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Measuring the Value of Designing for Uncertain Future Downward Budget Instabilities

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A method is presented for understanding the behavior of space system program costs under downward annual budget pressure, with a real options analysis incorporated for determining the maximum worth of an architecture transition option to hedge against program budget uncertainty. The relationship between program schedule extension and resulting program cost growth is examined. As downward pressure is applied to a program's yearly budget, its overall length and, hence, cost increase. It is found that sets of candidate space system architectures for a given program can be in one of three stages of behavior in response to downward annual budget pressure, and expressions are derived indicating stage transition points. Each of these three stages of behavior indicates a different level of space system architecture robustness to annual budget levels and implies different recommended actions for a system designer or program manager. For the middle stage of behavior, maintaining an option to transition to a lower cost architecture would be one way of achieving robustness under downward budget pressure. Then real options are examined as a valuation method for understanding the maximum value that might be placed on the ability to switch to a lower cost architecture.

Nomenclature

b	=	policy-adjusted annual program budget level, \$/year
b_{cv1}	=	critical transition value from stage 0 to stage 1, \$/year
b_{cv2}	=	critical transition value from stage 1 to stage 2, \$/year
c_i	=	total nominal program development cost for architecture i, \$
c_i'	=	total program development cost for architecture i under downward annual budget, \$
$c_{\max}$	=	cost of the architecture in i with performance $p_{\max}$, \$
$c_{\min}$	=	cost of the architecture in i with performance $p_{\min}$, \$
d_i	=	nominal total program development duration for architecture i, year
d_i'	=	total program development duration for architecture i under downward annual budget, year
$d_{\max}$	=	duration of the architecture in i with performance $p_{\max}$, year
$d_{\min}$	=	duration of the architecture in i with performance $p_{\min}$, year
i	=	set of Pareto optimal space system architectures bounded by $p_{\max}$ and $p_{\min}$
p_c	=	probability of budget cut
r	=	risk free rate of return
TC	=	cost to transition to a new architecture from an initial architecture, \$
t	=	time horizon of real option, year
x	=	fraction of total program schedule change
y	=	fraction of total program cost change

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Introduction

THE creation of a government space system today requires the contributions of many groups and organizations. These groups can be classified roughly into four domains: the technical domain, the political domain, the operational domain, and the architectural domain. The technical domain might consist of those who do the detailed design and assembly of the space system. The political domain might consist of those who create national policy and appropriate funds for space systems. The operational domain might consist of the users of the space systems. Last, the architectural domain might consist of those responsible for creating the top-level system architecture and brokering information and concerns between the other three domains. This interacting domain concept for the creation of government space systems is shown graphically in Fig. 1.[1]

For a space system architecture to be robust, it must successfully weather any changes that may occur during the course of the system development or operation. It is immediately clear from Fig. 1 that there are many sources of potential changes, or instabilities, in the space system architecture creation process given the large number of domains that are involved. Understanding the sources and nature of instabilities is important for the space system architect or program manager or designer striving for a robust system.

Perhaps one of the least well understood sources of instability in space systems is the political domain. Yet, actions taken in the political domain have profound effects on space systems. Overnight, new policies can restrict the launch vehicles available, or revised lower budgets can force a dramatic descoping or even cancellation of government space system programs. Understanding the effects on space systems of such political domain instabilities as uncertain future annual budgets is the focus of this paper.

Understanding Budget Policy Instability on Space Systems

In research interviews with space system senior managers in government and industry, budget adjustments are the most frequently reported policy actions taken by the U.S. Congress on government space system programs, and it is not hard to understand why. Government and military space system programs are subject to budget approvals each year by their own agencies, as well as the Congress. Each year, a program budget can, and frequently does, change. For fiscal years 1996–1998, 32% of defense programs experienced a budget reduction by the Congress, 53% experienced a budget increase, and only 15% received the budget they requested. Hence, a space system program manager can conclude that the probability

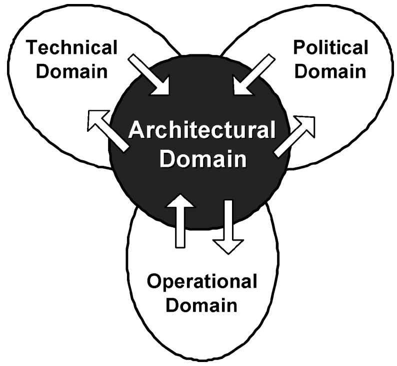


Fig. 1 Domains and interactions involved in creating government space systems.

that the budget will change is much larger than the probability that it will stay on the nominal path. Thus, budget uncertainty is possibly the most pervasive policy uncertainty facing civil and military space systems today.

How space system designers and program managers can gain an understanding of their system's behavior under various budget conditions while they are still in the conceptual design phase of a program is explored in this paper. In addition, a real options methodology is suggested to measure the value of designing for potential budget instabilities. This early understanding and measurement of system behavior in response to budget conditions can point out which space system architecture candidates may be more robust than others. The paper begins with an examination of the relationship between schedule increases and cost increases. As downward pressure is applied to a program's yearly budget, its overall length and, hence, total cost increase. Generalized behaviors are observed for space system cost behavior as a result of downward pressure on yearly program budget levels. It is found that sets of candidate space system architectures for a given program can be in one of three stages of behavior in response to downward annual budget pressure, and expressions are derived indicating stage transition points. Each of these three stages of behavior indicates a different level of space system architecture robustness to annual budget policy levels and implies different recommended actions for the program manager in working toward a budget policy robust space system. For the middle stage of behavior, maintaining an option to transition to a lower cost architecture would be one way of achieving robustness under downward budget pressure. Then real options are examined as a valuation method for understanding the maximum value a program manager might place on the ability to switch to a lower cost architecture. Throughout the paper, methods presented are illustrated using a specific mission as a case example.

Relationship of Schedule Extension and Cost Increase

As downward annual budget pressure is applied to a space system program, its annual budget is lowered. As a result, the program schedule becomes stretched out. The relationship that relates such schedule increases to resulting program cost increases on space systems is inherently unique to each individual space system. Factors such as the type of program, nature of mission, management structure, contract structure, etc., are primary factors in shaping such a relationship. Because most of this data is proprietary, this research turns to publicly available data to craft a simple relationship for illustrative purposes. Augustine, former aerospace industry executive, generated 52 laws describing many aspects of aerospace systems. Law 24 includes data that relate schedule increases on aerospace and defense programs to resulting program cost increases.[2] These data are used to estimate a linear relationship between the two program variables of schedule increase x and cost increase y:

$$y = 0.24x + 0.017 \tag{1}$$

with a Pearson's correlation squared $R^2 = 0.56$. This relationship has several limitations. First, it assumes that cost increases are a linear function of schedule increases. Second, it further assumes that cost increases are solely a function of schedule increases. In reality, neither of these assumptions is particularly valid for most programs, likely resulting in the low R^2. Cost increases are more complex than a simple linear relationship with schedule extension, taking on different nonlinear forms for each stage of program development. In addition, many more factors other than schedule extension drive cost changes on programs. Although the authors recognize all of these limitations, the preceding linear relationship was selected for illustrative purposes only to demonstrate the process of analyzing how downward annual budget pressure can affect space systems. System designers and program managers are encouraged to develop their own unique and appropriate relationships for each program stage and apply the analytical processes described in this paper.

Terrestrial Observer Swarm Iteration B (B-TOS) Case Study Illustration

The terrestrial observer swarm iteration B (B-TOS) mission is used as a case study to illustrate the effects of downward pressure on annual space system program budgets, employing Eq. (1) as an illustrative relationship between program schedule extension and cost increase. B-TOS is a space-based atmospheric mapping mission designed to characterize the structure of the ionosphere using topside sounding techniques. To accomplish these goals, the B-TOS space system concepts use a swarm architecture of distributed small mother and daughter satellites in multiple collaborating clusters. There were 4000 candidate B-TOS architectures created by varying the orbit altitude, number of orbital planes, number of swarms per plane, number of satellites per swarm, the radius of the swarm, and the capability of the payload for the B-TOS mission.

These 4000 unique architecture candidates comprise the completely enumerated tradespace for the B-TOS mission. The high performing and low-cost portion of this tradespace is shown in cost–utility space in Fig. 2, where cost is total program life-cycle cost and utility is a measure of how well user needs are satisfied. In the B-TOS case study discussions that follow, architecture candidates will frequently be represented in such cost–utility space, where each dot in Figs. 2–8 represents a single and unique space system architecture candidate that can accomplish the B-TOS mission.

A Pareto front emerges in cost–utility space (for example, dashed line in Fig. 3), which contains four of the B-TOS architecture candidates, labeled A, B, C, or D in order of increasing utility and cost. By definition, the Pareto optimal front includes all nondominated solutions, or those whose performance cannot be surpassed without higher costs. Thus, those architectures lying along the Pareto front (called the Pareto front set of architectures) provide the best performance per dollar values.

Figures 3–8 show the B-TOS architecture candidates plotted in cost–utility space. The solid diamonds represent the B-TOS architectures under their nominal planned annual budgets, and the open squares represent the same B-TOS architectures under a specific

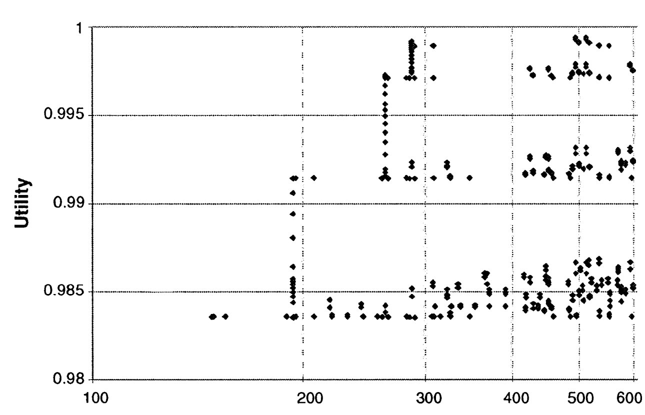


Fig. 2 B-TOS architecture tradespace plotted in cost-utility space.

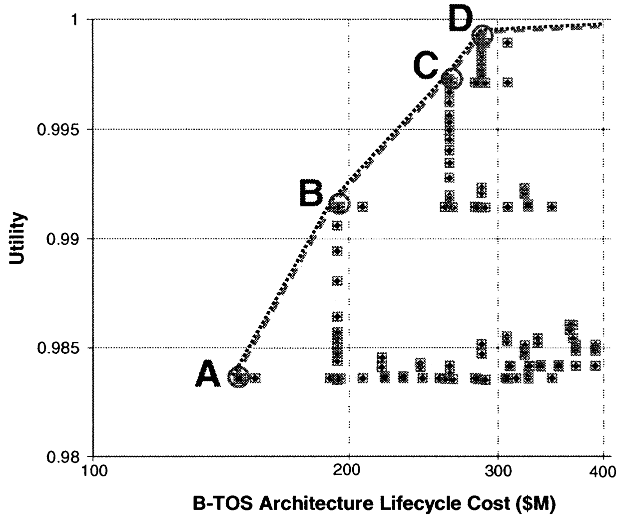


Fig. 3 B-TOS case study: Comparison of nominal and $80 million/year program budget: ◆, nominal yearly program budget and □, $5 million yearly program budget.

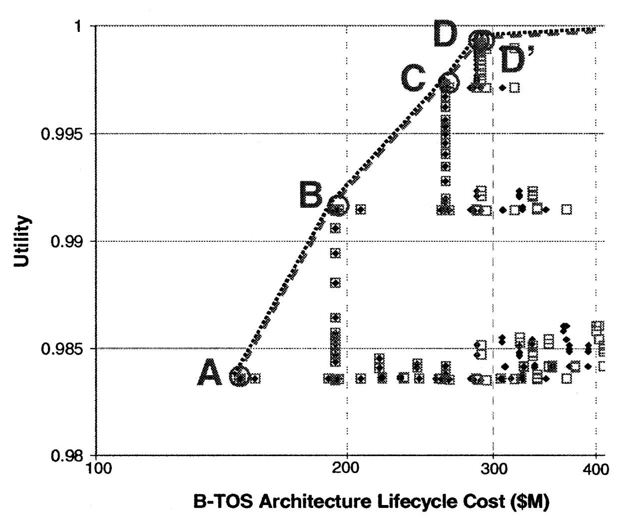


Fig. 4 B-TOS case study: Comparison of nominal and $40 million/year program budget: ◆, nominal yearly program budget and □, $5 million yearly program budget.

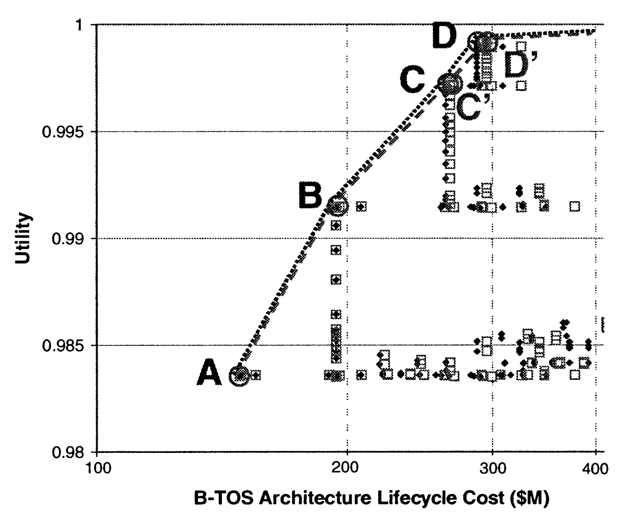


Fig. 5 B-TOS case study: Comparison of nominal and $35 million/year program budget: ◆, nominal yearly program budget and □, $5 million yearly program budget.

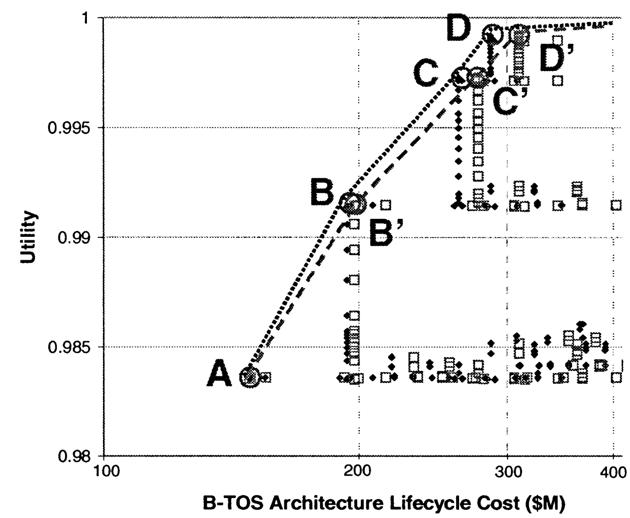


Fig. 6 B-TOS case study: Comparison of nominal and $25 million/year program budget: ◆, nominal yearly program budget and □, $5 million yearly program budget.

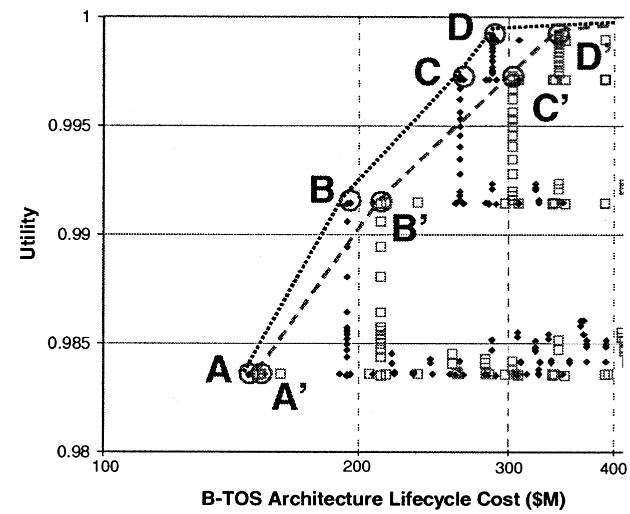


Fig. 7 B-TOS case study: Comparison of nominal and $15 million/year program budget: ◆, nominal yearly program budget and □, $5 million yearly program budget.

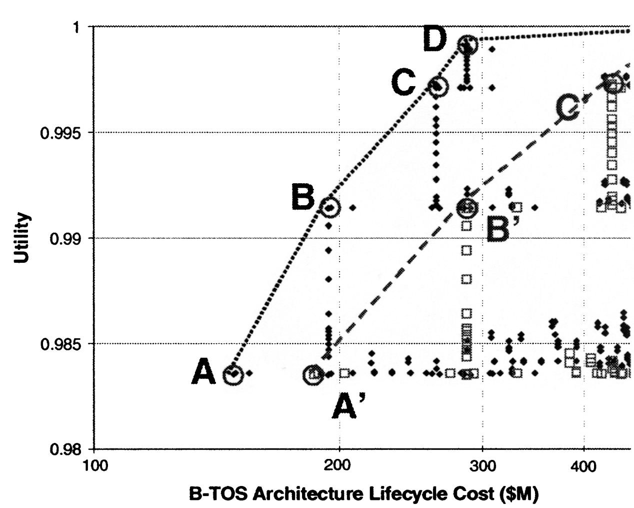


Fig. 8 B-TOS case study: Comparison of nominal and $5 million/year program budget: ◆, nominal yearly program budget and □, $5 million yearly program budget.

annual budget level that varies in Figs. 3–8. In this analysis, all aspects of the architectures (performance requirements, etc.) were kept constant besides spacecraft development costs. The baseline nominal planned development duration for B-TOS was three years. The nominal total spacecraft cost for each Pareto front architecture was \$56 million, \$83 million, \$110 million, and \$126 million for architectures A, B, C, and D, respectively. A constant spending profile was assumed for simplicity of illustration, but varying levels of spending can certainly be used in a highly detailed analysis.

Figure 3 shows a comparison of the nominal annual program budget for each B-TOS architecture to a policy-adjusted annual program budget of \$80 million. Each of the four Pareto front architectures (labeled A, B, C, and D for the nominal budget case and A′, B′, C′, and D′ for the policy-adjusted budget case when different from the nominal case) is seen to have identical total program costs in both situations. Thus, an annual program budget of \$80 million will not have a detrimental impact on costs of the Pareto front architectures and the Pareto fronts of the nominal case and the policy-adjusted case overlap. Figure 4 shows the effects of a \$40 million annual program budget. It can be seen that architecture D has been affected by this level of annual program budgeting, demonstrated by the increased total cost of architecture D when subject to the \$40 million budget level (D′ in Fig. 4). This results in the beginning of the separation of the nominal case Pareto front and the policy-adjusted case Pareto front.

As the trend in downward annual budgets continues, with a \$35 million annual budget, architecture C is additionally impacted in Fig. 5 (C′). Stepping down further to a \$25 million annual budget (Fig. 6) adds a detrimental cost increase on architecture B as well, denoted by B′. Finally, arriving at an annual budget of \$15 million in Fig. 7, architecture A, the least expensive of the B-TOS Pareto front architectures, is negatively affected (denoted by A′) by the low annual policy-adjusted budget. A still lower level of annual budget at \$5 million (shown in Fig. 8) readily indicates a dramatic separation of the Pareto fronts of the nominal budget case and the policy-adjusted budget case.

Generalizing Downward Annual Budget Effects

When the movement of the nominal budget case and the policy-adjusted budget case Pareto fronts in Figs. 3–8 is observed, three distinct stages of behavior emerge. One stage is represented by Fig. 3, where both Pareto fronts overlap. In this stage, called stage 0, none of the Pareto front architecture set is affected by the policy-adjusted annual budget level, although other non-Pareto architectures may be affected. Another stage is represented by Fig. 5, where part of the two Pareto fronts overlap but other parts are separated. In this stage, called stage 1, some architectures in the Pareto set are affected by the policy-adjusted annual budget level, whereas others are not. The last stage of behavior is represented by Fig. 8, where both Pareto fronts have completely separated. In this stage, called Stage 2, all of the Pareto front architecture set is affected by the policy-adjusted annual budget level. A graphical representation of this progression of Pareto front behavior under downward annual budget pressure is shown in Fig. 9. The solid line represents the Pareto front architecture set under nominal annual budget levels, and the dashed line represents the Pareto front architecture set under policy-adjusted annual budget levels. What is most useful for a system designer or program manager is to understand the critical transition points between these stages.

Bounding the Architecture Set

The first step in understanding the critical transition points between stages is to bound the architectures under consideration usefully such that $p_{\max}$ and $p_{\min}$ define the extremes of the acceptable performance range. Of the architectures within this range, the subset that lies along the Pareto front between $p_{\max}$ and $p_{\min}$ comprise i. Here $c_{\max}$ is the cost of the architecture in the Pareto optimal set i with performance $p_{\max}$, and $c_{\min}$ is the cost of the architecture in i with performance $p_{\min}$.

Constructing Quantitative Relationships

Constructing equations that quantify policy-adjusted program duration d_i' and policy-adjusted program cost c_i' is a necessary input to the eventual valuation of a real option to accommodate budget instabilities. Note that the equations presented here are specific to the schedule extension and resulting cost increase relationship assumed and the assumption of a constant spending profile. The equations will be different for each unique space program and their spending profile, but can be constructed in a similar manner as the example presented.

Within the Pareto optimal set of architectures, the annual cost of a program assuming a constant spending profile is the total program cost divided by the program development duration. Under a policy-adjusted budget b, the modified program duration is $d_i' = c_i/b$. With use of Eq. (1), the corresponding total program development cost under a policy-adjusted annual budget is

$$c_i' = c_i[0.24(c_i/bd_i - 1) + 0.017] \tag{2}$$

for values of $c_i/bd_i \leq 1$.

Identifying Critical Stage Transition Point Values

Figure 9 shows the three stages of Pareto front behavior under downward annual budget pressure. Stage 0 occurs when b exceeds the maximum annual expenditures of all i architectures. For B-TOS, this is when $c_i/d_i \leq b$. In this stage, $c_i', d_i' = c_i, d_i$ because no Pareto front architectures are adversely impacted. The transition from stage 0 to stage 1 occurs at the point b_{cv1} where a maximum annual expenditure of at least one architecture in i exceeds b. For B-TOS, the simple case where annual program expenditures are assumed constant,

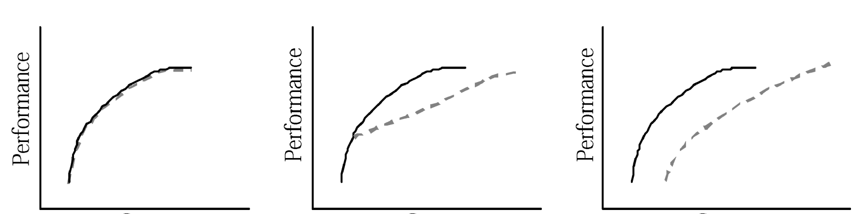
$$b_{\mathrm{cv1}} = c_{\max}/d_{\max} \tag{3}$$

Stage 1 occurs when the maximum annual expenditures of some architectures exceed b and the maximum annual expenditures of the remaining i architectures do not exceed b. For B-TOS, this is when $c_i/d_i \leq b$ for some i and $c_i/d_i > b$ for all other i. In this stage for B-TOS, $c_i', d_i' = c_i, d_i$ when $c_i/d_i \leq b$. When $c_i/d_i > b$, $c_i', d_i' \neq c_i, d_i$ because some Pareto front architectures are being adversely impacted by downward annual budget pressure. The transition from stage 1 to stage 2 occurs at the point b_{cv2} where a maximum annual expenditure in all i architectures exceed b. For B-TOS, this occurs at

$$b_{\mathrm{cv2}} = c_{\min}/d_{\min} \tag{4}$$

All Pareto front architectures are adversely impacted by downward annual budget pressure, and all $c_i', d_i', \neq c_i, d_i$. In stage 2 for B-TOS, $c_i/d_i > b$ for all i.

Each stage of the budget policy-adjusted Pareto front behavior indicates different levels of robustness of a Pareto optimal set of



a) Stage 0: no Pareto architectures affected **b) Stage 1: some Pareto architectures affected** **c) Stage 2: all Pareto architectures affected**

Fig. 9 Three stages of behavior of the Pareto front set of architectures under downward annual budget pressure.

architecture candidates associated with a given b. For stage 0 behavior, the architecture set is very robust to budget adjustments because the architecture costs are not affected by b. Conversely, for stage 2 behavior, the architecture set is not robust to budget adjustments because all architectures within the acceptable range of performance on the Pareto front are adversely affected by b. Similarly, stage 1 behavior indicates that some of the architectures in the optimal set are unaffected by b and are robust, whereas others are not.

What Do We Learn?

A space system designer, program manager, or other decision maker should be concerned about what stage of behavior the system will exhibit under the range of likely b for the program. If b is likely to be less than b_{cv1}, then the system is exhibiting stage 0 behavior and all architectures in the Pareto optimal set i are robust to budget policy changes. If b is likely to be greater than b_{cv2}, then the system is exhibiting stage 2 behavior, where no architectures in i are likely to be robust to budget uncertainty. Stage 2 behavior can be remedied be redefining i such that b for this newly defined i is less than b_{cv2}.

If b is likely to be greater than b_{cv1} but less than b_{cv2}, the system is exhibiting stage 1 behavior, where some architectures are robust to budget uncertainty whereas others are not. In stage 1, system designers and program managers may find it useful to use budget robustness as a selection criterion in choosing a final architecture. They might also consider concurrently investing in the development of an alternative architecture as a fallback plan should downward annual budget pressure become so great that the original architecture becomes infeasible. We shall call this the transition option and think of it as a budget-robust alternative architecture that a program might transition to at some point in its development when downward annual budget pressure surfaces. The value of a transition option cannot be precisely known in advance, but a real-options analysis technique can provide a useful upper bound to its worth. A designer or program manager would view this as the maximum amount that might be invested as a hedge against program budget uncertainty. The remainder of this paper examines the application of real-options analysis to valuing an architecture transition option.

Real-Options Background

Real options is a valuation technique for risky projects and product developments that emerged out of financial sector techniques to value options on stocks. An option is a right, but not an obligation, to take an action. This right permits someone to take the action when the outcome is favorable, but they are not obliged to take the action if the outcome is unfavorable. This basic nature of options creates the situation of asymmetric returns. It allows decision makers to manage risks by avoiding unfavorable exposure to uncertainty. Real-options analysis recognizes the managerial opportunities that are embedded in strategic investment. Managers make decisions over time, and their choices that can be actively directed are the real options. Space constraints do not permit a very detailed review of real-options analysis techniques, but in Refs. 3–5 more information is provided for those interested.

Real options is a fundamentally different way of framing the valuation process from traditional methods such as variations on discounted cash flow analysis. Although these techniques are fine for situations without uncertainty, they fall short for situations that do involve uncertainty. As any experienced government space system program manager will attest, program budgets are anything but certain.

There are six basic steps to performing a real options valuation analysis[3]:

1) Identify decisions. What decisions can be made? When might they be made, and who is making them? These decisions are the options.

2) Identify uncertainty. What are the sources of uncertainty? Examine private and public risk. Private risk refers to sources of risk that are contained in the project itself and are under the control of the project managers (such as technical performance risk, schedule risk, etc.). Public risk refers to sources of risk external to the project that are not under the control of the project manager, such as market risks or budget appropriations.

3) Identify decision rule. This is a simple mathematical expression that describes the favorable conditions under which the option would be exercised.

4) Establish option valuation model inputs. The value of an option depends only on five parameters: the current value of the underlying asset, the cash flows/yields/payoffs of the options, the volatility of each source of uncertainty, the time horizon associated with each option, and the risk-free rate of return.

5) Implement option value calculations. Several computation methods can be employed depending on the nature of the real-options problem, including analytical approaches, dynamic programming approaches, and simulation approaches. Black–Scholes equations and binomial models are very common.

6) Review results and analyze sensitivity. After calculating option values, sensitivities to uncertain parameters can be investigated.

The output of a real-options analysis is the measured value of the real-options examined, along with sensitivity to the parameters of the analysis. Based on this output of option value, a decision maker can decide whether maintaining the real options is worthwhile for the specific project.

Applying Real Options to Space Systems and Budget Uncertainty

The first step in investigating the value of a transition option to switch architectures on a space system program during the program's development life is to identify the decision available: to transition to a lower cost Pareto front architecture when downward annual budget pressure surfaces. The second step is to identify the primary source of uncertainty that will be modeled: budget level uncertainty. This is a public source of uncertainty, external to the space system program. The third step is to formulate the decision rule: transition architectures if the cost of transitioning is less than the cost of not transitioning. This is much like the common decision rule on refinancing a home mortgage; one would only refinance at a new rate if the total cost were less than continuing with the current mortgage.

Model Inputs and Volatility

The fourth step in real-options analysis is to determine the five input parameters to an option valuation model. The risk-free rate of return is the rate a riskless investment would return. The option time horizon is the duration over which the real option is held and could possibly be exercised. The option payoff is the cash flow or yield that would be realized if the option was exercised, and the current value of the underlying asset is simply the present worth of the real property on which the option is held. For space systems and the scenario of downward annual budget pressure, the risk-free rate of return could be approximated by the U.S. Treasury rate for a note of length approximating the option time horizon. The option time horizon would likely be the development duration of the program, although it could extend further if the option could be exercised during the operational phase of the mission. The option payoff would be the cost to transition to a new architecture, and the current value of the underlying asset would be the initial projected cost of the space system architecture selected. The last input to the options valuation model is the volatility of the source of uncertainty, which for government satellite system programs is the uncertainty associated with being allocated the full requested program budget each year. This volatility measure is the probability that will be used in a decision tree model to calculate the value of the real option.

To measure volatility of budgets, historical data were collected on congressional budget adjustments for nearly 1000 Department of Defense procurement and research, development, testing, and evaluation programs from fiscal years 1996–1998. For each program, the president's budget request was compared with the final conference resolution.[6,7] A histogram of these comparisons is shown in

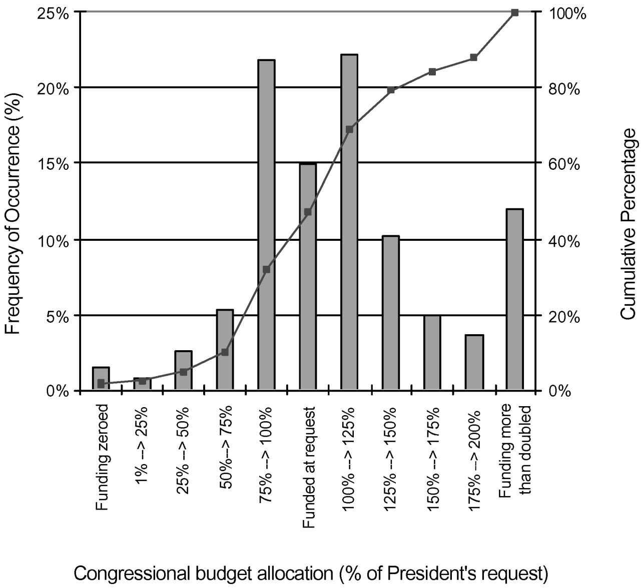


Fig. 10 Historical distribution of annual program budget adjustments for DOD programs, fiscal years 1996–1998.

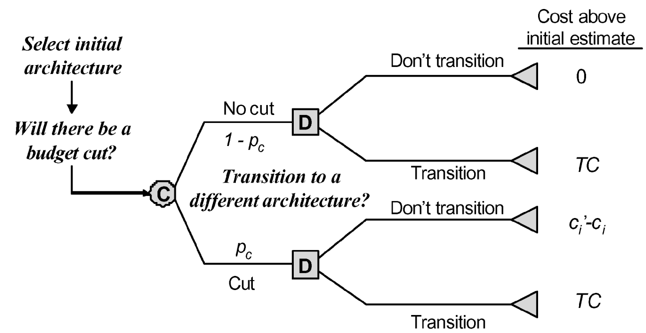


Fig. 11 Simple architecture transition option decision tree model for two architectures: value of option $= p_c[\min(c_i' - c_i, \mathrm{TC})] + (1 - p_c)[\min(0, \mathrm{TC})]$ and maximum present value of option $= p_c(p_c' - c_i)/e^{-rt}$.

Fig. 10, with the congressional conference budget allocations represented as a percent of the president's budget request. These fiscal years of 1996–1998 do not appear to represent any special circumstances and, thus, are considered for this research to represent an average cross section of DOD budget volatility. However, there is no guarantee that the future will always look like the past. When the budget environment changes, the volatility measures provided here will need to be reevaluated under the new circumstances expected in the future.

For a program manager, the real concern with budget allocation uncertainty is the downside, or the risk that the program budget will be reduced. It is only under reduced budgets that the option to transition to a lower cost architecture might be exercised. If the full program budget is allocated or increased, and the program requirements have not changed, then there is no obvious need for a program manager to exercise a transition option to a lower cost architecture.

To model the downside volatility more easily, it is useful to find a probability function that approximates the actual data shown in Fig. 10. An exponential probability density function (PDF) of the form

$$f_x(x_o) = \begin{cases} \lambda e^{-\lambda x_o}, & x_o > 0 \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

with $\lambda = 4.65$ is the best fit. The exponential cumulative PDF was used as the basis for estimating, and yielded a standard error of the estimate of 6% and a Pearson's correlation squared $R^2 = 0.99$.

Option Value Calculations

The fifth step in real-options analysis is to calculate the option value using the assumptions just made. To calculate the value of the architecture transition option, a decision tree binomial model is used as shown in Fig. 11. An initial architecture will be selected, and then there is the chance in each year that the program will receive a budget cut. The volatility assessment in the preceding section forms the basis for the probability that a budget cut will occur. If there is no budget cut, a program manager could choose to stay with the initial architecture with no cost penalty, or transition to a new architecture with a cost penalty equal to the cost to transition to the new architecture (represented by the variable TC). Because the assumed goal of the program manager is to minimize costs, no transition will occur if no budget cut occurs.

If there is a budget cut, the program manager is faced with the same choice of whether to transition architectures. Transitioning will incur a program cost increase of TC, whereas not transitioning while under a budget cut will incur a cost equal to $c_i' - c_i$. In this case, the program manager, wishing to minimize costs, will choose to transition only if the cost of transition TC is lower than the costs to not transition, $c_i' - c_i$.

Rolling back the decision tree yields the value of the transition option. As shown in Fig. 11, the net present value of the option to transition from an architecture is

$$p_c[\min(c_i' - c_i, \mathrm{TC})] \big/ e^{-rt} \tag{6}$$

The cost to transition to a new architecture is unknown and theoretically is able to take on any value from zero to infinity, whereas $c_i' - c_i$ is finite and known. Although the exact value of the option is not known because TC is unknown, the maximum net present value of the option can be evaluated, and this occurs at

$$p_c(c_i' - c_i) \big/ e^{-rt} \tag{7}$$

It is a simple matter to extend this equation and the decision tree it was derived from to accommodate the possibility to transition to an infinite number of architecture candidates. This yields the same maximum net present value of the option regardless of the transition costs that are associated with each transition architecture possibility.

An important consideration in real options is understanding when the option has value. This is shown graphically in Fig. 12. In stage 0, there is no downward budget pressure, and thus, there is no need to transition architectures. Hence, the value of a transition option in this stage is zero. In stage 2, the downward annual budget pressure is so great that there are no architectures in the Pareto optimal set unaffected by this pressure. Thus, there are no Pareto optimal architectures to transition to, and the value of the transition option here is also zero. In addition, when a program is canceled or has been completed, obviously a transition option no longer has value.

Stage 1 during a program's development life is where a transition option may have value. In stage 1, some of the Pareto architectures are affected by lower budget levels, and some are not. The affected architectures will have a positive transition option value, whereas the unaffected architectures will not. These unaffected architectures provide a fallback position for the affected architectures in stage 1, and become the set of possible transition architectures. In Fig. 12, this can be represented by initially choosing a Pareto front architecture on the upper right-hand portion of the solid line, where it is separated from the dashed line, and selecting a transition option architecture from the lower left-hand portion of the graph, where the solid and dashed lines overlap.

Analyze Option Model Sensitivities

The sixth step in the real-options analysis process is to examine the sensitivity of the results to changes in the assumptions. The magnitude of the impact indicates which assumptions are really driving the value of the transition option. Assumptions on b, r, t, and p_c will be examined in this section, and the B-TOS mission will serve as a case study to illustrate how sensitivity analysis can yield useful insights.

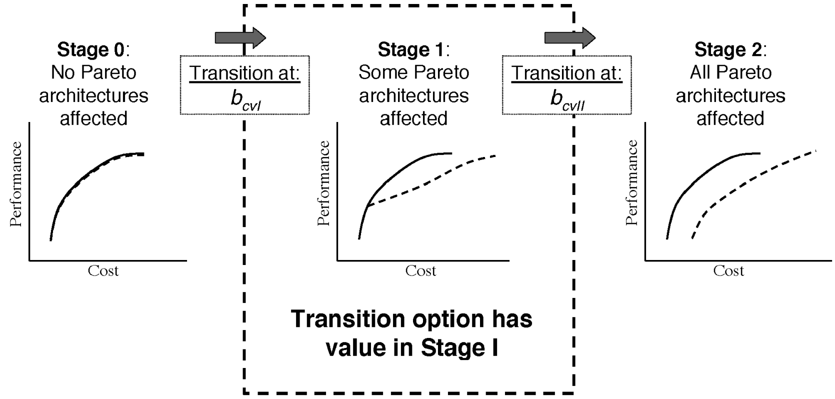


Fig. 12 Transition values between stages of behavior.

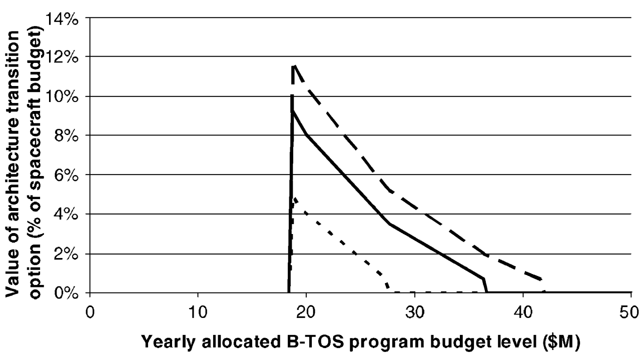


Fig. 13 Expected maximum transition option net present value for B-TOS Pareto front architectures; sensitivity to variation in annual program budget level: ---, architecture D; ——, architecture C; and - - - -, architecture B.

For the B-TOS case study, volatility was assumed to follow the exponential approximation of observed historical budget adjustments present earlier, with $p_c = 0.32$. Time t was assumed to be 3 years, which is the development duration of the B-TOS program. Here, r was assumed to be 5%. The expectation of the option value was derived from the decision tree formulation of the real-option problem presented in Fig. 11. Equation (7) shows the formula used to calculate the expectation of the maximum transition option value. For the four Pareto optimal B-TOS architectures, the maximum transition option value varied in dollar amount from \$2.6 million to \$7.4 million but was a constant 3% of total spacecraft development and production budget. If it is believed that the B-TOS program budget allocations will follow the DOD's recent historical patterns, 3% of the spacecraft budget is the maximum a program manager should be willing to invest to own an option to transition to a lower cost architecture. What are the sensitivities of the assumptions that resulted in a 3% value?

Univariate Sensitivities

Univariate sensitivity analysis varies only one assumption at a time while holding all others constant and looks at the impacts that result. Figure 13 shows the sensitivity of the B-TOS transition option value to the annual allocated program budget level. The transition option value exhibits the greatest sensitivity to this variable, as demonstrated by the sharp slopes in Fig. 13. Figure 13 also shows the bounds of option values at b_{cv1}, and b_{cv2}, which are approximately \$42 million and \$18 million, respectively, for B-TOS, outside which the transition option has no value.

The usefulness of this sensitivity analysis can be demonstrated with an example. Assume the B-TOS program initially chooses architecture D but would like to carry an option to transition to a lower cost architecture if budget priorities should change later on in the program development schedule. Historic volatility levels would suggest that the value of the transition option is about 3% of the total spacecraft budget. However, what if the B-TOS program manager

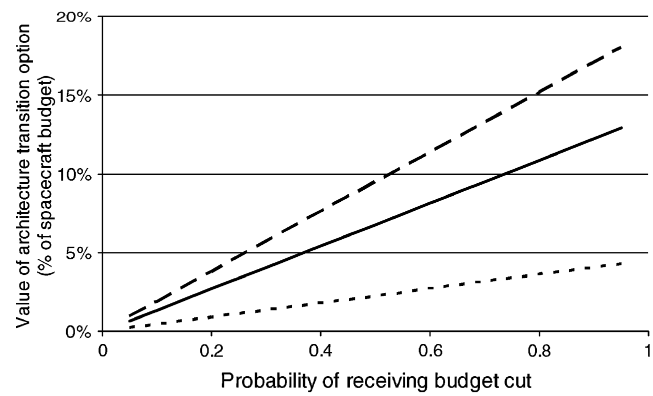


Fig. 14 Expected maximum transition option net present value for B-TOS Pareto front architectures at \$25 million annual program budget; effects of varying probabilities of budget cut: ---, architecture D; ——, architecture C; and - - - -, architecture B.

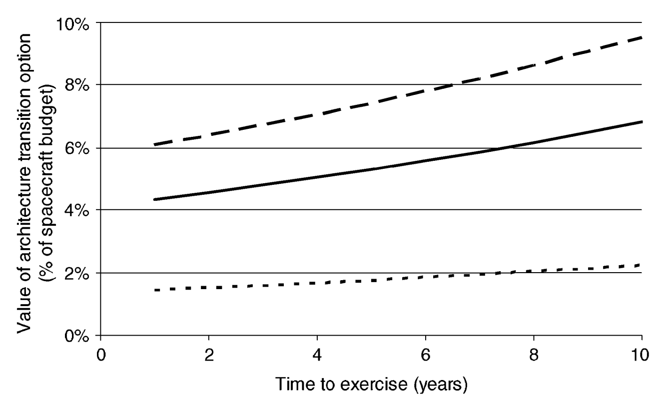


Fig. 15 Expected maximum transition option net present value for B-TOS Pareto front architectures at \$25 million annual program budget; effects of varying time to exercise: ---, architecture D; ——, architecture C; and - - - -, architecture B.

has reason to believe that the upcoming years will be particularly tight budget years and that the B-TOS program will probably be subject to more downward budget pressure than history would predict? By an examination of Fig. 13, the program manager can quickly discern the value of the transition option for the entire range of potential annual budgets that might be allocated. If the manager feels that the annual program budget has a reasonable chance of being cut to \$25 million, then the transition option value increases from 3 to about 7%.

Figures 14–16 show the univariate sensitivities of the B-TOS transition option value to p_c, r, and d_i, respectively. The annual budget is fixed at \$25 million to demonstrate these sensitivities.

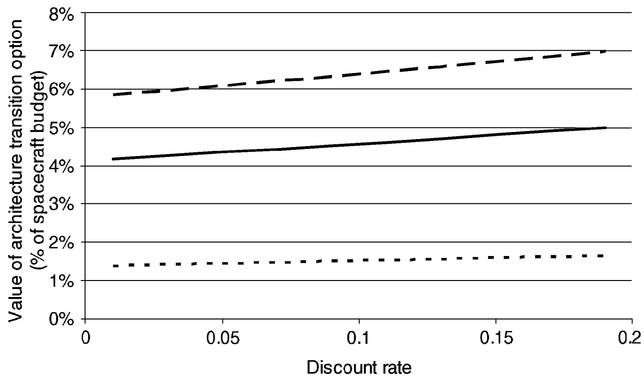


Fig. 16 Expected maximum transition option NPV for B-TOS Pareto front architectures at $25 million annual program budget; effects of varying discount rates: – – –, architecture D; ——, architecture C; and - - - -, architecture B.

The B-TOS transition option value demonstrates a high sensitivity to the probability of budget cut, a moderate sensitivity to option time horizon, and the least sensitivity to the risk-free rate of return.

Multivariate Sensitivity

Multivariate sensitivity analysis simultaneously varies the assumptions on multiple variables and examines the impact on the maximum transition option value. For a program manager facing a high degree of uncertainty in estimating the several parameters of probability of budget cut, option time horizon, and likely annual program budget levels, multivariate sensitivity analysis permits an understanding of concurrent changes in assumptions.

Results of multivariate sensitivity analysis can be shown on a three-dimensional colored graph, where the x axis is the time to exercise the option, the y axis is probability of budget cut, and the z axis is the maximum transition option value as a percent of spacecraft budget. Each surface plotted on the graph represents a different annual program budget level. Color gradations on the surfaces can correspond to the magnitude of the transition option value, with darker colors indicating smaller option values, and the lighter colors indicating larger option values. Interested readers may contact the authors for sample color graphs of multivariate sensitivity of the architecture transition option illustrated using the B-TOS mission.

Owning an Architecture Transition Option

The various stages of behavior of architecture sets under downward annual budget pressure have been examined, where transition options have value has been identified, how real options can be applied to valuing an option to transition architectures in mid program development has been demonstrated, and what sensitivities can be expected around that value has been explored. An upper bound has been established on the maximum value of the transition option. Now that the program managers understand the most they should be willing to pay to own such transition options in theory, how might program managers actually go about buying and owning them in practice?

An architecture transition option is a risk mitigation strategy, or insurance policy, against budget policy instabilities. System designers should assess the commonalities and differences between their initial architecture choice and their transition architecture choice. By funding the development of the initial architecture choice, the program manager will ostensibly be funding the development of the commonalities also found in the transition architecture for no additional cost. Purchasing a transition option involves funding the development of the differences in the two architectures, so that, when it comes time to transition, the transition architecture will be at a similar level of development so that transition happens in an ideal world with no additional costs beyond the investment already made in purchasing the transition option.

To illustrate this buying of an option in practice, consider an example drawn from the B-TOS mission. Two main distinguishing attributes of the Pareto front architectures are the number of satellites per swarm and the swarm radius. Performance of these architectures increases with increasing swarm radius, making architecture D the highest performing architecture in the Pareto optimal set, C is the second highest performing architecture, and so on down to A, which is the lowest performing architecture in the Pareto set.

Assume that architecture D is the initial architecture chosen and that architecture A will be held as the transition option. When the commonalities and differences between the two architectures are examined, one primary difference found is that architecture D has a swarm radius of 50 km, whereas architecture A has a radius of only 0.18 km. To buy the option on architecture A, the program manager needs to fund the differences between the two architectures. The key question is then, what do the architecture attributes of satellites per swarm and swarm radius imply about technical design differences between the two architectures? It is those differences that the program manager will need to fund the development of to own the transition option. The smaller swarm radius of architecture A implies that it has more stringent requirements in some regards than architecture D. A smaller swarm radius requires a higher precision in controlling position within the swarm than a large swarm radius. In addition, a smaller swarm radius imposes thruster plume impingement management requirements, unlike a larger swarm radius where propellant byproducts will not interfere with other spacecraft because the distances between spacecraft are large. Thus, key differences between architecture D and A would be in the control system and the propulsion system. To buy the right to transition from architecture D to architecture A, a program manager might fund research and development work on more precise control systems, as well as nonimpinging propulsion options for the spacecraft.

Conclusions

A method has been presented for understanding the behavior of space system program costs under downward annual budget pressure, with a real-options analysis incorporated in determining the maximum worth of an architecture transition option that hedges against program budget uncertainty. The steps of the analysis can be summarized as follows: First, establish an appropriate relationship between schedule extension and cost increase specific to the program under consideration. Second, determine the critical budget levels (b_{cv1} and b_{cv2}) that indicate transition points between stages of Pareto front behavior under downward budget pressure. Third, if the desired architecture and likely budget levels place the program in stage 1, proceed with a real-options analysis to determine the value of owning an architecture transition option in the event downward budget pressure surfaces. Fourth, determine the uncertainties, decisions and inputs to the real-options valuation model. Fifth, evaluate the real-options valuation model and examine sensitivities to assumptions. Sixth, assess the commonalities and differences between the desired architecture and the architecture of the transition option and determine how to own the transition option appropriately.

It is important to highlight two key points. Real options have in part been explored as both a strategy for accommodating budget uncertainties in programs and as an analysis technique for measuring the value of designing for uncertain budgets. From the analysis, it is seen that real options provides a reasonably straightforward way to measure the worth of actions and contingent decisions. However, what also must be understood is that the analysis technique is not appropriate to use if the strategy of real options cannot be employed on a program. In the end, it is the underlying strategy of having real choices on a program that gives real options its power.

The second point concerns the implementation of purchasing and owning architecture transition options. Although the real-option valuation techniques presented have attempted to place an upper bound on the investment a program manager should be willing to make in securing an architecture transition option, no evidence has been offered that such amount invested up front will in any way guarantee a successful transition later on. This is fundamentally new territory, but as programs test out some of these techniques for creating budget robust space systems, future researchers will be able to fill in the missing pieces and validate or amend this work as appropriate.

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Guest Editor