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A MULTI-ATTRIBUTE-UTILITY-THEORY MODEL THAT MINIMIZES INTERVIEW-DATA REQUIREMENTS: A CONSOLIDATION OF SPACE LAUNCH DECISIONS

THESIS

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A MULTI-ATTRIBUTE-UTILITY-THEORY MODEL THAT MINIMIZES INTERVIEW-DATA REQUIREMENTS: A CONSOLIDATION OF SPACE LAUNCH DECISIONS

THESIS

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Acknowledgments

This thesis is the culmination of nine months of research, interviews, questions, frustrating answers and sleepless nights. It was my goal was to produce something that was not just theoretical in nature, but to produce a tool which others might actually apply to make their jobs somewhat easier to accomplish. Only time will prove whether I have been successful.

There are many to thank for making this a successful effort. Certainly, I owe my advisor, Dr. Yupo Chan, a debt of gratitude. He gave me a lot of free reign to pursue my own paths in this research. His guidance and patience have been greatly appreciated. My thanks to Major J. Andreas Howell, who first sparked my interest in this subject and to Major Roger Burk, who stepped in at the last minute as a reader when Major Howell was suddenly transferred to Georgia to a new job after separating from the Air Force.

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Abstract

This research uses multi-attribute utility theory (MAUT) to define a mathematical representation of a decision maker's utility associated with a satellite system. While developing the survey instrument, we focused on making it simpler to administer, primarily by eliminating the use of lottery questions. These simplifications enabled us to shorten our interview with the decision maker to under two hours for a rather complex model.

The MAUT model gives National Air Intelligence Center (NAIC) analysts the ability to rank order satellite systems using the common measurement scale of "utiles." This tool allows a meaningful comparison of vastly different satellites.

Properly prioritized launch of space assets will be key to maintaining our capabilities in the long term. The ordering methodology of this model was extended to a multi-criterion optimization (MCO) problem to demonstrate its potential use in prioritizing and scheduling limited launch resources.

The results of these two case studies and the MCO application are combined to develop some characterizations of a theoretical group utility function. Most complex decisions are made by groups rather than by an individual. This research concludes with some insights on the impact of an individual's preferences on a decision that is ultimately made by the group.

A MULTI-ATTRIBUTE-UTILITY-THEORY MODEL THAT MINIMIZES INTERVIEW-DATA REQUIREMENTS: A CONSOLIDATION OF SPACE LAUNCH DECISIONS

I. Introduction

1.1 Theoretical Background

One of the limitations in applying multi-attribute utility theory to actual decision problems lies in the survey process. For a fairly large model the survey required to capture the decision maker's (DM) preference structure is exceptionally complex and contains questions and methodologies which are very difficult to understand. In particular, the use of the *lottery questions*, characteristic of MAUT, in the survey is quite cumbersome. Typically, binary lottery questions are posed as follows. The DM is given two outcomes, A and B, such that the probability that A occurs is p and the probability that B occurs is $1-p$. The DM is then asked to specify C such that he is indifferent between obtaining C with certainty and the outcome of the lottery. Lottery questions can be graphically represented as shown in Figure 1.1.

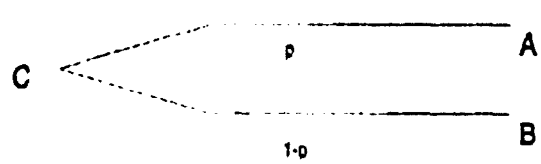

Figure 1.1 Lottery Question

Problems with this method quickly become apparent when working with a DM who is not familiar with MAUT. A great deal of time must be spent by the interviewer in an attempt to make the DM feel comfortable with the questions being asked. The interviewer must review the axioms of probability and thoroughly introduce the lottery concept to the DM. The survey takes a great deal of time to complete (sometimes days) and too often the DM never completely understands the questions he is answering. As a result, the DM loses confidence in the model that is being developed. A simpler method is needed to make the survey simpler and shorter.

1.2 Applications

Rather than confine our research to only theoretical interests, we chose to apply the theory we developed to a model that could be used as a real decision and analysis tool. We concentrated on developing a model for evaluating satellite systems. The model, using our improved multi-attribute utility theory, was used for two case studies. One focused on satellite analysis by intelligence experts, while the other addressed launch scheduling and prioritization of the Titan IV launch vehicle.

Analysts at the National Air Intelligence Center (NAIC) at Wright-Patterson AFB, OH, assemble data to assess the space capabilities of foreign nations. However, it is often difficult to compare systems which differ vastly, as there is no common measurement tool. Analysts would like to place a "value" on a satellite relative to other satellites, but have no means to a compare a communications satellite from one country, for example, with an early warning satellite from another. One solution was to build and use a MAUT model to assess the utilities of the satellites. The satellites could then be compared using the common utile scale of the muti-attribute utility function.

Prioritizing space launch continues to be a major concern in the current environment of limited resources. Space missions have conflicting requirements for building and replenishing satellite constellations. Launch schedulers face the dilemma of scheduling resources that cannot accommodate all of the space community's launch needs.

A useful tool in this process would be a MAUT model that can be used to assess the utilities of the proposed satellites to be launched. The model's results can then be used in a multi-criterion optimization (MCO) problem to maximize the total utility of the satellites launched using constrained launch resources.

1.3 Problem Statement

The problem was to build a MAUT model that could be used to assess the utility of a space system. The model needed to be flexible enough to be used in our two case studies.

In the first case study we used the model to determine utilities and rank order a set of foreign satellites and determined whether the model rankings match the informed opinions of the intelligence experts at NAIC.

In the second case study we used the model to determine the utilities of a set of satellites launched by the 5th Space Launch Squadron (5 SLS) at Cape Canaveral AFS. FL, using the Titan IV launch vehicle. The model's results were then used in a MCO problem to generate a theoretical selection of launches and a notional processing schedule.

In developing the survey instrument for the model, we integrated existing multi-attribute utility theories to simplify the survey. In particular, eliminating the use of lottery questions was our primary goal.

1.4 Problem Scope

Research and analysis was limited to the unclassified level. Due to potential classification concerns, the designations for many of the satellites whose utilities were assessed in the case studies was omitted. This does not represent any limitation to our research. We were not concerned with the actual satellites, only that the model's output accurately reflected the preferences of the DM in each case study The DM in each case study selected the satellites that were assessed.

1.5 Research Approach

This research used a phased, analyst-directed approach (6:63). We constructed a model of the decision maker's preferences based on his responses to a systematically administered survey. The results of the survey were then used to construct a multiattribute utility function.

Prior to developing a survey. a set of criteria was proposed that adequately describe what satellite attributes are considered in assessing its utility. An initial set was adopted and then modified through consultation with experts working with space systems. The survey itself was also used to verify that the criterion set was acceptable.

Satellite data was then added to the model to obtain a cardinal rank ordering of the satellites. The model rankings were then compared to the ranking predicted by the DM.

A linear programming model was developed to represent the Titan IV launch process. The MAUT model results were used with this model to formulate a MCO problem to optimize the total utility of the satellites selected for launch and to build a notional processing schedule.

II. Theoretical Background

In this chapter, we will outline some of the key multicriterion decision making concepts that are necessary to develop and test our model. We'll discuss the conditions that allow us to create a multicriteria utility function that adequately describes the decision maker's preferences.

2.1 Pareto Preference

Basic to multicriteria theory is the concept of Pareto preference. Simply stated, it is the idea that "the more of something there is, the better off we feel." This has an intuitive feel--we prefer more money. more clothes, more food, etc. When selecting criteria in an optimization problem, it seems natural to assume Pareto Preference for the criteria. However, this leads us into a trap.

2.1.1 Unbounded Problem. Consider the example given by Po-Lung Yu (35:184), where a person states that he is willing to work on Sunday, if he's paid more than $50 per hour. Clearly, the person is making a trade off between leisure time and money. It seems plausible that Pareto preference holds; that is, he prefers more money and more leisure time. Suppose we wish to formulate a value function, of the form:

$$V(\lambda) = \lambda_1 f_1 + \lambda_2 f_2 \tag{2-1}$$

where f_1 and f_2 are the value functions for money and leisure time, and the λs are weighting factors. Now we wish to find the optimal point (maximum) for this person. If Pareto preference holds, then this is an unbounded problem, as Yu points out. In fact, Yu warns that, in general, we can't use a value function to represent Pareto preferences (35:98).

2.1.2 Bounding the Criteria. This does not stop us from using the concept of Pareto preference in our model. The problem lies in the unboundedness of the optimization problem. Hence we concern ourselves with bounding the criteria. In other words, is there a point, $x_0 \sim v(x_0)$, such that if we increase x further, v(x) no longer increases? We look at two types of cases where this occurs.

Take the case where we measure a system's value by its level of mission accomplishment. As we increase the level of mission accomplishment, our value for the system increases--that is, more is better. Once we've reached 100% mission accomplishment, however, it is clear there is no added value in having further improvements. Our bound here is that it makes no sense to complete greater than 100% of the mission. Hence, the optimal point for this single criterion can be determined.

A natural bound occurs when there is a limit to how much of an attribute can possibly be attained. Technology limitations provide an obvious case. For example, more accuracy in weapons targeting is preferred to less. However, there is a limit to how accurate we can be, due to limits imposed by the hardware we use (misalignments, etc.) and the environment (atmospheric effects, etc.). Our optimal point in this case is at the accuracy limit, since we cannot possibly do better.

2.1.3 Tradeoffs and the Efficient Frontier. Now we can begin to put the value functions associated with each criterion together into a multicriterion value function. The methods for accomplishing this will be discussed later. Our optimal value is clearly the point where all of the criteria are maximized, if that is possible. But what if they cannot all be maximized at the same time due to a set of constraints? Here the decision maker begins making tradeoffs between the criteria in an effort to maximize his overall utility. We study the way these tradeoffs are made to begin determining what the decision maker's multicriterion value function looks like.

Even without a formally defined value function, the decision maker (DM) can establish a set of points which are non-dominated, called the *efficient frontier* (14:70) or *Pareto optimal points* (6:8). While the DM may not reach a single optimal solution, those which are clearly inferior can be eliminated. By determining upper bounds on our criteria, we can now employ mathematical methods to determine the point that maximizes the DM's utility.

2.2 Utility Function Construction

A great deal of the research in this thesis is devoted to deriving the multivariate utility function that can be used to assess the decision maker's valuation of a space system. There are a multitude of methods available to accomplish this. In particular, we'll look at three--multicriterion optimization (MCO), the interactive approach, and multi-attribute utility theory (MAUT). Each method has its own strengths and weaknesses.

2.2.1 Multicriterion Optimization. MCO problems typically begin with a set of criteria with the associated univariate value functions. We then attempt to optimize them simultaneously, subject to a set of constraints, using multicriterion linear or non-linear programming. This method yields the entire efficient frontier. When there are several criterion functions to be optimized, the process becomes computationally intensive, but several computer algorithms have been developed to handle this, including ADBASE (6:20). One weakness in this approach is that the concept of what is the optimum solution is not well defined when the multiple objectives are substantially different (8:173). This research first attempts to find a utility for each space system so that differing systems may be compared. MCO is inappropriate for this task.

However, once we have obtained a multi-variate utility function to evaluate satellites, we can use these results to solve a problem that optimizes total utility subject to constraints on available resources.

2.2.2 Interactive Approach. There is currently a great deal of interest in interactive methods to gain insight into the decision maker's preferences. This method is exceptionally useful when it is not possible to determine a complete preference function. The decision maker need only express "localized" preferences (6:23). The Franke-Wolfe algorithm works well in the single criterion case, and the Geoffrion, Dyer and Feinberg methodology extends this to the multicriterion situation (32:84).

There are, however, some disadvantages in this approach, particularly as it applies to this research. First, the interactive approach is generally limited to ordinal rankings (6:34). Second, the method is very much a "trial and error" procedure, and with several criteria, it can take a great deal of time to converge on an optimal solution. Worse yet, if the DM is not consistent with answers, convergence may not occur at all. Finally, these methods do not lay out a general utility function, but instead a series of localized preferences (points or neighborhoods). We wish to have a general form in which a new space system can be assessed without having to reconstruct the utility function.

2.2.3 Multiattribute Utility Theory. MAUT will be the approach used in this research. It allows us to express a definitive multiattribute utility function that can be used to compare vastly differing systems against a constant cardinal scale. Utility functions derived in this manner can take on many forms, but are commonly either additive or multiplicative. The axiom "the utility of an alternative is the sum of the utilities of each of the possible outcomes" (6:34) provides the basis for this approach.

Typically, univariate utility functions are constructed by asking the decision-maker a series of lottery questions and determining certainty equivalents. One method using lotteries is *bracketing*, whereby the interviewee is asked a series of questions designed to "close in" on the certainty equivalent (8:378). de Neufville suggests the use of an interactive computer program to avoid possible biases from the interviewer (8:379). Another method is the *fractile method*, where certainty equivalents are obtained across progressively smaller intervals. The *lottery equivalent probability (LEP) method* uses lottery equivalents instead of certainty equivalents. de Neufville cites some problems with the consistency of the fractile method, and suggests that LEP alleviates much of this (8:383).

The univariate utility functions are then aggregated into a multivariate function. Zeleny (36:419) lays out a five step process, shown in Figure 2.1, for calibrating this utility function.

1. Familiarize DM with the concepts and techniques of utility function measurement.
2. Verify independence conditions and identify appropriate utility decomposition form, $v(y)$.
3. Assess the component value functions $v_i(y_i)$.
4. Determine the parameters: k, w's
5. Validate the consistency of $v(y)$ against the DM's observed rankings

Figure 2.1 Utility Function Measurement Steps

The key advantage of this approach is that we can seek a utility function that fully represents the decision maker's preferences. Once the function has been calibrated, known univariate utility function values for a given system can be inserted and the overall utility of the system can be calculated. At this point, substantially different systems are compared using a single cardinal scale.

2.3 Independence of Attributes

The MAUT process will take a set of individual univariate utility functions and aggregate them into a single multivariate utility function. Chan points out that this is not a valid process if the attributes are not independent (6:38). There are three types of independence we will be concerned with in this research, *preferential*, *utility*, and *additive* independence.

2.3.1 Preferential Independence. Preferential independence is concerned with ordinal preferences. Zeleny (36 420) states that a pair of attributes, X and Y, are preferentially independent of a third, Z, if the value-trade off between X and Y is not dependent on the level of Z. Preferential independence commonly holds for most decision problems, or is at least well approximated (7.478).

2.3.2 Utility Independence. Utility independence addresses itself with cardinal preferences. A cardinal utility function is necessary to apply it's results to a multi-criterion optimization problem. When revealed lottery preferences of an attribute, X, do not depend on the given level of another attribute, Y, then we say that X is utility independent of Y (36:421). In general, X being utility independent of Y does not necessarily imply the reverse. When the reverse does hold true, then X and Y are said to be *mutually utility independent*. Zeleny notes that utility independence implies preferential independence (36:421), and is a necessary condition of a multiplicative utility function.

2.3.3 Additive Independence. Additive independence also addresses cardinal preferences. It is the strongest of the three forms. In this case, revealed lottery preferences over attribute X, do not depend on changes in lotteries for attribute Y (7:482). Thus, when comparing uncertain outcomes over multiple attributes, the problem can be evaluated one attribute at a time. Additive independence is necessary for an additive utility function to be cardinal. Parnell cites previous research which concludes that additive independence rarely holds in real situations (25:Ch 16; 5). We will show later that additive independence clearly does not hold for the model we propose.

2.4 The Survey Process

As discussed before, MAUT relies heavily on an extensive survey conducted with the DM. The complexity and length of the survey is therefore the subject of common criticism of this methodology. In this research, we pay close attention to the survey process and attempt to simplify it as much as possible.

2.4.1 Constructing Univariate Utility Curves. The use of fractile or bracketing methods to determine the shape of the univariate utility functions is cumbersome and difficult for the DM to understand. Kirkwood offers a simplifying assumption that alleviates this problem (15:44). He cites extensive empirical research which concludes that univariate utility functions are well approximated using an exponential form. Hence, the DM needs only to indicate one point (for example, where utility equals 0.5) from which the constant to the exponential function, called the Risk Attitude Constant, is derived. The univariate utility curve is then fully defined for the entire range of the attribute.

2.4.2 Verifying Independence Properties. When there is a large number of criteria, verifying the independence of attributes is completely impractical.

Let's examine the case of a decision problem with five attributes. To show preferential independence, preferences shown over a pair attributes are compared with a third attribute at a fixed value, and then the comparisons are repeated as the level of the third attribute is varied across it's range. With five attributes, this requires 30 sets of comparisons! To verify mutual utility independence, 20 more pairwise comparisons must be made. Clearly, the survey quickly becomes too burdensome for a decision maker to complete in a reasonable amount of time.

Keeney and Raiffa come to our rescue. They state and prove as a theorem the following (14:292):

> Given attributes X_1, X_2,...,X_n, the following are equivalent: 1) Attributes X_1, X_2,...,X_n are mutually utility independent, and 2) X_1 is utility independent and $\{X_1, X_i\}$ is preferentially independent for i = 1, 2, 3, ..., n and $n \geq 3$.

This immediately eliminates 15 pairwise comparisons from the survey. In addition, if we carefully define our criteria, we can reasonably make the assumption of preferential independence, thereby eliminating 30 more sets of comparisons. Now a forbidding portion of the survey has been reduced to a manageable size.

2.4.3 Assigning Criterion Weights. Traditionally in MAUT criterion weights are determined using lottery questions As stated before, this methodology is often confusing to the decision maker. Simplification is necessary to achieve consistent responses. Seo and Sakawa suggest a method to break this process down into smaller, more manageable steps (29:199).

First, we ask the decision maker to rank the attributes in descending order of importance, which is normally a fairly easy task. Next, we assess relative weights. Using one attribute (a good choice is the attribute ranked highest) as the base, we can examine tradeoffs between the base attribute and the other attributes. We ask the question, "How much of the base attribute can be given up to gain and additional unit of another attribute?" In this manner, we collect information on the preference intensities between the attributes. Consistency can be checked by using a different attribute as the base and reasking the same questions.

Finally, the weight of our base attribute must be determined. Here we substitute the swing weight method proposed by Clemen (7:448) for the traditional lottery question. In this method, we start with all attributes at their worst level (the worst possible alternative) assigning this hypothetical alternative a utility of 0. Next, we "swing" the base attribute to its best possible level, and ask the decision maker to assign a utility that describes his/her assessment of such an alternative. The utility thus assigned can be mathematically shown to be the weight of the base attribute.

Together with the relative weights already determined, we now can derive all of the attribute weights. The key benefit of this methodology is that we have completely eliminated the use of lottery questions.

2.4.4 Ratio Versus Interval Scales. Using the combination of ratio scale comparison of criteria and interval scale scoring of alternatives is not without precedent. Seo and Sakawa specify this combination in their approach to measuring utility functions (29:199). Marvin and Hutchinson of the Analytic Sciences Corporation also reported success in using this methodology (20:8).

There has been considerable debate as to whether this combination is appropriate (20:1). The method proposed in this research takes advantage of both scales to measure the criterion weights, as suggested by Seo & Sakawa. A ratio scale measurement requires a explicit (or at least implicit) zero point. The swing method specifies the zero point as the case when the multivariate utility does not increase when the criterion is varied from its low value to its high value. That is, the criterion weight is zero. Therefore, it is valid to express one criterion weight as a ratio to another criterion weight. Once all weights are expressed as ratios to each other, the swing weight experiment only needs to be performed once to place the weights on an interval scale. The advantage gained is that ratio comparisons are easier to obtain from the DM than swing weights.

2.5 The Decision Makers

Once we have examined the underlying theory required to make our model plausible, we need to turn our attention to the decision maker. Since every individual has a unique system of preferences, whom we select to conduct our interviews with is very important More importantly, most major decisions are made by a group of decision makers, rather than by an individual. MAUT provides the framework for deriving an individual's utility function, but not a group's.

2.5.1 Modeling Group Decisions Using Group Utility Functions. One approach is to attempt to aggregate the individual utility functions into a group utility function (GUF). However, what should be the form of the aggregated function? de Neufville indicates that finding an appropriate form to represent the GUF is problematic and usually does not yield satisfactory results (8:431). Seo and Sakawa show that under certain conditions an additive form of a GUF, combining individual DM preferences, may be appropriate via their "Representation Theorem for a GUF" (29:236) They suggest two methods to determine the weighting factors for each DM, the "benevolent dictator" approach and the "collective response" approach. In the former, the weights are specified by a knowledgeable individual. This approach is trivial in its application but often unsatisfactory in its results (29:237). The latter approach requires an extensive "interpersonal comparison of preferences" including an "interpersonal comparison of preference differences" (29:239). This process is too complex for the purpose of this research, but would make an interesting follow-on study.

2.5.2 Modeling Group Decisions Using An Individual's Utility Function. Another approach is to model the group's choices as that of an individual. This eliminates the problem of determining the functional form since we use the MAUT process. Nobel prize winner Kenneth Arrow noted problems with this approach, however. We are given the example of "Arrow's Paradox" (8:433) where a series of expressed preferences by a group proved to be intransitive. This intransitivity is unacceptable for a utility function.

Keeney and Raiffa (14:8) again offer some help in this area. In deciding whether to use an individual as the DM or a group, we need to step back and examine the purpose of our research. Are we trying to *describe* the decision process, or *prescribe* what decision should be made? Keeney and Raiffa propose that a unitary decision maker is appropriate for the prescriptive approach--our model is to indicate what solution the decision maker should propose. In this research we are attempting to define a measurement tool for space systems which can then be used to make the best decision possible, according to a decision maker's preference structure. We can incorporate into the model the DM's perceived notions about what others might do (i.e. the political environment), as part of the uncertainties he faces. Hence, we will build our model using a unitary decision maker.

2.5.3 Characterizing A Group Utility Function. As mentioned earlier, once utilities have been calculated for a set of satellites, we can use the information to formulate a multi-criterion optimization problem. Using vector sensitivity analysis, we can define some limits for weighting factors that will affect the optimum decision. Richard Wendell outlines a "tolerance" approach that determines how much each objective function coefficient (in this case, satellite utilities) can simultaneously and independently vary. The tolerance, τ, is determined from the formula (34:567):

$$\tau = \underset{k \in K}{Min} \left\{ \frac{\hat{c}_B \cdot B^{-1} \cdot A_{\cdot k} - \hat{c}_k}{\left| c'_k - \sum_{i=1}^{m} \left| c'_{h_i} \cdot B^{-1}_{i\cdot} \cdot A_{\cdot k} \right| \right|} \right\} \qquad (2\text{-}2)$$

The numerator in Equation (2-2) is the "reduced cost" of the kth non-basic variable, where K is the set of non-basic variables. The formula is derived from the classic linear program, which is "perturbed" by $\gamma \cdot c'_j$, as shown in Equation (2-3). When c'_j is set equal to $\hat{c}_j$, γ represents a percentage variation from each original coefficient.

$$\text{Max} \quad \sum_{j=1}^{n} (\hat{c}_j + \gamma_j \cdot c_j') \cdot x_j$$

$$\text{Subject To} \quad \sum_{j=1}^{n} A_{ij} \cdot x_j \qquad (2\text{-}3)$$

$$\text{for } i = 1,\ldots m$$

In Equation (2-3) τ is a conservative estimate of the coefficient variation that can occur while still maintaining the original optimal basis. In Chapter 4 we will characterize the effects of aggregating an individual utility function with another into a GUF. We will analytically determine how the resulting variance of the original objective function coefficients from their original values affects the optimal solution for prioritizing satellite launch resources.

III. Model Formulation

This chapter discusses the formulation of the multicriterion utility function that was derived as a result of this research. Once the utility function is calibrated, it can be used to assess the value of any space system of interest.

3.1 Criteria

Four criteria, which are in turn decomposed into sub-criteria, were chosen such that, as a set, are necessary and sufficient to describe the decision maker's entire process of considering the utility of a space system. This two-tier hierarchy is shown in Figure 3.1.

Each sub-criterion is scaled from 0 to 1, with 0 the low extreme, and 1 the high extreme. The scale is benchmarked at equal intervals (for convenience) with word descriptions. When assessing a satellite, the ratings may fall on these benchmarks or anywhere in between. Foreign satellites are evaluated from the "owner's point of view."

The model is organized into a two tier hierarchy. Seo and Sakawa refer to this method as "nesting of preferences" (29:206). In the lowest tier, similar criteria are grouped together. Each group has only three or four criteria, and are referred to as sub-criteria in this model. At this level pairwise comparisons are done only between sub-criteria within the same group This eliminates the need for awkward comparisons of greatly dissimilar sub-criteria. A multivariate utility function is formulated for each group of sub-criteria, and are called the criterion functions in this model. Pairwise comparisons are then conducted for the second tier of criteria, just as they were for the sub-criteria. Seo and Sakawa show that MAUT techniques are equally applicable to a tiered model (29:207). The overall utility function is then formulated. The nesting approach is advantageous as it allows us to work with a model that has thirteen criteria without

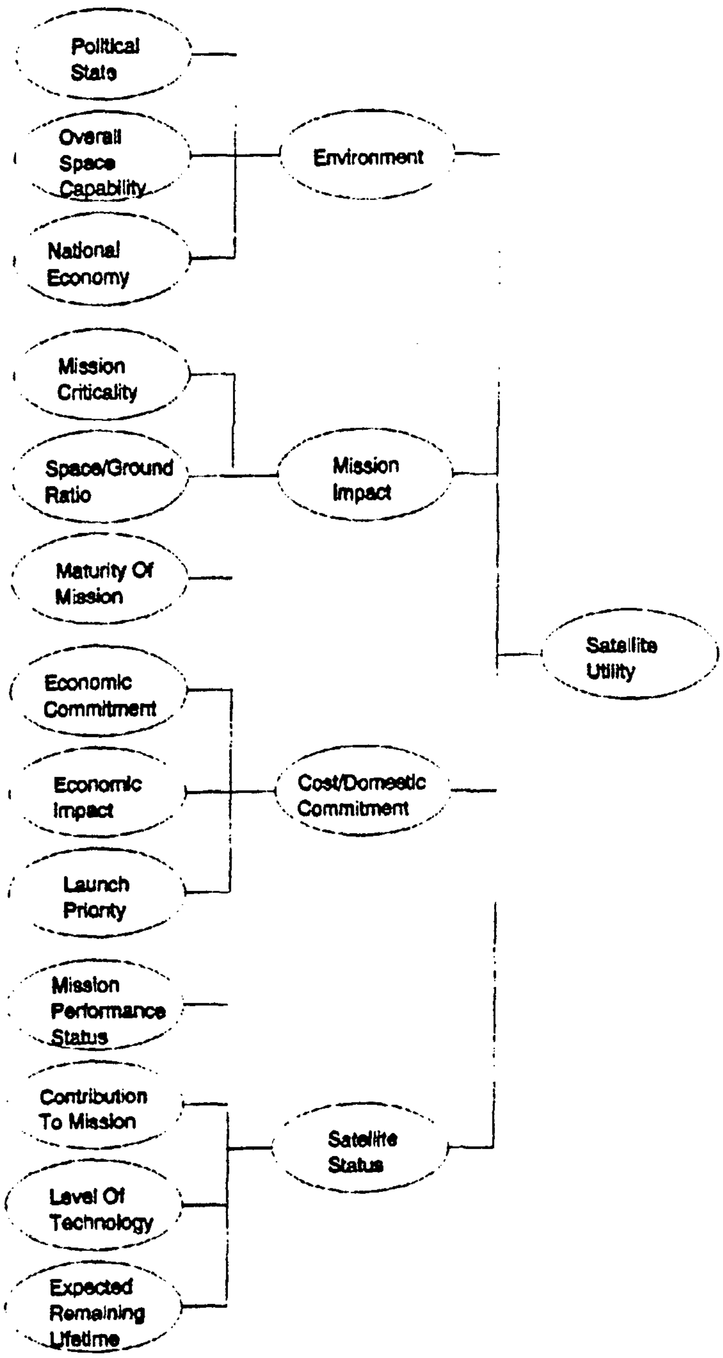

Figure 3.1 Model Criteria

becoming overburdened with the pairwise comparisons. Without the hierarchical organization, the model would have required comparisons of 78 paired sets of criteria. Our model reduces this to 21 paired sets.

3.1.1 Criterion 1: Environment. This criterion defines the value associated with the time dependent "state of the world." To provide consistent value ratings for the satellites, a "snapshot" is taken and scored. This criterion, since it can be thought of as time dependent, allows a time series of satellite utility to be shown, since multiple "snapshots" can be taken over a period of time. In addition, this criterion allows some "what ifing" to be done. Note that the scores in this criterion will be identical for all satellites owned by a single country.

3.1.1.1 Sub-Criterion 1-1: Political State. This sub-criterion describes the current international political environment.

Table 3.1 Political States

Level	Level Title	Description
0.00	Peaceful Stability	International relations are stable and the world is absent of any significant military/political crises. Obviously, this state is rare.
0.25	Minor Crises/Degraded Stability	One or more minor local/regional crises are in progress that do not immediately threaten national security. Relations with allies or adversaries may be degraded, but negotiations are continuing. *For most countries, this is the most common state during the 20th century.*
0.50	Major Crisis	One or more regional crises are in progress that potentially threaten national security. Relations with allies or adversaries are substantially degraded, and negotiations are seemingly at an impasse. This would describe the political landscape throughout most of the 1930's.
0.75	Limited War	Tensions between nations are high. Regional conflict has broken out that threatens national security. General War threatens. The Korean and Vietnam Wars are examples.
1.00	General War	National forces are fully mobilized and committed to intense combat. World War II exemplifies this state.

3.1.1.2 Sub-Criterion 1-2: Overall Space Capability. This sub-criterion examines the overall space capability of the nation. The Pareto assumption here is that the more overall space-capable a nation is, the more individual space assets are relied upon.

Table 3.2 Space Capabilities

Level	Level Title	Description
0.00	Primitive	Nation has virtually no space assets whatsoever. In addition, it has little or no ability to interfere with other nation's deployed assets.
0.25	Minor Space Power	Possesses limited space assets, deployed primarily in support roles. Some interference/jamming capability is likely.
0.50	Medium Space Power	Assets are deployed in support and force enhancement roles. Demonstrated capability to interfere/jam enemy satellite systems.
0.75	Major Space Power	Assets are deployed across nearly the full range of mission areas and are integrated somewhat with terrestrial forces. Likely offensive anti-satellite capability.
1.00	Space Superpower	Fully deployed and integrated systems across the full range of missions. Demonstrated offensive/defensive anti-satellite capability.

3.1.1.3 Sub-Criterion 1-3: National Economy. This sub-criterion describes the state of the nation's economy. This sub-criterion may at first appear to be scaled in reverse. However, we are considering a satellite's value in terms of the economic conditions, where the value placed on the asset increases as economic conditions worsen.

Table 3.3 National Economies

Level	Level Title	Description
0.00	Boom	Characterized by rapid economic growth and vigorous international trade.
0.25	Growth	Overall, economy is healthy and expanding. Trade barriers are minimal.
0.50	Stable	The most common economic state. Trade relations and currency exchanges are stable. Trade barriers may be present, but do not seriously hamper trade relations.
0.75	Recession	Economy is shrinking. Currency exchanges may be unstable. Trade relations are constrained and protectionism is prevalent.
1.00	Depression	Economy is in collapse. International trade is minimal, with trade barriers dominating.

3.1.2 Criterion 2: Mission Impact. This criterion attempts to determine the value of a satellite's mission(s) relative to the mission(s) of other satellites. As such, the rating given may reflect an entire class of satellites, for example, those used for early warning.

3.1.2.1 Sub-Criterion 2-1: Mission Criticality. This sub-criterion rates the relative importance of satellite missions, such as early warning, communications, weather, etc. For example, General Charles A. Horner, former Commander-In-Chief of Air Force Space Command, considered Early Warning to be the most critical space mission, communications the second most critical, with remaining space missions less important relative to these two (11).

Table 3.4 Mission Criticalities

Level	Level Title	Description
0.00	Trivial/Scientific	Mission is primarily scientific in nature, and has virtually no impact to the warfighter. This does not mean the satellite is useless, but that it has no direct or current application to military offensive/defensive capabilities.
0.25	Minor Component	While not contributing directly to warfighting capabilities, the satellite aids forces that do.
0.50	Medium Component	Satellite plays a collateral role and increases the effectiveness of other forces.
0.75	Major Component	Satellite mission plays a significant role in force offensive/defensive strategy.
1.00	Critical	Mission constitutes a critical capability, without which it would be difficult or nearly impossible to conduct wartime operations.

3.1.2.2 Sub-Criterion 2-2: Space/Ground Ratio. Here the relative amount of the mission accomplished by space-based assets versus terrestrial-based assets is examined.

Table 3.5 Space/Ground Ratios

Level	Level Title	Description
0.00	100% Ground	Terrestrial assets perform the entire operational mission.
0.25	Primarily Ground	Space assets are sometimes used for the operational mission, however, ground counterparts dominate. Space systems tend to be seen as experimental, and serve primarily in backup roles.
0.50	50/50 Mix	Space and ground assets are equally relied upon to perform an assigned mission.
0.75	Primarily Space	Space assets dominate mission accomplishment. Ground assets are secondary or used as a backup.
1.00	100% Space	The entire operational mission is performed by space assets. Ground backup is not available or is unreliable.

3.1.2.3 Sub-Criterion 2-3: Maturity of Mission. How well the satellite's mission is understood by warfighters and integrated into overall capabilities is considered in this sub-criterion.

Table 3.6 Mission Maturities

Level	Level Title	Description
0.00	Unknown/Unused	Satellite's capabilities are not understood or utilized by strategic and tactical commanders. Satellite remains largely an R&D project.
0.25	Little Known	Satellite capability is partially understood and used. but only on a basic level. R&D community possesses the expertise to operate the satellite.
0.50	Somewhat Integrated	Operational Turnover of the satellite has occurred from the R&D community to the operational unit. Capabilities are still being explored. Information concerning the satellite is reaching field commanders and experimental/tentative use has begun.
0.75	Widely Known/Substantially Integrated	Operation of the satellite is "normalized." Field commanders understand capabilities and routinely use them. Some integration problems still exist. and alternate assets are maintained and frequently relied upon.
1.00	Fully Integrated	Satellite is fully understood and exploited. and capabilities are fully integrated into theater operations.

3.1.3 Criterion 3: Cost/Domestic Commitment. The value placed on a satellite is demonstrated by the level of commitment a nation makes to supporting the continuation of its mission.

3.1.3.1 Sub-Criterion 3-1: Economic Commitment. The funding status of the satellite's production, operations, maintenance and related infrastructure is evaluated here.

Table 3.7 Economic Commitments

Level	Level Title	Description
0.00	Near Cancellation	Commitment to satellite (program) is minimal or near termination. Natural reasons for this to occur is that it is near the end of the satellite (program) life cycle, or upon the advent of a new technology that renders the satellite obsolete. Political considerations may also cause termination.
0.25	Drawdown	Support is in decline. This may be due to political/economic considerations, or it may be late in the satellite's (program's) life cycle.
0.50	Stable	Funding is stable. Typical of a satellite (program) near the midpoint of its life cycle.
0.75	Growth	Funding is growing steadily. Typical of a young satellite (program), when political support is growing and infrastructure is still being added.
1.00	Explosive Growth	Political support and funding for the satellite is rapidly expanding. Political support is consolidating.

3.1.3.2 Sub-Criterion 3-2: Economic Impact. While the previous sub-criterion looks at the growth rate, this sub-criterion examines the current size and impact due to the commitment to the satellite.

Table 3.8 Economic Impacts

Level	Level Title	Description
0.00	"Mom & Pop" Program	Very small organization that impacts only a small local economy. Production facilities might consist of a single small plant.
0.25	Minor Program	Dominates only a local economy. Production facilities might consist of a few small plants or a single large one.
0.50	Regional Program	Program infrastructure is significant to a regional economy. Program is large enough to receive some national legislative scrutiny.
0.75	Major Program	Program infrastructure is significant to national economy and receives substantial public and legislative attention.
1.00	Intense Program	Substantial sacrifices are made at the national level to continue funding of the satellite's infrastructure. Single-minded economic priority is given to the satellite.

3.1.3.3 **Sub-Criterion 3-3: Launch Priority.** Launch priority given to a satellite is an excellent indicator of the value placed on that asset. This sub-criterion also includes the "sparing" strategy, as the presence of spare satellites on the ground or on-orbit affects the priority given to a new launch.

Table 3.9 Launch Priorities

Level	Level Title	Description
0.00	No Near Term Launch/No Spares	No capability exists to replace the satellite in the near term. Replacement satellites have not been constructed and/or no launch vehicles are available.
0.25	Delayed Schedule/Limited Sparing	Replacement satellites have been partially constructed, but are not available for near term launch. A launch schedule does not exist, is incomplete, or delayed.
0.50	Stable Launch Schedule/Substantial Sparing	Launch of replacement satellites can be accomplished on a schedule. However, the schedule is somewhat inflexible. Spares are available, but most are on the ground, and those in orbit are not positioned for immediate use.
0.75	Accelerated Schedule/Near Complete Sparing	Launch of replacement satellites can be accomplished on an accelerated schedule. Several spares are constructed, with most placed in orbit to be positioned in the short term.
1.00	Launch On Need/Comprehensive Sparing	Launch possible on short notice. Comprehensive sparing strategy is in place. On-orbit spares can be made operational quickly

3.1.4 Criterion 4: Satellite Status.

This criterion takes into account the individual characteristics of the satellite.

3.1.4.1 **Sub-Criterion 4-1: Mission Performance Status.** How well the satellite is performing its assigned mission is directly applicable to the value that is placed on it.

Table 3.10 Mission Performance Status

Level	Level Title	Description
0.00	Non-Operational	Satellite is degraded to the extent that it cannot be considered operational.
0.25	Severely Degraded/Turned Off Spare	Satellite is capable of performing its mission only to a marginal extent. Satellite may be configured as a spare, with secondary power turned off until needed.
0.50	Significantly Degraded	Satellite satisfactorily performs its mission, but at a substantially degraded level.
0.75	Slightly Degraded	Satellite performs its mission as expected, but some minor degradation is present.
1.00	No Degradation	Satellite is fully capable of performing its mission--no failed or degraded units.

3.1.4.2 Sub-Criterion 4-2: Contribution To Mission. Rarely does a single satellite accomplish an entire space mission. Typically, satellites are grouped into constellation to complete an assigned mission. Here the satellite's contribution to completing the mission is measured.

Table 3.11 Mission Contributions

Level	Level Title	Description
0.00	Spare/No Direct Impact To Mission	Loss of the satellite will not adversely impact the capability to accomplish a mission. A typical case would be a satellite configured as a spare.
0.25	Secondary Impact To Mission	Loss of satellite would impact mission accomplishment at a secondary level only. The mission completed by this satellite can be readily transferred to another satellite.
0.50	Impacts Mission	Loss of the satellite would adversely impact mission accomplishment. Much of the satellite's duties can be transferred, but noticeable degradation will occur.
0.75	Strongly Impacts Mission	Loss of satellite significantly impacts mission accomplishment. Satellite mission duties are largely irreplaceable, hence substantial degradation occurs.
1.00	Critical To Mission	Loss of satellite critically impairs mission accomplishment.

3.1.4.3 **Sub-Criterion 4-3: Level of Technology.** In general, more modern satellites that employ improved technologies have greater capabilities. In particular, satellites that employ newer technologies represent a significant investment in research and development. While high tech has no value by itself, the investment in technology to achieve a capability, is a direct indicator of the value placed on that capability.

Table 3.12 Technology Levels

Level	Level Title	Description
0.00	Primitive	Space technology is at the most rudimentary level. A satellite such as this hearkens back to the days of Sputnik.
0.25	30 Year Old State of the Art	This represents technology developed and employed by advanced nations in the 1960's.
0.50	20 Year Old State of the Art	This represents technology developed and employed by advanced nations in the 1970's.
0.75	10 Year Old State of the Art	This represents technology developed and employed by advanced nations in the 1980's.
1.00	State of the Art	Represents the current best possible fielded space technology

3.1.4.4 **Sub-Criterion 4-4: Expected Remaining Lifetime.** It would seem obvious that the value placed on a satellite depends on an estimation of how long the satellite will remain operational. This is to be distinguished from a satellite's planned life cycle, which is a fixed timespan estimated by satellite designers. The expected remaining lifetime is a changing estimate, affected by the spacecraft's age, fuel reserves, and known satellite subsystem failures.

Table 3.13 Expected Remaining Lifetimes

Level	Level Title	Description
0.00	0 Years	Complete failure is expected at any time.
0.20	3 Years	self-explanatory
0.40	6 Years	"
0.60	9 Years	"
0.80	12 Years	"
1.00	More Than 15 Years	"

3.2 The Survey Instrument

Conduct of the survey with the decision maker is perhaps the most critical portion of this research. The survey was designed with four goals in mind: clarity, simplicity, brevity, and consistency. The survey is written using Microsoft Excel Version 5.0 software. All mathematical calculations are performed in a separate section that is transparent to the DM. Completed surveys for the two case studies conducted in this research are included as Appendix A and Appendix B.

3.2.1 Survey Preparation. The survey is designed to be used in a face-to-face interview. The analyst provides initial background information, guides the decision maker through questions, and records responses. As de Neufville points out, an experienced analyst is important to this process (8:376). The analyst should conduct a few practice sessions with trial decision makers before conducting the survey with the actual DM.

The DM must be gradually introduced to the concepts of utility theory. Clemens very neatly lays out a set of "axioms of expected utility" that is useful in accomplishing this (7:405-406). Further, the DM must be reminded that there are no "right or wrong" answers. Remember, the goal of the survey is to capture the DM's preference structure.

The survey is divided into five sections to assist the DM in understanding the survey flow. Each section has a specific purpose which should be explained to the DM before proceeding. Survey questions are worded to be as clear as possible. In particular, we make use of theory developed in Chapter 2 to eliminate difficult lottery questions.

The survey is designed to take no more than two hours to complete. An exhausted DM is unlikely to give reliable or consistent responses. The role of the analyst is key to success in this area, as shown by decreasing survey completion times in this research as the analyst became more experienced. The first test survey (the results of which are not included in this final report) took more than four hours, and yielded some very contradictory results. The first case study, in contrast, took 2 1/4 hours to complete, while the second case study survey was done in less than 1 1/2 hours.

Finally, consistency is achieved by using a written survey. As Clemens astutely points out, how questions are posed can greatly influence the answers given. By using a written survey, we are assured that the DM for both case studies are given identical survey instruments.

3.2.2 Survey Section I: Mapping the Sub-Criterion Utility Functions.

The DM is given some information and answers a question concerning each sub-criterion. First, the sub-criterion is defined. Each sub-criterion is scaled from zero to one, and discrete levels of the sub-criterion between these points are defined. Next, the DM is told that the lowest level of the attribute is assigned a minimum utility of 0, while the highest level of the attribute is assigned a maximum utility of 1. That is:

$$\begin{aligned} Utility(0) &= 0 \\ Utility(1) &= 1 \end{aligned} \tag{3-1}$$

The DM is then asked to define an attribute level such that he/she feels has a utility of 0.5.

$$Utility(?) = 0.5 \qquad (3\text{-}2)$$

These three points allow the univariate utility function to be drawn, using the method proposed by Kirkwood and discussed in section 2.5.1.

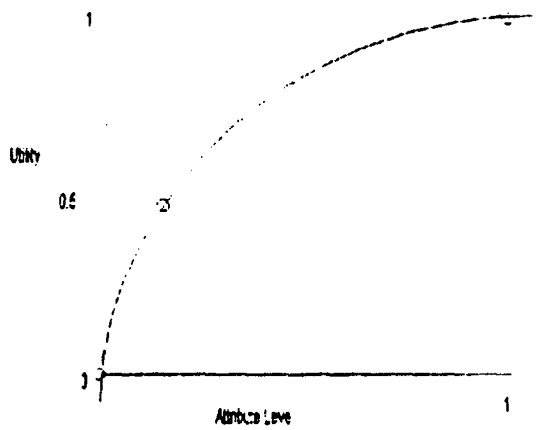

Figure 3.2 Univariate Utility Curve

The mathematical representation of this univariate utility function takes the form:

$$Utility(X) = \frac{1 - \exp\{RAC \times X\}}{1 - \exp\{RAC\}} \qquad (3\text{-}3)$$

where $X \in [0,1]$ and the risk attitude constant, RAC, $(RAC \neq 0)$ is determined from the 0.5 utility point specified by the decision maker. The RAC is determined using a "0.5 Utility Point versus RAC" lookup table that was created using Kirkwood's Decision Analysis software (16).

If the DM indicates that the utility midpoint (0.5) occurs at the attribute midpoint (0.5), then the univariate utility function is linear, and the RAC = 0. In this case, the mathematical representation of the utility function is simply.

$$Utility(X) = X \tag{3-4}$$

3.2.3 Survey Section II: Independence Verification. Preferential Independence is assumed for this model for two reasons. First, as Keeney points out, Preferential Independence is a reasonable assumption for most multi-attribute decision models and cases where it does not hold are fairly rare (13:140). Second, as the criteria were being defined, careful attention was paid to the requirement of preferential independence to avoid any violation of this condition.

A single sub-criterion is then chosen as a basis for comparison. We ask a series of questions to determine whether this sub-criterion is utility independent of each of the other twelve sub-criteria. The DM is asked whether the utility midpoint chosen in section I of the survey for the base sub-criterion is affected by changing the level of any of the other sub-criteria. If it is not, then the base sub-criterion is utility independent of the other sub-criterion. Here we make full use of Keeney's weaker conditions for utility independence described in section 2.5.2. Hence, mutual utility independence is verified.

3.2.4 Survey Section III: Multivariate Criterion Utility Functions. In this section the sub-criteria are grouped into their respective criteria. The DM is asked to rank, in descending order of importance, the sub-criterion in each group. Once the sub-criteria are rank ordered, the DM is asked to indicate their relative importance.

3.2.5 Survey Section IV: Multivariate Criterion Utility Functions, Part 2. This is perhaps the most difficult section of the survey. The sub-criteria are again grouped into their respective criteria. Then for each group, the following definitions are given:

$$\begin{aligned} Utility(x_1^{min}, x_2^{min}, \ldots, x_n^{min}) &= 0 \\ Utility(x_1^{max}, x_2^{max} \ldots, x_n^{max}) &= 1 \end{aligned} \tag{3-5}$$

Given these definitions, the DM is now asked to assign a utility value to a satellite where the highest ranked sub-criterion is set at its maximum level while the other sub-criteria are set at their respective minimum levels.

$$Utility(x_1^{max}, x_2^{min}, \ldots x_n^{min}) = ? \tag{3-6}$$

Seo and Sakawa prove that the utility value given by the DM for this type of formulation is the weighting factor of the maximized sub-criterion, x_i (29:200). The process is repeated for each group of sub-criteria.

3.2.6 Survey Sections V and VI: Creating the Overall Utility Function. In section V, just as in section III, the DM now ranks the criteria in descending order, then assesses their relative weights. Section VI parallels section IV. This section has proven to be a little bit tricky. Maximizing a criterion takes place when all of its respective sub-criteria are maximized. Similarly, a criterion is minimized when all its sub-criteria are minimized. Hence, the DM is attempting to assign a utility to a situation where thirteen sub-criteria are set a fixed values. Despite the difficulty, this method is still infinitely superior to lottery selections, as it is still much easier to work with than with lottery questions. The analyst's guidance in this section, along with the experience gained by the DM in section IV, made this task manageable.

3.3 Utility Function Calibration

Once the survey has been completed, the Excel software (21) is programmed to automatically determine weighting factors and calibration constants. The analyst does not need to perform any mathematical calculations, but simply presses {F9} to have the Excel program begin the calculations, which take about 30 seconds to complete.

3.3.1 Functional Form of the Multivariate Utility Function. The reason for establishing preferential and utility independence in Section II of the survey is that they are necessary conditions for a multiplicative utility function of the form (8:408):

$$U(X) = \frac{\prod(k \cdot w_i \cdot U(X_i) + 1) - 1}{k} \tag{3-7}$$

where the $U(X_i)$'s are the univariate utility functions, the w_i's are the calibrated weighting factors, and k is the normalizing parameter that allows multivariate utility function to also be scaled from 0 (worst) to 1 (best). The same functional form holds for both the criterion utility functions and the overall utility function.

3.3.2 Weighting Factors. Sub-criterion weights are derived from questions in sections III and IV of the survey, and the criterion weights are calculated using information in sections V and VI. A sub-criterion's (criterion's) weighting factor is found by multiplying the weighting factor assigned to the highest-ranked sub-criterion (criterion) by the sub-criterion's (criterion's) relative weight.

Clemens offers some discussion on an interesting implication of these weighting factors. When the weights of a set of criteria are summed, if they add to less than one, the criteria are said to be *substitutes* for each other. Conversely, if the sum is greater than one, they are *complements* of each other (7:484). This insight, provided to the DM during the survey process, can greatly assist the DM's thought process when assigning weights.

3.3.3 Calibration Constant Calculation.

Once the weights have been determined, the calibration constant k can be calculated. We begin with the multiplicative form in Equation (3-7). We then set all of the criteria to their maximum values, making each $U(X_i) = 1$. This simplifies the equation to:

$$1 = \frac{\prod (k \cdot w_i + 1) - 1}{k} \tag{3-8}$$

Equation (3-8) is expanded and the constant is moved to the right-hand side. For the four criteria case we now have:

$$\begin{aligned} 0 = w_1 + w_2 + w_3 + w_4 + k(w_1 w_2 + w_1 w_3 + w_1 w_4 + w_2 w_3 + w_2 w_4 + w_3 w_4) + \\ k^2(w_1 w_2 w_3 + w_1 w_2 w_4 + w_1 w_3 w_4 + w_2 w_3 w_4) - k^3 w_1 w_2 w_3 w_4 - 1 \end{aligned} \tag{3-9}$$

We can solve for k by finding the root of this equation. The Excel spreadsheet is programmed to iterate to find this root. We now have a fully calibrated multivariate utility function. The process is repeated for each criterion and finally for the overall function.

3.3.4 Calculating Satellite Utilities.

After the utility function has been created, satellites can be scored in each of the thirteen sub-criteria. The Excel spreadsheet uses this data to first calculate the univariate utilities. The univariate utilities are then used to calculate the criterion utilities, which are in turn used to calculate the final utility.

3.4 Titan Launch Optimization Model

Once satellite utilities are calculated, we can use them to optimize the use of limited launch resources. First we will need to develop a mathematical model to represent the launch process.

3.4.1 Launch Processing Flow. The Titan IV launch process is shown in Figure 3.3 (31). The processing flow is complex, including separate flows for the core vehicle, Inertial Upper Stage (IUS) or Centaur Upper Stage, and the solid rocket motors. However, our model size is limited by the available PC software (26:10-2), hence for this

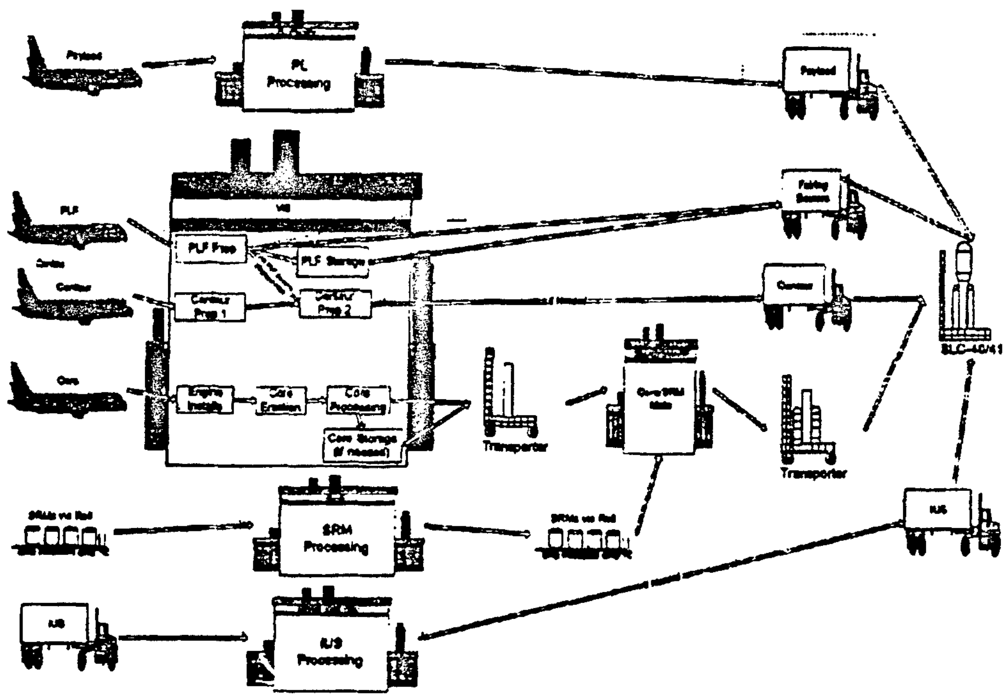

Figure 3.3 Titan IV East Coast Top Level Processing Flow

research we must simplify the process so that a linear program model can be constructed. We chose to use the core vehicle flow for the simplified model for several reasons. First, as Figure 3.4 shows, vehicle processing problems cause the majority of time delays (3:atch 7). Second, the Centaur and IUS flows are "optional" in that these upper stages are not used for every launch. Finally, core processing takes the longest to complete, and all other components are eventually integrated into it. Core processing appears then to be the critical flow, and a reasonable portion to represent the overall flow.

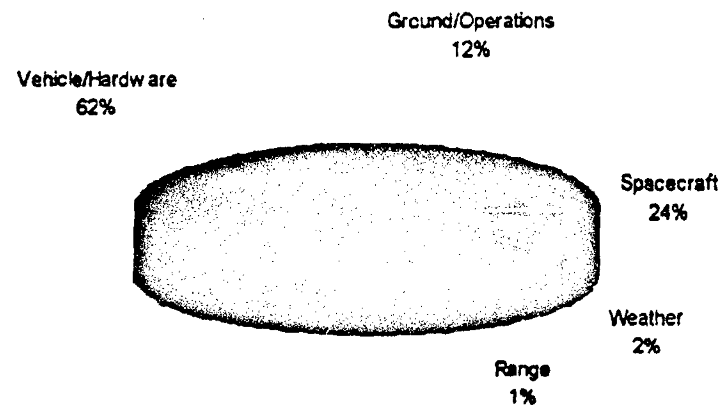

Figure 3.4 Duration of Delays: Titan 1982 - Present

Our model traces the flow through three points, the Vertical Integration Building (VIB), the Solid Motor Assembly Building (SMAB)/Solid Motor Assembly and Readiness Facility (SMARF), and the two launch pads (SLC 40/41). The network flow is extended into a dynamic program with the incorporation of time as a variable. This inclusion will enable us to create a launch process schedule in addition to optimizing the utility gained from satellite launches. The model flow is shown in Figure 3.5. The processing time in each node is modeled deterministicly, using average processing times from Titan launch history. The mathematical formulation of the model is contained in Appendix C.

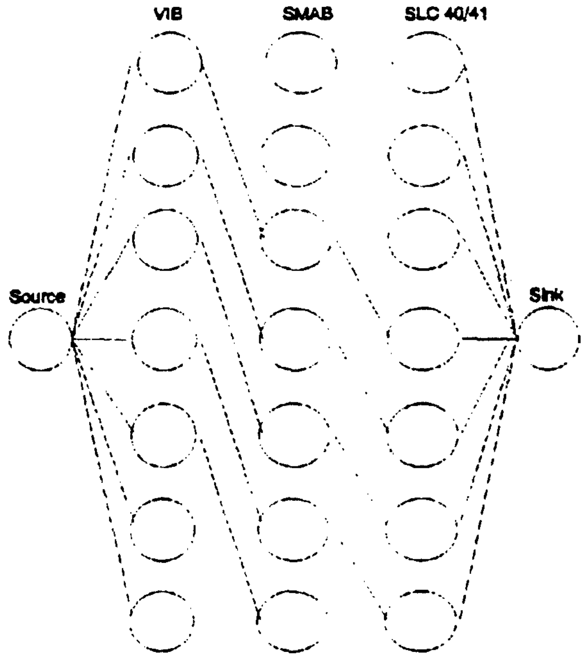

Figure 3.5 Launch Processing Model

The average time for complete processing of the launch vehicle is approximately 8 months: 4 months in the VIB, 2 months in the SMAB, and 2 months on the launch pad (18). This includes the time necessary to refurbish the launch pad. Refurbish time is included as part of the pad processing time, as that resource is unavailable for the next launch vehicle until refurbishment is complete.

3.4.2 Resource Constraints. Once the launch vehicle flow is modeled, we add a set of resource constraints to the optimization problem. The VIB is capable of processing five vehicles simultaneously. The SMAB/SMARF can process two vehicles at a time, and the launch pads can process one each (18).

3.4.3 Launch Windows. Normally, each satellite has an optimal time period for launch. In the case of interplanetary missions, launch times are critical to achieve necessary rendezvous times for mission phases such as gravity assist trajectories. For earth satellites, launch deadlines may be set to achieve specific mission objectives, such as replenishing satellite constellations. These launch windows cause satellites to compete for the constrained launch resources. Solution of our model will show how these sometimes conflicting requirements are traded off and use of the launch facilities is optimized.

IV. Research Results

In this chapter, we present the results of this research, and demonstrate some applications for the data obtained.

4.1 Primary Results: Case Study #1

The first case study attempts to take a set of foreign satellites and compare them using a common measurement tool, our utility function. The DM is this case study is the head of an intelligence team at the National Air Intelligence Center, Wright-Patterson AFB, OH. The model is expected to generate a mathematically-based cardinal rank ordering of systems, which accurately reflects the intuitive judgment of an experienced intelligence analyst. The successful model will enable a less experienced analyst to achieve similar results by simply collecting satellite technical data and inputting it into the model.

Eight real-world operational satellites from three foreign countries were selected and their respective utilities assessed. To avoid any potential release of sensitive information, the actual satellite designations and country of origin are omitted. The satellites are numbered, with the owning country indicated by a letter designation. Satellites 1 through 5 are surveillance satellites, while satellites 6 through 8 are communications satellites.

After collecting data for the satellites, the DM was asked to indicate an intuitive rank ordering for the satellites, with ties allowed. The data collected are shown in Appendix A. The overall results are shown in Table 4.1. The satellites are grouped by mission and ranked within their respective group. Overall, the results were excellent. No reversals between the expected rankings and the model rankings occurred.

Table 4.1 Case Study #1 Results

	A1	A2	A3	B1	C1	A4	A5	A6
Predicted Rank Ordering	2	1	3	4	5	1	2	3
Utility Determined by Model	.65	.66	.57	.55	.52	.67	.58	.52
Model Rank Ordering (By Mission)	2	1	3	4	5	1	2	3
Model Rank Ordering (Overall)	3	2	6	5	8	1	4	7

4.2 Primary Results: Case Study #2

In the second case study we assessed the utilities of a set of satellites that are launched on the Titan IV, the United States' largest launch vehicle. The cardinal rank ordering obtained can be used to prioritize limited launch resources, using multi-criterion optimization (MCO) tools. The DM used in this case was the Titan launch squadron's (5 SLS) long range mission planning officer.

Five satellites due to be launched on the Titan IV in the coming years were chosen. The launch designated K-a is Milstar DFS-2, part of the DOD's newest and most modern satellite communications system. Launch K-b is a Defense Support Program early warning satellite. Launch K-c is Cassini, NASA's mission to Saturn, scheduled for take-off during October 1997. Launches K-d and K-e are typical payloads whose identities are concealed for the purpose of this research.

As in the last case study, data were collected for the satellites and put into the model. The DM is asked for an intuitive rank ordering to compare the model against. The data collected are in Appendix B, while the overall results are shown in Table 4.2. Just as in the first case study, the model rankings accurately reflected those predicted by the decision maker.

Table 4.2 Case Study #2 Results

	K-a	K-b	K-c	K-d	K-e
Predicted Rank Ordering	2	1	5	4	3
Utility Determined by Model	.45	.64	.38	.39	.45
Model Rank Ordering	2	1	5	4	3

4.3 Strategic Equivalence With Additive Utility Function

At this point, we turned our research towards seeing if our utility function could be expressed using a simpler form. We were interested if an additive function, rather than a multiplicative one, could still yield equivalent results. In particular, we were looking for *strategic equivalence*. Strategic equivalence applies to the ordinal ranking of alternatives. If two utility functions yield the same rank ordering for a set of alternatives, they are said to be strategically equivalent (6:45). If we can show this, we must still address the cardinality of the alternative rankings, that is, whether the strength of preferences calculated using the additive and multiplicative forms are "equivalent." The additive form of a multivariate utility function is shown in Equation (4-1).

$$utility(X) = \sum_i w_i \cdot u(x_i) \tag{4-1}$$

4.3.1 Criterion Weights. Rather than re-administer the survey instrument to the DM, we used the data collected in the original survey. Recall that in the additive form, the weights of the criteria sum to one, whereas in the multiplicative form they do not. In re-using the original survey, we assume that the relative weights between criteria which were reported by the DM are unchanged when adding the constraint that they sum to one.

This is a reasonable assumption, since the DM was not made aware in the original survey of how the weights would be summed.

Once this assumption is made, calculating the weights for additive functions is simple. The following formulation is used, showing the three criterion case as an example:

$$w_1 + \frac{w_2}{w_1} \cdot w_1 + \frac{w_3}{w_1} \cdot w_1 = 1 \tag{4-2}$$

Here $\boldsymbol{w_1}$ is the most important criterion, as indicated by the DM, and $\boldsymbol{w_2/w_1}$ and $\boldsymbol{w_3/w_1}$ are the relative weights reported by the DM. We used the results of Case Study #1 for our comparison, and calculated the new sub-criterion and criterion weights shown in Table 4.3 and Table 4.4.

Table 4.3 Sub-Criterion Weights

	1-1	1-2	1-3	2-1	2-2	2-3	3-1	3-2	3-3	4-1	4-2	4-3	4-4
Multiplicative	.675	.75	.563	.043	.045	.05	.63	.63	.7	.1	.085	.075	.09
Additive	.377	.340	.283	.309	.327	.364	.321	.321	.358	.286	.243	.214	.257

Table 4.4 Criterion Weights

	Environment	Mission Impact	Cost/Domestic Commitment	Satellite Status
Multiplicative	.3	.27	.285	.27
Additive	.267	.24	.253	.24

4.3.2 General Case. With the weights calculated, the satellite data we collected earlier was put in to the additive model. A comparison of the rank ordering achieved for each utility function form is shown in Table 4.5. The additive model uses the additive form of Equation (4-1) for both the criterion utility functions and the overall utility function.

Table 4.5 Ranking Comparison

	A1	A2	A3	B1	C1	A4	A5	A6
Multiplicative	3	2	6	5	8	1	4	7
Additive	3	1	5	7	8	2	6	4

Clearly the rank orderings are different. The additive form is not strategically equivalent to the multiplicative form.

We tried two other approaches as well. First, we used multiplicative criterion functions and an additive overall function. This also was not strategically equivalent to the original function. Finally, we tried using additive criterion functions with a multiplicative overall function. This yielded similar results--no strategic equivalence with the original utility function. We conclude that, in general, the simpler additive model is not appropriate to substitute for the multiplicative model.

4.3.3 Limited Case. We found that there can be strategic equivalence under certain limited circumstances, at least for the overall utility function. We examined the case where the Environment and Mission Impact criteria are held constant while the other two criteria are varied. This corresponds to the situation where a group of satellites from the same country (Environment scores are equal for all satellites from the same country) with the same mission (hence Mission Impact scores are equal) are rank ordered.

Given these limitations, we found that strategic equivalence holds between the multiplicative and additive forms of the utility function. This was true for all values of the varied criteria, and for all values tested for the criteria held constant. Figure 4.1 graphically shows strategic equivalence for the case where the Environment and Mission Impact criteria scores are both 0.5. Note that the equivalent utility isovalue lines for the additive and multiplicative functional forms do not cross each other within the range of the

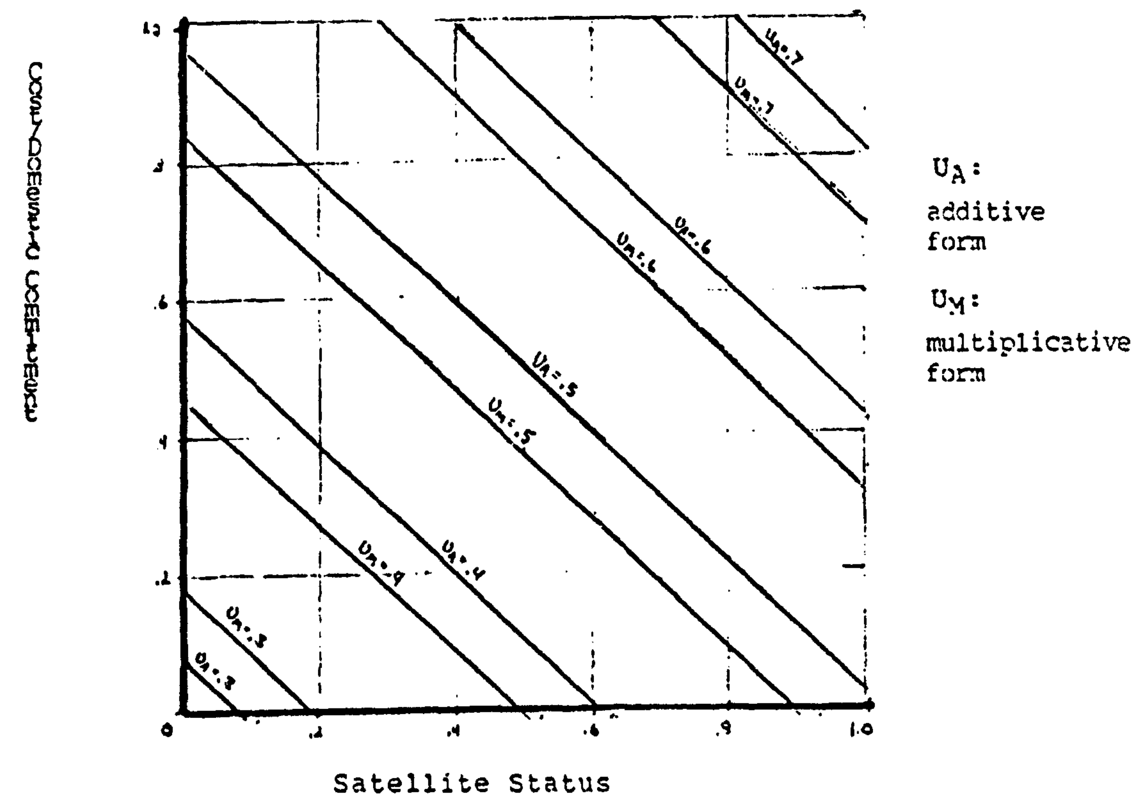

Figure 4.1 Strategic Equivalence

varied criteria. In this particular case, they are very nearly parallel. Strategic equivalence was indicated in this limited case for both case studies. Hence, while strategic equivalence does not hold in general, we find that in at least one practical application, the additive form may be used to achieve the same ordinal rankings as the original function.

4.4 Launch Prioritization and Scheduling

In case study #2, five satellites were scored and their respective utilities calculated. The scores and utilities are shown in Appendix B, and are used to formulate the launch optimization problem.

4.4.1 Model Assumptions and Restrictions. One year was chosen as the time period for study. The model could have been built for any period of time, however, as noted before, our model size was limited by the available PC software. Notional launch windows were created, with the intent that some would conflict with each other. In particular, we required that satellites K-a (Milstar), K-b (DSP), and K-e be launched during time period 7 (during months 11 and 12, with pad refurbishment complete at beginning of month 13). Satellite K-c's launch window was time period 6, and K-d's was period 5. In addition, it was assumed that continuous processing of satellites (rather than early process starts that are later put "on hold") was the most efficient method. These restrictions were written into the linear program model contained in Appendix C.

4.4.2 Model Solution. The model successfully reached an optimal solution for maximizing utility along with a processing schedule achieving this optimum. The model also indicated that there were alternative optimum schedules. One optimum launch processing schedule, using the restrictions set forth in Section 4.4.1, is shown in Table 4.6. Note that K-c, which had the lowest utility, was selected for launch. This is because K-e, which has a higher utility than K-c, was constrained by its launch window requirement. This shows that when optimizing with multiple constraints, the highest utility satellites are not automatically the ones chosen.

Table 4.6 Titan Launch Schedule

	Move To VIB	Move To SMAB/SMARF	Move To Pad	Launched/Pad Refurbished
K-a	3	5	6	7
K-b	3	5	6	7
K-c	2	4	5	6
K-d	1	3	4	5
K-e	--	--	--	--

4.5 Characterizing A Group Utility Function

In Section 4.4, we showed how the results from analyzing the launch DM's preference structure can be used to optimize a launch schedule. But the decisions made concerning launch schedules are certainly not made by a single individual. More likely, launch decisions will be made by a group, with the operational launch squadron's preferences only one of many. Other decision makers include those from HQ Air Force Space Command, the Pentagon, the various satellite user communities, and the launch vehicle and satellite contractors. Having calculated an optimal solution to our launch scheduling problem, how much can the individual satellite utilities simultaneously and independently vary from those originally determined by the launch DM, and still be assured of this same optimal solution? We use Wendell's tolerance approach, discussed in Chapter 2, to answer this question.

4.5.1 Deficiency in the Tolerance Approach. A substantial weakness in this approach is found when there are alternate optimal solutions to the linear problem. Alternate optimal solutions are indicated when there is at least one "reduced cost" equal to zero for a non-basic variable. When this occurs, the tolerance, τ, equals zero (34:567).

This means that when any change to any of the objective function coefficients (the satellite utilities) occurs, we cannot be assured of the same optimal solution. This is precisely the case with the solution to our launch scheduling model. Unfortunately, Wendell's methodology offers no way to work around this situation. We must make some changes to the model to avoid alternate optimal solutions.

4.5.2 Model Simplifications. We start by examining the output of the original model. This network is also a maximum flow problem. The maximum flow through the network is equal to the most constrained point. Recall that two satellites can be processed simultaneously through the SMAB/SMARF and the launch pads. Either of these two points can be modeled as the critical point in the processing flow. We will use the launch pads in our adjusted model.

Each satellite takes eight months to complete, which means that if no satellites start the year already being processed, none can be launch prior to the eighth month, and the pad will not be ready for the next launch until the beginning of the ninth month. Hence, in our reduced model, we are only concerned with launch options during time periods 5, 6, and 7.

The reduced model is shown in Appendix D. The model is now small enough to be solved using LINDO. It yields the same optimum solution, 1.859 utiles, as the original model. However, analysis of the optimal tableau reveals reduced costs of non-basic variables equal to zero, again indicating alternate optimal solutions. Another modification is necessary.

If we confine our interest now to only whether a satellite is launched, discarding the scheduling portion of the problem, the model can again be simplified. Since two satellites can be simultaneously processed on the pads, satellites K-c and K-d are not constrained, as they are each the only satellite to be launched within their respective launch windows. However, there are three satellites, K-a, K-b, and K-e, with the same launch window, which are constrained by the pad capacities. This second reduced model is also shown in Appendix B. It yields the same optimal objective function value as the two previous models, however, the solution is at last unique, and we can now apply the tolerance approach.

4.5.3 The Tolerance Approach Applied. We formulate the "perturbed" linear program described by Equation (2-3). In this formulation, c_j is the vector of objective function coefficients, and K is the set of non-basic variables.

$$
\begin{aligned}
c_j &= (0.452,\ 0.644,\ 0.377,\ 0.386,\ 0.450,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0) \\
K &= \{E,\ SLC_3,\ SLC_4,\ SLC_5,\ SLC_7\}
\end{aligned}
\tag{4-3}
$$

The zero values in c_j are the slack variable coefficients, which are added during the problem solution. Likewise, the SLC_is are also slack variables, in this case those that are not in the optimal basis. Applying Equation (2-2), we find that τ equals 0.0022. That is, each coefficient in the objective function (the satellite utilities) can simultaneously and independently vary up to 0.22 % without changing the optimum solution.

The interpretation of this solution is most easily seen by comparing the linear program objective function that corresponds to the launch squadron's preferences, shown in Equation (4-4), to the objective function that corresponds to a group's preferences, shown in Equation (4-5).

$$
\begin{aligned}
\text{MAX}\quad & U_i(K-a)\cdot Y_{K-a} + U_i(K-b)\cdot Y_{K-b} + U_i(K-c)\cdot Y_{K-c} \\
& + U_i(K-d)\cdot Y_{K-d} + U_i(K-e)\cdot Y_{K-e}
\end{aligned}
\tag{4-4}
$$

$$
\begin{aligned}
\text{MAX}\quad & GUF(K-a)\cdot Y_{K-a} + GUF(K-b)\cdot Y_{K-b} + GUF(K-c)\cdot Y_{K-c} \\
& + GUF(K-d)\cdot Y_{K-d} + GUF(K-e)\cdot Y_{K-e}
\end{aligned}
\tag{4-5}
$$

To be assured that the group's optimum decision is the same as that of the launch squadron's decision maker, the coefficients of Equation (4-5) must be such that for each satellite:

$$U_1(K-i) - [U_1(K-i)\cdot 0.0022] \leq GUF(K-i) \leq U_1(K-i) - [U_1(K-i)\cdot 0.0022] \qquad (4\text{-}6)$$

4.5.4 Using Tolerances to Characterize a Group Utility Function. To show how a GUF can be characterized by the tolerance calculated in the last section, we assume that the group being modeled has two decision makers--the localized perspective of the launch squadron DM, and a DM with a more global perspective, such as a DM at a major command headquarters. For simplicity, in this case we'll use the preference structure we obtained from Case Study #1 as our global perspective.

First, we'll compare the utilities obtained for the same set of satellites using the two different preference structures. The comparison is shown in Table 4.7. Note that the rank ordering of the satellites is not the same for the two DM's.

Table 4.7 Comparison of Decision Maker Preferences

	K-a	K-b	K-c	K-d	K-e
Launch DM Utilities	.452	.644	.377	.386	.450
Launch DM Rank Ordering	2	1	5	4	3
NAIC DM Utilities	.669	.740	.623	.610	.673
NAIC DM Rank Ordering	3	1	4	5	2

If we assume the GUF takes on an additive form such as the one shown in Equation (4-7), we can specify, using the tolerance. limits to the weighting factors that allow the optimal solution to be unchanged:

$$GUF(x) = w_1U_1(x) + w_2U_2(x) \tag{4-7}$$

The greatest percentage difference in satellite utilities between the DM's occurs with satellite K-c. To calculate the critical weights (where a change in optimal solution can take place) we solve the following set of equations:

$$\begin{aligned} .377 \cdot w1 + .623 \cdot w2 &= .377 \cdot \tau \\ w1 + w2 &= 1 \end{aligned} \tag{4-8}$$

Solving these equations, we find that $w1 \geq 0.9967$. This means that we are guaranteed the same optimum solution only if the launch DM's preferences are weighted at least 99.67%. Figure 4.2 graphically shows this result. The GUF isovalue curve is a straight line since we've assumed an additive GUF for this case. When $w_1 \geq .9967$ the tangent point to the highest attainable GUF isovalue is along the efficient frontier defined for the launch squadron. When w_1 is varied below the 0.9967 threshold (and the corresponding slope of the GUF isovalue lines decrease) the point of tangency is on the undefined efficient frontier of either the proxy DM or the group.

Remember that this result is obtained independent of any satellite utilities associated with the proxy DM. When the preferences of the proxy DM are specified, the range of GUF weights that allows the launch DM's preferences to prevail is considerably wider. Figure 4.3 graphically shows this result. Note that the optimum GUF isovalue

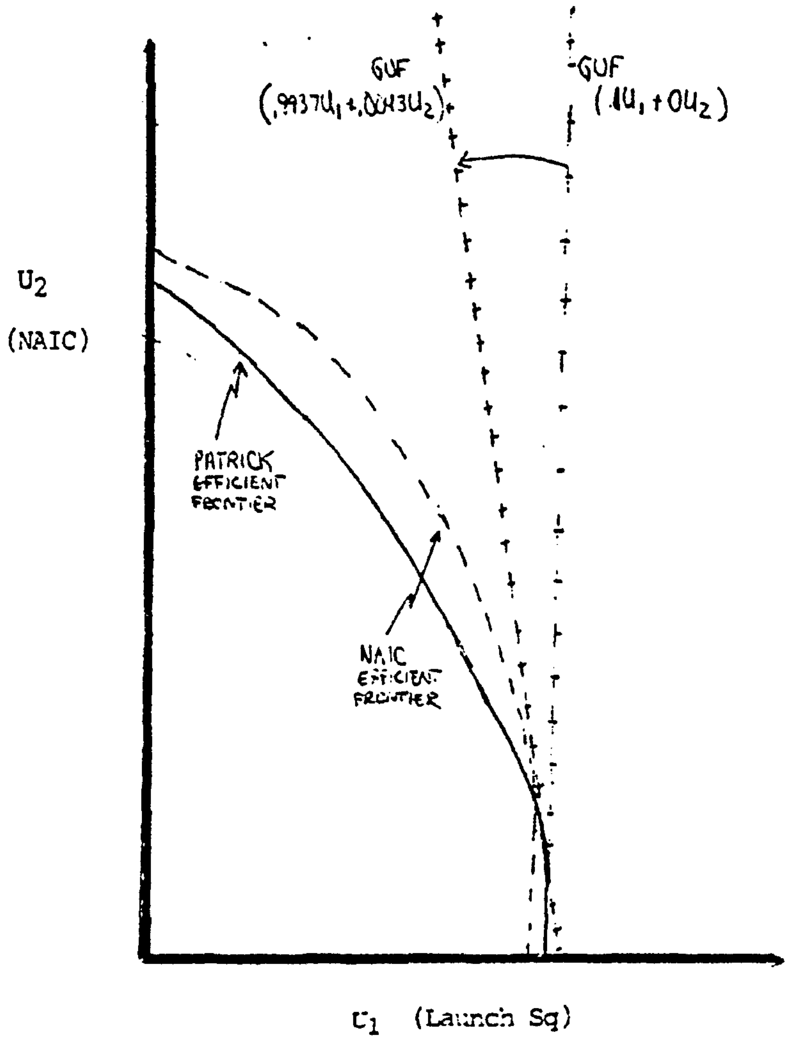

Figure 4.2 GUF Characterization

always falls tangent to either the launch squadron's or the proxy DM's efficient frontier. A group efficient frontier does not become apparent in this case.

Now we can make some statements concerning the GUF. Given the launch DM's utilities, we can specify a range of weighting factors where we can guarantee that the launch DM's preferences will prevail in optimizing the launch schedule. In this particular case, the range is exceptionally tight. This is because two of the satellites competing for the same launch window, K-a and K-e, have utilities which differ by only 0.02. If we

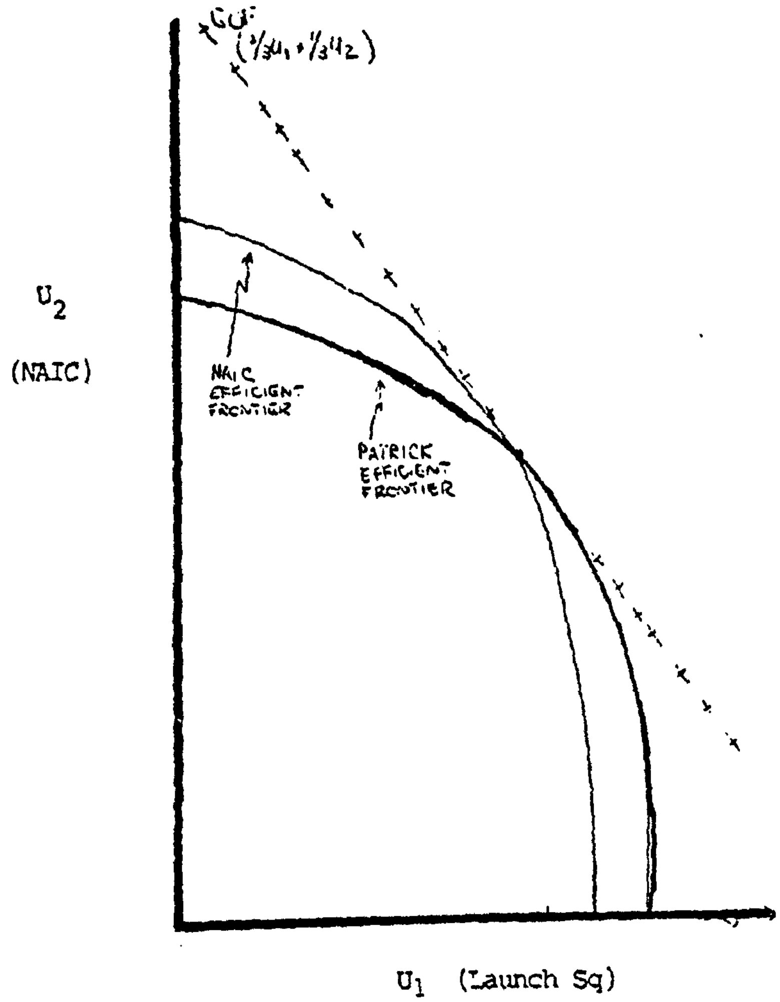

Figure 4.3 GUF Characterization With Proxy DM Efficient Frontier

re-run this model where K-e is replaced by K-d, we can calculate a tolerance of 5.12%, and a corresponding range of $w_1 \geq 0.92$

The tolerances and weighting ranges should at first appear extremely conservative. When the proxy DM's preferences are defined, the group's optimum solution differs from the launch DM's optimal solution only if $w_1 \leq 2/3$ in the GUF. Further, when K-e is replaced by K-d, the optimum solution remains the same regardless of the weighting factors! However, the tolerance approach does not consider the individual utilities associated with other DMs. It assesses a "worst scenario" situation, which in this case is where the utility of K-e (originally 0.450) rises 0.22%, and the utility of K-a (originally 0.452) falls 0.22%. When we use K-d vice K-e, the weights used in the GUF are trivial because both DMs agree on the rank ordering of the satellites. Thus, we see that if the changes in satellite utilities (the coefficients of the LP's objective function) remain within our tolerance, we are guaranteed the same optimal solution for the group's decision and for the original individual's decision.

V. Conclusion

We now discuss the conclusions reached as a result of this research, and offer some suggestions for future research.

5.1 Research Results

Overall, this research was quite successful. All of the major goals stated in Chapter 1 were met as planned.

5.1.1 Simplifying the Survey Process. Our prime theoretical concern was whether we could substantially simplify the MAUT survey process. Usually, survey instruments are so complex that the DM is confused to the extent that his responses become inconsistent, and the DM often leaves the process with little confidence in its validity.

We made three major simplifications to the survey instrument, which were primarily centered on eliminating the the need to use lottery questions to capture the DM's preference structure. Kirkwood's assumption of exponential univariate utility curves provided the first simplification. This eliminated the need for using the fractile method. The fractile method has been criticized for its lack of consistent results (8:383).

Next we reduced the number of pairwise comparisons required to verify utility independence by taking advantage of Keeney & Raiffa's "weaker conditions." As they point out, without these conditions we must examine $2^n - 2$ utility independence assumptions for n attributes (14:292). For our model, this is 8190 verifications! These conditions reduced the number of verifications to 12, a far more manageable undertaking.

To determine the preferences between criteria without using lottery questions, we used a combination of methodologies by Seo, Sakawa and Clemens. As a result of our applying Seo and Sakawa's theory, the DM needed only to indicate the most important criterion, and then express the weights of the other criteria as a ratio to this criterion. Clemen provided the means to determine the weight to be assigned to the most important criterion via the swing weight method. Using this weight and the weight ratios between the criteria, the remaining weights could be derived.

The MAUT model we constructed was fairly complex, having thirteen criteria. Taking advantage of a hierarchical organization reduced the number of required paired criteria comparisons from 78 to 21. This organization allowed a logical grouping of criteria, and eliminated the difficult task of comparing criteria which were greatly dissimiliar.

Our survey simplifications allowed the entire survey to be administered in an average time of less than two hours, without the use of frustrating lottery questions. In both case studies, the DM left the survey with a good understanding of the process and was confident in the outcome of the model.

5.1.2 Automating the Model's Utility Calculations. This task was not particularly difficult, but it will greatly enhance the ability of NAIC analysts to update the preference structure they use to evaluate satellite utilities. The program is written using Microsoft Excel Version 5.0. The analyst does not need to be trained in MAUT to use the program. The model only requires the analyst to update the survey, if desired, and enter the sub-criterion scores for each satellite being assessed. The Excel program calculates the weighting factors and calibration constants, and outputs the respective satellite utilities.

5.1.3 Strategic Equivalence. We determined that in general an additive utility functional form could not be successfully substituted for the multiplicative form. However, we showed that the additive form can be used for at least one limited case, when rank ordering satellites from a single country that all perform the same mission.

5.1.4 Application of the Model to an Optimization Problem. Here we demonstrated that the utilities calculated for a set of satellites can be used to optimize the use of limited launch resources. We showed that a set of constraints can preclude a satellite with a high utility from being selected for launch, while selecting a satellite with a relatively lower utility for launch. In general, simply taking the rank ordering of a set of alternatives and selecting the top *n* alternatives as the optimal solution is not appropriate in a constrained environment. A cardinal scaling and an explicit model of limited-resource allocation is necessary for the final implementation of decisions.

5.1.5 Characterizing a Group Utility Function. Using the results of the optimization problem, we were able to make some observations about how the use of a group utility function might influence the decision being made. Using the tolerance approach, we were able to state the conditions under which the launch DM's decision would be guaranteed to prevail in a group environment. More importantly, in the two DM cases we examined, we were able to state these conditions without determining the efficient frontier of the second DM, and without specifying the form of the group utility function.

5.2 Recommendations for Further Study

During the course of this research, some difficulties were encountered which should be addressed in future research. In addition, there are several areas of interest that can be explored as extensions to the results presented here.

5.2.1 Group Utility Functions. There is a great deal of potential for future research in this area. First, the case of three or more decision makers should be examined. Rather than use a proxy DM, actual participants in the launch decision process should be interviewed to determine their preference structures. In addition, future research should attempt to model the GUF using a multiplicative form, since the additive form rarely applies to real decision problems. Historical launch decisions should then be used to validate the improved model. While the exact form of a GUF is difficult to explicitly determine, these theoretical advances might be used to approximate the launch decision makers' preferences. The improved model can then be used as a tool to assist in making future launch decisions.

5.2.2 Launch Model Simplicity. Since the launch optimization model was not the primary focus of this research, it was greatly simplified to allow for a timely demonstration of the possible extensions of our MAUT results. For the model to be appropriately used to represent the Titan launch process, it should be expanded to include the other processing flows, such as that of the Centaur Upper Stage. The model was also deterministic with respect to activity durations. A more realistic model should use a stochastic approach.

5.2.3 Modeling Uncertainties In Assessments. When satellites are scored in a sub-criterion, the analyst chooses a point on the sub-criterion's scale that best describes the satellite. But often the analyst is not certain of the satellite's characteristics. More likely, the analyst's knowledge is limited to a range of values for the sub-criterion due to limitations in their ability to collect precise intelligence information. Classical sensitivity analysis can be used to study the effects of varying the level of a single sub-criterion. However, if ranges are used for several sub-criterion scores, the process of determining the corresponding range of utility scores would be mathematically intensive. One of the goals of the model was to make it simple for the analyst to use. The Excel program should be modified to allow the analyst to enter ranges for the sub-criterion scores. The program should then calculate and display the resulting satellite utility as a range

Appendix A: Case Study #1, NAIC Survey

Decision Maker: Mr. Bill Banks
NAIC/TASX

Interview Date: 7 September 1994

Section I: Mapping The Single Variable Utility Functions

Criterion 1: Environment

This criterion defines the value associated with the time dependent "state of the world." To provide consistent value ratings for the satellites, a "snapshot" is taken and ranked. This criterion since it can be thought of as time dependent, allows a time series of satellite utility to be shown, since multiple "snapshots" can be taken over a period of time. In addition, this criterion allows some "what ifing" to be done. This criterion is evaluated only once, as the scores will be the same for any set of satellites (from the same country) evaluated at a particular time.

Sub-Criterion 1-1: Political State

This sub-criterion describes the current international political environment.

- **0.00** - "Peaceful Stability" International relations are stable and the world is absent of any significant military/political crises. Obviously, this state is exceptionally rare.
- **0.25** - "Minor Crises/Degrading Stability" One or more minor local/regional crises are in progress, that do not immediately threaten national security. Relations with allies or adversaries may be degraded, but negotiations are continuing. For most countries, this is the most common state during the 20th century.
- **0.50** - "Major Crisis" One or more regional crises are in progress, that potentially threaten national security. Relations with allies or adversaries are substantially degraded, and negotiations are seemingly at an impasse. This would describe the political landscape throughout most of the 1930's.
- **0.75** - "Limited War" Tensions between nations are high. Regional conflict has broken out that threatens national security. General war threatens. The Korean and Vietnam Wars are examples of this environment.
- **1.00** - "General War" National forces are fully mobilized and committed to intense combat. World War II exemplifies this environment.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5]

ANS: 0.4

Sub-Criterion 1-2: Adversary's Space Capability

This sub-criterion examines the overall space capability of the nation. The Pareto assumption here is that the more space-capable a nation is, the more individual space assets are relied upon

- **0.00** - "Primitive" Nation has virtually no space assets whatsoever. In addition, it has little or no ability to interfere with other nation's deployed assets
- **0.25** - "Minor Space Power" Possesses has limited space assets, deployed primarily in support roles. Some interference/jamming capability is likely.
- **0.50** - "Medium Space Power" Assets are deployed in support and force enhancement roles. Demonstrated capability to interfere/jam enemy satellite systems.
- **0.75** - "Major Space Power" Assets are deployed across nearly the full range of mission areas, and has integrated them somewhat with terrestrial forces. Likely offensive anti-satellite capability.
- **1.00** - "Space Superpower" Fully deployed and integrated systems across the full range of missions. Demonstrated offensive/defensive anti-satellite capability.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.55

Sub-Criterion 1-3: International Economy

This sub-criterion describes the state of the nation's economy. This sub-criterion may at first appear to be scaled in reverse. However, we are considering a satellite's value in terms of the economic conditions, where the value placed on the asset increases as economic conditions worsen.

- **0.00** - "Boom" Characterized by rapid economic growth and vigorous international trade.
- **0.25** - "Growth" Overall, economy is healthy and growing. Trade barriers are minimal.
- **0.50** - "Stable" Most common economic state. Trade relations and currency exchanges are stable. Trade barriers may be present, but do not seriously hamper trade relations.
- **0.75** - "Recession" Economy is shrinking. Currency exchanges may be unstable. Trade relations are constrained, protectionism is prevalent.
- **1.00** - "Depression" Economy is in collapse. International trade is minimal, with trade barriers dominating.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5]

ANS: 0.6

Criterion 2: Mission Impact

This criterion attempts to determine the value of a satellite's mission(s) relative to the mission(s) of other satellites. As such the rating given may reflect an entire class of satellites, for example, those used for early warning.

Sub-Criterion 2-1: "Mission Criticality"

This sub-criterion rates the relative importance of satellite missions, such as early warning, communications, weather, etc.

- **0.00** - "Trivial/Scientific" Mission is primarily scientific in nature, and has virtually no impact to the warfighter. This does not mean the satellite is useless, but that it has no direct or current application to military offensive/defensive capabilities.
- **0.25** - "Minor Component" While not contributing directly to warfighting capability, the satellite directly aids forces that do.
- **0.50** - "Medium Component" Satellites plays a significant role in force offensive/defensive
- **0.75** - "Major Component" Satellite mission plays a significant in force offensive/defensive strategy.
- **1.00** - "Critical!" Mission constitutes a critical capability, without which it would be difficult or nearly impossible to conduct wartime operations.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.4

Sub-Criterion 2-2: "Space/Ground Ratio"

Here the relative amount of the mission accomplished in space versus on the ground is examined.

- **0.00** - "100% Ground" Terrestrial assets perform the entire operational mission.
- **0.25** - "Primarily Ground" Space assets are sometimes used for the operational mission, however, ground counterparts dominate. Space systems seen as somewhat experimental, and serve primarily in backup roles
- **0.50** - "50/50 Mix" Space and ground assets are equally relied upon to perform an assigned mission.
- **0.75** - "Primarily Space" Space assets dominate mission accomplishment. Ground assets are secondary or used as a backup.
- **1.00** - "100% Space" The entire mission is performed by space assets. Ground backup is not available or unreliable

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.5

Sub-Criterion 2-3: Maturity Of Mission

How well the satellite's mission is understood by warfighters and integrated into overall capabilities is considered in this sub-criterion

0.00 - "Unknown/Unused" Satellite's capabilities are not understood or utilized by strategic and tactical commanders. Satellite remains largely an R&D project.

0.25 - "Little Known" Satellite capacity is partially understood and used, but only on a basic level. R&D community possesses the expertise to operate the satellite.

0.50 - "Somewhat Integrated" Operational Turnover of the satellite has occurred from the R&D community to an operational unit. Capabilities are still being explored. Information concerning the satellite has reached field commanders and experimental/tentative use has begun.

0.75 - "Widely Known/Substantially Integrated" Operation of the satellite is normalized. Field commanders understand capabilities and routinely use them. Some problems still exist, and alternate assets are maintained and frequently relied upon.

1.00 - "Fully Integrated" Satellite is fully understood and exploited, and capabilities are fully integrated into theater operations.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.45

Criterion 3: Cost/Domestic Commitment

The value placed on a satellite is demonstrated by the level of commitment a nation makes to supporting the continuation of its mission.

Sub-Criterion 3-1: Economic Commitment

The funding status of the satellite's production, operations and infrastructure is evaluated here.

0.00 - "Near Cancellation" Commitment to the satellite (program) is minimal or near termination. Natural reasons for this to occur is that it is near the end of the satellite's (program) life cycle, or upon the advent of a new technology that renders the satellite obsolete. Political considerations may also cause termination.

0.25 - *"Drawdown" Support is in decline. This may be due to political/economic considerations, or it may be late in the satellite's (program's) life cycle.*

0.50 - "Stable" Funding is stable. Typical of a satellite (program) early or near the mid-point of its life-cycle.

0.75 - "Growth" Funding is growing steadily. This is typical of a fairly young satellite (program), when political support is growing and infrastructure is still being added.

1.00 - "Explosive Growth" Political support and funding for the satellite is rapidly expanding. Political support is consolidating.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.55

Sub-Criterion 3-2: Economic Impact

While the previous sub-criterion looks at the growth rate, this sub-criterion examines the current size and impact due to the commitment to the satellite.

- **0.00** - "Mom & Pop' Program" Very small organization that impacts only a small local economy Production facilities might consist of a single small plant.
- **0.25** - "Minor Program" Dominates only a local economy Production facilities might consist of a few small plants or a single large one.
- **0.50** - "Regional Program" Program infrastructure is significant to a regional economy. Program is large enough to receive some national legislative scrutiny.
- **0.75** - "Major Program" Program infrastructure is significant to national economy and receives significant substantial national public and legislative attention
- **1.00** - "Intense Program" Substantial sacrifices are made at the national level to continue funding of the satellite's infrastructure. Single-minded economic priority is given to the satellite.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.6

Sub-Criterion 3-3: Launch Priority

Launch priority given to a satellite is an excellent indicator of the value placed on that asset. This sub-criterion also includes the "sparing" strategy, as the presence of spare satellites on the ground or on-orbit affects the priority given to a new launch.

- **0.00** - "No Near Term Launch/No Spares" No capability exists to replace the satellite in the near term. Replacement satellites have not been constructed and/or no launch vehicles are available.
- **0.25** - "Delayed Schedule/Limited Sparing" Replacement satellites have been partially constructed, but are not available for near term launch. A launch schedule does not exist, is incomplete, or delayed.
- **0.50** - "Stable Launch Schedule/Substantial Sparing" Launch of replacement satellites can be accomplished on a schedule. However, the schedule is somewhat inflexible. Spares are available, but most are on the ground, and those in orbit are not positioned for immediate use.
- **0.75** - "Accelerated Schedule/Near Complete Sparing" Launch of replacement satellites can be accomplished on an accelerated schedule. Several spares are constructed, with most placed in orbit to be positioned in the short term.
- **1.00** - "Launch On Need/Comprehensive Sparing" Launch is possible on relatively short notice. A comprehensive sparing strategy is in place. On-orbit spares can be made operational quickly.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.5

Criterion 4: Satellite Status

This criterion takes into account the individual characteristics of the satellite

Sub-Criterion 4-1: Mission Performance Status

How well the satellite is performing its assigned mission is directly applicable to the value that is placed on it.

- **0.00** - "Non-Operational" Satellite is degraded to the extent that it cannot be considered operational.
- **0.25** - "Severely Degraded/Turned Off Spare" Satellite is capable of performing its mission only to a marginal extent. Satellite may be configured as a spare, with secondary power turned off until needed.
- **0.50** - "Significantly Degraded" Satellite satisfactorily performs it mission, but at a substantially degraded level.
- **0.75** - "Slightly Degraded" Satellite performs its mission as expected, but some minor degradation is present.
- **1.00** - "No Degradation" Satellite is fully capable of performing its mission with no failed or degraded units.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1 00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.55

Sub-Criterion 4-2: Contribution To Mission

Rarely does a single satellite accomplish an entire mission. Typically, satellites are grouped into a constellation to complete an assigned mission. Here the satellite's contribution to completing the mission is measured.

- **0.00** - "Spare/No Direct Impact To Mission" Loss of the satellite will not adversely impact the capability to accomplish a mission. A typical case would be a satellite configured as an on-orbit spare.
- **0.25** - "Secondary Impact To Mission" Loss of satellite would impact the constellation at a secondary level only. The mission completed by this satellite can be readily transferred to another satellites.
- **0.50** - "Impacts Constellation Mission" Loss of the satellite would adversely impact mission accomplishment. Much of the satellite's duties can be transferred, but noticeable degradation will occur.
- **0.75** - "Strongly Impacts Mission" Loss of the satellite significantly impacts mission accomplishment. Satellite mission duties are largely irreplaceable, hence substantial degradation results.
- **1.00** - "Critical To Mission" Loss of satellite critically impairs mission accomplishment.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1 00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.5

Sub-Criterion 4-3: Level Of Technology

In general, more modern satellites that employ improved technologies have greater capabilities. In particular, satellites that employ newer technologies represent a significant investment in research and development. Presumably, this investment has purpose and value.

0.00 - "Primitive" Space technology is at the most rudimentary level. A satellite such as this would hearken back to the days of Sputnik.

0.25 - "30 Year Old State of the Art" Today (1994), this represents technology developed and employed by advanced nations in the 1960's.

0.50 - "20 Year Old State of the Art" Technology originally developed and fielded the most advanced nations in the 1970's.

0.75 - "10 Year Old State of the Art" Technology originally developed and fielded by the most advanced nations during the 1980's.

1.00 - "State of the Art" Represents the current possible fielded space technology.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.6

Sub-Criterion 4-4: Expected Remaining Lifetime

It would seem obvious that the value placed on a satellite depends on an estimation of how long the satellite will remain operational. This is to be distinguished from a satellite's planned life cycle, which is a fixed timespan estimated by satellite designers. The expected remaining lifetime is a changing estimate, affected by the spacecraft's age, fuel reserves, and known satellite subsystem failures.

0.00 - "0 years" Complete failure is anticipated at any time.

0.20 - "3 years"

0.40 - "6 years"

0.60 - "9 years"

0.80 - "12 years"

1.00 - "15 years or more"

0.00 0.20 0.40 0.60 0.80 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.5

Section II: Independence Verification

For sub-criterion 4-1, Mission Accomplishment, you indicated that the level of this attribute that yields a utility of 0.5 is

0.55

Assume now that the level of sub-criterion 1-1, Political State, is **0.00**. Does this change your assessment above for sub-criterion 4-1?	NO
What if the level of sub-criterion 1-1 is changed to **0.50** ?	NO
What if the level of sub-criterion 1-1 is changed to **1.00** ?	NO
Assume now that the level of sub-criterion 1-2, Overall Space Capability, is **0.00**. Does this change your assessment above for sub-criterion 4-1?	NO
What if the level of sub-criterion 1-2 is changed to **0.50** ?	NO
What if the level of sub-criterion 1-2 is changed to **1.00** ?	NO
Assume now that the level of sub-criterion 1-3, National Economy, is **0.00**. Does this change your assessment above for sub-criterion 4-1?	NO
What if the level of sub-criterion 1-3 is changed to **0.50** ?	NO
What if the level of sub-criterion 1-3 is changed to **1.00** ?	NO
Assume now that the level of sub-criterion 2-1, Mission Criticality, is **0.00**. Does this change your assessment above for sub-criterion 4-1?	NO
What if the level of sub-criterion 2-1 is changed to **0.50** ?	NO
What if the level of sub-criterion 2-1 is changed to **1.00** ?	NO
Assume now that the level of sub-criterion 2-2, Space/Ground Ratio, is **0.00** Does this change your assessment above for sub-criterion 4-1?	NO
What if the level of sub-criterion 2-2 is changed to **0.50** ?	NO
What if the level of sub-criterion 2-2 is changed to **1.00** ?	NO
Assume now that the level of sub-criterion 2-3, Maturity of Mission, is **0.00**. Does this change your assessment above for sub-criterion 4-1?	NO
What if the level of sub-criterion 2-3 is changed to **0.50** ?	NO
What if the level of sub-criterion 2-3 is changed to **1.00** ?	NO
Assume now that the level of sub-criterion 3-1, Economic Commitment, is **0.00**. Does this change your assessment above for sub-criterion 4-1?	NO
What if the level of sub-criterion 3-1 is changed to **0.50** ?	NO
What if the level of sub-criterion 3-1 is changed to **1.00** ?	NO
Assume now that the level of sub-criterion 3-2, Economic Impact, is **0.00**. Does this change your assessment above for sub-criterion 4-1?	NO
What if the level of sub-criterion 3-2 is changed to **0.50** ?	NO
What if the level of sub-criterion 3-2 is changed to **1.00** ?	NO

Assume now that the level of sub-criterion 3-3, Launch Priority, is **0.00**. Does this change your assessment above for sub-criterion 4-1?

Assume now that the level of sub-criterion 3-3, Launch Priority, is 0.00. Does this change your assessment above for sub-criterion 4-1?	NO
What if the level of sub-criterion 3-3 is changed to **0.50** ?	NO
What if the level of sub-criterion 3-3 is changed to **1.00** ?	NO

Assume now that the level of sub-criterion 4-2, Contribution to Mission, is **0.00**. Does this change your assessment above for sub-criterion 4-1?	NO
What if the level of sub-criterion 4-2 is changed to **0.50** ?	NO
What if the level of sub-criterion 4-2 is changed to **1.00** ?	NO

Assume now that the level of sub-criterion 4-3, Level of Technology, is **0.00**. Does this change your assessment above for sub-criterion 4-1?	NO
What if the level of sub-criterion 4-3 is changed to **0.50** ?	NO
What if the level of sub-criterion 4-3 is changed to **1.00** ?	NO

Assume now that the level of sub-criterion 4-4, Expected Remaining Lifetime, is **0.00** Does this change your assessment above for sub-criterion 4-1?	NO
What if the level of sub-criterion 4-4 is changed to **0.50** ?	NO
What if the level of sub-criterion 4-4 is changed to **1.00** ?	NO

Section III: Creating The Multi-Variate Criterion Utility Functions

Criterion 1: Environment

Rank order the three sub-criterion in order of importance, from highest to lowest.

| 2 | **Sub-Criterion 1-1: Political State** |

This sub-criterion describes the current international political environment.

| 1 | **Sub-Criterion 1-2: Adversary's Space Capability** |

This criterion examines the relative space capability of a potential or actual adversary.

| 3 | **Sub-Criterion 1-3: International Economy** |

This sub-criterion describes the state of the worldwide economy. This sub-criterion may at first appear to be scaled in reverse, however, as we consider a satellite's value in terms of the economic times, the value placed on the asset increases as economic conditions worsen.

Assume for now that the sub-criterion you ranked as #1 has a weighting factor of 1. On the scale below, indicate the relative weights for the other two sub-criterion, by placing them on the scale.

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Relative Weights:

0.9
1
0.75

Criterion 2: Mission Impact

Rank order the three sub-criterion in order of importance, from highest to lowest.

| 2 | **Sub-Criterion 2-1: Mission Criticality** |

This sub-criterion rates the relative importance of satellite missions, such as early warning, communications, weather, etc.

| 3 | **Sub-Criterion 2-2: Space/Ground Ratio** |

Here the relative amount of the mission accomplished in space versus on the ground is examined.

| 1 | **Sub-Criterion 2-3: Maturity Of Mission** |

How well the satellite's mission is understood by warfighters and integrated into overall capabilities is considered in this sub-criterion.

Assume for now that the sub-criterion you ranked as #1 has a weighting factor of 1. On the scale below, indicate the relative weights for the other two sub-criterion, by placing them on the scale.

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Relative Weights:

0.85
0.9
1

Criterion 3: Cost/Domestic Commitment

Rank order the three sub-criterion in order of importance, from highest to lowest.

[2] **Sub-Criterion 3-1: Economic Commitment**

The funding status of the satellite's production, operations and infrastructure is evaluated here.

[2] **Sub-Criterion 3-2: Economic Impact**

While the previous sub-criterion looks at the growth rate, this sub-criterion examines the current size and impact of the commitment to the satellite.

[1] **Sub-Criterion 3-3: Launch Priority**

Launch priority given to a satellite is an excellent indicator of the value placed on that asset. This sub-criterion also includes the "sparing" strategy, as the presence of spare satellites on the ground or on-orbit affects the priority given to a new launch.

Assume for now that the sub-criterion you ranked as #1 has a weighting factor of 1. On the scale below, indicate the relative weights for the other two sub-criterion, by placing them on the scale.

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Relative Weights:

0.9
0.9
1

Criterion 4: Satellite Status

Rank order the four sub-criterion in order of importance, from highest to lowest.

[1] **Sub-Criterion 4-1: Mission Performance Status**

How well the satellite is performing its assigned mission is directly applicable to the value that is placed on it.

[3] ***Sub-Criterion 4-2: Contribution To Mission***

Rarely does a single satellite accomplish an entire mission. Typically, satellites are grouped into a constellation to complete an assigned mission. Here the satellite's contribution to completing the constellation's mission is measured.

[4] **Sub-Criterion 4-3: Level Of Technology**

In general, more modern satellites that employ improved technologies have greater capabilities. In particular, satellites that employ newer technologies represent a significant investment in research and development. Presumably, this investment has purpose and value

2

Sub-Criterion 4-4: Expected Remaining Lifetime

It would seem obvious that the value placed on a satellite depends on an estimation of how long the satellite will remain operational. This is to be distinguished from a satellite's planned life cycle, which is a fixed timespan estimated by satellite designers. The expected remaining lifetime is a changing estimate, affected by the spacecraft's age, fuel reserves, and known satellite subsystem failures

Assume for now that the sub-criterion you ranked as #1 has a weighting factor of 1. On the scale below, indicate the relative weights for the other two sub-criterion, by placing them on the scale.

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Relative Weights:

1
0.85
0.75
0.9

Section IV, Creating The Multi-Variate Criterion Utility Functions, Part II

Criterion 1: Environment

We define a satellite used in the environment below as having a utility = 1.

Political State	General War
Adversary's Space Capability	Space Superpower
International Economy	Depression

Now we define a satellite used in the environment below as having a utility = 0.

Political State	Peaceful Stability
Adversary's Space Capability	Primitive
International Economy	Boom

Imagine a satellite used in the environment described below:

Political State	Peaceful Stability
Adversary's Space Capability	Space Superpower
International Economy	Boom

Assign a number between 0 and 1 that best describes the utility value you place on a satellite that is used in this environment. Assume that these three attributes are the only attributes to describe the satellite **0.75**

Criterion 2: Mission Impact

We define a satellite with the mission attributes below as having utility = 1.

Mission Criticality	Critical To Force Survival
Space/Ground Ratio	100% Space
Maturity Of Mission	Fully Integrated

Now we define a satellite with the mission attributes as having utility = 0.

Mission Criticality	Trivial/Scientific
Space/Ground Ratio	100% Ground
Maturity Of Mission	Unknown/Unused

Now imagine a satellite with the mission attributes described below:

Mission Criticality	Trivial/Scientific
Space/Ground Ratio	100% Ground
Maturity Of Mission	Fully Integrated

Assign a number between 0 and 1 that best describes the utility value you place on a satellite with this mission attributes. Assume that these attributes are the only attributes to describe the satellite. **0.05**

Criterion 3: Cost/Domestic Commitment

We define a satellite with cost domestic commitment below as having utility = 1

Economic Commitment	Explosive Growth
Economic Impact	Intense Program
Launch Priority	Launch On Need/Comprehensive Sparing

Next we define a satellite with cost domestic commitment below as having utility = 0

Economic Commitment	Near Cancellation
Economic Impact	Mom & Pop Program
Launch Priority	No Near Term Launch/No Spares

This time imagine a satellite where the cost domestic commitment is as follows

Economic Commitment	Near Cancellation
Economic Impact	Mom & Pop Program
Launch Priority	Launch On Need Comprehensive Sparing

Assign a number between 0 and 1 that best describes the utility of a satellite which the commitment levels shown above. Assume that these attributes are the only applicable ones to describe the satellite. 0.7

Criterion 4: Satellite Status

A satellite with status below is defined as having utility = 1

Mission Performance Status	No Degradation
Contribution To Mission	Critical To Mission
Level Of Technology	State Of The Art
Expected Remaining Lifetime	15 Years or More

A satellite with the status below is defined as having utility = 0

Mission Performance Status	Non-Operational
Contribution To Mission	Spare No Direct Impact To Mission
Level Of Technology	Primitive
Expected Remaining Lifetime	0 Years

Finally imagine a satellite whose status is described below

Mission Performance Status	No Degradation
Contribution To Mission	Spare No Direct Impact To Mission
Level Of Technology	Primitive
Expected Remaining Lifetime	0 Years

Assign a number between 0 and 1 that best describes the utility of a satellite with the status above. Assume that these attributes are the only ones to describe the satellite. 0.1

Section V, Creating The Overall Utility Function

Rank order the four criterion in order of importance from highest to lowest

1	**Criterion 1: Environment**

This criterion defines the value associated with the time dependent "state of the world." To provide consistent value ratings for the satellites, a "snapshot" is taken and ranked. This criterion since it can be thought of as time dependent, allows a time series of satellite utility to be shown, since multiple "snapshots" can be taken over a period of time. In addition, this criterion allows some "what ifing" to be done. This criterion is evaluated only once, as the scores will be the same for any set of satellites evaluated at a particular time.

3	**Criterion 2: Mission Impact**

This criterion attempts to determine the value of a satellite's mission(s) relative to the mission(s) of other satellites. As such, the rating given may reflect an entire class of satellites, for example, those used for early warning.

2	**Criterion 3: Cost/Domestic Commitment**

The value of a satellite is demonstrated by the level of commitment a nation makes to supporting the continuation of its mission.

3	**Criterion 4: Satellite Status**

This criterion takes into account the individual characteristics of the satellite.

Assume for now that the criterion you ranked as #1 has a weighting factor of 1. On the scale below, indicate the relative weights for the other three criterion by placing them on the scale.

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Relative Weights	
	1
	0.9
	0.95
	0.9

Section VI, Creating The Overall Utility Function, Part II

We define the satellite described below as one with utility = 1

Environment	General War, Space Superpower, Depression
Mission impact	Mission Criticality, 100% Space, Fully Integrated
Cost/Domestic Commitment	Explosive Growth, Intense Program, Launch On Need/ Comprehensive Sparing
Satellite Status	No Degradation, Critical To Mission, State Of The Art, 15 Years

We define the satellite described below as one with utility = 0

Environment	Peaceful Stability, Primitive, Boom
Mission Impact	Trivial/Scientific, 100% Ground, Unknown/Unused
Cost/Domestic Commitment	Near Cancelation, Mom & Pop Program, No Near Term Launch/ No Spares
Satellite Status	Non-Operational, Spare/No Direct Impact To Mission, Primitive, 0 Years

Imagine a satellite with the characteristics described below:

Environment	General War, Space Superpower, Depression
Mission Impact	Trivial/Scientific, 100% Ground, Unknown/Unused
Cost/Domestic Commitment	Near Cancelation, Mom & Pop Program, No Near Term Launch/ No Spares
Satellite Status	Non-Operational, Spare/No Direct Impact To Mission, Primitive, 0 Years

Assign a number between 0 and 1 that best describes the utility of a satellite with these characteristics

0.3

Section VII, Calculations

Risk Attitude Constants

1-1:	0.822163
1-2:	-0.40269
1-3:	-0.82216
2-1:	0.822163
2-2:	0
2-3:	0.402692
3-1:	-0.40269
3-2:	-0.82216
3-3.	0
4-1:	-0.40269
4-2:	0
4-3:	-0.82216
4-4:	0

Calibration Constants

Criteria 1	-0.95271
Criteria 2	67.62506
Criteria 3	-0.9444
Criteria 4	8.826142
Overall	-0.27771

Criterion Weights:

Criteria 1	0.3
Criteria 2	0.27
Criteria 3	0.285
Criteria 4	0.27

Sub-Criterion Weights:

1-1:	0.675
1-2:	0.75
1-3:	0.5625
2-1:	0.0425
2-2:	0.045
2-3:	0.05
3-1:	0.63
3-2:	0.63
3-3.	0.7
4-1	0.1
4-2:	0.085
4-3:	0.075
4-4.	0.09

Risk Attitude Constant Lookup Table:

.5 Utility Point	RAC
0.05	13.86292
0.1	6.921614
0.15	4.55097
0.2	3.28128
0.25	2.437511
0.3	1.801071
0.35	1.278652
0.4	0.822163
0.45	0.402692
0.5	0
0.55	-0.402692
0.6	-0.822163
0.65	-1.278652
0.7	-1.801071
0.75	-2.437511
0.8	-3.28128
0.85	-4.55097
0.9	-6.921614
0.95	-13.86292

Calibration Constant Calculations (1000 Iterations)

Criteria 1	Criteria 2	Criteria 3	Criteria 4	Overall
-0.95271	67.62506	-0.9444	8.826142	-0.27771
0	-3.8E-09	0	-7.8E-16	-1.1E-16
-0.95271	67.62506	-0.9444	8.826142	-0.27771

Section VIII, Satellite Utility Data

	A1	A2	A3	B1	C1	A4	A5	A6
1-1: International Political State	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
1-2: Adversary's Space Capability	0.825	0.825	0.825	0.5	0.3	0.825	0.825	0.825
1-3: International Economy	0.675	0.675	0.675	0.6	0.6	0.675	0.675	0.675
2-1: Mission Criticality	1	1	1	0.8	0.4	0.6	0.6	0.25
2-2: Space/Ground Ratio	0.4	0.4	0.4	0.35	0.4	0.5	0.5	0.25
2-3: Maturity Of Mission	1	1	1	0.7	0.8	0.5	1	0.6
3-1: Economic Commitment	0.4	0.5	0.3	0.7	0.8	0.75	0.5	0.7
3-2: Economic Impact	0.8	0.8	0.6	0.65	0.6	0.75	0.5	0.4
3-3: Launch Priority	0.7	0.6	0.4	0	0	0.4	0.3	0.5
4-1: Mission Performance Status	1	0.9	0.6	0.85	1	1	1	1
4-2: Contribution To Mission	0.6	0.7	0.4	1	0.8	0.9	0.25	0.25
4-3: Level Of Technology	0.7	0.8	0.5	0.8	0.85	1	0.5	0.5
4-4: Expected Remaining Lifetime	0	0.1	0.1	0.15	0.1	0.35	0.35	0.2

U(1-1)	0.27051	0.27051	0.27051	0.27051	0.27051	0.27051	0.27051	0.27051
U(1-2)	0.79472	0.79472	0.79472	0.44983	0.25897	0.79472	0.79472	0.79472
U(1-3)	0.58167	0.58167	0.58167	0.5	0.5	0.58167	0.58167	0.58167
U(2-1)	1	1	1	0.85987	0.5	0.6947	0.6947	0.33147
U(2-2)	0.4	0.4	0.4	0.35	0.4	0.5	0.5	0.25
U(2-3)	1	1	1	0.74103	0.83085	0.55017	1	0.64752
U(3-1)	0.35248	0.44983	0.25897	0.65671	0.76656	0.71108	0.44983	0.65671
U(3-2)	0.72949	0.72949	0.5	0.55389	0.5	0.66853	0.39865	0.3053
U(3-3)	0.7	0.6	0.4	0	0	0.4	0.3	0.5
U(4-1)	1	0.88093	0.55119	0.82317	1	1	1	1
U(4-2)	0.6	0.7	0.4	1	0.8	0.9	0.25	0.25
U(4-3)	0.61003	0.72949	0.39865	0.72949	0.79301	1	0.39865	0.39865
U(4-4)	0	0.1	0.1	0.15	0.1	0.35	0.35	0.2
Environment Utility	0.79174	0.79174	0.79174	0.61893	0.53237	0.79174	0.79174	0.79174
Mission Impact Utility	0.54172	0.54172	0.54172	0.35683	0.28959	0.3048	0.47475	0.14737
Cost/Domestic Commitment Utility	0.80443	0.79406	0.59601	0.62633	0.65427	0.78825	0.58465	0.70543
Satellite Status Utility	0.32092	0.37836	0.18542	0.4549	0.44853	0.64565	0.29586	0.25771
SATELLITE UTILITY	0.65228	0.66272	0.5691	0.54958	0.51612	0.66861	0.57597	0.52108
Rank	3	2	6	5	8	1	4	7

Appendix B: Case Study #2, Titan Launch Survey

Decision Maker: Capt. Paul Krey
5 SLS/DOO

Interview Date: 20 September 1994

Section I: Mapping The Single Variable Utility Functions

Criterion 1: Environment

This criterion defines the value associated with the time dependent "state of the world." To provide consistent value ratings for the satellites, a "snapshot" is taken and ranked. This criterion since it can be thought of as time dependent, allows a time series of satellite utility to be shown, since multiple "snapshots" can be taken over a period of time. In addition, this criterion allows some "what ifing" to be done. This criterion is evaluated only once, as the scores will be the same for any set of satellites (from the same country) evaluated at a particular time.

Sub-Criterion 1-1: Political State

This sub-criterion describes the current international political environment.

- **0.00** - "Peaceful Stability" International relations are stable and the world is absent of any significant military/political crises. Obviously, this state is exceptionally rare.
- **0.25** - "Minor Crises/Degrading Stability" One or more minor local/regional crises are in progress, that do not immediately threaten national security. Relations with allies or adversaries may be degraded, but negotiations are continuing. For most countries, this is the most common state during the 20th century.
- **0.50** - "Major Crisis" One or more regional crises are in progress, that potentially threaten national security. Relations with allies or adversaries are substantially degraded, and negotiations are seemingly at an impasse. This would describe the political landscape throughout most of the 1930's.
- **0.75** - "Limited War" Tensions between nations are high. Regional conflict has broken out that threatens national security. General war threatens. The Korean and Vietnam Wars are examples of this environment.
- **1.00** - "General War" National forces are fully mobilized and committed to intense combat. World War II exemplifies this environment.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5]

ANS: 0.25

Sub-Criterion 1-2: Adversary's Space Capability

This sub-criterion examines the overall space capability of the nation The Pareto assumption here is that the more space-capable a nation is, the more individual space assets are relied upon

- **0.00** - "Primitive" Nation has virtually no space assets whatsoever. In addition, it has little or no ability to interfere with other nation's deployed assets
- **0.25** - "Minor Space Power" Possesses has limited space assets, deployed primarily in support roles Some interference/jamming capability is likely
- **0.50** - "Medium Space Power" Assets are deployed in support and force enhancement roles. Demonstrated capability to interfere/jam enemy satellite systems.
- **0.75** - "Major Space Power" Assets are deployed across nearly the full range of mission areas, and has integrated them somewhat with terrestrial forces. Likely offensive anti-satellite capability.
- **1.00** - "Space Superpower" Fully deployed and integrated systems across the full range of missions. Demonstrated offensive/defensive anti-satellite capability.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1 00 [u(1 00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.75

Sub-Criterion 1-3: International Economy

This sub-criterion describes the state of the nation's economy This sub-criterion may at first appear to be scaled in reverse. However, we are considering a satellite's value in terms of the economic conditions, where the value placed on the asset increases as economic conditions worsen.

- **0.00** - "Boom" Characterized by rapid economic growth and vigorous international trade.
- **0.25** - "Growth" Overall, economy is healthy and growing Trade barriers are minimal.
- **0.50** - "Stable" Most common economic state. Trade relations and currency exchanges are stable. Trade barriers may be present, but do not seriously hamper trade relations.
- **0.75** - "Recession" Economy is shrinking. Currency exchanges may be unstable. Trade relations are constrained, protectionism is prevalent
- **1.00** - "Depression" Economy is in collapse International trade is minimal, with trade barriers dominating.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5]

ANS: 0.5

Criterion 2: Mission Impact

This criterion attempts to determine the value of a satellite's mission(s) relative to the mission(s) of other satellites As such, the rating given may reflect an entire class of satellites, for example. those used for early warning

Sub-Criterion 2-1: "Mission Criticality"

This sub-criterion rates the relative importance of satellite missions, such as early warning, communications, weather, etc.

- **0.00** - "Trivial/Scientific" Mission is primarily scientific in nature, and has virtually no impact to the warfighter. This does not mean the satellite is useless, but that it has no direct or current application to military offensive/defensive capabilities.
- **0.25** - "Minor Component" While not contributing directly to warfighting capability, the satellite directly aids forces that do.
- **0.50** - "Medium Component" Satellites plays a significant role in force offensive/defensive
- **0.75** - "Major Component" Satellite mission plays a significant in force offensive/defensive strategy.
- **1.00** - "Critical!" Mission constitutes a critical capability, without which it would be difficult or nearly impossible to conduct wartime operations.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.9

Sub-Criterion 2-2: "Space/Ground Ratio"

Here the relative amount of the mission accomplished in space versus on the ground is examined.

- **0.00** - "100% Ground" Terrestrial assets perform the entire operational mission
- **0.25** - "Primarily Ground" Space assets are sometimes used for the operational mission, however, ground counterparts dominate. Space systems seen as somewhat experimental, and serve primarily in backup roles
- **0.50** - "50/50 Mix" Space and ground assets are equally relied upon to perform an assigned mission.
- **0.75** - "Primarily Space" Space assets dominate mission accomplishment. Ground assets are secondary or used as a backup.
- **1.00** - "100% Space" The entire mission is performed by space assets Ground backup is not available or unreliable

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5]

ANS: 0.5

Sub-Criterion 2-3: Maturity Of Mission

How well the satellite's mission is understood by warfighters and integrated into overall capabilities is considered in this sub-criterion

0.00 - "Unknown/Unused" Satellite's capabilities are not understood or utilized by strategic and tactical commanders. Satellite remains largely an R&D project.

0.25 - "Little Known" Satellite capacity is partially understood and used, but only on a basic level. R&D community possesses the expertise to operate the satellite.

0.50 - "Somewhat Integrated" Operational Turnover of the satellite has occurred from the R&D community to an operational unit. Capabilities are still being explored. Information concerning the satellite has reached field commanders and experimental/tentative use has begun.

0.75 - "Widely Known/Substantially Integrated" Operation of the satellite is normalized. Field commanders understand capabilities and routinely use them. Some problems still exist, and alternate assets are maintained and frequently relied upon.

1.00 - "Fully Integrated" Satellite is fully understood and exploited, and capabilities are fully integrated into theater operations.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 { u(?) = 0.5].

ANS: 0.6

Criterion 3: Cost/Domestic Commitment

The value placed on a satellite is demonstrated by the level of commitment a nation makes to supporting the continuation of its mission.

Sub-Criterion 3-1: Economic Commitment

The funding status of the satellite's production, operations and infrastructure is evaluated here

0.00 - "Near Cancellation" Commitment to the satellite (program) is minimal or near termination. Natural reasons for this to occur is that it is near the end of the satellite's (program) life cycle, or upon the advent of a new technology that renders the satellite obsolete. Political considerations may also cause termination.

0.25 - "Drawdown" Support is in decline. This may be due to political/economic considerations, or it may be late in the satellite's (program's) life cycle.

0.50 - "Stable" Funding is stable. Typical of a satellite (program) early or near the mid-point of its life-cycle.

0.75 - "Growth" Funding is growing steadily. This is typical of a fairly young satellite (program), when political support is growing and infrastructure is still being added.

1.00 - "Explosive Growth" Political support and funding for the satellite is rapidly expanding. Political support is consolidating.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5]

ANS: 0.4

Sub-Criterion 3-2: Economic Impact

While the previous sub-criterion looks at the growth rate, this sub-criterion examines the current size and impact due to the commitment to the satellite.

0.00 - "'Mom & Pop' Program" Very small organization that impacts only a small local economy. Production facilities might consist of a single small plant.

0.25 - "Minor Program" Dominates only a local economy Production facilities might consist of a few small plants or a single large one.

0.50 - "Regional Program" Program infrastructure is significant to a regional economy. Program is large enough to receive some national legislative scrutiny.

0.75 - "Major Program" Program infrastructure is significant to national economy and receives significant substantial national public and legislative attention.

1.00 - "Intense Program" Substantial sacrifices are made at the national level to continue funding of the satellite's infrastructure. Single-minded economic priority is given to the satellite.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.75

Sub-Criterion 3-3: Launch Priority

Launch priority given to a satellite is an excellent indicator of the value placed on that asset. This sub-criterion also includes the "sparing" strategy, as the presence of spare satellites on the ground or on-orbit affects the priority given to a new launch.

0.00 - "No Near Term Launch/No Spares" No capability exists to replace the satellite in the near term. Replacement satellites have not been constructed and/or no launch vehicles are available.

0.25 - "Delayed Schedule/Limited Sparing" Replacement satellites have been partially constructed, but are not available for near term launch A launch schedule does not exist, is incomplete, or delayed

0.50 - "Stable Launch Schedule/Substantial Sparing" Launch of replacement satellites can be accomplished on a schedule However the schedule is somewhat inflexible Spares are available, but most are on the ground, and those in orbit are not positioned for immediate use

0.75 - "Accelerated Schedule/Near Complete Sparing" Launch of replacement satellites can be accomplished on an accelerated schedule. Several spares are constructed with most placed in orbit to be positioned in the short term.

1.00 - "Launch On Need/Comprehensive Sparing" Launch is possible on relatively short notice. A comprehensive sparing strategy is in place. On-orbit spares can be made operational quickly

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.5

Criterion 4: Satellite Status

This criterion takes into account the individual characteristics of the satellite.

Sub-Criterion 4-1: Mission Performance Status

How well the satellite is performing its assigned mission is directly applicable to the value that is placed on it.

- **0.00** - "Non-Operational" Satellite is degraded to the extent that it cannot be considered operational.
- **0.25** - "Severely Degraded/Turned Off Spare" Satellite is capable of performing its mission only to a marginal extent. Satellite may be configured as a spare, with secondary power turned off until needed.
- **0.50** - "Significantly Degraded" Satellite satisfactorily performs it mission, but at a substantially degraded level.
- **0.75** - "Slightly Degraded" Satellite performs its mission as expected, but some minor degradation is present.
- **1.00** - "No Degradation" Satellite is fully capable of performing its mission with no failed or degraded units.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.75

Sub-Criterion 4-2: Contribution To Mission

Rarely does a single satellite accomplish an entire mission. Typically, satellites are grouped into a constellation to complete an assigned mission. Here the satellite's contribution to completing the mission is measured.

- **0.00** - "Spare/No Direct Impact To Mission" Loss of the satellite will not adversely impact the capability to accomplish a mission. A typical case would be a satellite configured as an on-orbit spare.
- **0.25** - "Secondary Impact To Mission" Loss of satellite would impact the constellation at a secondary level only. The mission completed by this satellite can be readily transferred to another satellites
- **0.50** - "Impacts Constellation Mission" Loss of the satellite would adversely impact mission accomplishment. Much of the satellite's duties can be transferred but noticeable degradation will occur
- **0.75** - "Strongly Impacts Mission" Loss of the satellite significantly impacts mission accomplishment. Satellite mission duties are largely irreplaceable, hence substantial degradation results.
- **1.00** - "Critical To Mission" Loss of satellite critically impairs mission accomplishment.

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0] and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1] show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5]

ANS: 0.6

Sub-Criterion 4-3: Level Of Technology

In general, more modern satellites that employ improved technologies have greater capabilities. In particular, satellites that employ newer technologies represent a significant investment in research and development. Presumably, this investment has purpose and value.

- **0.00** - "Primitive" Space technology is at the most rudimentary level. A satellite such as this would hearken back to the days of Sputnik.
- **0.25** - "30 Year Old State of the Art" Today (1994), this represents technology developed and employed by advanced nations in the 1960's.
- **0.50** - "20 Year Old State of the Art" Technology originally developed and fielded the most advanced nations in the 1970's.
- **0.75** - "10 Year Old State of the Art" Technology originally developed and fielded by the most advanced nations during the 1980's.
- **1.00** - "State of the Art" Represents the current possible fielded space technology

0.00 0.25 0.50 0.75 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5].

ANS: 0.8

Sub-Criterion 4-4: Expected Remaining Lifetime

It would seem obvious that the value placed on a satellite depends on an estimation of how long the satellite will remain operational. This is to be distinguished from a satellite's planned life cycle, which is a fixed timespan estimated by satellite designers. The expected remaining lifetime is a changing estimate, affected by the spacecraft's age, fuel reserves, and known satellite subsystem failures.

- **0.00** - "0 years" Complete failure is anticipated at any time.
- **0.20** - "3 years"
- **0.40** - "6 years"
- **0.60** - "9 years"
- **0.80** - "12 years"
- **1.00** - "15 years or more"

0.00 0.20 0.40 0.60 0.80 1.00

If the satellite is assigned a value (utility) of 0 when the criterion is at level 0.00 [we assign u(0.00) = 0], and the satellite is assigned a utility of 1 when the criterion is at level 1.00 [u(1.00) = 1], show on the scale above the criterion level that you think would yield a satellite utility of 0.5 [u(?) = 0.5]

ANS: 0.55

Section II: Independence Verification

For sub-criterion 4-1, Mission Accomplishment, you indicated that the level of this attribute that yields a utility of 0.5 is

0.75

Assume now that the level of sub-criterion 1-1, Political State, is **0.00**. Does this change your assessment above for sub-criterion 4-1? NO

What if the level of sub-criterion 1-1 is changed to **0.50** ? NO

What if the level of sub-criterion 1-1 is changed to **1.00** ? NO

Assume now that the level of sub-criterion 1-2, Overall Space Capability, is **0.00**. Does this change your assessment above for sub-criterion 4-1? NO

What if the level of sub-criterion 1-2 is changed to **0.50** ? NO

What if the level of sub-criterion 1-2 is changed to **1.00** ? NO

Assume now that the level of sub-criterion 1-3 National Economy, is **0.00** Does this change your assessment above for sub-criterion 4-1? NO

What if the level of sub-criterion 1-3 is changed to **0.50** ? NO

What if the level of sub-criterion 1-3 is changed to **1.00** ? NO

Assume now that the level of sub-criterion 2-1, Mission Criticality, is **0.00** Does this change your assessment above for sub-criterion 4-1? NO

What if the level of sub-criterion 2-1 is changed to **0.50** ? NO

What if the level of sub-criterion 2-1 is changed to **1.00** ? NO

Assume now that the level of sub-criterion 2-2, Space/Ground Ratio, is **0.00** Does this change your assessment above for sub-criterion 4-1? NO

What if the level of sub-criterion 2-2 is changed to **0.50** ? NO

What if the level of sub-criterion 2-2 is changed to **1.00** ? NO

Assume now that the level of sub-criterion 2-3, Maturity of Mission, is **0.00** Does this change your assessment above for sub-criterion 4-1? NO

What if the level of sub-criterion 2-3 is changed to **0.50** ? NO

What if the level of sub-criterion 2-3 is changed to **1.00** ? NO

Assume now that the level of sub-criterion 3-1, Economic Commitment, is **0.00** Does this change your assessment above for sub-criterion 4-1? NO

What if the level of sub-criterion 3-1 is changed to **0.50** ? NO

What if the level of sub-criterion 3-1 is changed to **1.00** ? NO

Assume now that the level of sub-criterion 3-2 Economic Impact, is **0.00** Does this change your assessment above for sub-criterion 4-1? NO

What if the level of sub-criterion 3-2 is changed to **0.50** ? NO

What if the level of sub-criterion 3-2 is changed to **1.00** ? NO

Assume now that the level of sub-criterion 3-3, Launch Priority, is **0.00**. Does this change your assessment above for sub-criterion 4-1? **NO**

What if the level of sub-criterion 3-3 is changed to **0.50** ? **NO**

What if the level of sub-criterion 3-3 is changed to **1.00** ? **NO**

Assume now that the level of sub-criterion 4-2, Contribution to Mission, is **0.00**. Does this change your assessment above for sub-criterion 4-1? **NO**

What if the level of sub-criterion 4-2 is changed to **0.50** ? **NO**

What if the level of sub-criterion 4-2 is changed to **1.00** ? **NO**

Assume now that the level of sub-criterion 4-3, Level of Technology, is **0.00** Does this change your assessment above for sub-criterion 4-1? **NO**

What if the level of sub-criterion 4-3 is changed to **0.50** ? **NO**

What if the level of sub-criterion 4-3 is changed to **1.00** ? **NO**

Assume now that the level of sub-criterion 4-4 Expected Remaining Lifetime, is **0.00**. Does this change your assessment above for sub-criterion 4-1? **NO**

What if the level of sub-criterion 4-4 is changed to **0.50** ? **NO**

What if the level of sub-criterion 4-4 is changed to **1.00** ? **NO**

Section III: Creating The Multi-Variate Criterion Utility Functions

Criterion 1: Environment

Rank order the three sub-cnterion in order of importance from highest to lowest.

[1] **Sub-Criterion 1-1: Political State**

This sub-criterion describes the current international political environment.

[2] **Sub-Criterion 1-2: Adversary's Space Capability**

This criterion examines the relative space capability of a potential or actual adversary

[3] **Sub-Criterion 1-3: International Economy**

This sub-criterion describes the state of the worldwide economy. This sub-criterion may at first appear to be scaled in reverse, however, as we consider a satellite's value in terms of the economic times the value placed on the asset increases as economic conditions worsen

Assume for now that the sub-criterion you ranked as #1 has a weighting factor of 1. On the scale below, indicate the relative weights for the other two sub-criterion, by placing them on the scale.

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Relative Weights.

1
0.6
0.3

Criterion 2: Mission Impact

Rank order the three sub-criterion in order of importance, from highest to lowest.

[1] **Sub-Criterion 2-1: Mission Criticality**

This sub-criterion rates the relative importance of satellite missions, such as early warning, communications, weather, etc.

[3] **Sub-Criterion 2-2: Space/Ground Ratio**

Here the relative amount of the mission accomplished in space versus on the ground is examined.

[2] **Sub-Criterion 2-3: Maturity Of Mission**

How well the satellite's mission is understood by warfighters and integrated into overall capabilities is considered in this sub-criterion.

Assume for now that the sub-criterion you ranked as #1 has a weighting factor of 1. On the scale below, indicate the relative weights for the other two sub-criterion, by placing them on the scale.

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Relative Weights:

1
0.3
0.5

Criterion 3: Cost/Domestic Commitment

Rank order the three sub-criterion in order of importance, from highest to lowest.

2	**Sub-Criterion 3-1: Economic Commitment**
	The funding status of the satellite's production, operations and infrastructure is evaluated here.
3	**Sub-Criterion 3-2: Economic Impact**
	While the previous sub-criterion looks at the growth rate, this sub-criterion examines the current size and impact of the commitment to the satellite.
1	**Sub-Criterion 3-3: Launch Priority**
	Launch priority given to a satellite is an excellent indicator of the value placed on that asset. This sub-criterion also includes the "sparing" strategy, as the presence of spare satellites on the ground or on-orbit affects the priority given to a new launch.

Assume for now that the sub-criterion you ranked as #1 has a weighting factor of 1. On the scale below indicate the relative weights for the other two sub-criterion, by placing them on the scale.

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Relative Weights:

0.8
0.35
1

Criterion 4: Satellite Status

Rank order the four sub-criterion in order of importance, from highest to lowest.

1	**Sub-Criterion 4-1: Mission Performance Status**
	How well the satellite is performing its assigned mission is directly applicable to the value that is placed on it.
2	**Sub-Criterion 4-2: Contribution To Mission**
	Rarely does a single satellite accomplish an entire mission. Typically, satellites are grouped into a constellation to complete an assigned mission. Here the satellite's contribution to completing the constellation's mission is measured.
4	**Sub-Criterion 4-3: Level Of Technology**
	In general, more modern satellites that employ improved technologies have greater capabilities. In particular, satellites that employ newer technologies represent a significant investment in research and development. Presumably, this investment has purpose and value.

3	**Sub-Criterion 4-4: Expected Remaining Lifetime**

It would seem obvious that the value placed on a satellite depends on an estimation of how long the satellite will remain operational. This is to be distinguished from a satellite's planned life cycle, which is a fixed timespan estimated by satellite designers. The expected remaining lifetime is a changing estimate, affected by the spacecraft's age, fuel reserves, and known satellite subsystem failures.

Assume for now that the sub-criterion you ranked as #1 has a weighting factor of 1. On the scale below, indicate the relative weights for the other two sub-criterion, by placing them on the scale.

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Relative Weights:

1
0.9
0.35
0.65

Section IV, Creating The Multi-Variate Criterion Utility Functions, Part II

Criterion 1: Environment

We define a satellite used in the environment below as having a utility = 1

Political State	General War
Adversary's Space Capability	Space Superpower
International Economy	Depression

Now we define a satellite used in the environment below as having a utility = 0.

Political State	Peaceful Stability
Adversary's Space Capability	Primitive
International Economy	Boom

Imagine a satellite used in the environment described below:

Political State	General War
Adversary's Space Capability	Primitive
International Economy	Boom

Assign a number between 0 and 1 that best describes the utility value you place on a satellite that is used in this environment. Assume that these three attributes are the only attributes to describe the satellite. **0.9**

Criterion 2: Mission Impact

We define a satellite with the mission attributes below as having utility = 1.

Mission Criticality	Critical To Force Survival
Space/Ground Ratio	100% Space
Maturity Of Mission	Fully Integrated

Now we define a satellite with the mission attributes as having utility = 0.

Mission Criticality	Trivial/Scientific
Space/Ground Ratio	100% Ground
Maturity Of Mission	Unknown/Unused

Now imagine a satellite with the mission attributes described below:

Mission Criticality	Critical To Force Survival
Space/Ground Ratio	100% Ground
Maturity Of Mission	Unknown/Unused

Assign a number between 0 and 1 that best describes the utility value you place on a satellite with this mission attributes. Assume that these attributes are the only attributes to describe the satellite **0.75**

Criterion 3: Cost/Domestic Commitment

We define a satellite with cost/domestic commitment below as having utility = 1.

Economic Commitment	Explosive Growth
Economic Impact	Intense Program
Launch Priority	Launch On Need/Comprehensive Sparing

Next we define a satellite with cost/domestic commitment below as having utility = 0.

Economic Commitment	Near Cancellation
Economic Impact	Mom & Pop Program
Launch Priority	No Near Term Launch/No Spares

This time imagine a satellite where the cost/domestic commitment is as follows:

Economic Commitment	Near Cancellation
Economic Impact	Mom & Pop Program
Launch Priority	Launch On Need/Comprehensive Sparing

Assign a number between 0 and 1 that best describes the utility of a satellite which the commitment levels shown above Assume that these attributes are the only applicable ones to describe the satellite

0.7

Criterion 4: Satellite Status

A satellite with status below is defined as having utility = 1.

Mission Performance Status	No Degradation
Contribution To Mission	Critical To Mission
Level Of Technology	State Of The Art
Expected Remaining Lifetime	15 Years or More

A satellite with the status below is defined as having utility = 0

Mission Performance Status	Non-Operational
Contribution To Mission	Spare/No Direct Impact To Mission
Level Of Technology	Primitive
Expected Remaining Lifetime	0 Years

Finally, imagine a satellite whose status is described below:

Mission Performance Status	No Degradation
Contribution To Mission	Spare/No Direct Impact To Mission
Level Of Technology	Primitive
Expected Remaining Lifetime	0 Years

Assign a number between 0 and 1 that best describes the utility of a satellite with the status above. Assume that these attributes are the only ones to describe the satellite.

0.8

Section V, Creating The Overall Utility Function

Rank order the four criterion in order of importance, from highest to lowest.

[3] Criterion 1: Environment

This criterion defines the value associated with the time dependent "state of the world." To provide consistent value ratings for the satellites, a "snapshot" is taken and ranked. This criterion since it can be thought of as time dependent, allows a time series of satellite utility to be shown, since multiple "snapshots" can be taken over a period of time. In addition, this criterion allows some "what ifing" to be done. This criterion is evaluated only once, as the scores will be the same for any set of satellites evaluated at a particular time.

[1] Criterion 2: Mission Impact

This criterion attempts to determine the value of a satellite's mission(s) relative to the mission(s) of other satellites. As such, the rating given may reflect an entire class of satellites, for example, those used for early warning.

[3] Criterion 3: Cost/Domestic Commitment

The value of a satellite is demonstrated by the level of commitment a nation makes to supporting the continuation of its mission.

[2] Criterion 4: Satellite Status

This criterion takes into account the individual characteristics of the satellite.

Assume for now that the criterion you ranked as #1 has a weighting factor of 1. On the scale below, indicate the relative weights for the other three criterion, by placing them on the scale.

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Relative Weights:

0.55
1
0.55
0.9

Section VI, Creating The Overall Utility Function, Part II

We define the satellite described below as one with utility = 1.

Environment	General War, Space Superpower, Depression
Mission Impact	Mission Criticality, 100% Space Fully Integrated
Cost/Domestic Commitment	Explosive Growth, Intense Program, Launch On Need/ Comprehensive Sparing
Satellite Status	No Degradation, Critical To Mission State Of The Art, 15 Years

We define the satellite described below as one with utility = 0.

Environment	Peaceful Stability, Primitive, Boom
Mission Impact	Trivial/Scientific, 100% Ground, Unknown/Unused
Cost/Domestic Commitment	Near Cancellation. Mom & Pop Program, No Near Term Launch/ No Spares
Satellite Status	Non-Operational, Spare/No Direct Impact To Mission. Primitive. 0 Years

Imagine a satellite with the characteritics described below:

Environment	Peaceful Stability, Primitive, Boom
Mission Impact	Mission Criticality, 100% Space, Fully Integrated
Cost/Domestic Commitment	Near Cancellation. Mom & Pop Program, No Near Term Launch/ No Spares
Satellite Status	Non-Operational, Spare/No Direct Impact To Mission, Primitive, 0 Years

Assign a number between 0 and 1 that best describes the utility of a satellite with these characteristics

0.1

Section VII, Calculations

Risk Attitude Constants

1-1:	2.437511
1-2:	-2.43751
1-3:	0
2-1:	-6.92161
2-2:	0
2-3:	-0.82216
3-1:	0.822163
3-2:	-2.43751
3-3:	0
4-1:	-2.43751
4-2:	-0.82216
4-3:	-3.28128
4-4:	-0.40269

Calibration Constants

Criteria 1	-0.94579
Criteria 2	-0.71561
Criteria 3	-0.81082
Criteria 4	-0.97682
Overall	12.39082

Criterion Weights:

Criteria 1	0.055
Criteria 2	0.1
Criteria 3	0.055
Criteria 4	0.09

Sub-Criterion Weights:

1-1:	0.9
1-2:	0.54
1-3:	0.27
2-1:	0.75
2-2:	0.225
2-3:	0.375
3-1:	0.56
3-2:	0.245
3-3:	0.7
4-1:	0.8
4-2:	0.72
4-3:	0.28
4-4:	0.52

Risk Attitude Constant Lookup Table:

.5 Utility Point	RAC
0.05	13.86292
0.1	6.921614
0.15	4.55097
0.2	3.28128
0.25	2.437511
0.3	1.801071
0.35	1.278652
0.4	0.822163
0.45	0.402692
0.5	0
0.55	-0.402692
0.6	-0.822163
0.65	-1.278652
0.7	-1.801071
0.75	-2.437511
0.8	-3.28128
0.85	-4.55097
0.9	-6.921614
0.95	-13.86292

Calibration Constant Calculations (1000 Iterations)

Criteria 1	Criteria 2	Criteria 3	Criteria 4	Overall
-0.94579	-0.71561	-0.81082	-0.97682	12.39082
0	0	0	0	-8.8E-12
-0.94579	-0.71561	-0.81082	-0.97682	12.39082

Section VIII, Satellite Utility Data

	K-a Milstar DFS-2	K-b DSP 17	K-c NASA Cassini	K-d *	K-e *			
1-1: International Political State	0.25	0.25	0.25	0.25	0.25			
1-2: Adversary's Space Capability	0.75	0.75	0.75	0.75	0.75			
1-3: International Economy	0.5	0.5	0.5	0.5	0.5			
2-1: Mission Criticality	0.75	0.95	0.1	0.7	0.7			
2-2: Space/Ground Ratio	0.5	0.75	1	0.75	0.75			
2-3: Maturity Of Mission	0.8	1	0	0.3	0.6			
3-1: Economic Commitment	0.35	0.5	0.5	0.35	0.5			
3-2: Economic Impact	0.75	0.75	0.8	0.75	0.75			
3-3: Launch Priority	0.5	0.6	0.5	0.5	0.6			
4-1: Mission Performance Status	1	1	1	1	1			
4-2: Contribution To Mission	0.5	0.75	1	0.5	0.6			
4-3: Level Of Technology	1	0.75	0.85	0.8	0.9			
4-4: Expected Remaining Lifetime [1]	0.7	0.5	0.7	0.6	0.5			

U(1-1)	0.5	0.5	0.5	0.5	0.5	0	0	0
U(1-2)	0.5	0.5	0.5	0.5	0.5	0	0	0
U(1-3)	0.5	0.5	0.5	0.5	0.5	0	0	0
U(2-1)	0.1764	0.70717	0.00099	0.12451	0.12451	0	0	0
U(2-2)	0.5	0.75	1	0.75	0.75	0	0	0
U(2-3)	0.72949	1	0	0.21932	0.5	0	0	0
U(3-1)	0.44611	0.60135	0.60135	0.44611	0.60135	0	0	0
U(3-2)	0.5	0.5	0.57722	0.5	0.5	0	0	0
U(3-3)	0.5	0.6	0.5	0.5	0.6	0	0	0
U(4-1)	1	1	1	1	1	0	0	0
U(4-2)	0.39865	0.66853	1	0.39865	0.5	0	0	0
U(4-3)	1	0.41844	0.59611	0.5	0.70935	0	0	0
U(4-4)	0.65671	0.44983	0.65671	0.55119	0.44983	0	0	0
Environment Utility	0.66283	0.66283	0.66283	0.66283	0.66283	0	0	0
Mission Impact Utility	0.46187	0.83965	0.22562	0.31834	0.40469	0	0	0
Cost/Domestic Commitment Utility	0.59889	0.7008	0.66482	0.59889	0.7008	0	0	0
Satellite Status Utility	0.94578	0.94274	0.9867	0.92366	0.93353	0	0	0
SATELLITE UTILITY	0.45228	0.64387	0.37683	0.38631	0.44981	0	0	0
Rank	2	1	5	4	3			

[1] A median value was used for the Expected Remaining Lifetime for satellite K-b. The actual value could not be used in this unclassified document

Appendix C: Titan Simplified Launch Processing & Scheduling Optimization LP

```
LP83 thesis2 output t2.out alternate 1 costanalysis yes

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  San Marino, California  91108   U.S.A.

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* DEFINITIONS
*
* Variables = X _ _ _
*
* 1st placeholder:  Satellite Designation - a, b, c, d, e
* 2nd placeholder:  Process location -  i = move to VIB and process
*                                       j = continue or hold VIB processing
*                                       k = move to SMAB and process
*                                       l = continue or hold SMAB processing
*                                       m = move to launch pad (SLC 40/41) and process
*                                       n = continue or hold launch processing
*                                       o = launch completed and pad refurbished
* 3rd placeholder:  time(2 month increments)- 1, 2, 3, 4, 5, 6, 7
*                                       time 1 = beginning of month 1 (end of month 0)
*                                       time 2 = beginning of month 3 (end of month 2)
*                                       time 3 = beginning of month 5 (end of month 4)
*                                       time 4 = beginning of month 7 (end of month 6)
*                                       time 5 = beginning of month 9 (end of month 8)
*                                       time 6 = beginning of month 11 (end of month 10)
*                                       time 7 = beginning of month 13 (end of month 12)
*
*
..TITLE
  Launch Prioritization
*
* utility(K-a) = .452
* utility(K-b) = .644
* utility(K-c) = .377
* utility(K-d) = .386
* utility(K-e) = .450
*
*
..OBJECTIVE MAXIMIZE
*
        .452 Xai1 + .644 Xbi1 + .377 Xci1 + .386 Xdi1 + .450 Xei1
      + .452 Xai2 + .644 Xbi2 + .377 Xci2 + .386 Xdi2 + .450 Xei2
      + .452 Xai3 + .644 Xbi3 + .377 Xci3 + .386 Xdi3 + .450 Xei3
      + .452 Xai4 + .644 Xbi4 + .377 Xci4 + .386 Xdi4 + .450 Xei4
      + .452 Xai5 + .644 Xbi5 + .377 Xci5 + .386 Xdi5 + .450 Xei5
      + .452 Xai6 + .644 Xbi6 + .377 Xci6 + .386 Xdi6 + .450 Xei6
      + .452 Xai7 + .644 Xbi7 + .377 Xci7 + .386 Xdi7 + .450 Xei7
      + 0 Xaj1 + 0 Xbj1 + 0 Xcj1 + 0 Xdj1 + 0 Xej1
      + 0 Xaj2 + 0 Xbj2 + 0 Xcj2 + 0 Xdj2 + 0 Xej2
      + 0 Xaj3 + 0 Xbj3 + 0 Xcj3 + 0 Xdj3 + 0 Xej3
      + 0 Xaj4 + 0 Xbj4 + 0 Xcj4 + 0 Xdj4 + 0 Xej4
      + 0 Xaj5 + 0 Xbj5 + 0 Xcj5 + 0 Xdj5 + 0 Xej5
      + 0 Xaj6 + 0 Xbj6 + 0 Xcj6 + 0 Xdj6 + 0 Xej6
      + 0 Xaj7 + 0 Xbj7 + 0 Xcj7 + 0 Xdj7 + 0 Xej7
      + 0 Xak1 + 0 Xbk1 + 0 Xck1 + 0 Xdk1 + 0 Xek1
      + 0 Xak2 + 0 Xbk2 + 0 Xck2 + 0 Xdk2 + 0 Xek2
      + 0 Xak3 + 0 Xbk3 + 0 Xck3 + 0 Xdk3 + 0 Xek3
```

```
        + 0 Xak4 + 0 Xbk4 + 0 Xck4 + 0 Xdk4 + 0 Xek4
        + 0 Xak5 + 0 Xbk5 + 0 Xck5 + 0 Xdk5 + 0 Xek5
        + 0 Xak6 + 0 Xbk6 + 0 Xck6 + 0 Xdk6 + 0 Xek6
        + 0 Xak7 + 0 Xbk7 + 0 Xck7 + 0 Xdk7 + 0 Xek7
        + 0 Xal1 + 0 Xbl1 + 0 Xcl1 + 0 Xdl1 + 0 Xel1
        + 0 Xal2 + 0 Xbl2 + 0 Xcl2 + 0 Xdl2 + 0 Xel2
        + 0 Xal3 + 0 Xbl3 + 0 Xcl3 + 0 Xdl3 + 0 Xel3
        + 0 Xal4 + 0 Xbl4 + 0 Xcl4 + 0 Xdl4 + 0 Xel4
        + 0 Xal5 + 0 Xbl5 + 0 Xcl5 + 0 Xdl5 + 0 Xel5
        + 0 Xal6 + 0 Xbl6 + 0 Xcl6 + 0 Xdl6 + 0 Xel6
        + 0 Xal7 + 0 Xbl7 + 0 Xcl7 + 0 Xdl7 + 0 Xel7
        + 0 Xam1 + 0 Xbm1 + 0 Xcm1 + 0 Xdm1 + 0 Xem1
        + 0 Xam2 + 0 Xbm2 + 0 Xcm2 + 0 Xdm2 + 0 Xem2
        + 0 Xam3 + 0 Xbm3 + 0 Xcm3 + 0 Xdm3 + 0 Xem3
        + 0 Xam4 + 0 Xbm4 + 0 Xcm4 + 0 Xdm4 + 0 Xem4
        + 0 Xam5 + 0 Xbm5 + 0 Xcm5 + 0 Xdm5 + 0 Xem5
        + 0 Xam6 + 0 Xbm6 + 0 Xcm6 + 0 Xdm6 + 0 Xem6
        + 0 Xam7 + 0 Xbm7 + 0 Xcm7 + 0 Xdm7 + 0 Xem7
        + 0 Xan1 + 0 Xbn1 + 0 Xcn1 + 0 Xdn1 + 0 Xen1
        + 0 Xan2 + 0 Xbn2 + 0 Xcn2 + 0 Xdn2 + 0 Xen2
        + 0 Xan3 + 0 Xbn3 + 0 Xcn3 + 0 Xdn3 + 0 Xen3
        + 0 Xan4 + 0 Xbn4 + 0 Xcn4 + 0 Xdn4 + 0 Xen4
        + 0 Xan5 + 0 Xbn5 + 0 Xcn5 + 0 Xdn5 + 0 Xen5
        + 0 Xan6 + 0 Xbn6 + 0 Xcn6 + 0 Xdn6 + 0 Xen6
        + 0 Xan7 + 0 Xbn7 + 0 Xcn7 + 0 Xdn7 + 0 Xen7
        + 0 Xao1 + 0 Xbo1 + 0 Xco1 + 0 Xdo1 + 0 Xeo1
        + 0 Xao2 + 0 Xbo2 + 0 Xco2 + 0 Xdo2 + 0 Xeo2
        + 0 Xao3 + 0 Xbo3 + 0 Xco3 + 0 Xdo3 + 0 Xeo3
        + 0 Xao4 + 0 Xbo4 + 0 Xco4 + 0 Xdo4 + 0 Xeo4
        + 0 Xao5 + 0 Xbo5 + 0 Xco5 + 0 Xdo5 + 0 Xeo5
        + 0 Xao6 + 0 Xbo6 + 0 Xco6 + 0 Xdo6 + 0 Xeo6
        + 0 Xao7 + 0 Xbo7 + 0 Xco7 + 0 Xdo7 + 0 Xeo7
*
..CONSTRAINTS
*
*  Satellite goes through flow either 0 or 1 time:
*
        Xai1 + Xai2 + Xai3 + Xai4 + Xai5 + Xai6 + Xai7 <= 1
*
        Xbi1 + Xbi2 + Xbi3 + Xbi4 + Xbi5 + Xbi6 + Xbi7 <= 1
*
        Xci1 + Xci2 + Xci3 + Xci4 + Xci5 + Xci6 + Xci7 <= 1
*
        Xdi1 + Xdi2 + Xdi3 + Xdi4 + Xdi5 + Xdi6 + Xdi7 <= 1
*
        Xei1 + Xei2 + Xei3 + Xei4 + Xei5 + Xei6 + Xei7 <= 1
*
*  Satellites that start processing must complete through launch:
*
        Xai1 + Xai2 + Xai3 + Xai4 + Xai5 + Xai6 + Xai7 - Xao1 - Xao2
      - Xao3 - Xao4 - Xao5 - Xao6 - Xao7 = 0
*
        Xbi1 + Xbi2 + Xbi3 + Xbi4 + Xbi5 + Xbi6 + Xbi7 - Xbo1 - Xbo2
      - Xbo3 - Xbo4 - Xbo5 - Xbo6 - Xbo7 = 0
*
        Xci1 + Xci2 + Xci3 + Xci4 + Xci5 + Xci6 + Xci7 - Xco1 - Xco2
      - Xco3 - Xco4 - Xco5 - Xco6 - Xco7 = 0
*
        Xdi1 + Xdi2 + Xdi3 + Xdi4 + Xdi5 + Xdi6 + Xdi7 - Xdo1 - Xdo2
      - Xdo3 - Xdo4 - Xdo5 - Xdo6 - Xdo7 = 0
*
        Xei1 + Xei2 + Xei3 + Xei4 + Xei5 + Xei6 + Xei7 - Xeo1 - Xeo2
      - Xeo3 - Xeo4 - Xeo5 - Xeo6 - Xeo7 = 0
*
*  VIB Capacity
*
        Xai1 + Xbi1 + Xci1 + Xdi1 + Xei1 + Xaj1 + Xbj1 + Xcj1 + Xdj1
```

```
    + Xej1 <= 5
*
      Xai2 + Xbi2 + Xci2 + Xdi2 + Xei2 + Xaj2 + Xbj2 + Xcj2 + Xdj2
    + Xej2 <= 5
*
      Xai3 + Xbi3 + Xci3 + Xdi3 + Xei3 + Xaj3 + Xbj3 + Xcj3 + Xdj3
    + Xej3 <= 5
*
      Xai4 + Xbi4 + Xci4 + Xdi4 + Xei4 + Xaj4 + Xbj4 + Xcj4 + Xdj4
    + Xej4 <= 5
*
      Xai5 + Xbi5 + Xci5 + Xdi5 + Xei5 + Xaj5 + Xbj5 + Xcj5 + Xdj5
    + Xej5 <= 5
*
      Xai6 + Xbi6 + Xci6 + Xdi6 + Xei6 + Xaj6 + Xbj6 + Xcj6 + Xdj6
    + Xej6 <= 5
*
      Xai7 + Xbi7 + Xci7 + Xdi7 + Xei7 + Xaj7 + Xbj7 + Xcj7 + Xdj7
    + Xej7 <= 5
*
*  SMAB/SMARF Capacity:
*
      Xak1 + Xbk1 + Xck1 + Xdk1 + Xek1 + Xal1 + Xbl1 + Xcl1 + Xdl1
    + Xel1 <= 2
*
      Xak2 + Xbk2 + Xck2 + Xdk2 + Xek2 + Xal2 + Xbl2 + Xcl2 + Xdl2
    + Xel2 <= 2
*
      Xak3 + Xbk3 + Xck3 + Xdk3 + Xek3 + Xal3 + Xbl3 + Xcl3 + Xdl3
    + Xel3 <= 2
*
      Xak4 + Xbk4 + Xck4 + Xdk4 + Xek4 + Xal4 + Xbl4 + Xcl4 + Xdl4
    + Xel4 <= 2
*
      Xak5 + Xbk5 + Xck5 + Xdk5 + Xek5 + Xal5 + Xbl5 + Xcl5 + Xdl5
    + Xel5 <= 2
*
      Xak6 + Xbk6 + Xck6 + Xdk6 + Xek6 + Xal6 + Xbl6 + Xcl6 + Xdl6
    + Xel6 <= 2
*
      Xak7 + Xbk7 + Xck7 + Xdk7 + Xek7 + Xal7 + Xbl7 + Xcl7 + Xdl7
    + Xel7 <= 2
*
*  PAD 40/41 Capacity:
*
      Xam1 + Xbm1 + Xcm1 + Xdm1 + Xem1 + Xan1 + Xbn1 + Xcn1 + Xdn1
    + Xen1 <= 2
*
      Xam2 + Xbm2 + Xcm2 + Xdm2 + Xem2 + Xan2 + Xbn2 + Xcn2 + Xdn2
    + Xen2 <= 2
*
      Xam3 + Xbm3 + Xcm3 + Xdm3 + Xem3 + Xan3 + Xbn3 + Xcn3 + Xdn3
    + Xen3 <= 2
*
      Xam4 + Xbm4 + Xcm4 + Xdm4 + Xem4 + Xan4 + Xbn4 + Xcn4 + Xdn4
    + Xen4 <= 2
*
      Xam5 + Xbm5 + Xcm5 + Xdm5 + Xem5 + Xan5 + Xbn5 + Xcn5 + Xdn5
    + Xen5 <= 2
*
      Xam6 + Xbm6 + Xcm6 + Xdm6 + Xem6 + Xan6 + Xbn6 + Xcn6 + Xdn6
    + Xen6 <= 2
*
      Xam7 + Xbm7 + Xcm7 + Xdm7 + Xem7 + Xan7 + Xbn7 + Xcn7 + Xdn7
    + Xen7 <= 2
*
*  Each satellite can be at most in one process at a given time:
```

```
*
      Xai1 + Xaj1 + Xak1 + Xal1 + Xam1 + Xan1 + Xao1 <= 1
      Xai2 + Xaj2 + Xak2 + Xal2 + Xam2 + Xan2 + Xao2 <= 1
      Xai3 + Xaj3 + Xak3 + Xal3 + Xam3 + Xan3 + Xao3 <= 1
      Xai4 + Xaj4 + Xak4 + Xal4 + Xam4 + Xan4 + Xao4 <= 1
      Xai5 + Xaj5 + Xak5 + Xal5 + Xam5 + Xan5 + Xao5 <= 1
      Xai6 + Xaj6 + Xak6 + Xal6 + Xam6 + Xan6 + Xao6 <= 1
      Xai7 + Xaj7 + Xak7 + Xal7 + Xam7 + Xan7 + Xao7 <= 1
*
      Xbi1 + Xbj1 + Xbk1 + Xbl1 + Xbm1 + Xbn1 + Xbo1 <= 1
      Xbi2 + Xbj2 + Xbk2 + Xbl2 + Xbm2 + Xbn2 + Xbo2 <= 1
      Xbi3 + Xbj3 + Xbk3 + Xbl3 + Xbm3 + Xbn3 + Xbo3 <= 1
      Xbi4 + Xbj4 + Xbk4 + Xbl4 + Xbm4 + Xbn4 + Xbo4 <= 1
      Xbi5 + Xbj5 + Xbk5 + Xbl5 + Xbm5 + Xbn5 + Xbo5 <= 1
      Xbi6 + Xbj6 + Xbk6 + Xbl6 + Xbm6 + Xbn6 + Xbo6 <= 1
      Xbi7 + Xbj7 + Xbk7 + Xbl7 + Xbm7 + Xbn7 + Xbo7 <= 1
*
      Xci1 + Xcj1 + Xck1 + Xcl1 + Xcm1 + Xcn1 + Xco1 <= 1
      Xci2 + Xcj2 + Xck2 + Xcl2 + Xcm2 + Xcn2 + Xco2 <= 1
      Xci3 + Xcj3 + Xck3 + Xcl3 + Xcm3 + Xcn3 + Xco3 <= 1
      Xci4 + Xcj4 + Xck4 + Xcl4 + Xcm4 + Xcn4 + Xco4 <= 1
      Xci5 + Xcj5 + Xck5 + Xcl5 + Xcm5 + Xcn5 + Xco5 <= 1
      Xci6 + Xcj6 + Xck6 + Xcl6 + Xcm6 + Xcn6 + Xco6 <= 1
      Xci7 + Xcj7 + Xck7 + Xcl7 + Xcm7 + Xcn7 + Xco7 <= 1
*
      Xdi1 + Xdj1 + Xdk1 + Xdl1 + Xdm1 + Xdn1 + Xdo1 <= 1
      Xdi2 + Xdj2 + Xdk2 + Xdl2 + Xdm2 + Xdn2 + Xdo2 <= 1
      Xdi3 + Xdj3 + Xdk3 + Xdl3 + Xdm3 + Xdn3 + Xdo3 <= 1
      Xdi4 + Xdj4 + Xdk4 + Xdl4 + Xdm4 + Xdn4 + Xdo4 <= 1
      Xdi5 + Xdj5 + Xdk5 + Xdl5 + Xdm5 + Xdn5 + Xdo5 <= 1
      Xdi6 + Xdj6 + Xdk6 + Xdl6 + Xdm6 + Xdn6 + Xdo6 <= 1
      Xdi7 + Xdj7 + Xdk7 + Xdl7 + Xdm7 + Xdn7 + Xdo7 <= 1
*
      Xei1 + Xej1 + Xek1 + Xel1 + Xem1 + Xen1 + Xeo1 <= 1
      Xei2 + Xej2 + Xek2 + Xel2 + Xem2 + Xen2 + Xeo2 <= 1
      Xei3 + Xej3 + Xek3 + Xel3 + Xem3 + Xen3 + Xeo3 <= 1
      Xei4 + Xej4 + Xek4 + Xel4 + Xem4 + Xen4 + Xeo4 <= 1
      Xei5 + Xej5 + Xek5 + Xel5 + Xem5 + Xen5 + Xeo5 <= 1
      Xei6 + Xej6 + Xek6 + Xel6 + Xem6 + Xen6 + Xeo6 <= 1
      Xei7 + Xej7 + Xek7 + Xel7 + Xem7 + Xen7 + Xeo7 <= 1
*
*  VIB processing time (4 months):
*
      Xai1 - Xaj2 <= 0
      Xai2 - Xaj3 <= 0
      Xai3 - Xaj4 <= 0
      Xai4 - Xaj5 <= 0
      Xai5 - Xaj6 <= 0
      Xai6 - Xaj7 <= 0
*
      Xai1 - Xak3 <= 0
      Xai2 - Xak4 <= 0
      Xai3 - Xak5 <= 0
      Xai4 - Xak6 <= 0
      Xai5 - Xak7 <= 0
*
      Xbi1 - Xbj2 <= 0
      Xbi2 - Xbj3 <= 0
      Xbi3 - Xbj4 <= 0
      Xbi4 - Xbj5 <= 0
      Xbi5 - Xbj6 <= 0
      Xbi6 - Xbj7 <= 0

      Xbi1 - Xbk3 <= 0
      Xbi2 - Xbk4 <= 0
      Xbi3 - Xbk5 <= 0
      Xbi4 - Xbk6 <= 0
```

```
        Xbi5 - Xbk7 <= 0
*
        Xci1 - Xcj2 <= 0
        Xci2 - Xcj3 <= 0
        Xci3 - Xcj4 <= 0
        Xci4 - Xcj5 <= 0
        Xci5 - Xcj6 <= 0
        Xci6 - Xcj7 <= 0
*
        Xci1 - Xck3 <= 0
        Xci2 - Xck4 <= 0
        Xci3 - Xck5 <= 0
        Xci4 - Xck6 <= 0
        Xci5 - Xck7 <= 0
*
        Xdi1 - Xdj2 <= 0
        Xdi2 - Xdj3 <= 0
        Xdi3 - Xdj4 <= 0
        Xdi4 - Xdj5 <= 0
        Xdi5 - Xdj6 <= 0
        Xdi6 - Xdj7 <= 0
*
        Xdi1 - Xdk3 <= 0
        Xdi2 - Xdk4 <= 0
        Xdi3 - Xdk5 <= 0
        Xdi4 - Xdk6 <= 0
        Xdi5 - Xdk7 <= 0
*
        Xei1 - Xej2 <= 0
        Xei2 - Xej3 <= 0
        Xei3 - Xej4 <= 0
        Xei4 - Xej5 <= 0
        Xei5 - Xej6 <= 0
        Xei6 - Xej7 <= 0
*
        Xei1 - Xek3 <= 0
        Xei2 - Xek4 <= 0
        Xei3 - Xek5 <= 0
        Xei4 - Xek6 <= 0
        Xei5 - Xek7 <= 0
*
*  Satellite cannot be put "on hold" in V 5:
*
        Xaj1 + Xaj2 + Xaj3 + Xaj4 + Xaj5 + Xaj6 + Xaj7 = 1
        Xbj1 + Xbj2 + Xbj3 + Xbj4 + Xbj5 + Xbj6 + Xbj7 = 1
        Xcj1 + Xcj2 + Xcj3 + Xcj4 + Xcj5 + Xcj6 + Xcj7 = 1
        Xdj1 + Xdj2 + Xdj3 + Xdj4 + Xdj5 + Xdj6 + Xdj7 = 1
        Xej1 + Xej2 + Xej3 + Xej4 + Xej5 + Xej6 + Xej7 = 1
*
*  SMAB/SMARF processing time (2 months):
*
        Xak1 - Xam2 <= 0
        Xak2 - Xam3 <= 0
        Xak3 - Xam4 <= 0
        Xak4 - Xam5 <= 0
        Xak5 - Xam6 <= 0
        Xak6 - Xam7 <= 0
*
        Xbk1 - Xbm2 <= 0
        Xbk2 - Xbm3 <= 0
        Xbk3 - Xbm4 <= 0
        Xbk4 - Xbm5 <= 0
        Xbk5 - Xbm6 <= 0
        Xbk6 - Xbm7 <= 0
*
        Xck1 - Xcm2 <= 0
        Xck2 - Xcm3 <= 0
```

```
        Xck3 - Xcm4 <= 0
        Xck4 - Xcm5 <= 0
        Xck5 - Xcm6 <= 0
        Xck6 - Xcm7 <= 0
*
        Xdk1 - Xdm2 <= 0
        Xdk2 - Xdm3 <= 0
        Xdk3 - Xdm4 <= 0
        Xdk4 - Xdm5 <= 0
        Xdk5 - Xdm6 <= 0
        Xdk6 - Xdm7 <= 0
*
        Xek1 - Xem2 <= 0
        Xek2 - Xem3 <= 0
        Xek3 - Xem4 <= 0
        Xek4 - Xem5 <= 0
        Xek5 - Xem6 <= 0
        Xek6 - Xem7 <= 0
*
*  Satellite cannot be put "on hold" in SMAB/SMARF:
*
        Xal1 + Xal2 + Xal3 + Xal4 + Xal5 + Xal6 + Xal7 = 0
        Xbl1 + Xbl2 + Xbl3 + Xbl4 + Xbl5 + Xbl6 + Xbl7 = 0
        Xcl1 + Xcl2 + Xcl3 + Xcl4 + Xcl5 + Xcl6 + Xcl7 = 0
        Xdl1 + Xdl2 + Xdl3 + Xdl4 + Xdl5 + Xdl6 + Xdl7 = 0
        Xel1 + Xel2 + Xel3 + Xel4 + Xel5 + Xel6 + Xel7 = 0
*
*  PAD processing time (2 months):
*
        Xam1 - Xao2 <= 0
        Xam2 - Xao3 <= 0
        Xam3 - Xao4 <= 0
        Xam4 - Xao5 <= 0
        Xam5 - Xao6 <= 0
        Xam6 - Xao7 <= 0
*
        Xbm1 - Xbo2 <= 0
        Xbm2 - Xbo3 <= 0
        Xbm3 - Xbo4 <= 0
        Xbm4 - Xbo5 <= 0
        Xbm5 - Xbo6 <= 0
        Xbm6 - Xbo7 <= 0
*
        Xcm1 - Xco2 <= 0
        Xcm2 - Xco3 <= 0
        Xcm3 - Xco4 <= 0
        Xcm4 - Xco5 <= 0
        Xcm5 - Xco6 <= 0
        Xcm6 - Xco7 <= 0
*
        Xdm1 - Xdo2 <= 0
        Xdm2 - Xdo3 <= 0
        Xdm3 - Xdo4 <= 0
        Xdm4 - Xdo5 <= 0
        Xdm5 - Xdo6 <= 0
        Xdm6 - Xdo7 <= 0
*
        Xem1 - Xeo2 <= 0
        Xem2 - Xeo3 <= 0
        Xem3 - Xeo4 <= 0
        Xem4 - Xeo5 <= 0
        Xem5 - Xeo6 <= 0
        Xem6 - Xeo7 <= 0
*
*  Satellite cannot be put "on hold" on PAD:
*
        Xan1 + Xan2 + Xan3 + Xan4 + Xan5 + Xan6 + Xan7 = 0
```

```
        Xbn1 + Xbn2 + Xbn3 + Xbn4 + Xbn5 + Xbn6 + Xbn7 = 0
        Xcn1 + Xcn2 + Xcn3 + Xcn4 + Xcn5 + Xcn6 + Xcn7 = 0
        Xdn1 + Xdn2 + Xdn3 + Xdn4 + Xdn5 + Xdn6 + Xdn7 = 0
        Xen1 + Xen2 + Xen3 + Xen4 + Xen5 + Xen6 + Xen7 = 0
*
  Process cannot be completed unless started by t=3:
*
        Xai7 = 0
        Xbi7 = 0
        Xci7 = 0
        Xdi7 = 0
        Xei7 = 0
*
        Xai6 = 0
        Xbi6 = 0
        Xci6 = 0
        Xdi6 = 0
        Xei6 = 0
*
        Xai5 = 0
        Xbi5 = 0
        Xci5 = 0
        Xdi5 = 0
        Xei5 = 0
*
        Xai4 = 0
        Xbi4 = 0
        Xci4 = 0
        Xdi4 = 0
        Xei4 = 0
*
* Satellite Launch Windows:
*
*   Satellites A, B, E launched at end of time = 6 (start of 7):
        Xao5 + Xao6 = 0
        Xbo5 + Xbo6 = 0
        Xeo5 + Xeo6 = 0
*   Satellite C launched at end of time = 5 (start of 6)
        Xco5 + Xco7 = 0
*   Satellite D launched at end of time = 4 (start of 5)
        Xdo6 + Xdo7 = 0
*

Statistics-
  LP83 Version 5.00a
  Machine memory:  640K bytes.
  Pagable memory:  402K bytes.
  Objective Function is MAXIMIZED.
  Variables:        245
  Constraints:      221
   176 LE,  45 EQ,   0 GE.
  Non-zero LP elements:      925
  Disk Space:     0K bytes.
  Page Space:   425K bytes.
  Capacity: 52.0% used.
  Estimated Time: 00:09:56

Iter   94
Solution Time:  00:00:48
A L T E R N A T E   S O L U T I O N S
```

Appendix D: Reduced Launch Optimization Linear Programs

```
! Launch Prioritization (Reduced Version)
!
! DEFINITIONS:
!
! Launch Decision Variables - Go/No Go:  A, B, C, D, E
!              - Time Period of Launch:  A _, B _, C _, D _, E _
!                                        (time = 5:  beginning of month 9, or end of month 8)
!                                        (time = 6:  beginning of month 11, or end of month 10)
!                                        (time = 7:  beginning of month 13, or end of month 12)
!
! utility(K-A) = .452
! utility(K-B) = .644
! utility(K-C) = .377
! utility(K-D) = .386
! utility(K-E) = .450
!
MAX     .452 A + .644 B + .377 C + .386 D + .450 E
!
SUBJECT TO
!
     A5 + A6 + A7 - A = 0
!
     B5 + B6 + B7 - B = 0
!
     C5 + C6 + C7 - C = 0
!
     D5 + D6 + D7 - D = 0
!
     E5 + E6 + E7 - E = 0
!
     A5 + A6 + A7 <= 1
!
     B5 + B6 + B7 <= 1
!
     C5 + C6 + C7 <= 1
!
     D5 + D6 + D7 <= 1
!
     E5 + E6 + E7 <= 1
!
!  PAD 40/41 Capacity:
!
     A5 + B5 + C5 + D5 + E5 <= 2
     A6 + B6 + C6 + D6 + E6 <= 2
     A7 + B7 + C7 + D7 + E7 <= 2
!
! SATELLITE LAUNCH WINDOWS:
!
     A5 + A6 = 0
     B5 + B6 = 0
     C5 + C7 = 0
     D6 + D7 = 0
     E5 + E6 = 0
!
!
END
LEAVE
```

LP OPTIMUM FOUND AT STEP 7

OBJECTIVE FUNCTION VALUE

1) 1.8590000

VARIABLE	VALUE	REDUCED COST
A	1.000000	.000000
B	1.000000	.000000
C	1.000000	.000000
D	1.000000	.000000
E	.000000	.002000
A5	.000000	.000000
A6	.000000	.000000
A7	1.000000	.000000
B5	.000000	.000000
B6	.000000	.000000
B7	1.000000	.000000
C5	.000000	.000000
C6	1.000000	.000000
C7	.000000	.452000
D5	1.000000	.000000
D6	.000000	.000000
D7	.000000	.452000
E5	.000000	.000000
E6	.000000	.000000
E7	.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	.000000	-.452000
3)	.000000	-.644000
4)	.000000	-.377000
5)	.000000	-.386000
6)	.000000	-.452000
7)	.000000	.000000
8)	.000000	.192000
9)	.000000	.377000
10)	.000000	.386000
11)	1.000000	.000000
12)	1.000000	.000000
13)	1.000000	.000000
14)	.000000	.452000
15)	.000000	.452000
16)	.000000	.452000
17)	.000000	.000000
18)	.000000	.000000
19)	.000000	.452000

NO. ITERATIONS= 7

RANGES IN WHICH THE BASIS IS UNCHANGED:

		OBJ COEFFICIENT RANGES	
VARIABLE	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
A	.452000	.192000	.002000
B	.644000	INFINITY	.192000
C	.377000	INFINITY	.377000
D	.386000	INFINITY	.386000
E	.450000	.002000	INFINITY
A5	.000000	INFINITY	.000000
A6	.000000	.000000	INFINITY
A7	.000000	.192000	.002000
B5	.000000	.000000	INFINITY
B6	.000000	INFINITY	.000000
B7	.000000	INFINITY	.192000

C5	.000000	.000000	INFINITY
C6	.000000	INFINITY	.000000
C7	.000000	.452000	INFINITY
D5	.000000	INFINITY	.000000
D6	.000000	.000000	INFINITY
D7	.000000	.452000	INFINITY
E5	.000000	.000000	INFINITY
E6	.000000	INFINITY	.000000
E7	.000000	.002000	INFINITY

RIGHTHAND SIDE RANGES

ROW	CURRENT RHS	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	.000000	1.000000	INFINITY
3	.000000	1.000000	INFINITY
4	.000000	1.000000	INFINITY
5	.000000	1.000000	INFINITY
6	.000000	1.000000	.000000
7	1.000000	INFINITY	.000000
8	1.000000	1.000000	.000000
9	1.000000	1.000000	1.000000
10	1.000000	1.000000	1.000000
11	1.000000	INFINITY	1.000000
12	2.000000	INFINITY	1.000000
13	2.000000	INFINITY	1.000000
14	2.000000	.000000	1.000000
15	.000000	.000000	.000000
16	.000000	.000000	.000000
17	.000000	.000000	.000000
18	.000000	.000000	.000000
19	.000000	.000000	.000000

```
! Launch Prioritization (Second Reduced Version)
!
! u(K-A) = .452
! u(K-B) = .644
! u(K-C) = .377
! u(K-D) = .386
! u(K-E) = .450
!
MAX     .452 A + .644 B + .377 C + .386 D + .450 E
!
SUBJECT TO
!
        A <= 1
        B <= 1
        C <= 1
        D <= 1
        E <= 1
        A + B + E <=2
!
END
LEAVE


LP OPTIMUM FOUND AT STEP      4

       OBJECTIVE FUNCTION VALUE

       1)      1.8590000

 VARIABLE        VALUE          REDUCED COST
        A         1.000000          .000000
        B         1.000000          .000000
        C         1.000000          .000000
        D         1.000000          .000000
        E          .000000          .002000


      ROW   SLACK OR SURPLUS     DUAL PRICES
       2)          .000000          .000000
       3)          .000000          .192000
       4)          .000000          .377000
       5)          .000000          .386000
       6)         1.000000          .000000
       7)          .000000          .452000

NO. ITERATIONS=       4

RANGES IN WHICH THE BASIS IS UNCHANGED:

                           OBJ COEFFICIENT RANGES
VARIABLE         CURRENT        ALLOWABLE         ALLOWABLE
                  COEF          INCREASE          DECREASE
       A         .452000         .192000           .002000
       B         .644000        INFINITY           .192000
       C         .377000        INFINITY           .377000
       D         .386000        INFINITY           .386000
       E         .450000         .002000          INFINITY

                           RIGHTHAND SIDE RANGES
     ROW         CURRENT        ALLOWABLE         ALLOWABLE
                  RHS           INCREASE          DECREASE
       2        1.000000        INFINITY           .000000
       3        1.000000        1.000000           .000000
       4        1.000000        INFINITY          1.000000
       5        1.000000        INFINITY          1.000000
       6        1.000000        INFINITY          1.000000
       7        2.000000         .000000          1.000000
```

THE TABLEAU

ROW	(BASIS)		A	B	C	D	E
1	ART		.000	.000	.000	.000	.002
2	SLK	2	.000	.000	.000	.000	-1.000
3		B	.000	1.000	.000	.000	.000
4		C	.000	.000	1.000	.000	.000
5		D	.000	.000	.000	1.000	.000
6	SLK	6	.000	.000	.000	.000	1.000
7		A	1.000	.000	.000	.000	1.000

ROW	SLK 2	SLK 3	SLK 4	SLK 5	SLK 6
1	.000	.192	.377	.386	.000
2	1.000	1.000	.000	.000	.000
3	.000	1.000	.000	.000	.000
4	.000	.000	1.000	.000	.000
5	.000	.000	.000	1.000	.000
6	.000	.000	.000	.000	1.000
7	.000	-1.000	.000	.000	.000

ROW	SLK 7	
1	.452	1.859
2	-1.000	.000
3	.000	1.000
4	.000	1.000
5	.000	1.000
6	.000	1.000
7	1.000	1.000

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Vita

Captain Raymond W. Staats was born April 3, 1966 in Syracuse, New York where he graduated from Cicero-North Syracuse High School in 1984. He earned a bachelor of arts degree in mathematics from Syracuse University in 1988 and received a regular commission as a distinguished graduate of the Air Force Reserve Officer Training Corps.

After completing Undergraduate Space Training, he was assigned to the 3d Space Operations Squadron as a Satellite Operations Planning/Analysis Officer, specializing in the Defense Satellite Communications System III. There he conducted the squadron's first contingency mission for the DSCS III program. He was then selected as a staff instructor where he implemented the squadron's new operational concept and upgraded to the position of Crew Commander Instructor. He then began extensive unit Instructional Systems Development work as Chief, Operations Training Development, completely redefining the training requirements for AFSPACECOM's largest mission-ready crew force. In January 1992, he was chosen to serve as the squadron's Executive Officer and subsequently as the 50th Operations Group Executive Officer. After completing Squadron Officer School in residence, he entered the Air Force Institute of Technology's School of Engineering in May 1993.

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13. ABSTRACT (Maximum 200 words)

This research uses multi-attribute utility theory (MAUT) to define a mathematical representation of a decision maker's utility associated with a satellite system. While developing the survey instrument, we focused on making it simpler to administer, primarily by eliminating the use of lottery questions. These simplifications enabled us to shorten our interview with the decision maker under two hours for a rather complex model.

The MAUT model gives National Air Intelligence Center (NAIC) analysts the ability to rank order satellite systems using the common measurement scale of "utiles." This tool allows a meaningful comparison of vastly different satellites.

Properly prioritized launch of space assets will be key to maintaining our capabilities in the long term. The ordering methodology of this model was extended to a multi-criterion optimization (MCO) problem to demonstrate its potential use in prioritizing and scheduling limited launch resources.

The results of these two case studies and the MCO application are combined to develop some characterizations of a theoretical group utility function. Most complex decisions are made by groups rather than by an individual. This research concludes with some insights on the impact of an individual's preferences on a decision that is ultimately made by the group.

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