BRINGING POLICY INTO SPACE SYSTEMS CONCEPTUAL DESIGN: QUALITATIVE AND QUANTITATIVE METHODS

by

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Abstract

A change in government policy can send waves of crippling impacts through the design and development of publicly funded complex engineering systems. Thus it is important for system architects and designers to understand the interaction of policy with their systems, and to strive for policy robustness in their systems. To be policy robust is to successfully pass through policy changes that might arise during the course of system development in order to bring the system into operational use.

The goal of this thesis research is to enable the creation of policy robust system architectures and designs through making policy an active consideration in the engineering systems architecting and design process. Qualitative and quantitative analysis methods are brought to bear on the problem using space systems as the application domain, and a process is set down through which policy can become an active consideration instead of a static constraint.

Unique contributions of this thesis in the qualitative analysis of policy robust systems include new heuristics describing the interaction of policy and publicly funded engineering systems, as well as impact flow path diagrams for tracing policy interactions with technical engineering system parameters. Quantitative contributions include general relationships for the behavior of engineering system architecture sets under downward annual budget policy pressure, and the application of real options to measure the value of designing an engineering system to be policy robust to budget policy instabilities. Lastly, this research presents the first comprehensive quantification of U.S. space launch policy economic costs, and contributes relationships for estimating these costs on new space systems.

The analysis techniques presented in this thesis for assessing and insuring policy robustness can be applied as early as the conceptualization phase of system architecting and design, and the earlier they are applied in the process, the greater the benefits that can be derived. As the architecture and system design solidify, time and opportunities are lost to tailor a system for policy robustness.

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This thesis is dedicated to the men and women of the United States military, whose sacrifice and vigilance permit us all the freedom of academic pursuits.

To Bob Dickman, Jeff Norton, Hal Haggemeir, Sue Hegg, Bill Harding, Roger Odle, Frank Prautzsch, Steve Stoops, Mike Hubbell, Paul Popejoy, Kevin O'Brien, Tricia Tiernan, Don Brubaker, and all my former colleagues at the DoD Office of the Space Architect, whose daily challenge of analyzing the performance and politics of complex space system architectures inspired this work.

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Professor Sheila Widnall and Professor Tom Allen, as members of my Doctoral Committee, have also made tremendous contributions to my research efforts as well as my personal development while here at MIT. Professor Widnall's keen insights from her time as Secretary of the Air Force, and her ability to bring a big picture view to this thesis, have been invaluable in keeping the research sharply focused on the perspectives of senior leaders and policy makers. Professor Allen's remarkable ability to frame a problem and decompose it into a practical research plan helped greatly in getting this research going and staying on track. Both Professors Widnall and Allen have been, and continue to be, inspiring role models for me.

Many others at MIT and elsewhere were contributors to my research efforts. I would like to especially acknowledge Adam Ross of MIT, my partner on the launch policy impact analysis, for his diligent work programming software modules. Without his expertise and time, that essential and groundbreaking piece of this thesis would not have been possible. Cyrus Jilla of MIT kindly provided several architecture models of space systems to use as case studies in my research, as well as a launch vehicle selection optimization scheme used in the launch policy analysis. Seth Guikema and Professor Elisabeth Paté-Cornell of Stanford University graciously provided a Bayesian assessment of launch vehicle reliabilities used in the launch policy analysis. Commander Sue Hegg of the National Security Space Architect Office and the Commission on the Future of the U.S. Aerospace Industry was essential in arranging several interviews for this research. Lastly, I would like to acknowledge the many senior leaders and managers in industry and government who participated in interviews for this research. They may not be named here due to confidentiality agreements, but they know who they are, and I am indebted to them for their time and insights.

This research has benefited a great deal from interaction with faculty and staff from several laboratory groups at MIT including the Space Systems Policy and Architecture Research Consortium (SSPARC), the Lean Aerospace Initiative (LAI), and the Space Systems Laboratory (SSL). Dr. Joyce Warmkessel, Dr. Hugh McManus, Professor Earll Murman, Professor Debbie Nightingale, Dr. Eric Rebentisch, and Professor Dave Miller were particularly helpful in reviews and presentations of this research over the past several years.

One of the wonderful aspects of MIT is the incredibly bright and motivated students it attracts. My graduate student colleagues and officemates in SSPARC, LAI, and SSL have simultaneously been my friends, colleagues, and unwitting teachers. They have helped to shape this research and myself more than they likely realize, and I am forever indebted to them for their camaraderie and kindness. I would like to thank Joe Saleh, Elisabeth Lamassoure, Pete Panetta, Adam Ross,

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In closing, I would like to thank my family who have provided unwavering support in my graduate school pursuits. My parents, Arthur and Lillian Weigel, have always encouraged me to pursue my dreams wherever they may take me. And when those dreams took me back to graduate school at MIT to be the first of our family to complete a Ph.D., they were there for me both morally and financially. Most importantly, I would like to thank my husband and fellow SSPARC Ph.D. student Myles Walton. His infinite encouragement and guidance have been more valuable to me than can be expressed here in words. It has been wonderful to share these Ph.D. student years together with Myles as husband and wife – to work in the same lab groups, to share in each other's research, to travel together to conferences and research meetings, and to ultimately successfully defend our doctoral dissertations on the same day. I would not have traded this special and unique experience with him for anything in the world.

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"Here is Edward Bear, coming downstairs now, bump, bump, bump, on the back of his head behind Christopher Robin. It is, as far as he knows, the only way of coming downstairs, but sometimes he feels that there really is another way, if only he could stop bumping for a moment and think of it..."

— A. A. Milne

Policy considerations typically enter the system architecting phase of a complex, publicly funded technical system as external constraints. Why? No one likely knows for sure. It has just always been done that way, probably owing to the great divide that separates the mathematical logic of the engineering domain from the rhetorical logic of the political domain. But if system architects and system designers stopped to contemplate the underlying nature of policy for a moment, they might reconsider the treatment of policy as a constraint on system design. Constraints are typically static, making them ideal for bounding a system concept from the development phase through the end of its operational life. But policy is dynamic. It can change tomorrow, with little warning. And its interactions with the technical design of a system have feedback loops. Such dynamic and connected aspects of the environment cannot adequately be treated as traditional constraints are treated in system architecting and design.

And it is no wonder that systems often fail when policy changes, because they were not designed to accommodate a change in static constraints. This misconstrual of political aspects as static and disconnected instead of dynamic and integrated has been the downfall of many projects. The Space Exploration Initiative (SEI), for example, was hard hit by a change in politics. In 1990, President George H. W. Bush announced that the U.S. was embarking on a journey back to the moon and on to Mars. SEI barely made a dent in engineering plans before a change in Presidential policy cancelled the program entirely. President Clinton was elected in 1992 and opted for a cooperative foreign policy using the space station over a competitive foreign policy

based on beating the Russians to Mars. The old program could not fit successfully into this changed constraint, and it was cancelled soon afterwards. Thus, this program was not policy robust, or able to successfully weather the tides of policy to ultimately come to fruition.

1.1. Wanted: Policy robust architectures and designs

The purpose of this thesis research is to enable the creation of policy robust system architectures and designs. To be policy robust is to successfully pass through policy changes that might arise during the course of system development and bring the system into operational use. This thesis demonstrates various methods, both quantitative and qualitative, that will assist a system architect, designer or program manager in assessing and assuring policy robustness. These methods can be applied as early as the conceptualization phase of architectures and design, and the earlier they are applied in the process, the greater the benefits that can be derived.

There are many different kinds of "policy" and the reader will do well to wonder what specific type of policy is being address in this thesis. We will define policy in this thesis as " a plan or course of action adopted by a government or organization designed to influence and determine decisions, actions, and other matters." In the course of its development, a complex, publicly funded technical system may run into international policy created by the United Nations, local town policy created by town councilors, and everything in between. While the survival of policy changes at all these levels is required of a policy robust architecture, this thesis focuses on U.S. national policy made at the level of the Congress and the White House. For example, budget reductions – those that are precipitated due to technical difficulties arising on such complex engineered systems, as well as those simply due to changing national priorities – is just one kind of national-level policy this thesis examines.

Furthermore, this thesis narrows down the kind of complex, publicly funded technical systems examined to space systems in the military, national security and civil communities. Collectively, these space systems are estimated to receive over $30 billion in annual U.S. government funding, making them a significant representation of complex, publicly funded technical systems. While this thesis focuses on space systems, the methods it presents for assessing and assuring policy robustness are generalizable to other application domains.

1.2. Why policy and technical interactions are important to research

Policy decisions are connected to the technical design of a system. Policy decisions impact system architecture objectives, which in turn impact technical requirements of the system. Technical requirements drive program cost, performance, schedule, and risk. Ironically, it is these things – cost, performance, schedule, and risk – that are of prime importance to the policy maker. Thus, the policy domain and the technical domain are integrally connected, though the connection is not frequently acknowledged or understood. As before, this may be owed to the great divide that separates the political and the technical domains.

To illustrate how policy decisions impact technical requirements of a system, take the interstate highway system in the United States, officially called the Dwight D. Eisenhower System of

Interstate and Defense Highways[1]. One of the policy decisions on the system was to have it serve not only passenger cars, commercial trucks, and military tanks and equipment, but also function as a provisional or emergency runway for military airplanes in times of crisis. This dual purpose policy of both highway and runway impacted the technical requirements of the highway system: there now had to be one mile of straight highway every five miles in the system. This technical requirement in turn impacted system cost, schedule and performance. For example, the requirement for straight highway would mean extra cost and time for grading of the land to remove hills and turns. And this straight highway requirement might prevent mountainous regions from being connected to the interstate system if the mountainous terrain does not permit straight sections of road.

Perhaps the policy makers at the time the Interstate System was approved would have liked to know the magnitude of these cost, schedule and performance impacts of their policy. And perhaps being enlightened as to these answers would have generated a different policy, if even only slightly.

1.3. Key research questions

The preceding discussions on the dynamic nature of policy, and the importance of understanding policy and technical interactions, lay the foundation for five key questions that guided this thesis research from its inception. The answers to these questions will enable the creation of policy robust space system architectures.

1. *What is the environment in which space systems architecting and design occurs?*

Understanding the communities of people involved in system architecting, including their cultures, languages, and logics, provides context for understanding the ways in which policy decisions and technical requirements interact. Without such understanding, it is possible to misinterpret the complex interactions of policy and technology.

2. *What are the historical ways in which policy has driven space system architecture and designs?*

Looking to the past to understand what has happened previously is usually a good indicator of what may occur in the future. In addition, it provides further context for the research and supplements Key Question 1 above.

3. *How can policy effects on space architecture and design choices be quantified?*

Typically, policy impacts on system architectures and designs are qualified instead of quantified. Quantifying the impacts provides a more concrete basis for assessing the benefits against the costs of policies, and better informs the policy debate. What this research brings to light, however, is that not all policy impacts are able to be quantified at this point in time, given the limitations of

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[1] For more information see Weingroff, Richard (1996). "Federal-Aid Highway Act of 1956: Creating the Interstate System." *Public Road* Summer. Also Seely, Bruce E. (1987). *Building the American Highway System: Engineers as Policy Makers.* Philadelphia, PA, Temple University Press.

our current knowledge of policy and technical requirement interactions. Thus, both qualitative and quantitative analysis methods will be presented in this thesis.

4. *What is the value of designing for policy or designing for policy instabilities?*

If policy effects can be quantified, and policies are dynamic in nature, what is the value to a system architect or program manager to design their system to successfully weather policy instabilities? Investigating the value sets an upper limit on what system architects or program managers may wish to invest in making their architectures policy robust.

5. *How can policy become an active consideration in the conceptual design of space systems?*

The last question really brings together the previous four questions, with the goal of providing a strategy to system architects and program managers for understanding and dealing with policy in an active manner during the conceptual phase of the system.

1.4. Review of relevant literature

This thesis undertakes interdisciplinary research on the impacts of policy on space system architecture and design. As can often be the case with interdisciplinary research, little has previously been published on the subject. This can be both encouraging and simultaneously disheartening to the researcher. While it is encouraging to study a nearly virgin area with nothing off the table, the researcher must also wonder why little has been published. Is it because few venues exist for publishing such interdisciplinary work? Or is it because no one is really interested in the area? Fortunately for this research, it appears to be the former. Frequent updates on this thesis research have been given to decision makers in both government and the space industry, and on each occasion they reaffirm the deep value of this research.

In new interdisciplinary research lacking its own significant base of literature, we turn to the literature bases of the individual disciplines that are melded together to form the interdisciplinary topic. For this thesis research, these are the areas of space policy and space systems engineering and architecting. The knowledge base and analysis techniques of each subject become the relevant literature for the new interdisciplinary topic.

The fundamental literature contributions of this thesis are not made exclusively to the space policy literature or the space systems engineering and architecting literature. The contribution is in melding the two, and thus bringing the influence of policy to systems engineering and architecting, and the influence of systems engineering and architecting to policy. This strategy of attempting to impact both literatures with this thesis work is being implemented with submissions to refereed journals in both the space policy and space systems engineering areas.

1.4.1. Space policy

The space policy literature is very much in the tradition of political science literature. It is a social science approach concerned chiefly with the description and analysis of political and governmental institutions and processes involved in creating and executing space policy. This involves understanding the key players involved, both as individuals and groups, their motivations

and behaviors, and the processes of formulating space policy. In other words, who did what when, to whom, and why. The authors and their works discussed in this section contributed to this thesis an understanding of the context in which political interaction takes places on space systems, the several model of space policy over the years, and the many ways in which policy has historically interacted with and impacted on space systems.

Perhaps the most seminal writing in the field comes from Walter McDougall[2]. In his work ...*The Heavens and the Earth*, for which he won a Pulitzer Prize, he describes the early political history of the space age, beginning before Sputnik and continuing through the Apollo moon landings. He argues that the origin of the Apollo moon project was due to the competition between nations for preeminence and technology. John Logsdon argues for similar national interest motivations for Apollo in his early work[3]. McDougall as well as Logsdon point out that a rivalry developed between the U.S. and the former Soviet Union, a competition of democracy versus communism, and the prize of this game was influence over newly forming national governments in third world nations. These nations were determining which model of governance to implement, and technological accomplishment was seen as a key indicator of a good form of government. Thus, space policy, from the very beginning of its history, has served as a political tool to achieve much broader and arguably more important national goals than simply the exploration of space. A space policy model built upon competition between nations marked this early era of the Mercury, Gemini and Apollo programs.

McDougall also argues for the strong role played by U.S. President John Kennedy in setting firm political leadership on the program, and how the President's leadership contributed to the success of the Apollo project. Howard McCurdy and Roger Launius argue on this same theme, but examine it beyond President Kennedy's tenure and into the mid 1990s.[4] McCurdy and Launius point out that the space policy model of presidential directives and mandates has lost much of the success it enjoyed under President Kennedy. This is due, they argue, to a general weakening of the Presidential Office and a coincident strengthening of Congressional Committees and Congressional leadership offices.

So we have seen the progression in the literature from the early national competition model of space policy involving a high degree of Presidential leadership, to a post-Cold War cooperative model mostly devoid of Presidential presence. Yet now, with the change in world focus towards the War on Terrorism, we are left to wonder if the space policy model will change yet again. If previous history is any guide, it likely will. But one aspect has remained constant since the birth of the Space Age, and that is the motivation of achieving broader national objectives through space programs.

This thesis research will expand the space policy literature beyond national models of space policy and traditional examinations of the players, organizations, and actions in creating space policy, to

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[2] McDougall, Walter A. (1985). *The heavens and the earth : a political history of the space age.* New York, Basic Books.

[3] Logsdon, John M. (1970). *The decision to go to the moon: Project Apollo and the national interest.* Cambridge, Mass., MIT Press.

[4] Launius, Roger D. and Howard E. McCurdy (1997). *Spaceflight and the myth of presidential leadership.* Urbana, University of Illinois Press.

investigate and quantify the impacts of policy on the way space systems are designed from a technical standpoint. This is a novel contribution to the space policy literature.

1.4.2. *Space systems engineering and architecting*

The space systems architecting and systems engineering literature provides this thesis research with the foundations for technical analysis of the impacts of policy on complex engineered space systems.

The origins of systems engineering in large-scale government technical endeavors can be traced back to the post-World War II development of military systems such as missiles. In the 1940s, Bell Laboratories was the first to use the term "systems engineering." In 1950, probably the first attempt to teach systems engineering was made at MIT by G. W. Gilman.[5]

If we look at the progress of systems engineering texts from 1960-2000, we see that all of them contained a common set of chapters[6]. These were usually on the topics of identifying user needs, translating needs to requirements, the trade study process, system analysis methods, integration and test, and verification and validation. As systems engineering progressed into the 1970s, 1980s and 1990s, more chapters were added in the new books, such as design for manufacturing, design for reliability, design for maintainability, and so on. These are what Joel Moses refers to as "the –ilities." There are even chapters in systems engineering books on dealing with politics, policy and legal issues. But all these added chapters appear as "afterthoughts" to the systems engineering process. They are literally tacked onto the end of books, sometimes contributed by different authors than the rest of the book, and their discussion is not integrated into the core process that is presented in the book as systems engineering. This reflects that these "–ilities," including policy, have not truly become integral parts of the systems architecting and engineering process yet.

This is likely reflective of the stage of systems thinking we currently find ourselves in for the area of engineering systems. If the history of systems engineering thinking is broken down into phases[7], we are currently at the end of the second phase and the beginning of the third phase in most fields of engineering systems. The first phase, which consists of recognizing that systems thinking is applicable to a problem, likely encompassed the years between World War I and World War II for politico-technical systems. An early example of this first phase of systems thinking is offered by David Mindell[8] as he traces an attempt by Ivan Getting to improve gunfire control through considering its parts as a system. The second phase, which consists of applying

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[5] Brill, James H. (1999). "System Engineering - A Retrospective View." *Systems Engineering* 1(4): 258-266.

[6] See a progression of systems engineering texts from 1960-2000, for example Hall, Arthur D. (1962). *A methodology for systems engineering*. Princeton, N.J.,, Van Nostrand. Also Chestnut, Harold (1967). *Systems engineering methods*. New York, NY, Wiley. Also Blanchard, Benjamin S. and W. J. Fabrycky (1981). *Systems engineering and analysis*. Englewood Cliffs, N.J., Prentice-Hall. Also Sage, Andrew P. (1992). *Systems engineering*. New York, J. Wiley. Also Stevens, Richard (1998). *Systems engineering : coping with complexity*. London ;, New York : Prentice Hall Europe.

[7] Mindell, David A. (2000). "ESD.83: Research Seminar in Engineering Systems." *Class notes, MIT graduate course*, Cambridge, Massachusetts.

[8] in Hughes, Agatha C. and Thomas Parke Hughes (2000). *Systems, experts, and computers : the systems approach in management and engineering, World War II and after*. Cambridge, Mass., MIT Press.

decomposition principles and analysis techniques to systems, could be considered to have started after World War II with the introduction of what came to be called systems engineering. The NASA Apollo lunar landing program in the 1960s is a classic example of the decomposition approach to systems thinking on a complex project.

The beginning of the third phase of systems thinking is now emerging. This phase thus far appears to be characterized by expanding the boundaries of the system under consideration. Users, infrastructure, control, regulation, policy, and so on are now being included within the boundary of the system. Accompanying this expansion of system boundaries is the need to synthesize the multitude of new components and their relationships in some meaningful way that predicts or evaluates system behavior. This has given rise to the birth of "engineering systems" as a field of study, perhaps the first visible sign of which was seen at MIT with the creation of the Engineering Systems Division in 2000. As this third stage progresses over the coming decades, perhaps the many systems engineering "afterthoughts" or "–ilities" described earlier will become more integrated into the mainstream thinking and approach to conceiving, designing, implementing and operating complex, publicly-funded engineering systems.

Another byproduct of expanding the boundaries of systems thinking is the evolution of system architecture as a related discipline to systems engineering. Maier and Rechtin popularized the system architecture concept as concerns aerospace systems design in their 1991 book called *Systems Architecting: Creating and Building Complex Systems.*[9] They perceive a system architecture as a concept of the system's interfaces, components, and interactions, and liken the process of system architecting on aerospace systems to the creative architecting process of a traditional building architect. Since then, much discussion has taken place in the aerospace engineering community to precisely define what a system architecture is, and a process for creating a system architecture. While little agreement has been reached, it would seem that most government agencies involved in space projects have embraced the concepts. An office has been established in the Department of Defense solely for the purpose of creating space system architectures. And NASA first applied the system architecture concept to its series of Mars missions. The common theme in these attempts at system architecting is the high system-of-systems level of application.

The most directly relevant system architecting literature for this thesis that investigates the impacts of policy on technical system design is contained as a single chapter authored by Brenda Forman in Maier and Rechtin[10] entitled "The political process and systems architecting." Forman reviews how the political process affects complex, publicly-funded engineering systems, and presents heuristics for evaluating how policy will affect systems. These heuristics are qualitative assessment techniques, and represent the state of the art in evaluating policy impacts on systems today. This thesis significantly expands this literature to include analysis methods for quantifying the impact of policy on systems design, and the fundamental idea of designing of policy as an important "-ility" in the creation of complex, publicly-funded engineering systems.

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[9] Rechtin, Eberhardt (1991). *Systems architecting : creating and building complex systems.* Englewood Cliffs, N.J., Prentice Hall.

[10] Rechtin, Eberhardt and Mark Maier (1997). *The art of systems architecting.* Boca Raton, CRC Press.

1.5. Review of U.S. national space policy and current issues

With an understanding of the key questions guiding this thesis research, as well as a grasp of the relevant literature in hand, we now turn to a brief overview of U.S. national space policies in force, as well as current issues in the U.S. space policy arena.[11]

1.5.1. Major U.S. national space policy documents

At the White House and Congressional levels, two policy documents in force guide national activities in space. These are the U.S. National Space Policy of 1996, and the U.S. Space Transportation Policy of 1994.

1.5.1.1. U.S. Space Transportation Policy of 1994

The U.S. Space Transportation Policy of 1994 establishes space transportation capabilities as a fundamental goal of the U.S. space program, critical for achieving national level objectives in science, technology, commerce, national security, and foreign policy.

The policy accomplishes four fundamental objectives[12]:

1. Establishes new national policy for federal space transportation spending, consistent with current budget constraints and the opportunities presented by emerging technologies.
2. Establishes policy on federal agencies' use of foreign launch systems and components., in order to prevent adverse impacts on the U.S. space launch industry.
3. Establishes policy on federal agencies' use of excess U.S. ballistic missile assets for space launch, to prevent adverse impacts on the U.S. commercial space launch industry.
4. Provides for an expanded private sector role in the federal space transportation R&D decision making process.

The policy also contains detailed implementation guidelines, as well as sector guidelines for the civil, national security, and commercial space communities. For more details, the reader is referred to the fact sheet and actual policy text available from the U.S. Office of Science and Technology Policy.

1.5.1.2. U.S. National Space Policy of 1996

The U.S. National Space Policy of 1996 stresses the importance of maintaining U.S. leadership in space, directs agencies to partner and cooperate internationally on space projects, and recommits the U.S. to reserving space for peaceful purposes and activities. In addition, it continues the separation of national security and civil space systems and programs, as was established in the very first U.S. national space policy in 1958.

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[11] It is assumed that the reader of this thesis is more likely to have a grounding in engineering, but unfamiliar with policy; hence this brief overview here in the introduction.

[12] Policy objectives are taken directly from *Statement on National Space Transportation Policy* (1994) United States Office of Science and Technology Policy, Washington, DC.

The present day national policy lays out the five primary goals for the U.S. space program as follows[13]:

1. Enhance knowledge of the Earth, the solar system and the universe through human and robotic exploration.
2. Strengthen and maintain the national security of the United States.
3. Enhance the economic competitiveness, and scientific and technical capabilities of the United States.
4. Encourage State, local and private sector investment in, and use of, space technologies.
5. Promote international cooperation to further U.S. domestic, national security, and foreign policies.

The policy continues with specific guidance for the civil, national security, and commercial sectors. For more details, the reader is again referred to the fact sheet published on the policy and available from the U.S. Office of Science and Technology Policy.

1.5.2. Current issues in the space policy arena

While the national space policy of 1996 and the space transportation policy of 1994 are still technically in force, many changes have taken place in the world since 1994 and 1996. In the present day (2002), we find that the U.S. Administration has changed over to Republican, the Senate has become controlled by the Democrats, and the Republican majority in the House has shrunk. In addition, the Cold War is now a much more distant memory, replaced by the War on Terrorism which brings a new policy context and new demands on space systems.

So what are the policy issues that are currently facing U.S. space policy makers in this new world environment? This was the subject of thesis research interviews with leading decision makers in the government. Seven themes were raised:

1. <u>Budget restrictions</u> – Reduced space program budgets was the most frequently reported current Congressional policy action among interviewees in this research. With other national priorities such as the War on Terrorism competing for funding, budgets for space programs are trending down. In addition, policy makers will frequently further reduce the budget of a program that is experiencing overruns or other difficulties. For example, the Space-based Infrared System (SBIRS) recently had its budget descoped due to technical difficulties that was causing an overrun on the program.
2. <u>Space programs as cooperative foreign policy tools</u> – In the Cold War era, space programs were used as competitive foreign policy tools, where the U.S. and the former Soviet Union competed for space achievements. With the end of the Cold War in the early 1990s, space programs shifted focus from competitive foreign policy tools to cooperative foreign policy tools, engaging foreign countries in joint projects instead of competing head to head with them on identical aims. It is anticipated that space programs will continue to be used as cooperative foreign policy tools in the near

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13 *Fact Sheet - National Space Policy* (1996) United States Office of Science and Technology Policy, Washington, DC.

future, much like the International Space Station has been. Science missions are extremely useful in this area, and cooperation is also being explored with allies for military space missions.

2. Export restrictions on space products – In a world concerned with missile and weapon technology transfer, export restrictions on space products are likely to remain the policy norm. For example, communications satellites are on the State Department controlled munitions list. In addition, this export restriction extends to technical discussions with foreign nationals, limiting the ability of U.S. government agencies and companies to engage in cooperative design of space systems with other countries. For example, the Sea Launch program, which is a joint venture between companies in the United States, the Ukraine, and Norway, needs to apply to the U.S. State Department for permits *each* and *every* time it engages in *any* kind of technical interchange with its foreign company partners. These permits can take six weeks or more to receive, and severely limit the ability to engage in truly cooperative technical design.

3. Restrictions on foreign launches – Much like the general export issue above, it is currently feared that launching U.S. commercial satellites on foreign launch vehicles will inadvertently transfer sensitive technology to potential adversaries. As long as the current world security climate continues, this implicit launch policy restriction on commercial satellites, previously only applicable to government satellites, can expect to be continued. A recent example demonstrates this where Boeing (formerly Hughes) wished to build a satellite for a Chinese customer and launch it on a Chinese rocket. The U.S. State Department refused to issue the necessary export permits for Boeing to ship their satellite to China for launch, and as a result, Boeing lost the contract with the Chinese customer.

4. Space weaponization – There is increasing debate at the White House and Congressional levels about the issue of using weapons in space, and potential abrogation of the Outer Space Treaty of 1967. While most of the technological development enabling such space weapons systems is classified, the philosophical debate rages on in Washington even in absence of such information. While many think the weaponization of space is perhaps inevitable given a long enough time horizon, there is little agreement on the evolution path or time scale of that state.

5. Security of space assets – Perhaps spurred on by the debate on space weaponization is concern over the security of space assets on orbit, also called space control. In the past, spacecraft on orbit have been treated as national property of the sovereign state that put them there, and attacks on a spacecraft could be considered an act of war. But much like the open seas, the key policy question is how to ensure safe passage of your own crafts through an environment that belongs to everyone while not infringing on the rights of other crafts. As each day passes, more and more people become more and more dependent on space-based services for everything from communications to navigation. Protecting the satellites that enable these critical infrastructure services is thus a prime concern for policy makers.

6. Interoperability with space mission partners – The desire to cooperate internationally on space systems brings demands for interoperability of disparate national space assets. The goals of this policy, aside from foreign policy objectives, are to increase functionality cooperatively over what the U.S. could achieve alone and save money in the process. The interoperability can be across branches of the U.S. military, across different government agencies, or across countries.

7. <u>Balancing national priorities</u> – As the global geopolitical climate changes and U.S. priorities begin to shift, the future importance of space in U.S. national military, economic and foreign policy strategy may shift from its previous critical and highly visible role in the Cold War. U.S. government agencies should realize that the future federal budget available for space programs is not fixed, and shifts in proportion to national priorities.

For other indications of current space policy issues, we can turn to an assessment of recent topics in the peer-reviewed journal *Space Policy*. There has not been a single dominant trend to topics between the timeframe 2000-2002; rather, several different topics seem to come up equally often. In no particular order, these are:

- Military space policy, and military use of space, in the post-Cold War era
- Anti-ballistic missile treaty implications in the age of increased space control
- Commercialization of space, and how business in space is growing
- Telecommunications and spectrum policy, including more coordinated national and global regulations
- Solar power energy from space
- Export policy, and the impacts from recent tightening
- Space-based positioning systems and global standards policy
- Space-based global disaster monitoring systems and coordination of relief efforts
- The pros and cons of international cooperation on space programs

1.6. Structure of the thesis

After having covered sufficient introductory and background material, we return to the main thrust of this thesis: to enable the creation of policy robust space system architecture. The following seven chapters explore various methods of assessing and assuring policy robust space system architectures. They are arranged in three parts as shown graphically in Figure 1-1.

Part I contains Chapter 2 entitled "Understanding the environment: How policy and engineering interact." It explores the environment in which policy and engineering interact to create a space system architecture. This understanding of the environment lays a solid foundation for investigating policy robust architectures. Four domains – the political domain, the technical domain, the end user domain, and the architectural domain – are identified. Their language, culture and logic is presented, as well as how impacts emanating from the political domain can be traced through to the technical domain.

Part II presents two qualitative methods: heuristics and influence diagrams. Chapter 3 "Heuristics to navigate by: A guide to policy and engineering interactions" presents ten new heuristics system architects and program managers can put into their toolboxes to guide the creation of policy robust system architectures. Chapter 4 "Semi-quantitative methods: When you can't yet quantify" presents aggregative influence diagrams as a method for assessing the degree of policy and technical interaction in a space system architecture when the relationships between

policy and technical interactions is not understood mathematically. The chapter then demonstrates this method using an example of a space transportation system, and identifies under which policies the transportation system is more robust.

Part I　　　　Part II　　　　Part III

		Chapter 5. Quantifying policy effects I: *U.S. space transportation policy*
Chapter 2. Understanding the environment: *How policy and engineering interact*	Chapter 3. Heuristics to navigate by: *A guide to policy and engineering interactions*	
		Chapter 6. Quantifying policy effects II: *Budget adjustments*
	Chapter 4. Semi-quantitative methods: *When you can't yet quantify*	Chapter 7. Measuring the value of designing for policy instabilities: *The architecture transition option*

Chapter 8.
Policy as an active consideration in the design process

Figure 1-1.　Graphical guide to thesis structure.

Part III extends the policy robust analysis to quantitative techniques, for situations where there exists a mathematical understanding of the relationship between policy and technical interactions. Chapter 5 is entitled "Quantifying policy effects I: U.S. Space Transportation Policy of 1994" and explores the cost and risk effects of the current U.S. launch policy on different types of decision makers. General cost impact estimating relationships are derived for the policy, and can be applied to space systems early in conceptual design to estimate the cost impact of the policy. Chapter 6 "Quantifying policy effects II: Budget adjustments" identifies the behavior of increasing total system costs under downward annual budget policy pressure, and derives general equations a program can use to understand how it will respond to such pressures. This analysis identifies which architectures in a candidate set will be more robust to budget policy than others. Finishing out Part II is Chapter 7 "Measuring the Value of Designing for Policy Instability: The architecture transition option." A companion to Chapter 6, it employs real options methods for valuing the ability to transition architectures during system development in the face of downward annual budget pressure. This value establishes an upper bound on what program managers should be willing to pay for budget policy robustness in their program.

The thesis wraps up with Chapter 8 "Putting it all together: Policy as an active consideration in the design process." This chapter ties together the various analysis methods presented throughout the thesis into an overarching strategy to make policy an active consideration in the system architecting and design process. By doing so enables architectures to become policy robust.

UNDERSTANDING THE ENVIRONMENT:

HOW POLICY AND ENGINEERING INTERACT

Space systems are "politico-technical" systems because they are very complex technical systems fielded with the assistance of national governments. Governments finance satellite and launch vehicle research and development, maintain launch ranges, issue a variety of licenses and permits, indemnify commercial launch providers from certain liabilities, purchase and operate a large percentage of satellites and launch vehicles, and purchase services provided by space systems. This high degree of government involvement coupled with the high degree of technical complexity in these space systems calls for analysis that integrates both technical and political aspects as the system is conceived. The foundation for this analysis is a sound understanding of the environment in which political aspects and technical aspects of politio-technical systems design interact.

The objective of this chapter is to present a framework for understanding how government policy choices affect the technical requirements for complex, space-based, politico-technical systems. A better understanding of these impacts in the system *ab initio* will lead to increased policy robustness of space systems. The chapter begins by examining the environment in which politico-technical systems design occurs, and describes four different domains (or communities) that come together to create a space system. The domains are the political domain, the end user domain, the technical domain, and the architecture domain. A framework describing the interaction of these domains then sets the stage for understanding how impacts flow from the political domain to the technical domain, and how these impacts can be traced and presented. It is this fundamental idea of understanding and evaluating how impacts flow from a political domain to the technical domain that underpins this thesis work.

2.1. The domain framework

A conceptual framework of the environment in which political aspects and technical aspects of politico-technical systems design interact is useful in setting the context for this thesis research. No such explicit framework has been found in the literature, so an original concept has been created. (Hereafter, all references to systems, systems design, systems engineering, systems architecture, etc. refer to politico-technical systems unless otherwise noted.)

The politico-technical environment can be considered to have four layers or domains in which organizations and groups work to bring forth a system design. These are:

- Technical Domain
- Operational Domain
- Political Domain
- Architectural Domain

They are represented in summary form in Table 2-1. Each domain utilizes a particular process and produces a particular outcome from that process. In the following sections, each domain will be discussed, including definitions of their processes and outcomes, what kind of work takes place in the domain, and what groups and organizations lie in each domain. In addition, a space-based example using the Global Positioning Satellite System (GPS) will run through each section to provide a more concrete illustration specific to the space sector. GPS is a constellation of about two dozen satellites in medium earth orbit that provide precision positioning, navigation and timing services to military and civilian users on the ground.

Table 2-1. Processes and outputs of domains involved in politico-technical system design.

Domain	Process	Output
Political	Politics	Policy
Technical	Systems Engineering	Physical System
Operational	User Needs Analysis	Validated User Needs
Architectural	Systems Architecting	System Architecture

2.1.1. Political domain

In the context of politico-technical system design, the purpose of the political domain is to represent the voice of the customer in the process. The work of the political domain is accomplished through the process of politics, and the outcome of the political process is a policy. Politics and policy mean many things to many people. For the purposes of this research work, we will define them here as:

Politics: "the properly constituted and legal mechanism by which the general public expresses its judgments on the value to it of the goods and services that it needs[14]" [

Policy: a plan or course of action adopted by a government or organization designed to influence and determine decisions, actions, and other matters[15]

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[14] Rechtin, Eberhardt and Mark Maier (1997). *The art of systems architecting*. Boca Raton, CRC Press. p. 197.

The definition of politics is very important. The public, as the ultimate buyer and client (though not end user) of politico-technical systems, needs to decide what systems to buy. Politics, as it is described here, is the mechanism through which that value judgment process occurs. The public expresses its values to its elected representatives who then work in the Congress or Parliament or other political body to determine what kinds of systems to buy. In essence, the political domain represents the client or customer of politico-technical systems, and controls the budgets for all such projects. This is an important and necessary role – the role of the customer – in system design.

In the United States, the primary political domain actors are the Congress, the White House, advocacy groups, the media and the general public. Take GPS as an illustrative example to put a more concrete face on these U.S. actors. The political domain actors in Congress are the House and Senate Armed Services Committees (HASC and SASC) that provide authorization oversight, as well as the House and Senate Appropriations Committees (HAC and SAC) that provide appropriations oversight. In the White House, the National Security Council is the policy body responsible for space policy issues on GPS and all other military space-based systems. Advocacy groups in the political domain include grass roots organizations like the National Space Society and The Planetary Society which represent the interests of the citizens who are constituents of the political domain actors.

The action in the political domain formally takes place in Washington, DC in the offices and the hearing rooms of the Congressional buildings. Arguably universal across nations, actors in the political domain are guided by the logic of politics. For elected officials, this focuses around security, benefits, jobs and revenue to their respective districts. The logic of politics is further built on personal experiences, relationships, negotiations and compromise. Proof in the logic of politics involves having the majority of votes, and little more.[16] This is in marked contrast with the technical domain, which sees proof as the culmination of mathematical and analytical investigation. For the political domain, the proof of having the majority of votes is the result of discussions, negotiations, exchanges of favors, and existing trust between political members. Thus proof here requires no mathematics – except to count a majority of votes – nor are any desired.

2.1.2. Technical domain

In the context of politico-technical system design, the purpose of the technical domain is to perform the detailed engineering design, fabrication and testing of the system. The work of the technical domain is accomplished through the process of systems engineering, and the outcome of the technical process is a finished and complete physical system. There are instances when the systems engineering effort does not reach completion, for example when a program gets cancelled before the physical system is finished being designed and built. But when permitted to carry through to the end of the systems engineering process, the outcome will be a finished and complete system. There is ongoing debate within the field of systems engineering on the correct definition of the systems engineering process as well as its outcome. For further definitions of

[15] Morris, William (1969). *The American Heritage dictionary of the English language.* New York, American Heritage Pub. Co.

[16] Brenda Forman in Rechtin, Eberhardt and Mark Maier (1997). *The art of systems architecting.* Boca Raton, CRC Press.

systems engineering, see Sage, Blanchard & Fabrycky, Martin, and Rechtin & Maier[17]. For the purposes of this research work, we will define them here as:

> Systems Engineering: The "identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals[18]"

> Physical System: The physical instantiation of the system designed through the systems engineering process. "The system is a collection of things or elements which, working together, produce a result not achievable by the things alone[19]"

The primary technical domain actors are the private sector aerospace companies or government laboratories contracted to build systems, the government program offices that oversee the technical system development, and advocacy groups that represent each area. Again for an illustrative example we can turn to GPS to put a more concrete face on these actors in the U.S. Since GPS is a very large system that has been around for nearly two decades, and has gone through many upgrades, nearly all the main U.S. aerospace companies have been involved in the system in some capacity. These companies include TRW, Lockheed Martin and Boeing among others. The government program office in charge of GPS is called the Navstar Global Positioning System Joint Program Office of the Air Force Space and Missile Systems Center. The advocacy groups in the technical domain are those that represent the companies, such as the Aerospace Industries Association and the Satellite Industry Association.

The individual technical domain actors in the companies come from scientific and engineering backgrounds, and most are engaged in performing actual engineering. The exceptions would be the various levels of program managers necessary to coordinate the project, but most of them have worked their way up through the engineering ranks to become managers. The individual people in the government program offices are military officers or government employees, depending on whether the program is a military or civil space program, and are of varying backgrounds (not all are technically trained).

The action in the technical domain takes place at company facilities, where teams of engineers execute the quantitative and analytical systems engineering process described above by Shishko. It also takes place at the government program offices, where periodic reviews and evaluations of the technical progress of the contractor are held. Actors in the technical domain are guided by the logic of engineering and science. The logic of engineering and science is built upon mathematics and physical principles. Engineers prove their points with equations and numbers;

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[17] See Sage, Andrew P. (1992). *Systems engineering.* New York, J. Wiley. Also Sage, Andrew P. and Charles L. Lynch (1998). "Systems Integration and Architecting: An Overview of Principles, Practices, and Perspectives." *Systems Engineering* 1(3): 176-226. Also Blanchard, Benjamin S. and W. J. Fabrycky (1981). *Systems engineering and analysis.* Englewood Cliffs, N.J., Prentice-Hall. Also Martin, James N. (1997). *Systems engineering guidebook : a process for developing systems and products.* Boca Raton, Fla, CRC Press. Also [Rechtin, 1997 #71

[18] Shishko, Robert, Robert Aster and Randy Cassingham (1995). *NASA systems engineering handbook.* Washington, D.C., National Aeronautics and Space Administration. p. 4.

[19] Rechtin, Eberhardt and Mark Maier (1997). *The art of systems architecting.* Boca Raton, CRC Press. p.253.

oftentimes these artifacts speak for themselves. This is in marked contrast with the political domain, which does not speak the language of math and physics and instead opts for rhetoric and negotiation.

2.1.3. Operational domain

In the context of politico-technical system design, the purpose of the operational domain is to collect, analyze, select and validate user needs for the system. The work of the operational domain is accomplished through the process of user needs analysis, and the outcome of the process is validated user needs. For the purposes of this research work, we define these terms here in the context of politico-technical systems as:

> <u>User Needs Analysis</u>: survey and analysis of end users to determine what needs they have and how those needs should be prioritized.
>
> <u>Validated User Needs</u>: certain user needs that have been assessed, documented, prioritized and approved by an appropriate government agency.

The operational domain plays an important role in system design – representing the ultimate end users of the system, they provide a list of user needs for the system to fulfill. It is important to keep in mind the distinction between end user and customer in the context of politico-technical systems, for they are different people. The end user is the person or group that will use and operate the system after it is created, while the customer is the tax-paying public that purchases the system for the end user's use.

The primary operational domain actors are system end users and needs validation groups associated with the government agency that sponsors the work of the end users. Additionally, advocacy groups for specific end users can be found in this domain. End users may be scientists for a science satellite mission or a national accelerator facility, or warfighters for a defense-related politico-technical system. The background of the end users varies depending on the community to which the end user belongs. For example, the end user community of space scientists has extensive academic training in space science, and many of them hold doctorate degrees. End users from the military come from all different backgrounds, but are united in the common mission they are responsible for executing.

To briefly illustrate the end user domain actors with an example, take GPS again. The end users for GPS are the warfighters who operate aircraft, ships and other systems that use GPS for navigation. The user needs validation group for the warfighters is the Joint Requirements Oversight Council (JROC) in the DoD.

The action in the operational domain takes place in the domain actor's organizations, where users are surveyed for their future needs and these needs are evaluated and assessed. Action also takes place in a series of needs approval meetings, where needs are further evaluated, prioritized and eventually validated for inclusion in a future system design effort. The logic of end users in the operational domain, regardless of what community they come from, is built on getting their job done. This logic stresses operational capabilities and end user accountability for performance, and necessitates a desire for direct control over resources to do their jobs (ie. politico-technical systems). The language of the operational domain tends to be specific and unique to each

community of end users. So though it varies depending on the type of end user, within a single community of end users, the language is a shared and common one among its members.

2.1.4. Architectural domain

There is a fundamental communications gap between the political, technical and operational domains, due to the different prevailing cultures and the different languages spoken in each domain. Without someone or some group to translate between the two and provide links, it is unlikely that a successful integration of political, technical and operational aspects of a system would ever take place naturally. This is where the architectural domain comes in and plays the roles of translator and go-between for the political, technical and operational domains.

In the context of politico-technical system design, the purpose of the architectural domain is to bring together elements of the political, technical and operational domains to create a system architecture. The work of the architectural domain is accomplished through the process of system architecting, and the outcome of the architecting process is a system architecture. "System architecture" is a new concept to the aerospace world, and thus we can expect considerable debate on the precise meaning of the term. Rechtin and Maier authored a popular work in this area, and we turn to it for insights. For the purposes of this research work, we will define system architecting and system architecture as:

> System Architecting: "The process of creating and building architectures; those aspects of systems development most concerned with conceptualization, objective definition, and certification for use[20]"

> System Architecture: "The structure – in terms of components, connections, and constraints – of a product, process, or element[21]"

The primary actors in the architectural domain are a more diverse set of groups than for the other domains, as might be expected given their translation or "ambassadorial" role between the other domains. They are systems architecture offices, government acquisition offices, legislative liaison offices, long-range planning offices, local support contractors, and advocacy groups. Take GPS again as an illustration. In the DoD, the architectural domain actors comprise the National Security Space Architect office, the Office of the Secretary of the Air Force for Acquisition, the Air Force Legislative Liaison Office, the Air Force Long Range Planning Office. Additionally, there are non-profit and for-profit contractors that support the work of these offices, including the Aerospace Corporation, ANSER, SAIC, Booze Allen Hamilton, and TASC, among others.

The work of the architectural domain – creating system architectures – involves defining architecture objectives based on user needs, and creating and evaluating architecture concepts. This work takes places within the offices of the primary architectural domain actors, at visits to government program offices and system contractor sites, and in the legislative buildings in meetings with staffers. The language of the architectural domain is a mix of political and technical terminology, combined with the distinctive lexicon associated with procuring systems for the

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[20] Rechtin, Eberhardt and Mark Maier (1997). *The art of systems architecting.* Boca Raton, CRC Press. p. 251.

[21] Rechtin, Eberhardt and Mark Maier (1997). *The art of systems architecting.* Boca Raton, CRC Press. p. 251.

government and letting contracts. The logic of the architectural domain revolves around user needs, legacy systems, budgets, risk, personalities, agency rivalries, and power.

2.2. Action between the domains, or how politico-technical systems are created

The framework just presented describes the environment in which political aspects and technical aspects of politico-technical systems design interact. Figure 2-1 shows a graphical representation of this framework. The three leaves of this clover diagram – the political domain, the technical domain, and the operational domain – are independent and do not usually overlap in membership. Yet, there must be connections between these three that facilitate architecture development. These connections necessary to create a system architecture are provided by the architectural domain. The architectural domain reaches out to other three, and brings in and feeds back out the information from the other three domains necessary to do its system architecting job. It is important to remember that these four domains, while reasonably representing the main communities in a system architecting environment, do not collectively comprise a closed system. These domains all interact with other issues and constraints at their outer boundaries.
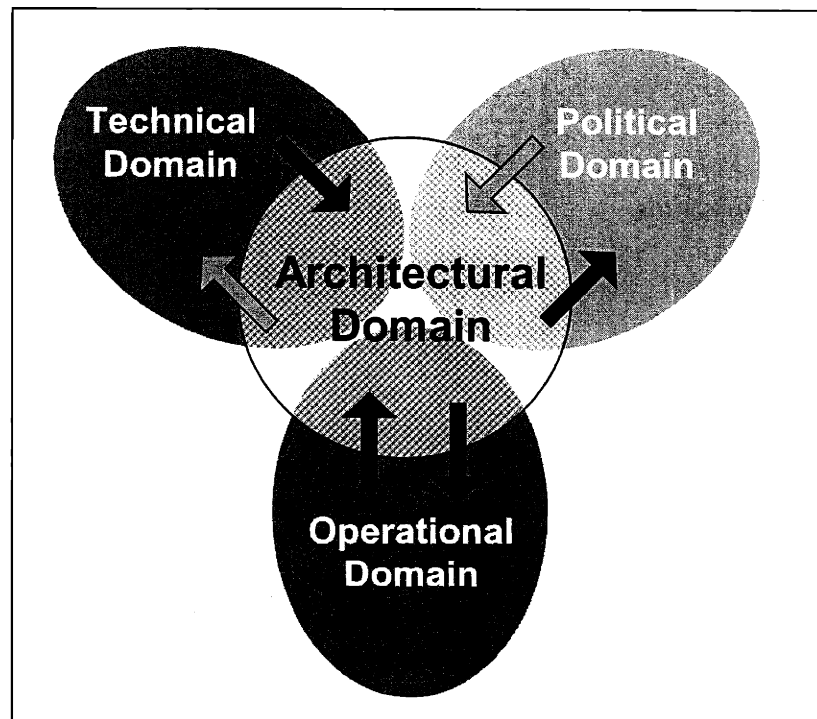
Figure 2-1:   Graphical representation of the domains and interactions involved in creating politico-technical system designs.

The architectural domain also filters information between the three domains. In this capacity, the architectural domain acts like a mediator and translator. This translation function, while necessary given the organizational structure of the government and the nature of politico-technical systems, adds delays and time lags into the system. These delays can foster misunderstandings between the political, technical and operational domains, and may be the root of program failures.

The success of the architectural domain in creating a system architecture should determine the overall success of the system, as a sound architecture usually results in a successful system[22]. For success in politico-technical systems, information from the political side, the technical side and the operational side is critical. Thus, the degree to which the architectural domain is able to extract and feed back accurate, timely and needed information from the other domains may indicate its potential for success.

2.3. Influence of policy on architectural objectives and technical parameters

A more integrated view of technical and political aspects of system design is important because policy choices and technical choices are related. As we saw in the cloverleaf diagram in Figure 2-1, there are information flows into and out of the architectural domain from the three other domains. Thus, there can be impacts to the operational domain from the technical domain, impacts to the operational domain from the political domain, and so on. This paper is concerned with one set of impacts, namely those to the technical domain from the political domain, which is represented by the gray arrows in Figure 2-1.
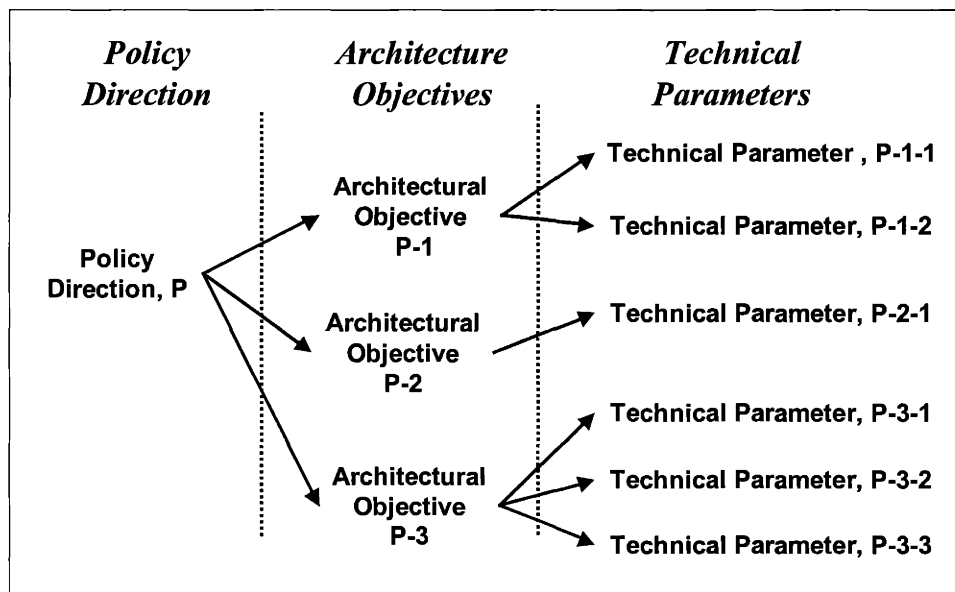
Figure 2-2. Translating policy parameter effects into the technical domain: An influence diagram.

[22] Crawley, Edward F. (1999). "16.882J: Systems Architecture." *Class notes, MIT graduate course*, Cambridge, Massachusetts.

The diagram in Figure 2-2 shows the notional path of impacts stemming from a policy direction originating in the political domain. The policy direction manifests itself in the architectural domain in the form of impacts to the architectural objectives. Changes to these architectural objectives manifest themselves in the technical domain in terms of related quantifiable technical parameters of the physical system. Studying the impact of policy directions on technical parameters is thus particularly enticing because technical parameters can readily be quantified and measured in terms of cost, schedule, performance and risk impacts on a system.

2.3.1. Creating the influence diagram

The best way to illustrate how a policy direction translates into the technical domain is through a real-life example. Consider the Discover II (D2) mission, which was being contemplated in 1999 as a joint program between the U.S. Air Force, the U.S. National Reconnaissance Office, and the U.S. Defense Advanced Research Projects Agency. D2 was to be a two-satellite flight demonstration intended to prove the feasibility of tracking moving ground targets using a large constellation of radar spacecraft. Due to Congressional doubts that the program could meet its projected objectives and costs, funding was eventually denied and the program cancelled.

But at one point in the program's short-lived existence, policy makers suggested that the D2 program expand to include international partners, as a way to defray program investment costs borne by the U.S. The influence diagram of the impact of this policy direction on the technical domain is shown in Figure 2-3.
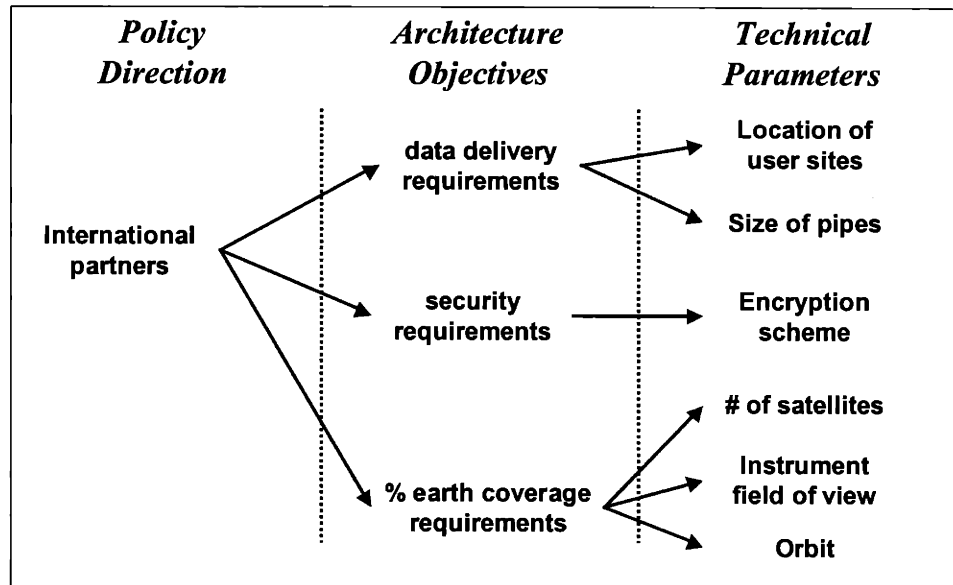
Figure 2-3. An example of translating policy parameters into the technical domain using an influence diagram.

As shown in the figure, the policy direction to have international partners on the D2 program primarily impacts three architecture objectives, which in turn impact six technical parameters of the mission. Thus, this policy direction creates three streams of impacts emanating from the policy direction. We can explain these three impact streams as follows:

- Impact Stream 1: If international partners are included in the program, they will of course wish to have access to the space-based radar data from the D2 mission. This will impact the architecture objective of data delivery requirements, because data will have to now be delivered to other organizations besides just the U.S. military, and these organizations will be located outside the U.S. This change in data delivery objectives implies a change to two technical parameters. The technical parameter of the location of user sites now expands to include users internationally as well as in the U.S. And the technical parameter of the size of the data distribution pipes will need to expand to accommodate the additional data distribution going to the international partners.

- Impact Stream 2: If international partners are included in the program, they will impose additional consideration for the architecture objective of security requirements on the data delivered from the mission. With more than one country involved, protection of nationally sensitive data for all national parties involved will be necessary. This changed architecture objective will in turn impact the technical parameter of the encryption scheme on the data downlinked and distributed from the D2 satellites. This encryption scheme will have to suit all national users, and may require the development of an entirely new encryption scheme that is compatible with existing ground processing equipment in all participating counties.

- Impact Stream 3: If international partners are included in the program, the will impose changes in the architecture objective of earth coverage requirements. These partners will likely want the D2 mission to be able to cover their territories as well as their security interests around the globe. These can be different from U.S. interests, and if so, will impact that architecture objective. The architecture objective of earth coverage requirements in turn impacts three technical parameters, including the number of satellites, the orbits those satellites are in, and the field of view of the instruments and payloads on the satellites. If a larger portion of earth coverage is required due to the involvement of international partners, the number of satellites required may increase. The orbits they are in may also change in altitude, inclination, and phasing of multiple orbital planes. Lastly, if a larger portion of earth coverage is required, instruments with larger fields of view, or perhaps phased array instruments, may be required to meet that increased coverage objective.

Influence diagrams describing the flow of policy direction impacts into the technical domain are unique for each system and each policy direction. By following the logical path from policy directions to architecture objectives to technical parameters, an influence diagram can be created for any situation. These influence diagrams can become valuable communication tools within and outside a space system architecture development team as they explore the potential impacts of policy on their technical system.

2.4. Conclusions

This chapter has presented a domain framework for understanding how government policy choices affect the technical requirements for complex, space-based, politico-technical systems. Many players in four different domains – political, technical, end user, and architectural – are required to create a space system architecture. These domains each have their own unique culture, and oftentimes communications and information flow between domains suffer from the misunderstandings and misinterpretations that are typical of cross-cultural communications.

Influence diagrams and the concept of impact flow paths provide space system architects with techniques for conceptualizing policy impacts on technical systems. These diagrams, while only qualitative in nature, can serve as valuable communication objects both within and outside a system architecture development team. Rooted in an understanding of the domain framework, the influence diagram process of tracing impacts from the policy domain to the architecture domain to the technical domain is the first step in making policy considerations an active part of the space system architecture conceptual design process.

HEURISTICS TO NAVIGATE BY:

A GUIDE TO POLICY AND ENGINEERING INTERACTIONS

With a sound understanding in hand of the environment in which space system architecture creation takes place, we now turn to the main focus of this thesis: qualitative and quantitative methods for bringing policy into space system architecture conceptual design. The next five chapters each showcase a method or cohesive set of methods for understanding some of the impacts of policy on system design at a very early point in the architecture process.

This chapter, "Heuristics to navigate by: A guide to policy and engineering interactions," discusses heuristics as one qualitative method for understanding the impacts of policy on system design. Heuristics are natural language guidelines for architecting and design based on lessons learned through experience. After a brief introduction to heuristics and their applications, this chapter describes the research process used in this thesis to generate new heuristics. The research process included both literature reviews and semi-structured interviews, and these were both used to uncover heuristics about how policy impacts system design. The research turned up ten new heuristics, and garnered additional support for five existing heuristics about the political process and system design. The chapter concludes with some comments on when to use policy heuristics in the system architecture design process.

3.1. Heuristics defined

The word "heuristic" derives from Greek and Old Irish words meaning "to discover" or "to find." The adjective form of heuristic is given two definitions in the dictionary:

> "Heuristic (hyu-'ris-tik) [*adj*]: 1. involving or serving as an aid to learning, discovery, or problem-solving by experimental and especially trial-and-error methods; 2. of or relating to exploratory problem-solving techniques that utilize self-educating techniques (as the evaluation of feedback) to improve performance[23]"

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[23] Morris, William (1969). *The American Heritage dictionary of the English language.* New York, American Heritage Pub. Co.

This is not inconsistent with the description given to heuristics (in the noun form) by Maier and Rechtin in their book *The Art of System Architecting*. They describe a heuristic as a guideline for architecting, engineering, or designing a system. To put it another way, they describe it as a natural language expression of a lesson learned through experience that is expressed as a guideline. Heuristics typically come in one of two varieties, descriptive or prescriptive. Descriptive heuristics describe a situation, while prescriptive heuristics indicate a course of action.

"At their strongest, they [heuristics] are seen as self-evident truths requiring no proof." But what constitutes a good heuristic? A good heuristic must pass the following tests[24]:

- The heuristic must make sense in the original domain in which it was conceived.
- There must be readily apparent correlation between the heuristic and the successes or failures of programs and/or systems.
- The general sense of heuristic should apply beyond original context in which it was conceived.
- The heuristic must be easily rationalized in a few minutes or on less than a page.
- The opposite statement of a heuristic should be foolish.
- The basic lesson of the heuristic should have stood the test of time and earned a broad consensus.

3.2. Heuristics in application

Maier and Rechtin describe three common ways in which heuristics are applied in architecting and design[25]. First, people use heuristics as an evocative guide. When faced with a difficult problem, a personal toolkit of heuristics can be scanned for inspiration on the context of the problem, the root of the problem, or its solution. Second, people use heuristics as a pedagogical tool. They codify their experiences in a set of heuristics, and pass the heuristic, as well as the story behind it, along to others. Third, people use heuristics by integrating them into the system development process. These heuristics would typically be prescriptive heuristics, guiding the development process. The first and second types of applications would seem to be the most appropriate for the policy impact heuristics presented in this research.

Other suggestions from Maier and Rechtin on applying heuristics are[26]:

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[24] The criteria for a good heuristic were all taken from Rechtin, Eberhardt and Mark Maier (1997). *The art of systems architecting*. Boca Raton, CRC Press.

[25] The three kinds of applications taken from Rechtin, Eberhardt and Mark Maier (1997). *The art of systems architecting*. Boca Raton, CRC Press.

[26] Rechtin, Eberhardt and Mark Maier (1997). *The art of systems architecting*. Boca Raton, CRC Press.

- If the heuristic works, then it is useful
- Knowing when and how to use a heuristics is as important as knowing the what and why.
- Practice, practice, practice.
- Heuristics aren't reality, they are just guidelines.

Before leaving this brief discussion of applying heuristics, it should be mentioned that while heuristics can be shortcuts to a problem's solution, there is no guarantee that they will solve all problems encountered.

3.3. The research process for heuristics

Two methods of research were employed to generate new heuristics about the impacts of policy on system design: literature reviews and semi-structured interviews.

3.3.1. Literature reviews

The literature review focused on searching aerospace trade newspapers and magazines for stories about Congressional and Executive Branch involvement in space systems. These articles usually described a specific space system and what Congressional sentiment and action was towards that system. A follow-on search was then done on the specific system mentioned, to find additional articles and paint as complete a picture as possible of the system's interaction with policy makers during its lifetime. Then, with this more complete knowledge of the system in context with its interaction with policy makers, recurring themes that might serve as the basis for heuristics began to emerge. And for certain systems, it was possible to receive additional information from their program managers during subsequent interviews described below.

3.3.2. Interviews

The goal of the interviews was to collect the experiences of senior managers on specific space system program interactions with policy makers in Congress and the Executive Branch. Only very senior managers were deemed to have the insights into both the policy and the technical dimensions of programs to provide useful interview data. This population of senior managers is not only very small, but also has extremely busy calendars with little time to dedicate to research interviews. While only 12 senior managers were interviewed, they represented a good cross-section of military, civil, and commercial space programs. While these 12 managers were only a small sample of the population, over half of the themes raised during the interviews were brought up by multiple interviewees.

Semi-structured interviews were conducted with these 12 senior managers of military, civil and commercial space programs. Prior to the interview, the interviewee's biography was obtained that detailed their career and which programs they have led. To lead off the interview itself, the interviewer introduced herself, her career background, and described the purpose of the research. This served two purposes. First, the interviewer typically shared common career elements with the interviewees, thus describing her background was meant to put the interviewees at ease knowing they were being interviewed by someone with something in common. Second, the overview of the research purpose was meant to begin to focus the interviewee's thinking on the relevant memories to recall, namely the times when they witnessed the interaction of policy makers with systems that the interviewee was managing.

Next, the interviewer informed the interviewee that participation in the interview was completely voluntary, and that their responses would be kept confidential and their anonymity was assured. As the interview proceeded, the interviewee was asked to describe their specific space program interaction experiences with Congress and the Executive Branch. For each set of experiences related, the interviewee was asked to describe some basic background information on the specific program including the program's name and objectives, the timeframe of the experiences being related, and what position(s) they held on the program during that timeframe. The main substance of the interview focused on the interviewee's perceptions of the interactions of the policy makers and specific programs, including a description of the issue as they saw it, the set of actions that took place, and the outcomes. Most interviewees chose to add much additional information, such as how they personally felt about the interactions, their strategy for dealing with such interactions, and similar experiences which colleagues had related to them. All this additional information was very valuable in adding color and dimension to the scenarios they described, as well as revealing potential biases held by interviewees. All in all, the semi-structured interview process provided the right balance of collecting the minimum necessarily information from all interviewees, and letting the unique experience of each senior manager enhance the interview process and results.

After the interviews were completed, a content analysis was conducted on extensive notes taken both during and immediately following each interview The purpose of the content analysis was to identify main themes of policy and technical system design interaction. Main themes identified by more than one interviewee, along with support from the literature review described above, became the basis for generating heuristics on the impact of policy on system design.

3.3.3. Heuristic review and validation

The heuristics offered in this thesis were reviewed in both the academic community and the professional community. Feedback from professionals was received from both the space system design community and the policy maker community. The process of vetting these heuristics not only produced clearer descriptions and wordings, but also provided validation that they will be useful in the space system architecting process. However, the ultimate validation will occur as they are diffused into the space system architecture community and used in practice on future systems.

3.4. New support for old heuristics

Brenda Forman (in Maier and Rechtin) was the first to have published heuristics about the political process and aerospace system architecting and design. The heuristics she suggests are very poignant, needing relatively little explanation, and are well worth reviewing here. Her heuristics give impetus to this thesis research on the impacts of policy on systems.

Forman's Heuristic #1: *If the politics don't fly, the system never will.*

This heuristic fundamentally reflects the will of the customer in the process of procuring politico-technical systems as discussed in Chapter 2 "Understanding the environment: How policy and engineering interact." "If the politics don't fly" is simply another way of saying "If the customer doesn't like it." Politics is simply the legally constituted way taxpayers (the customers of politico-technical systems) express their desires.

Forman's Heuristic #2:   *Politics, not technology, sets the limits of what technology is allowed to achieve.*

The political domain and its resulting policies determine program budgets, and it is these budgets that limit resources to solve technical problems. Hence, policy is the limiting factor to technical performance, and the impact of policy on technical systems is important to understand.

Forman's Heuristic #3:   *A strong, coherent constituency is essential.*

The political domain doles out budgets based on the strength and staying power of a program's constituency. And without budget, programs do not happen.

Forman's Heuristic #4:   *Technical problems become political problems; there is no such thing as a purely technical problem.*

Technical problems frequently result in either direct budget changes on a program, or schedule changes that result in budget changes. And budget is unarguably the purview of the political domain.

Forman's Heuristic #5:   *With few exceptions, schedule delays are accepted grudgingly; cost overruns are not.*

When cost overruns occur, Congress has to go back and take money away from some other program to pay for the overrun. This of course doesn't make Congress happy, for among other things, Congresspersons now have to explain why that money was taken away from the poor blameless loser. This heuristic of Forman's, along with interview data, provide the motivation for quantitatively examining the effects of budget instabilities on programs later on in Chapters 6 and 7.

3.5. Ten new policy impact heuristics

The following ten heuristics were discovered through the heuristics research process involving literature reviews and interviews. Each is presented below, with a brief discussion. Readers are encouraged to incorporate the heuristics they identify with into their own personal toolkit of heuristics.

Policy Impacts Heuristic I: *A healthy relationship between a program and its appropriators is essential; a broken relationship results in increased oversight and budget instabilities.*

A healthy relationship requires frequent communication from the program's side on program progress and difficulties, as well as from the appropriators' side on their priorities and spending levels. A healthy relationship also involves delivering on promises and commitments. This includes meeting program schedule, program budget, and program performance from the program's side, as well as delivering on promised budget from the appropriators' side. To put it another way, mutual respect and understanding from the program side and the appropriator side

for the important role that each plays in delivering complex technical systems into the hands of government end users.

On the contrary, a broken relationship is characterized by mutual distrust between the program and the appropriators, the appearance of hidden agendas, and largely ineffective and infrequent communications. This broken relationship usually results in increased oversight from the appropriators, decreased transparency on the program, and program budget fluctuations from year to year. Over time, broken relationships also lead to program cancellations as the ultimate consequence.

Policy Impacts Heuristic II: *A relationship between a program and its appropriators is based on past performance.*

It doesn't matter how fiscally responsible, or cost effective, or just downright cheap, a new program promises to be. The relationship between a program or its sponsoring agency and its appropriators is built on past performance. There may be a new program manager, or there may be a new contractor. But the infrastructure of the agency remains largely the same over the years. And the past scars of battles between agencies and appropriators linger long on the minds and hearts of the appropriators.

Policy Impacts Heuristic III: *Nothing succeeds with appropriators like success.*

This heuristic is somewhat related to the one above, that a relationship between a program and its appropriate is based on past performance. Past program management successes go a long way towards creating a good future relationship with appropriators. This is evidenced by the many groups in government and industry that wish to be connected with, or take credit for, program successes such as the C-17 transport aircraft, or the global positioning system (GPS), or the joint defense attack munitions (JDAM).

Policy Impacts Heuristic IV: *Clear communications between a program and its appropriators is essential to the program's completion.*

A good relationship requires clear and constant lines of communications between a program and those who are paying the bills (the appropriators). This not only makes the appropriators feel that they are a part of the program, it keeps them personally invested in the program and its outcome. Good communications channels are also the best asset a program has when it begins to encounter difficulties. Delays and challenges in the program should be communicated to appropriators by the program, and not through secondary sources, rumors, or the media. However, this is often when communications breaks down, leading to program cancellation. In the end, government programs are paid for with taxpayer money, and good communications with the appropriators – or the managers of that money on behalf of the public – is part of being a good steward of that money.

Policy Impacts Heuristic V: *Cost overruns in one year are often followed by budget reductions the next year. Appropriators are always looking for bill payers.*

As Forman suggests in Heuristic #5 above, schedule delays are accepted grudgingly but cost overruns are not. Thus, cost overruns in a given year are frequently punished by subsequent budget cuts, and these overrunning programs are referred to as "bill payers." These programs are called bill payers because the money saved by cutting their budget goes to pay for other favorite programs of the appropriators. These favorite programs would likely be ones that have more direct economic benefits for the appropriators' constituents, and appropriators are often looking for any justification to fund them. So what lesson should a system architect or program manager take away from this heuristic? Cost overruns will mean lower future budgets, so having a contingency plan in place to operate under these lower budgets could not only prove very useful, but it could prove to be a program lifesaver.

Policy Impacts Heuristic VI: *Appropriators will always exploit the seams (or take advantage of the interfaces in programs).*

A politico-technical system program is like a large quilt: As many little pieces of fabric are joined together to form a quilt, so are many different offices in government agencies, industry contractors, and end users joined together to execute a program. The seams are the communication interfaces between these various parts of a program. Information passes between the different parts of a program, and often translation of this information is imperfect.

When appropriators request information from different parts of a program, the detriment in communication can result in the appearance that the program is not speaking with one voice, isn't all on the same page, is providing conflicting information, etc. Appropriators understand this imperfect information phenomenon – which is by nature a part of any large complex system – all too well, and can use it to their advantage when seeking out bill payers. Conflicting information from different parts of a program is typically viewed as a sign of poor program management, a justifiable reason for redirecting funds from one program to another.

Program managers who anticipate this behavior from appropriators can take extra measures to ensure accurate communications within the program. Determining what program information appropriators are likely to need, and communicating that clearly to all parts of the program, will help avoid disastrous disconnects at the seams.

Policy Impacts Heuristic VII: *Development programs have a weaker constituency than operational programs.*

Operational programs have visible, tangible proven benefits that system users are already enjoying today. Policy makers can go out and physically touch most of these operational systems, and see the actualized benefits they bring. In addition, operational programs have larger budgets than development programs, and they stretch on for many more years. This results in a strong constituency that can be rallied to support and defend the current benefits that operational systems are delivering. They have these proven benefits today, they want them to continue for a long time, and they are going to be very upset if they get taken away. Contrast this with a system that is still in development. The benefits of the system are unproven and not well understood to the majority of the appropriator's constituents. This typically places a development program in the position of having a weaker constituency than operational programs, and this disadvantaged

position needs to be recognized by the program manager and accounted for in the political strategy of the program.

Policy Impacts Heuristic VIII: *People's opinions and trusted experts – not equations – are the analysis methods of politics.*

This heuristic recognizes that the logic of engineering is not similar to the logic of politics. As discussed in Chapter 2 "Understanding the environment: How policy and engineering interact," the political and the technical domain have very different cultures, languages and logics. While the analysis of the engineering domain lies in equations and technical assessments, the analysis of politics is often just the opinions of trusted experts. And it is important to remember that the political domain defines who is "trusted" and who is an "expert." In many cases, the technical domain would likely not agree with the political domain's assessment of who is expert and trusted, but this does not matter to the political domain. An astute program manager will adapt to the political domain's analysis methods in trying to create a favorable impression of his or her program with appropriators. This may mean finding out who the trusted experts are and strategically focusing on these individuals in making the case for their program.

Policy Impacts Heuristic IX   *If a program is building facilities, some will be located in the district of the head appropriator.*

This heuristic recognizes the local nature of elected politics. Any government program manager or system architect should be aware of these pressures that elected officials have to bring tax dollars, employment and economic growth to their local district. It is these local constituents that are going to re-elect the Congressperson every few years, so the drive to make them happy is ongoing. While contract dollars to industry in the appropriators' district is good for the local economy, these are short-term in nature. A new facility typically promises decades of continuing cash flows and increased employment, far surpassing the benefits of short-term contracts. This is what makes facilities so very attractive to appropriators.

Policy Impacts Heuristic X: *A joint program executed by N groups will have 2^N times the amount of appropriator oversight.*

System architects on joint government programs will have many complications to be sure: different users, different requirements, issues about partitioning, and the list goes on and on. Equally as complicated can be the political appropriator oversight, and it is perhaps more important than any of the system design complications just mentioned. To justify this level of importance, we need look no further that Foreman's rule that "If the politics don't fly, the hardware never will."

For a single agency executing a program, appropriator oversight is accomplished by two committees of U.S. Congressmen, one in the House and one in the Senate. For a cooperative (or joint) program undertaken by two or more government agencies, there can be as many committees of Congressmen in each house as there are agencies cooperating on the project. Of course, each committee will want to give its input to the program, thus increasing the number of overseers in comparison to a single agency program. While 2^N is not a precise mathematical

formulation, it is meant to indicate that appropriator oversight increases more than merely linearly on a joint program. For example, a program between two agencies will have to report to two oversight committees in the House and two in the Senate. But then these committees will have to confer with one another, either formally or informally. This inter-committee communication is what accounts for the perception of more than linear growth in oversight.

3.6. Conclusions

This chapter has presented ten new heuristics and five old heuristics on the political process and system architecting. Program managers and system architects can incorporate these into their own personal heuristic toolkits, but when should they apply them? At the beginning of the program development? At the end? The answer is both, and at all times in between. The consideration of policy impacts on systems must be constantly borne in mind because the policy changes can occur at any point in the system development timeframe. There is not a fixed-in-time window of opportunity for policy makers to intervene in a program's course of development. One needs look no further than the annual U.S. Congressional budgeting process to realize that appropriators have at least a renewable yearly ability to impact a program.

SEMI-QUANTITATIVE METHODS:

WHEN YOU CAN'T YET QUANTIFY

There are some situations in space system architecture design where we have a good mathematical understanding of how policy directions from the political domain translate into impacts in the technical domain. Two of these situations revolve around launch vehicle selection and architecture cost, and will be discussed in the three chapters immediately following. But there are also many situations in space system architecture for which we do not have a detailed mathematical understanding of the nature in which policy directions translate into impacts in the technical domain. And this is likely to be the case for the foreseeable future. So what are we to do when faced with analyzing these situations with the goal of creating policy robust space system architectures? Semi-quantitative methods offer a solution.

This chapter presents a semi-quantitative technique for aggregating multiple influence diagrams, like the ones shown in Chapter 2 "Understanding the environment: How policy and engineering interact," to gain insights on policy impacts that are not fully understood mathematically. A case example of a space transportation infrastructure is used throughout the chapter to illustrate this technique. First, background information on a space transportation infrastructure is provided, highlighting the key information pieces that are necessary for performing this semi-quantitative analysis. Then, the semi-quantitative analysis is performed by constructing influence diagrams and aggregating their impacts into several matrices. The chapter concludes with a discussion of what insights system architects can gain from this analysis, as well as some cautionary notes.

4.1. Background: Understanding a Space Transportation Infrastructure

A key input to the semi-quantitative analysis process is an understanding of the policy directions, architecture objectives, and technical parameters associated with the space system being analyzed. In this chapter, we will use a space transportation infrastructure as an example space system. But before we begin discussing the detailed steps involved in the semi-quantitative analysis, the three areas of policy directions, architecture objectives, and technical parameters are presented here for a space transportation infrastructure.

A space transportation system includes the launch vehicles, the launch sites, the control centers, the regulatory agencies, the companies and their component suppliers that build launch vehicles,

and launch insurance providers. These collectively make up the space transportation infrastructure. The primary function of a space transportation infrastructure is to transport a payload to a specific orbital location. The payload may contain cargo, spacecraft, passengers or any combination of those. A space transportation infrastructure is a good example of a politico-technical system, being unarguably technically complex and requiring a high degree of involvement from the government to field the system. Governments finance launch vehicle development and improvement, maintain launch ranges and range safety equipment, issue launch licenses, and indemnify commercial launch providers from certain liabilities.

4.1.1. Elements of a Space Transportation Infrastructure

Both material and human elements make up a space transportation infrastructure. These are described below in two categories: physical components and stakeholder components.

4.1.1.1. Physical components

- Launch vehicles – a vehicle that will deliver a payload into space, these may be expendable rockets or reusable rockets
- Launch site – facilities and equipment to support launching at the location of the launch, to include launch pads for land-based launch systems, airplanes for air-based launch systems, or ships for sea-based launch systems, etc.
- Payload processing facilities – any equipment located at the launch site necessary to integrate the payload into the launch vehicle
- Control center – controls the launch procedures, usually includes computer stations, telemetry feeds, and control equipment
- Range safety center – responsible for safety of life actions during launch, usually includes computer stations and telemetry feeds
- Tracking and communications equipment – the ground-, air- or sea-based communications and tracking stations that receive and relay telemetry and commands during the launch
- Recovery equipment and facilities – any facility needed for recovery of reusable launch infrastructure components

4.1.1.2. Stakeholder components

- Launch vehicle prime contractors and their suppliers – the aerospace companies that produce the physical components of the space transportation infrastructure
- Launch site operators – the companies or government agencies that run the launch sites on a day-to-day basis
- Range safety operators – the government agencies that set technical standards for flight termination systems, and oversee flight termination activities in case of an emergency after launch
- Passengers/astronauts – the end users of a space transportation system that carries humans
- Payload customers – the end users of a space transportation system that carries non-human payloads (such as remote sensing satellites, communications satellites, etc.); they may be scientists, commercial companies, soldiers, etc.

- Payload contractors and their suppliers – the aerospace companies that produce the physical payload that will be launched
- Insurance companies – specialized insurance firms provide financial protection for the launching company and the payload customer in case of accidents
- Regulatory agencies – branches of national and local governments that license launch vehicles to ensure they are safe
- National, state and local governments – these groups pay for parts of the space transportation infrastructure by financing vehicle development and improvements, building and maintaining national launch ranges, etc.
- Communities around launch sites – support launch facilities by providing community infrastructure for employees of launch sites; communities can be positively affected by the space transportation infrastructure through increased commerce and jobs in their areas; they can be affected negatively by noise, pollution, accidents, etc.

4.1.2. Architectural Objectives of a Space Transportation Infrastructure

The architectural objectives of a space transportation infrastructure are derived from the validated user needs that feed into the architectural process from the operational domain.[27,28] These architectural objectives are primarily drawn from the DoD Advanced Launch System Operational Requirements Document from 1989 and are presented in Table 4-1.[29]

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[27] The process of deriving architectural objectives from user needs is not the focus of this thesis and will not be discussed in depth here. For more information, see Sage, Blanchard & Fabrycky, Martin, and Maier & Rechtin.

[28] Architectural objectives are based on user needs taken from the following references: *Advanced Launch System (ALS) System Operational Requirements Document* (1989) United States Air Force Space Command, Colorado Springs, Colorado. Also Hammond, Walter Edward (1999). *Space transportation : a systems approach to analysis and design.* Reston, VA, American Institute of Aeronautics and Astronautics.

[29] Newer launch system needs have arisen in the DoD community since 1989, such as assured access to space and launch on demand. This thesis does not specifically address those due to a lack of publicly available documentation on them, but they can be analyzed in the same manner as other architectural objectives that are examined here.

Table 4-1: Description of architectural objectives for a space transportation infrastructure.

Architectural Objectives	Description
Payload mass	How much mass the infrastructure must transport
Payload volume	How much volume the infrastructure must transport
Orbit altitude	How high off the surface of the earth the infrastructure must deliver a payload
Orbit inclination	How many degrees of angle off the equator the infrastructure must deliver a payload
Orbit insertion accuracy	How close to the target orbit altitude and inclination the infrastructure must perform
Frequency of launch	How often the infrastructure must transport a payload
Reliability	Percent of time the infrastructure must transport a payload successfully
Operability	The degree to which the infrastructure is easy to operate and maintain
Flexibility	The degree to which the infrastructure handles a variety of users
Safety	How safe the infrastructure must be for the surrounding community

4.1.3. Policy Directions for a Space Transportation Infrastructure

Policy directions that may affect a space transportation infrastructure can typically be found in governmental policy statements, legislative hearing transcripts, and the aerospace trade press. For this paper, we will use the example of space transportation policy directions currently facing the United States. These U.S. policy directions are documented officially in the form of a National Space Transportation Policy issued in 1994. Five policy directions are stated or implied, and these are summarized in the list below.

- Maintain a national security space transportation infrastructure: The U.S depends on space-based assets as part of its national security infrastructure, and thus it is important that a capability to launch these space-based assets be maintained.
- Encourage domestic commercial space transportation capability: A strong domestic commercial space transportation capability boosts the national economy and maintains a dual-purpose domestic industrial base for space transportation. In addition, the government may hope to leverage off of a strong commercial space transportation capability in the future instead of maintaining its own independent capability.
- Fair international trade in space transportation services: The U.S. is concerned that space transportation services from non-market-based economies will unfairly undercut prices

for space transportation services in market-based economies. Unfair trade would eventually drive U.S. space transportation service providers out of business, and this is undesirable for the U.S.

- Cooperate internationally on space transportation infrastructures: International cooperation promotes the peaceful engagement of many nations, and can possibly lower the very large costs of a space transportation infrastructure through cost-sharing among countries. In addition, the U.S can share in best practices and new technology developments coming from other countries.

- Control proliferation of missile technology: As a member of the Missile Technology Control Regime (MTCR), the U.S. is bound by treaty to control the proliferation of ballistic missile technology. Since space transportation utilizes many of the same technologies as ballistic missiles, the spread of space transportation technology to other countries must be closely monitored.

4.2. Analyzing the Impact of Policy Directions on Technical Parameters for a Space Transportation Infrastructure

Chapter 2 "Understanding the environment: How policy and engineering interact" of this thesis laid out the domain framework of the environment in which political and technical aspects of politico-technical system design interact. It also illustrated how policy directions from the political domain are translated into impacts on technical parameters in the technical domain. The preceding section of this chapter presented the elements, architectural objectives and policy directions for a space transportation infrastructure. Armed with all this necessary background information, we can now return to the main focus of this chapter: the process of analyzing the impact of policy directions on technical parameters for the specific case of a space transportation infrastructure.

The analysis process begins by determining the impact of each policy direction on the architecture objectives, and then determining which technical parameters are impacted by the architecture objectives. Taken together, this sequence of impacts becomes an influence diagram, like the notional one shown earlier in Figure 2-2 in Chapter 2. One influence diagram is constructed for each of the five policy directions identified earlier as applicable to a space transportation infrastructure. It is important to note that while other characteristics of the technical domain – such as its organizational structure or management philosophy – may be affected by architecture objectives, the focus of this paper is on technical system design impacts.

Shown below as an example in Figure 4-1 is the influence diagram for the policy direction "Cooperate internationally on space transportation infrastructures." It indicates that the policy direction has the potential to impact four of the architecture objectives. Cooperating internationally on space transportation infrastructure means the infrastructure would likely need to service the users of all cooperating countries as a minimum. This basic result of international cooperation – namely servicing multiple different space transportation infrastructure users – would drive the architectural objectives of orbital altitude, orbit inclination, flexibility and operability.

Orbit altitude and inclination would be affected because different countries sometimes have preferences for utilizing different orbit geometries. For example, the U.S. and other countries nearer the equator use geostationary orbits for communications satellites, whereas Russia, being at higher latitudes, uses molniya orbits for their communication satellites. While geostationary orbits have a perigee altitude of 35,786km and an inclination of zero degrees, molniya orbit perigees are around 26,000km and its inclination is 63.4 degrees.[30] In turn, orbit altitude affects the design of the propulsion subsystem of the launch vehicle, as the amount of thrust the vehicle needs is a function of orbit altitude. Likewise, orbit inclination also affects the design of the propulsion subsystem of the launch vehicle, as well as the design choice of the launch site location and the design and location of tracking and communications equipment.

Flexibility and operability would be affected because different countries have different payloads that would need to be accommodated in the infrastructure. Flexibility, which is the degree to which the infrastructure handles a variety of users, may be driven to a high state in such an international system. In turn, flexibility affects a variety of technical parameters. The launch vehicle propulsion subsystem, the launch site, and the tracking and communications equipment are affected in a manner similar to orbit altitude and inclination, since handling a variety of users requires the ability to accommodate differing orbit altitudes and inclinations. In addition, handling a variety of users may require a standard interface between payload and launch vehicle, affecting the design of the structures, electrical power, and data handling subsystems of the launch vehicle. These are the primary subsystems in the launch vehicle that interface with a payload. Lastly, the design of payload processing facilities, the control center, and recovery equipment and facilities may all be affected by the need to handle a variety of different users.

In a manner similar to flexibility, operability may also be affected. Operability is the degree to which the infrastructure is easy to operate and maintain. As the system is designed to accommodate multiple users, standards for interfaces between payloads and launch vehicles might develop, which would result in a system that is somewhat simpler and easier to operate. In that regard, the design of the primary launch vehicle subsystems that interface with the payload may be affected, including structures, electrical power, and data handling. Increased operability may also affect the design of the launch site, payload processing facilities, control center, and recovery equipment and facilities. As they are designed to accommodate a variety of different international users, these elements of the infrastructure may create standardized interfaces, common platforms of equipment that can be quickly reconfigured, and so on. All these impacts directly relate to the operability characteristics of the architecture.

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[30] Larson, Wiley J. and James Richard Wertz (1992). *Space mission analysis and design.* Torrance, California, Microcosm Press and Kluwer.

Orbit altitude

Orbit inclination

Cooperate internationally on space transportation infrastructure

Operability

Flexibility

● Launch vehicle propulsion subsystem

● Launch site

● Tracking and communications equipment

● Launch vehicle structures subsystem

● Launch vehicle electrical power subsystem

● Launch vehicle data handling subsystem

● Payload processing facilities

● Control center

● Recovery equipment and facilities
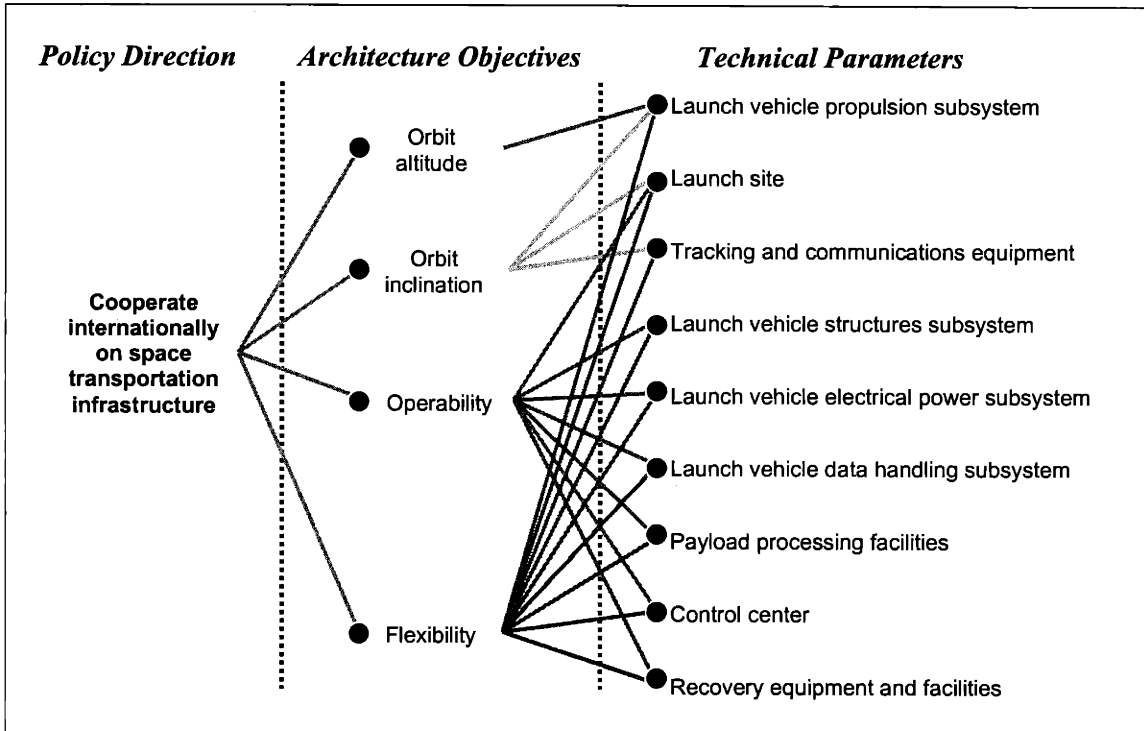
Figure 4-1:   An influence diagram translating policy effects into the technical domain for the case of a space transportation infrastructure.

Table 4-2:   Summary of impacts of policy directions on architecture objectives for a space transportation infrastructure.

Policy Directions	Payload mass	Payload volume	Orbit altitude	Orbit inclination	Orbit insertion accuracy	Frequency of launch	Reliability	Operability	Flexibility	Safety	Totals
Maintain a national security space transportation infrastructure	x	x	x	x	x	x	x				7
Encourage domestic commercial space transportation capability	x	x	x	x	x	x	x	x	x	x	10
Fair international trade in space transportation services								x	x		2
Cooperate internationally on space transportation infrastructures			x	x				x	x		4
Control proliferation of missile technology						x		x	x		3
Totals	2	2	3	3	2	3	3	4	4	1	

4.3. Discussion of semi-quantitative analysis results: What can we learn?

From the five policy direction influence diagrams, we can summarize the impact of each policy direction on each architecture objective, and subsequently on each technical parameter. Table 4-2 is a summary table of the impacts of the five policy directions on the ten architecture objectives of a space transportation infrastructure. Table 4-3 is similar, showing a summary table of the impacts of the ten architecture objectives on fifteen different technical parameters of a space transportation infrastructure. Table 4-4 quantifies the number of impacts caused by each policy direction.

There are many insights to be gained from examining the influence diagrams and the summary tables. This discussion will focus on the primary insight of interest to this chapter: *Which policy directions impact the greatest or least number of architecture objectives and technical parameters?*

Policy directions that impact a large number of architecture objectives and technical parameters have the potential for causing instabilities in the politico-technical system design process, yielding system architectures that are not policy robust. This is because policy directions can change over the long design period associated with politico-technical systems. Changes in these policy directions produce changes in the architecture objectives and technical parameters of a system, which may result in redesign efforts, requirements creep, or scrapping previous work. This can lead to cost overruns, delays in creating the system, or even cancellation of the system. For these reasons, policy directions that affect a large number of architecture objectives and technical parameters should be monitored closely for any changes.

Policy domain actors should recognize that changes made to policy directions will affect the system in an architectural and technical manner. Thus, knowing which policy directions will cause the least and most impact is very useful to them. The policy directions that cause the least number of impacts could be pursued vigorously without fear that changes in these directions will result in a large number of impacts to the system technically. Such a system illustrates the definition of policy robustness. Conversely, policy directions that cause the greatest number of impacts should be pursued carefully, being cognizant of the potential impacts of any changes in direction.

For a space transportation infrastructure, the policy directions that have the greatest number of impacts are "Encourage domestic commercial space transportation capability" and "Maintain a national security space transportation infrastructure." As shown in Table 4-4, these two directions have both the highest numbers of architecture objective impacts and the highest numbers of technical parameter impacts, as well as the highest numbers of impact paths from architecture objectives to technical parameters. This implies that these policy directions should be monitored closely by the architecture domain and approached carefully by the political domain. Conversely, the policy direction of "Fair international trade in space transportation services" has fewer architecture and technical impacts, and this policy direction might be able to be pursued with less fear of architectural and technical impacts.

Table 4-3: Summary of impacts of architectural objectives on technical parameters for a space transportation infrastructure.

Architecture Objectives \ Technical Parameters	Size of launch vehicle	Propulsion subsystem of launch vehicle	Structures subsystem of launch vehicle	Control subsystem of launch vehicle	Thermal subsystem of vehicle	Electrical power subsystem of launch vehicle	Communications subsystem of launch vehicle	Data handling subsystem of launch vehicle	Flight termination subsystem of launch vehicle	Launch site	Payload processing facilities	Control center	Range safety center	Tracking and communications equipment	Recovery equipment and facilities	Totals
Payload mass	x	x	x	x	x					x	x					7
Payload volume	x		x	x						x	x			x		6
Orbit altitude		x														1
Orbit inclination		x								x				x		3
Orbit insertion accuracy				x										x		2
Frequency of launch		x			x					x	x	x	x	x	x	8
Reliability		x	x	x	x	x	x	x		x	x	x		x		11
Operability		x			x			x		x	x	x			x	7
Flexibility		x	x		x			x		x	x	x		x	x	9
Safety		x							x	x			x	x		5
Totals	2	7	5	4	3	3	1	3	1	8	6	4	2	7	3	

Table 4-4: Summary numbers of impacted architecture objectives and technical parameters.

Policy Directions	Number of architecture objectives impacted	Number of technical parameters impacted	Number of impact paths from architecture objectives to technical parameters
Encourage domestic commercial space transportation capability	10	15	59
Maintain a national security space transportation infrastructure	7	13	38
Cooperate internationally on space transportation infrastructures	4	9	20
Control proliferation of missile technology	3	11	24
Fair international trade in space transportation services	2	9	16

It is important to note in Table 4-4 that a policy direction may have only a small number of architecture objective impacts, but a large number of technical parameter impacts, and vice versa. Another aspect to consider is the number of impact paths from the architecture objectives to the technical parameters. As the ratio of the number of impact paths to the number of technical parameters impacted approaches one, the coupling between the architecture objectives and the technical parameters decreases. Decreased coupling indicates that changes in the architecture objectives will impact fewer of the technical parameters, thus allowing the system to more easily accommodate changes in policy directions during the politico-technical system design process.

While this analysis has shown the numbers of impacts to architecture objectives and technical parameters that result from policy directions, it has not evaluated the degree of those impacts. It does not attempt to distinguish which policy directions may, for example, produce more costly impacts to technical parameters. However, the influence diagrams and impact matrices shown in this chapter can be easily appended to include a relative expert assessment of the degree of costs or risks of each impact. Including such expert assessments can add even greater insight from semi-quantitative analysis methods, however their fidelity is entirely dependent on the quality of the experts assembled to provide the relative rankings.

4.4. Conclusions

The semi-quantitative analysis process presented in this chapter has demonstrated a technique for examining policy impacts on space system design. It can become a communications tool, also known as a boundary object, to bridge the gap between the political, architectural and technical domains. It becomes an even more effective tool if several of the domains engage in the semi-quantitative analysis process together, building a common understanding and common view of the architecture as the analysis proceeds.

This semi-quantitative process involves aggregating multiple influence diagrams that show the impacts of policy directions on technical parameters. Once these influence diagrams are aggregated into matrices, the number of impacts flowing out from each policy direction can be quantified and the policy directions can be viewed in terms of which have the most or least technical impacts. This points the way towards understanding the degree of policy robustness in a given space system architecture. The more robust a space system architecture is to policy, the fewer policy directions it will have that impact it. Similarly, a policy robust space system architecture will have a low coupling ratio between the architecture objectives and the technical parameters.

QUANTIFYING POLICY EFFECTS I:

U.S. SPACE TRANSPORTATION POLICY OF 1994

Some policy impacts can be quantified given our current understanding of space systems. U.S. space transportation policy is one such policy that can be quantitatively evaluated. In brief, it is U.S. policy to restrict the launch of U.S. government payloads to U.S. launch vehicles. What are the cost and risk impacts of this policy? Are the impacts uniform or do they vary from satellite to satellite? Can the impacts be predicted with any certainty? These questions are the subject of this chapter entitled "Quantifying policy effects I: U.S. Space Transportation Policy of 1994."

This chapter first examines the characteristics that make a policy impact quantifiable, and then overviews various analysis methods that are used in this research work to aid in quantifying policy impacts. The U.S. policy on space transportation is presented in detail, as well as the modeling approach used to quantify the impacts of this policy.

The remainder of this chapter is spent on two applications of the quantitative policy impact modeling approach. First, B-TOS, a terrestrial observer ionosphere mapping satellite swarm, provides an example of applying the modeling approach to a very specific mission architecture scenario. Second, a broader set of space system architectures are modeled, and the results are used to create parametric estimating relationships that predict the costs of the policy as a function of attributes of the space system architectures. This chapter concludes by summarizing what has been learned in the effort to quantitatively model the impact of launch policy, and discusses what these findings imply for space system architecting and program management.

5.1. What enables policy impact quantification?

As discussed previously in Chapter 2 "Understanding the environment: How policy and engineering interact," policy impacts originate in the political domain as policy directives. These directives impact the architectural domain in the form of changes to architectural objectives. And in turn, these changed architectural objectives impact the technical domain in the form of changed technical parameters. Successful quantitative (mathematical) modeling of policy impacts can take place when all of these cascading impacts are well understood from both a conceptual standpoint as well as a mathematical standpoint. The fundamental mathematical equations that govern the effects of the policy on technical systems must be understood and accepted by

stakeholders that will view the results of the quantitative modeling. Successful quantitative modeling also requires the availability of appropriate analysis tools, algorithms, and computational resources. While these may appear trivial, the complex nature of policy and technical interactions on large engineering systems can demand powerful computational platforms and sophisticated heuristics search algorithms to work through the enormous solution space that is involved. In many situations that we would like to analyze today, we simply lack the computing power or heuristics necessary to solve the problem in some reasonable amount of time. As our understanding of the mathematical relationships between policy directives and technical parameters coevolves with our ability to solve large and complex mathematical problems, we will be well positioned for the future to achieve even more progress in the pursuit of the quantification of policy impacts on engineering systems.

5.2. Analysis methods for quantifying policy impacts

Several mathematical analysis methods are employed in quantifying the impacts of policy upon space system architectures. These include two methods that have been developed at MIT to analyze large space system architecture tradespaces, as well as optimization methods and parametric estimation methods. The use of these methods is made possible in large part due to very recent increases in computing power and speed, as well as very recent advances from the operations research world in optimization problem solving algorithms. Undertaking such analysis even ten years ago would have been prohibitively cumbersome, if not intractable for a university researcher. As computing ability and optimization algorithms continue to be advanced quickly and simultaneously in the coming years, the analysis methods presented here will become even more approachable.

5.2.1. GINA and MATE

GINA and MATE analysis techniques enable mathematical modeling of many architecture candidates, and evaluation of those candidates in various cost-performance tradespaces. GINA is the Generalized Information Network Analogy methodology, which had its beginnings at MIT. MATE is the Multi-Attribute Tradespace Exploration methodology, which also had its beginnings at MIT and built upon the GINA work.

The GINA methodology, initially conceived by Graeme Shaw, allows for the rapid comparison of space systems by mathematically modeling them as information transfer networks. The motivation for GINA arose from the desire of government and industry to better understand distributed satellite systems. Much as computers were becoming networked, it was thought that spacecraft, being essentially information gathering and processing systems located in space, should explore the benefits of operating as a network. This is the basis for distributed satellite constellations, and some of the potential benefits are expressed in Figure 5-1. What was critically needed were metrics to quantitatively evaluate these benefits. The GINA methodology answered this call.

Why Distribute Between and Within Satellites?

- Decentralized resources
  ⇨ *Survivable*
- Smaller, simpler satellites
  ⇨ *Reduced cost & time*
- Modular design
  ⇨ *Upgradable*
- Spatially distributed
  ⇨ *Improved revisit*
- Reduced range
  ⇨ *Reduced power-aperture*
- Separated, sparse apertures
  ⇨ *Improved resolution*

Assessment of USAF & DoD Mission Set

MILSATCOM

ISR/C² & WARNING

NAV & WEATHER
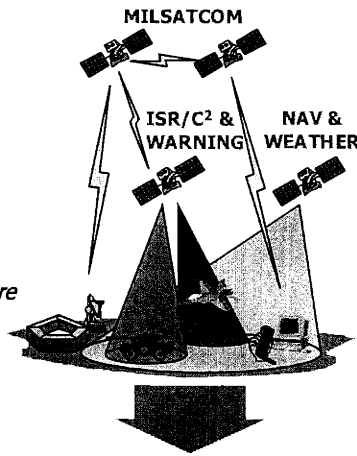
Quantify Impact Using Metrics

- Cost per Function
  - *Cost per billable minute*
  - *Cost per useful image*
- Capability
  - *Resolution*
  - *Rate*
  - *Integrity*
  - *Availability*
- Adaptability
  - *Cost and performance elasticity to changes in requirements*

Product: *Development of formal RDT&E tools for distributed satellite systems*

Figure 5-1.   GINA evolution and metrics.[31]

GINA "is a hybrid of information network flow analysis, signal and antenna theory, space systems engineering and econometrics, and specifies measurable, unambiguous metrics for the cost, capability, performance and adaptability of any space system"[32] whose mission is communications, navigation or remote sensing. These metrics are resolution, rate, integrity, and availability, and they are used to evaluate a distributed satellite system's cost per function and adaptability. GINA specifies satellite system attributes as either part of a "design vector" or a "constants vector." Attributes in the design vector vary across a given range, and distinguish one space system from another. Attributes in the constants vector remain unchanged across all space systems under consideration. Figure 5-2 shows a sample flow of GINA model inputs, computer code calculation modules, and outputs.

[31] Shaw, Graeme B. (1999). *The generalized information network analysis methodology for distributed satellite systems.* Aeronautics and Astronautics doctoral dissertation. Massachusetts Institute of Technology, Cambridge, Massachusetts.

[32] Shaw, Graeme B., David W. Miller and Daniel E. Hastings (2001). "Development of the Quantitative Generalized Information Network Analysis (GINA) Methodology for Satellite Systems." *Journal of Spacecraft and Rockets* 38(2): 257-269.. See also Shaw, Graeme B., David W. Miller and Daniel E. Hastings (2000). "Generalized Characteristics of Satellite Systems." *Journal of Spacecraft and Rockets* 37(6): 801-811. for additional background on GINA.

Inputs (Design Vector)

S/C per Cluster

Clusters

Constellation Altitude

Aperture Diameter

Antenna Power

MATLAB Models

Constellation → Radar

S/C Bus ← Payload

Launch & Operations → System Analysis

Key Outputs

Lifecycle Cost
Availability
Probability of Detection
Revisit Rate
Resolution & MDV
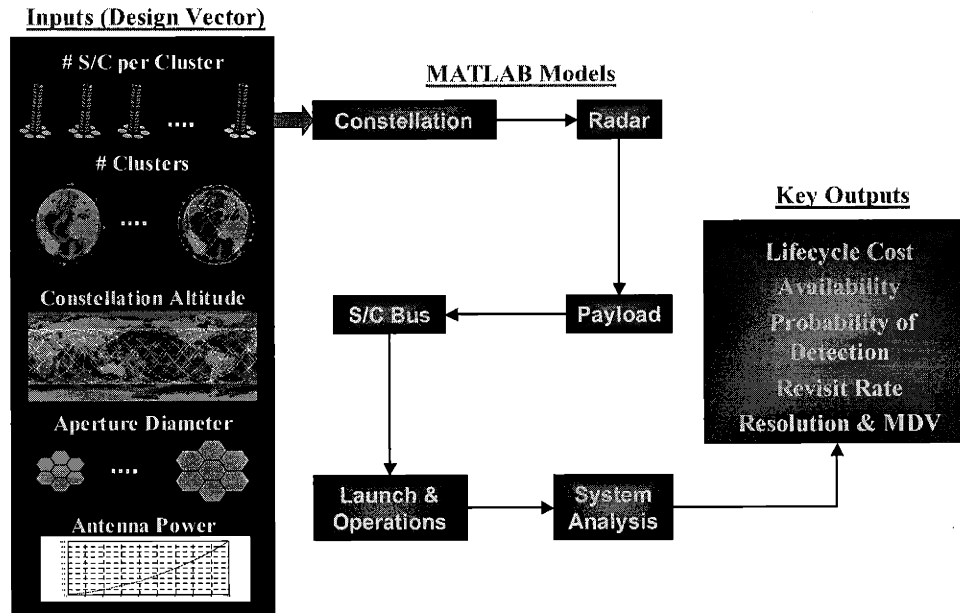
Figure 5-2.   Example GINA inputs, modules, and outputs.[33]

Rapid increases in computing power allowed GINA to expand over the years. Further work by the Space Systems Laboratory extended GINA analysis to examine thousands of architectures simultaneously, whereas Shaw examined hundreds simultaneously.   Cyrus Jilla's work on incorporating optimization algorithms into GINA to efficiently search a very large tradespace enabled tens of thousands of architectures to be analyzed simultaneously[34] Jilla made refinements to a simulated annealing heuristic algorithm for searching such a large trade space to find the Pareto optimal set of architecture candidates.

MATE builds upon the GINA research, and generalizes space system performance modeling from an absolute cost-per-function scale to a scale based on the concept of utility in economic theory[35].   As in GINA, MATE separates architecture attributes into two categories: Design vector and constants vector. The performance measure for MATE is not cost-per-function like GINA, but a utility of the space system.   Overall utility is measured on several component dimensions by using certainty equivalent lotteries with the space system customer. While utility is

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[33] Jilla, Cyrus (2002). *A multiobjective, multidisciplinary design optimization methodology for the conceptual design of distributed satellite systems.* Aeronautics and Astronautics doctoral dissertation. Massachusetts Institute of Technology, Cambridge, Massachusetts.

[34] Jilla, Cyrus (2002). *A multiobjective, multidisciplinary design optimization methodology for the conceptual design of distributed satellite systems.* Aeronautics and Astronautics doctoral dissertation. Massachusetts Institute of Technology, Cambridge, Massachusetts.

[35]   For more detailed information on MATE, see Ross, Adam and Nathan Diller (forthcoming). "Multi-Attribute Tradespace Exploration (MATE) as a Front-End for Space System Design." *Journal of Spacecraft and Rockets.*

not an absolute measure, it is a useful relative measure for comparing how well different space system candidates satisfy a user's needs[36].

MATE has been applied to a series of design projects at MIT, including X-TOS and B-TOS. X-TOS, a graduate space systems design class study in 2002, is a traditional single-satellite system whose mission is to measure neutrals in the ionosphere to increase the accuracy of orbit decay predictions. B-TOS, a graduate space systems design class study in 2001, is a terrestrial observer swarm of symbiotic distributed satellites whose mission is to map the ionosphere. B-TOS is used in this and subsequent chapters to illustrate methods for quantifying the impact of policy on space system architectures.

5.2.2. Integer Programming Optimization

A linear program is the minimization or maximization of a linear function subject to linear constraints, and all variables in the program are rational. However, when some or all of the variables must be integers, it is called a mixed or pure integer program, respectively. These integer programs can be used to formulate just about any discrete optimization problem.

While linear programs are useful for optimizing on variables that can take on a continuous range, or can be reasonably approximated to take on a linear range, integer programming is necessary for optimizing on integer quantities. Space systems are a good example of integer quantities. As an example, a linear program may indicate that a weekly production run on television sets should be optimized at 306.7. One can reasonably approximate that as 306 or even 300. But it is much harder to interpret a linear program that suggests 0.4 satellites should be launched on 0.7 of one launch vehicle and 0.6 satellites should be launched on 0.3 of another launch vehicle.

While pure or mixed integer programming solves the integrality problem of linear programs, integer programs fall in the class of optimization problems that, when they grow very large (where very large can be on the order of 50 variables), are unable to be solved in polynomial time and are considered formally intractable (NP-complete). Recent advances in solver algorithms, as well as increased computing power and speed, have enabled faster solving of some of the smaller of the larger mixed and pure integer programs. Without these recent advances, the work presented in this chapter evaluating the impacts of launch vehicle policy would have been impossible to undertake.

5.2.3. Parametric estimation and modeling

While parametric estimation is not a new technique, it has gained recent endorsement by government acquisition agencies as an acceptable method for predicting costs. Parametric relationships or parametric models are mathematical expressions that describe cost (the dependent variable) as a function of one or more cost driving (independent) variables. Creating parametric relationships involves several steps:[37]

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[36] For an in-depth treatment of applying utility theory to decision making, see Keeney, Ralph L. and Howard Raiffa (1976). *Decisions with multiple objectives : preferences and value tradeoffs*. New York, Wiley.

[37] Adapted from *Parametric Estimating Handbook (Second Edition)* (2002) International Society of Parametric Analysts, Chesterfield, Missouri.

- Data collection, evaluation and normalization of potential dependent and independent variables
- Selection of final variables, and testing of relationships between the final variables
- Regression and curve fitting of variables, data analysis and correlation
- Validation and approval

Parametric estimation relationships for cost of space systems are typically nonlinear and employ the multiplicative-error model where the error is proportional to the variables. The relationships tend to take the form of

$$y = a\,x^b\,\varepsilon$$

where y is true cost, x a cost driver, $a\,x^b$ is estimated cost, a and b are coefficients of the cost estimating relationship chosen to minimize the standard error of the estimate (SEE), and ε is one plus/minus the standard error of estimation (1 +/- SEE).[38] An example of such a nonlinear parametric estimating relationship is shown in Figure 5-3.
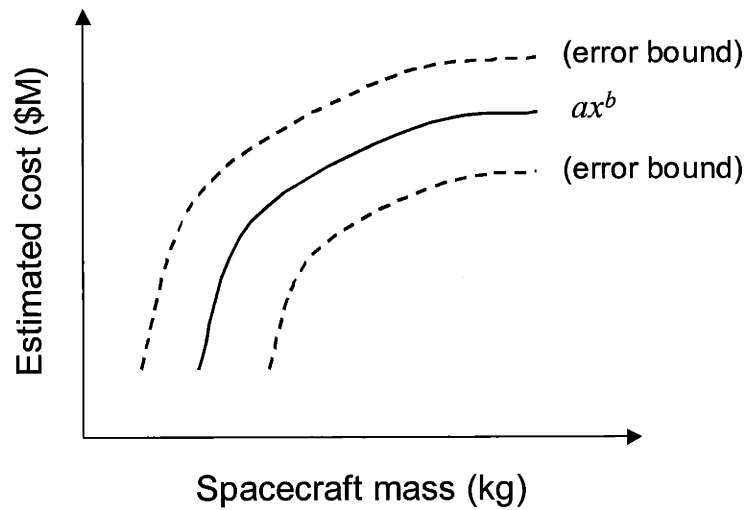
Figure 5-3. Notional nonlinear parametric estimating relationship with error bounds for spacecraft mass and cost.

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[38] For details specifically on space system parametric cost estimation, see Lao, N. Y., T. J. Mosher and J. M. Neff (1998). "Small Spacecraft Cost Model User's Guide", El Segundo, California. and Larson, Wiley J. and James Richard Wertz (1992). *Space mission analysis and design.* Torrance, California, Microcosm Press and Kluwer.

5.3. Background: Launch market and US Space Transportation Policy of 1994

The current international launch market is characterized by expendable launch vehicles offered primarily by a handful of leading countries around the world. The U.S., Russia, Ukraine, the European Union, China, Japan, Israel, India, and Brazil are considered to have currently operational space launch capabilities. To date, Israel, India and Brazil have only demonstrated small launch vehicles to lower earth orbits. The six other countries are considered to be significant players in the worldwide launch market, offering a total of approximately 20 families of launch vehicles that can serve a wide range of mass, orbital altitude and inclination requirements.

Many launch vehicles have their roots in national government-subsidized development programs. And to some degree, all launch vehicles around the world still benefit from government subsidies of various sorts in obvious as well as disguised forms. This creates a market pricing issue that many perceive to be anything but "free and fair trade" in launch services. Of particular concern are the economy-in-transition (EIT) countries of China, Russia and the Ukraine, where under-pricing of launch services may squeeze launch vehicle providers in free and fair trade economies like the U.S. and the European Union out of business. It is this concern, among others, that lead to the formulation of the U.S. Space Transportation policy of 1994.

The U.S. Space Transportation Policy of 1994, also discussed in the introductory chapter to this thesis, accomplishes four fundamental objectives[39]:

1. Establishes new national policy for federal space transportation spending, consistent with current budget constraints and the opportunities presented by emerging technologies.
2. Establishes policy on federal agencies' use of foreign launch systems and components.
3. Establishes policy on federal agencies' use of excess U.S. ballistic missile assets for space launch, to prevent adverse impacts on the U.S. commercial space launch industry.
4. Provides for an expanded private sector role in the federal space transportation R&D decision making process.

Objective two above is detailed in Section VI of the Space Transportation Policy of 1994. Section VI says "for the foreseeable future, the U.S. Government payloads will be launched on space launch vehicles manufactured in the U.S., unless exempted by the President or his designated representative.[40]" The policy further goes on to say that it "does not apply to use of foreign launch vehicles on a no-exchange-of-funds basis to support the following: flight of scientific

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[39] Policy objectives are taken directly from *Statement on National Space Transportation Policy* (1994) United States Office of Science and Technology Policy, Washington, DC..

[40] *Fact Sheet - Statement on National Space Transportation Policy* (1994) United States Office of Science and Technology Policy, Washington, DC..

instruments on foreign spacecraft, international scientific programs, or other cooperative government-to-government programs.[41]"

This restriction of government payloads to U.S. launch vehicles is the aspect of the Space Transportation Policy that is modeled in this research. In examining this policy aspect, we want to know what are its impacts on space systems. These impacts will manifest themselves as cost and risk deltas in space system architectures compared to an unrestrictive launch policy. Since costs and risks of space launch vehicles can be measured, this policy is ideally suited for quantitative evaluation.

Why is space launch policy particularly well positioned for quantitative analysis right now? There are several reasons. The first is that the policy directive is easy to translate conceptually into technical parameter impacts. If the policy directive contained in the U.S. Space Transportation Policy of 1994 can be summarized as:

"Protect the U.S. space launch industry by flying U.S. government payloads on U.S. launch vehicles."

Then the architecture objective that it impacts is:

- Launch space-based components into orbit.

And in turn, the technical parameters that the architecture objective impacts are:

- Launch vehicle available volume
- Launch vehicle available mass
- Launch vehicle performance (altitude and inclination)

Each of these technical parameters is now restricted to what is available in the U.S. launch vehicle fleet only. These technical parameters are what determine the performance of the space system architecture. In the case of launch vehicles, two performance attributes that are important are cost and risk.

The second reason why space launch policy is well positioned for quantitative analysis is that the mathematical relationships between satellites and launch vehicles and their resulting performance attributes are well understood. These relationships are primarily ones of volume and mass capacity to a determined altitude and inclination in orbit. And these altitudes and inclinations have known costs and risks associated with them peculiar to each launch vehicle.

The third reason why space launch policy is a good case for quantitative analysis is that the relationships between satellites and launch vehicles and their resulting performance depend primarily on a small number of parameters, namely payload mass, payload volume, final altitude and inclination. This small number of attributes keeps the solution space reasonable given current computational power and heuristic search algorithms.

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[41] *Fact Sheet - Statement on National Space Transportation Policy* (1994) United States Office of Science and Technology Policy, Washington, DC..

5.4. Modeling approach for quantifying launch policy impacts

Governments often put restrictive launch policies into place that limit the choice of launch vehicles a given satellite system may employ. A restrictive government launch policy is one that limits the choice of launch vehicles a satellite system may use. The restriction may be complete, such as a ban on using a particular launch vehicle, or it may be partial, such as launch quotas imposed on Chinese, Russian and Ukrainian launch vehicles by the United States in the 1990s. The purpose of these launch policies is usually to protect and foster a domestic launch capability. These policies may be implicit or explicit. They may apply to government satellite systems, or commercial satellite systems, or both.

As described above, the U.S. Space Transportation Policy of 1994 is one example of a restrictive government launch policy. It limits U.S. government satellites to be launched on U.S. launch vehicles. The impacts of this policy can be modeled using two scenarios, one with a restrictive launch policy and another with an unrestrictive launch policy. For each scenario, a mixed integer program optimization algorithm selects the best launch vehicle suite for each candidate space system architecture based on the selection rule of a decision maker. For a space system, this decision maker is likely the program director or manager. Three different types of decision makers are examined in this analysis of the impacts of launch vehicle policy: a minimum cost decision maker, a minimum risk decision maker, and a balance cost and risk decision maker. The impacts of the launch policy are a function of the decision maker type, because each decision maker uses a different selection rule to choose their launch vehicle suite.

5.4.1. Decision maker categories

Space systems under development today can be considered to fall into one of three different categories as regards their program's preferences on cost and risk:

- Programs that minimize cost
- Programs that minimize risk
- Programs that balance cost and risk

The program managers on these space systems – their decision makers – tend to follow the overall program's preferences as regards cost and risk when making their decisions. Accordingly, we can say that program managers on space systems can be considered to fall into one of three different categories of decision makers: minimize cost, minimize risk, or balance cost and risk.

These decision maker preferences will be reflected in the type of launch vehicles chosen for putting the space system in orbit. A minimum cost decision maker will opt for the least expensive launch vehicle, and not wish to pay a premium for decreasing risk. Conversely, a minimum risk decision maker will opt for the most reliable launch vehicle, and will not be concerned with how expensive it is. A balanced cost and risk decision maker will trade off cost and risk in each launch vehicle they consider, and equally minimize cost and risk in their chosen launch vehicles. While these three decision maker categories do not necessarily represent all real-world space system program managers, these categories are useful approximations for analysis purposes. They represent both extremes that a decision maker could assume, as well as the middle position a decision maker could take in striking a balance between the two extremes. In this manner, the

results of the analysis will illuminate U.S. launch policy impacts across the entire spectrum of possible decision maker types.

These three different kinds of decision makers can be found in each of the three main U.S. space communities: military/national security, civil and commercial. They are not unique to a specific community, as illustrated below and summarized in Table 5-1.

Military / national security space program decision makers

- A minimum cost decision maker in the military/national security space community might be represented by a DoD laboratory technology demonstration mission, where budgets are usually tight and fixed.
- A minimum risk decision maker in the military/national security space community might be represented by a highly critical and costly national security satellite, where launch success is the highest priority.
- A balance cost and risk decision maker in the military/national security space community might be represented by replenishment launches to a large distributed satellite constellation such as the Global Positioning System (GPS). While launch reliability is important, so may be costs since many launches will be required over the entire replenishment scheme. Such a large distributed constellation experiences slow and graceful degradation in capability, instead of catastrophic, making it more tolerable of launch failures.

Civil space program decision makers

- A minimum cost decision maker in the civil space community might be represented by a small Deep Space class science mission, where the program budget is capped under law.
- A minimum risk decision maker in the civil space community might be represented by a human space mission, where insuring safety of life is the highest priority.
- A balance cost and risk decision maker in the civil space community might be represented by an astronomical observatory satellite, where launch success is important because the space asset is of high value, but the budget is not robust enough nor the mission priority high enough to completely remove cost considerations.

Commercial space program decision makers

- A minimum cost decision maker in the commercial space community might be represented by a consumables re-supply service for satellites or space stations, where the payload being launched is inexpensive to replace and launch cost concerns, instead of reliability concerns, clearly dominate.
- A minimum risk decision maker in the commercial space community might be represented by a new space-based service, where there is no established market yet and a company wants to be the first to market in that service area. If other competitors are vying with the company for first to market status, high reliability of the launch vehicle will be a crucial factor to achieving this, and can justify the increase in launch costs based on the greater returns from being first to market.

- A balance cost and risk decision maker in the commercial space community might be represented by a broadcast satellite mission. While low costs are important to achieving a good rate of return on the mission in an already established market, launch success, and hence start of revenue generation in a timely manner, is equally important to ensure appropriate returns to investors.

Table 5-1. Illustration of three types of decision makers in each of three U.S. space communities.

	Minimum Cost Decision Maker	Minimum Risk Decision Maker	Balance Cost and Risk Decision Maker
Military / National Security Space Community	Small technology demonstration satellite	Costly and critical national security satellite	Replenishing satellite constellations where a launch failure does not render the system inoperable.
Civil Space Community	Small fixed budget science satellite	Human space flight	Astronomical observatory satellite
Commercial Space Community	Ventures with inexpensive payloads, such as consumables re-supply missions to satellites or space stations	New ventures where first-to-market status is critical	Established market ventures where risk and cost are more equally important

5.4.2. Launch vehicle selection: Mixed integer program optimization

For each type of decision maker described above, two scenarios are examined: one with a restrictive U.S.-only launch policy and another with an unrestrictive launch policy. For each scenario, a mixed integer program optimization algorithm selects the best launch vehicle suite for a given space system architecture based on the cost or risk selection rule for a particular type of decision maker. This selection rule is the objective function of the mixed integer program. These objective functions and constraints are detailed below[42].

5.4.2.1. Objective function for minimum cost decision maker

The objective function for this decision maker is to minimize total launch costs

$$\min \ \sum_{j} x_j c_j$$

Eq. 5-2

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[42] Objective functions based on work by Jeffrey Munson and Cyrus Jilla, see Munson, Jeffrey E. and Cyrus D. Jilla (2000). "An optimization approach to the launch vehicle process for satellite constellations." *AIAA 18th International Communications Satellite Systems Conference and Exhibit*, Oakland, California, AIAA. AIAA-2000-1122..

where c_j is the cost of launch vehicle j

and x_j is 1 if launch vehicle j selected, else 0

5.4.2.2. Objective function for minimum risk decision maker

The objective function for this decision maker is to minimize total launch risk

$$\min \quad \sum_j x_j [p(f_j)(c_j + s_j)]$$

<div align="right">Eq. 5-3</div>

where c_j is the cost of launch vehicle j

x_j is 1 if launch vehicle j selected, else 0

$p(f)$ is the probability of failure of launch vehicle j

and s_j is the cost of the spacecraft carried by launch vehicle j

5.4.2.3. Objective function for balance cost and risk decision maker

The objective function for this decision maker is to minimize total launch costs and risk by applying weights to both the cost and risk. The construction of the mixed integer program, allows for these weights to be variables and take on any range of relative values. For the purposes of this launch policy analysis, the weights were selected to be equal.

$$\min \quad \sum_j x_j [w_1 cj + w_2 p(f_j)(c_j + s_j)]$$

<div align="right">Eq. 5-4</div>

where c_j is the cost of launch vehicle j

x_j is 1 if launch vehicle j selected, else 0

$p(f)$ is the probability of failure of launch vehicle j

s_j is the cost of the spacecraft carried by launch vehicle j

and w_1 and w_2 are weights

5.4.2.4. Constraints

Each objective function is subject to the same set of constraints. These are:

- Total number of each launch vehicle used cannot exceed that vehicle's availability
- Total payload mass assigned to a launch vehicle cannot exceed the total payload mass capabilities of that launch vehicle
- Total payload volume and dimensions assigned to a launch vehicle cannot exceed the total payload volume and dimensions of that launch vehicle
- At least 1 launch vehicle is required to be used for each orbital plane

5.4.3. Launch vehicle characteristics

Thirty launch vehicles were used in the launch policy impacts analysis. These vehicles were available for the mixed integer program optimization algorithm to choose. The assumptions on performance, cost, size, availability, inclination, and other attributes of these vehicles[43] are shown in Table 5-2, Table 5-3, and Table 5-4. As the results of the optimization are entirely a function of the launch vehicle characteristics, it is important to understand these assumptions. Changes in these assumptions naturally change the results of the optimization. At a point in the future where launch vehicle cost or reliability or any other characteristic listed below changes materially, this launch policy impact analysis should be redone with new characteristics assumptions.

5.4.3.1. Sources of information

Launch costs, minimum and maximum inclinations, and launch vehicle family availability were taken from Isakowitz (1999). Fairing dimensions and mass performance to specific altitudes were taken both from Isakowitz (1999) and launch vehicle payload user's guides (when they were available, see footnote 43). Country of origin was determined by taking the country from which the launch vehicle launches. Exceptions are:

- The Ariane family that launches from French Guiana was attributed to Europe, where the Ariane parent company, Arianespace, is headquartered.
- Pegasus and Sea Launch that have mobile launch platforms were attributed to the U.S., where their parent companies are headquartered.

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[43] Launch vehicle attributes primarily drawn from Isakowitz, Steven J., Joseph P. Hopkins and Joshua B. Hopkins (1999). *International reference guide to space launch systems.* Reston, Va., American Institute of Aeronautics and Astronautics. with supplemental information from the following payload user guides: *Ariane 4 User's Manual, Issue No. 2* (1999) Arianespace, Evry, France.; *Ariane 5 User's Manual, Issue 3* (2000) Arianespace, Evry, France.; *Delta II Payload Planners Guide* (2000) The Boeing Company, Huntington Beach, California.; *Delta III Payload Planner's Guide* (2000) The Boeing Company, Huntington Beach, California.; *Delta IV Payload Planner's Guide* (2000) The Boeing Company, Huntingtno Beach, California.; *Sea Launch User's Guide, Revision B* (2000) Boeing Commercial Space Company, Seattle, Washington.; *Taurus Launch System Payload User's Guide, Release 3.0* (1999) Orbital Sciences Corporation, Dulles, Virginia.; *Pegasus User's Guide, Release 5.0* (2000) Orbital Sciences Corporation, Dulles, Virginia.; *Proton Launch System Mission Planner's Guide, Revision 4* (1999) International Launch Services, McLean, Virginia.; *Atlas Launch System Mission Planner's Guide, Revision 9* (2001) International Launch Services, McLean, Virginia.; *Soyuz User's Manual, Issue 3, Revision 0* (2001) Starsem, Paris, France..

Reliability was calculated using a Bayesian estimating process. The 'zero-order' estimate of the mean future fraction of launches successful for a given launch vehicle was based on updating a uniform (Beta(1,1)) prior with the available data using a binomial likelihood function[44] Launch vehicle success and failure data through November 2001 was used in the Bayesian analysis.

Table 5-2. Launch vehicle cost, fairing dimensions, reliability, nationality, family, and minimum and maximum inclination for launch policy impact analysis.

Vehicle name	Cost (FY99$M)	Fairing Diameter (m)	Fairing Height (m)	Cone Height (m)	Reliability	Country	Family	Minimum Inclination (degrees)	Maximum Inclination (degrees)
Athena I	17	2.057	2.294	2.002	0.60	U.S.	Athena	28	116
Athena II	24	2.057	2.294	2.002	0.60	U.S.	Athena	28	116
Ariane AR44LP	100	3.65	4.94	4.255	0.96	Europe	Ariane	7	100
Ariane AR40	75	3.65	4.94	4.255	0.96	Europe	Ariane	7	100
Ariane 5 ES	165	4.57	9.822	6.03	0.67	Europe	Ariane	7	100
Atlas IIAS	98	3.65	5.015	5.296	0.98	U.S.	Atlas II / III	28	120
Atlas IIIA	98	3.65	5.015	5.296	0.67	U.S.	Atlas II / III	28	120
Atlas V 402	83	3.65	5.015	5.296	0.50	U.S.	Atlas V	28	120
Atlas V 552	110	4.572	7.631	5.296	0.50	U.S.	Atlas V	28	120
Delta II 732X	47	2.743	4.553	2.285	0.96	U.S.	Delta II	28	145
Delta II 742X	52	2.743	4.553	2.285	0.96	U.S.	Delta II	28	145
Delta II 792X	55	2.743	4.553	2.285	0.96	U.S.	Delta II	28	145
Delta III	82	3.75	4.365	4.526	0.40	U.S.	Delta III	28	60
Delta IV-M	85	3.75	5.281	4.526	0.50	U.S.	Delta IV	28	120
Delta IV-M+ (5,4)	103	4.572	12.192	4.292	0.50	U.S.	Delta IV	28	120
Delta IV-H	155	4.572	12.192	4.292	0.50	U.S.	Delta IV	28	120
Dnepr-1	15	2.7	4.8	2.78	0.75	Ukraine	Dnepr	46	98
Japan H2A202	75	3.7	5.8	4.43	0.78	Japan	H2	28	100
Long March 2C	23	3.35	2	3	0.96	China	Long March	56	98
Long March 3B	60	3.65	4.61	2.24	0.67	China	Long March	56	98
Minotaur	12.5	1.118	1.11	1.016	0.75	U.S.	Minotaur	28	116
Pegasus XL	14	1.168	1.11	1.016	0.83	U.S.	Pegasus	0	130
Proton K/Block DM	94	3.97	3.505	2.817	0.95	Russia	Proton	51	73
Rockot	14	2.38	3.661	2.554	0.75	Russia	Rockot	50	98
LeoLink 1	13	1.188	1.675	1.675	0.67	Israel	LeoLink	4	100
LeoLink 2	19	2.2	2.7	2.7	0.67	Israel	LeoLink	4	100
Soyuz	40	3	3.018	2.1	0.97	Russia	Soyuz	52	98
Start-1	9	1.24	1.55	0.7	0.86	Russia	Start	52	98
Taurus	19	1.397	2.665	1.269	0.75	U.S.	Taurus	28	120
Sea Launch	85	3.75	4.937	3.6	0.75	U.S.	Sea Launch	0	360

5.4.3.2. Fitting satellites on launch vehicles

Satellite volume and dimensions were calculated as a function of spacecraft mass. By using an average spacecraft density of 79 kg/cubic meter taken from Wertz and Larson (1999), volume was calculated from mass. Satellite dimensions were calculated by assuming the satellite took on a

[44] The author would like to gratefully acknowledge Seth Guikema of Stanford who collaborated with the author on the launch policy impact analysis by calculating Bayesian launch vehicle reliabilities. Details on these Bayesian calculations can be found in Guikema, Seth D. and M. Elisabeth Pate-Cornell (2002). "Bayesian Updating for launch vehicle reliability (Working paper)". Department of Management Science and Engineering, Stanford University, Palo Alto, California. Also Pate-Cornell, M. Elisabeth, Robin Dillon and Seth D. Guikema (2001). "Mars Exploration Rover (MER) 2003 mission: A risk analysis framework for program management". Reoprt to the Jet Propulsion Laboratory, Pasadena, California.

square cylinder profile, based on its volume. Based on these resulting dimensions, satellites were assessed for how many would fit on each launch vehicle, staying within both volume and mass constraints of the launch vehicle to the desired altitude.[45]

Table 5-3. Launch vehicle performance to LEO, MEO and GEO altitudes for launch policy impact analysis.

Vehicle name	LEO (800 km)	MEO (20,000 km)	GEO (35,788 km)	Performance inclination (degrees)
Athena I	360	0	0	60
Athena II	900	0	440	60
Ariane AR44LP	6450	912	2430	60
Ariane AR40	3150	300	1158	60
Ariane 5 ES	19050	3600	4405	60
Atlas IIAS	6600	1450	1738	60
Atlas IIIA	7000	1950	1911	60
Atlas V 402	10100	2175	3316	55
Atlas V 552	16750	3575	4250	51
Delta II 732X	1830	354	508	60
Delta II 742X	2230	354	574	60
Delta II 792X	3630	780	949	60
Delta III	6950	2000	1929	60
Delta IV-M	7050	1600	2010	55
Delta IV-M+ (5,4)	10700	2400	3284	55
Delta IV-H	21350	5000	5491	55
Dnepr-1	600	0	0	64
Japan H2A202	6400	1600	2495	51
Long March 2C	0	0	842	63
Long March 3B	6000	0	3067	63
Minotaur	430	0	0	28
Pegasus XL	250	0	0	65
Proton K/Block DM	4850	3150	1700	64
Rockot	1550	0	0	63
LeoLink 1	470	0	0	0
LeoLink 2	1298	0	0	0
Soyuz	5450	1250	932	51
Start-1	220	0	0	90
Taurus	600	0	0	90
Sea Launch	6000	2000	2000	90

Table 5-4. Launch vehicle availability for launch policy impacts analysis.

Family name	Availability (vehicles/year)
Athena	10
Ariane	14
Atlas II / III	12
Atlas V	6
Delta II	12
Delta III	5
Delta IV	17
Dnepr	14
H2	7
Long March	6
Minotaur	2
Pegasus	8
Proton	12
Rockot	6
LeoLink	3
Soyuz	12
Start	6
Taurus	12
Sea Launch	8

5.4.4. Scenario analysis for a case study and the "universe"

For each decision maker type, two scenarios are assessed using the mixed integer program described above: a restrictive U.S.-only launch vehicle policy and an unrestrictive launch vehicle policy. This is first applied to a case study of a specific space system called B-TOS (described in the following section). This case study application demonstrates how specific space system programs might employ this launch policy analysis to understand the impacts on their specific mission situation. To achieve a set of results that are generalizable beyond any specific single space system case study, we move from case studies to a parametric exploration of the "universe" of space systems. The launch policy impacts analysis is then run over an extensive matrix of payload masses, dimensions, altitudes and inclinations that is a representative sample of the "universe" of possible space system architectures

5.5. B-TOS Case Study Background

B-TOS is a space-based atmospheric mapping mission to characterize the structure of the ionosphere using topside sounding techniques. The three primary goals of B-TOS are:

- Measurement of the ionosphere topside electron density profile
- Measurement of angle of arrival of signals from ground-based beacons
- Measurement of localized ionospheric turbulence

To accomplish these goals, the B-TOS space system uses a swarm architecture of distributed small satellites in multiple collaborating clusters. B-TOS is required to maintain at least a minimum altitude for topside sounding, operate at a frozen orbital inclination of 63.4 degrees, and use the Tracking and Data Relay Satellite System operated by NASA for communication with the ground.
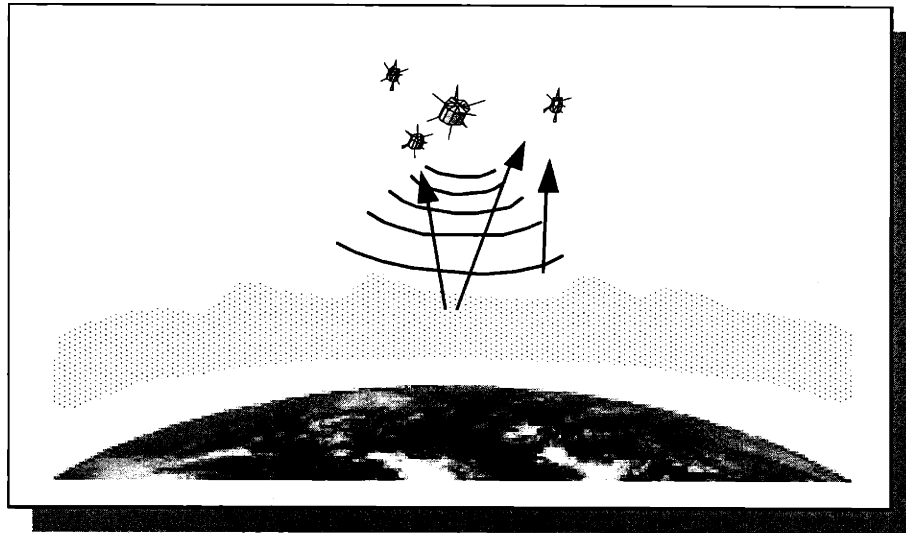
Figure 5-4. Conceptual rendering of a swarm of mother and daughter satellites performing a topside sounding mission.

GINA and MATE analysis techniques were used to develop the B-TOS mission architecture candidates. The B-TOS GINA/MATE design vector and resulting tradespace enumeration is shown in Table 5-5. The completely enumerated B-TOS tradespace encompassed over 4000 unique architectures for the mission. Each architecture was evaluated for how much utility it provided the end user, as well as how much the architecture cost. The mapping of these two measures into utility-cost space produces a Pareto optimal frontier of B-TOS architectures as shown in Figure 5-5. Five architectures along the frontier are especially interesting, as they represent places on the frontier where its slope changes. These are the points labeled A, B, C, D, and E on Figure 5-5 and their corresponding design vector values are shown in Table 5-6.[46]

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[46] For complete details on the B-TOS mission, see Diller, Nathan, Qi Dong, Carole Joppin, Sandra Jo Kassin-Deardorff, Scott Kimbrel, Dan Kirk, Michelle McVey, Brian Peck, Adam Ross and Brandon Wood (2001). *B-TOS Architecture Study: Second Iteration of the Terrestrial Observer Swarm Architecture*. Cambridge, Massachusetts, Massachusetts Institute of Technology.

Table 5-5. B-TOS design vector variables and values.

Design Vector Variable	Values
Circular orbit altitude (km)	1100, 1300
Number of orbital planes	1, 2, 3, 4, 5
Number of swarms per plane	1, 2, 3, 4, 5
Number of satellites per swarm	4, 7, 10, 13
Radius of swarm (km)	0.18, 1.5, 8.75, 50
Payload capability	5 configurations of number of sounding antennas and capability, short and long range communication capability, and on-board data processing capability

Table 5-6. (a) B-TOS Pareto optimal frontier architecture attributes. (b) B-TOS payload functionality attributes for Pareto optimal architectures A, B, C, D, and E.

(a)

Point	A	B	C	D	E
Altitude (km)	<-- 1100 -->				
Num of Planes	<-- 1 -->				
Swarms/Plane	1	1	1	1	2
Satellites/Swarm	4	7	10	13	13
Swarm Radius (km)	0.18	1.5	8.75	50	50
Functionality Study	<-- #5 -->				

(b)

Functionality Study	5	
Spacecraft Type	Mother	Daughter
Number	1	3+
Payload (Tx)	Yes	No
Payload (Rx)	Yes	Yes
Processing	Yes	No
TDRSS Link	Yes	No
Intra-Swarm Link	Yes	Yes

In the B-TOS case study discussions that follow, architecture candidates will frequently be represented in cost-utility space as they are in Figure 5-5. Each dot on Figure 5-5 represents a single and unique space system architecture that can accomplish the B-TOS mission, with its corresponding cost and utility.
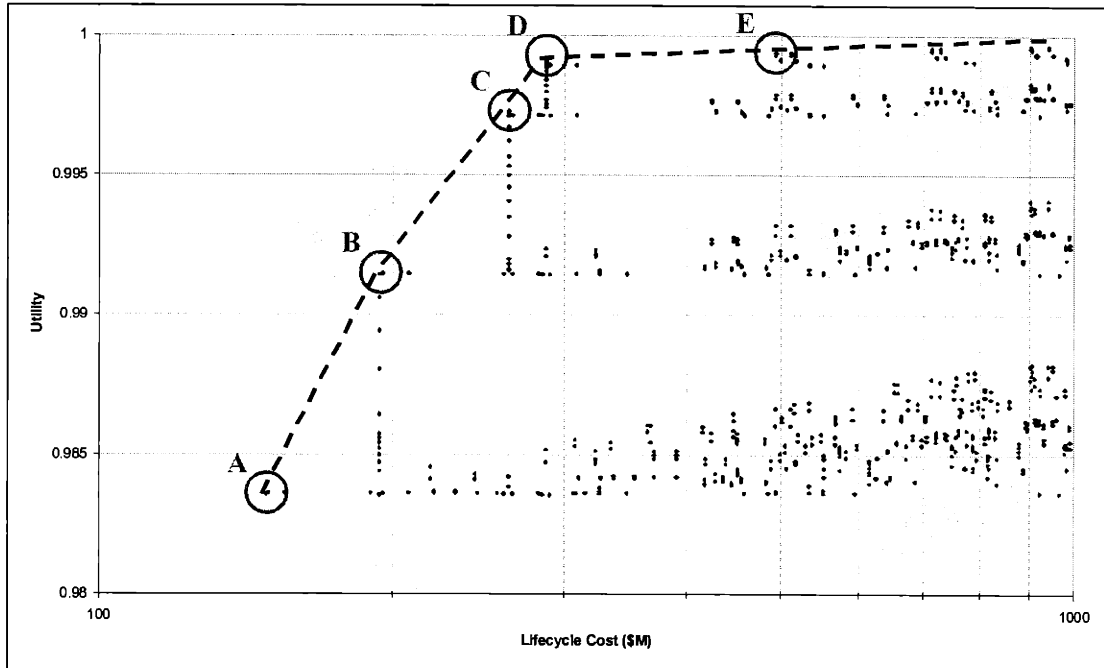
Figure 5-5.   The B-TOS architecture tradespace plotted in cost-utility space.

5.6. B-TOS Case Study Results

The entire B-TOS tradespace encompassed over 4000 architectures.   A subset of those architectures that met minimum performance standards (utility > 0.98) and cost less than $500M over the architecture's lifecycle were selected for the B-TOS launch policy impacts analysis. This subset numbered 281 architectures, and included the five Pareto front architectures – A, B, C, D, and E – shown in Figure 5-5. The results of the B-TOS launch policy impact analysis for the three different decision maker types are shown and discussed below. As anticipated, the results are different for each of the three different decision maker types.

5.6.1. Minimum cost decision maker results

Figure 5-6 is a plot of the B-TOS architectures in cost – utility space, and shows the total architecture cost for the case of a restrictive U.S. launch policy (solid diamond markers) and the case of an unrestrictive launch policy (open squares markers). The labels A, B, C, D and E indicate the five Pareto front architectures for the restrictive U.S. launch policy case, and the labels A', B', C', D' and E' indicate the five Pareto front architectures for the unrestrictive launch policy case.

Each of the five Pareto architectures costs more under a restrictive U.S. launch policy for a minimum cost decision maker. This is seen by the relative position of the two Pareto fronts, represented by the dashed lines on the graph. The Pareto front of the restrictive U.S. launch policy case is shifted to the right, or increasing cost direction, from the unrestrictive policy. This

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increased cost as a result of the restrictive U.S. launch policy was not just seen in the five Pareto front architectures, but also in all 281 architectures examined.
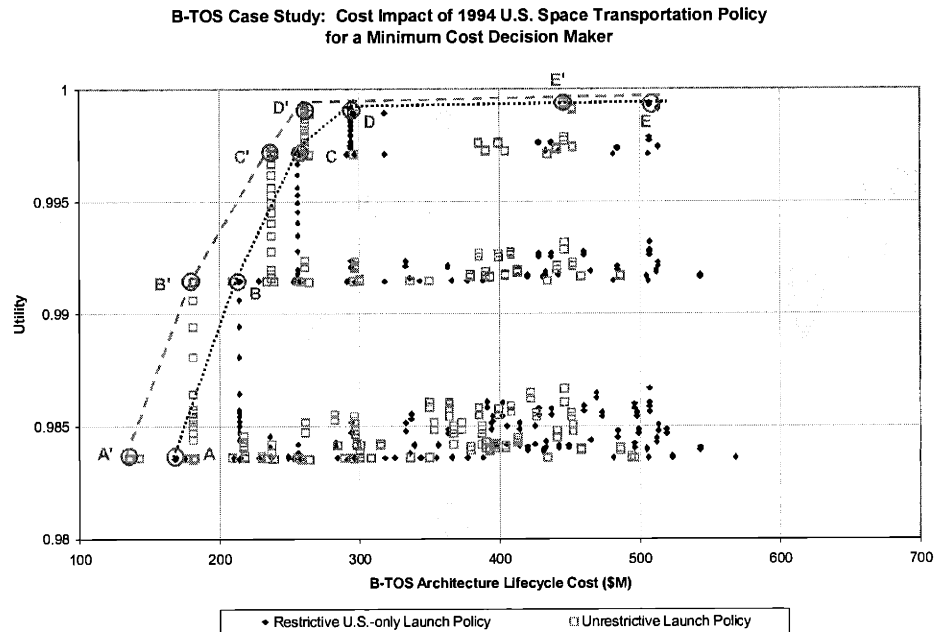
Figure 5-6. B-TOS case study: Cost impact of the 1994 U.S. Space Transportation Policy for a minimum cost decision maker.

But simply looking at the costs without examining the impact to probability of success is one-sided. Figure 5-7 is a plot of the B-TOS architectures in launch probability of success – utility space, and shows the total architecture launch probability of success for the case of a restrictive U.S. launch policy (solid diamond markers) and the case of an unrestrictive launch policy (open square markers). As above, the Pareto front architectures for both cases are labeled with letters.

Each of the five Pareto architectures has a greater launch probability of success under a restrictive U.S. launch policy for a minimum cost decision maker. This is seen by the relative position of the two Pareto fronts, represented by the dashed lines on the graph. The Pareto front of the restrictive U.S. launch policy case is shifted to the right, or increasing launch probability of success direction, from the unrestrictive policy. Only 3% of the 281 architectures examined suffered from decreased launch probability of success under the restrictive U.S. launch policy, while 97% demonstrated increased launch probability of success.
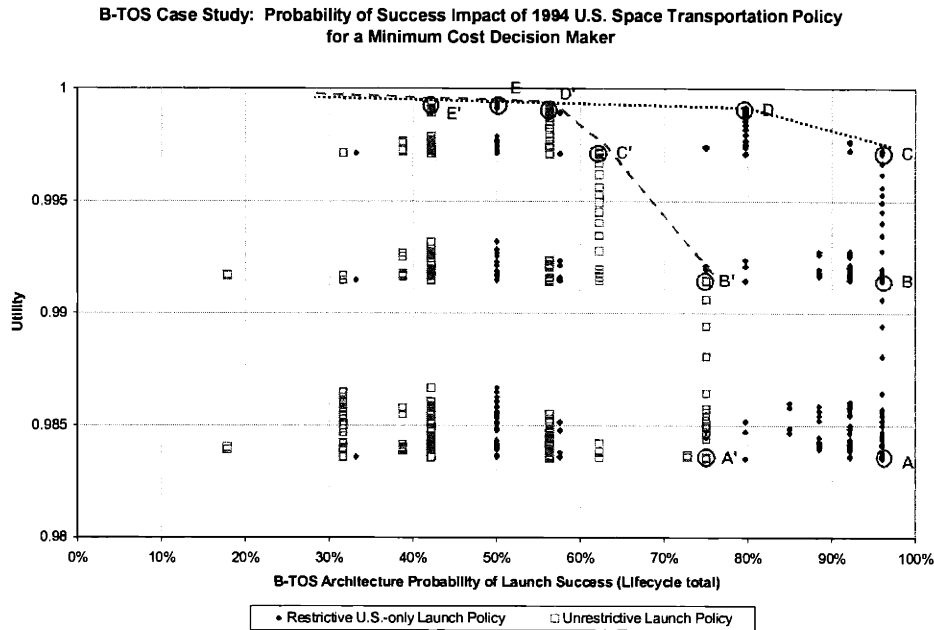
Figure 5-7. B-TOS case study: Probability of success impact of the 1994 U.S. Space Transportation Policy for a minimum cost decision maker.

To summarize the general impact on the B-TOS architectures for a minimum cost decision maker, the restrictive U.S. launch policy:

- Increases costs over an unrestrictive launch policy by an average of $45M for all architectures, and
- Increases launch probability of success by an average of 27% for almost all architectures.

This increase in costs is obviously not desirable for a minimum cost decision maker, where cost is the most important consideration. It is fortunate that these increased costs are not compounded by a decreased launch probability of success, but this may be little consolation to a decision maker who is truly interested in minimizing cost as their prime objective. As discussed earlier, these minimum cost decision makers might represent such programs as a small military technology demonstration satellite, a small fixed-budget civil science satellite, or a commercial consumables re-supply mission.

5.6.2. Minimum risk decision maker results

Similar to above, Figure 5-8 is a plot of the B-TOS architectures in cost – utility space for a minimum risk decision maker, and shows the total architecture cost for the case of a restrictive U.S. launch policy (solid diamond markers) and the case of an unrestrictive launch policy (open squares markers). The labels A, B, C, D and E indicate the five Pareto front architectures for the

restrictive U.S. launch policy case, and the labels A', B', C', D' and E' indicate the five Pareto front architectures for the unrestrictive launch policy case.

As shown in Figure 5-8, two of the five Pareto architectures cost more under a restrictive U.S. launch policy for a minimum risk decision maker. Three of the five Pareto architectures cost the same, as evidenced by the overlapping Pareto fronts between architectures B, B' through D, D'. Of all 281 architectures examined, 72% demonstrated no launch cost difference for the minimum risk decision maker, while 28% were more expensive under a restrictive U.S. launch policy.
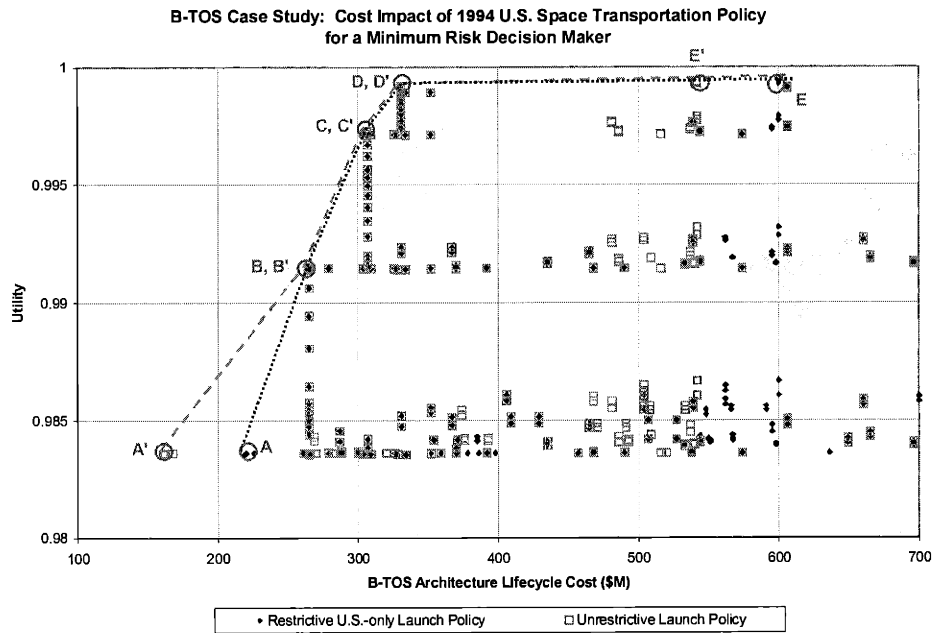
Figure 5-8.   B-TOS case study: Cost impact of the 1994 U.S. Space Transportation Policy for a minimum risk decision maker.

But for a minimum risk decision, launch probability of success is more important than cost in examining differences between the restrictive and unrestrictive launch policies. Figure 5-9 is a plot of the B-TOS architectures in launch probability of success – utility space, and shows the total architecture launch probability of success for the case of a restrictive U.S. launch policy (solid diamond markers) and the case of an unrestrictive launch policy (open square markers). As above, the Pareto front architectures for both cases are labeled with letters.

Each of the five Pareto architectures have very similar launch probabilities of success under both launch policies for a minimum risk decision maker. Only two Pareto architectures, A and E, show any difference at all, with a 2% increase in launch probability of success for the restrictive U.S. launch policy case. The similar crowding of both the restrictive launch policy case and the unrestrictive launch policy case into the far right portion of the graph in Figure 5-9 demonstrate

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the high probability of success rates achievable with both policy cases. Of all 281 architectures examined, 72% demonstrated no launch probability of success difference for the minimum risk decision maker, while 28% showed a few percent increase in probability of success under a restrictive U.S. launch policy.

B-TOS Case Study: Probability of Success Impact of 1994 U.S. Space Transportation Policy for a Minimum Risk Decision Maker
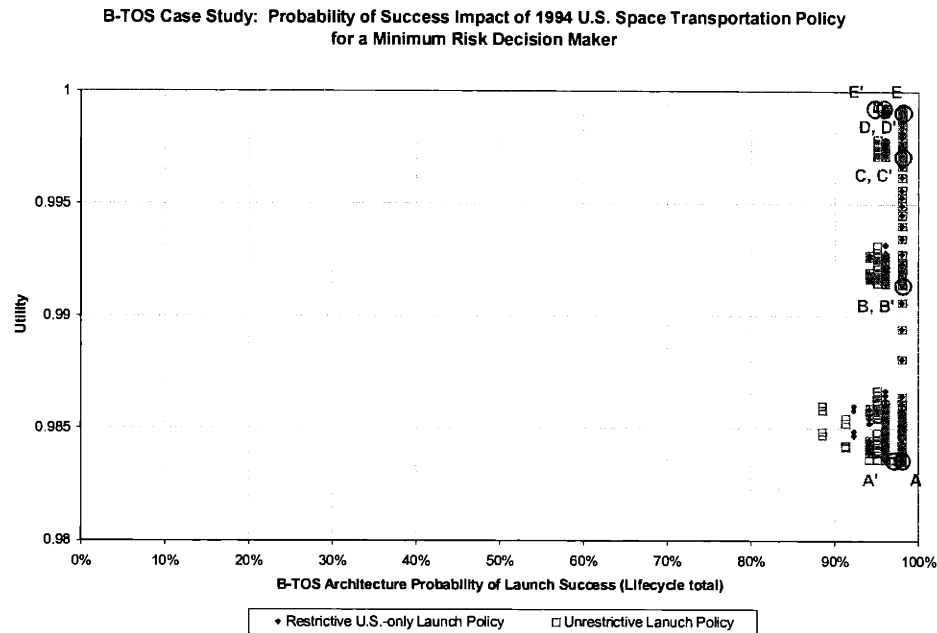
Figure 5-9. B-TOS case study: Probability of success impact of the 1994 U.S. Space Transportation Policy for a minimum risk decision maker.

To summarize the general impact on the B-TOS architectures for a minimum risk decision maker, the restrictive U.S. launch policy:

- Increases costs over an unrestrictive launch policy by an average of $86M for ¼ of the architectures, and
- Increases launch probability of success by an average of 1% for ¼ of the architectures.

Since a minimum risk decision maker's primary concern is launch probability of success, the good news is a restrictive U.S. launch policy does not impact him/her negatively in this area. And for nearly ¾ of the architectures, this high probability of success costs the same whether you use U.S-only vehicles or use the entire worldwide fleet. Unfortunately the other ¼ of the architectures will incur a cost penalty ranging from $56M - $232M for being restricted to U.S.-only launch vehicles. As discussed earlier, these minimum risk decision makers might represent such programs as a critical national security satellite, a civil human space flight mission, or a commercial venture in a new market.

5.6.3. Balance cost and risk decision maker results

Similar to above, Figure 5-10 is a plot of the B-TOS architectures in cost – utility space for a balance cost and risk decision maker, and shows the total architecture cost for the case of a restrictive U.S. launch policy (solid diamond markers) and the case of an unrestrictive launch policy (open squares markers). The labels A, B, C, D and E indicate the five Pareto front architectures for the restrictive U.S. launch policy case, and the labels A', B', C', D' and E' indicate the five Pareto front architectures for the unrestrictive launch policy case.

As shown in Figure 5-8, three of the five Pareto architectures cost more under a restrictive U.S. launch policy for a balance cost and risk decision maker. This is seen by the relative position of the two Pareto fronts, represented by the dashed lines on the graph. Two of the five Pareto architectures cost the same, as evidenced by the overlapping Pareto fronts between architectures C, C' through D, D'. Of all 281 architectures examined, 62% were more expensive under a restrictive U.S. launch policy, 36% demonstrated no cost difference under the restrictive policy, and 3% were less expensive under the restrictive policy.
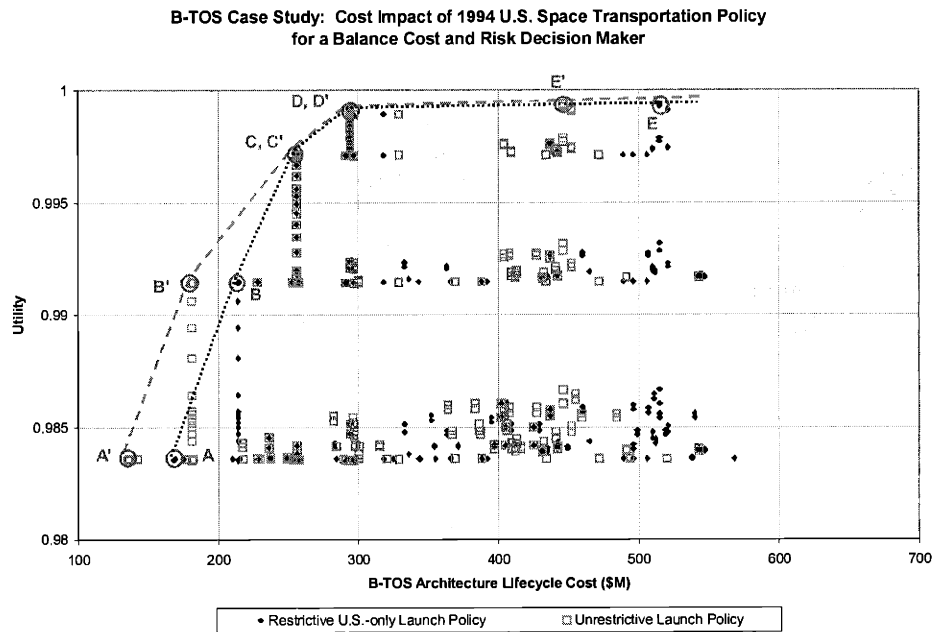
Figure 5-10. B-TOS case study: Cost impact of the 1994 U.S. Space Transportation Policy for a balance cost and risk decision maker.

For a balance cost and risk decision maker, launch probability of success is equal in importance to cost. Figure 5-11 is a plot of the B-TOS architectures in launch probability of success – utility space, and shows the total architecture launch probability of success for the case of a restrictive

U.S. launch policy (solid diamond markers) and the case of an unrestrictive launch policy (open square markers). As above, the Pareto front architectures for both cases are labeled with letters.

Two of the five Pareto architectures (C and D) have no difference in the launch probability of success under both launch policies for a balance cost and risk decision maker. The remaining three Pareto architectures (A, B, and E) have a greater launch probability of success under the restrictive launch policy. This can be seen in Figure 5-11 by the relative positions of the architectures in both policy cases. Of all 281 architectures examined, 58% showed an increase in probability of success under the restrictive policy, 36% showed no difference in probability of success under the restrictive policy, and 6% showed a decrease in probability of success under the restrictive policy.
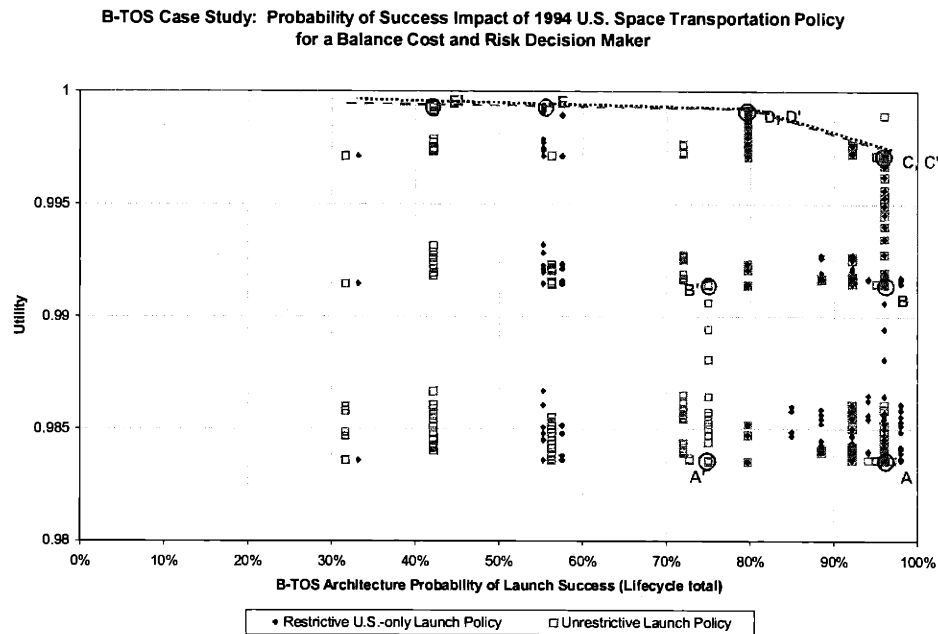
Figure 5-11. B-TOS case study: Probability of success impact of the 1994 U.S. Space Transportation Policy for a balance cost and risk decision maker.

To summarize the general impact on the B-TOS architectures for a balance cost and risk decision maker, the restrictive U.S. launch policy:

- Increases costs over an unrestrictive launch policy by an average of $53M for 3/5 of the architectures, and
- Increases launch probability of success by an average of 22% for 3/5 of the architectures.

While the good news is a restrictive U.S. launch policy does not have a large negative impact on launch probability of success, the bad news is that it does increase the cost in 3/5 of the architectures for a balance cost and risk decision maker. This cost penalty can range from $17M - $132M for being restricted to U.S.-only launch vehicles. As discussed earlier, these balance cost and risk decision makers might represent such programs as replenishment of a distributed military satellite constellation, a civil astronomical observatory, or a commercial venture in an established market.

5.6.4. Summary of B-TOS case study results

Now that we have individually examined the impacts of a restrictive U.S. launch policy on each of the three different types of decision makers, we can now compare and contrast the impacts across decision makers.

Launch probability of success faired very well for all decision makers. The minimum risk decision maker, who cared about risk the most, did not experience any kind of risk impact from the U.S. launch policy. And even the minimum cost decision maker, as well as the balance cost and risk decision maker, only took hits to the launch probability of success on 3-6% of their architectures. All in all, these decision makers were probably fairly happy as concerns launch probability of success.

But cost impacts are a far different story. Each decision maker suffered cost increases on a materially significant fraction of their architectures. The minimum risk decision makers fared the best, with only 25% of their architectures suffering cost increases. The balance cost and risk decision makers fared worse, with 60% of their architectures suffering cost increases. Lastly, the minimum cost decision makers fared the worst, with all of their architectures suffering cost increases due to a restrictive U.S. launch policy.

To sum up the impacts of a restrictive U.S. launch vehicle policy on the B-TOS program:

- Minimum risk decision makers will notice the least impact
- Minimum cost decision makers will notice the greatest impact
- Balance cost and risk decision makers will fall between these two

These effects of cost and launch probability of success impacts on decision maker types are summarized graphically in Figure 5-12.
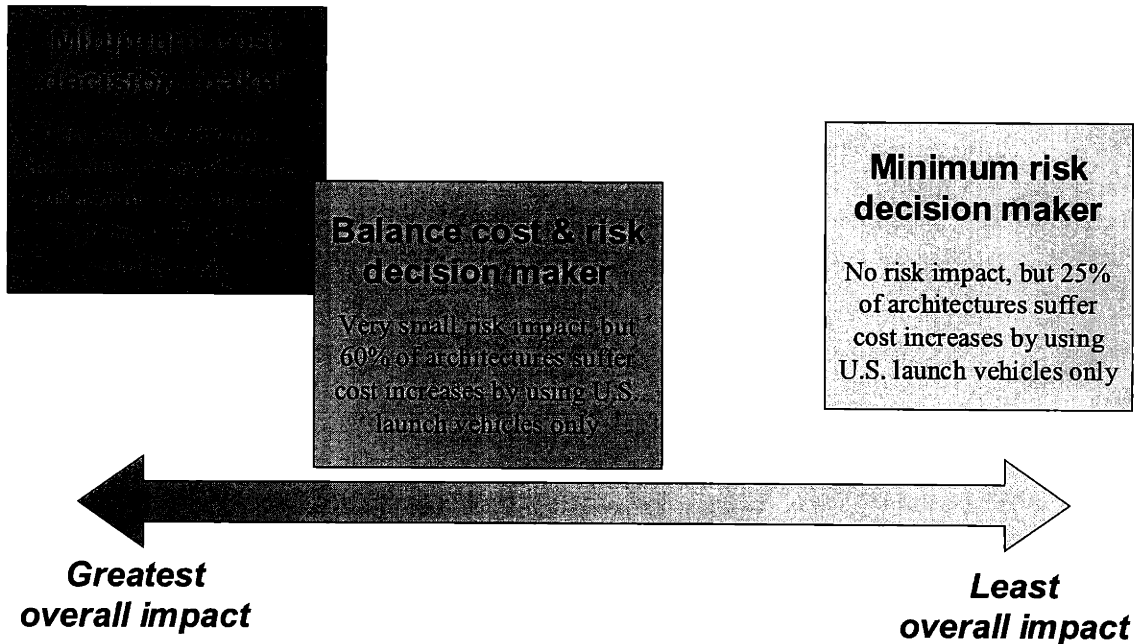
Figure 5-12. B-TOS case study: Summary of impacts of U.S. Space Transportation Policy of 1994.

Since B-TOS is a small military science mission, what kind of decision maker would likely be in charge of this program? Since it is a science mission, it is not likely to have a large budget. And since it is a science mission as opposed to an operational mission, it is not likely to be considered mission critical to the warfighter. So one might reasonably conclude that the B-TOS decision maker more likely resembles the minimum cost decision maker or the balance cost and risk decision maker, than the minimum risk decision maker. If that is assumed to be the case, then the B-TOS mission will indeed see a fairly large impact due to the restrictive U.S. launch policy.

5.7. Moving beyond case studies: the "universe" of space system

architectures

Can general findings based on a single case study be extrapolated to other space systems with different characteristics and different situations? The answer is that since the results of the analysis depend entirely on the specifics of the space system (its mass, orbital altitude, orbital inclination, etc.), the results will vary with the characteristics of the space system analyzed. Thus, results from a single case study of a specific space system should not form the basis for generalization.

To achieve a set of results that *are* generalizable beyond any specific single space system, we move from case studies to a parametric exploration of the "universe" of space systems. The launch policy impacts analysis is run over an extensive matrix of payload masses, dimensions, altitudes and inclinations that is a representative sample of the "universe" of possible space system architectures (at least from the point of view of the launch vehicle). The attributes of space

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systems that distinctly represent this universe are orbit altitude, orbital inclination, mass per satellite, number of orbital planes, and number of satellites per plane. These attributes and their range of values are shown for each orbital altitude in Table 5-7, Table 5-8, Table 5-9, and Table 5-10. Combining these attributes achieves a representative set of 3566 distinct space system architectures from which generalizations can more appropriately be made. These 3566 architectures consumed over 720 hours of computation time on three platforms during the running of the launch policy analysis mixed integer programming optimization routines.

Table 5-7. Parametric exploration attributes and values for small LEO space systems.

Attributes for Small Low Earth Orbit Space Systems	Values
Mass per satellite (kg)	50, 100, 150, 200, 250, 300
Number of orbital planes*	1, 2, 4, 6, 8
Number of satellites per plane	1, 3, 6, 10, 20, 30
Orbital inclination (degrees)	0, 15, 30, 45, 60, 75, 90

* 0-degree inclination has only 1 plane

Table 5-8. Parametric exploration attributes and values for big LEO space systems.

Attributes for Big Low Earth Orbit Space Systems	Values
Mass per satellite (kg)	500, 750, 1000, 1250, 1500, 2000, 2500, 3000, 5000, 10000
Number of orbital planes*	1, 2, 4, 6
Number of satellites per plane	1, 2, 4, 6, 8
Orbital inclination (degrees)	0, 15, 30, 45, 60, 75, 90

* 0-degree inclination has only 1 plane

Table 5-9. Parametric exploration attributes and values for MEO space systems.

Attributes for Medium Earth Orbit Space Systems	Values
Mass per satellite (kg)	50, 100, 150, 200, 250, 500, 750, 1000, 1500, 2000, 3000
Number of orbital planes*	1, 2, 4, 6
Number of satellites per plane	1, 2, 3, 5
Orbital inclination (degrees)	0, 15, 30, 45, 60, 75, 90

* 0-degree inclination has only 1 plane

Table 5-10. Parametric exploration attributes and values for GEO space systems.

Attributes for Geostationary Earth Orbit Space Systems	Values
Mass per satellite (kg)	250, 500, 750, 1000, 1250, 1500, 1750, 2000, 2250, 2500, 2750, 3000, 3250, 3500, 3750, 4000, 4250, 4500, 4750, 5000
Number of orbital planes*	1
Number of satellites per plane	1, 2, 3, 4, 5
Orbital inclination (degrees)	0

5.7.1. Regression models

The results from the launch policy impacts analysis on the "universe" of space system architectures are used as databases from which to perform parametric estimation of the costs of the restrictive U.S. launch vehicle policy. First, the independent and dependent data were tested for their relationships. The two dependent variables for each architecture are launch cost and launch probability of success. The independent variable that exhibited a statistically significant relationship with launch cost was launch mass per orbital plane. This is not surprising, as launch mass and launch cost are well known to be correlated. There was no satisfactory statistical significance between the dependent variable of launch probability of success and any of the independent variable. This is also not surprising, as the independent variables of satellite mass, number of orbital planes, satellites per plane, inclination and altitude would not be expected to exhibit any correlation with launch probability of success. Thus, that independent variable will not be the subject of parametric estimation in the launch policy impacts analysis.

Nonlinear multiplicative-error regression models were selected over linear and additive-error regression models for their greater applicability to space systems where errors depend on the parameters of the regression[47]. The nonlinear multiplicative-error regression models tend to take the form of

$$y = a \, x^b \, \varepsilon$$

Eq. 5-5

where y is true cost, x is a cost driver, $a \, x^b$ is estimated cost, and ε is the error of estimation.[48] a and b are referred to as the coefficients of the regression model. Creating the regression model involves solving the least-squares problem to find the coefficients that minimize the sum of squared relative errors from the predictions. In other words, the sum of squared percentage errors is minimized

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[47] Regression model in this research adapted from Lao, N. Y., T. J. Mosher and J. M. Neff (1998). "Small Spacecraft Cost Model User's Guide", El Segundo, California; also *Parametric Estimating Handbook (Second Edition)* (2002) International Society of Parametric Analysts, Chesterfield, Missouri.

[48] For details specifically on space system parametric cost estimation, see Lao, N. Y., T. J. Mosher and J. M. Neff (1998). "Small Spacecraft Cost Model User's Guide", El Segundo, California. and Larson, Wiley J. and James Richard Wertz (1992). *Space mission analysis and design.* Torrance, California, Microcosm Press and Kluwer.

$$\text{minimize} \quad \sum (\varepsilon - 1)^2 = \sum \left[\frac{y_i - ax_i^b}{ax_i^b} \right]^2$$

<div align="right">Eq. 5-6</div>

Two metrics describe the quality of a regression model: Pearson's Correlation Squared (R^2) and the standard error of estimate (SEE). R^2 measures the amount of correlation between estimates and corresponding actual measurements; in other words, the proportion of variance in the dependent estimate that is explained by the independent actual. The SEE is a percentage, and is the root mean square of all percentage errors made in estimating points of the data. The formula for SEE is

$$\text{SEE} = \sqrt{\frac{1}{n-m} \sum \left(\frac{y_i}{ax_i^b} - 1 \right)^2}$$

<div align="right">Eq. 5-7</div>

where n is the number of observed values, and m is the number of parameters being estimated.

5.7.2. Launch policy impact relationships

Recall that the impacts of the restrictive U.S. launch policy are different for different types of decision makers. Thus, regression was conducted separately on the impact data obtained from evaluating each of the three types of decision makers (minimum cost, minimum risk, and balance cost and risk).

For each type of decision maker, two different regression models were initially computed: one for the restrictive U.S. launch policy scenario, and one for the unrestrictive launch policy scenario. For each scenario, a regression model was found that related mass per orbital plane to the total launch cost per plane. These two models were then subtracted to generate a new model of the delta launch cost per plane between the restrictive U.S. launch policy scenario and the unrestrictive launch policy scenario. Because the correlation of the launch cost per plane in each of the two scenarios for each decision maker type was very strong (>.943 at the 0.001 level of significance), the initial regression models were considered dependent and their errors subtracted. The new regression models that resulted yield the cost impact estimating relationship for each type of decision maker.

The following sections discuss the cost impact estimating relationships that describe the delta launch cost per plane for each type of decision maker for each orbit altitude region. In short, these relationships describe the cost of the U.S. launch policy as a function of space system mass per plane for the case of a specific type of decision maker. These estimating relationships, along with their respective SEE and R^2, are shown and discussed in the following sections.

While the cost impact to an architecture is important, so is the launch probability of success impact. The delta launch probability of success for an architecture is calculated by subtracting the launch probability of success in the unrestrictive launch policy case from the launch probability of success in the restrictive launch policy case. Thus, a negative delta launch probability of success indicates that the restrictive U.S. launch policy decreases the launch probability of success for an

architecture. Similarly, a positive delta launch probability of success indicates that the restrictive U.S. launch policy increases the launch probability of success for an architecture.

It is useful to examine both of these impacts on an architecture simultaneously, as was done in the B-TOS case study. However, there is no correlation between launch mass per plane and launch probability of success, so regression relationships cannot be used as they are for cost impact. The delta launch probability of success is instead described with descriptive statistics, a histogram (frequency) plot, and a moving average plot for each altitude region and each type of decision maker.

- The descriptive statistics are shown in a table and include the mean and its standard error, mean confidence interval, trimmed mean, median, variance, standard deviation, minimum, maximum, range, interquartile range, skewness and its standard error, and kurtosis and its standard error.
- The histogram plot is segmented into 10% delta launch probability of success intervals ranging from −100% to +100%.
- A moving average of probability of launch success is shown in the cost impact graphs in the following sections to afford at least a gross level of comparison of cost and launch probability of success impacts in a single glance. A 50-sample moving average is used for LEO architectures of increasing mass, a 25-sample moving average is used for MEO architecture of increasing mass, and a 10-sample moving average is used for GEO architectures of increasing mass[49]. The reader should keep in mind that a moving average represents a very gross trend, and there can be significant variation and noise around the moving average line.

5.7.3. Minimum cost decision maker results

The cost impact estimating relationships for a minimum cost decision maker are shown in Table 5-11, and a graph of these relationships for a 1-plane space system architecture is shown in Figure 5-13. Also shown in Figure 5-13 is a moving average of the delta launch probability of success.

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[49] The population of architectures is not equally distributed among each altitude region, so the sample number for the moving average calculation differs.

Table 5-11. Minimum cost decision maker: Cost impact estimating relationships for using U.S.-only launch vehicles.

Orbital altitude region	Parameter, X (unit)	Parameter, Y (unit)	Input data range	Minimum cost decision maker U.S. launch policy cost impact estimating relationship (FY99$M)	SEE (%)	R^2
Low Earth Orbit	Space system mass per orbital plane (kg)	Number of orbital planes (number)	X: 50 – 10,000 Y: 1 – 6	$Y\left(5.61356\,X^{0.4061} - 1.79446\,X^{0.52458}\right)$	1	.65
Medium Earth Orbit	Space system mass per orbital plane (kg)	Number of orbital planes (number)	X: 50 – 1,000* Y: 1 – 6	$Y\left(9.541607\,X^{0.37998} - 6.855861\,X^{0.43082}\right)$	5	.68
Geo-stationary Earth Orbit	Space system mass per orbital plane (kg)	Number of orbital planes (number)	X: 250 – 10,000 Y: 1	$Y\left(0.45668\,X^{0.71050} - 0.215914\,X^{0.78564}\right)$	2	.94

* Beyond approximately 1000kg per plane, MEO cost impact is negligible.

As seen in Figure 5-13 for a minimum cost decision maker, the highest cost impact from a restrictive U.S. launch policy occurs in the low Earth orbit (LEO) altitude region. The magnitude of the impact decreases with increasing space system architecture mass per orbital plane. This impact pattern is closely paralleled in the geostationary (GEO) altitude region. For both altitudes, a minimum cost decision maker will suffer a cost impact on the architecture. The middle Earth orbit (MEO) altitude region behaves slightly differently, with the cost difference between the restrictive launch policy case and the unrestrictive case dwindling to negligible for greater than 1000kg per plane.

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Figure 5-13. Cost and probability of success impacts of the 1994 U.S. space transportation policy on a minimum cost decision maker. Cost impact curves use estimating relationships in Table 5-11 and are shown above for a 1-plane space system architecture. Probability of success impact curves are a 50-sample moving average for LEO architectures of increasing mass, a 25-sample moving average for MEO architecture of increasing mass, and a 10-sample moving average for GEO architectures of increasing mass.

Figure 5-14, Figure 5-15, and Figure 5-16 present descriptive statistics and histograms of LEO, MEO, and GEO architectures, respectively, for a minimum cost decision maker. The LEO delta launch probability of success ranges from –86% to 76%, with a mean of –1%. The histogram looks fairly balanced around 0%. In contrast, the MEO delta launch probability of success ranges from –86% to 0%, with a mean of –12%. The histogram shows this grouping on the left (negative) side of the graph. The GEO delta launch probability of success ranges from –52% to 5%, with a mean of –6%. Its histogram also shows a grouping of the data left of 0%.

So on average for the minimum cost decision maker, the MEO architectures tend to see the largest risk impact from the restrictive U.S. launch policy. The GEO architectures tend to see a lesser, but still material, impact. And the LEO architectures see a very small risk impact.

LEO Delta launch probability of success (in %) for a minimum cost decision maker	Statistic	Std. Error
Mean	-1.09	0.53
95% Confidence Interval for Mean		
Lower Bound	-2.13	
Upper Bound	-0.04	
5% Trimmed Mean	-1.56	
Median	0.00	
Variance	6.15	
Std. Deviation	24.81	
Minimum	-85.97	
Maximum	76.25	
Range	162.22	
Interquartile Range	7.49	
Skewness	38.22	5.26
Kurtosis	292.24	10.52
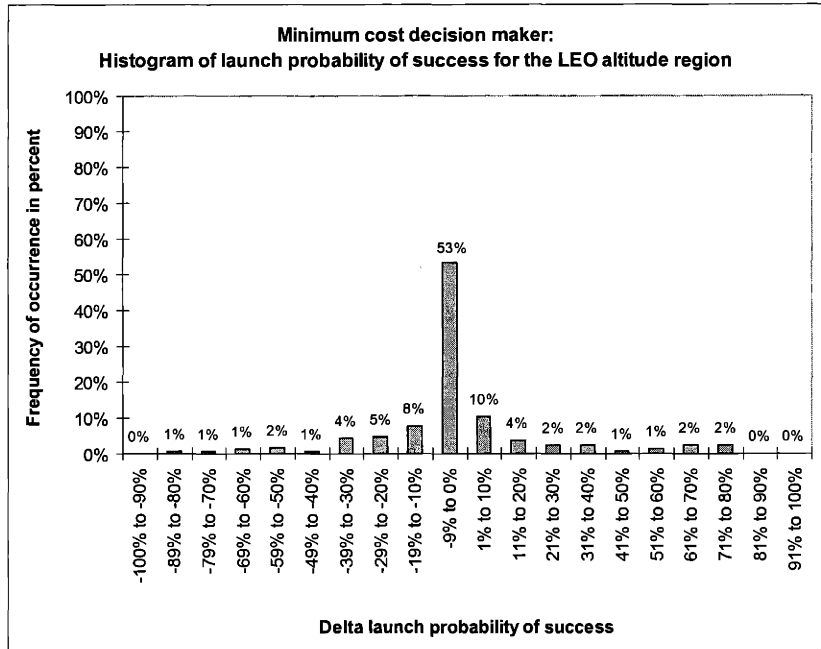
Figure 5-14. Descriptive statistics and histogram for LEO probability of success impacts of the 1994 U.S. space transportation policy on a minimum cost decision maker.

MEO Delta launch probability of success (in %) for a minimum cost decision maker	Statistic	Std. Error
Mean	-11.74	0.66
95% Confidence Interval for Mean		
Lower Bound	-13.03	
Upper Bound	-10.44	
5% Trimmed Mean	-8.78	
Median	0.00	
Variance	4.30	
Std. Deviation	20.73	
Minimum	-85.97	
Maximum	0.00	
Range	85.97	
Interquartile Range	20.96	
Skewness	-188.06	7.78
Kurtosis	281.12	15.55
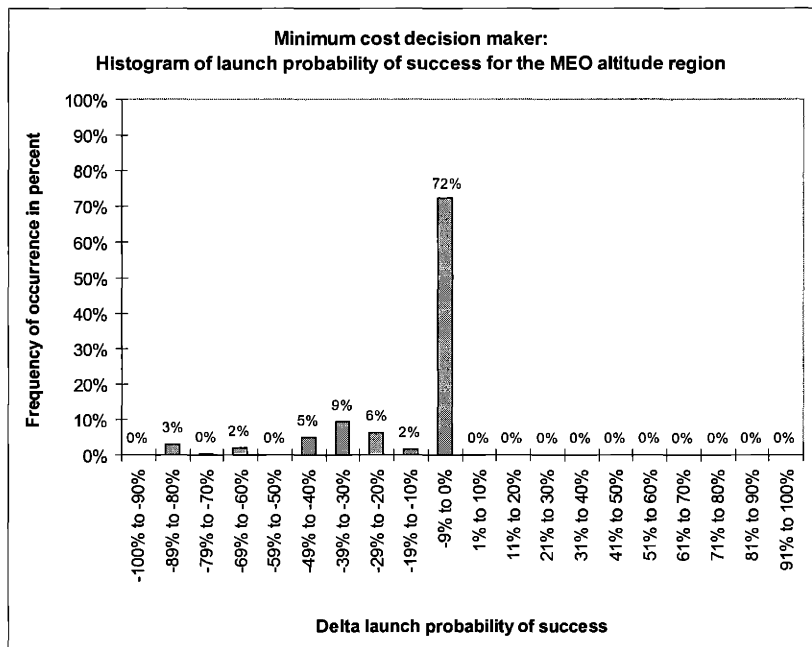
Figure 5-15. Descriptive statistics and histogram for MEO probability of success impacts of the 1994 U.S. space transportation policy on a minimum cost decision maker.

GEO Delta launch probability of success (in %) for a minimum cost decision maker	Statistic	Std. Error
Mean	-6.21	1.08
95% Confidence Interval for Mean		
Lower Bound	-8.35	
Upper Bound	-4.06	
5% Trimmed Mean	-5.16	
Median	0.00	
Variance	1.16	
Std. Deviation	10.79	
Minimum	-52.16	
Maximum	5.11	
Range	57.27	
Interquartile Range	13.80	
Skewness	-171.73	24.14
Kurtosis	292.77	47.83

Minimum cost decision maker: Histogram of launch probability of success for the GEO altitude region

Figure 5-16. Descriptive statistics and histogram for GEO probability of success impacts of the 1994 U.S. space transportation policy on a minimum cost decision maker.

In summary, there appears to be on average both a cost and risk impact to minimum cost decision makers who must adhere to the U.S. restrictive launch policy. LEO architectures have the largest cost impacts but the smallest risk impacts. MEO architectures have the smallest cost impacts but the largest risk impacts. Lastly, GEO architectures have a cost and risk impact that is in between.

5.7.4. Minimum risk decision maker results

The cost impact estimating relationships for a minimum risk decision maker are shown in Table 5-12, and a graph of these relationships is shown for the 1-plane space system architecture case in Figure 5-17. Also shown in Figure 5-17 is a moving average of the delta launch probability of success.

Table 5-12. Minimum risk decision maker: Cost impact estimating relationships for using U.S.-only launch vehicles.

Orbital altitude region	Parameter, X (unit)	Parameter, Y (unit)	Input data range	Minimum risk decision maker U.S. launch policy cost impact estimating relationship (FY99$M)	SEE (%)	R^2
Low Earth Orbit	Space system mass per orbital plane (kg)	Number of orbital planes (number)	X: 50 – 10,000 Y: 1 – 6	$Y(5.613533\,X^{0.4061} - 3.646785\,X^{0.50443})$	5	.69
Medium Earth Orbit	Space system mass per orbital plane (kg)	Number of orbital planes (number)	X: 50 – 10,000 Y: 1 – 6	$Y(5.822853\,X^{0.49754} - 8.229456\,X^{0.43978})$	1	.69
Geo-stationary Earth Orbit	Space system mass per orbital plane (kg)	Number of orbital planes (number)	X: 250 – 10,000 Y: 1	$Y(1.222979\,X^{0.62917} - 0.452867\,X^{0.7504})$	2	.79

As seen in Figure 5-17 for a minimum risk decision maker, there are altitude regions that have impacts for certain mass ranges and no impacts for other mass ranges. The GEO altitude region exhibits this behavior. For masses per plane below approximately 4000kg, there is a cost impact associated with the restrictive U.S. launch vehicle policy. The magnitude of this impact decreases with increasing mass. After 4000kg in the GEO altitude region, there is no cost impact. MEO altitude region architectures begin to exhibit a cost impact above approximately 500kg per plane. LEO altitude region architectures do not exhibit a significant cost impact from the restrictive U.S. launch policy.

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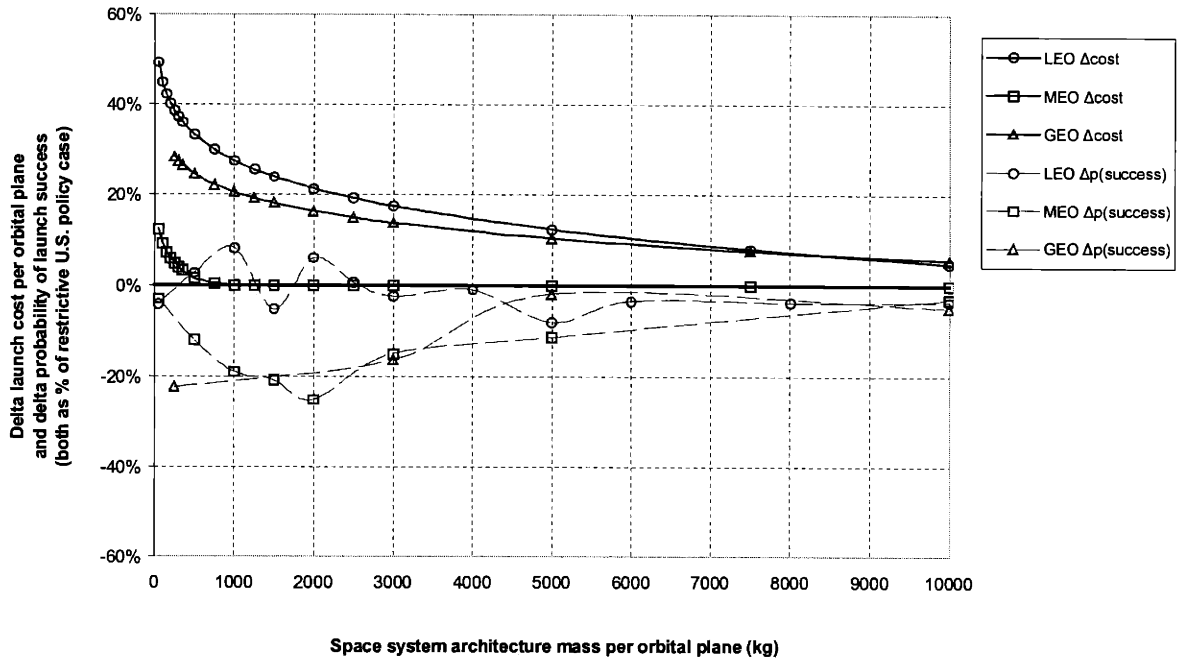Space system architecture mass per orbital plane (kg)

Figure 5-17. Cost and probability of success impacts of the 1994 U.S. space transportation policy on a minimum risk decision maker. Cost impact curves use estimating relationships in Table 5-12 and are shown above for a 1-plane space system architecture. Probability of success impact curves are a 50-sample moving average for LEO architectures of increasing mass, a 25-sample moving average for MEO architecture of increasing mass, and a 10-sample moving average for GEO architectures of increasing mass.

Figure 5-18, Figure 5-19, and Figure 5-20 present descriptive statistics and histograms of LEO, MEO, and GEO architectures, respectively, for a minimum risk decision maker. The LEO delta launch probability of success ranges from –62% to 13%, with a mean of –8%. The histogram shows a large reading near zero, and then smaller readings off to the left (negative) direction. The MEO delta launch probability of success ranges from –75% to 12%, with a mean of –2%. This histogram also shows a large reading near zero, but then exhibits more positive delta probability of success values. The GEO delta launch probability of success ranges from –69% to 6%, with a mean of –12%. Its histogram reflects this with larger frequencies appearing in the left (negative) half of the graph.

So on average for the minimum risk decision maker, the GEO architectures tend to see the largest risk impact from the restrictive U.S. launch policy. The LEO architectures tend to see a lesser, but still material, impact. And the MEO architectures see a very small risk impact.

LEO Delta launch probability of success (in %) for a minimum risk decision maker	Statistic	Std. Error
Mean	-8.21	0.39
95% Confidence Interval for Mean		
Lower Bound	-8.97	
Upper Bound	-7.45	
5% Trimmed Mean	-6.01	
Median	0.00	
Variance	3.25	
Std. Deviation	18.03	
Minimum	-62.13	
Maximum	13.44	
Range	75.56	
Interquartile Range	4.45	
Skewness	-207.29	5.26
Kurtosis	286.01	10.52
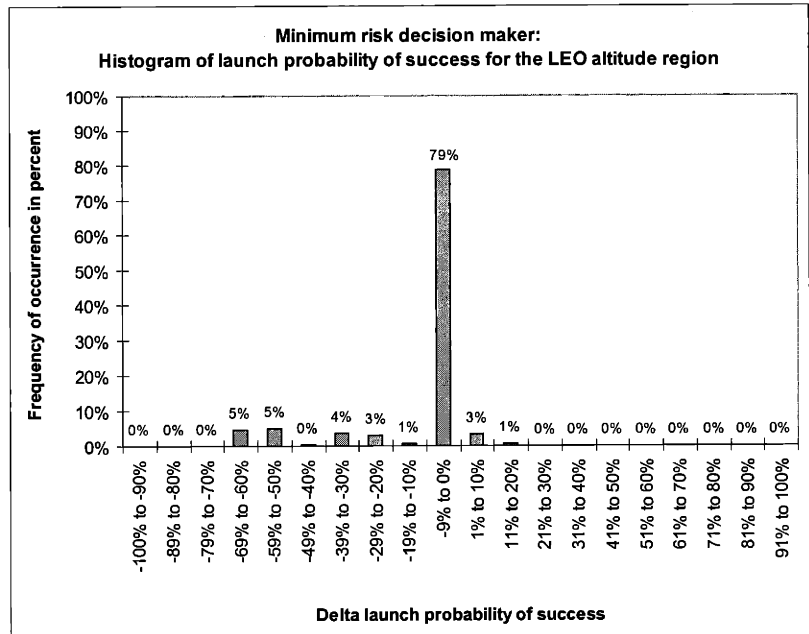
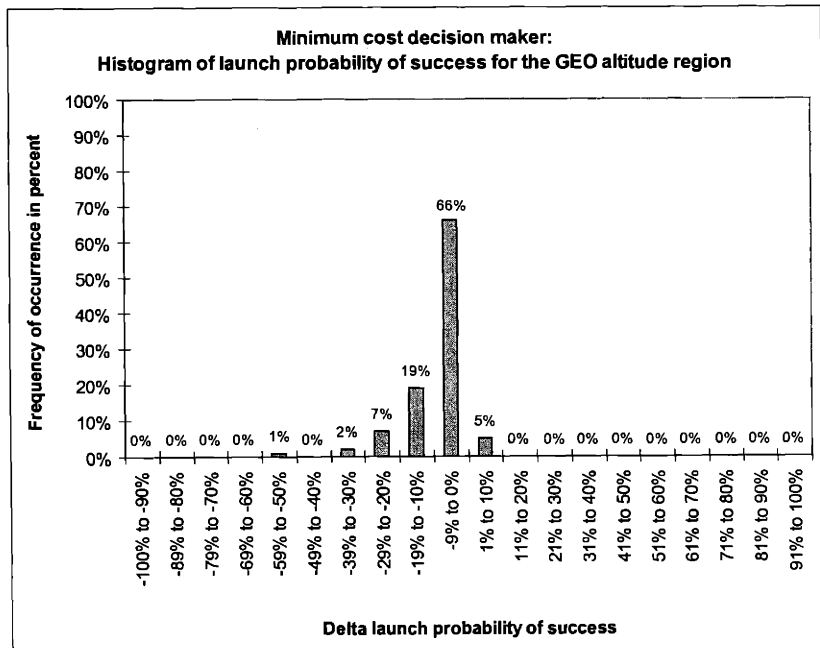

Figure 5-18. Descriptive statistics and histogram for LEO probability of success impacts of the 1994 U.S. space transportation policy on a minimum risk decision maker.

MEO Delta launch probability of success (in %) for a minimum risk decision maker	Statistic	Std. Error
Mean	-2.40	0.34
95% Confidence Interval for Mean		
Lower Bound	-3.06	
Upper Bound	-1.74	
5% Trimmed Mean	-0.73	
Median	0.00	
Variance	1.12	
Std. Deviation	10.59	
Minimum	-75.20	
Maximum	12.38	
Range	87.58	
Interquartile Range	0.00	
Skewness	-398.66	7.78
Kurtosis	1795.55	15.55
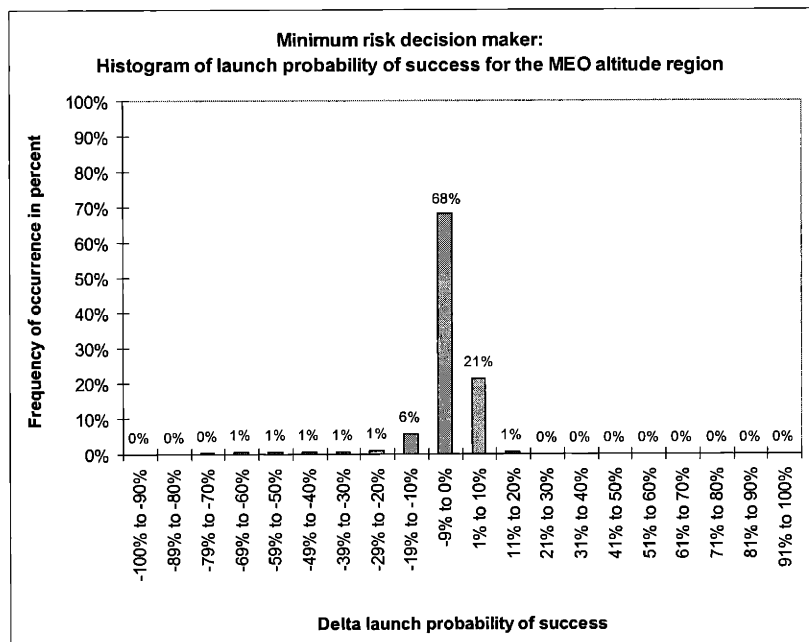
Figure 5-19. Descriptive statistics and histogram for MEO probability of success impacts of the 1994 U.S. space transportation policy on a minimum risk decision maker.

GEO Delta launch probability of success (in %) for a minimum risk decision maker	Statistic	Std. Error
Mean	-11.83	1.76
95% Confidence Interval for Mean		
Lower Bound	-15.32	
Upper Bound	-8.34	
5% Trimmed Mean	-9.97	
Median	-0.97	
Variance	3.09	
Std. Deviation	17.58	
Minimum	-69.04	
Maximum	5.84	
Range	74.88	
Interquartile Range	17.58	
Skewness	-162.31	24.14
Kurtosis	197.25	47.83

Minimum risk decision maker:
Histogram of launch probability of success for the GEO altitude region

(Frequency of occurrence in percent vs. Delta launch probability of success)

-100% to -90%: 0%; -89% to -80%: 0%; -79% to -70%: 0%; -69% to -60%: 2%; -59% to -50%: 5%; -49% to -40%: 4%; -39% to -30%: 2%; -29% to -20%: 2%; -19% to -10%: 31%; -9% to 0%: 47%; 1% to 10%: 7%; 11% to 20%: 0%; 21% to 30%: 0%; 31% to 40%: 0%; 41% to 50%: 0%; 51% to 60%: 0%; 61% to 70%: 0%; 71% to 80%: 0%; 81% to 90%: 0%; 91% to 100%: 0%
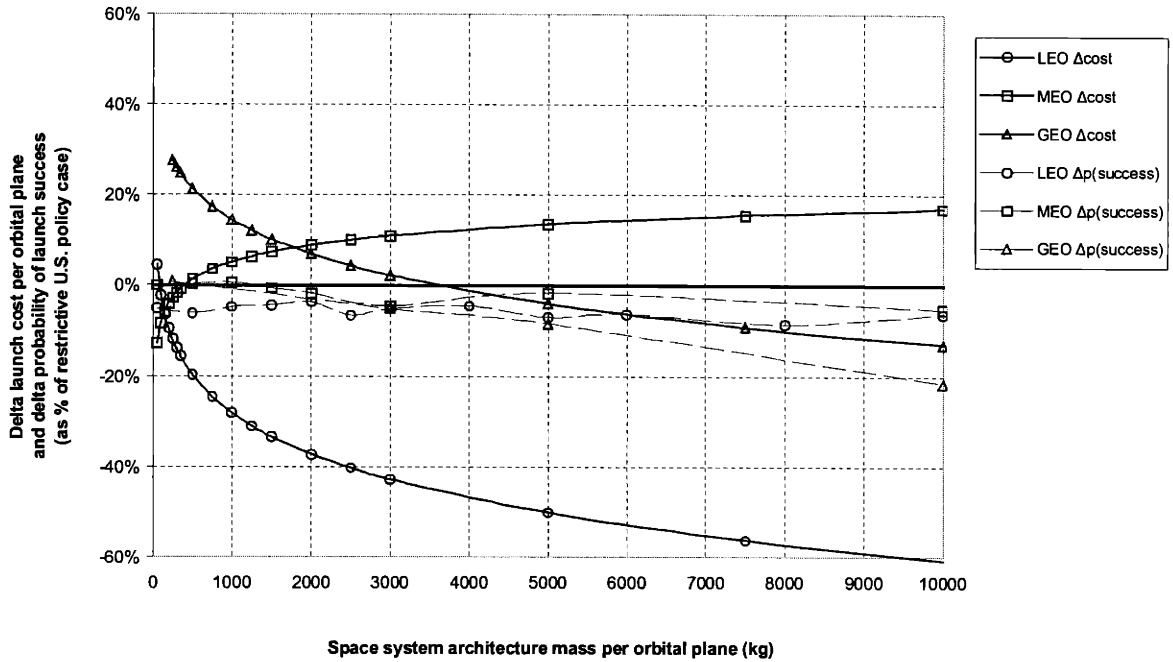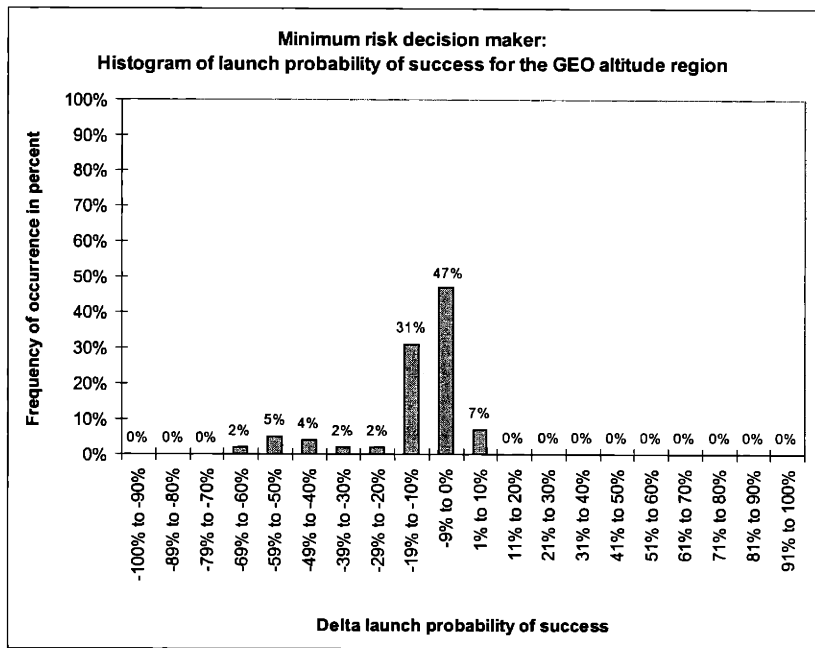
Figure 5-20. Descriptive statistics and histogram for GEO probability of success impacts of the 1994 U.S. space transportation policy on a minimum risk decision maker.

In summary, there appears to be on average a risk impact to minimum risk decision makers who must adhere to the U.S. restrictive launch policy. At some altitude regions, there is also a cost impact. GEO architecture have the largest risk impacts, as well as exhibiting cost impacts for masses under 4000kg. MEO architectures have the smallest risk impacts, but nearly all masses exhibit cost impacts. Lastly, LEO architectures have a large risk impact, but no not suffer a cost impact.

5.7.5. Balance cost and risk decision maker results

The cost impact estimating relationships for a minimum risk decision maker are shown in Table 5-13, and a graph of these relationships is shown for the 1-plane space system architecture case in Figure 5-21. Also shown in Figure 5-21 is a moving average of the delta launch probability of success.

Table 5-13. Balance cost and risk decision maker: Cost impact estimating relationships for using U.S.-only launch vehicles.

Orbital altitude region	Parameter, X (unit)	Parameter, Y (unit)	Input data range	Balance cost and risk decision maker U.S. launch policy cost impact estimating relationship (FY99$M)	SEE (%)	R^2
Low Earth Orbit	Space system mass per orbital plane (kg)	Number of orbital planes (number)	X: 50 – 10,000 Y: 1 – 6	$Y(2.466295\, X^{0.51172} - 1.746457\, X^{0.53137})$	4	.64
Medium Earth Orbit	Space system mass per orbital plane (kg)	Number of orbital planes (number)	X: 50 – 10,000 Y: 1 – 6	$Y(10.313407\, X^{0.37346} - 6.681547\, X^{0.43621})$	6	.67
Geo-stationary Earth Orbit	Space system mass per orbital plane (kg)	Number of orbital planes (number)	X: 250 – 10,000 Y: 1	$Y(0.62214\, X^{0.67826} - 0.260075\, X^{0.76646})$	1	.93

As seen in Figure 5-21 for a balance cost and risk decision maker, there is an altitude region that has cost impacts for certain mass ranges and no cost impacts for other mass ranges. The MEO altitude region exhibits this behavior. For masses per plane below approximately 1000kg, there is a cost impact associated with the restrictive U.S. launch vehicle policy. The magnitude of this impact decreases with increasing mass. After 1000kg in the MEO altitude region, there is no cost impact. For LEO and GEO architectures, all masses exhibit cost impacts from the restrictive U.S. launch policy that decrease with increasing mass per plane.

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Space system architecture total mass (kg)

Figure 5-21. Cost and probability of success impacts of the 1994 U.S. space transportation policy on a balance cost and risk decision maker. Cost impact curves use estimating relationships in Table 5-13 and are shown above for a 1-plane space system architecture. Probability of success impact curves are a 50-sample moving average for LEO architectures of increasing mass, a 25-sample moving average for MEO architecture of increasing mass, and a 10-sample moving average for GEO architectures of increasing mass.

Figure 5-22, Figure 5-23, and Figure 5-24 present descriptive statistics and histograms of LEO, MEO, and GEO architectures, respectively, for a balance cost and risk decision maker. The LEO delta launch probability of success ranges from –72% to 89%, with a mean of 3%. The histogram shows a large reading near zero, and then smaller readings off to both the left (negative) and right (positive) directions. The MEO delta launch probability of success ranges from –11% to 67%, with a mean of 0%. This histogram also shows the largest frequency reading near zero of all the altitudes and decision makers examined so far. The GEO delta launch probability of success ranges from –36% to 31%, with a mean of –2%. Its histogram reflects this with larger frequencies appearing in the left (negative) half of the graph.

So on average for the balance cost and risk decision maker, the LEO and MEO architecture exhibit not risk impact from the restrictive U.S. launch policy. The GEO architectures see a very small risk impact.

LEO Delta launch probability of success (in %) for a balance cost and risk decision maker	Statistic	Std. Error
Mean	3.13	0.55
95% Confidence Interval for Mean		
Lower Bound	2.04	
Upper Bound	4.21	
5% Trimmed Mean	2.53	
Median	0.00	
Variance	6.59	
Std. Deviation	25.67	
Minimum	-72.12	
Maximum	89.07	
Range	161.19	
Interquartile Range	5.05	
Skewness	70.67	5.26
Kurtosis	237.10	10.52

Balance cost and risk decision maker:
Histogram of launch probability of success for the LEO altitude region
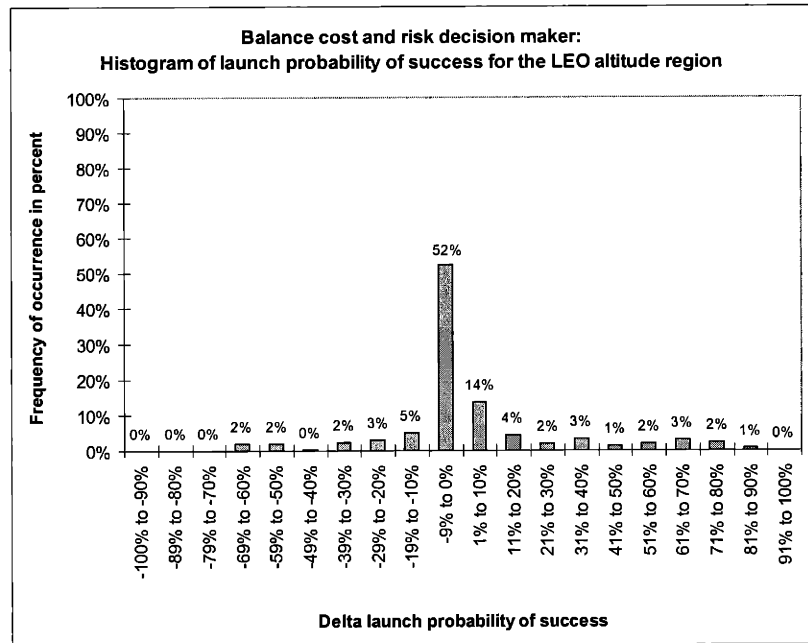
Figure 5-22. Descriptive statistics and histogram for LEO probability of success impacts of the 1994 U.S. space transportation policy on a balance cost and risk decision maker.

MEO Delta launch probability of success (in %) for a balance cost and risk decision maker	Statistic	Std. Error
Mean	0.14	0.09
95% Confidence Interval for Mean		
Lower Bound	-0.05	
Upper Bound	0.33	
5% Trimmed Mean	0.00	
Median	0.00	
Variance	0.09	
Std. Deviation	2.98	
Minimum	-11.07	
Maximum	67.14	
Range	78.20	
Interquartile Range	0.00	
Skewness	1819.60	7.78
Kurtosis	37149.32	15.55

Balance cost and risk decision maker:
Histogram of launch probability of success for the MEO altitude region
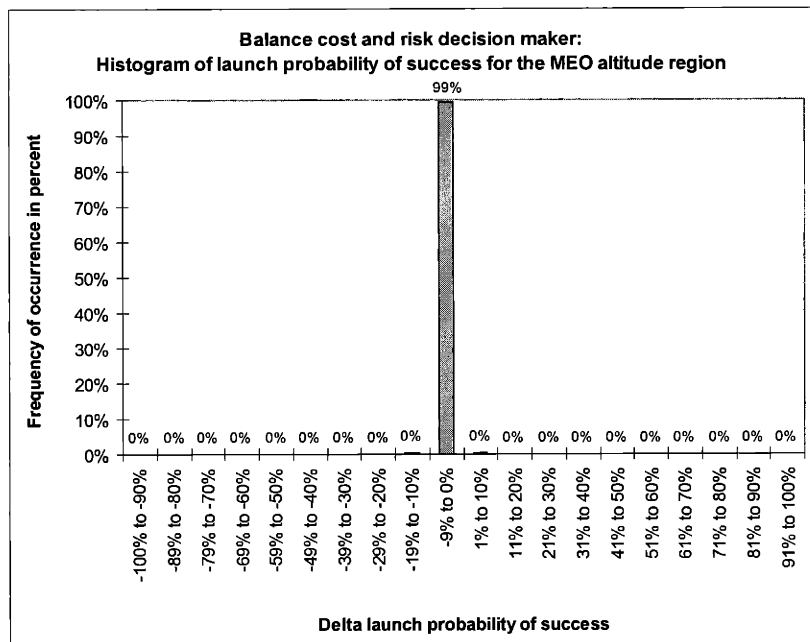
Figure 5-23. Descriptive statistics and histogram for MEO probability of success impacts of the 1994 U.S. space transportation policy on a balance cost and risk decision maker.

GEO Delta launch probability of success (in %) for a balance cost and risk decision maker	Statistic	Std. Error
Mean	-1.92	1.04
95% Confidence Interval for Mean		
Lower Bound	-3.98	
Upper Bound	0.14	
5% Trimmed Mean	-1.91	
Median	0.00	
Variance	1.08	
Std. Deviation	10.38	
Minimum	-36.00	
Maximum	31.00	
Range	67.00	
Interquartile Range	1.00	
Skewness	-16.90	24.14
Kurtosis	366.92	47.83

Balance cost and risk decision maker:
Histogram of launch probability of success for the GEO altitude region

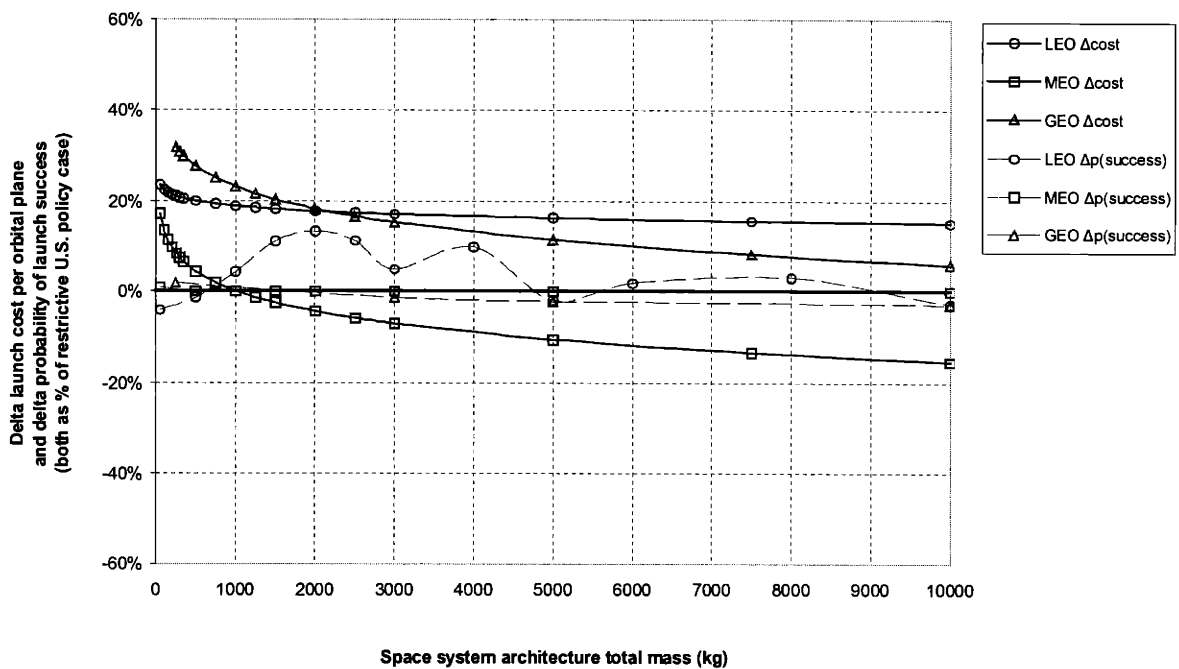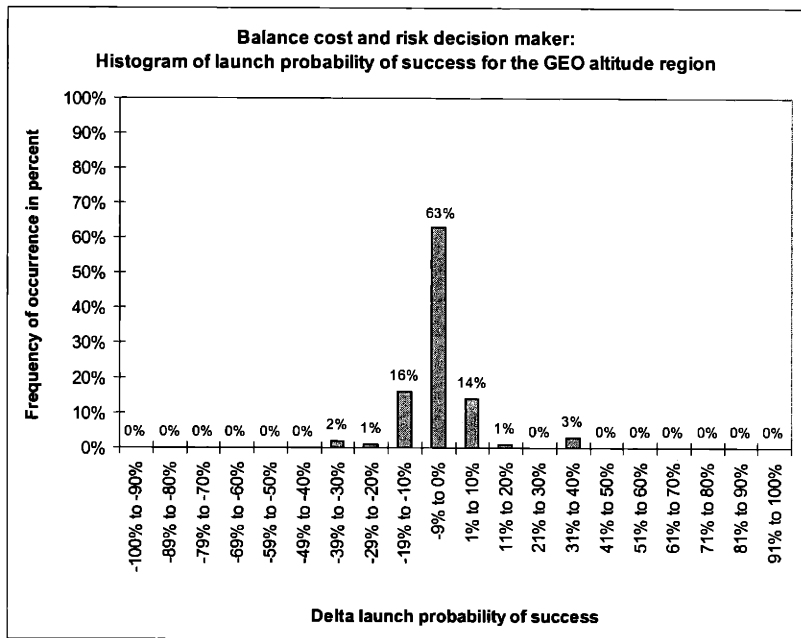Figure 5-24. Descriptive statistics and histogram for GEO probability of success impacts of the 1994 U.S. space transportation policy on a balance cost and risk decision maker.

In summary, there appears to be on average a cost impact for most altitude regions to balance cost and risk decision makers who must adhere to the U.S. restrictive launch policy. At some altitudes, there is also on average a very small risk impact. LEO architectures exhibit the most persistent cost impacts throughout the range of mass, yet they have no risk impact on average. GEO architectures exhibit a cost impact throughout the mass range, and they experience a very small risk impact. MEO architectures experience a cost impact below 1000kg per plane, but do not exhibit any risk impacts on average.

5.7.6. Summary of impacts

Table 5-14 shows a convenient summary of the cost and risk impacts of the U.S. Space Transportation Policy of 1994 for each decision maker type in each orbital altitude region. The cost impact range is shown, along with the risk impact range and average.

Table 5-14. Summary table of cost and risk impacts from the U.S. Space Transportation Policy of 1994 for all decision maker types and orbit altitude regions.

	Minimum Cost Decision Maker	Minimum Risk Decision Maker	Balance Cost and Risk Decision Maker
Low Earth Orbit (LEO)	Cost impact: *Range*: 49% to 5% Risk impact: *Range*: -86% to 76% *Average*: -1%	Cost impact: *Range*: 5% to 0% Risk impact: *Range*: -62% to 13% *Average*: -8%	Cost impact: *Range*: 24% to 15% Risk impact: *Range*: -72% to 89% *Average*: 3%
Medium Earth Orbit (MEO)	Cost impact: *Range*: 12% to 0% Risk impact: *Range*: -86% to 0% *Average*: -12%	Cost impact: *Range*: 17% to 0% Risk impact: *Range*: -75% to 12% *Average*: -2%	Cost impact: *Range*: 17% to 0% Risk impact: *Range*: -11% to 67% *Average*: 0%
Geostationary Earth Orbit (GEO)	Cost impact: *Range*: 37% to 6% Risk impact: *Range*: -52% to 5% *Average*: -6%	Cost impact: *Range*: 40% to 0% Risk impact: *Range*: -69% to 6% *Average*: -12%	Cost impact: *Range*: 41% to 6% Risk impact: *Range*: -36% to 31% *Average*: -2%

5.7.7. Applying the cost impact estimating relationships

System architects can apply these cost impact estimating relationships during conceptual design to generate rough estimates of how the restrictive U.S. launch policy impacts architectures under consideration. This knowledge can help discriminate between two architectures that otherwise meet the same technical performance level. If two similar performing architectures are found to have very different launch cost impacts, the system architect might choose to go with the one that has less of a cost impact.

But what if all the architecture candidates under consideration are adversely impacted by the restrictive U.S. launch policy? There are several options that might be explored, and these options are ways that might permit an architecture from being subject to the U.S. launch policy. These alternatives to being subject to the restrictive launch policy are more likely to be successfully implemented on a small or low profile mission than a large and highly visible one.

One option would be to seek international partners for the mission. In a situation where an international partner is contributing a payload or otherwise participating in the design and operation of the mission, that partner might also be able to provide the launch services as well. The division of tasks and responsibilities of each international partnering mission usually has to be

vetted and approved with the sponsoring agency. But if the launch cost penalties are high enough, the sponsoring agency might see justification in an international arrangement.

A second option would be to entirely change the acquisition approach to the mission. The traditional way to accomplish a mission is for an agency to procure, launch, own and operate a satellite. A new way is to procure the service that that satellite would be providing, and have a commercial company own and operate the satellite. By procuring a service instead of a system, the satellite that is used to accomplish the mission is no longer subject to the restrictive U.S. launch policy.

From examining the cost impact graphs in Figure 5-13, Figure 5-17, Figure 5-21, most combinations of mission orbit regions and program decision makers will incur cost impacts under the restrictive U.S. launch policy and may want to pursue some of the options discussed above. The combinations that would not be likely to incur cost increases and, hence, not be likely to pursue these options are:

- LEO missions with minimum risk decision makers.
- MEO missions with minimum risk decision makers, and MEO missions with mass per plane greater than 1000kg for minimum cost and balance cost and risk decision makers.
- GEO missions with a mass per plane greater than 4000kg for a minimum risk decision maker.

From examining the nine sets of histograms and descriptive statistics for the delta launch probability of success, we see that the restrictive U.S. launch policy causes increased launch risk ranging on average from 1% to 13%. The only combinations of mission orbit regions and program decision makers that will not, on average, experience any risk increase are LEO and MEO architectures for a balance cost and risk decision maker. All other combinations of decision makers and altitude regions will experience some risk impact on average, and might wish to pursue options to remove the policy restrictions from an architecture as indicated above.

5.8. Epilogue: Calculating the economic cost of launch policy

Using the cost impact estimating relationships derived in the previous section, we can compute the economic cost of the U.S. Space Transportation Policy of 1994. In other words, we can compute how much cost the government has incurred by having the policy in place. Conceptually, this economic cost is easy to understand. It is the difference in costs between a restrictive and unrestrictive launch policy for all satellites launched during the policy's lifetime that were subject to the restrictive policy.

We compute the difference in costs by applying the cost impact estimating relationships for the three orbital altitudes and the three types of decision makers to all U.S. government payloads launched since the inception of the restrictive launch policy. Government payloads include those from NASA, the Department of Defense and military services, the National Oceanic and Atmospheric Agency, the Department of Energy, and all other U.S. government agencies. Only unmanned spacecraft destined for low, medium or geostationary Earth orbit were included in the economic cost calculations, because those are the orbital altitudes for which cost impact equations were derived. The only payloads thus excluded were NASA human spaceflights, NASA

interplanetary space probes, and certain space science satellites operating at high earth orbit and beyond.

The risk impacts of the policy were computed by applying the appropriate average delta probability of success determined in the previous section for an altitude region and decision maker to each satellite launched since the inception of the policy. An average of these risk impacts was then taken to determine the average delta probability of success impact per launch since the inception of the policy.

The summary of the impacts of the U.S. Space Transportation Policy of 1994 is shown in Table 5-15. These impacts are presented for each type of decision maker. While in reality there was probably a mix of the three types of decision making going on, there is no base of information available on which to make an accurate judgment as to which type of decision maker each spacecraft represented. Thus, the results below are presented as if all spacecraft followed the followed the objective function of the same type of decision maker. This represents several ends of the spectrum along which the real cost and risk impacts likely lie.

Table 5-15. The economic cost impact and risk impact of the restrictive U.S. launch policy.

	Minimum cost decision maker	Minimum risk decision maker	Balance cost and risk decision maker
Impact summary for years 1995 - 2001	$1.7 billion cost impact	8.72% increase in probability of launch failure	$1.69 billion cost impact 1% increase in probability of launch success

If all spacecraft utilized a minimum cost decision making strategy, the restrictive U.S. launch policy would cost the nation $243M per year, or a total of $1.7B since the policy's inception. Since money is the important metric to a minimum cost decision maker, we state the impacts for that decision maker in terms of money. Since risk is the important metric to a minimum risk decision maker, we state the impacts for the decision maker in terms of increased probability of launch failure. If all spacecraft used a minimum risk decision making strategy, the restrictive U.S. launch policy would cost the nation an 8.72% increase in probability of launch failure per spacecraft launched. To put this another way, over the long run under this restrictive policy, the U.S. might reasonably expect to lose 8 out of every 100 launches. This is not an insignificant risk impact. So in summary, both the minimum cost and minimum risk decision-making strategies have suffered large impacts under the restrictive U.S. launch policy.

If all spacecraft utilized a balance cost and risk decision making strategy, the restrictive U.S. launch policy would cost the nation $241M per year, or a total of $1.69B since the policy's

inception. The small amount of good news is that this decision making strategy under the restrictive launch policy results in a 1% increase in probability of launch success. But the questions is certainly up for debate on whether the $1.69B expended by the U.S. is worth only a 1% increase on average in launch probability of success.

Prior to this research work, the costs of the launch policy for U.S. government payloads on the whole were largely notional. Specific situations for specific programs were likely evaluated, but no coherent parametric relationships existed for estimating the cost impacts. Knowing the economic cost of the policy informs the policy debate. When quantifiable costs and risks can be assigned to the policy, policy makers can decide if its benefits are worth its costs.

5.9. Conclusions

This chapter presented an analysis method for examining the cost and risk impacts of the U.S. Space Transportation Policy of 1994, and applied this in two situations. First, the B-TOS mission provided the setting for exploring the analysis as applied to one specific mission. Then, the analysis was broadened to include a representative "universe" of space system architectures. From this "universe" analysis, general cost impact estimating relationships were derived to enable space system architects to gauge the cost impacts of the launch policy very early during conceptual design.

From the system architects' point of view, analyzing the cost of launch policy for their architectures has the potential to motivate the very design of an architecture concept. As discussed above, if the cost impact of the U.S. launch policy is calculated to be very large during conceptual design, the system architect has several alternatives. The system could be re-architected to arrive at a concept that does not incur large cost impacts under the U.S. launch policy. Or, the system could be re-architected so that it is no longer subject to the restrictive U.S. launch policy. Options in the vein include international collaboration, or alternative acquisition strategies such as procuring services instead of systems.

From the policy makers' point of view, analyzing the economic cost of launch policy informs the policy debate. Especially in situations where the benefits are intangible or extremely difficult to measure, as with launch policy, it is important to at least be able to quantify the costs.

QUANTIFYING POLICY EFFECTS II:

BUDGET ADJUSTMENTS

As discussed in Chapter 1 "Breaking the old paradigms: Policy as a dynamic aspect of system architecting and design," budget adjustments are the most frequently reported policy direction 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's budget can – and frequently does – change. For fiscal years 1996-1998, 32% of defense programs experienced a budget reduction, 53% experienced a budget increase and only 15% received the budget they requested. Hence a space system architect can conclude that the probability that the budget will be changed is much larger than the probability that it will stay on the nominal plan. Thus, budget uncertainty is perhaps the most pervasive policy uncertainty facing government and military systems today.

But what are the causes of budget policy instability on complex publicly funded engineered systems? There are three main categories of causes, and they can be present either individually or together. The first cause is the risky technologies that are often necessary for complex engineered systems. These technologies don't always succeed, and when they don't, budgets need to be adjusted for an alternate system plan. The second cause is under budgeting or optimistic budgeting by programs. This results in programs later requesting larger budgets as the real challenges of a complex development program become apparent. The third cause of budget instabilities on a program is the nature of competing stakeholder demands that are balanced and adjudicated through the budget resolution process in Congress each year. Since these demands are constantly evolving, the budget for any given system will be subject to budget instability. While any of these three causes of budget policy instability can occur by itself, it is not uncommon for all three causes to be simultaneous contributing factors.

Given the likelihood of yearly budget adjustments, a vision of what constitutes a policy robust architecture must include robustness to budget instabilities. This chapter explores how space system architects 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. This early understanding of system behavior in response to budget conditions can point out which space system architecture candidates may be more robust than others.

This chapter begins by deriving a basic relationship from historical data relating program schedule extension and resulting program cost change. As downward pressure is applied to a program's yearly budget, its overall length, and hence cost, increases. This is demonstrated on the B-TOS mission as a case example. From this specific example, we move towards a generalized mathematical description of what is taking place as regards a space system's cost and program mortality as a result of this downward pressure on yearly program budget levels. We find 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 derive mathematical expressions indicating stage transition points. Each of these three stages of behavior indicates a different level of space system architecture robustness to policy involving annual budget levels. In addition, each stage of behavior implicitly contains different feedback messages for the system architect.

6.1. Augustine's relationships

Norman Augustine, former aerospace industry executive and professor at Princeton University, generated 52 laws describing many aspects of aerospace systems. Of particular interest to this research are Laws XXIV and XLVI.

Law XXIV includes data that relates schedule increases on aerospace and defense programs to resulting program cost increases. This data is plotted in Figure 6-1 and used to estimate a linear relationship between the two variables of schedule increase and cost increase:

$$y = 0.24x + 1.7$$

Eq. 6-1

where y = % total program cost change and x = % total program schedule change.

Schedule and Cost Changes
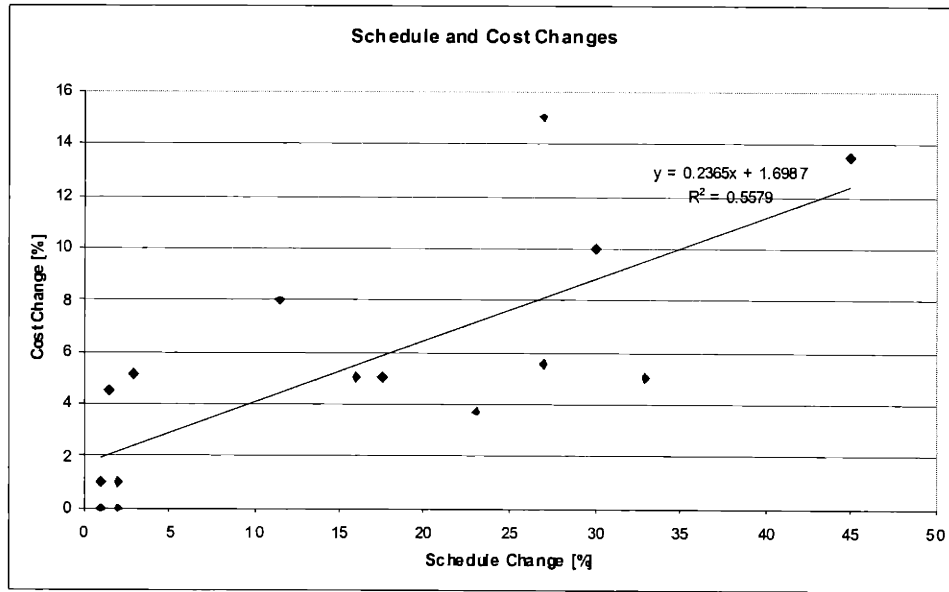
Figure 6-1.   Data relating the impact of aerospace and defense program schedule changes on program cost.[50]

Law XLVI describes a program's mortality expectation as a function of its time in existence. Government program budgets are voted upon many times each year, and each vote is an opportunity for opponents of the program to cancel it. Thus, the longer a program is in existence, the more times its budget is voted upon, and the greater the cumulative probability that it will be cancelled. Figure 6-2 shows the resulting program mortality relationship derived from over 300 significant projects conducted by the U.S. government during the 1970s and 1980s. "The data reveal the probability that any given project will fail to survive the threats to its existence which arise prior to any given year in its lifetime. It is seen that there is about a 4% probability of cancellation of a program each and every year except for the first year, sometimes referred to as the honeymoon. ... This appears to be relatively independent of program maturity.[51]" The mortality relationship can be written as

$$m = 4.4(t\text{-}1)$$

Eq. 6-2

where m = cumulative probability of program cancellation and t = program age in years.

[50] Augustine, Norman R. (1986). *Augustine's laws*. New York, Viking.

[51] Augustine, Norman R. (1986). *Augustine's laws*. New York, Viking.
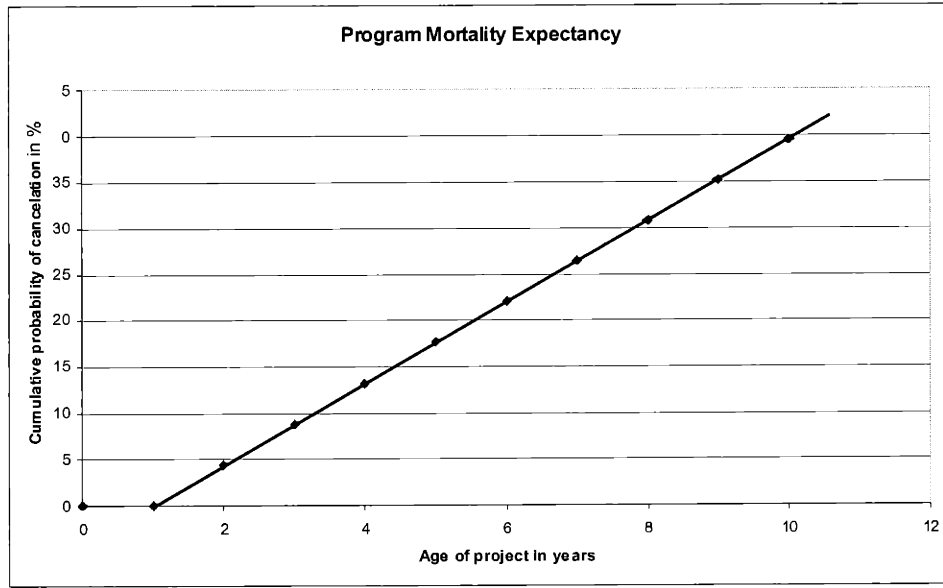
Figure 6-2.   Development program mortality expectancy as a function of the age of a program.[52]

6.2. Downward annual budget pressure effects: B-TOS case example

As downward pressure is applied to a space system program annual budget, the program schedule is stretched out and the program's mortality is increased.   For example, a $500M program, originally planned and scheduled to last 5 years at an annual funding level of $100M, is now subjected to an annual budget of $80M. This will require the program to extend its schedule an additional 1.25 years. But as Augustine points out, this schedule change does not come without a cost. The resulting cost increase from that schedule increase is represented by Law XXIV, which amounts to $38.5M. Recent experience of senior decision makers, however, suggests that current programs may be more adversely affected by schedule extensions, and that Augustine's Law XXIV might now be best considered as a lower bound to program cost increases.   Current government decision makers use a rule of thumb of three to fives times the budget cut amount as the additional program expense that will be incurred as a results.[53]

In addition to the cost increase, the program will experience an increase in cumulative probability of cancellation, also called mortality expectancy, of 5% (as represented by Law LXVI).

The B-TOS mission, a distributed small satellite system in low earth orbit performing ionospheric mapping, was first presented in Chapter 5 "Quantifying policy effects I: U.S. Space Transportation Policy of 1994." B-TOS is used to illustrate the effects of downward pressure on

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[52] Augustine, Norman R. (1986). *Augustine's laws*. New York, Viking.

[53] Conversation with senior government decision maker, May 2002.

annual budgets created by U.S. Congressional policy budget adjustments. Both cost effects and mortality effects are examined.

6.2.1. Cost effects

Figure 6-3 through Figure 6-10 show the B-TOS architecture candidates plotted in cost-utility space. The solid diamonds represent the B-TOS architectures under their original planned annual budgets, and the open squares represent the same B-TOS architectures under a specific annual budget level that varies between the figures. In this analysis, all aspects of the architectures were kept constant besides program cost. The baseline original planned development duration for B-TOS was three years, and a constant spending profile was assumed. Table 6-1 shows the nominal total spacecraft costs for each Pareto front architecture, labeled A, B, C, D, and E.

Table 6-1. Nominal total spacecraft costs for B-TOS Pareto front architectures.

Pareto Optimal Frontier Architecture	Total spacecraft cost ($M)
Architecture A	56
Architecture B	83
Architecture C	110
Architecture D	126
Architecture E	241

Figure 6-3 compares the nominal annual program budget for each B-TOS architecture to a policy-adjusted annual program budget of $100M. Each of the five Pareto front architectures (labeled A, B, C, D, and E for the nominal case and A', B', C', D', and E' for the adjusted budget case when different from the nominal case) are seen to have identical total program costs in both situations. Thus, an annual program budget of $100M will not have a negative impact on costs of the Pareto front architectures. Figure 6-4 shows the effects of an $80M annual program budget. In this case, we see that architecture E has been affected by this level of program budgeting, demonstrated by the increased total cost of the architecture subject to the $80M budget level (labeled as E' on the figure).

Figure 6-3.   B-TOS case study: Comparison of nominal and $100M per year program budget.

Figure 6-4.   B-TOS case study: Comparison of nominal and $80M per year program budget.
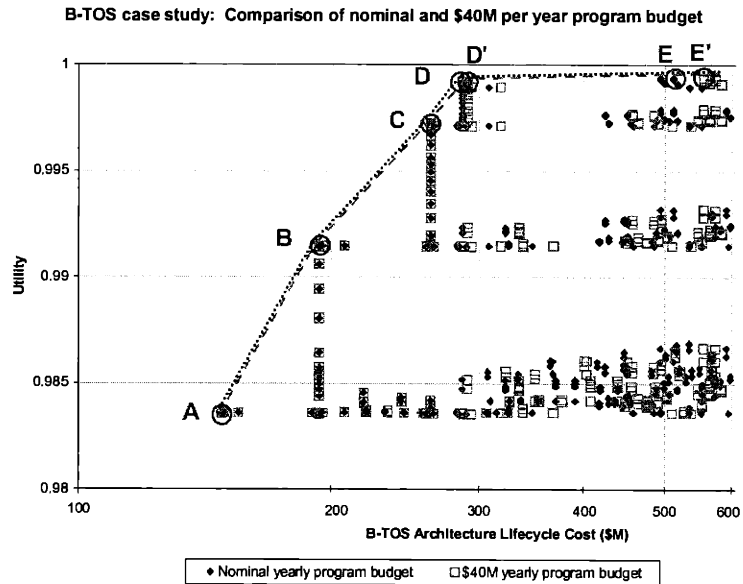
Figure 6-5. B-TOS case study: Comparison of nominal and $40M per year program budget.

As we continue the trend in downward annual budgets, we see that a $40M annual budget negatively impacts the cost of architecture D as well as architecture E (denoted by D' and E' on Figure 6-5). A $35M annual budget, represented in Figure 6-6, increases the total cost of architecture C (represented by C') in addition to architectures D and E. Stepping down further to a $25M annual budget sees a negative cost impact added to architecture B (represented by B' in Figure 6-7). Finally, arriving at an annual budget of $15M sees architecture A, the least expensive of the B-TOS Pareto front architectures, negatively affected by the low annual budget (represented by A' in Figure 6-8). And still lower levels of annual budget at $10M and $5M (shown in Figure 6-9 and Figure 6-10) readily indicate a separation of the Pareto fronts of the nominal case and the adjusted annual budget case.
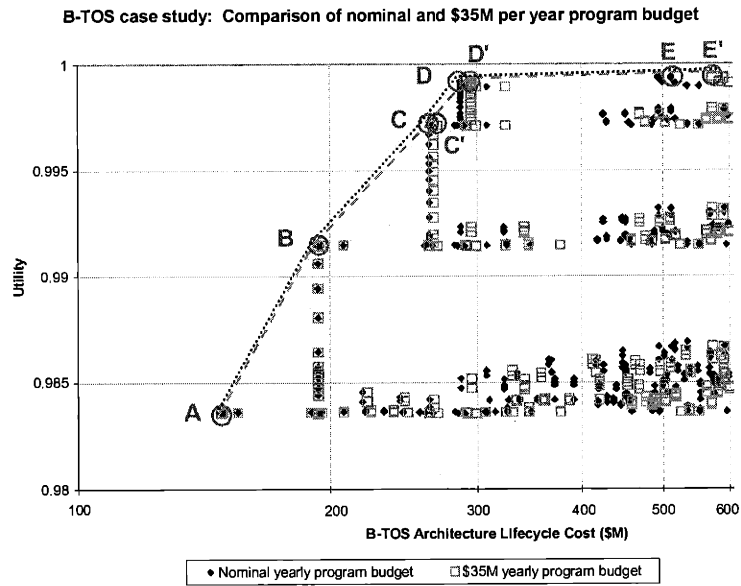
Figure 6-6. B-TOS case study: Comparison of nominal and $35M per year program budget.
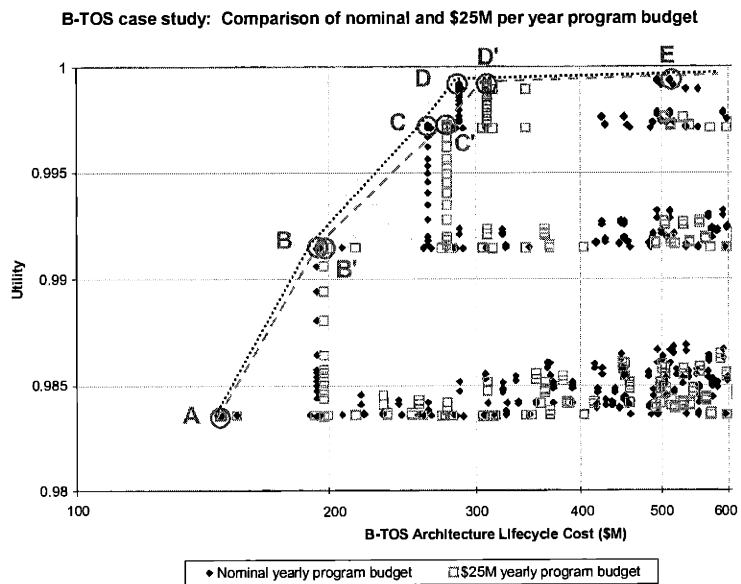
Figure 6-7. B-TOS case study: Comparison of nominal and $25M per year program budget.

B-TOS case study: Comparison of nominal and $15M per year program budget
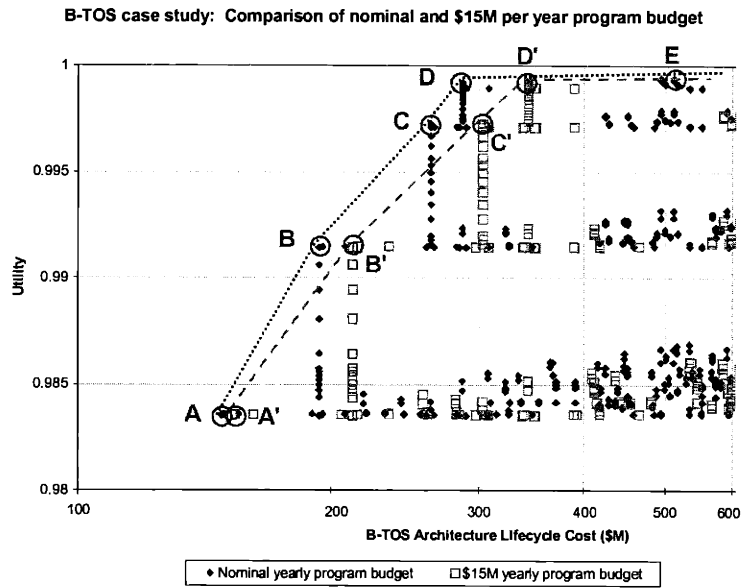
Figure 6-8. B-TOS case study: Comparison of nominal and $15M per year program budget.

B-TOS case study: Comparison of nominal and $10M per year program budget
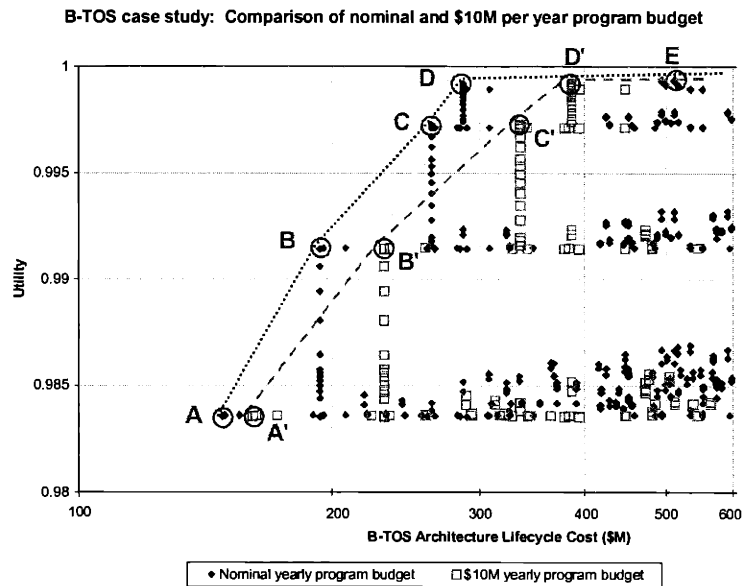
Figure 6-9. B-TOS case study: Comparison of nominal and $10M per year program budget.
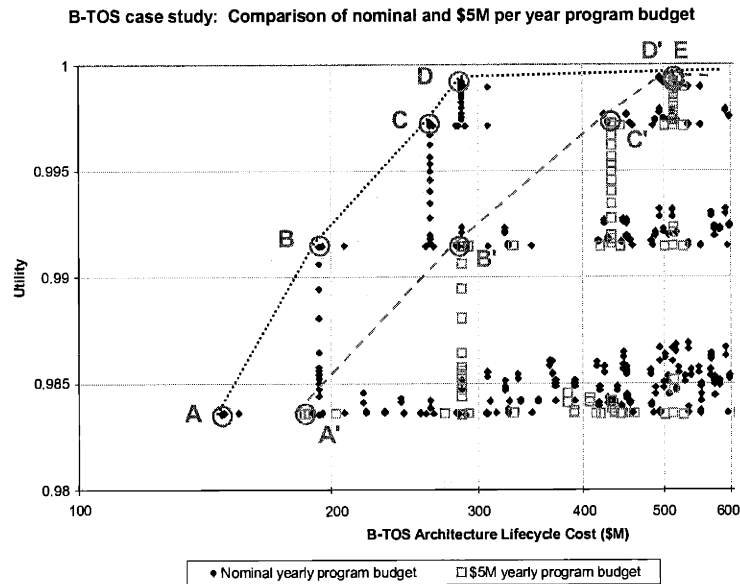
Figure 6-10. B-TOS case study: Comparison of nominal and $5M per year program budget.

6.2.2. Mortality effects

Figure 6-11 shows the increase in cumulative mortality expectancy that results from downward annual budget pressures. Mortality increases begin when the annual program budget allocated by Congress becomes lower than the nominal annual budget required by an architecture candidate. Nominal annual budgets for the five Pareto architectures are approximately: $19M for A, $28M for B, $37M for C, $42M for D, and $80M for E. As seen in the figure, sharp increases in program mortality occur as allocated annual budget levels become significantly lower than nominal annual budget levels.

B-TOS case study: Increase in cumulative probability of program cancellation as a result of downward annual budget pressure for five pareto front architectures
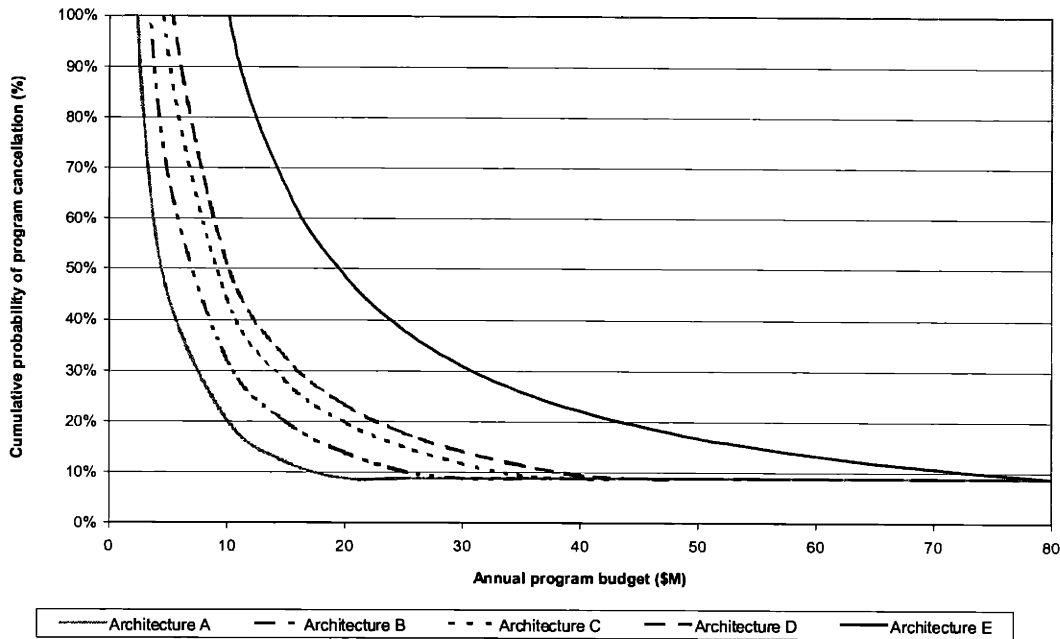
Figure 6-11. B-TOS case study: Increase in cumulative probability of program cancellation as a result of downward annual budget pressure for five Pareto front architectures.

6.3. Generalization of downward annual budget effects

In observing the movement of the nominal and the policy-adjusted budget level Pareto fronts in Figure 6-3 to Figure 6-10, we see that there are three distinct stages of behavior that emerge. One stage is represented by Figure 6-3, where both Pareto fronts overlap. In this stage, which we will call 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 Figure 6-6, where part of the Pareto fronts overlap but other parts are separated. In this stage, which we will call Stage I, some of the Pareto set of architectures are affected by the policy-adjusted annual budget level while others are not. The last stage of behavior is represented by Figure 6-10, where both Pareto fronts have completely separated. In this stage, which we will call Stage II, 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 level pressure is shown in Figure 6-12. 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 architect or program manager is to understand the critical transition points between these stages.
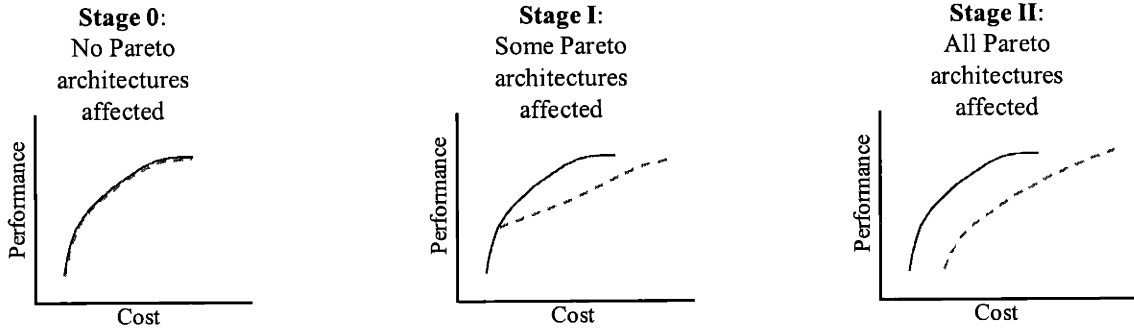
Figure 6-12. Three stages of behavior of the Pareto front set of architectures under downward annual budget level pressure.

6.3.1. Notation

Before we can capture the movement of the Pareto fronts with mathematical relationships and calculate the value of the transition points between the three stages of behavior, it is useful to specify a set of variables.

We first define the acceptable range of performance for a given space system, where p_{max} and p_{min} define the extremes of this acceptable range. We then look at the set of all architectures being considered for a space system. Of those, we will take a subset, i, that lie along the Pareto optimal frontier between p_{max} and p_{min}. This set i is denoted by the solid line in Figure 6-13. c_{max} represents the cost of the architecture in the Pareto optimal set i with performance p_{max}, and c_{min} represents the cost of the architecture in i with performance p_{min}.
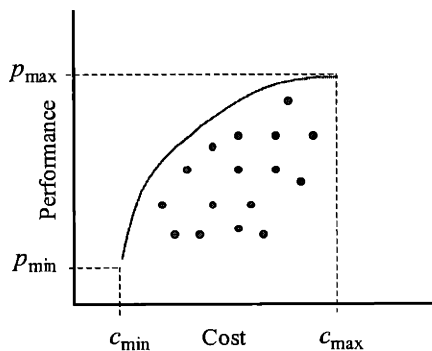
Set of pareto frontier architecture variables:

- p_{max} and p_{min} define the range of acceptable performance for the program

- c_{max} represents the cost of the architecture on the pareto front with p_{max}

- c_{min} represents the cost of the architecture on the pareto front with p_{min}

Figure 6-13. Defining the boundaries of the Pareto optimal frontier set of system architectures.

Additional variables are defined in Figure 6-14, and include variables that describe space system program duration, cost, and mortality under nominal and policy-adjusted annual budget levels. The variable b_i represents the policy-adjusted annual program budget level for architecture i.

Policy-adjusted annual budget variable:

b_i = policy-adjusted annual budget level on architecture i ($/year)

Initial program variables:

c_i = initial total program cost for architecture i ($)

d_i = initial total development duration for architecture i (years)

m_i = initial total program mortality expectancy for architecture i (probability)

i = set of all architectures lying on the pareto front between p_{max} and p_{min}

Altered program variables under policy-adjusted annual budget:

Δc = program cost increase under policy-adjusted annual budget ($)

c_i' = total program cost for architecture i under policy-adjusted annual budget adjustment ($)

Δd = program development duration increase under policy-adjusted annual budget (years)

d_i' = total program development duration for architecture i under policy-adjusted annual budget (years)

Δm = program mortality increase under policy-adjusted annual budget (probability)

m_i' = total program mortality expectancy for architecture i under policy-adjusted annual budget (probability)

Figure 6-14. Nominal and policy-adjusted budget variable notations.

6.3.2. General relationships

Employing the notation just laid out, and beginning with Augustine's Laws XXIV and LXVI, we can create general mathematical relationships that describe the association between annual program budget levels, program durations, program costs, and program mortality for large government programs. These equations are shown in Figure 6-15.

The basic schedule extension and resulting cost change relationship was presented earlier in this Chapter as Eq. 6-1 and forms the basis for the cost relations. The transformation is shown from Eq. 6-1 to the cost relations by substituting in a program duration based on total program cost and allocated annual budget level. The cumulative mortality expectancy described in Eq. 6-2 is the basis for the mortality relations.

**Basic schedule extension and resulting
cost change relationship:**
$$y = 0.24x + 1.7$$
where y = % cost change,
and x = % schedule change

$$x = \Delta d/d_i = 100(c_i/b_i - d_i)/d_i = 100(c_i/b_id_i - 1)$$
$$y = 24(c_i/b_id_i - 1) + 1.7$$

Duration relations:

$d_i' = c_i/b_i$ $\qquad\qquad\qquad \Delta d = c_i/b_i - d_i$

Cost relations:

$c_i' = c_i[0.24(c_i/b_id_i - 1) - 0.777]$ $\qquad \Delta c = c_i[0.24(c_i/b_id_i - 1) + .017]$

Mortality relations:

$m_i = 4.4(d_i - 1)$ $\qquad \Delta m = 4.4(c_i/b_i - d_i)$ $\qquad m_i' = 4.4(d_i' - 1)$

Figure 6-15. Annual budget adjustment relationships.

6.3.3. Critical transition point values

Figure 6-16 shows the three stages of Pareto front behavior under downward annual budget pressure, along with transition point values between the Stages and how key variables behave in each Stage.

The transition from Stage 0 to Stage I occurs at

$$b_{cvI} = \frac{c_{max}}{d_{max}}$$

Eq. 6-3

where b_{cvI} is the critical transition value from Stage 0 to Stage I, c_{max} is the cost of the architecture in the Pareto optimal set i with performance p_{max}, and d_{max} is the duration of the architecture in i with performance p_{max}.

The transition from Stage I to Stage II occurs at

$$b_{cvII} = \frac{c_{min}}{d_{min}}$$

Eq. 6-4

where b_{cvII} is the critical transition value from Stage I to Stage II, c_{min} is the cost of the architecture in the Pareto optimal set i with performance p_{min}, and d_{min} is the duration of the architecture in i with performance p_{min}.

Stage 0:
No Pareto architectures affected

Critical Value I:
$$c_{max}/d_{max} = b_{cv1}$$

Stage I:
Some Pareto architectures affected

Critical Value II:
$$c_{min}/d_{min} = b_{cv2}$$

Stage II:
All Pareto architectures affected

Performance vs Cost

Occurs when:
$c/d_i \leq b_i$, for all i

Occurs when:
$c/d_i \leq b_i$, for some i
$c/d_i > b_i$, for all other i

Occurs when:
$c/d_i > b_i$, for all i

In Stage 0:
$c', d', m', \Delta c, \Delta d, s = 0$

In Stage I:
when $c/d_i > b_i$,
$\quad c', d', m', \Delta c, \Delta d, s \neq 0$
when $c/d_i \leq b_i$,
$\quad c', d', m', \Delta c, \Delta d, s = 0$

In Stage II:
$c', d', m', \Delta c, \Delta d, s \neq 0$
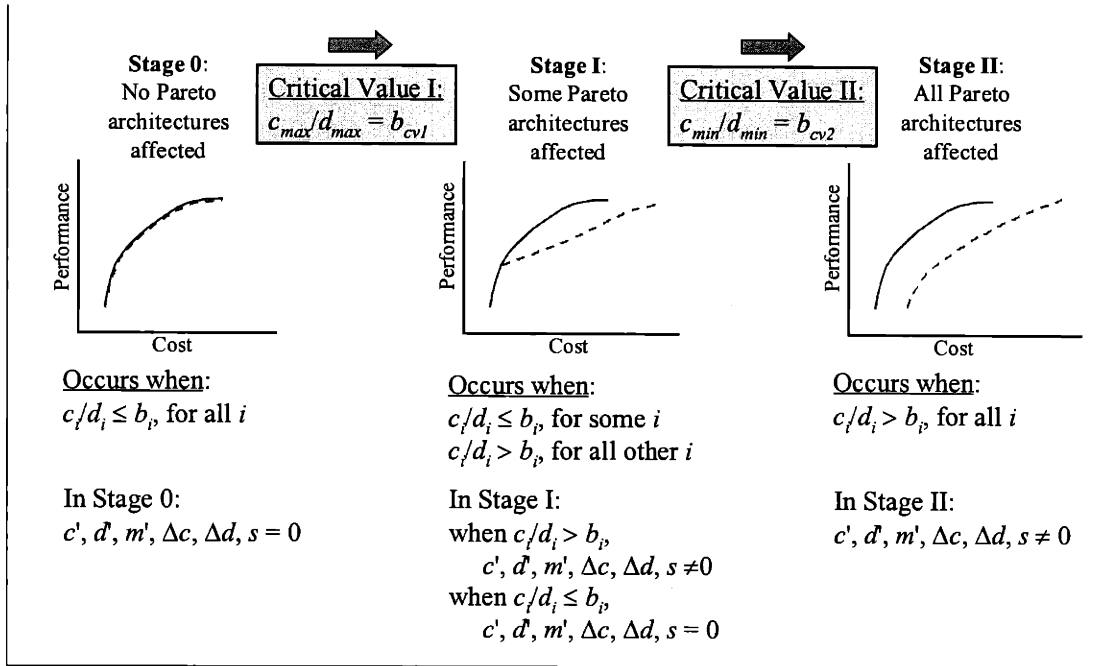
Figure 6-16. Critical values for transitioning between the three stages of policy-adjusted annual budget effects, and characterization of variables in each stage.

Each stage of policy-adjusted Pareto front behavior indicates different levels of policy robustness of a Pareto optimal set of architecture candidates associated with a given b_i. For Stage 0 behavior, the architecture set is very policy robust because the architecture costs are not affected by b_i. Conversely, for Stage II behavior, the architecture set is not policy robust because all architectures within the acceptable range of performance on the Pareto front are adversely affected by b_i. Similarly, Stage I behavior indicates that some of the architectures in the optimal set are unaffected by b_i and are policy robust, while others are not.

6.4. Applying the generalizations to the B-TOS mission: What can a decision maker learn?

The B-TOS Pareto optimal set of acceptable performance architectures, i, is bounded by $p_{max} = 1.0$ and $p_{min} = 0.98$. These boundaries correspond to total program development costs of \$241M

and \$56M, respectively. Using the equations above to calculate the critical values for transitioning between Stages 0, I and II, we find that b_{cvI} = \$80.3M/year and b_{cvII} = \$18.6M/year. This is summarized in Figure 6-17. *But what does this mean to a system architect or other decision maker?*

Critical stage transition point variable values:

p_{max} = 1.0	c_{max} = \$241M	**Critical Value I:** $241M/3yrs =\$80.3M/yr = b_{cvI}
P_{min} = 0.98	c_{min} = \$56M	**Critical Value II:** \$56M/3yrs = \$18.6M/yr = b_{cvII}
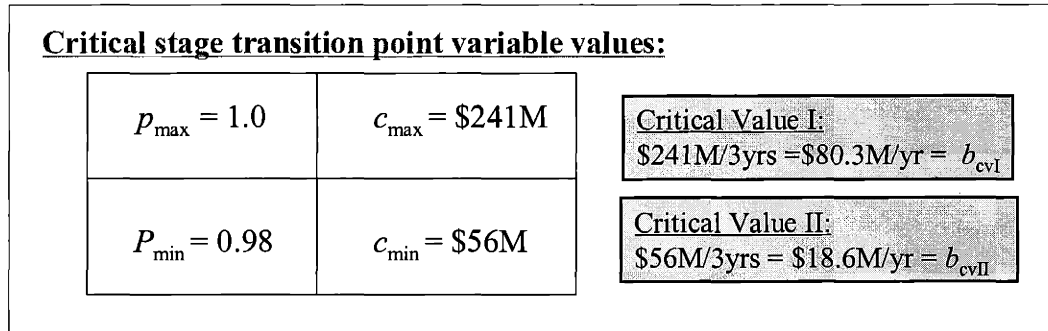
Figure 6-17. Critical stage transition point values for the B-TOS mission.

A system architect or decision maker should be concerned about what stage of behavior their system will exhibit under the range of likely expected annual budgets for their program.

- If the B-TOS likely expected annual budget is above \$80M per year, then all architectures in the Pareto optimal set *i* are budget policy robust and any can be pursued. The system architect should congratulate the system architecture team on generating such policy robust architectures.
- If the B-TOS likely expected annual budget is below \$80M but above \$18M per year, then some architectures in the Pareto optimal set *i* are policy robust while others are not. The system architect or program decision maker may wish to consider budget policy robustness as a selection criterion in choosing a final architecture, since cost and schedule overruns that can result from budget uncertainty will increase oversight and the probability of cancellation later on in the program. The system architect should pay careful attention to Congressional sentiment and budget tendencies as the program evolves.
- If the B-TOS likely expected annual budget is below \$18M per year, then none of the Pareto optimal architecture candidates are robust to budget uncertainty, and a system architect will want to take some action to avoid potential repercussions in the program's future. These might include (but are not limited to) generating new budget-robust architecture candidates to choose from, seeking increased protection from budget uncertainty from agency directors, or making a stronger case to appropriators for a larger budget.

Since B-TOS is a small military mission, the likelihood of its initially receiving or sustaining a \$80M annual budget is probably very small. Typically, such missions stay under \$20M - \$50M per year. Thus, a program manager concerned with budget uncertainty may not want to choose

architecture candidate E, even though it is the highest performing architecture, because it is adversely affected by annual budgets below $80M. If the program manager foresees that a annual budget of perhaps $25M is far more likely for a small military mission, then architecture candidate A would be a good choice, because it is robust to budget uncertainty. But if the annual budgets for small military missions are more likely to be in the $5M - $10M range, then none of these Pareto front architecture candidates for B-TOS would be robust to budget uncertainty. So what is the B-TOS system architect to do now? Unfortunately, a small military mission is unlikely to warrant the agency director making a special effort to fence this one particular program's budget, and it is also unlikely to attract much support from appropriators who have larger concerns. If these are the case, the system architect and the architecture development team may then wish to return to the drawing board and come up with less expensive architecture alternatives, or perhaps descope the program's requirements in an effort to create a budget robust architecture choice.

6.5. Conclusions

Quantifying the effects of policy-driven program budget adjustments on total architecture costs and mortality can be an extremely useful analysis to perform during space system architecture conceptual design. With Congressional oversight on government programs becoming more involved every year, space system architects should know how their candidate architectures will respond to varying budget levels. Why should they be concerned? When program budget levels get adjusted downward, and the program extends as a result, even more intensive oversight from appropriators follows. This reinforcing oversight spiral often leads to program cancellation. In an era of tight government budgets and appropriators looking for any reason to terminate programs, the wise system architect should take budget policy robustness into consideration when selecting a final architecture or set of architectures to pursue. Selecting the most expensive architecture that has little tolerance for reduced annual budget levels may end up being a recipe for cancellation, resulting in a waste of taxpayer resources and diminishing the agency's reputation for effective program management.

MEASURING THE VALUE OF DESIGNING FOR POLICY INSTABILITY:

THE ARCHITECTURE TRANSITION OPTION

Sometimes we can measure reasonably well how much a policy costs. This was demonstrated in Chapter 5 "Quantifying policy effects I: U.S. Space Transportation Policy of 1994" where the cost of launch policy was quantified. But in many other situations, we cannot accurately measure the costs of a policy. This may be due to the intangible nature of the costs involved, or to the lack of understanding of the mathematical relationship between policy directions and resulting cost impacts.

When cost impacts cannot be measured directly, the next best alternative is to turn the problem on its head and ask, "What might the policy impacts be *worth*?" This is certainly the case for budget instabilities, where the costs of transitioning system architectures in the middle of a program's lifetime to accommodate new budget levels are not well understood. For the case of budget policy instabilities, the critical question then becomes "What might it be *worth* to have a system architecture that is not impacted by budget instabilities?" Placing an upper bound on this worth also places a logical upper bound on what a system architect should be willing to pay to have a budget policy robust architecture. Real options, a valuation technique appropriate for situations involving uncertainty, allows us to calculate this upper bound.

This chapter begins with a brief introduction to real options theory, with definitions, examples and process steps. Real options is then used on the B-TOS mission example to value the worth to a system architect or program manager of an option to transition to a lower cost architecture when annual program budget levels are reduced by policy makers. Since reduced annual budget levels increase program cost and mortality, switching to a lower cost architecture that would not incur such penalties would be an attractive option to own. First, the volatility of budget reductions is measured, and calculations are derived using a binomial method for the maximum value of an architecture transition option. Then, the expectation of the maximum value of a B-TOS transition architecture option is presented along with an examination of sensitivities to assumptions in the calculations. The chapter concludes with a discussion of what decision makers can learn from valuing an architecture transition option, and how these lessons can be implemented to create budget policy robust system architectures.

7.1. 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. Fischer Black, Robert Merton and Myron Scholes pioneered the area of pricing financial option contracts for which they won a Nobel Prize. Their work, along with that of colleague Stewart Myers, forms the foundation of real options.[54]

Uncertainty and risk are two important and separate concepts to understand in discussing real options. Uncertainty is the "randomness of the external environment[55]." Since it is external to a project, uncertainty cannot be changed by decision makers. Uncertainty, in and of itself, is not a negative aspect. Risk, however, is different. Risk is the adverse consequences of a project's exposure to uncertainty. While the uncertainty cannot be altered, a project's risk can be managed and controlled to some degree through the choices of decision makers and how they expose the project to uncertainty[56]. These choices that decision makers have are the basis of options.

7.1.1. Options Defined

An option is a right, but not an obligation, to take an action. This "right" permits you to take the action when the outcome is favorable, but you 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.

To understand the nature of asymmetric returns, consider a simple financial options contract. Purchasing an options contract gives you the right to buy a certain stock at a price specified in the contract. For example, you purchase for $8 the option to buy one share of Intel Corporation stock at $85 six months from now. If Intel stock is selling for more than $93 per share, you would certainly exercise your option to buy the stock. This would yield you a profit equal to the stock price of Intel less the exercise price of $85 and the option cost of $8. But if Intel is selling for less than $93, you are not obligated to purchase the stock. In this scenario, exercising the option would have negative consequences and result in a further loss. By being able to avoid those negative consequences, asymmetric returns are created. These asymmetric returns are beneficial to the decision maker, as they minimize the exposure of projects to negative outcomes.[57] However, an investment or expenditure of assets is required to obtain these asymmetric returns – assets that could otherwise be used for other purposes.

Financial options come in two basic varieties: call options and put options. Call options give their holder the right to buy an asset at a certain price, while call options give their holder the right

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[54] Amram, Martha and Nalin Kulatilaka (1999). *Real options : managing strategic investment in an uncertain world.* Boston, Mass., Harvard Business School Press.

[55] Amram, Martha and Nalin Kulatilaka (1999). *Real options : managing strategic investment in an uncertain world.* Boston, Mass., Harvard Business School Press.

[56] Amram, Martha and Nalin Kulatilaka (1999). *Real options : managing strategic investment in an uncertain world.* Boston, Mass., Harvard Business School Press.

[57] Example taken wholesale from Brealey, Richard A. and Stewart C. Myers (2000). *Principles of corporate finance.* Boston, Irwin McGraw-Hill.

to sell an asset at a certain price. Combinations of these two option types can be used to describe any payoff scheme. The more complex the payoff scheme is, the more complex the combination of options necessary to represent it. Stepping back into the realm of system architectures and government space system programs for a moment, the option a system architect may hold to transition from an original architecture to a new architecture during the program's lifetime could be expressed in financial option shorthand as "*A put option on the original architecture and a call option on the new architecture.*"

While financial options applies to financial contracts and products, real options applies to non-financial assets. 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. Below are several examples of real options:

1. New manufacturing capacity can be implemented at different points in time and in different amounts. Each of these is an option to build a product in a different way58.
2. Performing R&D is an option to bring new products to the market59
3. Constructing a power plant that has the capability to burn two different kinds of fuel creates an option to choose the fuel used based on lowest operating costs at any given time[60]
4. Purchasing a lease on adjacent land to a production plant is an option to build a plant and expand production at a later date[61]

In the same way as financial options minimize the exposure of an investor to negative outcomes, so do real options protect the decision maker from certain unfavorable situations. Using the same examples as above shows how each situation has avoided negative outcomes:

1. An option to build a product in different ways prevents a firm from being locked into one method of production. This one method of production may not allow the firm to adapt to new manufacturing technologies or processes that are more efficient and less costly. Options on different production methods would give a firm flexibility to change their manufacturing should it become more profitable to do so.
2. Performing R&D enables a firm to have the technology necessary to bring new products to the market when the market is ready for them. Not performing R&D would take away a firm's ability to make a new product when the market demanded it, and result in the firm perhaps going out of business. At the same time, a firm is not obligated to take projects further after R&D if the market does not support it. This choice to not continue an R&D effort into full product development avoids the losses associated with products the market won't buy.

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[58] Trigeorgis, Lenos (1996). *Real options : managerial flexibility and strategy in resource allocation.* Cambridge, Mass., MIT Press.

[59] Neely, James E. III and Richard de Neufville (2001). "Hybrid real options valuation of risky product development projects." *International Journal of Technology Policy and Management* 1(1): 29-46.

[60] Amram, Martha and Nalin Kulatilaka (1999). *Real options : managing strategic investment in an uncertain world.* Boston, Mass., Harvard Business School Press.

[61] Amram, Martha and Nalin Kulatilaka (1999). *Real options : managing strategic investment in an uncertain world.* Boston, Mass., Harvard Business School Press.

3. Constructing a dual-fuel power plant gives its operators a choice of fuel. If a choice (option) were not available, the plan operators would be limited to one fuel only. If that fuel became so expensive that a profit could no longer be returned from generating energy, the power plant would go out of business. A dual-fuel plant minimizes adverse exposure to the uncertainty of fuel prices.

4. Purchasing a lease on adjacent land to expand plant production at a future time positions a firm to expand when the market is ready to support such expansion. If the lease on the land were not taken today, the firm would not be able to expand tomorrow. In a similar way, if future demand does not increase as expected, the firm does not have to expand, can terminate the land it leased, and end up with very minimal losses than if they had built the plant outright without waiting to see how the market developed.

What makes each of these real options so valuable is the uncertainty involved. The greater the uncertainty, the more valuable an option is. This may seem counter intuitive at first, but it is nonetheless true. In fact, if there is no uncertainty to a situation, then options have no value and are not needed.

7.1.2. Types of Real Options

There are five basic types of real options: waiting options, growth options, flexibility options, learning options, and exit options[62]. Each of these options and their benefits or strengths is discussed below.

- <u>Waiting options</u> – These options help you understand whether it is better to make an investment now or wait until later. Typically, options to wait are assessed against options to immediately take an action. A tradeoff is evaluated between the benefits to be gained by immediately taking action versus the losses avoided by waiting to resolve the uncertainty. A space-related example of a waiting option would involve the emergence of processed commercial satellite communication services. The DoD may be interested in evaluating the benefits of immediately becoming an anchor tenant on one such service versus potential losses avoided by waiting to see which player later becomes dominant in the market. Benefits of anchor tenancy might include reduced service prices, guaranteed access to service, and influence in the development of the service. Losses avoided by waiting might include buying into a company that later goes bankrupt thus losing the initial investment money as well as time

- <u>Growth options</u> – These options lay necessary groundwork for future follow-on projects. Growth options can be evaluated to determine if the entry investment required justifies the opportunities for future growth it creates. A space-related example might be the Global Broadcast System (GBS) satellites for the DoD. This initial wideband system includes installation of ground terminals in various platforms, and accustoms end users to wideband information systems in the

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[62] Option types and descriptions drawn from Amram, Martha and Nalin Kulatilaka (1999). *Real options : managing strategic investment in an uncertain world.* Boston, Mass., Harvard Business School Press. Also Brealey, Richard A. and Stewart C. Myers (2000). *Principles of corporate finance.* Boston, Irwin McGraw-Hill.

theater of engagement. This lays the groundwork for the future growth of wideband communications and information systems to in-theater platforms. Thus, GBS can be considered a growth option on a larger, more capable wideband system.

- Flexibility options – These options give a project greater flexibility to respond to uncertain conditions in the future. Investing in an option to switch project characteristics as needed creates value out of uncertain events. A space-related example of a flexibility option would involve leases with commercial satellite communications providers. A lease that does not lock the DoD into a specific transponder on a specific satellite provides flexibility. A lease that specifies a total amount of capacity but which enables the DoD to allocate that capacity dynamically on satellites and transponders in different orbital locations allows for flexibility to meet uncertain geographical demand requirements for military satellite communications services.

- Learning options – These options create better information on which to base future choices in a project. Each stage of a project creates information that can inform contingent decisions and options in future stages. A space-based example of a learning option would involve the testing of new communications terminal technologies in various operational environments to see which technologies perform best in the likely engagement environments of the future. Information gained from the testing informs the decision about which terminal technology to fully deploy, or how to best invest in a mix of terminal technologies for multiple environments. A decision at the outset of a project about which terminal type(s) to field is made without the benefit of useful testing information that will become available in the future. Testing reduces uncertainty that existed prior to the testing, and this learning lowers the adverse exposure that creates risk and negative consequences.

- Exit options – This is the ability to abandon a project if information received in the future indicates adverse consequences for continuing the project. Exit options provide the ability to minimize losses when the uncertainty in the future becomes unfavorable. When an exit option is taken, losses are typically contained to that invested up until the exit option is exercised, plus some termination costs. In all cases, the losses resulting from an exit option will be less than the losses from continuing the project, or else exiting would not be a good option. A space-related example of an exit option would be a staged development of a satellite system, where each phase of system development is a separate contract. Many large systems are already procured in this fashion. At the end of each phase of development, a contract ends and the DoD has the option to not award a contract for the following phase of development and instead abandon the project. This is an exit option.

In reality, most real options situations are combinations of these types. Such is the complex nature of real assets. Again stepping back for a moment to the realm of system architecture and government space programs, we can express the system architect's ability to transition from the original architecture to a new architecture as "*An exit option on the original architecture, and a flexibility option on the new architecture.*"

7.2. Valuing Real Options

Real options is a fundamentally different way of framing the valuation process from traditional methods such as variations on discounted cash flow analysis. While 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.

7.2.1. Why discounted cash flow doesn't work

The use of various discounted cash flow techniques, which use a single series of discounted cash flows to arrive at a present value for the project, is pervasive. These discounted cash flow techniques have two fundamental problems.

First, only a single cash flow is used. Not only does this bring the discounted cash flow analysis under heavy scrutiny from decision makers, it creates a false sense of certainty and definitiveness about the analysis. In addition, the single cash flow assumes that the value of the average cash flow equals the average value of a range of cash flows. However, this assumption cannot be made for real options, for it is false due to the asymmetric probability distribution of returns[63].

Second, discounted cash flow techniques use a set of investment decisions that are fixed at the outset. In other words, it assumes a commitment to the cash flow specified in the analysis. This ignores the ability of managers and decision makers to adjust investment plans as time progresses, making contingent decisions later on in a project only if favorable conditions still exist. These adjustments take advantage of new information that becomes available, and limits the exposure of a project to undesirable outcomes. This ability to change investment plans as time goes forward, and the choice to take certain actions, is the very basis of real options.

7.2.2. Process steps in valuing real options

There are six basic steps to performing a real options valuation analysis, shown in Figure 7-1. They are[64]:

1. Identify decisions: What decisions can be made? When might they be made, and who is making them? These decision 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 which are not under the control of the project manager, such as market risks.
3. Identify decision rule: This is a simple mathematical expression that describes the favorable conditions under which the option would be exercised.

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63 Neely, James E. III and Richard de Neufville (2001). "Hybrid real options valuation of risky product development projects." *International Journal of Technology Policy and Management* 1(1): 29-46.

64 Amram, Martha and Nalin Kulatilaka (1999). *Real options : managing strategic investment in an uncertain world.* Boston, Mass., Harvard Business School Press.

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.

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

The output of a real options analysis is of course the measured value of the real options contained in the analysis along with their 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 his or her specific project.
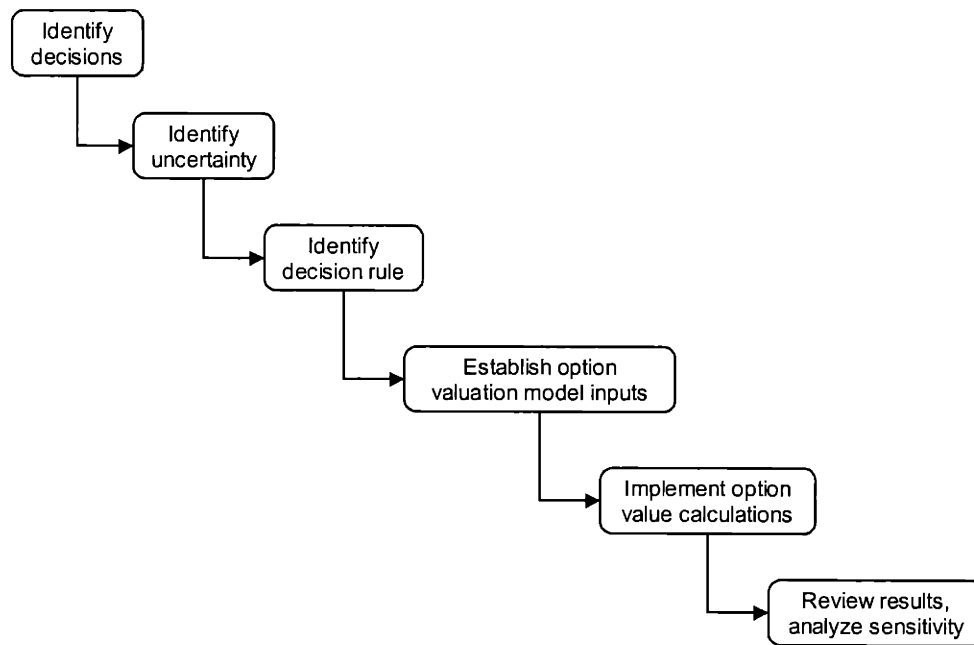

Figure 7-1. Six steps in performing a real options valuation analysis.[65]

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[65] Steps shown in the diagram drawn from Amram, Martha and Nalin Kulatilaka (1999). *Real options : managing strategic investment in an uncertain world.* Boston, Mass., Harvard Business School Press.

7.3. Setting up the B-TOS real options analysis

The B-TOS mission using small distributed satellites in low earth orbit to perform ionospheric mapping was first introduced in Chapter 5 "Quantifying policy effects I: U.S. Space Transportation Policy of 1994," and the reader is referred back to that chapter to refresh their understanding of the details of the B-TOS mission. The remainder of this chapter will investigate the value of a transition option to switch architectures on the B-TOS program during the program's development life. Such an option might be useful, for example, when policy makers reduce the annual budget allocation for a program, making it challenging to execute the original architecture under a new lower budget.

To prepare the B-TOS real options analysis, we begin by addressing the first three steps in the real options analysis process described above. The decision available in the scenario of lower annual program budgets is the decision to transition to a lower cost Pareto front architecture for the B-TOS mission. The primary source of uncertainty that we will model in this scenario is budget level uncertainty. This is a public source of uncertainty, external to the B-TOS program. The decision rule for the B-TOS program manager on the transition option is to transition architectures if the cost of transitioning is less than the cost of not transitioning. This is much like the 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.

7.3.1. Volatility

The next step in preparing the B-TOS real options analysis is assessing volatility of the source of uncertainty, which for B-TOS is the uncertainty associated with being allocated the full requested program budget each year. This volatility measure will indicate what appropriate probability to use in the decision tree in the following section.

To measure this volatility, historical data was collected on Congressional budget adjustments for Department of Defense programs from fiscal years 1996-1998[66]. Procurement programs (Title III), as well as Research, Development, Test and Evaluation programs (Title IV), were included in the assessment. Title III programs are fully developed procurement programs in full rate production, and include appropriations for all branches of the military covering everything from aircraft and ships to missiles and munitions. Title IV programs are those still under development, in various stages leading up to, but not including, full rate production. Like Title III, Title IV programs include appropriations for all branches of the military. Oftentimes, space programs spend their whole appropriations life within Title IV, because they never reach the high production rates necessary to transition to a Title III procurement program.

In the fiscal years 1996-1998, nearly 1000 programs were allocated a budget in Title III and Title IV of the Conference appropriations bills. For each program, the President's budget request was compared with the final Conference resolution. A histogram of these comparisons is shown in Figure 7-2, with the Congressional Conference budget allocations represented as a percent of the

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[66] *Making appropriations for the Department of Defense for the fiscal year ending September 30, 1996, and for other purposes (Report 104-344)* (1995) United States House of Representatives, Washington DC. Also *Making appropriations for the Department of Defense for the fiscal year ending September 30, 1998, and for other purposes (Report 105-265)* (1997) United States House of Representatives, Washington, DC.

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 never any guarantee that the future will always look like the past. So when the budget environment changes in the future, these volatility measures provided here will need to be reevaluated under the new circumstances expected in the future.

Many interesting observations can be made on the volatility of budget allocations. Perhaps the most striking observation is that a program is more likely to receive an increase (53% on average) or decrease (32% on average) than its original request (15% on average). It may surprise many cynics of the Congressional budget process who believe that Congress only takes away funds to learn that the majority of programs receive an increase in budget. Lastly, we can observe that the most likely budget decreases and increases are actually smaller ones, occurring fairly close to the original President's budget request.

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. Thus, only the downside of the budget allocation volatility is considered in this real options analysis.

Histogram of Congressional Budget Allocations FY1996 - FY1998 as Percent of President's Request
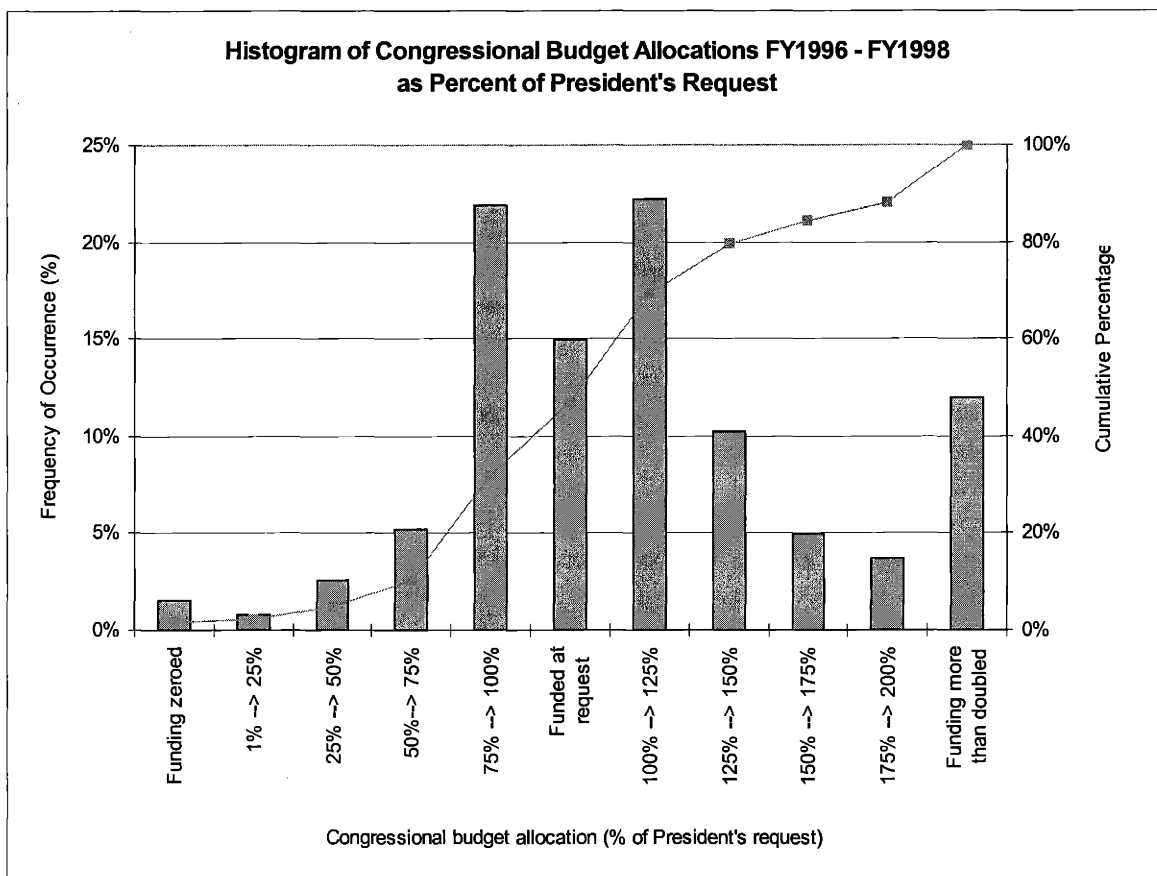
Figure 7-2. Historical distribution of annual program budget adjustments for DoD programs FY96-FY98.

In order to more easily model the downside volatility, it is useful to find a probability function that approximates the actual data shown in Figure 7-2. An exponential probability density function (PDF) of the form

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

Eq. 7-1

with $\lambda = 4.65$ works fairly well. The exponential cumulative probability density function (CDF) was used as the basis for estimating, with a standard error of the estimate of 6% and a Pearson's Correlation Squared (R^2) of 0.99 (see Section 5.7.1. for details on these statistics). The actual and estimated CDF and PDF are shown in Figure 7-3 and Figure 7-4 respectively.
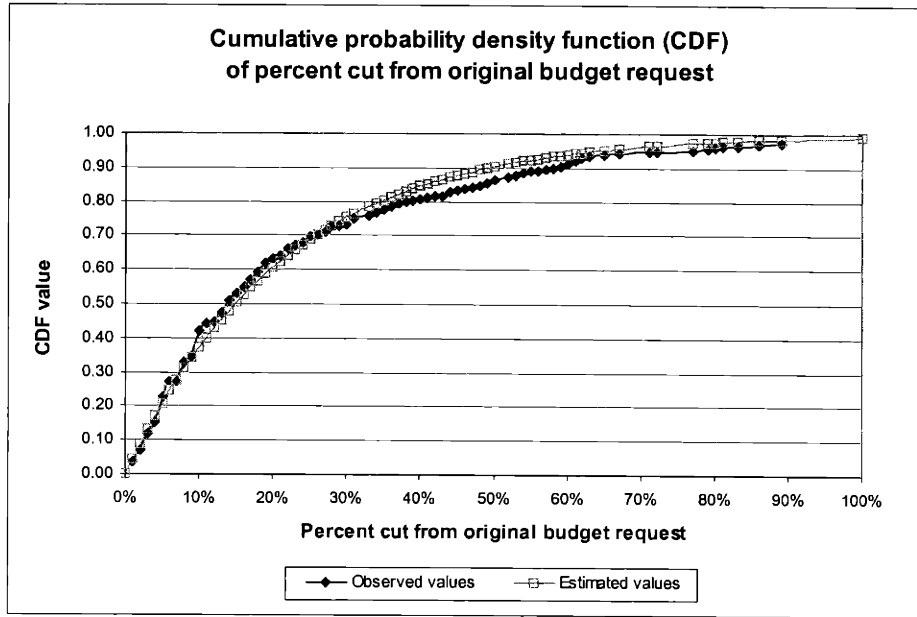
Figure 7-3.   Historical CDF of annual program budget adjustments (solid diamonds) compared to predicted CDF using

exponential CDF approximation with λ = 4.65.

Figure 7-4.   Historical PDF of annual program budget adjustments (solid diamonds) compared to predicted PDF using

exponential PDF approximation with λ = 4.65.

7.3.2. Option value calculations

To calculate the value of the architecture transition option for the B-TOS mission, we use a decision tree as shown in Figure 7-5. The B-TOS system architect will select an initial architecture, and then there is the chance that B-TOS will receive an annual budget cut from Congress. The volatility assessment in the previous section forms the basis for the probability that a budget cut will occ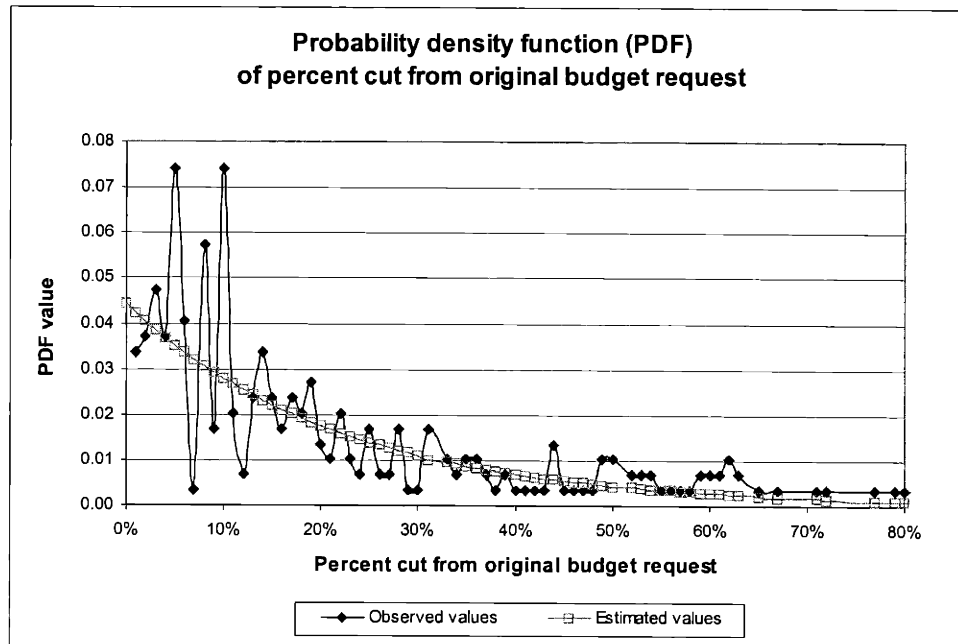ur. If there is no budget cut, the B-TOS manager could choose to stay with the initial architecture with no cost penalty, or transition to a new architecture with a cost penalty equal to the cost to transition to the new architecture (represented by the variable TC). Since the goal of the B-TOS program manager is to minimize costs, no transition will occur if no budget cut occurs.

If there is a budget cut, the B-TOS manager is faced with the same choice of whether or not to transition. Transitioning will incur a cost penalty of TC, while not transitioning while under a budget cut will incur a cost penalty equal to Δc. Δc was defined previously in Sections 6.3.1. and 6.3.2., and is the cost growth that occurs because of program schedule extension resulting from downward annual budget pressure. In this case, the B-TOS manager, wishing to minimize her costs, will choose to transition only if that transition cost, TC, is lower than the cost to not transition, Δc.
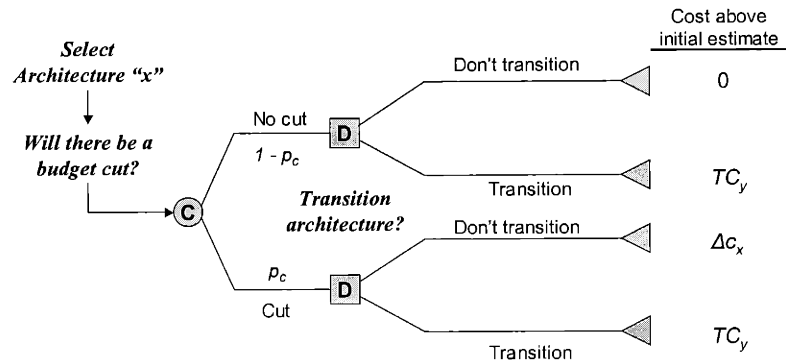
$$\textbf{Value of option} = p_c{}^* [\min(\Delta c_x, TC_y)] + (1 - p_c)^* [\min(0, TC_y)]$$

$$\textbf{Max present value of option} = p_c{}^* [\min(\Delta c_x, TC_y)] / e^{-rt}$$

$$\boxed{= p_c{}^* \Delta c_x / e^{-rt}}$$

Figure 7-5.   Simple transition option decision tree for two architectures.

Rolling back the decision tree yields the value of the transition option. As shown in Figure 7-5 the net present value of the option is

$$\frac{p_c\left[\min\left(\Delta c_x, TC_y\right)\right]}{e^{-rt}}$$

<div align="right">Eq. 7-2</div>

where p_c is the probability of a budget cut, TC_y is the cost to transition to architecture y from the initial architecture x, Δc_x is the cost growth of architecture x under the budget cut, r is the risk free rate of return, and t is the time horizon of the option. The cost to transition to a new architecture is unknown, and theoretically is able to take on any value from zero to infinity, while, Δc_x is finite and known. So while we cannot know the exact value of the option because we do not know TC_y we can evaluate the maximum net present value of the option, and this occurs at

$$\frac{p_c\,\Delta c_x}{e^{-rt}}$$

<div align="right">Eq. 7-3</div>

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 is shown in Figure 7-6, and yields the same maximum net present value of the option regardless of the transition costs that are associated with each transition architecture possibility.
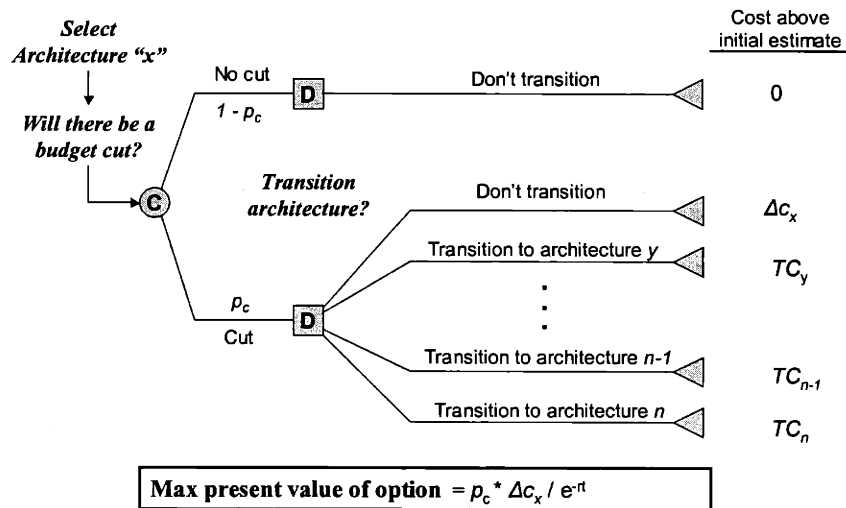
Figure 7-6. Option decision tree extended to n transition architecture possibilities.

Our equations for calculating transition option values are not complete until we set some bounds for their validity. An important consideration in real options is understanding when the option has value, and Figure 7-7 depicts this for architecture transition options. In the previous Chapter that addressed annual program budget policy, three Stages of behavior of Pareto optimal architecture sets under downward annual budget pressure were identified. 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 II, 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.

Stage I is where a transition option may have value, and this is bounded by annual program budgets of c_{max} / d_{max} and c_{min} / d_{min} as shown in Figure 7-7. In Stage I, 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, while the unaffected architectures will not. These unaffected architectures provide a "fallback position" for the affected architectures in Stage I, and become the set of possible transition architectures. In Figure 7-7, 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.

Stage 0:
No Pareto architectures affected

Transition at:
$c_{max}/d_{max} > b_i$

Performance

Cost

Transition option has no value in Stage 0, because there is no need to transition.

Stage I:
Some Pareto architectures affected

Transition at:
$c_{min}/d_{min} > b_i$

Performance

Cost

Transition option has value in Stage I

When
$c_{max}/d_{max} > b_i$
and $c_{min}/d_{min} < b_i$

Stage II:
All Pareto architectures affected

Performance

Cost

Transition option has no value in Stage II, because there is no architecture in the Pareto set to transition to.

Figure 7-7.   Graphical depiction of architecture transition option value bounds.

7.4. Value of B-TOS transition architecture option

With the real options analysis inputs and framework settled, we can now examine the results of the analysis and the sensitivity of those results to assumptions in the calculations. First, the expectation of the maximum transition option value based on historical volatility levels is presented. Then, univariate sensitivities are explored on r, t, p_c, and annual budget level b. Finally,

simultaneous multivariate sensitivity is explored on p_c, t, and b, which had the greatest univariate sensitivities.

7.4.1. Expectation of option value given historical volatility levels

Figure 7-8 shows a table of the expectation of the maximum transition option value for each B-TOS Pareto optimal architecture. Volatility was assumed to follow the exponential approximation of observed historical budget adjustments, with $p_c = .0.32$. t, the time horizon of the option, was assumed to be 3 years, which is the development duration of the B-TOS program. r, the risk free rate of return, was assumed to be 5%, which is an acceptable assumption for government projects. The expectation of the option value was derived from the decision tree formulation of the option problem presented in Figure 7-5. Eq. 7-3 shows the formula used to calculate the expectation of the maximum transition option value.

Expectation of maximum transition option value:	in $M	As % of spacecraft budget
For Architecture E	7.4	3.1%
For Architecture D	3.9	3.1%
For Architecture C	3.4	3.1%
For Architecture B	2.6	3.1%
For Architecture A	0	0%

Figure 7-8.   Expectation of maximum transition option value for each of the five B-TOS Pareto optimal front architectures.

For the five Pareto optimal B-TOS architectures, the maximum transition option value varied in dollar amount but was constant at 3% percent of total spacecraft budget (which is defined in this thesis as total program budget less launch and operations costs). This says to the B-TOS system architect or program manager that if they firmly believe their program's budget allocations will follow the Defense Department's recent historical patterns, 3% of the spacecraft budget is the maximum they should be willing to invest to own an option to transition to a lower cost architecture. But before the program manager decides that 3% is indeed the right number, she should check to see how much that value changes if the assumptions it was based upon change.

7.4.2. Univariate sensitivity of architecture transition option value

Univariate sensitivity analysis varies only one assumption at a time while holding all others constant, and looks at the impacts that result. Assumptions on b, r, t, and p_c will be examined in this section. Sensitivity analysis tells a system architect or program manager which assumptions are really driving the value of the transition option, and hence which assumptions she should focus most on.

Figure 7-9 shows the sensitivity of the 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 on the graph. This graph also nicely illustrates the bounds of option values at c_{max} / d_{max} and c_{min} / d_{min}, which are approximately \$80M and \$18M respectively for B-TOS, outside which the transition option has no value.

We can demonstrate the usefulness of this sensitivity graph with an example. Assume the B-TOS program chooses to embark initially on architecture E, but would like to carry an option to transition to a lower cost architecture if Congress should change its budget priorities 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. But what if the B-TOS program manager has reason to believe that the upcoming years will be particularly tight budget years, and her program will probably be subject to more downward budget pressure than history would predict? By looking at Figure 7-9, she can quickly discern the value of the transition option for the entire range of potential annual budgets that might be allocated by Congress. If she feels that the annual program budget has a reasonable chance of being cut to \$50M, then the transition option value increases from 3% to about 7%.
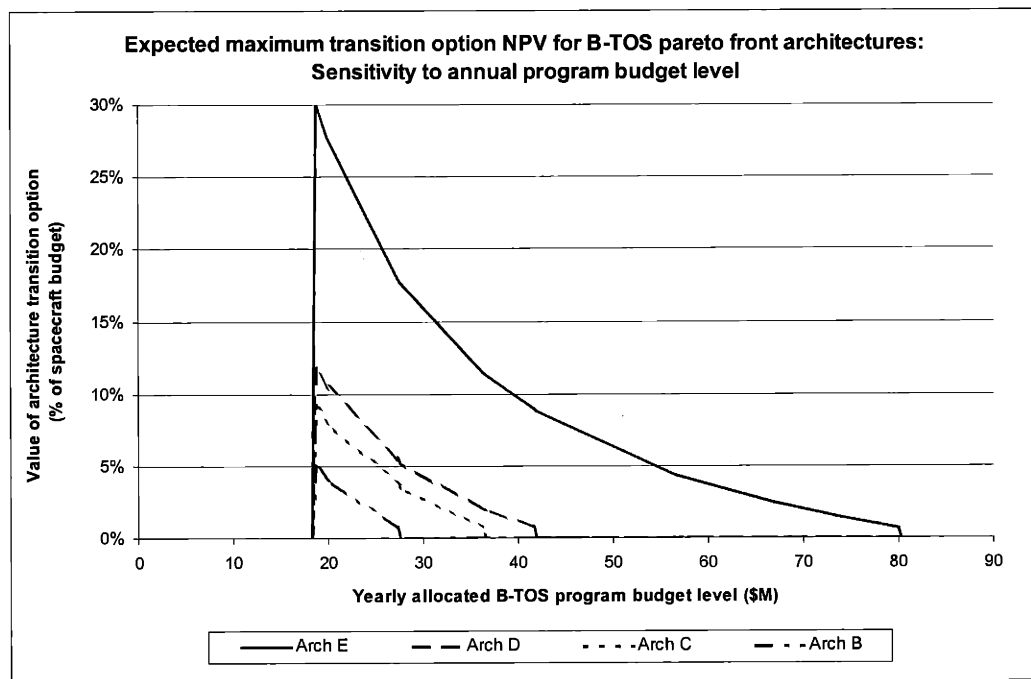
Figure 7-9.   Sensitivity of maximum transition option value to variation in annual program budget level.

Figure 7-10, Figure 7-11, and Figure 7-12 illustrate the univariate sensitivities of the transition option value to p_c, r, and t, respectively. The annual budget is fixed at \$25M to demonstrate these sensitivities. The 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.

Figure 7-10. Sensitivity of maximum transition option value to variation in probability of cut.
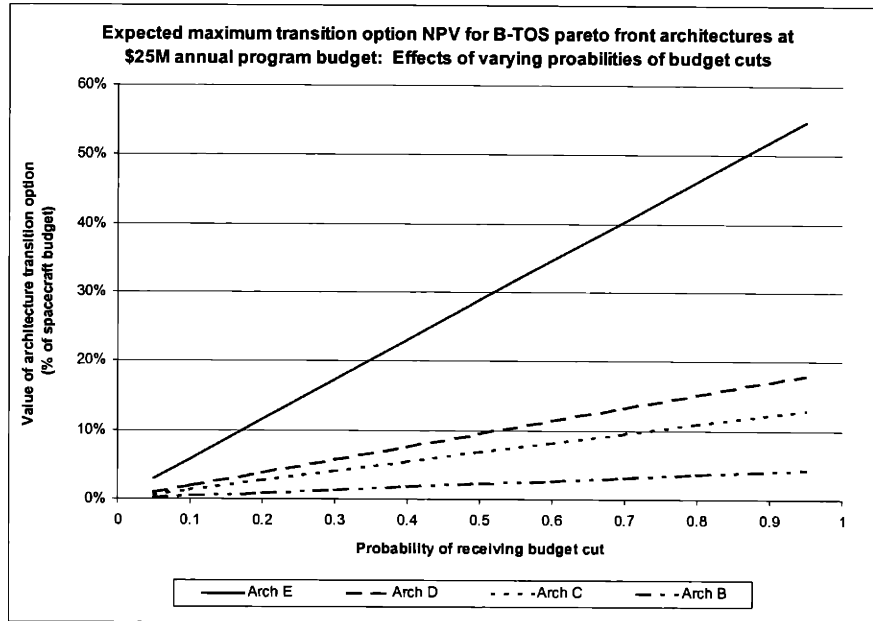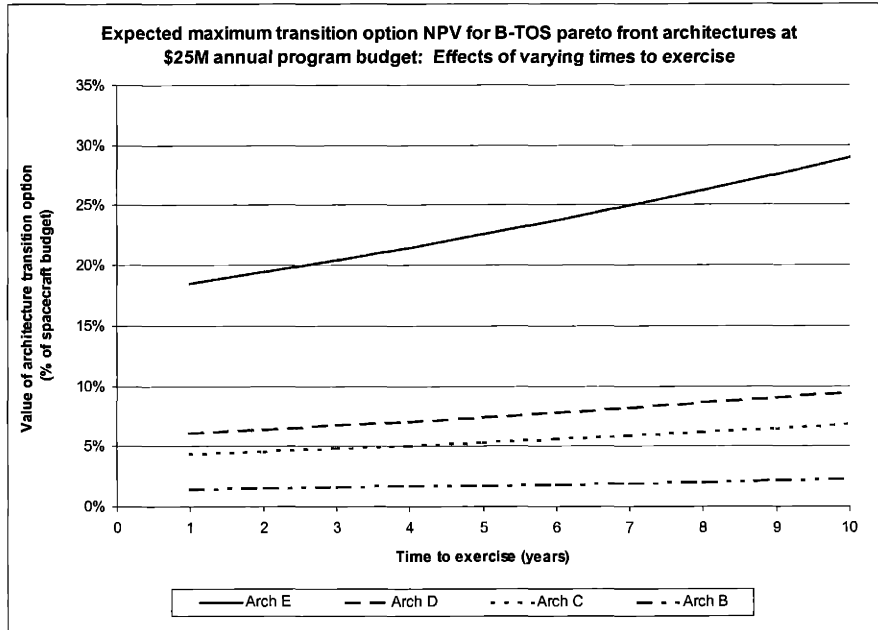
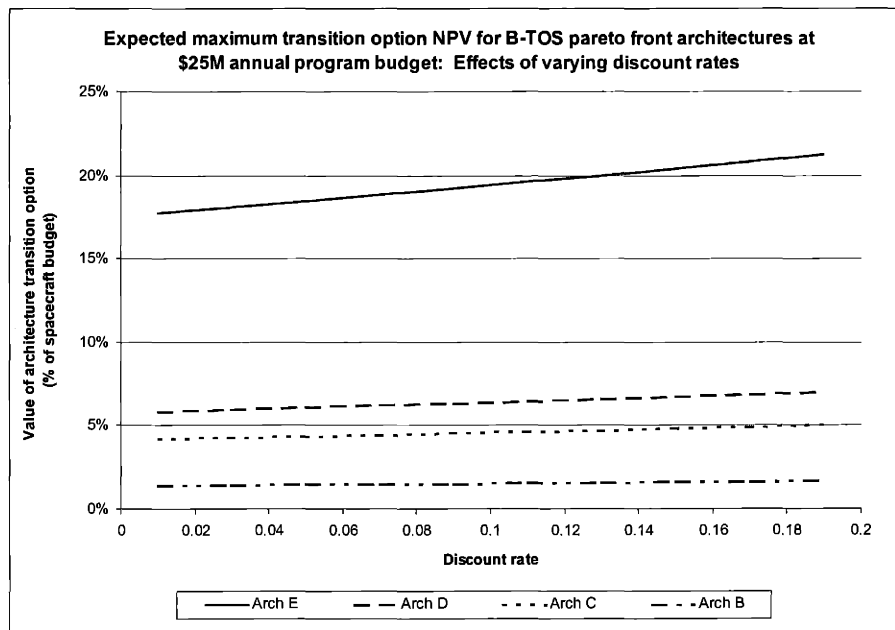Figure 7-11. Sensitivity of maximum transition option value to variation in time to exercise.

Figure 7-12. Sensitivity of maximum transition option value to variation in risk-free interest rate.

7.4.3. Multivariate sensitivity of architecture transition option value

Multivariate sensitivity analysis simultaneously varies the assumptions on multiple variables and examines the impact on the maximum transition option value. For a system architect or program manager facing a high degree of uncertainty in estimating the parameters of probability of budget cut, option time horizon, and likely annual program budget levels, multivariate sensitivity analysis allows a quick grasp of their impacts on the option value.

Figure 7-13 shows a three dimensional graph of the multivariate sensitivity for the maximum transition option value for B-TOS architecture E. 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 leaf in the figure is a different annual program budget level. The top leaf is $20M per year, the leaf immediately underneath that is $40M per year, the next leaf is $60M per year, and the bottom leaf is $80M per year. The color gradations on the leaves correspond to the values on the transition option value. The darker colors indicate smaller option values, and the lighter colors indicate larger option values.

Right away, the system architect or program manager can see how much more sensitive the transition option value to for lower annual budget levels. In addition, they can see how the transition option value increases with the time to exercise. And by looking at the top leaf in this view, they can also see how the option value increases with the probability of budget cuts. Overall, they can see that being in the upper left hand front corner implies a very different transition option value than being in the lower right hand back corner.
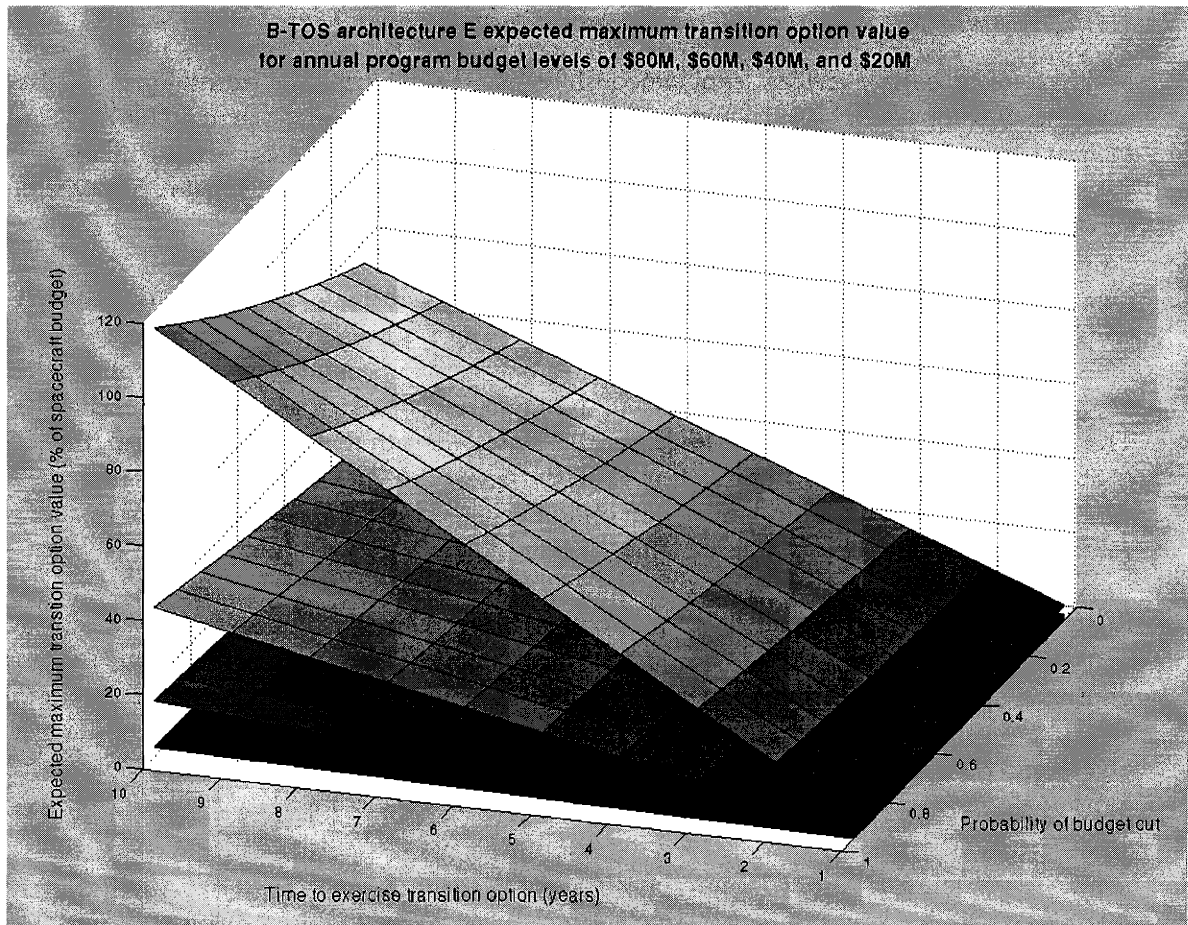
Figure 7-13. Sensitivity of the maximum transition option value to simultaneous variations in to p_c, t, and b.

Using this three dimensional representation on a computer enables a system architect or program manager to spin the graph around, and inspect different angles. They can use it to answer various "what-if" questions in real time, such as "What will the range of transition option values be for B-TOS architecture E if I expect the program to be cut with 20% - 40% probability, have an option time horizon of 6-8 years, and have an annual budget expectation of $40M?" By looking at the graph, the answer is found to be 7% - 15%. And then when someone else wishes to know the same "what-if" question except for an annual likely budget level of $60M, the answer is quickly found to be 3% - 6%.

7.5. Owning an architecture transition option

This chapter has covered the basics of real options analysis, how it can be applied to valuing an option to transition architectures in mid-program development, and what sensitivities can be expected around that value. All this has established an upper bound on the maximum value of the transition option. We can compare this maximum transition option value to the rule of thumb of carrying 20% to 30% management reserves in a spacecraft budget at preliminary design

to buffer for future changes and uncertainties.[67] Many of the scenarios that could be constructed for the B-TOS example yield maximum transition option values within this typical 20-30% range, somewhat validating the rule of thumb.

So now that the system architect or program manager understands the most they should pay to own such a transition option in theory, how do they actually go about "buying" it and "owning" it in practice?

An architecture transition option is a risk mitigation strategy, or insurance policy, against budget policy instabilities. System architects 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, we can look at an example drawn from the B-TOS mission. Table 7-1 shows the architecture attributes that distinguish one Pareto front architecture from another. The main differences occur in the number of satellites per swarm and the swarm radius. Performance of these architectures increases with increasing swarm radius, so thus E is the highest performing architecture in the Pareto optimal set, D is the second highest performing architecture, and so on down to A, which is the lowest performing architecture.

Table 7-1. B-TOS Pareto optimal frontier architecture attributes.

Point	A	B	C	D	E
Altitude (km)	<-- 1100 -->				
Num of Planes	<-- 1 -->				
Swarms/Plane	1	1	1	1	2
Satellites/Swarm	4	7	10	13	13
Swarm Radius (km)	0.18	1.5	8.75	50	50
Functionality Study	<-- #5 -->				

Let us assume that architecture D is the initial architecture chosen, and that architecture A will be held as the transition option. In examining the commonalities and differences between the two architectures, we see that the primary difference is in the number of satellites per swarm and the swarm radius. Architecture D has 13 satellites per swarm with a swarm radius of 50km, whereas architecture A only has 4 satellites per swarm at a radius of 0.18km. In order to "buy" the option on architecture A, the system architect needs to fund the differences between the two

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[67] Larson, Wiley J. and James Richard Wertz (1992). *Space mission analysis and design.* Torrance, California, Microcosm Press and Kluwer.

architectures. So the key question is what does the architecture attributes of satellites per swarm and swarm radius imply about technical design differences between the two architectures? It is those technical design differences that the system architect or program manager will need to fund the development of in order to own the transition option.

In the case of B-TOS, an increased number of satellites per swarm impose increased on-board processing and communications requirements for the mother ship in controlling and communicating with the increased number of daughter ships. So it appears that the requirements for on-board processing and communications for the mother ship in architecture A are subsumed within the more stringent requirements for these capabilities in architecture D where more satellites per swarm are utilized. Thus for the architecture attribute of satellites per swarm, there is nothing required of the transition architecture A that was not already required of the initial architecture D, so no differences in the architecture attribute need be funded in order to own the transition option.

However, this is not the case for the second architecture attribute that is different between architecture D and architecture A: swarm radius. For swarm radius, architecture A actually has more stringent requirements that architecture D in this regard. 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 them are large. Thus the key differences between architecture D and A are in the control system and the propulsion system. So in order to "buy" the right to transition from architecture D to architecture A, a system architect or program manager would fund research and development work on more precise control systems as well as non-impinging propulsion options for the spacecraft.

Work by Myles Walton in the area of managing co-varying uncertainty in space system architectures provides useful methods for identifying and assessing those architectures that share common development risks. System architects can expand on these techniques to select appropriate transition architectures with the proper level of co-varying development risk suitable for the program's level of risk aversion.[68]

7.6. Epilogue: Real options poses cultural challenges for the government

As may be apparent from the overview of real options presented earlier in this chapter, there exist several challenges that NASA and the DoD will need to overcome in order to implement and take full advantage of real options on space system programs. Two chief obstacles are a DoD culture that does not fully exploit an options mindset, and federal acquisition regulations that limit options.

Arguably, the NASA and the DoD cultures do not fully exploit an options mindset. For example, taking an "exit" or "abandonment" option in a program acquisition is often equated with failure. Success is rewarded in these agencies, not failure. And when success is equated with carefully

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[68] Walton, Myles A. (2002). *Managing Space System Design Uncertainty Using Portfolio Theory.* Aeronautics and Astronautics doctoral dissertation. Massachusetts Institute of Technology, Cambridge, Massachusetts.

executing on a static action plan created at the outset of a program, it is not difficult to see how an options mindset would not be rewarded in that environment.

Federal acquisition regulations (FAR) were created to ensure fair contracting practices in government agencies and equality in access to federal business contract opportunities. NASA and the DoD are obliged to follow these regulations. While ensuring fairness and some amount of protection to companies that do business with the federal government, the FAR limits the ability of government agencies to modify, expand and terminate procurement contracts. These are usually powerful options on a project, as illustrated in the B-TOS example throughout this chapter, which are restricted or removed from government projects due to the FAR.

While real options has much to offer the valuation of risky and complex space system projects in the uncertain budgetary environment likely in the future, there remain many challenges that need to be overcome in the government setting if the methodology and its benefits are to be embraced.

7.7. Conclusions

This chapter has explored real options as both a *strategy* for accommodating policy instabilities in programs and as an *analysis technique* for measuring the value of designing for policy instabilities. We see from the analysis that real options provides a reasonably straightforward way to measure the worth of actions and contingent decisions. But we also must understand 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.

One other point to address in closing concerns the implementation of purchasing and owning architecture transition options. While the valuation techniques presented in this chapter have attempted to put 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 with no guarantees, but as programs test out some of these techniques for creating policy robust architectures, future researchers will be able to fill in the missing pieces and validate or amend this work as appropriate.

PUTTING IT ALL TOGETHER:

POLICY AS AN ACTIVE CONSIDERATION IN THE DESIGN PROCESS

The purpose of this thesis research is to enable the creation of policy robust system architectures and designs. To be policy robust is to successfully pass through policy changes that might arise during the course of system development and bring the system into operational use. A system architecture becomes policy robust by making policy an active consideration in the architecting and design process.

Over the course of the preceding chapters, qualitative and quantitative methods have been derived and demonstrated for assessing and insuring policy robustness in a system architecture. These methods have been applied specifically in this thesis to the case of space systems, but there is little apparent reason why they cannot be used equally well in other domains of application.

These methods can be applied as early as the conceptualization phase of architectures and design, and the earlier they are applied in the process, the greater the benefits that can be derived. As the architecture and system design solidify, time and opportunities are lost to tailor a system for policy robustness.

Lest it seem that this thesis argues for policy robustness above all else in an architecture or design, it should be noted that designing for policy, much like designing for cost, or performance, or manufacturability, is yet another consideration in the very tangled web of creating complex engineering systems. However, for politico-technical systems like space systems, which have great involvement from the political domain, policy robustness should occupy a high place on the system architect or program manager's list of desired program attributes. As Brenda Forman so eloquently states it for the case of politico-technical systems, *"If the politics don't fly, the system never will."*

8.1. Thesis summary

This thesis set out to address five key questions, and has found some interesting answers in the process of investigation. Summaries of the chapters in the thesis are addressed where they fall under the five key questions below.

1. What is the environment in which space systems architecting and design occurs?

Chapter 2 presented a domain framework for understanding how government policy choices affect the technical requirements for complex, space-based, politico-technical systems. Many players in four different domains – political, technical, end user, and architectural – are required to create a space system architecture. These domains each have their own unique culture, and oftentimes communications and information flow between domains suffer from the misunderstandings and misinterpretations that are typical of cross-cultural communications.

Influence diagrams and the concept of impact flow paths provide space system architects with techniques for conceptualizing policy impacts on technical systems. These diagrams, while only qualitative in nature, can serve as valuable communication objects both within and outside a system architecture development team. Rooted in an understanding of the domain framework, the influence diagram process of tracing impacts from the policy domain to the architecture domain to the technical domain is the first step in making policy considerations an active part of the space system architecture conceptual design process.

2. What are the historical ways in which policy has driven space system architecture and designs?

Chapter 3 presented ten new heuristics on the political process and system architecting that result from researching literature and conducting first-hand interviews with space system program managers on their previous experience with how policy has driven space system architecture and design. Program managers and system architects can incorporate these into their own personal heuristic toolkits, and these can be applied at all times throughout system development. What the investigation of historical ways in which policy impacted systems design turned up was that the consideration of policy impacts on systems must be constantly borne in mind because the policy changes can occur at any point in the system development timeframe. There is not a fixed-in-time window of opportunity for policy makers to intervene in a program's course of development. One needs look no further than the annual U.S. Congressional budgeting process to realize that appropriators have at least a renewable yearly ability to impact a program.

3. How can policy effects on space architecture and design choices be quantified?

Typically, policy impacts on system architectures and designs are qualified instead of quantified. Quantifying the impacts provides a more concrete basis for assessing the benefits against the costs of policies, and better informs the policy debate. What this research brings to light, however, is that not all policy impacts can be completely quantified at this point in time, given the limitations of our current knowledge of policy and technical requirement interactions.

Chapter 4 presented a semi-quantitative analysis process for examining policy impacts on space system design. This semi-quantitative process involves aggregating multiple influence diagrams that show the impacts of policy directions on technical parameters. Once these influence diagrams are aggregated into matrices, the number of impacts flowing out from each policy direction can be quantified and the policy directions can be viewed in terms of which have the most or least technical impacts. This points the way towards understanding the degree of policy robustness in a given space system architecture. The more robust a space system architecture is to policy, the fewer policy directions it will have that impact it. Similarly, a policy robust space

system architecture will have a low coupling ratio between the architecture objectives and the technical parameters. In addition, this semi-quantitative analysis can become a communications tool to bridge the gap between the political, architectural and technical domains. It becomes an even more effective tool if several of the domains engage in the semi-quantitative analysis process together, building a common understanding and common view of the architecture as the analysis proceeds.

Chapter 5 presented a quantitative analysis method for examining the cost and risk impacts of the U.S. Space Transportation Policy of 1994, and applied this in two situations. First, the B-TOS mission provided the setting for exploring the analysis as applied to one specific mission. Then, the analysis was broadened to include a representative "universe" of space system architectures. From this "universe" analysis, general cost impact estimating relationships were derived to enable space system architects to gauge the cost impacts of the launch policy very early during conceptual design. Lastly, the cost impact estimating relationships were used to calculate an economic cost and risk incurred from the Space Transportation Policy of 1994. This is the first time such a comprehensive analysis has been undertaken to assess the costs of a particular U.S. space policy.

Chapter 6 presented a quantitative analysis technique for quantifying the effects of policy-driven downward annuals program budget pressure on total architecture costs and overall program mortality. With Congressional oversight on government programs becoming more involved every year, space system architects can use this analysis technique to understand how architectures will respond to varying annual budget levels and guide the selection of a budget policy robust architecture. General equations describing the behavior of Pareto optimal architecture sets under downward annual budget policy pressure, and relationships that describe key transition points in this behavior, are key contributions of this chapter.

4. *What is the value of designing for policy or designing for policy instabilities?*

Chapter 7 explored real options as both a *strategy* for accommodating policy instabilities in programs and as an *analysis technique* for measuring the value of designing for policy instabilities. Real options was used to value the worth to a system architect or program manager of an option to transition to a lower cost architecture when annual program budget levels were reduced by policy makers. Since reduced annual budget levels increase program cost and mortality, switching to a lower cost architecture that would not incur such penalties would be an attractive option to own, and would result in an architecture that is robust to budget policy changes. While real options promises to be a valuable analytical technique, it must be recognized 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, and currently options as a strategy is not fully embraced by government agencies.

5. *How can policy become an active consideration in the conceptual design of space systems?*

The last question really brings together the previous four questions and all the chapters of this thesis with the goal of providing a strategy to system architects and program managers for understanding and dealing with policy in an active manner during the conceptual phase of the system. The answer to this final question, which has been addressed throughout each chapter as

regards the specific analysis subject of that chapter, is brought together and summarized in the following section below.

8.2. Making policy an active consideration in architecting and design

Alternatively, we could entitle this section "How a system architect or program manager makes use of this thesis." To start with, he or she instills in their team – as soon as it is created – an understanding of what policy is, and how it may come to interact with their system. The starting point for this indoctrination is the system architecting domain framework, presented in Chapter 2, which explains the roles of the political, technical, end user, and architecture domains in the system architecting process. It is important for the system architects and program managers to understand the specific players and motivations that are involved in their specific system area, whether it is space systems, airplanes, high-speed trains, nuclear power plants, or other complex politico-technical systems.

The next step is to identify the important policy issues relevant to the specific system area. Here it is useful to follow the trade press reporting on Congressional actions and hearings, as well as consulting experts for their opinions on current and future policy issues. With a list of policy issues in hand, influence diagrams can be created that translate the effect of those policy issues on architecture objectives and on down to technical parameters of the system. This was illustrated in Chapter 4. From the influence diagrams, the system architect needs to decide which policy impact paths can be understood mathematically and which cannot.

For the policy impact paths that *cannot* be understood mathematically, expert opinion is likely the only avenue a system architect has to make an assessment of the effects of those impact paths. Even so, this expert opinion assessment can shed light on a weak aspect of the architecture that must be improved to increase architecture policy robustness.

For the policy impact paths that *can* be understood mathematically, the system architect now has the opportunity of doing an analysis to quantify the effect of those policy impact paths. This kind of analysis was demonstrated in this thesis in Chapter 5 for launch policy costs and risks, and Chapter 6 for downward annual budget policy costs and program mortality effects. The specific kind of analysis done depends entirely on the nature of the system area and the kind of mathematical relationships between the policy issue and the system's technical parameters.

After the expert assessments and quantitative analysis is done of the effects of the policy impacts paths, it is imperative that the system architecture follow through on actions indicated by these analyses to ensure a more policy robust architecture or design.

These various steps to making policy an active consideration in system architecting and design are summarized in brief checklist form in Figure 8-1. The most important thing to remember about this checklist is that it is not meant to be done once and put away. It must be continually reviewed at every step in the architecture or design process, since policy is dynamic and will change over time. But the good news is that if system architects and program managers apply this checklist with discipline and respect for the consequences of failure, it will lead to the creation of a more policy robust system.

**Process checklist for creating
policy robust system architectures and designs**

1. Understand the system architecting domain framework, the specific players involved for your project, and their motivations.

2. Identify the important current policy issues relevant to your system.

3. Construct influence diagrams for each policy issue, at each stage of your architecture creation and system design, to assess which policy issues most greatly impact your system.

4. Identify on the influence diagrams which policy impact paths can be understood mathematically and which cannot.

5. Seek expert opinion to evaluate those policy impact paths that cannot be understood mathematically.

6. Quantify the effects of those impact paths that can be understood mathematically, assess the volatility of the policy issues they stem from, and assess the value of designing for changes in those policies.

7. Take the necessary action indicated by preceding analyses to ensure a policy robust architecture.

Figure 8-1.   Seven step process checklist for creating policy robust system architectures and designs.

8.3. Fundamental contributions of this thesis

This thesis has made several important contributions to the state of the art in analyzing interactions between policy and politico-technical system architecture and design. Though this thesis examined these interactions in the context of space systems, many of the contributions it makes can translate without significant modification to other application areas for politico-technical systems. In order from the more general to the more specific, the fundamental contributions are:

1. The notion of policy robust system architectures, and that system architectures can be analyzed, conceived and created to be robust to changes in policy.

2. The notion that policy is a dynamic and interconnected element in system architecture and design, which cannot be successfully treated like a static, disconnected constraint.
3. The notion that there exist impact paths and feedback loops between the political domain and the technical domain, and methods for tracking and understanding these.
4. A detailed process guideline for system architects and program managers to follow to make policy an active consideration in the architecting and design process of politico-technical systems.
5. New heuristics on policy and engineering interactions to guide system architects and program managers as they seek to create policy robust system architectures and designs.
6. The identification of the behavior of system architecture sets under downward annual budget policy pressure, and relationships that describe key transition points in this behavior for system architects and program managers.
7. The application of real options-based analysis to measure the value of designing a system architecture to be robust to budget policy instabilities.
8. The first comprehensive quantification of U.S. launch policy costs, and the generation of cost impact estimating relationships for use in space system conceptual design.

8.4. Recommendations for future work

The wonderful part of research is that in the process of answering your original questions, you generate many new and equally interesting lines of inquiry. For those making research their profession, this is fortuitous, for it means an endless supply of questions to investigate. This thesis leaves behind many new questions, divided below into two categories: questions relating to policy and space systems, and questions about applying methods to other systems besides space systems.

8.4.1. Further work in policy and space systems interactions

Further work would be useful on calculating transition costs to switch from one architecture to another after program development has begun and significant investment in an initial architecture has already been made. This would involve issues of assessing commonality among architectures, design reuse, and the associated costs of these. This information on transition costs could then be used in the real options calculations to estimate the actual value of designing for budget policy instability, instead of just an upper bound.

While this thesis measured the value for carrying one transition option, more than one can be carried yielding a portfolio of options. While this is a variation on the simpler case of carrying a single option, further work should investigate any differences in value that might occur from the single transition option case to the portfolio of transition options case. There may be synergies, or "economies of scale" so to speak, that figure into to the portfolio case, and these are worth investigating. In addition, this thesis only examined options for one instance of a budget cut and possible transition. What is left undone is to examine how budget cuts in multiple years would influence the value of an option, as well as the types of options that should be carried to be policy robust to several budget cut occurrences.

Other useful work in the area of the real options valuation techniques would create short-cut analytical approximations for real options, just like the Black-Scholes formula provides for financial options. The modification necessary is the expansion of the formula to include situations where the volatility does not follow a normal distribution, but does follow some other known distribution.

In addition to the rather theoretical work described above, future research should attempt to measure the relative success space program experience as they try to apply the various methods in this thesis to become more policy robust. As well recognized, transferring academic theory to regular practical use often is harder than it looks.

Lastly, future research should expand to examine how to quantify other kinds of policy impacts besides those from launch policy and budget policy examined in this thesis. Spectrum policy, international cooperation policy, export restrictions policy, and space control policy are examples of current space policy issues facing national U.S. policy makers today. In addition, a relative assessment of the degree of impacts from each of these policies on space systems can help prioritize the assessment of space systems for policy robustness. Since such analysis is rather time-consuming, it would be useful to know what policy areas would have on average the largest payoffs from looking at first.

8.4.2. *Work on policy and technical interactions outside the application area of space systems*

Over the course of the preceding chapters, qualitative and quantitative methods have been derived and demonstrated for assessing and insuring policy robustness in a system architecture. These methods have been applied specifically in this thesis to the case of space systems. They would appear on the surface to be equally useful in other domains of application, but this should be investigated by other researchers in other system areas.

Closely related politico-technical systems that are prime candidates for further research would be other defense systems, such as aircraft, ships, and missiles. Non-defense politico-technical systems that could be investigated for policy robustness would include nuclear power plants, high-speed rail systems, alternative fuel transportation systems, energy distribution systems, and so forth.

8.5. Closing remarks

In the pursuit of system architectures and designs that are policy robust, this thesis focused on understanding the interaction between political and technical aspects of complex, publicly-funded engineering systems. The time is now perhaps right, as we as a community of system architects and engineers begin an expanded phase of systems thinking, for this idea to really take hold and achieve broad implementation. Harvey Brooks made a call for action like this in a 1972 paper where he wrote, "If engineers are to bring systems thinking to bear on social problems, they must learn how to incorporate social and political theory into their analytical framework *ab initio*.[69]" As a founding member of the International Institute of Applied Systems Analysis that very same

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[69] Brooks, Harvey (1972). "A Framework for Science and Technology Policy." *IEEE Transactions on Systems, Man and Cybernetics* SMC-2: 584-588.

year[70], Brooks was a strong proponent of applying systems thinking to socio-technical and politico-technical systems, especially in an international context. One wonders if, at that moment in time in 1972, Brooks really appreciated how challenging a task it would become to address socio-technical and politico-technical systems with a rigorous systems approach. Certainly this thesis has demonstrated the difficulties involved in such a task, as it applied a systematic approach to analyzing policy impacts on politic-technical systems.

But perhaps the final thought of this thesis should reiterate the importance of understanding policy and technical interactions, and make a plea for senior government agency leaders and elected officials in Congress to take up this just cause. This thesis has provided a framework for these leaders and Congresspersons to better understand the implications of their actions upon complex politico-technical engineered systems. If these policy and technical interactions are not well understood and accounted for in politico-technical systems design and policy making, the very survival and implementation of the system may well be at stake.

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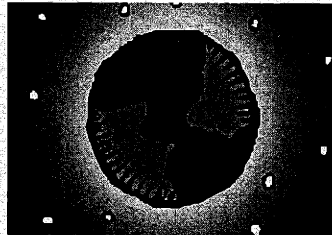
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