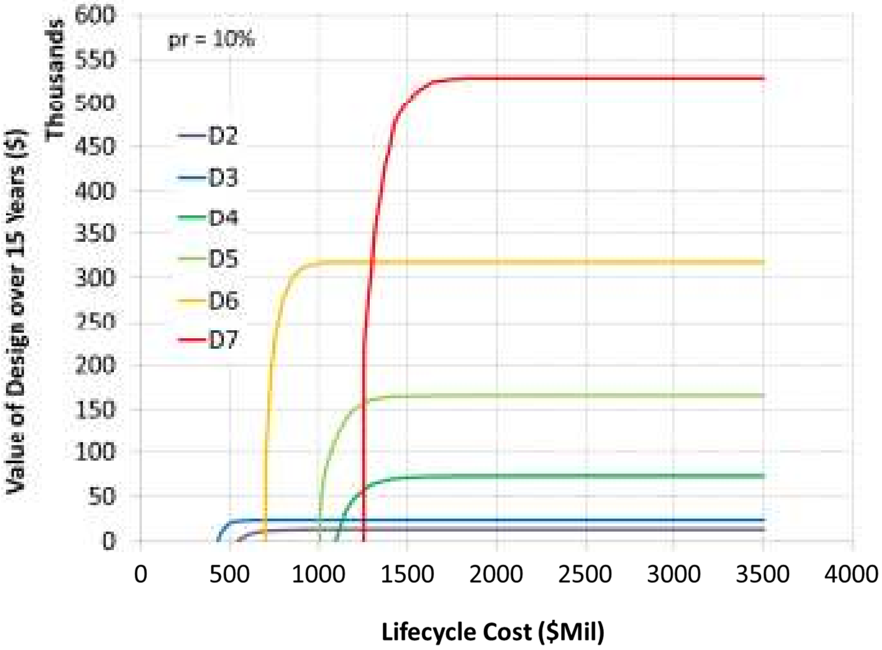

Figure 51. Iso-Probability curves (*pr* = 10%)

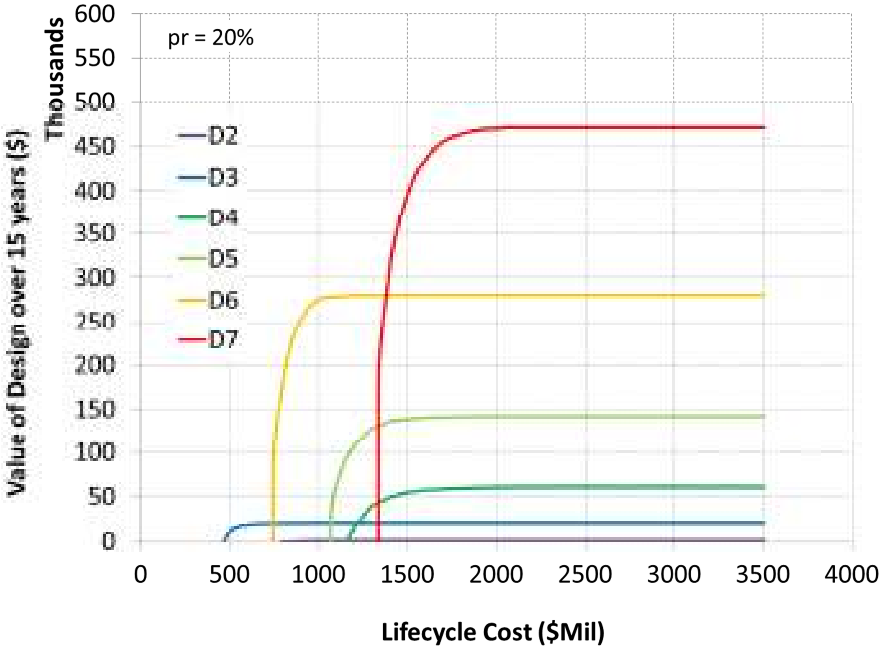

Figure 52. Iso-Probability curves (*pr* = 20%)

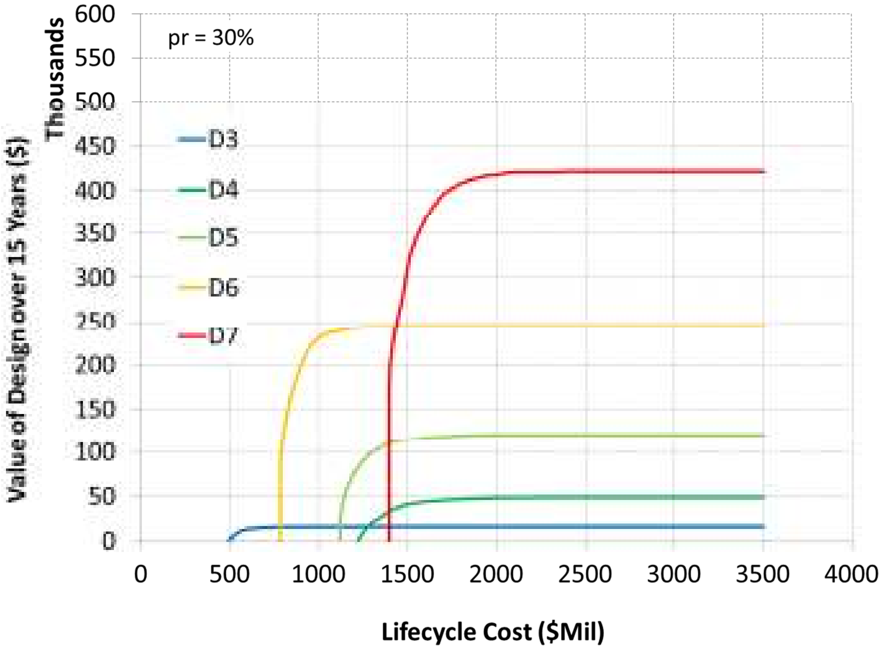

Figure 53. Iso-Probability curves (*pr* = 30%)

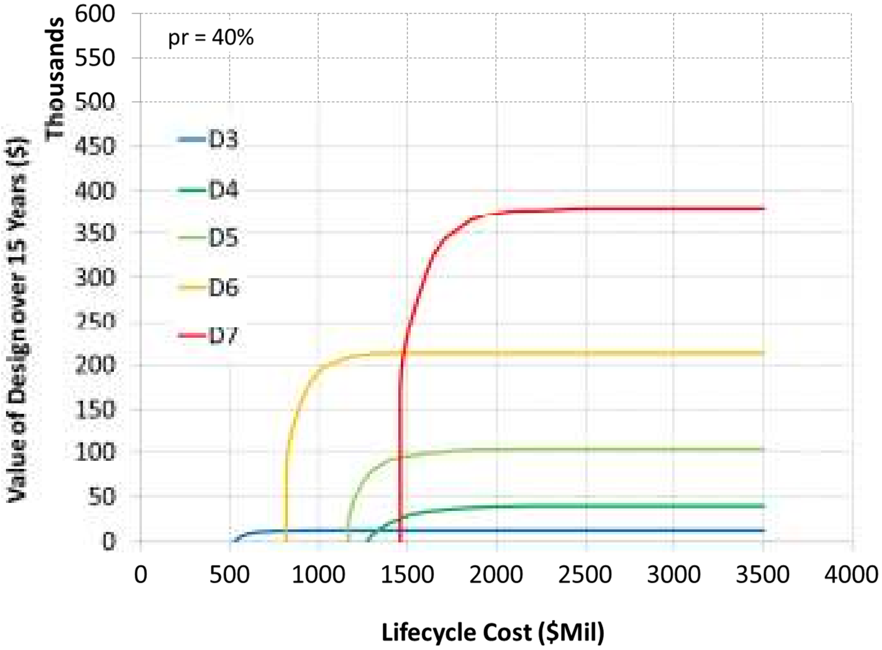

Figure 54. Iso-Probability curves (*pr* = 40%)

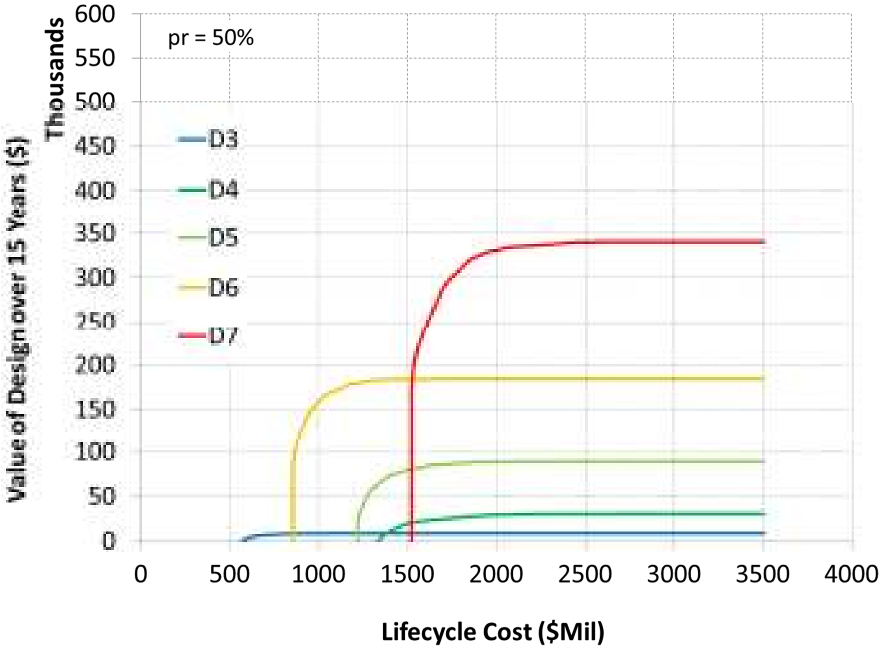

Figure 55. Iso-Probability curves (*pr* = 50%)

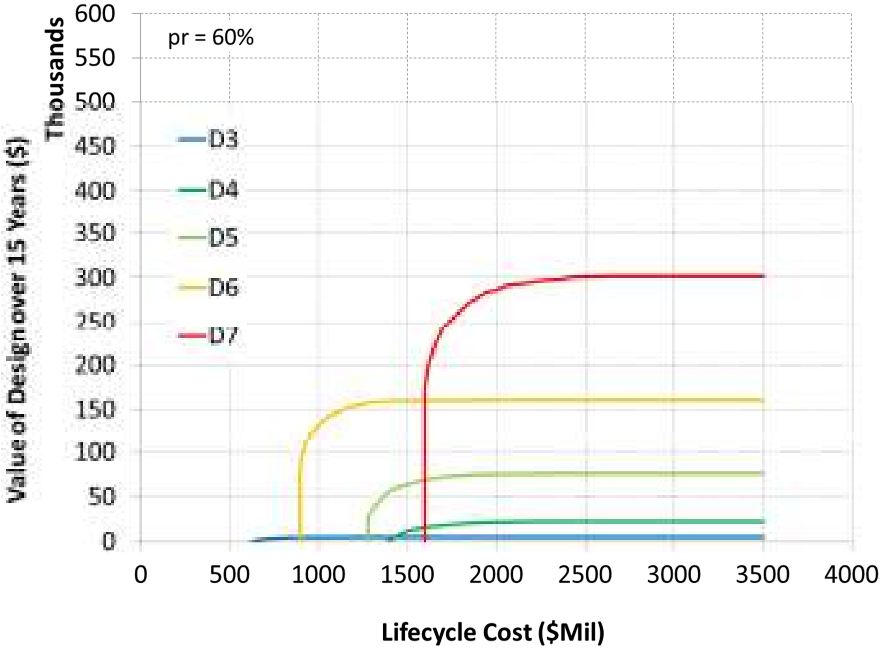

Figure 56. Iso-Probability curves (*pr* = 60%)

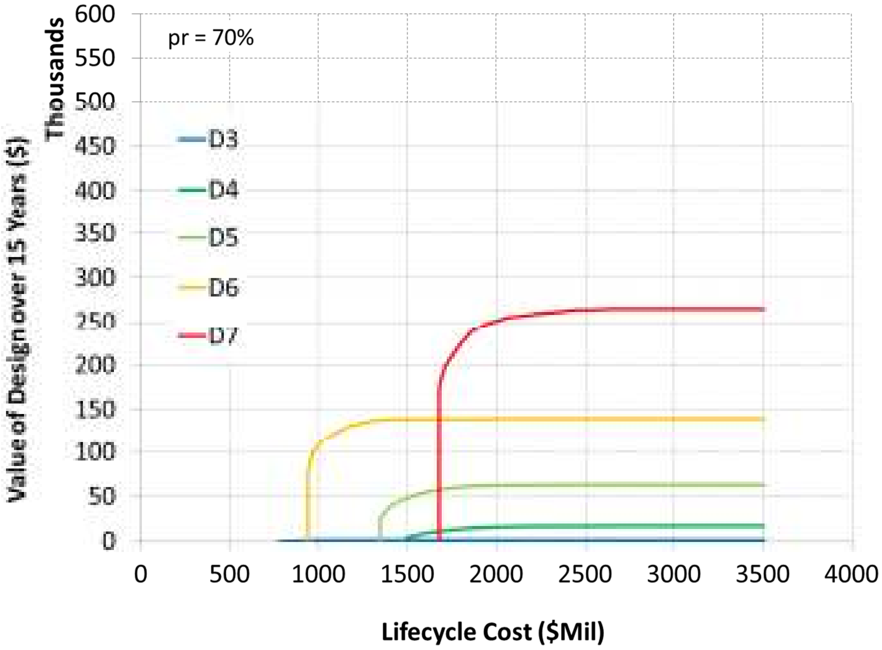

Figure 57. Iso-Probability curves (*pr* = 70%)

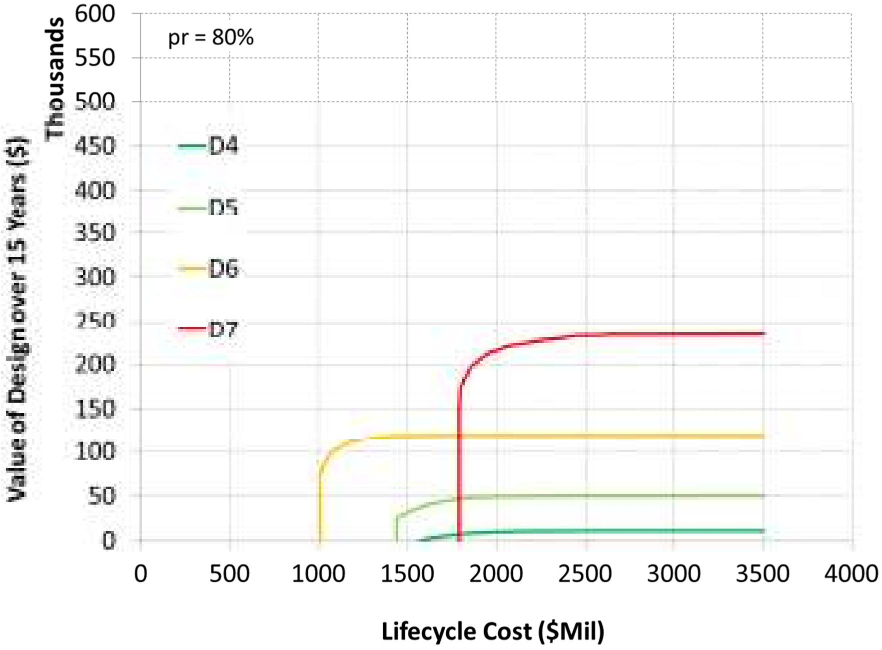

Figure 58. Iso-Probability curves (*pr* = 80%)

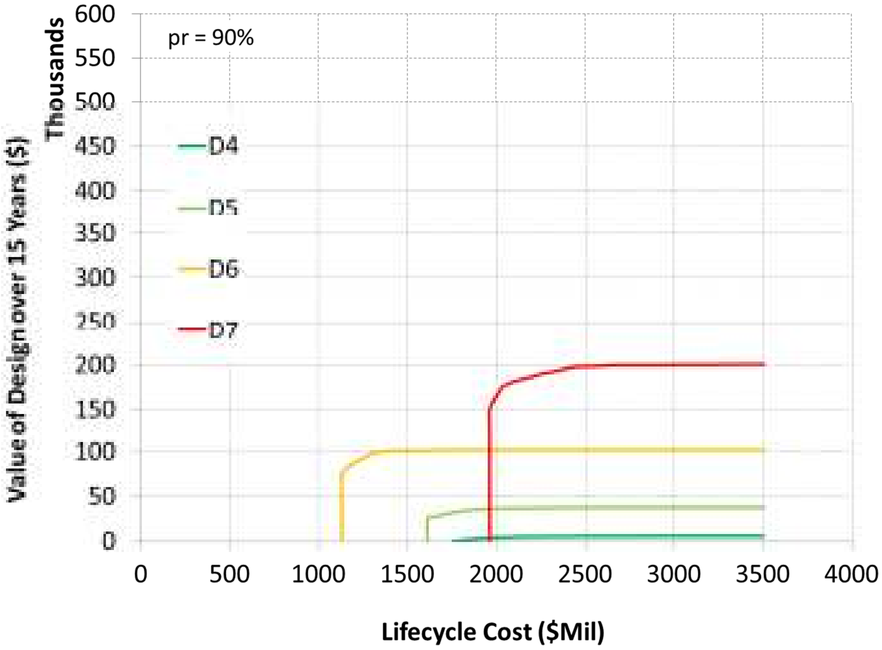

Figure 59. Iso-Probability curves (*pr* = 90%)

APPENDIX D

PRICED RESEARCH AND DEVELOPMENT ANALYSIS

The value-centric framework for priced space systems presented in Chapter 3 assessed the design and value implications in a constrained design space (see Section 3.3.3), with the imposed constraints being either technical in origin (e.g., payload sizes are limited by current satellite platforms or launch vehicle specifications), or economic in origin, (e.g., there is an investment cost constraint imposed by the satellite operator). For the analysis in Chapter 3, these economic or technical constraints notionally translated into a constraint of 80Tx in the design space. Stemming from the analysis conducted in Chapter 3, one interesting research question that arises is what are the technical factors and market conditions that may trigger Research and Development (R&D) investment by the satellite operator in order to move the design constraint[9].

To evaluate the technical and market triggers that would prompt the satellite operator to consider investing in moving the design constraint through R&D, a number of factors are considered. Among these factors are 1) the level of R&D investment needed to shift the constraint and 2) the increase in the expected NPV from shifting the design constraint. The level of R&D investment required to shift the design constraint is considered dependent on the final payload size developed. Larger payload sizes are

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[9] Although this appendix explores the market and technical triggers to shift the constraint in the design space from the perspective of the satellite operator, the general principles presented in this appendix may be applied when performing the analysis from the perspective of other stakeholders.

generally more technically complex thereby incurring higher levels of R&D investment. The payload sizes forming the possible system candidates for research and development ranged between 81Tx and 160Tx. Beyond the 80Tx constraint, the C_{ioc} per transponder is assumed to follow the general trend as that within the 80Tx constraint if no R&D investment is required to field these larger payload sizes. However if a R&D investment is required, this investment is measured as a percentage increase in the C_{ioc} per transponder. Three levels of R&D investment are considered for this analysis that resulted in a 10%, 30% and 50% increase in the C_{ioc} per transponder. These costs are shown in Figure 60.

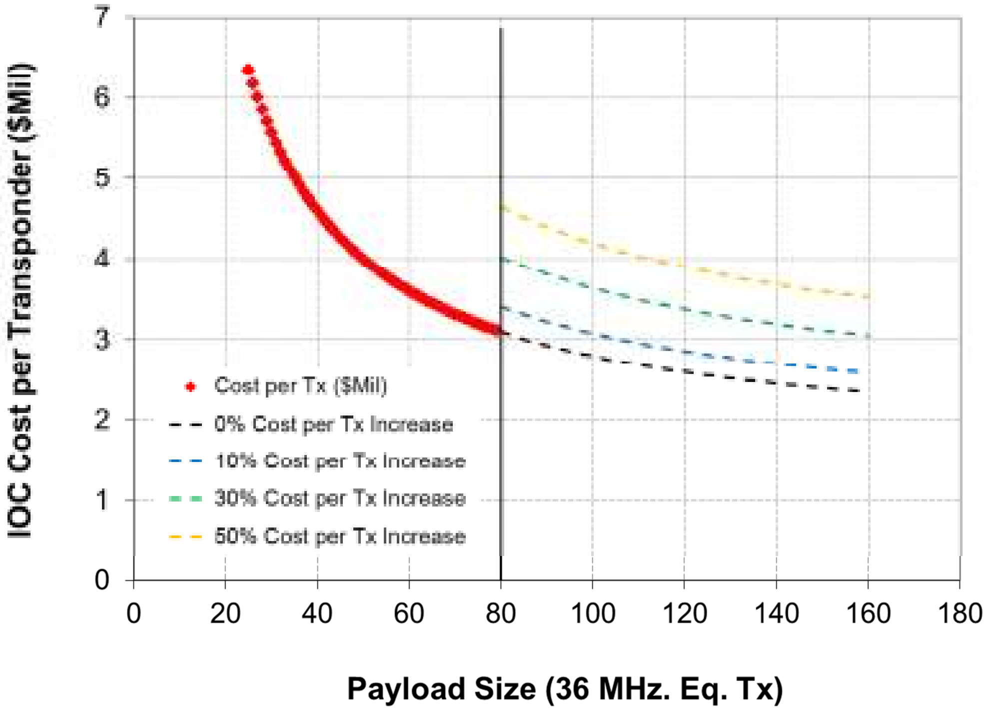

Figure 60. Research and development costs as a percentage of IOC cost per Tx

The increase in the expected NPV from shifting the design constraint to a larger payload size is modeled as a percentage increase over the maximum expected NPV that the satellite operator would attain in the presence of the 80Tx constraint, and is given by:

$$\alpha = \left(\frac{E[NPV \mid T_j] - \max_T E[NPV \mid T]}{\max_T E[NPV \mid T]} - 1 \right) \times 100 \qquad \textbf{Eqn. 87}$$

where α is the percentage increase in expected NPV from shifting the design constraint. An assessment of α may be divided into two categories, with the first category being an assessment in which market conditions are such that the optimal expected NPV occurs within the constrained design space, and the second being an assessment in which market conditions are such that the optimal expected NPV occurs beyond the constraint of 80Tx. The first category is not considered as shifting the design constraint will not lead to increases in the expected NPV given the additional R&D investment needed. The second category of assessment is conducted. The market conditions defining this category are initial market demands between 50Tx and 100Tx, with all other conditions remaining consistent with those given in Eqn. 20. For these market conditions, design and value convergence will occur, leading to the maximum expected NPV being that provided by an 80Tx payload size.

The results of the analysis are presented in Figure 61. The figure displays the minimum marginal increase in payload size over the 80Tx payload that would prompt the satellite operator to consider R&D investment for a given set of market conditions.

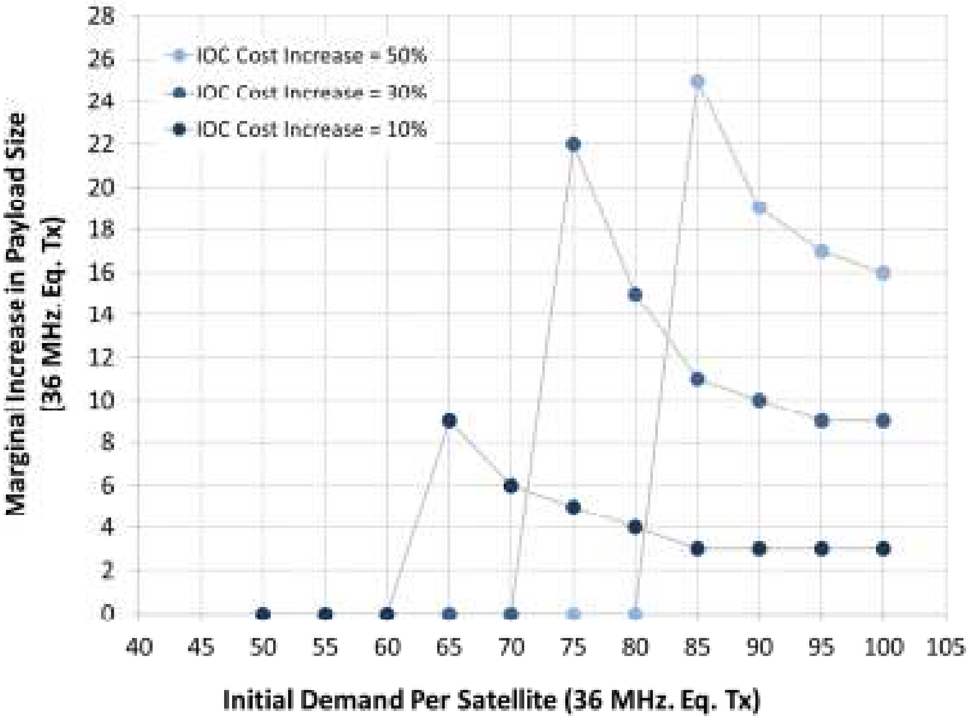

Figure 61. Market and technical triggers (α = 0%)

In particular, Figure 61 displays the marginal increase in the payload size for R&D investment levels of 10%, 30% and 50% given the initial market demand and conditioned on a minimum desired percentage increase in the expected NPV of α = 0% (i.e., the satellite operator is no better or worse off than had he acquired in the 80Tx satellite). First consider an R&D investment level of 10%. This is given by the dark blue data points on Figure 61. The figure indicates that for initial market demands below 60Tx, the satellite operator would not consider making an R&D investment. The expected NPV for payload sizes beyond 80Tx is not sufficient to compensate for the required R&D investment such that the satellite operator is no worse off than fielding the 80Tx satellite system. For initial market demands of 65Tx or larger, the additional increase in the expected NPV sufficiently exceeds the expected NPV gained from the

80Tx payload when accounting for the R&D costs. In these market conditions, the satellite operator may consider an R&D investment to develop satellite systems with larger payload sizes. It is interesting to note that the marginal increase in payload size over the 80Tx payload size decreases monotonically with increased initial market demand over the 65Tx, reflecting the reduced impact of R&D investment costs on overall expected NPV for a given system as market demand increases. In other words, increased market demand enables the system to generate expected present value as a higher percentage of expected NPV.

In assessing the market and technical triggers across various investment levels, a number of observations may be made. First, as the R&D investment costs increases the initial market demand at which the satellite operator would consider making this investment also rises. Second, the marginal increase in payload size that prompts the satellite operator to make the investment becomes greater as the R&D investment costs rise. This relationship between R&D investment costs and initial market demand stems from the fact that greater demand leads to higher expected NPV, which allows the satellite operator to recover their investment in the larger payload while at a minimum maintaining the level of value achieved from the 80Tx payload system. The relationship between the marginal increase in the payload size and R&D costs suggests that for a given set of market conditions, a certain level of payload size beyond the 80Tx is needed to capture a sufficient potion of the demand, and generate the value needed to off-set the R&D investment.

Finally, in summary a number of general inferences may be drawn from the analysis. Among these inferences are greater payload sizes and larger initial market demands are required to prompt the satellite operator to consider R&D investment as the needed level of investment increases, the impact of the R&D investment cost on the overall expected NPV gained by the satellite operator declines for larger initial demand, and the satellite operator will be more inclined to engaged in R&D investment as the mismatch between the supply dynamics of the market and the demand dynamics become greater (i.e., demand outpaces supply).

APPENDIX E

INFORMATION AS A PUBLIC GOOD

The information provided by public agencies such as NASA and NOAA may be effectively considered a public good, that is, no rivalry exists between consumers for the provided information [33,167]. As a public good, consumption by a single user does not affect or preclude consumption by another user, and supply-demand issues are not overly relevant. However, a non-rival good does not mean a non-exclusive good. Although no competition exists for a public good, users may be excluded from accessing the goods. For example, while cable television may be a public good, some consumers are excluded from accessing cable channels if they are not subscribers. Information provided by agencies such as NASA and NOAA may be considered exclusive as the user pays a small fee for accessibility to information [166]. This fee is often marginal, and for all intent and purposes, may be considered inconsequential in the value analysis. Thus information from agencies such as NASA and NOAA create positive externalities as users are allowed to access the information with no adverse impact on other users for minimal costs. Given the benefits of the provided information generally outweigh the costs incurred from accessing the information, this thesis focused primarily on the benefits the information provides to the various stakeholder with limited consideration given to any transaction costs that are incurred by said stakeholders.

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VITA

JOY D. BRATHWAITE

Joy Brathwaite was born and raised in the tranquil island of Barbados. She was educated at the distinguished institution of Combermere Secondary school where she became a highly regarded National Scholar in 1998. In Fall 1999, Joy enrolled in Georgia Tech to pursue studies in Aerospace Engineering where she won academic awards such as the OMED Tower Award. In 2003, Joy received a Bachelor's Degree in Aerospace Engineering, followed by a Master's Degree in Economics two years later. After completing her tertiary education in Economics, Joy returned to Barbados to work, first as a Research Assistant at the Caribbean Development Bank performing socioeconomic analysis, and then as a Research Analyst at the Signia Financial Group as its primary investment analyst. In 2007, Joy returned to Georgia Tech to pursue a doctoral degree in Aerospace Engineering with a focus on value-centric analysis, under the guidance of Dr. Joseph Saleh, in the Space Systems Design Lab. Throughout her various roles and studies, Joy has won a number of fellowships as well as published papers in the areas of economics, aerospace engineering and policy.