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Evaluating the Cost and Risk Impacts of Launch Choices

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A method is presented for quantitatively assessing the generalized cost and risk impacts to a space system architecture of a restrictive government launch policy and application is made to the case of the U.S. space transportation policy of 1994. For both a restrictive and unrestrictive launch policy scenario, a mixed integer optimization algorithm is used to select the best launch vehicle suite for a given satellite system architecture based on the cost or risk selection rule for a particular type of decision maker. The cost and risk impacts that result in the two scenarios are compared over an extensive matrix of satellite masses, altitudes, inclinations, and constellation arrangements. Generalized launch policy cost impact estimating relationships are derived, and risk impacts are represented by descriptive statistics. The analysis finds that the 1994 U.S. launch policy affects the launch cost and launch risk of many types of satellite system architectures.

Nomenclature

C_r	=	total architecture launch cost under a restrictive launch policy, \$
C_u	=	total architecture launch cost under an unrestrictive launch policy, \$
c_j	=	cost of launch vehicle j, \$
P_r	=	total architecture launch probability of success under a restrictive launch policy
P_u	=	total architecture launch probability of success under an unrestrictive launch policy
$p(f_j)$	=	probability of failure of launch vehicle j
s_j	=	cost of spacecraft carried by launch vehicle j, \$
w_c	=	weight of cost consideration
w_r	=	weight of risk consideration
x_j	=	1 if launch vehicle j selected, else 0
ΔC	=	architecture Δ launch cost, \$
ΔP	=	architecture Δ launch probability of success

Introduction

THE goal of this paper is to assess quantitatively and comprehensively the generalized cost and risk impacts on space systems of a restrictive launch policy such as the one currently in place in the United States. The results of this assessment provide satellite system designers with shorthand relationships that can be used early in the conceptual design phase to estimate the cost and risk impacts of the U.S. launch policy on their systems. From a space system designer's perspective, analyzing cost and risk impacts early has the potential to shape the very design of the architecture concept.

With increased computing power and advances in multidisciplinary optimization (MDO) techniques, space system architectures can be mathematically modeled and optimized under a wide range of criteria. Thousands of space system architectures can be explored virtually with computer-based MDO models and compared with each other during the conceptual design phase.[1–3] These models permit quantification of the performance and cost effects of different design choices, including those design choices driven by government policy. Using these models in the early conceptual design phase and tailoring them to explore government policy-related effects allow one to quantify policy effects on the system a priori. A priori knowledge of the quantified costs and effects of government policy on space systems will help engineers, designers, and program managers to make sound choices during system conceptual design and development.

This paper examines the specific government policy of space launch and offers the first comprehensive quantification of the cost and risk impacts of a restrictive government launch policy. Governments often put restrictive launch policies into place that limit the choice of launch vehicles a given satellite system may employ. 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. Currently, the U.S. government is operating under a restrictive launch policy. The U.S. space transportation policy of 1994 requires U.S. government payloads to fly on U.S. launch vehicles.[4] In addition, the United States is arguably applying a similar implicit policy to commercial payloads built in the United States by making it difficult for them to obtain export licenses for launches outside the country.

Modeling Approach and Analysis Methods

Again, the goal of this paper is to assess quantitatively the generalized cost and risk impacts of a restrictive launch policy. Generalized means the cost and risk impacts presented will apply to a very broad range of satellite system architectures varying in mass, altitude, and inclination. The cost impact refers to the total launch cost differential between a restrictive launch policy and an unrestrictive launch policy. The risk impact refers to the total launch probability of success differential between a restrictive launch policy and an unrestrictive launch policy. Although the methods presented can be applied to any instance of a restrictive launch policy, the remainder of this paper will use the specific case of U.S. launch policy to illustrate the methods and results.

The impacts of launch policy are modeled using two scenarios, one with a restrictive launch policy and another with an unrestrictive launch policy. These scenarios are then compared to arrive at the cost and risk impacts of the restrictive policy. For each scenario, a mixed integer program optimization algorithm selects the best launch vehicle suite for a given satellite system architecture based on the selection rule of a decision maker. For a satellite system, this decision maker is most likely the program manager. Three different

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types of decision makers are examined in this analysis: a minimum-cost decision maker, a minimum-risk decision maker, and a balance-cost-and-risk decision maker. As the analysis results demonstrate, the impacts of the launch policy are a function of the decision maker type because each decision maker uses a different selection rule to optimize their launch vehicle suite for a given satellite architecture.

Decision Maker Categories

Satellite systems under development today can be considered to fall into one of three categories as regards their program's preferences on cost and risk: 1) programs that minimize cost, 2) programs that minimize risk, and 3) 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, the 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 placing the satellite 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 balance-cost-and-risk decision maker will trade off cost and risk in each launch vehicle considered and minimize both cost and risk in the chosen launch vehicles. Although these three decision maker categories do not necessarily represent all real-world satellite 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 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 summarized in Table 1. Examples of military/national security space program decision makers are as follows: First, a minimum-cost decision maker might be represented by a Department of Defense laboratory technology demonstration mission, where budgets are usually tight and fixed. Second, a minimum-risk decision maker might be represented by a highly critical and costly national security satellite, where launch success is the highest priority. Third, a balance-cost-and-risk decision maker might be represented by replenishment launches to a large distributed satellite constellation such as the global positioning system. Whereas launch reliability is important, so, too, may be costs because 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.

Examples of civil space program decision makers are as follow: First, a minimum-cost decision maker might be represented by a small deep space class science mission, where the program budget is capped under law. Second, a minimum-risk decision maker might be represented by a human space mission, where ensuring safety of life is the highest priority. Third, a balance-cost-and-risk decision maker 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 remove cost considerations completely.

Examples of commercial space program decision makers are as follows: First, a minimum cost-decision maker might be represented by a consumables resupply 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. Second, a minimum-risk decision maker 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 resulting greater returns. Third, a balance-cost-and-risk decision maker might be represented by a broadcast satellite mission. Whereas 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.

Launch Vehicle Selection: Mixed Integer Program Optimization

For each type of decision maker, two scenarios are examined: one with a restrictive U.S.-only launch policy, where only U.S. vehicles are used, and another with an unrestrictive launch policy, where any vehicle (including U.S. vehicles) in the world launch vehicle fleet can be used. For each scenario, a mixed integer program optimization algorithm selects the best launch vehicle suite for a given satellite 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 optimization program.[5] The objective function for the minimum-cost decision maker is to minimize total launch costs:

$$\text{minimize} \sum_j x_j c_j \tag{1}$$

The objective function for the minimum-risk decision maker is to minimize total launch risks:

$$\text{minimize} \sum_j x_j [p(f_j)(c_j + s_j)] \tag{2}$$

The objective function for the balance-cost-and-risk decision maker is to minimize total launch costs and risks 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:

$$\text{minimize} \sum_j x_j [w_c cj \; + \; w_r p(f_j)(c_j + s_j)] \tag{3}$$

Each objective function is subject to the same set of constraints. These constraints are as follows: First, the total number of each launch vehicle used cannot exceed that vehicle's availability. Second, the total payload mass assigned to a launch vehicle cannot exceed the total payload mass capabilities of that launch vehicle. Third, the total payload volume and dimensions assigned to a launch vehicle cannot exceed the total payload volume and dimensions of that launch vehicle. Fourth, at least one launch vehicle is required

Table 1 Three types of decision makers in each of three U.S. space communities

Decision maker community	Minimum-cost decision maker	Minimum-risk decision maker	Balance-cost-and-risk decision maker
Military/national security space	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	Small fixed budget science satellite	Human space flight	Astronomical observatory satellite
Commercial space	Ventures with inexpensive payloads, such as consumables resupply 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

to be used for each orbital plane, a guideline frequently used in constructing launch architectures for constellations of satellites.

Launch Vehicle Characteristics

In the launch policy impacts analysis for this paper, 30 launch vehicles were used. 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 are shown in Tables 2–4. Because 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. In the future, when launch vehicle cost or reliability or any other characteristic listed subsequently changes materially, this launch policy impact analysis should be redone with new characteristics assumptions.

Sources of Information

Launch costs, minimum and maximum inclinations, and launch vehicle family availability were taken from Ref. 6. The launch costs used in this analysis represent the market price of launch services and do not include special items such as transportation to the launch site, etc., which are beyond the scope of this paper. Fairing dimensions and mass performance to specific altitudes were taken from Refs. 6 and launch vehicle payload user guides where available (Refs. 7–17). Country of origin was determined by taking the country from which the launch vehicle typically launches. Exceptions were as follows: First, the Ariane family that launches from French Guiana was attributed to Europe. Second, the Pegasus and Sea Launch programs that have mobile launch platforms were attributed to the United States.

Reliability was calculated using a Bayesian estimating process, which is a commonly used and accepted practice. The zero-order

Table 3 Launch vehicle performance (kilograms) to LEO, MEO, and GEO altitudes used for launch policy impacts analysis

Vehicle name	LEO at 800 km, kg	MEO at 20,000 km, kg	GEO at 35,788 km, kg	Performance inclination, deg
Athena I	360	0	0	60
Athena II	900	0	440	60
Ariane AR44LP	6,450	912	2,430	60
Ariane AR40	3,150	300	1,158	60
Ariane 5 ES	19,050	3,600	4,405	60
Atlas IIAS	6,600	1,450	1,738	60
Atlas IIIA	7,000	1,950	1,911	60
Atlas V402	10,100	2,175	3,316	55
Atlas V552	16,750	3,575	4,250	51
Delta II 732X	1,830	354	508	60
Delta II 742X	2,230	354	574	60
Delta II 792X	3,630	780	949	60
Delta III	6,950	2,000	1,929	60
Delta IV-M	7,050	1,600	2,010	55
Delta IV-M+(5,4)	10,700	2,400	3,284	55
Delta IV-H	21,350	5,000	5,491	55
Dnepr-1	600	0	0	64
Japan H2A202	6,400	1,600	2,495	51
Long March 2C	0	0	842	63
Long March 3B	6,000	0	3,067	63
Minotaur	430	0	0	28
Pegasus XL	250	0	0	65
Proton K/Block DM	4,850	3,150	1,700	64
Rockot	1,550	0	0	63
LeoLink 1	470	0	0	0
LeoLink 2	1,298	0	0	0
Soyuz	5,450	1,250	932	51
Start-1	220	0	0	90
Taurus	600	0	0	90
Sea Launch	6,000	2,000	2,000	90

Table 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	Location	Family	Minimum inclination, deg	Maximum inclination, deg
Athena I	17	2.057	2.294	2.002	0.60	United States	Athena	28	116
Athena II	24	2.057	2.294	2.002	0.60	United States	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	United States	Atlas II/III	28	120
Atlas IIIA	98	3.65	5.015	5.296	0.67	United States	Atlas II/III	28	120
Atlas V402	83	3.65	5.015	5.296	0.50	United States	Atlas V	28	120
Atlas V552	110	4.572	7.631	5.296	0.50	United States	Atlas V	28	120
Delta II 732X	47	2.743	4.553	2.285	0.96	United States	Delta II	28	145
Delta II 742X	52	2.743	4.553	2.285	0.96	United States	Delta II	28	145
Delta II 792X	55	2.743	4.553	2.285	0.96	United States	Delta II	28	145
Delta III	82	3.75	4.365	4.526	0.40	United States	Delta III	28	60
Delta IV-M	85	3.75	5.281	4.526	0.50	United States	Delta IV	28	120
Delta IV-M+(5,4)	103	4.572	12.192	4.292	0.50	United States	Delta IV	28	120
Delta IV-H	155	4.572	12.192	4.292	0.50	United States	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	People's Republic of China	Long March	56	98
Long March 3B	60	3.65	4.61	2.24	0.67	People's Republic of China	Long March	56	98
Minotaur	12.5	1.118	1.11	1.016	0.75	United States	Minotaur	28	116
Pegasus XL	14	1.168	1.11	1.016	0.83	United States	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	United States	Taurus	28	120
Sea Launch	85	3.75	4.937	3.6	0.75	United States	Sea Launch	0	360

Table 4 Launch vehicle availability used for launch policy impact 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

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

Attributes for small LEO space systems	Values
Mass per satellite, kg	50, 100, 150, 200, 250, 300
Number of orbital planes[a]	1, 2, 4, 6, 8
Number of satellites per plane	1, 3, 6, 10, 20, 30
Orbital inclination, deg	0, 15, 30, 45, 60, 75, 90

[a]Inclination of 0 deg has only one plane.

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.[18,19] Launch vehicle success and failure data through November 2001 were used in the Bayesian analysis. Note that launch vehicle reliability could potentially be calculated in any number of ways, and using different reliability estimates than those presented in this paper will of course yield different results. Future research may investigate the effect on the optimization results of different reliability calculation methods.

Fitting Satellites on Launch Vehicles

Satellite volume and dimensions were calculated as a function of spacecraft mass. Using an average spacecraft density of 79 kg/m^3 from Ref. 20, volume was calculated from mass. Satellite dimensions were calculated by assuming the satellite took on a square cylinder profile as a function of its volume. Based on these resulting dimensions, satellites were assessed for how many would fit on each launch vehicle, staying within both payload fairing envelope volume and mass constraints of the launch vehicle to the desired altitude.

Matrix of Satellite System Architectures

The results of the optimization algorithm depend not only on the launch vehicle characteristics but also on the satellite system characteristics. Thus, to create generalized launch policy impacts, it is important to examine a wide variety of satellite system architectures, varying in such attributes as mass per satellite, orbit altitude, orbit inclination, number of orbital planes, and number of satellites per plane. These attributes can be considered to nearly make up a representative sample of the universe of possible satellite system architectures from the point of view of the launch vehicle. These attributes and their range of values as assumed in this analysis are shown for each orbital altitude in Tables 5–8. Combining these attributes achieves a representative set of 3566 distinct satellite system architectures from which generalizations about launch policy cost and risk impacts can appropriately be made. It is certainly possible to examine more combinations of these attributes, but computation time grows with each added combination.

Table 6 Parametric exploration attributes and values for big LEO space systems

Attributes for big LEO space systems	Values
Mass per satellite, kg	500, 750, 1000, 1250, 1500, 2000, 2500, 3000, 5000, 10000
Number of orbital planes[a]	1, 2, 4, 6
Number of satellites per plane	1, 2, 4, 6, 8
Orbital inclination, deg	0, 15, 30, 45, 60, 75, 90

[a]Inclination of 0 deg has only one plane.

Table 7 Parametric exploration attributes and values for MEO space systems

Attributes for MEO space systems	Values
Mass per satellite, kg	50, 100, 150, 200, 250, 500, 750, 1000, 1500, 2000, 3000
Number of orbital planes[a]	1, 2, 4, 6
Number of satellites per plane	1, 2, 3, 5
Orbital inclination, deg	0, 15, 30, 45, 60, 75, 90

[a]Inclination of 0 deg has only one plane.

Table 8 Parametric exploration attributes and values for GEO space systems

Attributes for GEO 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[a]	1
Number of satellites per plane	1, 2, 3, 4, 5
Orbital inclination, deg	0

[a]Inclination of 0 deg has only one plane.

Regression Models

The results from the launch policy impacts analysis on the universe of satellite system architectures are used as a database 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 satellite architecture are launch cost and launch probability of success. The independent variables considered were satellite mass, satellite mass per orbital plane, number of orbital planes, satellites per plane, inclination, and altitude. The independent variable that exhibited a statistically significant relationship with launch cost was launch mass per orbital plane. There was no satisfactory statistical significance between the dependent variable of launch probability of success and any of the independent variables. Thus, the launch probability of success will not be the subject of parametric estimation in the launch policy impacts analysis. Instead, descriptive statistics and histogram frequency plots (available from the authors) were used to understand the general behavior of that independent variable.

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.[21,22] For each type of decision maker, two different regression models were initially computed that describe the launch policy cost impacts: 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 Δ 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 (>0.943 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 U.S. launch policy cost impact estimating relationships for each type of decision maker. In short, these relationships describe the cost of the restrictive U.S. launch policy as a function of space system mass per plane for the case of a specific type of decision maker.

Results

The following sections discuss the launch policy cost impact estimating relationships (CIERs) and descriptive statistics for the Δ launch cost (ΔC) and Δ launch probability of success (ΔP) for each type of decision maker for each orbit altitude region. ΔC for an architecture is calculated by subtracting the total launch cost in the unrestrictive launch policy case from the total launch cost in the restrictive case:

$$\Delta C = C_r - C_u \tag{4}$$

Thus, a negative ΔC indicates that the restrictive U.S. launch policy decreases the launch costs for an architecture. Similarly, a positive ΔC indicates that the restrictive U.S. launch policy increases the launch costs for an architecture. These CIERs for calculating launch policy costs, along with their respective standard error of estimate (SEE) and R^2 (proportion of variance in the dependent estimate that is explained by the independent actual), are shown and discussed in the following sections. Graphs of these relationships for a 1-plane satellite system architecture are also given. The parameters in the CIERs are the space system mass per orbital plane and the number of orbital planes. Each orbital region has a different CIER.

The ΔP impact for an architecture is calculated by subtracting the total launch probability of success in the unrestrictive launch policy case from the total launch probability of success in the restrictive case:

$$\Delta P = P_r - P_u \tag{5}$$

Thus, a negative ΔP impact indicates that the restrictive U.S. launch policy decreases the launch probability of success, or increases risk, for an architecture. Similarly, a positive ΔP impact indicates that the restrictive U.S. launch policy increases the launch probability of success, or decreases risk, for an architecture. The ΔP impact is described with descriptive statistics presented in a modified boxplot.

Detailed discussion is presented for the balance-cost-and-risk decision maker case. A summary discussion is presented for the minimum-cost and minimum-risk decision maker cases because space constraints do not permit a full discussion here. Interested readers may contact the authors for a more detailed discourse on these two cases.

Balance-Cost-and-Risk Decision Maker Results

The CIERs for a minimum-risk decision maker are shown in Table 9, and these relationships are shown for the 1-plane space system architecture case in Fig. 1. As seen in Fig. 1 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 medium-Earth-orbit (MEO) altitude region exhibits this behavior. For masses per plane below approximately 1000 kg, there is a cost impact associated with the restrictive U.S. launch vehicle policy. The magnitude of this impact decreases with increasing mass. After 1000 kg in the MEO altitude region, there is no cost impact. For low-Earth-orbit (LEO) and geostationar-Earth-orbit (GEO) architectures, all masses exhibit cost impacts from the restrictive U.S. launch policy that decrease with increasing mass per plane.

Figure 2 presents modified boxplots of the Δ launch probability of success for LEO, MEO, and GEO architectures for a balance-cost-and-risk decision maker. A boxplot is a useful way to describe a set of data that do not follow a normal distribution or other common probability distributions. The box in each of the three columns in Fig. 2 represents the interquartile range, or the difference between the 25th and 75th percentiles, where the middle 50% of the data set values lie. The mean of the data set is represented by the horizontal line, which may or may not lie within the box. The vertical lines extending from the bottom and top of the box show the range of data

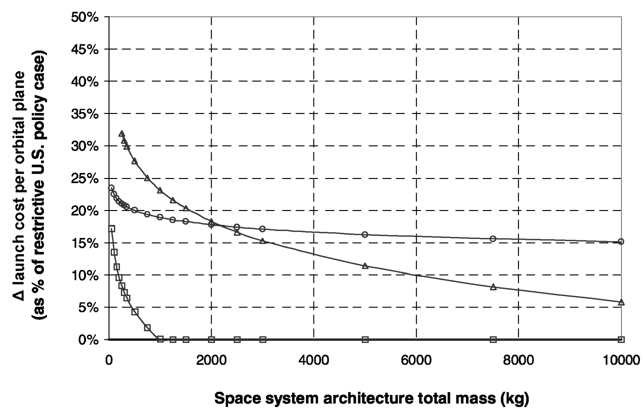

Fig. 1 Cost impacts of the 1994 U.S. space transportation policy on a balance-cost-and-risk decision maker using estimating relationships in Table 9 for a 1-plane space system architecture: ○, LEO △ cost; □, MEO △ cost; and △, GEO △ cost.

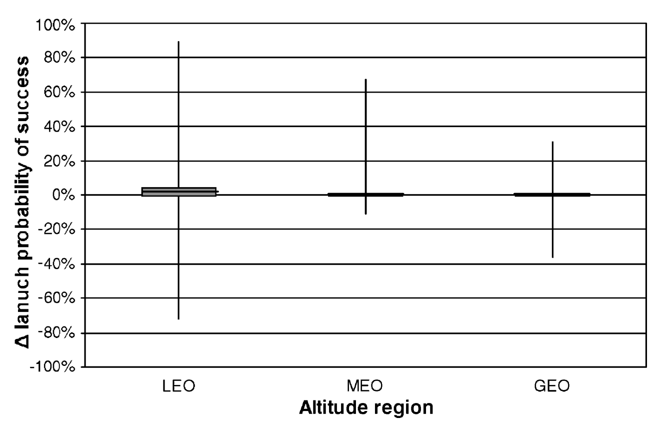

Fig. 2 Maximum, minimum, mean, and interquartile range for Δ launch probability of success impacts of the 1994 U.S. space transportation policy on a balance-cost-and-risk decision maker.

Table 9 Balance-cost-and-risk decision maker: cost impact estimating relationships for using U.S.-only launch vehicles

Orbital altitude region	Space system mass per orbital plane X, kg	Number of orbital planes, Y	Balance-cost-and-risk decision maker U.S. launch policy cost impact estimating relationship fiscal year 1999 million dollars (FY99\$M)	SEE, %	R^2
LEO	50–10,000	1–6	$Y(2.466295\,X^{0.51172} - 1.746457\,X^{0.53137})$	4	0.64
MEO	50–10,000	1–6	$Y(10.313407\,X^{0.37346} - 6.681547\,X^{0.43621})$	6	0.67
GEO	250–10,000	1	$Y(0.62214\,X^{0.67826} - 0.260075\,X^{0.76646})$	1	0.93

set values below the 25th percentile and above the 75th percentile, respectively. The minimum and maximum data set values occur at the ends of these vertical lines.

A number of things may be observed from the modified boxplots, such as those shown in Fig. 2, that describe the Δ launch probability of success impacts. First, the height of the box indicates the concentration of the central 50% of the impacts. A short box indicates a tight concentration of the central 50% of impacts, and a tall box indicates a dispersed concentration. In addition, the location of the mean along the vertical line describing the range of data set values indicates the relationship of the mean to the range as well as to the 25th and 75th percentiles. Last, the length of the vertical lines indicates the length of the tails in the distribution of the data set.

The LEO Δ launch probability of success impacts range from −72 to 89%, with a mean of 3%. The range of impacts is fairly balanced and extended with long tails on either side of the mean, but the interquartile range is only 5 percentage points as measured by the width of the box. The MEO Δ launch probability of success ranges from −11 to 67%, with a mean of 0%. The interquartile range of less than 1 percentage point is so small that it appears only as a line in Fig. 2, and it also coincides with the mean. This indicates a high concentration of Δ launch probability of success impacts for MEO, and closer examination of the data reveals that 99% of the impacts occur between the Δ launch probability of success impacts values of −1 and 1%. The GEO Δ launch probability of success impacts range from −36 to 31%, with a mean of −2%. The interquartile range of 1 percentage point appears as a line at 0%, which is above the mean line at −2%.

On average for the balance-cost-and-risk decision maker, the LEO and MEO architecture exhibit no risk impact from the restrictive U.S. launch policy. The GEO architectures see a very small risk impact. In summary, there appears to be on average a cost impact for most altitude regions to the 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 1000 kg per plane but do not exhibit any risk impacts on average.

Minimum-Cost Decision Maker Results

The CIERs for a minimum cost decision maker are shown in Table 10, and these relationships for a 1-plane space system architecture are shown in Fig. 3. Figure 4 presents modified boxplots of the Δ launch probability of success for LEO, MEO, and GEO architectures for a minimum-cost decision maker.

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. The LEO architectures see a very small risk impact. 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. Last, GEO architectures have a cost and risk impact that is in between these two.

Minimum-Risk Decision Maker Results

The CIERs for a minimum-risk decision maker are shown in Table 11, and these relationships are shown for the 1-plane space system architecture case in Fig. 5. Figure 6 presents modified boxplots of the Δ launch probability of success for

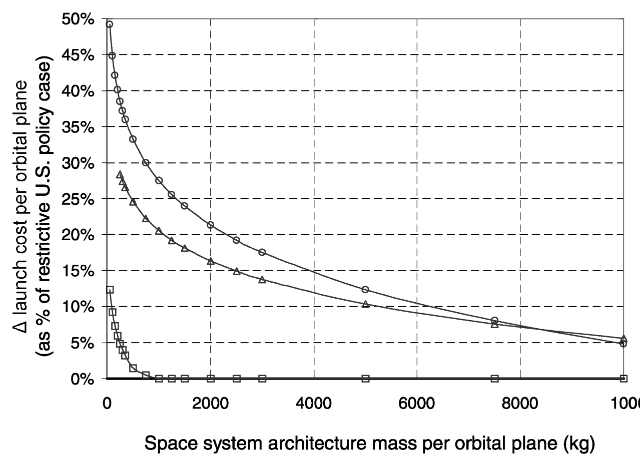

Fig. 3 Cost impact of the 1994 U.S. space transportation policy on a minimum-cost decision maker using estimating relationships in Table 10 for a 1-plane space system architecture: ○, LEO △ cost; □, MEO △ cost; and △, GEO △ cost.

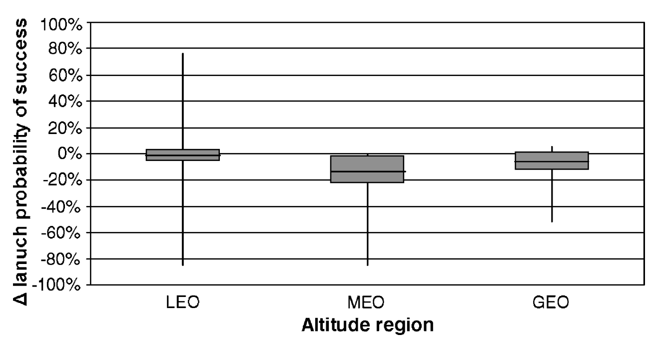

Fig. 4 Maximum, minimum, mean, and interquartile range for Δ launch probability of success impacts of the 1994 U.S. space transportation policy on a minimum-cost decision maker.

Table 10 Minimum-cost decision maker: cost impact estimating relationships for using U.S. only launch vehicles

Orbital altitude region	Space system mass per orbital plane X, kg	Number of orbital planes, Y	Minimum-cost decision maker U.S. launch policy cost impact estimating relationship (FY99\$M)	SEE, %	R^2
LEO	50–10,000	1–6	$Y(5.61356\ X^{0.4061} - 1.79446\ X^{0.52458})$	1	0.65
MEO	50–10,000[a]	1–6	$Y(9.541607\ X^{0.37998} - 6.855861\ X^{0.43082})$	5	0.68
GEO	250–10,000	1	$Y(0.45668\ X^{0.71050} - 0.215914\ X^{0.78564})$	2	0.94

[a]Beyond approximately 1000 kg per plane, MEO cost impact is negligible.

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

Orbital altitude region	Space system mass per orbital plane X, kg	Number of orbital planes, Y	Minimum-risk decision maker U.S. launch policy cost impact estimating relationship (FY99\$M)	SEE, %	R^2
LEO	50–10,000	1–6	$Y(5.613533\ X^{0.4061} - 3.646785\ X^{0.50443})$	5	0.69
MEO	50–10,000	1–6	$Y(5.822853\ X^{0.49754} - 8.229456\ X^{0.43978})$	1	0.69
GEO	250–10,000	1	$Y(1.222979\ X^{0.62917} - 0.452867\ X^{0.7504})$	2	0.79

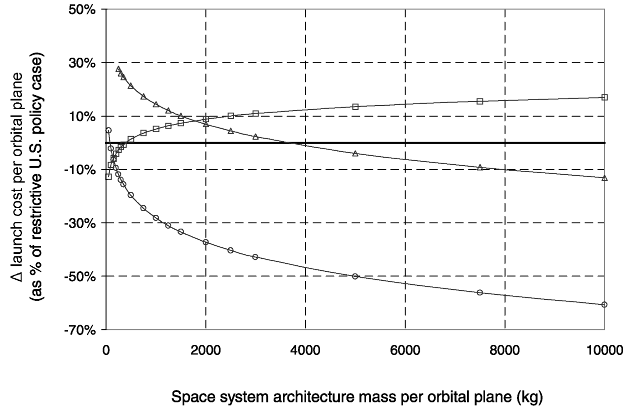

Fig. 5 Cost impacts of the 1994 U.S. space transportation policy on a minimum-risk decision maker using estimating relationships in Table 11 for a 1-plane space system architecture: ○, LEO △ cost; □, MEO △ cost; and △, GEO △ cost.

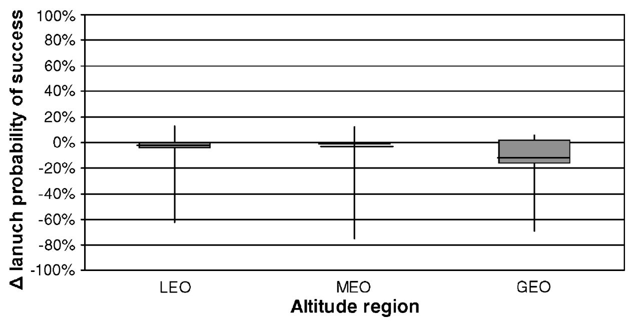

Fig. 6 Maximum, minimum, mean, and interquartile range for Δ launch probability of success impacts of the 1994 U.S. space transportation policy on a minimum-risk decision maker.

LEO, MEO, and GEO architectures for a minimum-risk decision maker.

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. 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 architectures have the largest risk impacts, as well as exhibiting cost impacts for masses less than 4000 kg. MEO architectures have the smallest risk impacts, but nearly all masses exhibit cost impacts. Last, LEO architectures have a large risk impact but do not incur a cost impact.

Summary of Launch Policy Impacts

Table 12 shows a 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 its average.

Applying CIERs

Satellite system designers can apply the U.S. launch policy CIERs given in this paper during the conceptual design phase to generate rough estimates of how the restrictive U.S. launch policy impacts satellite system 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 U.S. launch policy cost impacts, the program manager might choose to go with the one that has less of a cost impact.

Examining the cost impacts summarized in Table 12 finds that most combinations of mission orbit regions and program decision makers will incur cost impacts under the restrictive U.S. launch policy. The combinations that would not be likely to incur cost increases are as follows: LEO missions with minimum-risk decision makers, MEO missions with minimum-risk decision makers, MEO missions with mass per plane greater than 1000 kg for minimum-cost and balance-cost-and-risk decision makers, and GEO missions with a mass per plane greater than 4000 kg for a minimum-risk decision maker.

Table 12 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

Orbital region	Minimum-cost decision maker	Minimum-risk decision maker	Balance-cost-and-risk decision maker
LEO			
Cost impact range, %	49–5	5–0	24–15
Risk impact range, %	−86–76	−62–13	−72–89
Average risk impact, %	−1	−8	3
MEO			
Cost impact range, %	12–0	17–0	17–0
Risk impact range, %	−86–0	−75–12	−11–67
Average risk impact, %	−12	−2	0
GEO			
Cost impact range, %	37–6	40–0	41–6
Risk impact range, %	−52–5	−69–6	−36–31
Average risk impact, %	−6	−12	−2

Examining the modified boxplots for ΔP impacts present in Figs. 2, 4, and 6 shows 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 launch risk increase are LEO and MEO satellite system 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.

Conclusions

This paper has presented a method for quantitatively assessing the generalized cost and risk impacts of a restrictive government launch policy and applied it to the case of the U.S. space transportation policy of 1994. For both a restrictive and unrestrictive launch policy scenario, a mixed integer optimization algorithm was used to select the best launch vehicle suite for a given satellite system architecture based on the cost or risk selection rule for a particular type of decision maker. The cost and risk impacts from the two scenarios were compared over an extensive matrix of satellite masses, altitudes, inclinations, and constellation arrangements. The cost impacts were represented generally by a regression model, and the risk impacts were represented generally by descriptive statistics.

This paper has contributed cost impact estimating relationships that describe the cost impact of the current U.S. launch policy. Satellite system designers can use these relationships early in the conceptual design phase to estimate the cost impacts of the U.S. launch policy on their systems. It has also contributed descriptive statistics on the generalized risk impacts of the current U.S. launch policy. From a satellite system designer's perspective, analyzing the cost and risk impacts of launch policy has the potential to motivate the very design of a satellite system architecture concept. If the impacts of a restrictive launch policy are calculated to be very large during conceptual design, the satellite system designer has several alternatives. First, the system could be redesigned to arrive at a concept design that does not incur large cost and risk impacts under the restrictive launch policy. Second, the system could be reconceived with international partnering, or alternative acquisition strategies such as procuring services instead of systems, which could potentially exempt it from restrictive launch conditions under current policy.

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