SYSTEM, COST, AND RISK ANALYSIS FOR ACCESS TO SPACE

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Abstract

A critical element of every space mission is the cost and risk of access to space. Analyzing these costs and risks is often difficult, due to their high dependence on the design of the mission. Thus, cost and risk are generally assessed only through a conceptual system design process of the entire mission. This paper proposes the use of a new tool to more quickly develop initial cost and risk estimates of alternative flight options for both single missions and the partnering of missions into a single space flight. This work is particularly useful for small missions that require low-cost opportunities for accessing space.

An overview of the tool is presented, along with an example that demonstrates its use for generating quick cost and risk estimates. Preliminary results from this tool highlight the cost/risk tradeoff for partnering with other payloads or missions.

Introduction

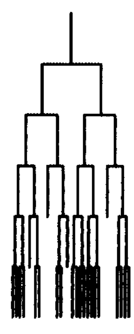
Launching into Earth orbit is particularly difficult for small payloads, which may lack the funds for a dedicated launch vehicle. Small payloads will often try to "piggy-back" with other missions, which while reducing the cost also increases the risk. The primary payload may encounter schedule delays, reductions in the mass available for secondary payloads, or even cancellation as a flight project.

In an effort to mitigate this risk, this study was initiated to evaluate flight options for accessing space. Although the emphasis of this study has been on small payloads that need partners to reduce the cost, the work is also applicable in designing many types of space missions.

Small payloads may consist of either individual subsystems (such as an instrument or small experiment) or a satellite (such as a micro-spacecraft). In this study, the primary consideration is of subsystems, which require a platform (typically a spacecraft bus) to function. These subsystem payloads include instruments for conducting science and various experiments seeking space flight.

As a first step, a logic tree was developed to demonstrate the complexity of the possible system architectures. Depending on the payload, platform, and launch vehicle, there were 106 viable flight options (see Table 1). These options include traditional concepts, such as launching a single payload on a spacecraft from an expendable launch vehicle (ELV), to more exotic combinations that combine multiple payloads and spacecraft from different organizations to reduce the overall system cost.

Payload Options
Single vs. multiple payloads Primary vs. secondary payload
Platform Options
Spacecraft vs. shuttle vs. ISS Generic vs. custom spacecraft Dedicated vs. shared spacecraft Primary vs. secondary spacecraft
Launch Vehicle Options
Shuttle vs. ELV Dedicated vs. shared ride



106 Options

Table 1: Logic Tree of Viable Flight Options

The next level of analysis is the selection of specific flight options, including specifying which platform and launch vehicle are used. For example, one selection might include a

LeoStar spacecraft bus as the platform and a Pegasus ELV as the launch vehicle. This added level of detail produces thousands of possible flight options. To model these flight options and understand their cost and risk, a tool is being developed to perform rapid analyses of multiple flight options.

Although the type and size of the individual system elements may vary greatly, Figure 1 is representative of the type of missions that this study considers. The terminology is highlighted in Figure 1 and is further explained in the following paragraphs.

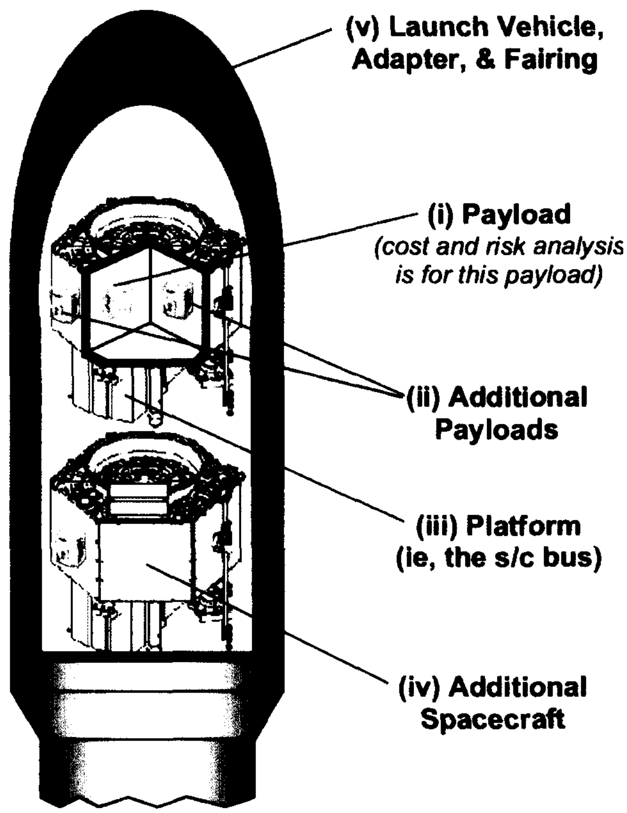


Figure 1: Primary System Elements for this Study

(i) The payload of the user, for which the system, cost, and risk estimates are generated. These are typically either science instruments or small experiments

(ii) Additional ridesharing payloads that share a common platform with the user

(iii) The platform (only spacecraft buses are currently considered, but as this work evolves other atypical platforms will be considered, including the shuttle, space station, and suborbital vehicles)

(iv) Additional ridesharing spacecraft that share a launch vehicle with the user

(v) The launch vehicle, which includes a fairing and adapter to accommodate the spacecraft

The objective of the tool being developed is to quickly evaluate the compatibility, cost, and risk of multiple flight options. This should be considered a high-level estimate for identifying the candidate flight options, and thus this evaluation must still be followed by detailed point designs for the purposes of design selection.

The next section of this paper presents the software architecture for the tool, followed by a section that discusses its supporting databases. The paper then uses the tool to examine potential rides (that is, access to space flight options) for eight small payloads that are listed on the Goddard Access to Space website[1] as presently looking for rides. The tool first determines which dedicated flight options (options that do not include ridesharing) are available for each payload and their associated cost and risk. Next, flight options for all combinations of these eight payloads are examined. These examples provide insight in studying the cost and risk of dedicated and ridesharing flight options.

Software Architecture

The architecture of the tool is shown in Figure 2, which is a conceptual representation of the actual framework based in Excel™. It is composed of three primary areas: the graphical user interface, the analytical engine, and the database. The graphical user interface interacts with the user to obtain inputs and display results. The analytical engine uses the user inputs to sort through all of the system elements to find the compatible options, along with estimates of system margins, cost, and risk. Finally, the database pulls the relevant information as needed.

The approach of this tool is to compare the compatibility of each system element with respect to a list of system requirements. These requirements include schedule, cost, risk, and technical performance specifications. For example, some of the more than 40 individual requirements are integration date, launch date, mass capability provided, mass capability required, power, volume, data rates, and others.

Each system element requires and/or provides some of these requirements. The tool then does comparisons to see if the requirements from the individual system elements are compatible to produce a single valid flight option. In most cases, the comparisons are fairly simple, such as checking to see if the launch vehicle provides sufficient capability to accommodate the spacecraft mass. The strength of this software is not in the detailed design comparisons, but rather in the ability to compare numerous system elements and surface those that show the potential of being compatible as more detailed point-designs are considered.

The first step of using this tool is entering the payload requirements, as shown in Figure 2. The requirements highlighted in red are required, and ranges may be entered in as necessary. The user is not required to enter data for every parameter, although additional data eliminates more options and produces a better overall analysis.

GE REQUIREMENTS			Current User Input (default)		
	Description	Units	Text		
A.1	Name		ST6 - 311 Example		
A.2	Developing Organizations		?		
A.3	Sponsor		?		
A.4	Funding Status		Fully Funded		
A.5	Description		Inertial Stellar Camera		
	Schedule	Units	Earliest	Mean	Latest
B.3	Integration Date	m-y	May-04		Apr-07
B.4	Launch Date	m-y	Jan-05		Dec-07
	Risk	Units	Min	Mean	Max
C.1	Reliability	[illegible]			
	Cost	Units	Min	Mean	Max
D.1	Cost	[illegible]			
				REQUIRES	
	Level 1 Requirements	Units	Min	Mean	Max
E.1	Power	Y/N	Y		
E.2	Nuclear subsystems onboard	Y/N	N		
E.3	Validation experiment duration	days	3		4
E.4	Toxic materials onboard	Y/N	Y		
E.5	3-axis attitude control	Y/N	Y		
E.6	Spin attitude control	Y/N	N		
E.7	Deployable components onboard	Y/N	N		
E.8	Separation distance required for multiple s/c	# of m / N		N	
E.9	Crew interface for control/monitoring	Y/N	N		
	Level 2 Requirements	Units	Min	Mean	Max
F.1	Mass	kg	1.5		3
F.2	Rectangular or Cylindrical Volume	R/C		R	
F.3	Height (shortest)	m		0.87	
F.4	Width (middle)	m		0.87	
F.5	Length (longest)	m		0.87	
F.6					
F.7					
F.8	Volume	m^3		0.658503	
F.9	LEO Circular, Elliptical, or High Energy	L/E/H		L	
F.10	Altitude	km	200		2000
F.11	Inclination	deg	28.5		110

Figure 2: Payload Requirements Sheet

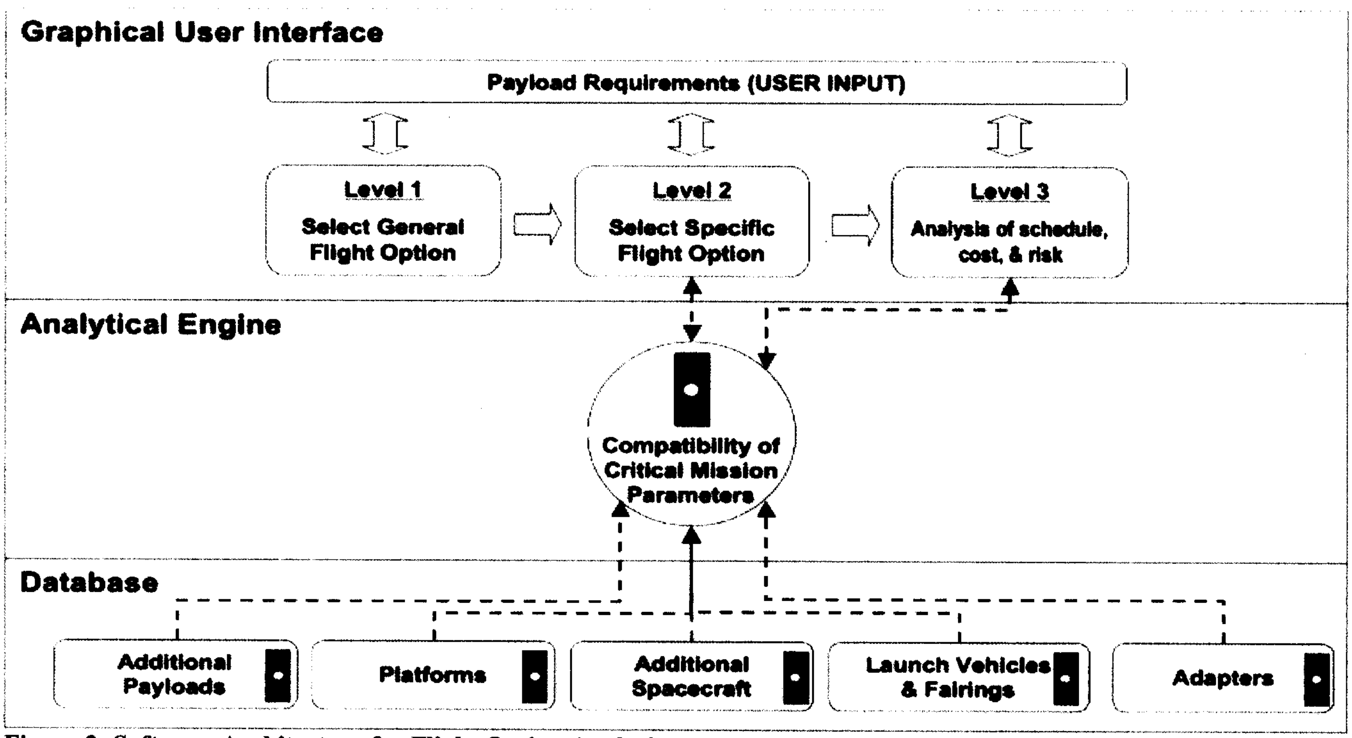


Figure 3: Software Architecture for Flight Option Analysis

A Level 1 analysis is the next step of using the tool. It consists of using the logic tree (of Table 1) to make an initial down-selection of what general options should be considered. For example, this addresses the questions of whether the user is interested in adding other payloads or spacecraft to the system concept or whether the payload should fly on a spacecraft, the shuttle, or the space station. The output of this analysis is a set of general flight options to be further analyzed in Level 2.

Figure 4 depicts a conceptual view of Level 2, illustrating how the compatibility of each system element is crosschecked with the requirements of the other system elements (shown in parallel columns). The compatibility is denoted by either a "Y", "?", or "N", as shown in the figure. Given the large amount of data required for complete comparisons, it is rare for a system element to be fully compatible. Instead, compatibility is generally identified with a "?", meaning that while there is some data missing, the data that is available shows that the system is compatible. The user may then look at the individual requirements to determine where the missing data or incompatibility is found. In this fashion, the user can select each element to produce an entire system concept.

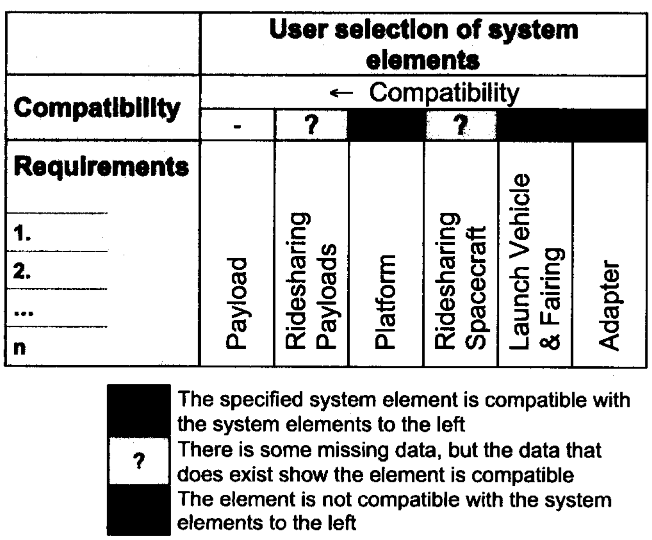


Figure 4: Conceptual View of Level 2

The user interface for Level 2 is accessed following the selection of a general flight option. The results of this prior selection aid the user in selecting the appropriate system elements that correspond with their earlier inputs.

Corresponding with Figure 4, there are a total of six columns in this user-interface. The first column is for the selection of the payload being considered. As a default, it assumes the payload requirements already entered are being used. The second column allows for the selection of four additional payloads (or instruments as labeled in the figure). The remaining columns correspond with the selections for the platform, additional spacecraft, launch vehicle, and adapter. Additionally, if ridesharing spacecraft are selected, the user may choose one primary spacecraft and/or up to three secondary spacecraft.

Below the area for selecting each system element is the list of system requirements. Of the more than 40 system requirements, only the first few are shown. The compatibility of each requirement is displayed, providing a quick visual aid for the overall compatibility of the system element chosen.

In this manner, the user can quickly sort through a large number of options to find which are compatible. Once a configuration is chosen, it can be saved for further analysis with respect to cost and risk (see Figure 5).

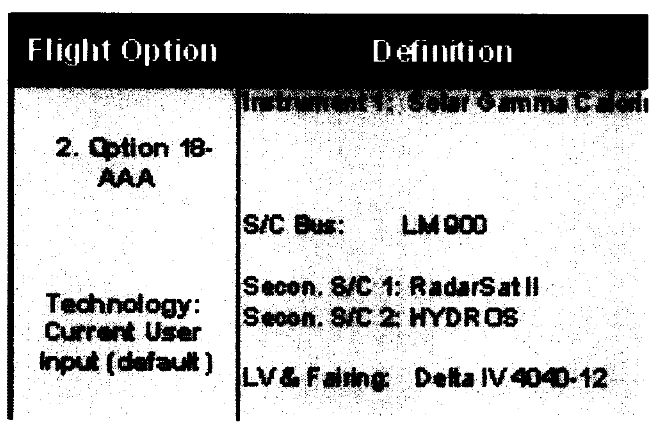


Figure 5: System Configuration Output

Additionally, Level 2 has the capability to automatically sort through all combinations of options to find those that are compatible. Thus, the user can generate results that show the trade space for a given payload or set of payloads.

Level 3 of the analysis calculates schedule, cost, and risk estimates for the proposed compatible flight option(s), as determined from Level 2. Schedule is calculated based on a few key constraints that are known from either the user-inputs or the system selections. These constraints include the start date, lead time for platform development, launch date, and mission duration.

The cost estimate for this model is straightforward, since specific system elements (with real costs) are being chosen. The cost is composed of the platform, launch vehicle, and integration costs. The platform and launch vehicle costs (which generally represent more than 95% of the cost) are known from industry sources, and the integration cost is estimated based on the number of elements and their complexity. Additionally, the cost is then reduced depending the number, type, and mass proportion of any partners that are sharing the platform or launch vehicle. It is assumed that additional partners will contribute funds proportionate to their mass fraction to as low as 10% of the cost.

Estimating project risk is more challenging, particularly for missions that rely on one or more ridesharing partners. To help understand the risks associated with these types of payloads, a fault tree was developed by the Futron Corporation (see Figure 6). This fault tree decomposes the high-level risks associated with launching spacecraft where several partners are involved. The primary areas of risk are listed in the following section.

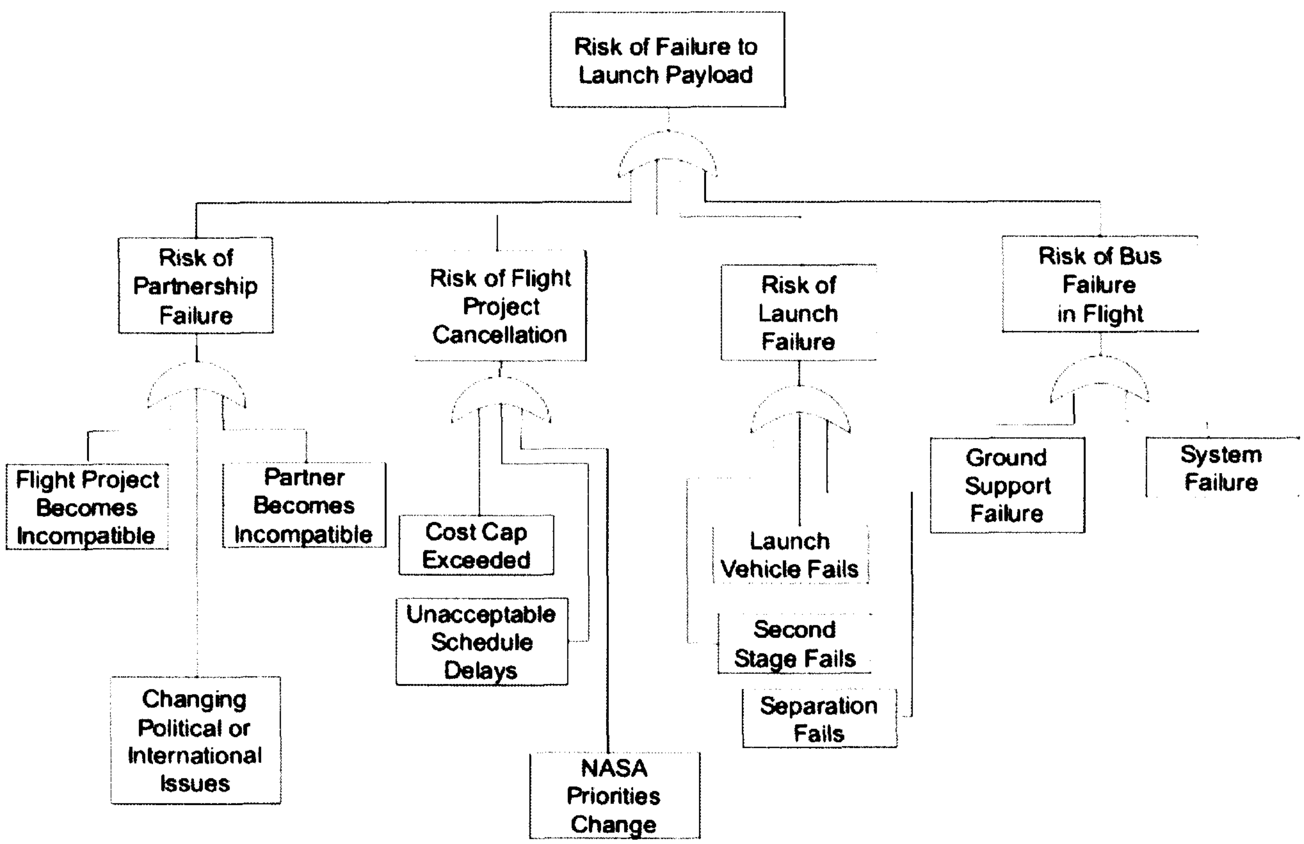


Figure 6: Preliminary Fault Tree for Flight Options (adapted from a fault tree chart by Barney Roberts, 2003)

- **Project Cancellation** – Resulting from cost and schedule growth related to technical challenges or management shortfalls
- **Partnership Failure** – Resulting from the withdrawal of one or more critical partners due to their internal priorities, funding, or technical challenges.
- **Platform or Launch Failure** – Resulting from the loss of critical systems

For estimating these risks, Futron has developed a risk model, which is being integrated into the software tool. The Fault Tree in Figure 6 describes the risk model. It combines user-inputs with data from the database to produce a risk index for each area listed. These numbers are then combined as either a maximum or a weighted average of the four risk areas to provide a total risk for the flight option. An example is shown in Table 2, which provides green, yellow, and red indicators to identify the severity of each risk. Although the analysis found later in this paper uses an aggregation of these risks, it is important to note that they cannot easily be combined and should, in general, be considered as a set.

Project Risks	Risk Index (1-100)	Risk Indicator
1. Project cancellation	16	[illegible]
2. Partnership failure	28	[illegible]
3. Launch failure	84	[illegible]
4. S/C bus or platform failure	32	**Medium**
Total Risk	40	**Medium**

Table 2: Example of the FLOAT Risk Matrix

Database Architecture

The tool has a large database of information that archives key information associated with each system element. This database contains the information in two formats linked together: raw data taken directly from a variety of NASA and industry databases and formatted data that can be directly used to cross-compare the requirements of each system element. This architecture allows for the relatively easy integration of new data, yet supports the cross-comparison capability that is central to the tool.

The database contains five types of information, gathered from a variety of sources (as shown in Table 3). Each area of the database includes brief descriptions, schedule information or lead-time, available funding or cost, risk metrics, key technical parameters, and contact information. The data is gathered from NASA, DoD, and industry resources, along with contacting specific individuals.

Area	Entry	Source
Payloads	13 looking for rides	GSFC Access to Space[1]
Platforms	23 RSDO and other s/c buses	RSDO catalog and industry partners[2]
Spacecraft	19 offering or looking for rides	GSFC Access to Space[1]
Launch Vehicles	40 NASA and US approved launch vehicles and fairings	KSC Expendable Launch Vehicles and USAF[3]
Adapters	35 primary and secondary adapters	JPL Launch Services Planning and industry partners[4]

Table 3: Types and Sources of Data

Given the sensitivity of the information, the data is entered into the database by manual entry, as opposed to linking electronically to online sources. Thus, the tool requires regular updates to ensure that the data is useful for current studies.

As the database expands to include other flight options (such as suborbital rockets, shuttle rides, space station racks, etc.), data will be gathered from other organizations such as NASA Wallops and the NRO. This trend will continue as the database evolves over time to provide a detailed library of flight options.

Case Study of Access to Space Payloads

To test this model and help validate the approach that was used, data from the NASA Goddard Access to Space site[1] was used as a test case. This data populates both the list of payloads that are being evaluating and a larger list of compatible payloads. Once the list of payload requirements was entered, it took approximately five hours for the tool to generate the results shown in Table 4, along with the data used in generating the remaining graphs. Additionally, only single spacecraft combinations were analyzed, and additional ridesharing spacecraft in the launch vehicle are not considered.

Designated Payload	Compatible Payloads	Compatible Platforms	Total Options
Possible Options	13	23	1.5M*
A	6	14	139
B	6	10	79
C	6	10	109
D	4	7	36
E	7	6	68
F	7	5	57
G	6	8	53
H	0	0	0
* 1.5 million possible permutations			541

Table 4: Compatible Flight Options

Table 4 shows the total number of permutations, along with the number of compatible flight options. The figure of 1.5 million represents the total number of permutations of payload and platform combinations. Of these, only 541 are compatible, suggesting two important insights: (i) there are few compatible options when looking for partners and (ii) it would be impossible to study all of these combinations individually. This highlights the advantage of being able to make quick comparisons based on a set of high-level requirements.

In Figure 7, the 541 options are graphed with respect to cost and risk. The result is a scattered plot that, while showing good data distribution, does not suggest that spending additional money reduces risk. In studying the data more closely, two reasons were found:

- Nearly all of the dedicated missions are launched from less used launch vehicles (such as the Pegasus and the Taurus), producing results that are both high cost and high risk
- Shared missions with multiple payload partners often require a larger launch vehicle (such as the Delta II) that coincidentally offers higher reliability, resulting in low risk and low cost.

The interplay of these two factors leads to a wide range of results. Additionally, Figure 7 illustrates the ability to survey a large amount of data and to quickly determine what the most suitable flight options may be. Since the results are not necessarily intuitively obvious, an investigator could spend a significant amount of time looking at individual options without finding a suitable one if they do not have access to automated searches.

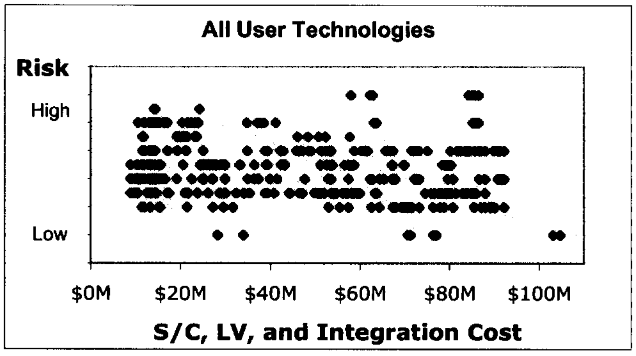


Figure 7: Cost versus Risk of All Flight Options

In Figure 8, several compatible flight options are examined for a specific payload, assuming a dedicated spacecraft (that is, no additional or shared payloads). The results show that the lowest cost flight option has a risk that is comparable to the higher cost flight options. From this figure, a project engineer might select the last two or three flight options to do a more in-depth analysis.

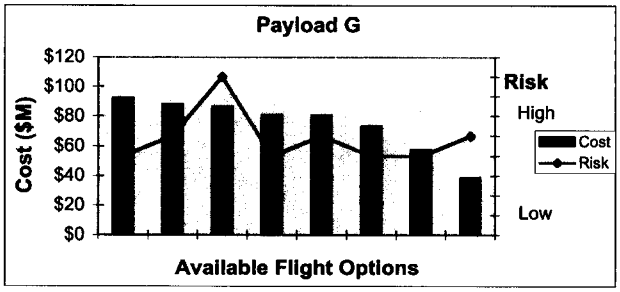


Figure 8: Flight Options for Single, Dedicated Payload

Additionally, comparisons may be made between multiple payloads, each of which is flying on a dedicated spacecraft. The results of this comparison are shown in Figure 9. Of the seven payloads with compatible flight options, Figure 9 shows how their cost and risks compare. Setting aside the function of each payload (such as the type of science instrument), the graph provides insight on which payloads may have higher or lower cost and risk.

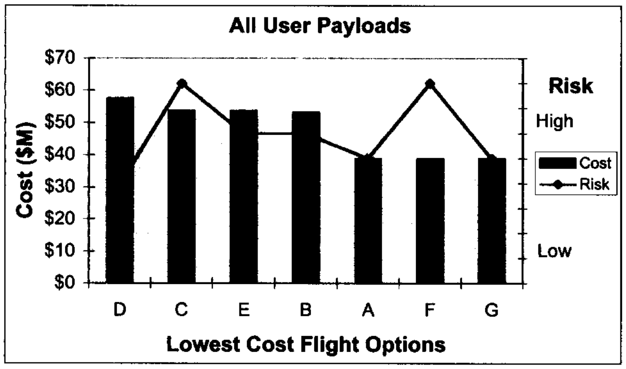


Figure 9: Lowest-cost Flight Option for each Payload

The graphs above emphasize estimating the cost and risk of dedicated missions. However, it has been suggested that adding additional payloads (that is, cost and risk sharing partners) might sufficiently reduce the cost to justify the increased risk. Thus, the payloads were further analyzed by adding combinations of payloads flying together on the same spacecraft bus. Figure 10 shows the number of compatible flight options given one to four additional payloads. There are two predominant effects that produce the hill-shaped curve. As the number of payloads increases, the number of permutations increases exponentially. However, the capability to integrate more and more payloads on a single spacecraft bus and launch vehicle becomes more difficult. For this set of payloads, it is very difficult to add more than three independent payloads.

As before, each individual payload was also studied to determine which flight options are available, depending on the number of partners. Figure 11 shows this relationship for Payload G, which is representative of the other payloads. The figure shows that there is significant benefit for adding one partner, but that adding additional partners will not lower the cost sufficiently to justify the increased risk.

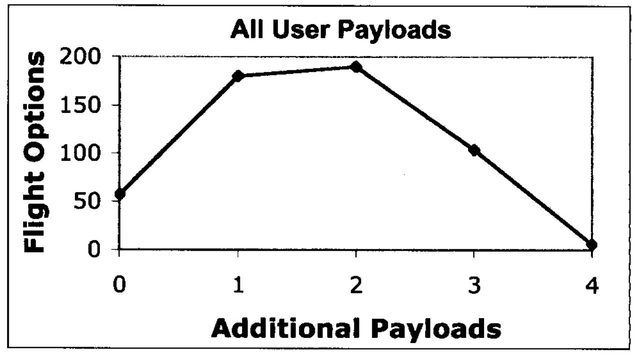


Figure 10: Number Compatible Options versus Additional Payloads

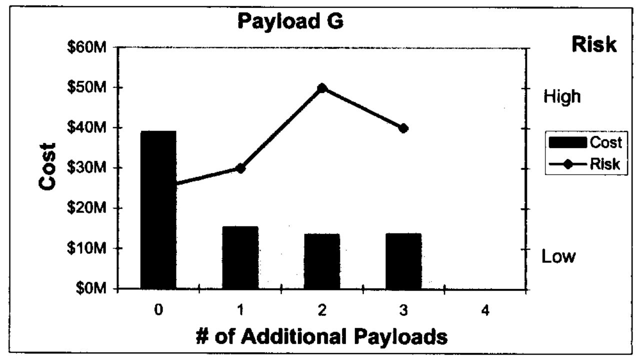


Figure 11: Cost/Risk for a Shared Spacecraft

In Figure 12, the average cost and risk are displayed for all of the payloads versus zero through four additional partners. This graph, which includes standard deviations, clearly supports the trend in Figure 11 that adding a single partner is advantageous, but adding any more partners can greatly increase the risk with only minor reductions in cost.

The underlying reason for the trend in Figure 12 is the increasing difficulty of adding more partners. A single partner that has matching requirements *and* fits on a low cost spacecraft bus is much easier to find than several payloads that also fit. Thus, while additional instruments can be combined into one low-cost flight option, the added requirements and increased risk may not justify this approach. This conclusion, however, is only valid for this set of data, which is biased towards payloads that have had more difficulty in finding rides. As this work continues, larger data sets will be studied to determine how they compare to these results.

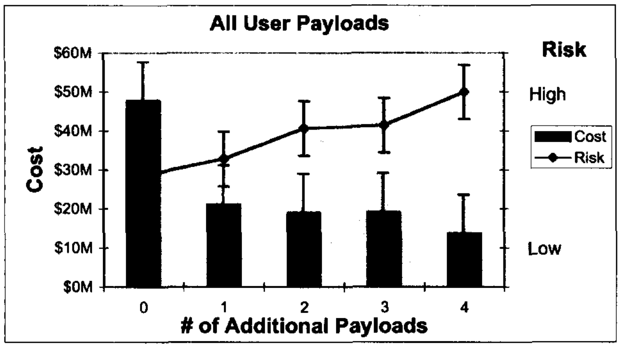


Figure 12: Average Cost/Risk for a Shared Spacecraft

Conclusion

Optimizing access to space options is a complex problem that requires significant definition in the project in order to reduce the risk of finding a reliable, low-cost ride. However, in designing and building small payloads or spacecraft, it is vital to understand the trade space for flight options, including the cost and risk of pursuing various alternatives. To address this difficult problem, a tool was created to define first order system, cost, and risk estimates for the flight options of small payloads.

In addition to producing quick estimates for a range of payloads, the tool provides a consistent method for evaluating alternatives, along with understanding the minimum cost necessary for gaining access to space.

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Author Biographies

The authors are from the Jet Propulsion Laboratory in Pasadena, CA. Jim Chase, a staff engineer, is developing the tool as part of an effort to identify and utilize less expensive flight options for validating new technologies. Additionally, Jim is a member of JPL's Team X, where he performs mission design and trajectory analysis. Rebecca Carter is an associate engineer working with the team to analyze flight options and maintain the database. Jeffrey L. Smith is managing the task, and he has considerable experience as the former director of the Project Design Center.