Methodology for Reliability-Cost-Risk Analysis of Satellite Networks

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The increased capabilities afforded by the Space Shuttle-Space Tug Space Transportation System, especially retrieval and on-orbit refurbishment of failed or "worn-out" satellites, will significantly affect the design philosophy, orbital operations, and economics of doing business in space. Techniques are developed and described which allow the cost of operations, and associated present values, to be established explicitly taking into account less-than-unity reliability of operations of the Space Transportation System and satellites and uncertainties associated with basic costs. Quantitative measures of risk are developed and the effect of satellite failure characteristics, orbital operations, etc., on risk are evaluated for a typical service mission.

Introduction

THE costs associated with the development, manufacture, deployment, and use of a fleet of satellites are measured in terms of tens and, perhaps, hundreds of millions of dollars. Add to this basic cost the fact that a variety of failures can occur that can cause considerable cost deviations from the zero-failure case and it is generally apparent that such programs warrant thorough analysis in order to provide management with data relevant to major program decisions. These data should include the expected value of the costs for each option and also, recognizing that costs are not deterministic quantities, a measure of the risk, for example, the chance that costs will exceed various levels. Since costs can be incurred over a long period of time, it is necessary to make adjustments for the "time value" of money. Costs that have been adjusted for their time of occurrence are referred to as present values. Thus, three factors contribute to the expected present value and uncertainty of costs: launch vehicle, satellite, and operational system reliabilities, development and operational costs and their uncertainties, and the actual time history of events which determines when the various costs are incurred.

The reliability of the Space Transportation System and the satellite determines the probability of successfully launching and deploying the satellite and, if the launch and deployment are successful, yields the expected useful lifetime of the satellite. In the case that the satellite is used to provide a service, for example, communications, certain failures can require cost incurring actions if indeed failure recovery and subsequent service are to be provided. If a satellite launch is unsuccessful and the launch vehicle and satellite are lost, a new launch vehicle and satellite must be purchased and a second launch attempt made. Using the current fleet of expendable launch vehicles, the probability of a successful launch and satellite deployment can be expressed in terms of a single number and the failure recovery mode is to purchase a new launch vehicle and satellite and try again. However, the Space Shuttle Transportation System could provide a variety of new capabilities including recovery and reuse or on-orbit servicing of failed satellites. Thus, instead of the simple success-failure situation that occurs for the current expendable launch vehicles, the Space Shuttle Transportation System can fail in a variety of ways, not all catastrophic, from which there are different recovery modes. The analysis of these launch and orbital operations failure modes and their subsequent cost incurring recovery, that is, the number of events that occur, is herein referred to as operational analysis.

Costs associated with a space program can generally be classified as nonrecurring (RDT&E) and recurring. In the planning phase, because it is difficult to predict the future with precision, there must be some uncertainty associated with both types of costs. In addition to the cost per event, such as a satellite purchase, due to imperfect reliabilities, the number of events is uncertain and this yields additional program cost uncertainties.

As the costs and cost uncertainties are summed up accounting for the time value of money one obtains the expected value and standard deviation (or risk) of the present value of costs. It is both of these bits of information that a program manager needs for each program alternative to make educated decisions.

The purpose of this paper is to describe a methodology for the economic analysis of service-type space missions. The methodology for operational analysis and cost analysis is given with example applications to a hypothetical communications satellite mission using the Space Shuttle and a Space Tug for orbital operations. It is not the purpose of this paper to make specific comparisons of various operational modes or mission alternatives and the results obtained should not be viewed as an indication of preferences.

The methodology developed in this paper represents an extension and generalization of previous techniques that did not allow for cost uncertainties and Space Transportation System failures.[1,2] This approach has been applied also to problems in the Advanced Propulsion Comparison Study[3] and to an analysis of a Pluto flyby mission.[4]

Operational Analysis

Space system operational analysis is the quantification of the probability distributions of the numbers of recurring cost-associated events required to establish and maintain a space program. These events may include the number of satellites purchased, the number of launches, the number of satellite retrievals or refurbishments, and so on. Each of these events has associated with it a cost that, at least in the planning phase, includes some uncertainty. The random nature of the number of events can be due to hardware failures, failure to accomplish certain prescribed events, for example, a rendezvous and docking

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maneuver, or variability in certain wearout phenomena such as running out of attitude control gas. Thus, in addition to analyzing the number of events, operational analysis must also be concerned with their time of occurrence.

Operational analysis explicitly considers the possibility of failures both in the Space Transportation System and the satellites, the chance of these failures occurring, and the consequences if the failures do indeed occur. More specifically the analysis considers the following: 1) the number, sequence, and complexity of operations to be performed; 2) the recovery modes, that is, given that a failure has occurred, the possible resulting sequences of events; 3) the probability of successfully performing each of the required operations, both in the success and failure recovery sequences; and 4) scheduling (or lack thereof) of events. The results of an operational analysis in toto are referred to as the operational risk.

Space Transportation System Operational Analysis

The Space Transportation System operational analysis includes all those events associated with the orbital placement, refurbishment, and retrieval of satellites, including the satellite deployment and initial operation. These last two events are included as transportation system events because if failures occur during these operations, the recovery modes sometimes involve components of the Space Transportation System.

The first step in performing an operational analysis of a given mission (for example a satellite placement, a satellite placement and retrieval, etc.) is to establish the success-oriented mission profile. The success-oriented mission profile consists of the nominal mission timeline (sequence of events) and may be comprised of many hundreds of individual events. Each event may be successfully accomplished or unsuccessful. If the event is accomplished successfully, the mission proceeds on to the next event. If the event is unsuccessful, a failure recovery mode must be adopted. Sometimes the failure recovery mode can return the mission to the nominal timeline and sometimes major modifications are necessary in the mission. Some failures, such as the loss of a redundant subsystem, cause mainly inconvenience and possibly a minor cost item; others, such as the loss of a Space Tug and satellite, result in major cost items. In the latter case this involves the purchase of a new Space Tug and satellite and another launch attempt. It is generally possible and helpful to sketch the resultant success-oriented mission profile in cartoon form as shown by the example of Fig. 1 for a Space Shuttle-Space Tug satellite placement and retrieval mission.

The second step of an operational analysis requires an explicit definition of what constitutes completion of a mission. In a service type space program, if a satellite is required to provide the service and the mission is to place that satellite in orbit, then the satellite must be successfully placed and operational for the mission to be complete. If a particular flight fails to accomplish

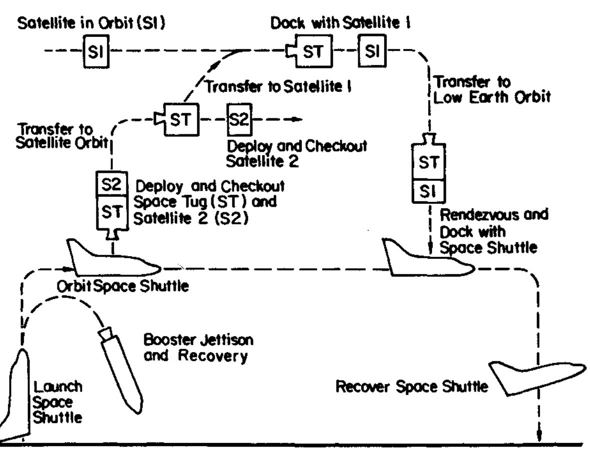


Fig. 1 Space shuttle-space tug satellite placement and retrieval mission profile.

this it must be repeated. On the other hand, if a satellite is to be retrieved from space and the retrieval fails, one may elect not to make a second retrieval attempt, but instead to augment the ground-based inventory via the purchase of a new satellite. Here it becomes apparent that one of a variety of failure recovery modes must be chosen in order to proceed. Ultimately, each of the alternatives should be investigated and the choice made on an economic basis.

The third step involves establishing the mission scenario. The mission scenario is defined as the timeline sequence of all possible events (within the desired level of detail) that can occur from start to completion of a mission. The success-oriented path through the mission scenario is the mission profile; however, the mission scenario includes all of the pertinent failure recovery paths as well. The mission scenario can be thought of as a series of nodes connected by branches. Each node is a decision point representing a group of events. Emanating from each node are branches for the success and failure recovery paths. The probability of departing the node on one branch or another depends upon the probability of success (or failure) of the events represented by the node. The failure recovery paths must ultimately provide a route to mission completion as defined in step two above. In any event, mission completion requires a proper restoration of the inventory to its pre-mission level. For example, if the mission is to place a satellite and retrieve a satellite, and if there is a failure to retrieve the satellite, then the purchase of a new satellite is necessary to restore the inventory to its proper level.

The mission scenario can also be shown as a logic flow diagram as in Fig. 2 for the example mission shown in Fig. 1. In Fig. 2, the nodes are represented by the diamond-shaped boxes and the branches as lines with major cost-associated events given in the rectangular boxes. By tracing through all the paths of the mission scenario, it is apparent that the probabilities given in Table 1 are necessary for the operational analysis.

When the mission scenario is established and the corresponding probability data are available, the operational analysis can be programed for computer analysis. One method of computer analysis is by Monte-Carlo techniques wherein many random walks (typically 1000) are made through the mission scenario and

Table 1 Reliability aspects considered—Shuttle/Tug payload placement and retrieval mission

Probability of success for	Estimated values[a] as a function of time from start of analysis, years 1	2	3	4
Booster burn	0.99	0.992	0.994	0.994
Booster recovery given booster[b] success	0.93	0.94	0.95	0.95
Booster recovery given booster failure	0.40	0.45	0.50	0.50
Orbiter recovery given booster failure	0.97	0.98	0.99	0.99
Orbiter achieves low earth orbit	0.99	0.994	0.998	0.998
Orbiter recovery given abort to orbit	0.97	0.975	0.98	0.98
Orbiter recovery from low earth orbit	0.99	0.995	0.999	0.999
Space Tug checks out successfully in low earth orbit	0.97	0.975	0.98	0.98
Space Tug transfers to satellite placement orbit	0.98	0.984	0.988	0.988
Space Tug transfers from terminal orbit to low earth orbit and rendezvous with orbiter	0.98	0.984	0.988	0.988
Space Tug docking with satellite to be returned	0.97	0.975	0.98	0.98
Satellite check-out in terminal orbit	0.97	0.975	0.98	0.98
Space Tug reacquiring satellite which does not check-out in terminal orbit	0.98	0.985	0.99	0.99
Probabilities not shown are assumed to be high				

[a] Estimates for years 3 and 4 are similar to those appearing in Ref. 1.
[b] Space Shuttle Transportation System consists of solid rocket motor booster, Space Shuttle orbiter and Space Tug.

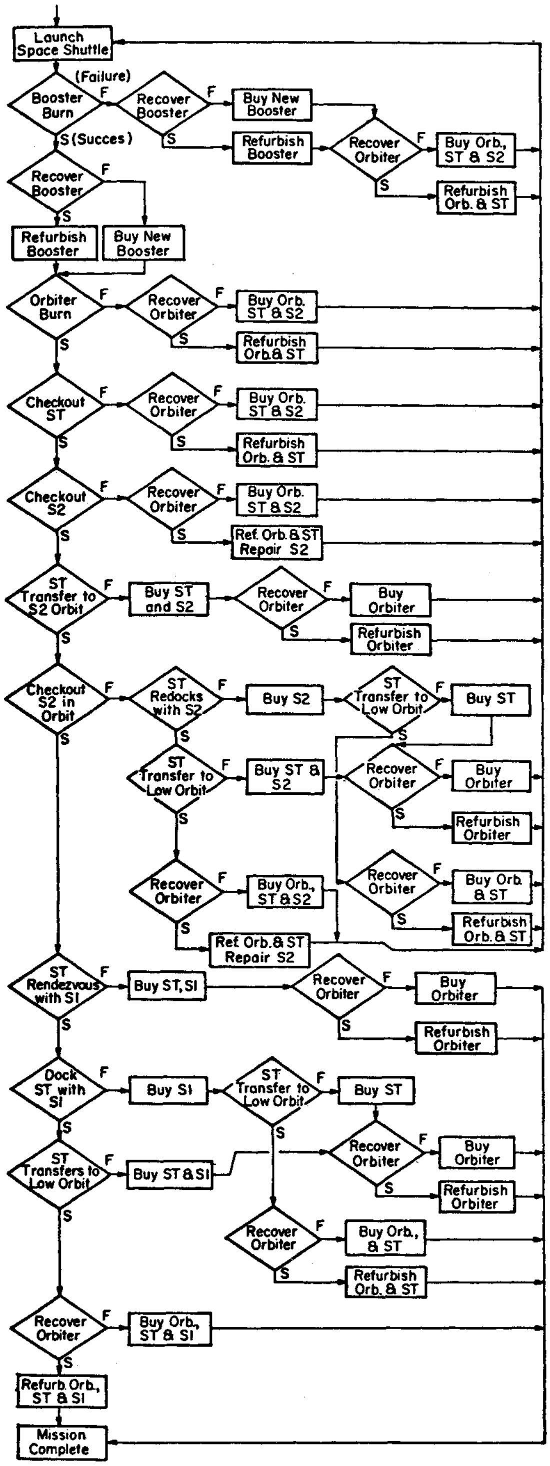


Fig. 2 Space shuttle-space tug satellite placement and retrieval mission scenario.

events counted. Because of the extremely low probability associated with certain of the paths, the finite Monte Carlo analysis can yield only approximate results.

The outputs from the Space Transportation System operational analysis consist of histograms or probability distributions of the number of occurrences of each major cost-associated event required to perform a given mission.

Satellite Operational Analysis

A service mission typically consists of two phases, namely the establishment of a desired level of service and the maintenance of that level of service. The establishment of the service is concerned with successfully placing a number of satellites in orbit

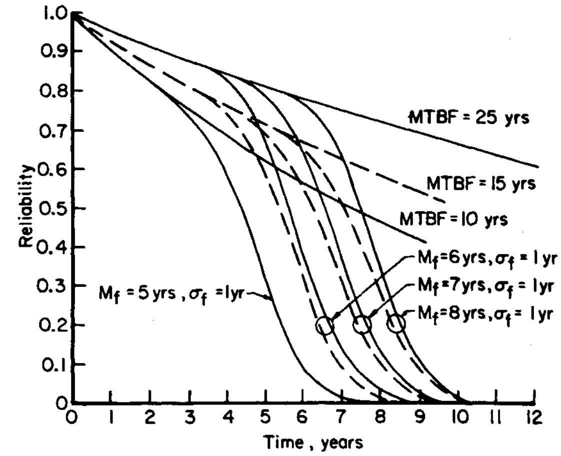


Fig. 3 Satellite reliability function.

over a period of time as determined by service needs. If it is assumed that both the need and the capability of the satellites are known, it follows that the number of satellites required to establish the service is deterministic. The maintenance of the service is concerned with maintaining the desired number of operational satellites in service. As a result of less-than-perfect reliability and variability associated with wearout phenomena, such as attitude control gas depletion, satellite failures will occur in a random manner with the result that the traffic associated with the maintenance of the service will be known only in a probabilistic sense. The probabilistic nature of the traffic due to satellite failures and replacements adds an important degree of uncertainty and risk to the service mission. It is, therefore, necessary to consider the impact of satellite reliability on the over-all mission.

Satellite failures occur as the result of four causes: improper design or manufacture generally due to an incomplete understanding of all related physical principles, imperfect quality control during manufacture, uncertainties in the environment during storage, transportation and operation, and because of design and technology limitations generally associated with lifetime. These failure causes generally manifest themselves in three different types of failures: early, chance, and wearout. In this paper, early satellite failures are considered in the Space Transportation System operational analysis. Their consequences are dependent upon the Space Transportation System and the operational modes.

The satellite failure model utilized in this analysis considers both random and wearout failures and is given by

$$R(n) = \frac{\exp(-\lambda n)}{\sigma_f (2\pi)^{1/2}} \int_n^\infty \exp\left[-\frac{(a-M_f)^2}{2\sigma_f^2}\right] da$$

This expresses the combined effects of the random and wearout phenomena as the probability of surviving through the nth time period (years) and λ is the failure rate (failures/year) or reciprocal of the mean-time between failures (MTBF), M_f is the mean or expected wearout life (years) and σ_f is the standard deviation of wearout life (years). The general shape of the reliability function is illustrated in Fig. 3. The probability of a satellite failing in time period n, $F(n)$ is thus

$$F(n) = R(n-1) - R(n)$$

The failure characteristics of the satellite can be modeled by estimating, based on current design and/or past experience, the anticipated MTBF $(1/\lambda)$ for the random failures and the expected wearout life and the standard deviation of wearout life. Although this satellite failure model is a very simple one, it serves to illustrate the way in which satellite reliabilities enter into the economic analysis. More detailed reliability models could be developed as necessary.

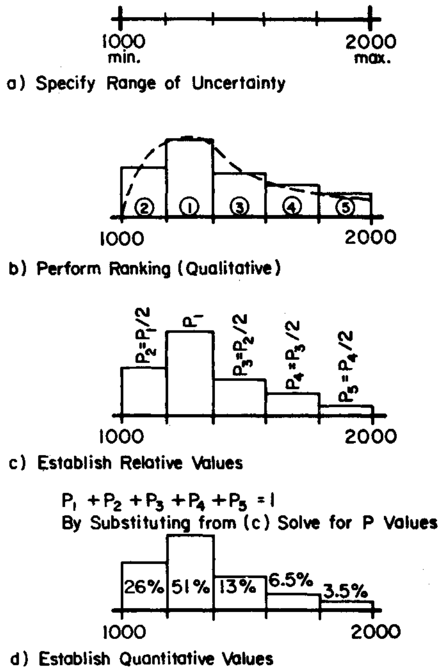


Fig. 4 Methodology for establishing shape of cost uncertainty profile (*Pdf*).

The reliability model is used to establish the number of satellites which fail each year, based on the number in orbit and operational during that year, and thus need to be replaced. This, together with the Space Transportation System operational analysis, establishes the probability distributions of all pertinent cost-associated events as a function of time.

Cost Analysis

Costs can generally be categorized as either nonrecurring, that is, one-time costs such as RDT&E, or recurring, namely those costs which are activity related. During the planning phase of a program, both nonrecurring and recurring costs are nondeterministic quantities. Nonrecurring cost uncertainties arise from all aspects of a program with which there may be any amount of uncertainty: the outcome of a test, the purchase of various equipments, manpower requirements, etc. Recurring cost uncertainties arise from the difficulties of predicting the cost of producing an item before it has been designed. An over-all economic analysis must be concerned with the uncertainties in both nonrecurring and recurring costs; however, this paper focuses on the evaluation of the recurring costs with uncertainty and their implementation into the economic analysis.

The problem addressed is how to quantify uncertainty. This requires that informed estimates be made of the ranges of uncertainty of key cost variables and their probability distributions within the range. The estimates of uncertainty might be made, for example, at the CER (cost estimating relationship) level or they might be made at the unit cost (Space Tug, satellite, etc.) level. The uncertainty assessments can be made by individuals with the assistance of an experienced analyst or they can be made by an experienced group of individuals using Delphi type techniques.[5,6] The estimates are very subjective in nature and quantitatively express the attitudes regarding the uncertainties. The estimates reflect past experience with similar efforts, problems which have been encountered in the past, insights into problem areas which might develop, etc.

Cost uncertainties can be quantified. In fact, most large corporations use risk analysis techniques which employ uncertainty assessments as a standard procedure in the evaluation and comparison of new business alternatives.[7-13]

A methodology for establishing the shape of the cost uncertainty profiles, illustrated in Fig. 4, has been employed in risk analysis performed for numerous industrial corporations. The first step is to establish the range of uncertainty based on knowledgeable persons assessing what can go right and what can go wrong. The range is then divided into five equal intervals and a relative ranking of the likelihood of the cost variable falling into each of the intervals is performed. The general shape (skewed left, skewed right, central, etc.) of the uncertainty profile is thus established. The next step is to establish relative values of the chance of falling into each of the intervals. For example, in the illustration, the chance of falling into the first interval is estimated to be half as likely as falling into the second interval. This is repeated for each interval relative to the previously considered interval. The last step is to solve the illustrated equation for the quantitative values by substituting the data from the previous step.

In order to simplify this procedure, a large number of typical uncertainty profiles may be stored in the computer. The evaluator may thus simply specify the range of uncertainty (minimum and maximum values) and the name of the uncertainty profile which reasonably represents his feelings. If none of the stored profiles is suitable, then the previously described procedure may be followed and the appropriate uncertainty profile data provided as part of the input data.

Economic Analysis

The economic analysis of space programs involves cash flow patterns that occur over several (n) years; thus, it is desirable to present the results of the economic analysis in terms of the present value of costs. The present value, which explicitly takes into account the magnitude and the timing of the cash flow patterns, is defined as the summation of future annual costs‡ discounted to the present and is given by

$$PV = \sum_{i=1}^{n} \frac{C_i}{[1+(r/100)]^i}$$

where PV = present value of cost, C_i = cost in the ith year, and r = discount rate (%) or cost of capital.

The costs entering into the above equation, however, are not deterministic quantities. Variations in the yearly costs, C_i, occur because of the uncertainties in predicting future item (or per event) costs and due to the uncertainty both in the number of events necessary to perform the desired program and the time of occurrence of these events. Thus the present value of costs must also be characterized by a probability distribution. The probability of present value exceeding a specified level is the area under the probability distribution curve for all values greater than the specified level and is henceforth referred to as a risk profile. Typical risk profiles of present value are shown in Fig. 5 where the probability or chance, p, of exceeding the various levels of present value, PV, is indicated. In general,

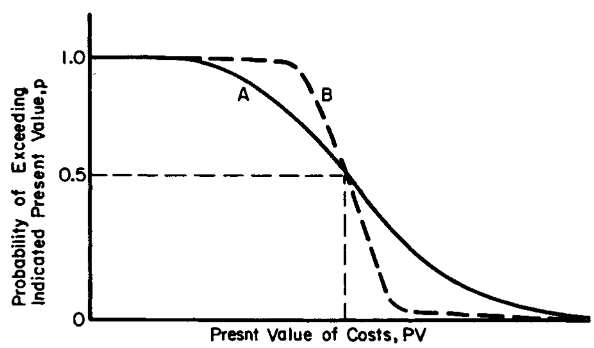


Fig. 5 Risk profile of present value.

‡ To simplify the analysis, only costs are considered since it is assumed that the same revenue stream will be available independent of the choice of alternative. It must be emphasized that in a profit oriented venture, total annual cash flows should be utilized.

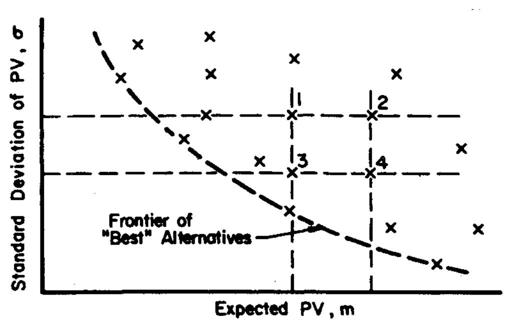


Fig. 6 General problem of decision making under uncertainty.

the steeper the curve, the lower the risk (or variability). When comparing alternatives, it is important to compare the expected or most likely present values. It is equally important to also compare risk levels.

Figure 5 illustrates the risk profiles of present value for two hypothetical alternatives, A and B. It should be noted that the expected ($p = 0.5$) or most likely§ present values of the two alternatives are equal. A decision maker performing a traditional analysis usually evaluates only the most likely present value. To this uninformed decision maker, alternatives A and B "look alike."

In the certainty situation, it is generally desirable to select the alternative which yields the minimum present value of costs when all alternatives are evaluated on an equal capability¶ basis. When present values are equal, the choice is immaterial. The selection process becomes more difficult when uncertainties are considered; tradeoffs must be made between alternatives possessing different expected present values and associated levels of risk. When the risk dimension is available, alternatives A and B are found to be quite different. The risk associated with Alternative A is greater than that of Alternative B. Thus a conservative decision maker** would normally select Alternative B provided that other, unquantified pressures to select Alternative A do not exist.

Generally, associated with a large space program, one can identify many alternatives that must be compared for selection of the best one. The problems of comparison are eased somewhat by the fact that the probability distributions of the present value of costs are usually very nearly normal. Thus, the distributions can be fully characterized by their mean, m, and standard deviation, σ, and each alternative can be represented by a point on the m-σ plane. An example is illustrated in Fig. 6. Here Alternatives 1 and 2 have the same level of risk (i.e., $\sigma_1 = \sigma_2$) but the expected PV of the cost of Alternative 2 is greater than that of Alternative 1. Therefore, Alternative 1 is preferable to Alternative 2. In a similar manner, it can be argued that Alternative 3 is preferable to Alternative 4. Also in a similar manner, Alternative 3 is preferable to Alternative 1 since both have the same expected PV but Alternative 1 is riskier.†† This process can be continued with all alternatives being considered. In the limit, it can be seen that a frontier of "best" alternatives can be established. Each of the points or alternatives represented by the frontier are different in the respect that the risk and expected PV are different. The class of best alternatives has thus been obtained and the "best" alternative can then be selected based on the decision maker's risk judgement. That is, the decision maker must decide what the tradeoff is between a reduction in expected PV of cost and an accompanying increase in risk.

§ Since present value probability distributions generally tend to be normal, the expected value and the most likely value are approximately the same.

¶ Equal capability is defined for service type space programs as providing the same level of service and revenue generating capability.

** Conservative in the sense that risk aversion preferences are evident.

†† This assumes a rational risk averse decision maker.

The risk judgement may be purely intuitive or it may be based on a quantified utility function.[14-16] In either case the tradeoff between expected rewards and risk is made explicitly clear to the decision maker.

Computer Simulation

Computer simulation of a service mission requires modeling the operational, cost and economic factors discussed above.[17,18] The logic flow of the computer code is illustrated in Fig. 7 and makes use of three following mathematical models.

1) A Satellite Addition/Replacement Model which establishes the number of satellites that must be added or replaced as a function of time based on the satellite reliability function. This model keeps track of each satellite to establish if and when a failure occurs and, based upon the operational requirements, determines the number of satellites which must be added and/or retrieved and refurbished.

2) A Space Transportation System Operational Model which simulates the events that take place during the process of placing and retrieving satellites from orbit.

3) A Cost Model which, utilizing learning curves, establishes the recurring costs of the various events including replacement and refurbishment costs for the Space Shuttle, Space Tug and satellites. The Cost Model combines the results of the operational analyses (1 and 2) with the appropriate cost per event. The cost data are then used to establish the present value of costs for the entire program.

The current simulation uses Monte-Carlo techniques to establish the probability distributions (risk profiles) of the different events, their associated costs, total program cost, and present value of costs.

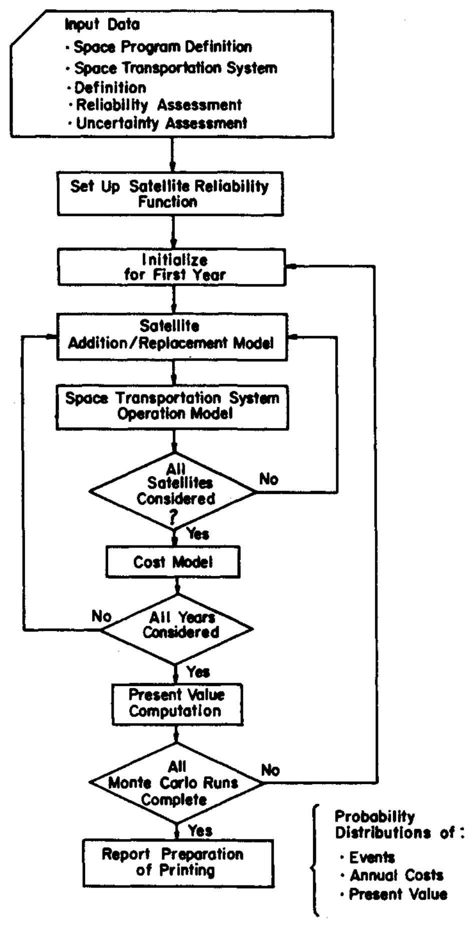
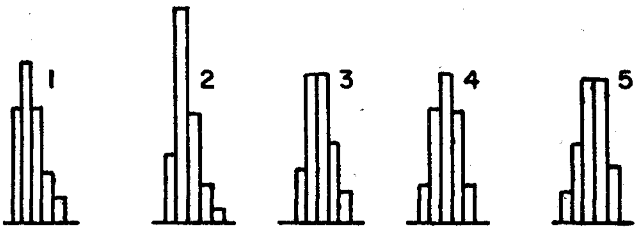


Fig. 7 Simulation model for evaluating effect of reliability and cost uncertainties.

Table 2 Cost components and nominal values (millions of dollars) and uncertainty estimates

Cost component	Nominal value	Uncertainty estimate: Minimum	Maximum	Pdf[b]
Booster expendable cost	3.5	3.1	5.25	3
Booster reusable cost	5.5	5.0	6.0	4
Booster refurbishment cost	1.0	0.8	1.8	3
Orbiter expendable cost	2.2	2.0	3.0	3
Orbiter reusable cost	300.0	250.0	350.0	5
Orbiter refurbishment cost	3.7	3.0	4.5	3
Space Tug expendable cost	0.01	0.008	0.011	3
Space Tug reusable cost	18.9	15.2	28.5	3
Space Tug refurbishment cost	0.38	0.3	0.57	1
Satellite cost[a]	20.0	15.0	28.0	3
Satellite refurbishment cost[a] (% of satellite cost)	15.0	10.0	20.0	3
Operations cost/flight	0.15	0.12	0.17	2

[a] Based upon a satellite retrieval capability. It is assumed that when a satellite is not to be retrieved its cost can be reduced to 16 million dollars.
[b] Uncertainty profiles (Pdf).[14]



The Cost Model treats the following costs as uncertainty variables: 1) booster cost (reusable portion), 2) booster cost (expendable portion), 3) orbiter cost (reusable portion), 4) orbiter cost (expendable portion), 5) Space Tug cost (reusable portion), 6) Space Tug cost (expendable portion), 7) satellite cost, 8) booster refurbishment cost, 9) orbiter refurbishment cost, 10) Space Tug refurbishment cost, 11) satellite refurbishment cost, and 12) operations cost per launch. Each of these uncertainty variables is characterized by a range of uncertainty and a probability distribution of cost within the range. The method for establishing the uncertainty profiles is discussed above. It is assumed that future costs will be highly correlated with the initial values of costs selected by the sampling of the uncertainty profiles. The computation of the future costs is, therefore, based on learning curves. The learning curves

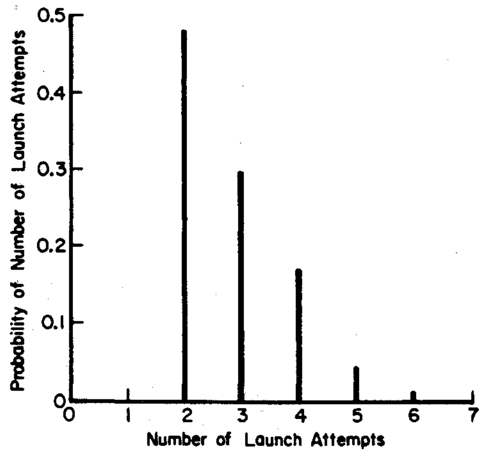


Fig. 8 Probability distribution of launch attempts in year 3.

assume[19] that costs will decrease by a constant percentage each time the production quantity is doubled. Since only one space program out of all space programs is being examined, it is difficult to make judgements based directly on production level. Therefore, it is assumed that learning effects are related instead to time. If production is proportional to time, then learning is proportional to production.

Typical results of the computer simulation, i.e., the event, cost and present value probability distributions, follow.

Typical Space Service Mission

To illustrate the results obtained from the explicit consideration of reliability and cost uncertainties, a typical space service mission is considered over a ten year time period. It is assumed that 2, 4, and 6 operational satellites are required during the first three years, respectively and that it is then desired to maintain a level of service based on 6 operational satellites. The reliability values shown in Table 1 are assumed as are the nominal values of cost and the uncertainty estimates shown in Table 2. The nominal satellite reliability characteristics are assumed as MTBF = 10 yr, $M_f = 5$ yr, and $\sigma_f = 1$ yr (see Fig. 3). These nominal parameters are varied so that the effect of satellite reliability and Space Tug retrieval capability on the events, cost and present cost can be evaluated.

Table 3 illustrates the effect of satellite reliability and Space Tug retrieval capability upon the events. Only two events are

Table 3 Summary of events

Satellite retrieval capability	Case: satellite MTBF[a] (yr)	Expected wearout time (yr)	Event (10 yr total): Launch attempts: Nominal	Expected	Std. Dev.	Satellites: Nominal	Expected	Std. Dev.
No	10	5	12	18.6	3.3	12	19.0	3.1
No	5	5	12	22.0	3.4	12	22.3	3.4
No	15	5	12	17.5	3.2	12	18.0	3.0
No	10	7	12	15.7	3.0	12	16.1	2.8
No	5	7	12	18.8	3.5	12	19.3	3.3
No	15	7	12	14.5	2.8	12	15.0	2.6
Yes	10	5	12	18.6	3.3	7[b]	7.6	0.8
Yes	5	5	12	22.0	3.4	7[b]	7.8	0.9
Yes	15	5	12	17.5	3.2	7[b]	7.6	0.8
Yes	10	7	12	15.7	3.0	7[b]	7.5	0.7
Yes	5	7	12	18.8	3.5	7[b]	7.6	0.8
Yes	15	7	12	14.5	2.8	7[b]	7.5	0.7

[a] MTBF is based upon random failures and is differentiated from wearout failures.
[b] A spare must be available so that a placement and retrieval can be performed in a single flight.

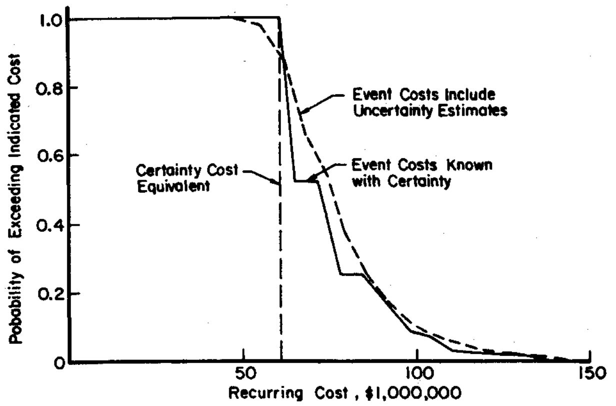


Fig. 9 Probability distribution of recurring cost for year 3 with satellite retrieval capability.

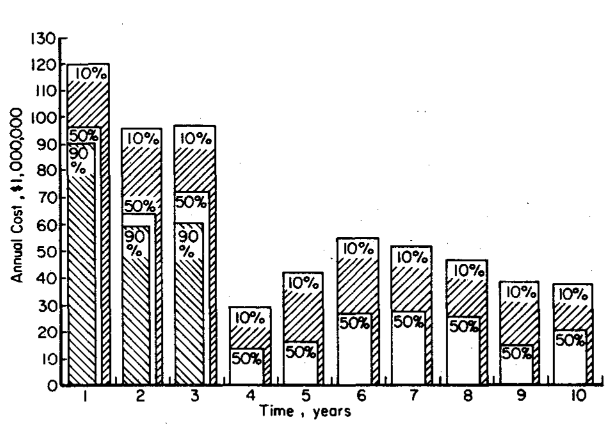


Fig. 10 Annual costs equaled or exceeded with 10, 50, and 90% chance (satellite retrieval capability; cost per event known with certainty).

illustrated; similar data are available on all pertinent events. For each event, a nominal value, expected or mean value and standard deviation are presented. The nominal value corresponds to the certainty situation, i.e., no random failures occur and wearout occurs at the expected wearout time. The standard deviation represents a measure of dispersion about the expected value. The probability distributions of the 10 yr total of events tend toward normal according to the central limit theorem, but are not truly normal. Therefore, care must be exercised in associating a probability value (as is commonly done with the normal distribution) with the standard deviation. A typical probability distribution of the annual number of launch attempts is illustrated in Fig. 8. It should be noted that if failures did not occur, only two launch attempts would be required; in fact there is more than a 50% chance of exceeding two launch attempts.

The primary concern with the events is their effect on cost. Typical annual recurring cost probability distributions are illustrated in Fig. 9. Two curves are shown. One probability distribution considers that the costs are known with certainty (the nominal values given in Table 2); the other assumes that cost uncertainties exist. The effect of the cost uncertainties can thus be seen. Also shown is the certainty cost which would be obtained if failures did not occur and costs were known with certainty. This is the cost which is all too frequently used in the planning and evaluation process. It should be noted that there is, for the case illustrated, at least an 85% chance that the certainty cost will be exceeded; in fact there is a 15% chance that it will be exceeded by more than 50%. This can have disastrous effects when operating in a cash restrictive situation.

In the absence of detailed knowledge of the charge by NASA to a user of the Space Transportation System it has been assumed that amortization would be included. It is also assumed, that in one way or another, the user will pay for refurbishments. These costs are, therefore, included in the analysis. Different assumptions are possible and do not effect the demonstrated methodology.

Figure 10 illustrates in summary form the probability distributions of annual cost. Three costs are shown for each year, namely the costs equalled or exceeded with probabilities 0.10, 0.50, and 0.90. For example, in the first year there is a 10% chance that costs will be equal to or greater than $120 million, a 50% chance that costs will be equal to or greater than $96 million, etc. In the fourth year there is a 10% chance that costs will exceed $30 million and a 50% chance that costs will exceed $14 million. The 90% chance level corresponds to zero annual costs implying about 10% or more chance of cost being zero.

The present value risk profiles, based upon the nominal data in Tables 1 and 2, are illustrated in Fig. 11 for the situations where a satellite retrieval capability exists and when it does not exist. Also shown are the present values associated with the certainty situations. Note that there is a 50% chance that present values can exceed those of the certainty cases by more than 40–50%. It should also be noted that the expected present value and risk are increased when satellite retrieval and refurbishment are not possible. No attempt has been made in this paper to evaluate costs and present values associated with on-orbit refurbishment. The same basic techniques, however, are applicable.

The importance of satellite reliability is addressed in Fig. 12, which indicates the effect of satellite MTBF and expected wearout time (σ_f held constant). Curves are presented for both retrieval and no retrieval capability. The value of achieving different MTBF's and M_f's is apparent. Point A, corresponding

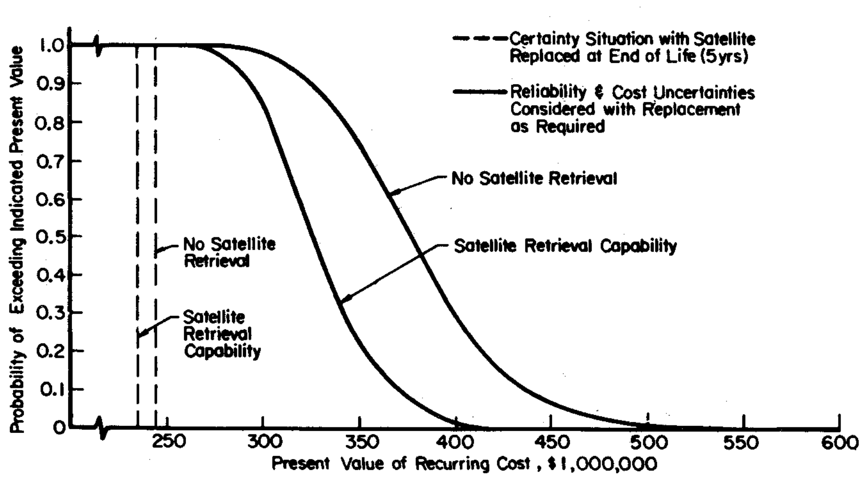


Fig. 11 Probability distribution of present value of recurring cost at a 10% discount rate.

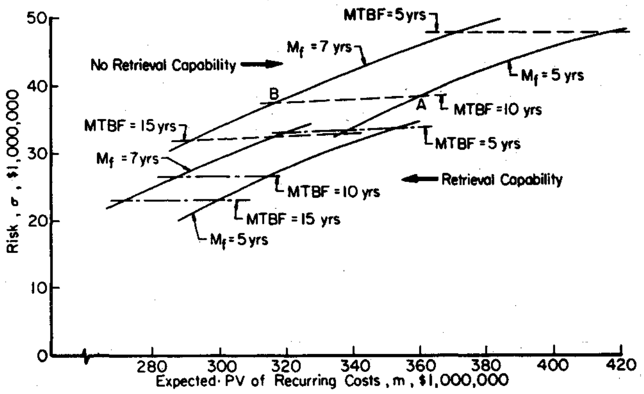


Fig. 12 Effect of satellite reliability on present value of recurring cost.

to an MTBF of 10 yr and an expected wearout life of 5 yr, yields an expected present value of cost of $360 million. Moving to point B, that is increasing the wearout life to 7 yr, reduces the expected present value to $315 million. Thus, moving from point A to point B is worth a present value of $45 million. Thus, if the present value of additional RDT&E and incremental satellite costs is less than $45 million, the design associated with B is superior to that of A, otherwise A is superior to B. Note that no mention has been made as to the effect of risk reduction in moving from A to B and therefore this must be considered as only a partial solution or approximation. To do a more thorough comparison of the relative merits of A vs B requires the determination of the present value of the complete (including RDT&E) cost flow patterns associated with A and B. Once this has been accomplished the probability of the present value of A exceeding that of B by various amounts can be established (this is relatively straight forward if, as is usually the case, the present value probability distributions are normal). At this point, the decision maker, either explicitly or implicitly, can exercise his risk aversion preferences and make an informed choice between A and B.

Discussion

An economic analysis methodology which explicitly considers less-than-perfect reliability and imperfect a priori knowledge of costs is developed that provides the probability distribution of the present value of program costs. It is shown that there can be significant differences between the program costs and present values when developed with and without the explicit consideration of less-than-perfect reliability and cost uncertainties. In general, optimistic costs are obtained when reliability and cost uncertainties are not explicitly considered. These cost differences develop as a result of two basic causes.

The first cause regards the method for making cost estimates. Costs for complex systems are generally developed by breaking a total system into many parts. Cost estimates for each part are normally expressed as those values which are most likely to be achieved. However, upon investigation of the random structure of each estimate, it is common to find that the probability distribution of projected cost is skewed so that the mean or expected cost is higher than the most likely cost. When many random variables (of similar magnitude but various distributions) are summed, the probability distribution of the sum tends toward a Gaussian or normal distribution for which the mean and the most likely values are the same. Thus, the most likely cost of the total system is the sum of the expected values of the costs of the parts. It is in general mathematically incorrect to say that the total system cost is the sum of the most likely cost estimates for the parts that comprise the system. Hence, to neglect cost uncertainties is to commit a mathematical error. Many program directors have learned to cope with this error by adding a contingency fund. However, the size of this fund is all too often obtained by gut feeling and does not provide a true picture of financial risk.

The second cause for higher than anticipated costs lies in the fact that the system reliability is generally not explicitly considered when cost estimates are made. The most commonly used argument for not explicitly accounting for system unreliability is that accurate reliability data are not available. But a decision to neglect to explicitly include the effects of system reliability upon costs is precisely equivalent to performing a thorough analysis of these effects under the assumption that all components of the system are perfectly reliable. Certainly, it should be possible to do better than this, even with crude reliability estimates.

The methodology developed in this study can be put to use in either of two contexts. First, it provides a new tool, based on sound mathematical principles, for a more accurate prediction of program costs. It simultaneously adds a new dimension, that of risk, to the cost data. Second, the methodology provides a mechanism for linking the effects of imperfect reliability to costs and, hence, makes it possible to study the effects of varying reliability specifications upon costs.

References

[1] "Risk Acceptance and Logistics Approaches for Shuttle Automated Payloads," Final Rept., June 1973, Vol. IV, LMSC-D336292, Lockheed Missiles and Space Co., Inc., Sunnyvale, Calif.

[2] Fragola, J. R. and Spahn, J. F., "Economic Models for Satellite System Effectiveness," *Proceedings of the 1973 Annual Reliability and Maintainability Symposium*, 1973, pp. 167–176.

[3] "Economic Analysis of Advanced Propulsion Systems," Mathematica, Inc., Princeton, N.J., 1973.

[4] Greenberg, J. S. and Hazelrigg, G. A., "Performance and Reliability Analysis of a Pluto Flyby Mission," AMS Rept. 1060, Dec. 1972, Princeton Univ., Princeton, N.J.

[5] Dole, S. H., Fisher, G. H., Harris, E. D., and String, J., "Establishment of a Long-Range Planning Capability," RM-6151-NASA, Sept. 1969, Rand Corp., Santa Monica, Calif.

[6] Quade, E. S. and Boucher, W. I., eds., *Systems Analysis and Policy Planning*, Elsevier, New York, 1968.

[7] Hess, S. W. and Quigley, H. A., "Analysis of Risk in Investments Using Monte Carlo Techniques," *Chemical Engineering Progress*, Sec. 42, Vol. 59, 1963.

[8] Hertz, D., "Risk Analysis in Capital Investment," *Harvard Business Review*, Jan.–Feb. 1964.

[9] Hertz, D., "Investment Policies that Pay Off," *Harvard Business Review*, Jan.–Feb. 1968.

[10] VanHorne, J., "Capital Budgeting Decisions Involving Combinations of Risky Investments," *Management Science*, Vol. 13, No. 2, Oct. 1966.

[11] Hillier, F. S., "The Derivation of Probabilistic Information for the Evaluation of Risky Investments," *Management Science*, April 1963.

[12] Greenberg, J. S. and Edelman, F., "Venture Analysis: The Assessment of Uncertainty and Risk," *Financial Executive*, Aug. 1969.

[13] Spetzler, C. S., "The Development of a Corporate Risk Policy for Capital Investment Decisions," *IEEE Transactions on Systems Science and Cybernetics*, Vol. SSC-4, No. 3, Sept. 1968.

[14] Swalm, R., "Utility Theory-Insights into Risk Taking," *Harvard Business Review*, Nov.–Dec. 1966.

[15] Chernoff, H. and Moses, L. E., *Elementary Decision Theory*, Wiley, New York, 1965.

[16] Fishburn, P. C., "Utility Theory," *Management Science*, Vol. 14, No. 5, Jan. 1968, pp.

[17] Greenberg, J. S., "An Approach to Reliability, Uncertainty and Risk Assessment of Space Systems," AMS Rept. 1051, June 1972, Princeton Univ., Princeton, N.J.

[18] Greenberg, J. S., "Reliability, Uncertainty and Risk Analysis of Space Systems—A Methodology for Decision Making," AMS Rept. 1085, Dec. 1972, Princeton Univ., Princeton, N.J.

[19] Fabrycky, W. J., Torgersen, P. E., *Operations Economy: Industrial Applications of Operations Research*, Prentice-Hall, Englewood Cliffs, N.J., 1966.