An Analysis of Low Earth Orbit Launch Capabilities

Final Project Report
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1.0 Executive Summary

Constantly changing political agendas have stagnated the progress of a space industry that relies on NASA and other government agencies for its growth. The private sector has responded to this challenge in the last ten years, with a flood of space-related investment from space tourism to innovative rocket design. SPEC Innovations hopes to take advantage of investment opportunities available in the private space sector by implementing their Interstellar Action Alliance project. This initiative is a long-term space exploration plan that uses private sector investment and a series of stepping-stones with individual Return on Investment to go from where we are today to interstellar travel. The first step in this project is to establish a permanent base in Low Earth Orbit, which can facilitate construction, and can be a base of operations for longer-range missions. A primary concern in the construction of this permanent base is the cost and feasibility of transporting materials and construction workers to Low Earth Orbit.

This project is an analysis of the current Low Earth Orbit Launch (LEO) Capabilities of Technology Readiness Level (TRL) of seven or above according to the NASA TRL scale. Constraints and goals were set by SPEC Innovations to provide bounds for the proposed model. The primary goals consisted of transporting 1000 metric tons of material to LEO in a timeframe of 30 months with a maximum total cost of $32 Billion.

The team constructed an optimization model taking into account the following variables: cost per launch, turnaround time, mass transporter, capability provider, and TRL for each launch capability. Both man-rated and pure cargo launches were considered with the ability to mix cargo and man-rated launches. The optimization model was executed to determine which mix of launch capabilities would be optimal for transporting the mass and personnel to LEO.

Once these original optimal launch methods were determined the team conducted an extensive sensitivity analysis on the parameters of individual launch capabilities and groups of capabilities. This sensitivity analysis was performed in part to determine how sensitive the optimal solution was to changing variables, however another important goal was to account for risk involved with immature technologies. The risks of cost estimation for immature technologies were mitigated by providing optimal ranges for the costs for these technologies to account for variation. Another risk addressed was the possible consequences of political dispute resulting in certain countries' technologies becoming unavailable. The result of removing these technologies from the list of possibilities was considered and studied through model variation.

Through many iterations of the model it becomes apparent that limiting choices has the repercussion of raising the total costs required in order to achieve objectives. In general it is more expensive across the board when eliminating choices, as there are not as many combinations present to mix and match. It was also determined that if either the Falcon Heavy or the Proton Launch Vehicle were to become unavailable, total project cost would increase $200-$300 Million. It was also determined that without the Falcon Heavy launch vehicle, the total number of launches needed to complete the mission would increase by around 1/3. This leads to the conclusion that the Falcon Heavy and the Proton Launch Vehicle are the most promising technologies for use by SPEC Innovations.

2.0 Problem Definition

2.1 Introduction

On June 28th, 2010 President Obama revealed his administration's space policy and vision. A New York Times article on that same day reflected upon how this policy demonstrated the changing climate in the space industry. Authors Broad and Chang remark "On the civilian use of space, the policy…. puts renewed emphasis on the commercial space industry, reflecting the administration's desire to get the National Aeronautics and Space Administration [NASA] out of the business of launching astronauts." This policy, which comes in direct opposition to the Bush Administration's policy of placing astronauts on the moon, demonstrates several key components of the changing climate of the space industry. The first is the instability of government agencies, such as NASA to conduct a concentrated long-term effort without significant setbacks due to administration policy changes. Each new administration has its own vision and set of policies regarding space programs and in the domain of long term projects like the space industry it can be difficult to maintain cost and schedule. USA Today estimates that the USA has spent $9 billion and 6 years of research on the Bush administration shuttle program, much of which must be scrapped with Obama's new agenda. A second component of the changing space industry is the influx of private industry, particularly in the area of launch capabilities. Another news article from Space.com names eight wealthy individuals worth a combined $64 billion, who are investing in the privatized space industry, in everything from space tourism and launch capabilities to asteroid mining. Private companies are able to avoid the challenges that government agencies face, and produce results in a quicker and more efficient way.

A good example of the difficulties faced by government-controlled projects is the International Space Station. The International Space Station (ISS) has been under construction since 1998 and cost the U.S. alone an estimated $150 billion. The difficulties with this effort include a phased construction plan, lack of an overall construction plan, difficulty with international cooperation, and escalating costs among other shortcomings. Many of these shortcomings could be overcome with the proper application of competition through private industry. The ISS provides an excellent case study that can be learned from in future efforts to create permanent bases in orbit above the earth.

2.2 Sponsor Involvement

SPEC Innovations is a small, system engineering firm located in Manassas Virginia. It was established in 1993 and provides SPEC Innovations provides a variety of technical and proposal development services for government and commercial customers. Their experience ranges from advanced concept technology demonstrations to enterprise architecture developments to system designs to test and evaluations to operations and maintenance.

In early 2011, Defense Advanced Research Projects Agency (DARPA) released a Request for Proposal (RFP) offering seed money for any company that would be able to develop a sustainable model for an organization to build a vehicle capable of interstellar travel. SPEC Innovations responded to this RFP with a plan for the slow but steady buildup of a space infrastructure that would be sustainable, profitable, and allow for long-term space exploration, extending even to interstellar travel. This plan, called the Interstellar Action Alliance (IAA), is based on initial research providing recommendations to SPEC in terms of the technologies to be focused on and the research to fund. Investments will be gathered based on these recommendations and RFPs released to private companies to build the pieces of the infrastructure on a contract basis. This gradual build up will continue until a permanent space infrastructure is completed and work on a starship can begin. One of the primary tasks associated with the IAA is the initial research that provides the basis for investors to support the initiative, providing the money to fund research. This project fills a critical role in the IAA by providing analysis and modeling of the launch capabilities available to put mass into low earth orbit, enabling the potentially profitable construction of permanent infrastructure in space due to a reduction in launch costs.

2.3 Need Statement

There are over 100 different launch capabilities for placing mass and astronauts in Low Earth Orbit (LEO). SPEC Innovations, Interstellar Action Alliance will require use of some of those capabilities to place both men, and construction materials in LEO for construction of a permanent space platform. SPEC Innovations and associated investors have limited resources and require an optimal use of their materials to meet IAA goals. Therefore SPEC Innovations is in need of a detailed analysis of the current launch capabilities, in order to choose capabilities that optimally meet IAA goals while minimizing cost and schedule.

2.4 Problem Statement

This project will provide a detailed analysis of differing launch capabilities for placing mass and astronauts into LEO. This analysis will be based on attributes of Cost, Schedule, Launch Load, and company past performance for each launch capability. It will provide an optimal set of man and cargo launch capabilities, given certain characteristics, which can be used by SPEC Innovations to make informed decisions regarding the feasibility of pursuing IAA.

2.5 Project Scope and Objectives

The primary objectives of this project, relating to both SPEC Innovations' needs and the considerations of George Mason University are as follows:

- Demonstrate the ability to provide problem definition, stakeholder analysis, operation modeling, analysis of results, and a viable way forward to our sponsor.
- Demonstrate the training and skills received from the George Mason University SEOR department and the ability to apply those skills to a diverse set of problems.
- Provide SPEC Innovations with an analysis of current launch capabilities, giving them reasonable estimates regarding the implementation of the launch capabilities portion of the IAA, as well as an optimal mix of launch capabilities given current cost and schedule constraints.
- Provide SPEC Innovations with an analysis of our resulting including a sensitivity analysis for our optimization model, demonstrating how the optimal set of launch capabilities are sensitive to variation within model inputs.
- Provide SPEC Innovations with a risk analysis of current launch capabilities, taking into consideration the risks involved in various launch capabilities and focusing in particular on the companies or governments providing the capabilities.
- Provide SPEC Innovations with recommendations for possible future efforts continuing the work detailed in this paper as well as future efforts centered on the IAA.

These recommendations bring to bear several scoping constraints that define the problem addressed in this paper. Due to time constraints and the needs of our sponsor the analysis model was unable to address every aspect of this problem, however there was significant value added to our sponsor in the scope of the problem addressed. These scoping concerns are detailed below:

- We were given a timeframe of execution for the launch techniques of 5-10 years. This means that we will not consider launch capabilities that could be developed in the future. We consider only capabilities that are immediately available or will be available in 5-10 years. This eliminated many technologies that are in early stages of development.
- Each company or government agency that provides a launch capability to our sponsor would be considered a contractor on the IAA project. This means that as such they will handle all construction, licensing, and interaction with government airspace agencies. Any discussion of timeframes for construction of

launch capabilities, or consideration of interaction with space control agencies will be handled by the contractor is considered out of scope for this project.

- Furthermore any consideration of how the material will be converted from the launch vehicles and be constructed into a space station will be considered out of scope for this project. Aside from a basic constraint involving the number of construction workers needed per given time frame any construction scheduling is not in the scope of this project.
- The possible risk of collision with space debris is also not considered in the scope of this project. It is understand that the large amount of debris in Low Earth Orbit is a serious flight risk for any launch vehicle, however our analysis is exclusively considering cost and schedule of launch capabilities, not risks involved in launch.
- Finally we assume that the numbers provided by companies and agencies are considered accurate to the best of our ability. It is understood that projects of this magnitude often have greater costs then are reported by the capability provider, however it is not the goal of this analysis to determine the accuracy of a particular providers' costs. This project is focused on comparing different launch capabilities not validating those capabilities cost estimations.

2.6 Stakeholders

There are three primary categories of stakeholders involves in this project

a) Private sector:

   i. Potential investors: These are the parties that are involved in investing in space travel. Some are actively involved yet and some are passive. They provide the resources at their disposal to fund space initiatives.

   ii. Primary Stakeholder: SPEC Innovations are the primary stakeholder for this project as they put together all the resources to create a blue print on how the project is going to be carried out and return on investment to the investors

   iii. U.S. Launch Capability Providers: The most promising of these is Space X. These are the companies whose business is to provide and launch capabilities to LEO.

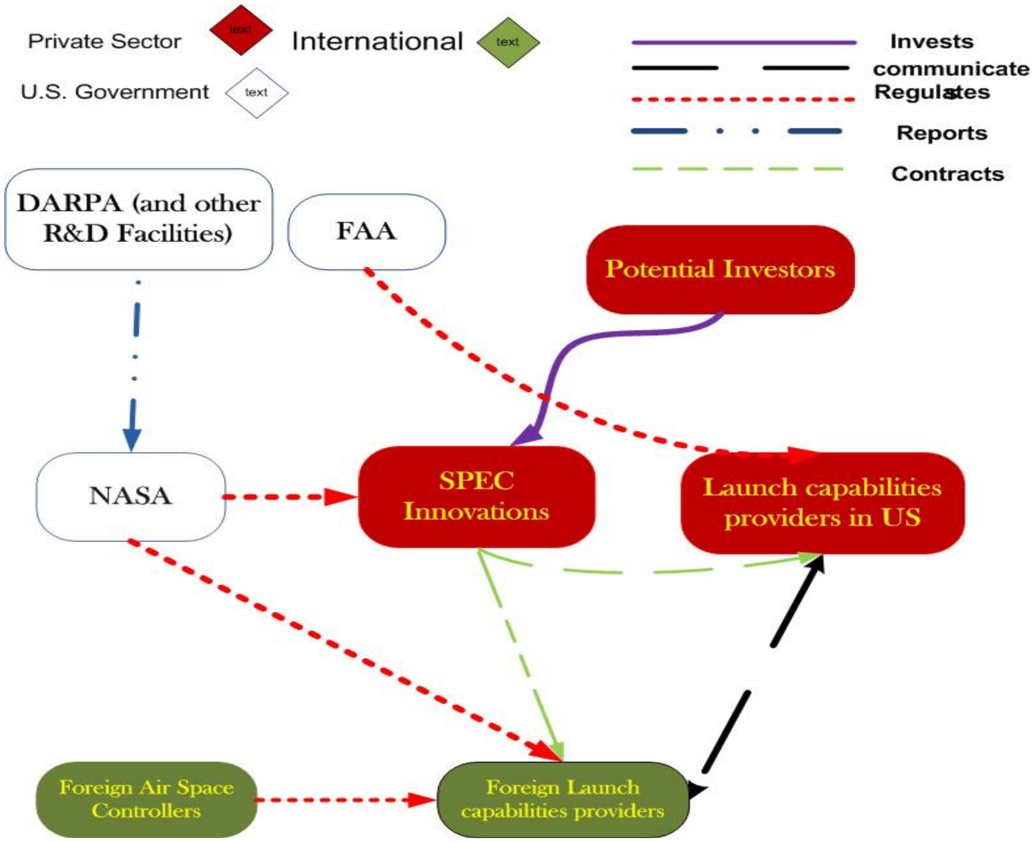
b) US Government agencies:

   i. NASA: The National Aeronautics and Space Administration (NASA) is an American government agency that runs the civilian arm of the space program. The aim of NASA is to increase human understanding of the solar system and the universe that contains it, and to improve American aeronautics ability. NASA as part of its mission cooperates with agencies within the United States and international aeronautics agencies. This fostering of international cooperation will hopefully continue as humans explore space and the possibility of off-Earth human settlements becomes possible. NASA also actively team up with companies in the private sector in developing new and safer technologies for commercial air travel.   NASA is responsible for man-rating the launch vehicles, certifying them to carry passengers.

ii. FAA: This is the government agency that regulate and oversee all aspects of civil aviation in the U.S. they also Regulate civil aviation to promote safety within the U.S. and abroad. The FAA exchanges information with foreign aviation authorities. Regulating U.S. commercial space transportation. The FAA licenses commercial space launch facilities and private launches of space payloads on expendable launch vehicles.

iii. DARPA: This is the government agency within the DoD that apply multi-disciplinary approaches to both advance knowledge through basic research and create innovative technologies that address current practical problems through applied research.

c) International Aeronautics: This is the group of the foreign agencies or governments that would be involved in space transportation. Due to the complex nature of this project, many foreign Space capabilities like Proton would be involved, it is important that international laws guiding space travel are put in consideration and they too be in constant communication with NASA and FAA to ensure smooth running of the project.



Stakeholder Interaction Diagram

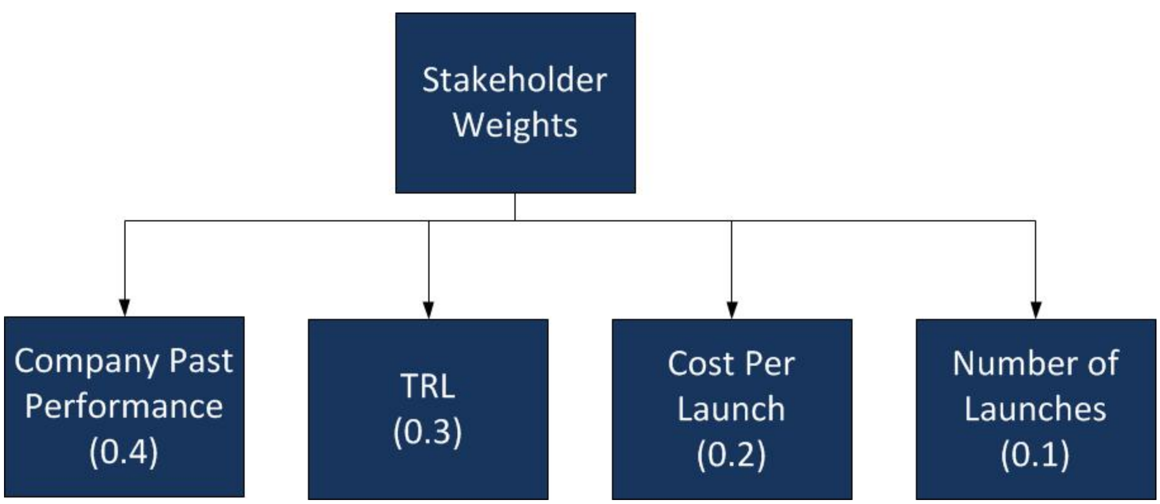
2.7 Stakeholder Value Function

An important aspect to the success of this project is an understanding of what is important to our primary stakeholder, SPEC Innovations. The importance placed on certain attributes of the launch capabilities by our sponsor will determine which capability we ultimately recommend to be used in the pursuit of IAA. The important attributes of the analysis of launch capabilities are as follows:

- Launch Companies Past Performance. This attribute deals with the launch capability provider whether that is a foreign government, a U.S. Government agency, or a private company. The companies past performance is the single most important factor in our model to our stakeholder. The extreme risk involved in long term launch capability projects makes new companies a potential liability. A company or entities past performance is the greatest indicator as to their potential future success and thus is weighted of highest importance by our stakeholder.

- Number of Launches required to reach a set minimum threshold. This attribute reflects the weight carried by each rocket per launch. Due to a target of 1000 metric tons set by our stakeholder the number of launches required to reach that threshold by a particular launch capability is a attribute that our stakeholder cares about and is reflected in the decision analysis.
- Cost per Launch. This attribute deals with the cost per launch. As with any large project, keeping costs low is always important to our stakeholders and thus must be considered in the weight function.
- Technology Readiness Level (TRL). The TRL for a particular technology is an estimation of how soon the technology will reach full capability, essentially a measurement of maturity for a launch capability. The team is using NASA's TRL maturity model to estimate the TRL of any particular technology. This factor is also important to our stakeholder due to a constraint of this project being completed in the next five to 10 years. This means that a greater maturity in a model will reduce the risk of depending on that technology and allow an expedition in the next five to 10 years.

The weights of each factor for our model were gathered from interview with our sponsors Dr. Steven Dam and Dr. Keith Taggart of SPEC Innovations. Using a swing weight analysis method the weights were calculated using input from these interviews and are displayed below.



The weight company past performance is a particularly difficult one determine due to the subjective nature of this weight. It was impossible to estimate this from the literature available, therefore for every company or government entity considered in the model, we elicited values from our stakeholders. Through email and interview, each company was ranked on a scale of zero to one where zero is not trusted at all and one is most trusted. These weights allowed us to see the value our stakeholder placed on each launch capability provider. This table as well as the weight elicitation method is available in Appendix C.

Although it was not possible due to time constraints to include the weight functions directly into the model we were able to analyze the results of our model based on these weights, giving us more insight into the needs of our sponsor. This was accomplished in two ways:

- SPEC Innovations weighed company past performance as the most important factor in choosing a launch capability. Therefore we ran several variations of the model based on this attribute, eliminating some companies and seeing optimal results in several different cases.
- A second way in which these weights were factored into our model is in the elimination of low rated launch techniques. Companies that were rated below a 0.4 by our sponsor were eliminated from the model in one variation in order to determine what companies would be considered optimal under these conditions.

3.0 Technical Approach

In order to provide useful information to Spec Innovations pertaining to capabilities and costs of various launch methods, it was necessary to create an optimization problem. The good thing about an optimization problem is that once the costs, mass transported and turnaround times are more concretely defined, the model can easily be adjusted to account for this. At any rate, it is necessary to include the following disclaimer: the numbers presented, results, and conclusions drawn are based upon the availability of data at this point time and are therefore subject to change.

Before creating the model in MPL, the first objective was to create a generic mathematical model that accurately represents what would later be modeled. This is represented below:

$$min \sum_{i}^{j} C_i X_i + \sum_{k}^{l} C_k Y_k$$

$$such\ that:$$

$$\sum_{i}^{j} S_i X_i, \sum_{k}^{l} S_k Y_k \leq t \ \ (time\ constraint)$$

$$\sum_{i}^{j} W_i Y_i + \sum_{k}^{l} W_k Y_k \geq 1000\ (weight\ constraint)$$

$$\sum_{k}^{l} Y_k \ \geq 10\ (personnel\ constraint)$$

$$X_i, Y_k \in \mathbb{Z}$$

$X_i = cargo\ launch\ of\ type\ i$
$Y_k = mixed\ launch\ oftype\ k$
$C_i\ = cost\ per\ launch\ of\ type\ i$
$C_k\ = cost\ per\ launch\ of\ type\ k$
$S_i\ = Setup\ time\ per\ launch\ of\ type\ i$
$S_k\ = Setup\ time\ per\ launch\ of\ type\ k$
$W_i\ = Mass\ transported\ per\ launch\ of\ type\ i$
$W_k\ = Mass\ transported\ per\ launch\ of\ type\ k$
t = turnaround time between launches

Several variations of an optimization problem were created in order to account for different scenarios that may occur. The first base model consists of a cost minimization, based upon the desire to transport 1000 metric tons over the course of two and a half years, excluding the turnaround time constraint. By solving this problem first as a cost minimization problem, and then adding the turnaround constraints in subsequent models, it can be gauged when there is an effect on the optimal solution.

The objective function demonstrates the desire to minimize the cost, with each launch method's cost included as a coefficient:

```
MIN

        Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105
               + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111
               + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 +
               13X118 + 40X119 + 61X200 + 48X201 + 45X202
```

Concerning the constraints, one of the first challenges encountered was a lack of availability of "turnaround times", which is defined here as the time taken between launches to perform cleanup, as well as the preparation of the rocket and launch site for another launch. These numbers are held in quite a high level of confidentiality, so it was expected and understood when the companies contacted to obtain these figures labeled such information as proprietary. In order to mitigate a lack of data with respect to this figure, there are scenarios starting from no turnaround time, and ending with a turnaround time that renders the problem infeasible. It is also worth mentioning that infeasible is to mean that solving the problem is impossible, as opposed to what Spec Innovations may label as unrealistic for its purposes.

Turnaround time is computed by dividing the number of days available, by the number of days required on average, to perform turnaround tasks. Since this is an unknown quantity for all launches, there was a decision to make this average consistent for all launch methods. For the base models, the following turnaround times have been included:

Total Time (Days)	Turnaround Time (Days)	Turnaround Constraint
900	0	0
900	30	30
900	60	15
900	90	10
900	100	9
900	112.5	8
900	128.6	7

900	150	6
900	180	5
900	225	4
900	300	3
900	450	2

As can be seen from the spreadsheet above, the number of times a given launch method may be utilized is directly related to the turnaround time allotted to each launch. Since the vast majority of the launch methods compared use different launch sites, the limitation only applies to the continued use of an individual launch method since the statistic is meant to be used independently in relation to each launch method.

One hard constraint that exists consistently throughout all of the variations of the models is the weight transport constraint. This enforces the requirement of 1000 metric tons, which must be satisfied in all models. While there were some thoughts of performing sensitivity analysis relative to mass capacity of a chosen launch method, the data obtained for each launch method is not conducive to it. There are only a few methods of transport, capable of carrying a large amount of mass per launch, while the rest have comparable costs and capacity. So even by varying the weight of a launch by a small amount, a completely different solution, consisting of a different launch (of small size) may satisfy the new requirements. This is however, only an affect to be had on the smaller capacity launch methods, and does not affect the solution as it pertains to the larger launch methods. The weight constraint is shown below:

```
50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106
+ 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 +
17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200
+ 4.2X201 + 4.6X202 >= 1000;
```

An additional constraint present in this model is the requirement to have six astronauts in space at a time, with each team staying in space for six months at a time. There are only four launch methods in the model that are man rated for the transport of astronauts into low earth orbit. An assumption built into the model is that each individual manned launch can carry 3 astronauts. Since the time constraint to build the space station is two and a half years, there must be 2 launches, every six months to carry astronauts to space. This is represented below as follows:

```
3X100 + 3X200 + 3X201 + 3X202 >= 30;
```

By making the number of manned launches greater than or equal to 30, it allows manned launches to be used in the case that there is only a small amount of cargo needed to be transported, but does not warrant a cargo only launch, which is universally more expensive. The coefficient of three on each launch method represents the number of men each launch transports. The statement that it must be equal to or greater than 30 stems from six astronauts being transported every six months. Since all coefficients are divisible, this can be further reduced the final representation of:

```
X100 + X200 + X201 + X202 >= 10;
```

It is important to demonstrate this simplification in order to show that should the manned capacity of a given launch method change, it can be easily represented by using the non-reduced form of the constraint. With the simplified constraint, a total of at least ten manned launches must be executed in order to satisfy this constraint. Another factor included in the model is that manned launches are all capable of carrying different amounts of cargo into space. From research, it has been determined that six astronauts need approximately 2.5 metric tons of supplies such as food, water, and oxygen every three months. In order to account for this nuance, all manned launches have a reduction in cargo of 2.5 metric tons represented in the weight transport constraint. This satisfies the requirement of six astronauts having five metric tons of supplies for every six months by each manned launch, in essence transporting their own supplies for sustainment in low earth orbit.

Man Rated Launches				
Capability	**Cost per launch**	**Mass to LEO**	**Company**	**Mass - supplies (for manned)**
Falcon Heavy	128	53	Space X	50.5
Zenith-2M	61	13.9	Yuzhnoye Design Bureau	11.4
Soyuz-U	48	6.7	TsSKB-Progress	4.2
Soyuz- FG	45	7.1	TsSKB-Progress	4.6

The far right column shows the actual cargo minus supplies transported per manned launch. This is incorporated into the weight constraint as follows:

```
50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106
+ 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 +
17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200
+ 4.2X201 + 4.6X202 >= 1000;
```

The final constraint, which is universally present in each variation of the model, is the requirement that each variable is an integer. This is necessary because it is not possible to have a fraction of a launch that would transport cargo into low earth orbit. This is represented in MPL accordingly.

```
INTEGER
        X100, X101, X102, X103, X104, X105, X106, X107, X108, X109,
        X110, X111, X112, X113, X114, X115, X116, X117, X118, X119,
        X200, X201, X202;
```

Aside from cost minimization models, also included are models where the goal to minimize the total number of launches is present. This is useful in the case that cost is not of the highest priority. The model is almost identical except for the elimination of coefficients in the objective function:

```
MIN

        Trips = X100 + X101 + X102 + X103 + X104 + X105 + X106 + X107 + X108
               + X109 + X110 + X111 + X112 + X113 + X114 + X115 + X116 +
               X117 + X118 + X119 + X200 + X201 + X202
```

This gives a minimum number of trips required in order to satisfy the constraints of the model, which mirror the cost minimization models. Since there are no costs written into the objective function, this is a tool to show an absolute minimum number of trips required. From this, turnaround times needed for each launch method can be deduced by dividing the total time by the number of launches chosen.

To illustrate the fully constructed model, below is an example with a 60 day turnaround time.

```
TITLE Project_Full_Model_No_limitation_on_Diameter_No_limit_on_TRL

MIN

        Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105
               + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111
               + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 +
               13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

        50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106
        + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 +
        17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200
        + 4.2X201 + 4.6X202 >= 1000;

        X100 <= 15;
        X101 <= 15;
        X102 <= 15;
        X103 <= 15;
        X104 <= 15;
        X105 <= 15;
        X106 <= 15;
        X107 <= 15;
        X108 <= 15;
        X109 <= 15;
        X110 <= 15;
        X111 <= 15;
        X112 <= 15;
        X113 <= 15;
        X114 <= 15;
        X115 <= 15;
        X116 <= 15;
        X117 <= 15;
        X118 <= 15;
        X119 <= 15;

        X100 + X200 + X201 + X202 >= 10;

INTEGER
        X100, X101, X102, X103, X104, X105, X106, X107, X108, X109,
        X110, X111, X112, X113, X114, X115, X116, X117, X118, X119,
        X200, X201, X202;

END
```

Results will be presented in two different forms. There will first be results given as computed by MPL. Included will be an emphasis on sensitivity analysis stemming from "what-if" scenarios. The sole purpose behind providing this analysis is to solve the problem in the optimal manner specified, whether it is cost minimization, trip minimization, or scenarios analyzing the readiness and capabilities of individual launches. The value of this to Spec Innovations should be to have analysis of how their goals can be achieved through any combination of these specified launches, subject to the decided constraints.

Additionally, there will be another results section focused on analyzing the scenarios Spec Innovations finds desirable and/or realistic for its purposes. There may be companies that Spec Innovations feels are not reputable or reliable, and would therefore be eliminated according to their criteria. Although this project may serve as a way of showing Spec Innovations other alternatives to what it has in mind moving forward, there is a recognizance that there also should be an effort to meet its needs.

The table below illustrates the attributes for the launch capabilities involved in our model. A total of 23 launch methods were researched into during the course of this project. Some are in operation and some are in development. All capabilities are either cargo or mixed man and cargo.

Capability	Cost per launch ($ ' million)	Mass to LEO(' 000 kg)	Company	TRL	Type
Falcon Heavy	**128**	**53**	**Space X**	**7**	**Mixed**
Ariane 5ECB	**165**	**21**	**EADS Astrium**	**8**	**Cargo**
Chinese Long March5	110	25	CALT	**7**	Cargo
Chinese Long March3B	105	21.6	CALT	**9**	Cargo
Proton launch Vehicle	**95**	**44.2**	**Krunichev**	**9**	**Cargo**
Space Launch System SLS	**270**	**70**	**Allianttech system/ Boeing**	**7**	**Cargo**
Delta IV heavy	**271**	**25.8**	**United Launch Alliance**	**9**	**Cargo**
H-IIB Launch Vehicle	**165**	**19**	**Mitsubishi Heavy Industry**	**9**	**Cargo**
Ariane 5ECA	**165**	**21**	**EADS Astrium**	**9**	**Cargo**
Ariane 5ES	**165**	**21**	**EADS Astrium**	**9**	**Cargo**
Antares	45	5	Orbital Sciences	**7**	Cargo
PSLV-HP	17.5	3.7	ISRO	**9**	Cargo
GSLV- MkIII	54	10	ISRO	**7**	Cargo
Atlas V 541	180	15.3	United Launch Alliance	**8**	Cargo
Atlas V 531	170	17.1	United Launch Alliance	**8**	Cargo
Zenith-2M	61	13.9	Yuzhnoye Design Bureau	**9**	Mixed
PSLV-XL	36	3.8	ISRO	**9**	Cargo
Chinese Long March 4C	35	4.2	CALT	**9**	Cargo
Chinese Long March 4B	42	4.2	CALT	**9**	Cargo
Soyuz-U	48	6.7	TsSKB-Progress	**9**	Mixed
Dnepr-1	13	4.5	Yuzhnoye Design Bureau	**9**	Cargo
soyuz-2	40	7.8	TsSKB-Progress	**9**	Cargo
Soyuz- FG	45	7.1	TsSKB-Progress	**9**	Mixed

4.0 Results

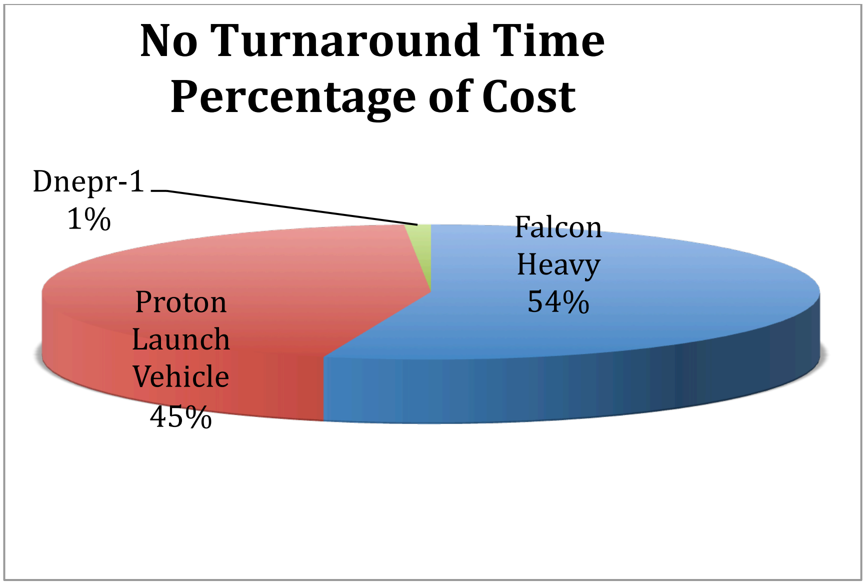
4.1 Results (without Individualization)

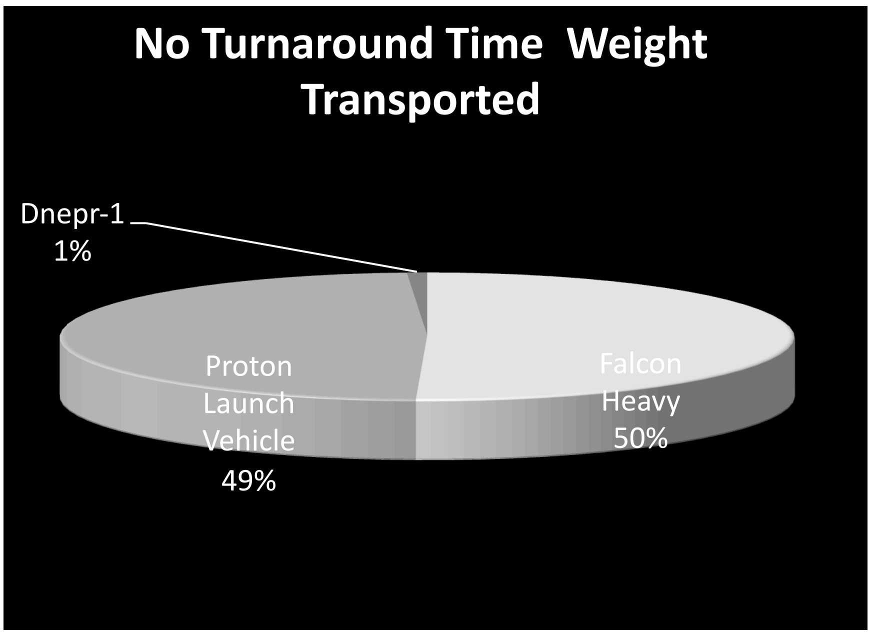
A. Turnaround Times Results

Turnaround times proved to be one of the most elusive statistics in the data gathering process. To mitigate the lack of availability of this data, a decision was made to represent the data as an average amongst all launch methods, and to be applied uniformly. To provide a baseline against which to compare, the optimization model was solved without turnaround times initially.

1. No Turnaround Time Results

With turnaround time excluded, the absolute minimum method of solving the optimization is given. In this scenario, it is found that by having 11 launches of the Falcon Heavy, 10 launches of the Proton Launch Vehicle, and 2 Dnepr-1 launches, all requirements can be met at a cost of $2.351 billion. 1000.2 metric tons are transported over the course of 23 trips. Falcon Heavy, being the only man rated launch method will provide all of the manned transport. The following is a graph of the cost breakdown of each launch method:



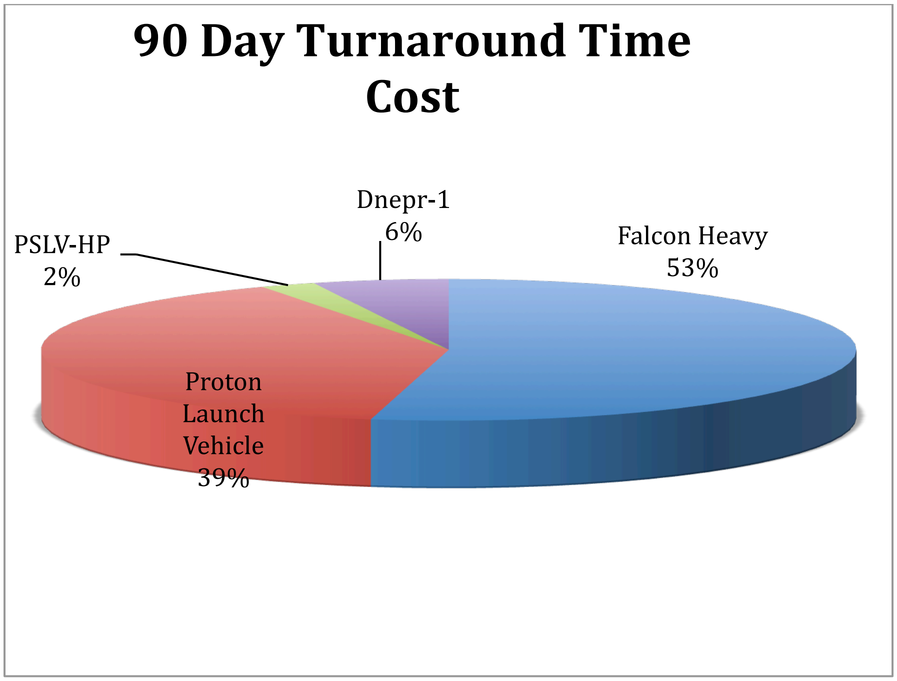


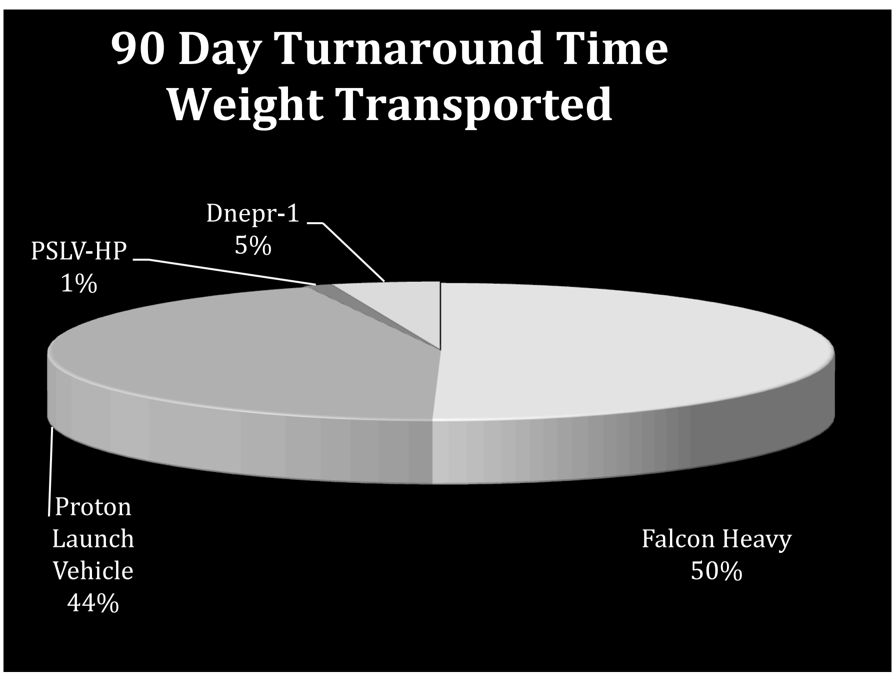
2. 60 Day Turnaround Results

In this variation of the problem, each individual launch method is limited to a 60 day turnaround time. This allows for each launch method to be used 15 times. Since none of the optimal solutions are used over 15 times, the solution is the same as that of the No Turnaround variation, with 11 launches of Falcon Heavy, 10 of the Proton Launch Vehicle, and 2 of the Dnepr-1, totaling a cost of $2.351 billion.

3. 90 Day Turnaround Results

This is the point at which the optimal solution becomes affected by the turnaround time constraint. As each launch method is limited to being used ten times in order to satisfy the two and a half years construction requirement, the optimal solution is now different than that of the previous, less restrictive turnaround times. Falcon Heavy is used 10 times, as are the Proton Launch Vehicle and Dnepr-1. Additionally, PSLV-HP is used 3 times to close the gap. A total of 1003.1 metric tons are transported, at a cost of $2.4125 billion.



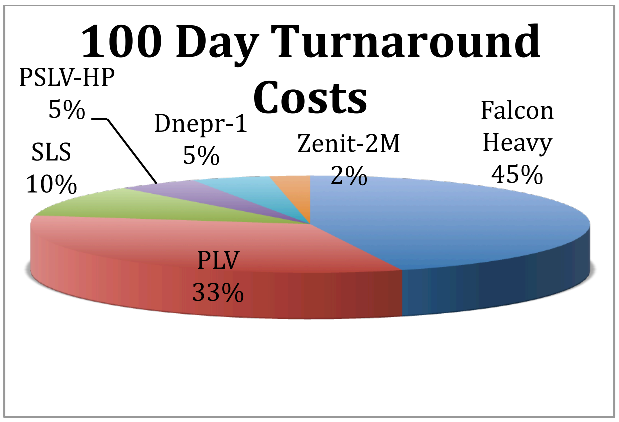


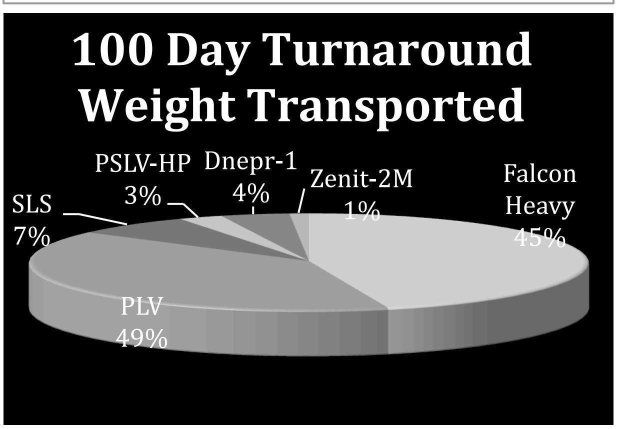
4. 100 Day Turnaround

The optimization problem further restricts a single launch method, necessitating the inclusion of more companies. A 100 day turnaround time limitation allows for a single launch to be used only nine times over the course of the two and a half years. At this point, the number of launch methods used is six.

Capability	Number of Trips
Falcon Heavy	**9**
Proton launch Vehicle	**9**
Space Launch System SLS	**1**
PSLV-HP	**7**
Dnepr-1	**9**
Zenit-2M	**1**

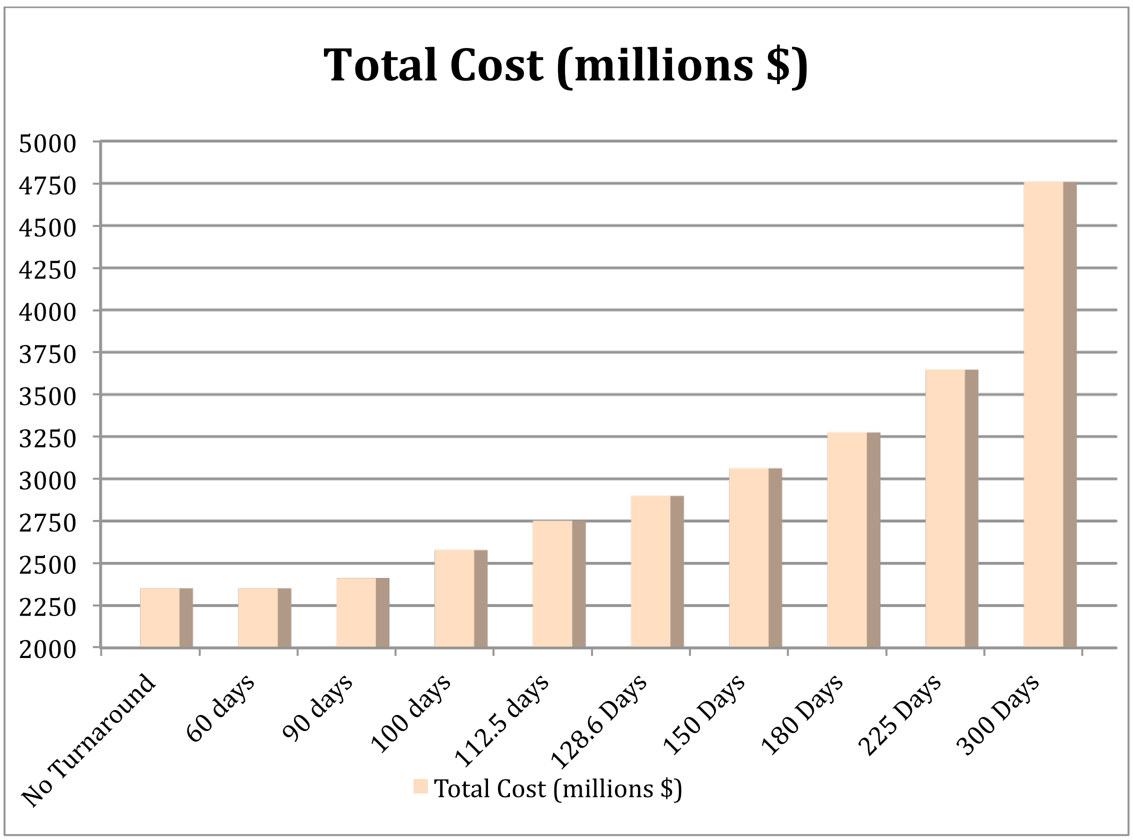
The total cost is $2.5775 billion, with a total of 36 launches.





5. Results of Turnaround Times Larger than 100 Days

At the 112.5 day turnaround time, where each launch is limited to only eight trips, an interesting shift occurs. From the no turnaround time to the 100 day turnaround time, the number of trips were steadily increasing, as the apparent minimization method was to first use as many Falcon Heavy, Proton Launch Vehicle, and Dnepr-1 launches as possible, and then fill in the gap with the cheapest launch method that would satisfy the weight requirement. Starting at the 112.5 turnaround time, more Space Launch Systems (SLS) launches are utilized, which has the effect of reducing the number of trips needed, because it has such a large capacity. The penalty of using SLS is steep however, with an increased optimal price of $174 million from the 100 day turnaround time's optimal strategy. It can be noted that from the 112.5 turnaround day point, the trend of number of trips used is upward. The problem finally becomes infeasible at a turnaround time of 450 days. However, the number of launches required at 300 days, and 225 days make it necessary to work with 18 and 11 different launch methods, respectively. At 225 days, the number of launches required is 41 and for 300 it is 47. Finally, the cost is nearly $1.3 billion steeper at 225 days than a turnaround time of 60 days. Comparing 300 days to 60 days yields an astronomical difference in cost of $2.41 billion, which is a 102% increase from the optimal cost. These costs are illustrated below:



B. Individual Launch Analysis

This section is devoted solely to analyzing a particular launch method to simulate events that may occur. If a launch method is not ready, not fully developed, experiences unforeseen reliability problems, or changes in costs between now and the time that Spec Innovations plans for construction to begin, it would be beneficial to understand the effects these events would have on choosing an optimal strategy. This is meant to explore the effect of changes and availability of the optimal launch methods upon the rest of the model.

1. Falcon Heavy

a. No Falcon Heavy (Cost Minimization)

The first scenario worth exploring is if for some reason, the Falcon Heavy is not available. The optimal solution for cost minimization changes to:

Capability	Type	Number of Trips	Total # of Trips
Proton Launch Vehicle	Cargo	21	**31**
Zenit-2M	Mixed	4	
Soyuz- FG	Mixed	6	

The total cost is $2.509 billion, and the number of trips required is 31 in this scenario. The Proton Launch Vehicle does the vast majority of the heavy lifting, as Zenit-2M and Soyuz-FG are for the most part, simply executing the manned launches.

b. No Falcon Heavy (Trip Minimization)

Another scenario worthy of consideration is the case where money is not as high a priority as minimizing the number of trips. This may be due to time constraints, or a desire to simplify the process by minimizing the number of companies involved. The minimum number of trips in this case would be 23, with 13 launches occurring using the Space Launch Systems, and 10 more using Zenit-2M. The total cost is $4.12 billion, which is a quite large jump from the cost minimization model that excludes the Falcon Heavy

c. Falcon Heavy Cost Analysis

The goal of including a cost analysis is to provide a range of optimality for using the Falcon Heavy. If the price is raised by a certain amount of dollars, it is no longer optimal to use Falcon Heavy for as many launches, or at all. Conversely, if the price falls enough, Falcon Heavy is the one launch method that is able to transport both large quantities of cargo and men, so the interest is on it being the only launch method. When Falcon Heavy is raised by $16 million per launch, 12.5%, its role is reduced in the optimal solution. Whereas in the optimal solution, Falcon Heavy is used 11 times, once the cost per launch reaches $144 million, the optimal solution changes to:

Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	4	**27**

Proton Launch Vehicle	Cargo	17	
Zenit-2M	Mixed	3	
Soyuz- FG	Mixed	3	

The extra Proton Launch Vehicle instances make up for the lost cargo Falcon Heavy would normally transport, and Zenit-2M is increased by 1 launch, as well as Soyuz-FG being added in to meet the manned launch constraint. The total cost of this configuration is $2.509 billion. Should Falcon Heavy's cost per launch increase by another $1 million, it is completely taken out of the optimal solution (which incidentally comes to the same total of $2.509 billion):

Capability	Type	Number of Trips	Total # of Trips
Proton Launch Vehicle	Cargo	21	**31**
Zenit-2M	Mixed	4	
Soyuz- FG	Mixed	6	

When the price of the Falcon Heavy drops by $20 million to $108 million per launch, 15.7%, it becomes beneficial to increase its usage. The total cost drops to $2.147 billion.

Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	19	**20**
Proton Launch Vehicle	Cargo	1	

This continues to be the optimal solution until Falcon Heavy's price is anywhere below $96 million per launch. It then becomes optimal to use it solely, only spending a total of $1.9 billion for 20 launches.

2. Proton Launch Vehicle

a. No Proton Launch Vehicle (Cost Minimization)

Without the Proton Launch Vehicle, the optimal solution changes to:

Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	19	**28**
Dnepr-1	Cargo	9	

The optimal solution comes at a price of $2.549 billion, which is not nearly as much off from the base model's optimal solution as it was for the exclusion of the Falcon Heavy.

b. No Proton Launch Vehicle (Trip Minimization)

Without the Proton Launch Vehicle, minimizing the number of trips with no regards to cost will result in the methods capable of carrying the most cargo and men per launch. It is no surprise that the following is optimal in this situation:

Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	10	**18**
Space Launch System	Cargo	8	

The cost is $3.44 billion.

c. Proton Launch Vehicle Cost Analysis

Increasing the cost per launch of the Proton Launch Vehicle by $18 million, or 15.6%, results in its decreased use. The optimal solution becomes to use the Falcon Heavy 17 times, the Proton Launch Vehicle only three times, and Dnepr-1 two times, at a total cost of $2.541 billion. If the Proton Launch Vehicle's price is raised by $20 million per launch, or 21.1%, the optimal solution again changes. The total cost is $2.547 billion, and the launch combination is:

Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	19	**20**
Proton Launch Vehicle	Cargo	1	

Anything over an increase of 23.1% of the original cost, or $22 million, and it becomes optimal to exclude Proton Launch Vehicle. The optimal solution changes to using Falcon Heavy 19 times, and Dnepr-1 nine times, at a total cost of $2.549 billion.

Decreasing Proton Launch Vehicle's cost per launch by $16 million, or 16.8% results in a total cost of $2.173 billion in the following manner:

Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	8	**23**
Proton Launch Vehicle	Cargo	13	
Zenit-2M	Mixed	2	

The number of Zenit-2M stays consistent, but it becomes more beneficial cost wise to use the Proton Launch Vehicle over the Falcon Heavy. When the price decreases by $17 million per launch or more, Falcon Heavy is completely written out of the optimal solution, with a total cost of $2.152 billion:

Capability	Type	Number of Trips	Total # of Trips
Proton Launch Vehicle	Cargo	21	**31**
Zenit-2M	Mixed	4	

Soyuz- FG	Mixed	6	

3. Dnepr-1

a. No Dnepr-1 (Cost Minimization)

Without Dnepr-1, the differences are relatively small, in comparison with the Falcon Heavy and Proton Launch Vehicle. There are two other launch methods used instead of the two instances of Dnepr-1. The total cost is $2.371 billion.

Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	9	**23**
Proton Launch Vehicle	Cargo	12	
PSLV-HP	Cargo	1	
Zenit-2M	Mixed	1	

b. No Dnepr-1 (Trip Minimization)

With trip minimization, the solution is the same as the trip minimization for the Proton Launch Vehicle. The total cost is $3.44 billion

Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	10	**18**
Space Launch System	Cargo	8	

c. Dnepr-1 Cost Analysis

Increasing the cost per launch of Dnepr-1 by $10 million or more, 76.9%, results in its exclusion from any cost optimization solutions. The optimal solution is then a cost of $2.371 billion and is the same solution that the original Dnepr-1 exclusion chart shows. Decreasing the cost per launch by $4 million or more, 30.8%, increases the number of times Dnepr-1 is used, albeit at a minimal cost savings. The total cost is $2.338 billion:

Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	10	**32**
Proton Launch Vehicle	Cargo	10	
Dnepr-1	Cargo	12	

4.2 Spec-cific Results

These results are geared towards meeting Spec Innovations' requirements. In the previous models, the launch methods compared consisted of an exhaustive list that satisfies the criteria set forth. As this is designed to be useful to Spec Innovations moving forward in its decision making pertaining to the selection of launch technologies, it is important to accommodate the customer's desire. Whereas the previous section can hopefully be viewed as alternatives based solely upon available launch methods meeting criteria, this section may be of more immediate use. There will be analysis mirroring the previous section, which will consist of "what-if" scenarios centering around the availability of individual launch methods, as well as the effect of variance in their prices on optimality on cost minimizations and trip minimizations. Each individual company was ranked, and the following companies were eliminated based upon Spec Innovation's preferences:

Capability	Company
Chinese Long March5	CALT
Chinese Long March3B	CALT
Space Launch System SLS	Allianttech system/ Boeing
Antares	Orbital Sciences
PSLV-HP	ISRO
GSLV- MkIII	ISRO
PSLV-XL	ISRO
Chinese Long March 4C	CALT
Chinese Long March 4B	CALT
Dnepr-1	Yuzhnoye Design Bureau

The two shaded in pink, Space Launch System, and Dnepr-1 are the only launches that consistently showed up as optimal in different scenarios.

Spec-cific Optimal Results

Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	8	**23**
Proton Launch Vehicle	Cargo	13	
Zenit-2M	Cargo	2	

The total cost is $2.381 billion. This will be the model against which most others moving forward will be compared. The three individual launch methods that will be examined will be the Falcon Heavy, Proton Launch Vehicle, and Zenit-2M.

1. Falcon Heavy

a. No Falcon Heavy (cost minimization)

Excluding the Falcon Heavy yields the same optimal answer as that of the unbiased results. This can be attributed to the fact that none of the alternative launch methods have been eliminated from the Spec-cific model. The cost here is $2.509 billion.

Capability	Type	Number of Trips	Total # of Trips
Proton Launch Vehicle	Cargo	21	31
Zenit-2M	Mixed	4	
Soyuz- FG	Mixed	6	

b. No Falcon Heavy (Trip Minimization)

For previous trip minimizations, the Space Launch Systems was a very effective mechanism at carrying large amounts of cargo, as it is the highest capacity launch method being reviewed. This did however come at a very high cost. Spec has indicated that there is a very low likelihood that Space Launch Systems would be utilized. With its elimination as a solution, the total cost is now: $2.605 billion.

Capability	Type	Number of Trips	Total # of Trips
Proton Launch Vehicle	Cargo	21	31
Zenit-2M	Mixed	10	

c. Falcon Heavy Cost Analysis

Should Falcon Heavy's price per launch increase by $16 per million or less, the optimal techniques will stay the same. Once $17 million per launch is reached, the optimal solution changes to a total cost of $2.509 billion, with a configuration as follows:

Capability	Type	Number of Trips	Total # of Trips
Proton Launch Vehicle	Cargo	21	**31**
Zenit-2M	Mixed	4	
Soyuz- FG	Mixed	6	

At this point, it the Falcon Heavy is too expensive to be included in the optimal solution. Concerning decreasing the price, there are a few different phases of this process. Should the price decrease by as little as $3 million per launch, the optimal solution has a total cost of $2.355 billion:

Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	12	**21**
Proton Launch Vehicle	Cargo	9	

This stays consistent until the $20 million per launch threshold is met, at which is becomes beneficial to incorporate more launches of the Falcon Heavy for a total cost of: $2.147 billion:

Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	19	**20**
Proton Launch Vehicle	Cargo	1	

At the price per launch reduction of $34 million or more it becomes beneficial to just have 20 Falcon Heavy launches, which at $94 million per launch costs a total of $1.88 billion.

2. Proton Launch Vehicle

a. No Proton Launch Vehicle (Cost Minimization)

Without the Proton Launch Vehicle to consider, it becomes beneficial to strictly use the Falcon Heavy. The strategy is to have 20 launches, at a cost of $2.56 billion.

b. No Proton Launch Vehicle (Trip Minimization)

Excluding the Proton Launch Vehicle, satisfying the constraints with the fewest number of trips would also be achieved by simply launching the Falcon Heavy 20 times.

c. Proton Launch Vehicle Cost Analysis

A cost increase as relatively miniscule as $3 million per launch results in the Proton Launch Vehicle's role being reduced. At a total cost of $2.418 billion, the following takes place:

Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	12	**21**
Proton Launch Vehicle	Cargo	9	

If further increased to a price per launch of $113 million, an increase of $18 million from the original launch costs, the Proton Heavy is further marginalized. It is only chosen for one launch, while the Falcon Heavy takes on 19 at a total cost is $2.545 billion. Once the price per launch of the Proton Launch Vehicle is $129 million or more, it becomes beneficial to strictly use Falcon Heavy launches at a total cost of $2.56 billion. Reversing course, if the Proton Launch Vehicle decreases its price per launch by $17 million to $78 million, it becomes the heavy lifter, with 21 launches and employs smaller launch methods (Zenit-2M four times, Soyuz-FG six times) to satisfy the man requirement. The total cost in this scenario is $2.152 billion. Once the price of the Proton launch vehicle drops $32 million or more per launch, it is beneficial to add another PLV launch, and use only the Soyuz-FG ten times for an optimal solution costing $1.836 billion.

3. Zenit-2M

a. No Zenit-2M (Cost Minimization)

An optimal solution without Zenit-2M consists of and combination of 12 Falcon Heavy launches, and 9 Proton Launch Vehicles, for a total of $2.391 billion. Minimizing the number of trips gives a Falcon Heavy only solution consisting of costs of $2.56 billion, and 20 launches.

b. No Zenit-2M (Trip Minimization)

Minimizing the trips without the Zenit-2M gives us a value of 20 trips, using the Falcon Heavy solely.

c. Zenit-2M Cost Analysis

Increasing the price per launch of the Zenit-2M $5 million to a total of $66 million eliminates it from usage as a launch method. Instead, the Falcon Heavy and Proton Launch Vehicle are used 12 and 9 times, respectively for a cost of $2.355 billion. Once the Zenit-2M price decreases to $40 million per launch, it becomes beneficial to use it more in the optimal solution. For a total cost of $2.22 billion, the following configuration is now deemed optimal:

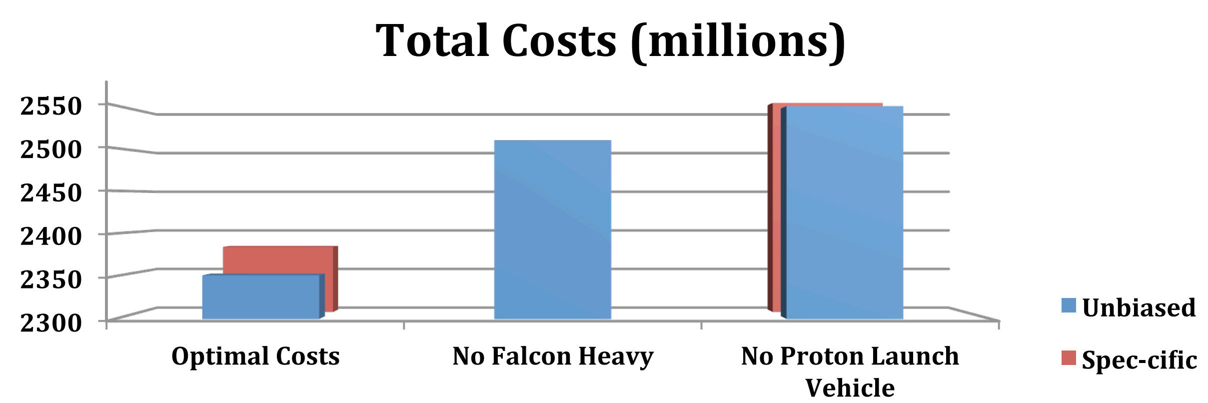
Capability	Type	Number of Trips	Total # of Trips
Falcon Heavy	Mixed	1	**30**
Proton Launch Vehicle	Cargo	19	
Zenit-2M	Mixed	10	

In order for Zenit-2M to handle all manned launches, its price per launch would have to drop by $29 million, to $32 million. For $2.252 billion, the following is possible:

Capability	Type	Number of Trips	Total # of Trips
Proton Launch Vehicle	Cargo	20	**31**
Zenit-2M	Mixed	11	

4.3 Analysis of Results

When comparing the full data set versus what Spec Innovations prefers, it becomes apparent that limiting choices has the repercussion of raising the total costs required in order to achieve objectives. In general it is more expensive across the board when eliminating choices, as there are not as many combinations present to mix and match. What was found in the Spec-cific results was that, as more scenarios were added, there were less individual instances of optimality. That is, since there were less possible combinations, this also reduced the number of optimal solutions. With the unbiased results, there was very little repetition amongst optimal answers pertaining to different scenarios. With there not being as many combinations to choose from, there was also an effect of changing optimal results (except in the case of No Falcon Heavy). To get a bigger picture concerning the optimality costs:

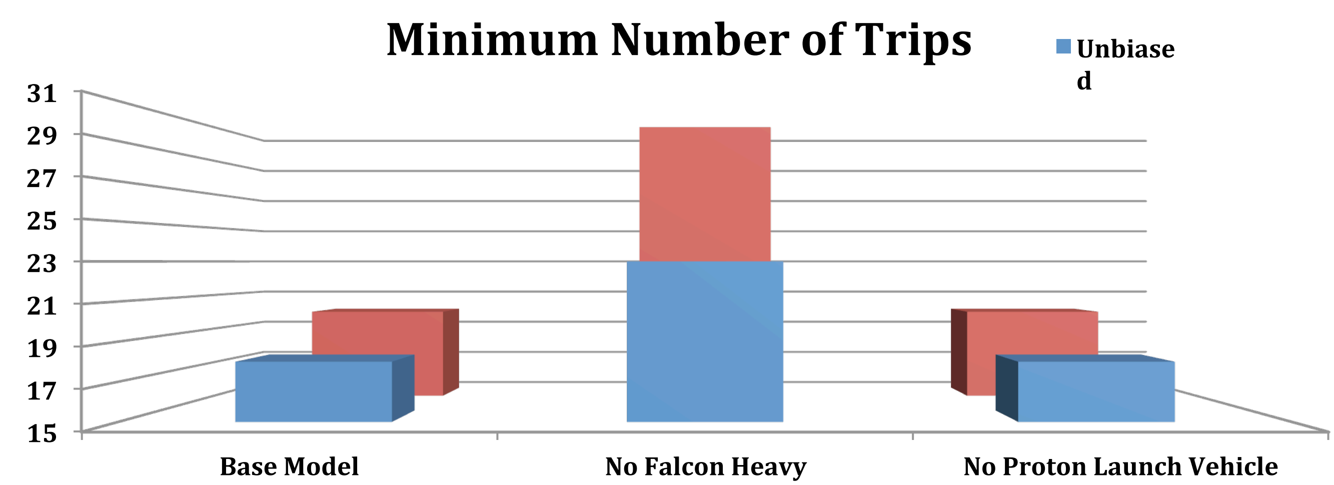


	Optimal Costs	No Falcon Heavy	No Proton Launch Vehicle
Unbiased	2351	2509	2549
Spec-cific	2381	2509	2560

As can be seen, the largest difference in cost occurs at the optimal costs portion. The cost is the exact same in both "No Falcon Heavy" scenarios, because none of the alternative launch techniques are eliminated from use by Spec Innovations. Finally, excluding the Proton Launch Vehicle from available launch techniques universally results in the largest jump in minimization of costs. For the Spec-cific results, it is a slightly higher value ($11 million). When considering the magnitude of costs, the

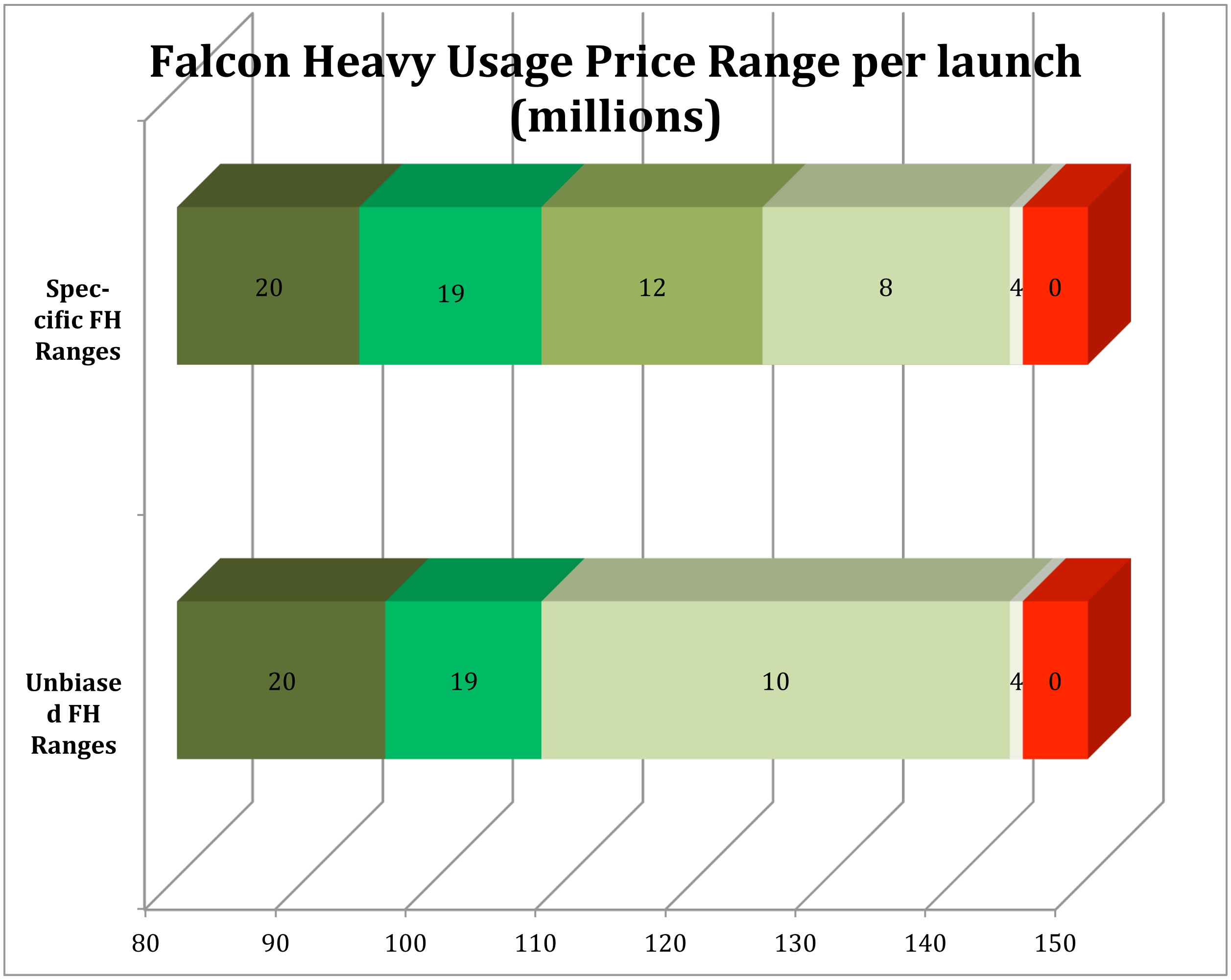
$30 million difference between optimal strategies does not seem as though it would be a limitation in choosing between launch methods, should this rubric remain consistent.

Another interesting situation to consider is the minimization of trips. Since the Space Launch System has been excluded from use in the Spec-cific results, there is a great deal of difference in minimizing the trips. For Spec-cific results, the global minimum number of trips involved simply using the Falcon Heavy twenty times. In the case of the unbiased results, the Falcon Heavy was used ten times, and the Space Launch System eight times.

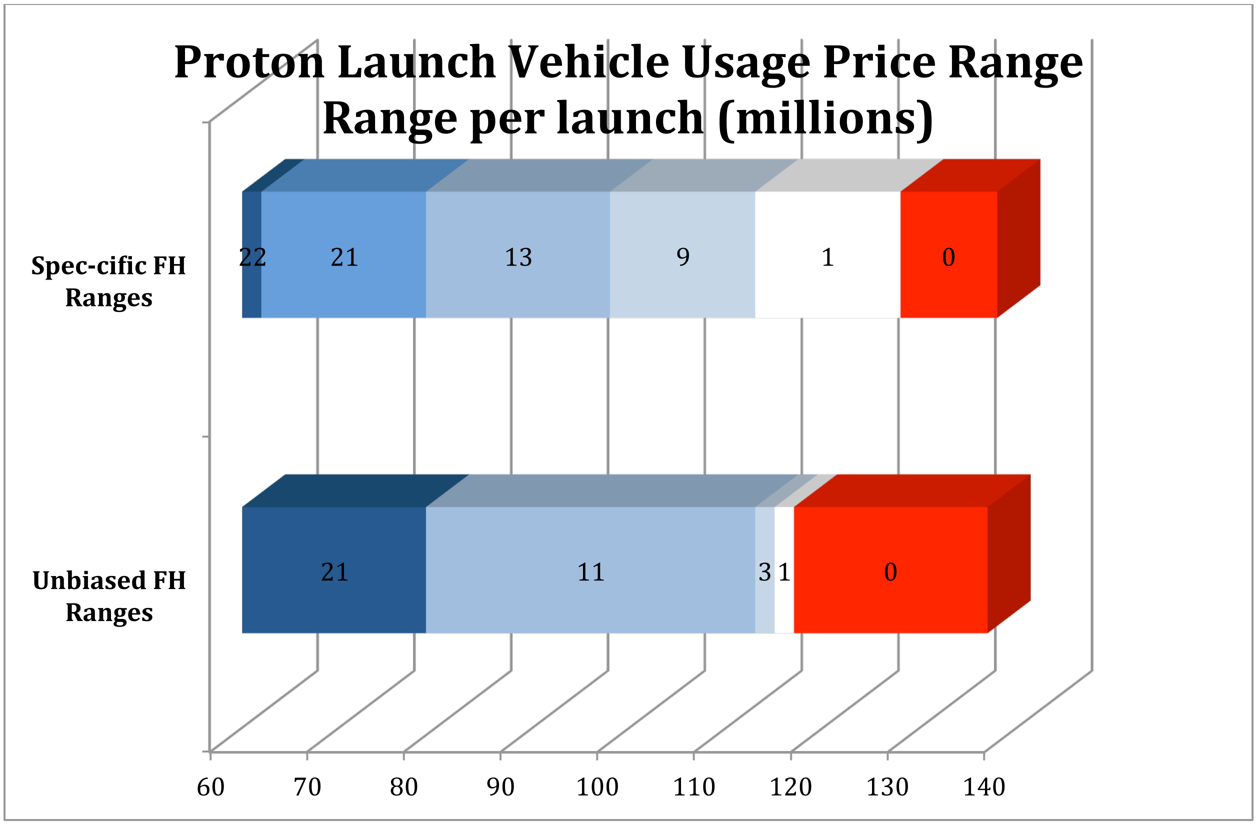


	Base Model	No Falcon Heavy	No Proton Launch Vehicle
Unbiased	18	23	18
Spec-cfic	20	31	20

To show a more detailed picture of the price range differences between the two consistent optimal launch techniques, the Falcon Heavy and the Proton Launch Vehicle also shows a few notable differences in optimality in different price per launch ranges, which can be directly attributed to the availability, or lack thereof, of different launch technologies. The numbers listed on each section of the bar charts indicates the number of launches that are used in that price range to be considered optimal.



The direct difference that can be seen between the price per launch range of $109 million - $143 million can be attributed to the fact that since the Dnepr-1 is not included in the Spec-cific results. The normal cost range for the unbiased results has a much larger area at which the solution stays the same, as opposed to the Spec-cific results which change as soon as the price per launch of the Falcon Heavy drops by $3 million. This can also be confirmed by viewing the same chart for the Proton Launch Vehicle, which has a similar outcome.



The results are not unexpected, considering that only two launch techniques, the Space Launch System, and Dnepr-1, have comparable cost per kg values as some of the optimal launch techniques. While it was originally thought that eliminating so many launch techniques would be detrimental to the outcome of the optimizations, it really came to be of little to no consequence due to the vast majority of them not currently being a good choice under any circumstances. The only scenarios it could be imagined under which a more dramatic difference would be apparent is in the case of Falcon Heavy, Proton Launch Vehicle, and several other launch methods simultaneously not being ready. However, in this particular scenario, based upon the expressed desire to not exceed the neighborhood of 30 launches total, the problem would not be feasible. The following warrants a disclaimer: if the Falcon Heavy is ready in the timeframe desired for construction of the space station to begin, it can be recommended as the primary source of transport. Also, barring any unforeseen technical difficulties pertaining to the Proton Launch Vehicle, and considering its reliable usage in the past, this is a problem that can be feasibly solved given the desired constraints. Should both of these change, the problem and its constraints must be reviewed for feasibility.

This particular model was designed to be forward compatible. While some of the numbers are born from assumptions that had to be made in order to present a viable solution, once these figures are better understood and defined in relation to the model, they can easily be substituted in. For example, should companies release data concerning turnaround times on individual launch methods, the constraints can be changed, and individualized. This is part of the reason why some of the coding may look redundant. This is a conscious effort to make the model easily updateable.

5.0 Recommendations

At this point, because so many variables pertaining to the model are subject to change, ideally it would be beneficial to revisit this model once more concrete number pertaining to capabilities and cost of each individual launch technique are better defined. It also bears mentioning that in many cases, repeated launches with a single company may yield discounts which would make going with one company, such as SpaceX with the Falcon Heavy, less costly. This however was not included in this particular model.

Moving forward, once capabilities and overall plan are better defined and developed, it would be ideal to reevaluate the problem as a scheduling one in order to next match the phases of construction, and transport of materials in a desired sequence, along with the manned launches to minimize idle time. At an even further point in time, a simulation can be constructed and ran, adding in stocasticity. This will be an important aspect of any model with so many uncertainties, and will further expand the scope of what is possible from a time and monetary standpoint.

6.0 Future Work

The analysis provided by our model had limitations due to time constraints that could be improved upon in future versions of our model. There is great potential for value addition in future versions of this model and future efforts should see much success. Due to time limitations our model was constrained to current launch capabilities, using a fixed construction schedule, and limited cost analysis. Any of these constraints could be lifted leading to a more complex model providing greater value to SPEC Innovations.

- One future effort that is recommended would be a thorough cost analysis for launch capabilities including better risk analysis. This cost analysis helps to create a more detailed model, leading to more accurate predictions and a more refined sensitivity analysis.
- A simulation (or simulations) could be run, with a revised model with more concrete capabilities, allowing a glimpse into how the model would function under the stresses of a tight schedule.
- A more detailed risk analysis on the launch capabilities will provide better information to SPEC Innovations regarding potential failures. This would allow them to come up with a risk mitigation strategy.
- The results of this analysis can be used as a basis for a more complex analysis involving a combination business plan and scheduling problem to model the entire lifecycle of the space station construction. Our model provides the basic results needed for costing of acquisition; a future effort would model the construction of the space station, as both a function of cost and schedule.
- If construction costs and times can be factored into the model, the model can be far more effective as lag times in launch setup can be utilized effectively.

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http://www.boeing.com/
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Appendix A: Model Formulations

Appendix A.1
Unbiased: No Turnaround Time

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.2
Unbiased: 60 Day Turnaround Time

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 <= 15;
X101 <= 15;
X102 <= 15;
X103 <= 15;
X104 <= 15;
X105 <= 15;
X106 <= 15;
X107 <= 15;
X108 <= 15;
X109 <= 15;
X110 <= 15;
X111 <= 15;
X112 <= 15;
X113 <= 15;
X114 <= 15;
X115 <= 15;
X116 <= 15;
X117 <= 15;
X118 <= 15;
X119 <= 15;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.3
Unbiased: 90 Day Turnaround Time

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 <= 10;
X101 <= 10;
X102 <= 10;
X103 <= 10;
X104 <= 10;
X105 <= 10;
X106 <= 10;
X107 <= 10;
X108 <= 10;
X109 <= 10;
X110 <= 10;
X111 <= 10;
X112 <= 10;
X113 <= 10;
X114 <= 10;
X115 <= 10;
X116 <= 10;
X117 <= 10;
X118 <= 10;
X119 <= 10;

X100 + X200 + X201 + X202 >= 10;

INTEGER
X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.4
Unbiased: 100 Day Turnaround Time

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 <= 9;
X101 <= 9;
X102 <= 9;
X103 <= 9;
X104 <= 9;
X105 <= 9;
X106 <= 9;
X107 <= 9;
X108 <= 9;
X109 <= 9;
X110 <= 9;
X111 <= 9;
X112 <= 9;
X113 <= 9;
X114 <= 9;
X115 <= 9;
X116 <= 9;
X117 <= 9;
X118 <= 9;
X119 <= 9;

X100 + X200 + X201 + X202 >= 10;

INTEGER
X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.5
Unbiased: 112.5 Day Turnaround Time

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 <= 8;
X101 <= 8;
X102 <= 8;
X103 <= 8;
X104 <= 8;
X105 <= 8;
X106 <= 8;
X107 <= 8;
X108 <= 8;
X109 <= 8;
X111 <= 8;
X112 <= 8;
X113 <= 8;
X114 <= 8;
X115 <= 8;
X116 <= 8;
X117 <= 8;
X118 <= 8;
X119 <= 8;
X200 <= 8;
X201 <= 8;
X202 <= 8;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.6
Unbiased: 128.6 Day Turnaround Time

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 <= 7;
X101 <= 7;
X102 <= 7;
X103 <= 7;
X104 <= 7;
X105 <= 7;
X106 <= 7;
X107 <= 7;
X108 <= 7;
X109 <= 7;
X110 <= 7;
X111 <= 7;
X112 <= 7;
X113 <= 7;
X114 <= 7;
X115 <= 7;
X116 <= 7;
X117 <= 7;
X118 <= 7;
X119 <= 7;
X200 <= 7;
X201 <= 7;
X202 <= 7;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.7
Unbiased: 150 Day Turnaround Time

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 <= 6;
X101 <= 6;
X102 <= 6;
X103 <= 6;
X104 <= 6;
X105 <= 6;
X106 <= 6;
X107 <= 6;
X108 <= 6;
X109 <= 6;
X111 <= 6;
X112 <= 6;
X113 <= 6;
X114 <= 6;
X115 <= 6;
X116 <= 6;
X117 <= 6;
X118 <= 6;
X119 <= 6;
X200 <= 6;
X201 <= 6;
X202 <= 6;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.8
Unbiased: 180 Day Turnaround Time

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 <= 5;
X101 <= 5;
X102 <= 5;
X103 <= 5;
X104 <= 5;
X105 <= 5;
X106 <= 5;
X107 <= 5;
X108 <= 5;
X109 <= 5;
X111 <= 5;
X112 <= 5;
X113 <= 5;
X114 <= 5;
X115 <= 5;
X116 <= 5;
X117 <= 5;
X118 <= 5;
X119 <= 5;
X200 <= 5;
X201 <= 5;
X202 <= 5;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.9
Unbiased: 225 Day Turnaround Time

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 <= 4;
X101 <= 4;
X102 <= 4;
X103 <= 4;
X104 <= 4;
X105 <= 4;
X106 <= 4;
X107 <= 4;
X108 <= 4;
X109 <= 4;
X111 <= 4;
X112 <= 4;
X113 <= 4;
X114 <= 4;
X115 <= 4;
X116 <= 4;
X117 <= 4;
X118 <= 4;
X119 <= 4;
X200 <= 4;
X201 <= 4;
X202 <= 4;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.10
Unbiased: 300 Day Turnaround Time

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 <= 3;
X101 <= 3;
X102 <= 3;
X103 <= 3;
X104 <= 3;
X105 <= 3;
X106 <= 3;
X107 <= 3;
X108 <= 3;
X109 <= 3;
X111 <= 3;
X112 <= 3;
X113 <= 3;
X114 <= 3;
X115 <= 3;
X116 <= 3;
X117 <= 3;
X118 <= 3;
X119 <= 3;
X200 <= 3;
X201 <= 3;
X202 <= 3;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.11
Unbiased: 450 Day Turnaround Time

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 <= 2;
X101 <= 2;
X102 <= 2;
X103 <= 2;
X104 <= 2;
X105 <= 2;
X106 <= 2;
X107 <= 2;
X108 <= 2;
X109 <= 2;
X111 <= 2;
X112 <= 2;
X113 <= 2;
X114 <= 2;
X115 <= 2;
X116 <= 2;
X117 <= 2;
X118 <= 2;
X119 <= 2;
X200 <= 2;
X201 <= 2;
X202 <= 2;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.12
Unbiased: No Falcon Heavy Cost Minimization

MIN

Cost = 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X200 + X201 + X202 >= 10;

INTEGER

X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.13
Unbiased: No Falcon Heavy Trip Minimization

MIN

Trips = X101 + X102 + X103 + X104 + X105 + X106 + X107 + X108 + X109 + X110 + X111 + X112 + X113 + X114 + X115 + X116 + X117 + X118 + X119 + X200 + X201 + X202

SUBJECT TO

21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X200 + X201 + X202 >= 10;

INTEGER
X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.14
Unbiased: Falcon Heavy Price Increase of 12.5%

MIN

Cost = 144X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.15
Unbiased: Falcon Heavy Price Increase of 13.2%

MIN

Cost = 145X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.16
Unbiased: Falcon Heavy Price Decrease of 15.7%

MIN

Cost = 108X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.17
Unbiased: Falcon Heavy Price Decrease of 25.8%

MIN

Cost = 95X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.18
Unbiased: No Proton Launch Vehicle Cost Minimization

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.19
Unbiased: No Proton Launch Vehicle Trip Minimization

MIN

Trip = X100 + X101 + X102 + X103 + X105 + X106 + X107 + X108 + X109 + X110 + X111 + X112 + X113 + X114 + X115 + X116 + X117 + X118 + X119 + X200 + X201 + X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.20
Unbiased: Proton Launch Vehicle Cost Increase 18.9%

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 113X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.21
Unbiased: Proton Launch Vehicle Cost Increase 21.1%

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 115X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.22
Unbiased: Proton Launch Vehicle Cost Increase 23.1%

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 117X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.23
Unbiased: Proton Launch Vehicle Cost Decrease 16.8%

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 79X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.24
Unbiased: Proton Launch Vehicle Cost Decrease 17.9%

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 78X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 13X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 4.5X118 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.25
Unbiased: No Dnepr-1 Cost Minimization

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X119, X200, X201, X202;

END

Appendix A.26
Unbiased: No Dnepr-1 Trip Minimization

MIN

Trip = X100 + X101 + X102 + X103 + X104 + X105 + X106 + X107 + X108 + X109 + X110 + X111 + X112 + X113 + X114 + X115 + X116 + X117 + X119 + X200 + X201 + X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X119, X200, X201, X202;

END

Appendix A.27
Unbiased: Dnepr-1 Cost Increase 76.9%

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 23X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.28
Unbiased: Dnepr-1 Cost Decrease 30.8%

MIN

Cost = 128X100 + 165X101 + 110X102 + 105X103 + 95X104 + 270X105 + 271X106 + 165X107 + 165X108 + 165X109 + 45X110 + 17.5X111 + 54X112 + 180X113 + 170X114 + 36X115 + 35X116 + 42X117 9X118 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25X102 + 21.6X103 + 44.2X104 + 70X105 + 25.8X106 + 19X107 + 21X108 + 21X109 + 5X110 + 3.7X111 + 10X112 + 15.3X113 + 17.1X114 + 3.8X115 + 4.2X116 + 4.2X117 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X102, X103, X104, X105, X106, X107, X108, X109, X110, X111, X112, X113, X114, X115, X116, X117, X118, X119, X200, X201, X202;

END

Appendix A.29
Spec-cific: Cost Minimization

MIN

Cost = 128X100 + 165X101 + 95X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.30
Spec-cific: No Falcon Heavy Cost Minimization

MIN

Cost = 165X101 + 95X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X200 + X201 + X202 >= 10;

INTEGER
X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.31
Spec-cific: No Falcon Heavy Trip Minimization

MIN

Cost = X101 + X104 + X106 + X107 + X108 + X109 + X113 + X114 + X115 + X119 + X200 + X201 + X202

SUBJECT TO

21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X200 + X201 + X202 >= 10;

INTEGER
X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.32
Spec-cific: Falcon Heavy Cost Increase 13.3%

MIN

Cost = 145X100 + 165X101 + 95X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER
X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.33
Spec-cific: Falcon Heavy Cost Decrease 2.3%

MIN

Cost = 125X100 + 165X101 + 95X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.34
Spec-cific: Falcon Heavy Cost Decrease 15.6%

MIN

Cost = 108X100 + 165X101 + 95X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.35
Spec-cific: Falcon Heavy Cost Decrease 26.6%

MIN

Cost = 94X100 + 165X101 + 95X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.36
Spec-cific: No Proton Launch Vehicle Cost Minimization

MIN

Cost = 128X100 + 165X101 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.37
Spec-cific: No Proton Launch Vehicle Trip Minimization

MIN

Cost = X100 + X101 + X106 + X107 + X108 + X109 + X113 + X114 + X115 + X119 + X200 + X201 + X202

SUBJECT TO

50.5X100 + 21X101 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER
X100, X101, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.38
Spec-cific: Proton Launch Vehicle Cost Increase 3.2%

MIN

Cost = 128X100 + 165X101 + 98X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.39
Spec-cific: Proton Launch Vehicle Cost Increase 18.9%

MIN

Cost = 128X100 + 165X101 + 113X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.40
Spec-cific: Proton Launch Vehicle Cost Increase 35.8%

MIN

Cost = 128X100 + 165X101 + 129X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.41
Spec-cific: Proton Launch Vehicle Cost Decrease 17.9%

MIN

Cost = 128X100 + 165X101 + 78X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.41
Spec-cific: Proton Launch Vehicle Cost Decrease 33.7%

MIN

Cost = 128X100 + 165X101 + 63X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 61X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.43
Spec-cific: No Zenit-2M Cost Minimization

MIN

Cost = 128X100 + 165X101 + 95X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 4.2X201 + 4.6X202 >= 1000;

X100 + X201 + X202 >= 10;

INTEGER
X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X201, X202;

END

Appendix A.44
Spec-cific: No Zenit-2M Trip Minimization

MIN

Trip = X100 + X101 + X104 + X106 + X107 + X108 + X109 + X113 + X114 + X115 + X119 + X201 + X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 4.2X201 + 4.6X202 >= 1000;

X100 + X201 + X202 >= 10;

INTEGER
X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X201, X202;

END

Appendix A.45
Spec-cific: Zenit-2M Cost Increase 8.2%

MIN

Cost = 128X100 + 165X101 + 95X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 66X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.46
Spec-cific: Zenit-2M Cost Decrease 34.4%

MIN

Cost = 128X100 + 165X101 + 95X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 40X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

INTEGER

X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix A.46
Spec-cific: Zenit-2M Cost Decrease 47.5%

MIN

Cost = 128X100 + 165X101 + 95X104 + 271X106 + 165X107 + 165X108 + 165X109 + 180X113 + 170X114 + 36X115 + 40X119 + 32X200 + 48X201 + 45X202

SUBJECT TO

50.5X100 + 21X101 + 44.2X104 + 25.8X106 + 19X107 + 21X108 + 21X109 + 15.3X113 + 17.1X114 + 3.8X115 + 7.8X119 + 11.4X200 + 4.2X201 + 4.6X202 >= 1000;

X100 + X200 + X201 + X202 >= 10;

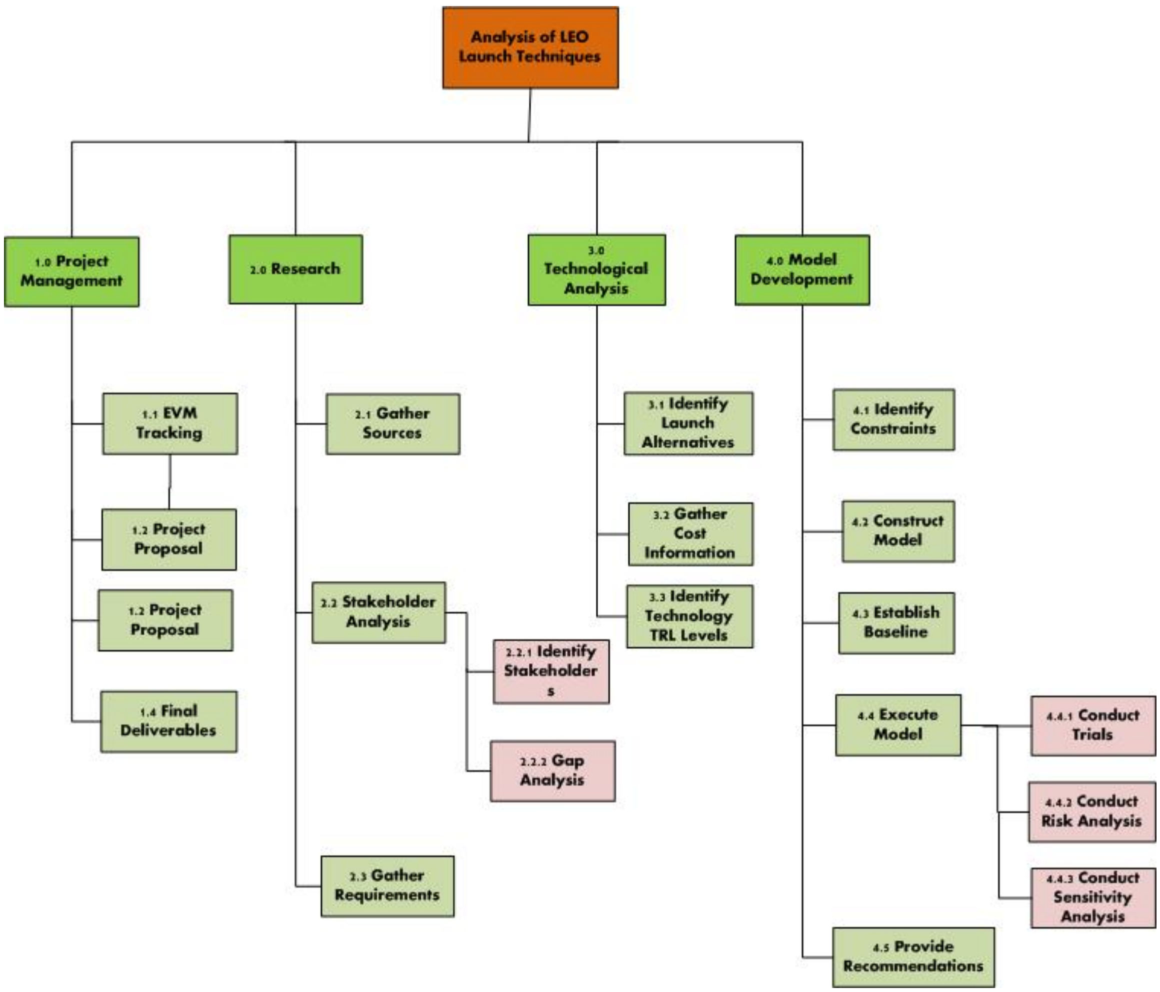
INTEGER
X100, X101, X104, X106, X107, X108, X109, X113, X114, X115, X119, X200, X201, X202;

END

Appendix B Project Management

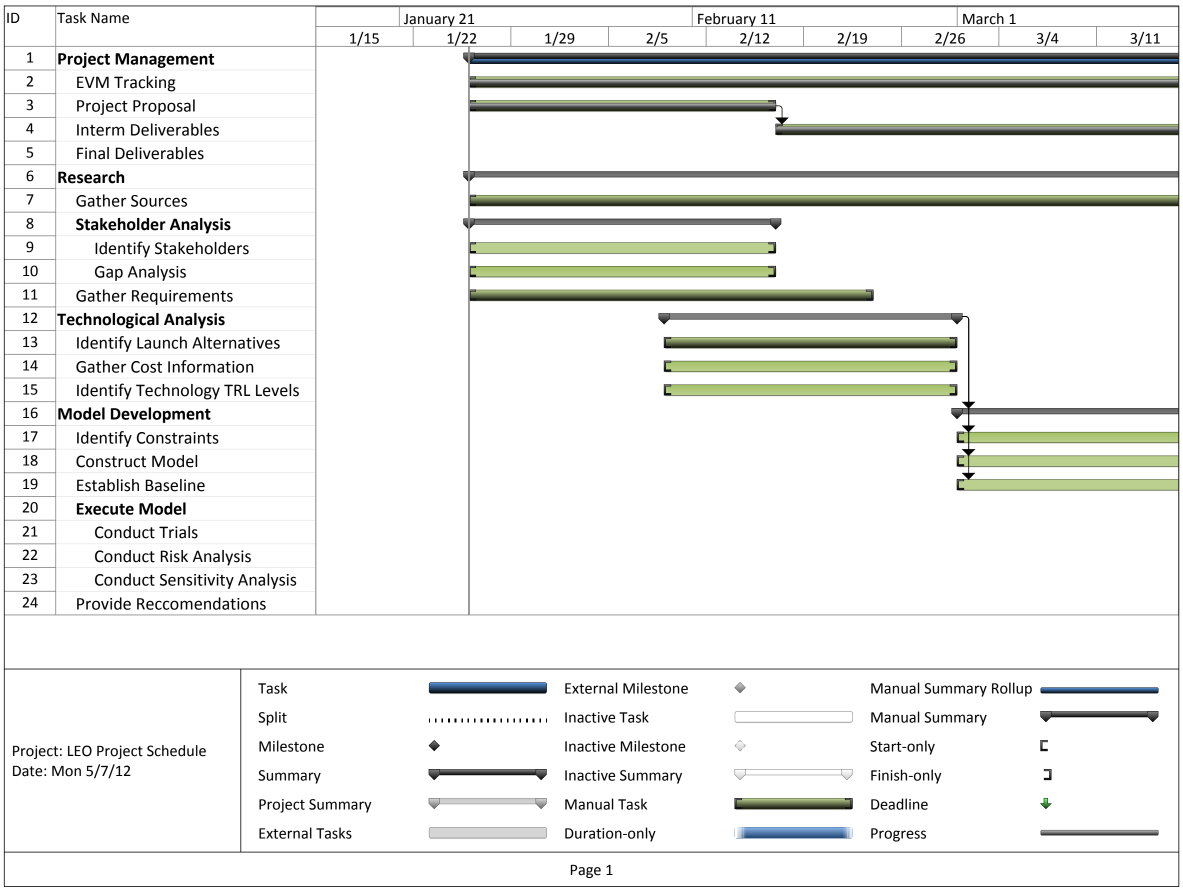
B.1 Work Breakdown Structure

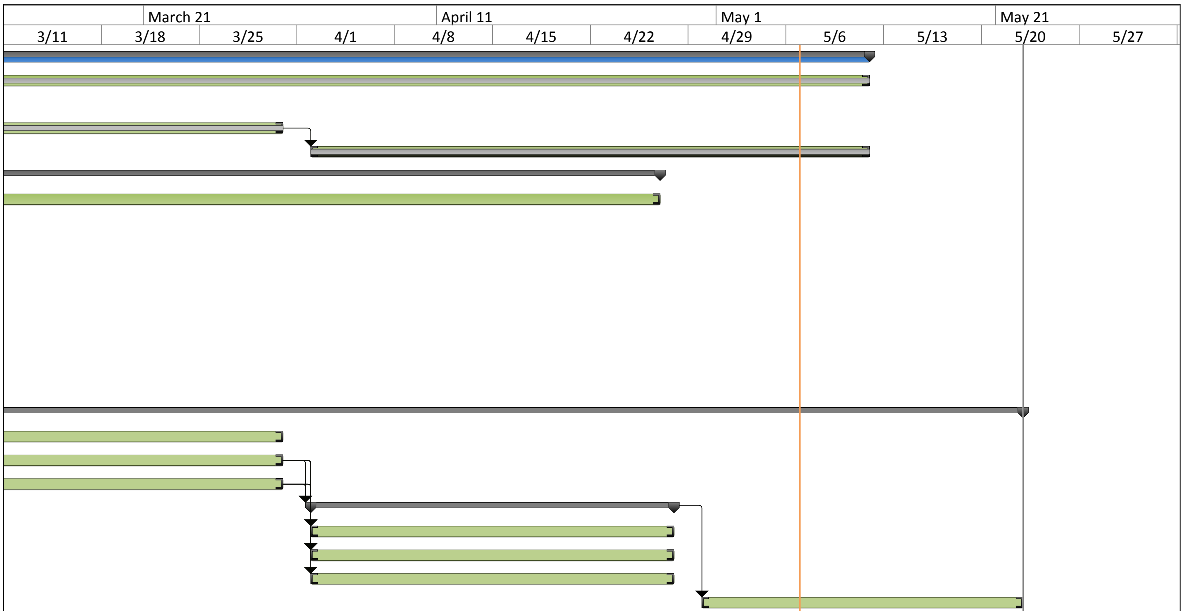
The WBS lays out the basic tasks our team must accomplish throughout the semester. This diagram shows the tasks and subtasks breakdown by category. These tasks are again reflected in our project schedule shown in section B.2.



B.2 Project Schedule

This project schedule was based on a 16 week semester that was allotted for the completion of the project.





Project: LEO Project Schedule
Date: Mon 5/7/12

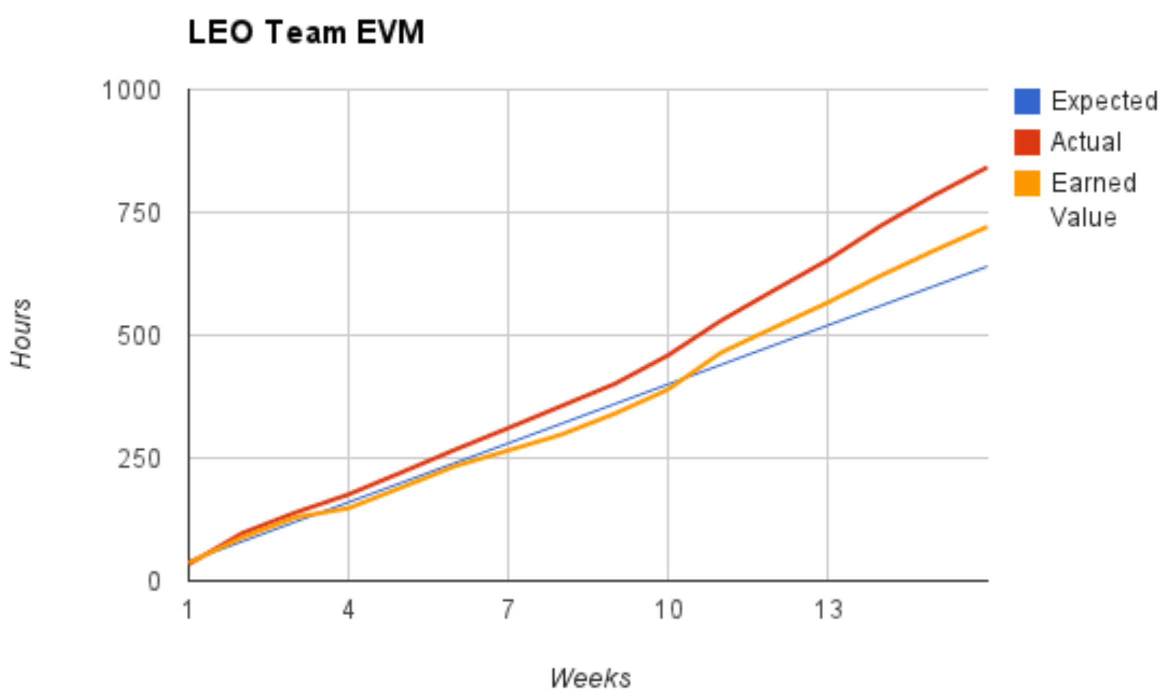
Task
Split
Milestone
Summary
Project Summary
External Tasks
External Milestone
Inactive Task
Inactive Milestone
Inactive Summary
Manual Task
Duration-only
Manual Summary Rollup
Manual Summary
Start-only
Finish-only
Deadline
Progress

Page 2

B.3 Earned Value Management

The Earned Value Management chart reflects our progress as a team in the completion of our project schedule. The Expected line shows the average expected work to be completed each week. The actual shows the actual hours put into the project and the earned value shows the value gained from the hours according to our project Gantt chart.

It can be seen our team was significantly over budget at the end of our project, however we were able to provide our sponsor with more value then expected. The actual cost override was due to two main factors. First the difficulty of finding accurate cost data. It was extremely difficult to find accurate cost data for many of the launch capabilities we wished to consider, therefore it took much more research then we had originally anticipated. Second we provided a much more detailed sensitivity analysis then we had originally intended. Although this additional analysis caused significant overruns on budget we believe it provided our sponsor with much more value as it gave them a greater ability to handle the potential risks for cost involved with immature technologies.



Team Hours: Total

	Research	Launch Method Analysis	Model Development	Project Managment	Totals
Week 1	19	0	0	15	34
Week 2	19	30	0	14	63
Week 3	17	10	0	15	42
Week 4	13	11	5	9	37
Week 5	17	20		3	45
Week 6	13	17	9	7	46
Week 7	14	14	8	8	44
Week 8	14	6	15	10	45
Week 9	13	11	12	9	45
Week 10	11	9	32	6	58
Week 11	9	4	48	10	71
Week 12	2	9	40	11	62
Week 13	10	2	41	8	61
Week 14	4	7	48	11	70
Week 15	4	0	42	16	62
Week 16	1	0	27	29	57
Totals	180	150	331	181	842

Team Hours: Colin Mullery

	Research	Launch Method Analysis	Model Development	Project Managment	Totals
Week 1	6			3	9
Week 2	5	2		5	12
Week 3	3			8	11
Week 4	2			5	7
Week 5	5	4	2		11
Week 6	3	1	5	4	13
Week 7	3	2		6	11
Week 8	5			5	10
Week 9	4	2	1	5	12
Week 10	5				5
Week 11	5			4	9
Week 12		1		5	6
Week 13	3			4	7
Week 14	2	1		8	11
Week 15	3			4	7
Week 16	1			13	14
Totals	55	13	8	79	155

Team Hours: James Belt

	Research	Launch Method Analysis	Model Development	Project Managment	Totals
Week 1	4			5	9
Week 2	3	6	0	9	18
Week 3	5			5	10
Week 4	4	4		1	9
Week 5	4	5	1	3	13
Week 6	5	4	1	3	13
Week 7	3	4	2	1	10
Week 8	2	3	4	2	11
Week 9	2	4	3	2	11
Week 10	2	5	10	2	19
Week 11	2	0	20	3	25
Week 12	0	0	20	0	20
Week 13	0	0	10	0	10
Week 14	0	0	15	0	15
Week 15	0	0	20	0	20
Week 16	0	0	10	0	10
Totals	36	35	116	36	223

Team Hours: Ashwini Narayan

	Research	Launch Method Analysis	Model Development	Project Managment	Totals
Week 1	4			4	8
Week 2	5	12	0	0	17
Week 3	4	6	0	1	11
Week 4	4	3	4	0	11
Week 5	3	6	2		11
Week 6		8	2		10
Week 7	2	3	6		11
Week 8	2		10		12
Week 9	4		8		12
Week 10			20	4	24
Week 11			25	1	26
Week 12			20	2	22
Week 13			30	1	31
Week 14			30	2	32
Week 15			20	3	23
Week 16			15	5	20
Totals	28	38	192	23	281

Team Hours: Ayobami Bamgbadi

	Research	Launch Method Analysis	Model Development	Project Managment	Totals
Week 1	5			3	8
Week 2	6	10	0	0	16
Week 3	5	4	0	1	10
Week 4	3	4	0	3	10
Week 5	5	5	0	0	10
Week 6	5	4	1	0	10
Week 7	6	5	0	1	12
Week 8	5	3	1	3	12
Week 9	3	5	0	2	10
Week 10	4	4	2	0	10
Week 11	2	4	3	2	11
Week 12	2	8	0	4	14
Week 13	7	2	1	3	13
Week 14	2	6	3	1	12
Week 15	1	0	2	9	12
Week 16	0	0	2	11	13
Totals	61	64	15	43	183

B.4 Project Deliverables

- Feb 9: Problem Definition and Scope
- Feb 16: Project Proposal Due
- Mar 8: Progress Report
- Mar 29: Progress Report
- April 26: Dry Run of Final Presentation

- May 7: Website and Final Report Due
- May 11: Final Presentation to faculty/sponsors

Appendix C Stakeholder Weight Elicitation

The weights for the values found in our model were elicited using the swing weight method. First for each attribute there was found a worst and best possible situation given the parameters of the analysis model. These best and worst scores are shown below in table C.1.

Factors	**# of Launches**	**Cost per Launch**	**TRL**	**Company**
Best Case	10	$80 Million	10	SpaceX
Worst Case	48	$254 Million	7	Nasa

Table C.1 Best and Worst Scores for Model Attributes

Once these best and worst scores were laid out a number of situations were laid out for our stakeholder in order to determine which factory they considered most important. For each situation one attribute was moved to best while all other attributes were held at the worst case. These four situations were then ranked by our stakeholder from worst to best. The weights were calculated from this ranking. Table C.2 displays the rankings of each situation by our stakeholder and table C.3 displays the resulting weights.

Ranking	3	2	4	1
	Option 1	**Option 2**	**Option 3**	**Option 4**
# Launches	48	48	10	48
Cost Per Launch (Millions)	80	254	254	254
TRL	7	10	7	7
Company	Nasa	Nasa	Nasa	SpaceX

Table C.2 Stakeholder Rankings

Factors	**# of Launches**	**Cost per Launch**	**TRL**	**Company**
Weights	0.1	0.2	0.3	0.4

Table C.3 Attribute Weights

The weight company past performance is a particularly difficult one determine due to the subjective nature of this weight. It was impossible to estimate this from the literature available, therefore for every company or government entity considered in the model, we elicited values from our stakeholders. Through email and interview, each company was ranked on a scale of zero to one where zero is not trusted at all and one is most trusted. These weights allowed us to see the value our stakeholder placed on each launch capability provider. This table is displayed below in Table C.4.

Company	Rating	Sponsor Comments
Space X:	0.9	
EADS Astrium	0.6	
Krunichev	0.8	These guys are Proton. I would rate them at 0.9 for heavy lift.
Allianttech system/ Boeing	0.2	
Boeing	0.4	
NASA	0.0	
United Launch Alliance	0.4	
Mitsubishi Heavy Industry	0.5	These guys do the H-II and the HTV supply pod to the ISS
Orbital Sciences	0.3	
ISRO	0.3	
Yuzhnoye Design Bureau	0.8	These guys are Sea Launch. I think that they are not a viable choice. I would rate them at 0.05
CALT	0.05	
TsSKB-Progress	0.8	These guys are Soyuz. Commercial marketing is handled by Starsem. I would rate them at 0.9 for human and resupply.

Table C.4 Sponsor Ratings of Companies