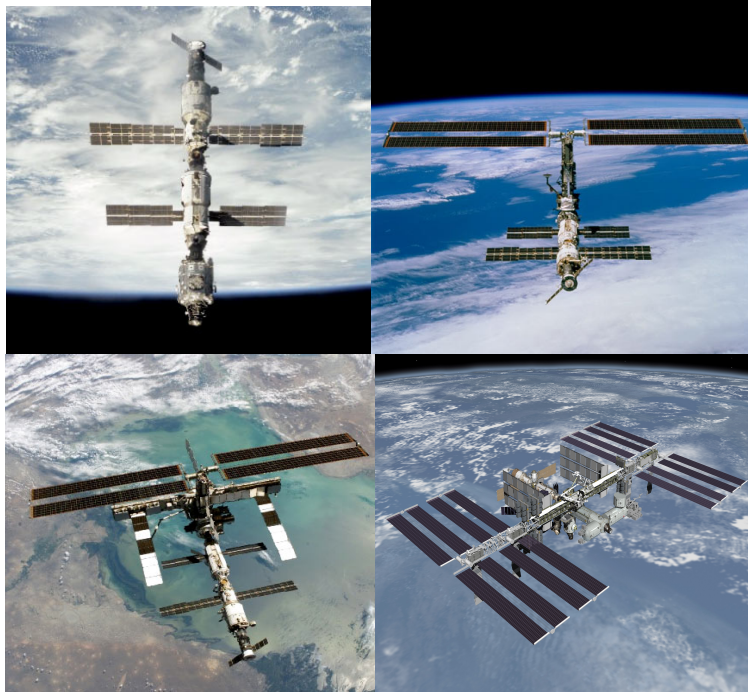


An Engineering Systems Analysis of Space Station Assembly and Supply



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ESD.71 – Engineering Systems Analysis for Design
Application Portfolio
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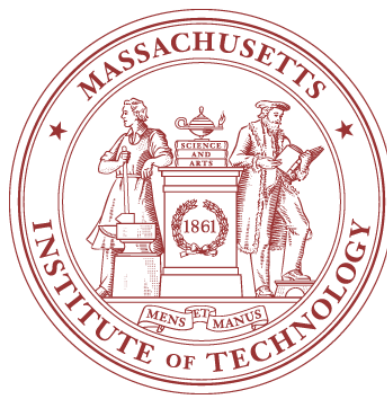


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¹ The images in the collage on the cover page of the International Space Station at different points in its assembly are available at <http://spaceflight.nasa.gov/home/index.html>

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List of Acronyms

| | |
|-------------------|---|
| ATO | Abort-To-Orbit |
| ATV | Automated Transfer Vehicle |
| EELV | Evolved Expendable Launch Vehicle |
| ELM-PS | Experiment Logistics Module-Pressurized Section |
| FY | Fiscal Year |
| IMAX [®] | Image Maximum |
| IMU | Inertial Measurement Unit |
| ISS | International Space Station |
| JEM-EF | Japanese Experiment Module-Exposed Facility |
| JEM-PM | Japanese Experiment Module-Pressurized Module |
| KSC | Kennedy Space Center |
| LEO | Low Earth Orbit |
| NASA | National Aeronautics and Space Administration |
| SSRMS | Space Station Remote Manipulator System |
| STS | Space Transportation System |

Abstract

In this document, the methods of decision analysis and binomial lattice modeling of uncertainties in complex systems are employed to analyze the usefulness of design and/or operational flexibility in the assembly and supply of a space station in Low Earth Orbit (LEO). First, the key uncertainties in the assembly and supply of the space station are identified and discussed. Next, a decision analysis is used to explore the utility of international cooperation and orbit selection alternatives in the launch manifest for space station assembly and supply. Then, binomial lattice modeling of the launch rate of the Space Shuttle is used to illustrate how a simple “option” for decreasing the crew size on the space station when launch rates are low can increase the overall returns the space station effort. Finally, the appropriateness of these techniques for this particular problem is discussed.

Introduction

A Space Station with “Options”

The system that is explored in this application portfolio is a multi-segment space station in LEO designed and deployed by NASA and/or the space agencies of other countries. For simplicity, the station is only considered to be comprised of a crew and three types of segments defined as: 1) “support segments,” 2) “payload segments,” and 3) “hybrid segments”. The support segments are devoted entirely to functions necessary to keep the station safe and operational (e.g. crew quarters, solar panels, return vehicle, airlock, storage modules, etc.). Payload segments are segments that can support payload operations. Finally, hybrid segments are segments that can support both payload operations and functions necessary to keep the station safe and operational (e.g. the Destiny Laboratory on the International Space Station supports some level of payload operations but also contains a substantial amount of equipment for functions such as life support, power, guidance, navigation, etc.).

In addition to the station itself, launch vehicles for the segments are considered to the extent that they are necessary to facilitate the assembly and supply of the station. The vehicles that are considered for assembly of the station are the U.S. Space Shuttle, the Russian Soyuz, the Russian Progress, and the Russian Proton—though the two latter vehicles are only considered in a supplementary analysis in one the appendices.

Ultimately, the system explored in this application portfolio is one with enormous uncertainty and complexity. In the pages that follow, decision analysis and binomial lattice modeling of the key uncertainties are utilized to identify ways in which designers might design “options” into such a system in order to take advantage of the upsides and avoid the downsides of these uncertainties.

Variable of Interest

The variable of interest in this system is the “profit” achieved through the return of payload mass to Earth. Essentially, the amount of payload mass returned to Earth is an indication the system’s ability to process science experiments and/or produce artifacts for museums and other organizations or companies (e.g. IMAX[®]). While the monetary value of this payload mass is extremely difficult to quantify, it is nevertheless important to analyze. In this report, a monetary value of \$21,000/kg of payload returned is assumed. This monetary value was used in a previous ESD.71 Application Portfolio (Robinson, 2005) and is thus assumed to be a reasonable figure for use in this Application Portfolio. However, it should be noted that the justification for this number is not clear in the prior Application Portfolio and thus, it should be considered to be a hypothetical value.

System Design Levers

The principal design levers of a typical space station are the number and types of space station segments, the order in which they are deployed, the launch vehicles that they are deployed with, the orbital inclination that they are deployed in, and the size of the crew that will utilize them. For simplicity, the design levers that will be considered in

this Application Portfolio are the size of the crew, the orbital inclination, and the amount of payload mass that can be launched on each flight.

Uncertainties in the Assembly and Supply of Space Stations

In the assembly and supply of a space station in LEO, the four primary uncertainties are the launch vehicle flight rate, launch vehicle success rate, annual budget for assembly and supply of the station, and station scope changes. Therefore, each of these could be a point of emphasis in an analysis of options that can be designed into the system. In the paragraphs that follow, each of these uncertainties is discussed.

Launch Vehicle Flight Rate:

The launch vehicle flight rate or launch rate is the number of flights a launch vehicle can achieve over a given period time. The reason that it is important is because it dictates how quickly the station will be built and the frequency with which payloads will be taken to and from it. Typically, a higher frequency of payload launch and return increases the value return from a launch system because a large percentage of the launch system costs goes to supporting a large staff of engineers and technicians that receive a fixed annual salary. Thus, a lower launch rate will result in fewer payloads returned per dollar spent per employee, unless the launch system staff is downsized. While this downsizing does happen for long-term, premeditated decreases in launch rate, it is typically not the case for temporary, unexpected decreases in launch rate.

The uncertainties in launch vehicle flight rate stem from a number of technical issues including: accidents and incidents during missions and/or vehicle processing, weather delays, the variation in mission objectives over time, etc. Individually modeling the effect of each of these issues on the launch rate is extremely difficult, and thus these issues are typically modeled aggregately from the historical flight rate of each of the launch vehicles considered for use in the assembly and supply of the station. The Space Shuttle, Soyuz, Progress, Proton, and Ariane V are among several launch vehicles that have or will be used for space station assembly and supply. Historical data for the amount of time between each launch of the Space Shuttle and Soyuz are provided below in Figure 1, Table 1, Figure 2, and Table 2, respectively. These data are also available for the Progress, Proton, and Ariane V launch vehicles in Appendix 1.

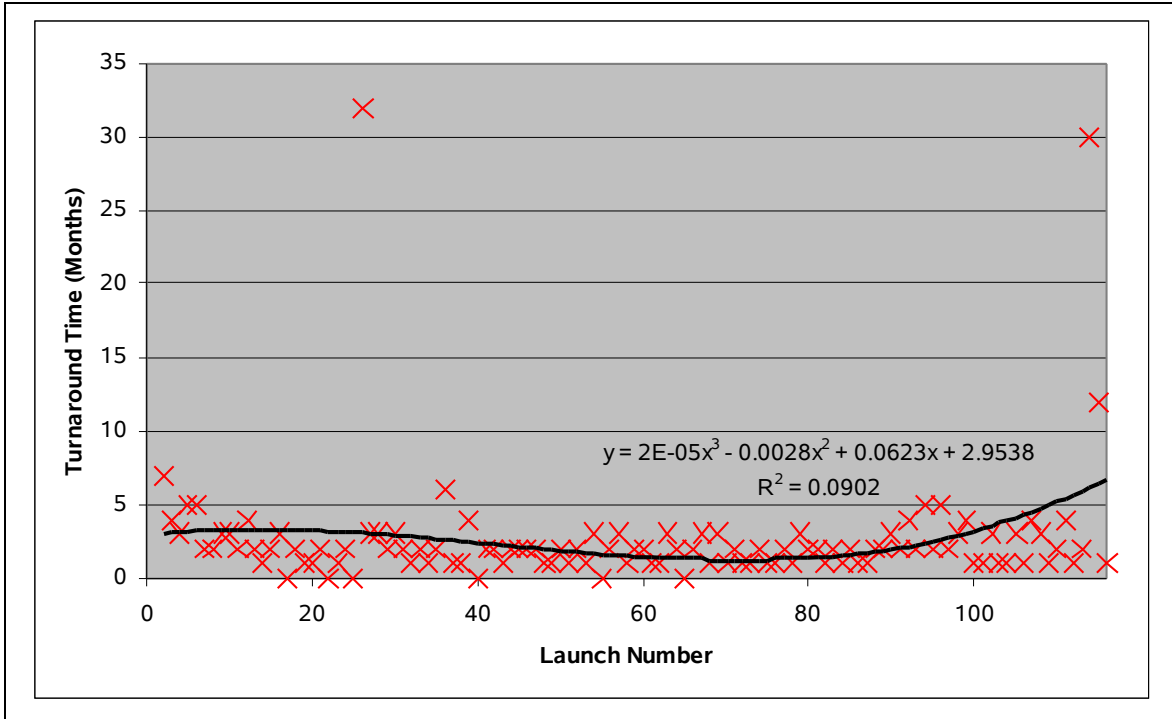


Figure 1. The historical turnaround time after each Space Shuttle flight.

(Derived from data available at: United States, National Aeronautics and Space Administration. NASA Space Shuttle: Past Missions Website)

| Statistical Parameter | Data (months) |
|-----------------------|---------------|
| Average | 2.64 |
| Min | 0 |
| Max | 32 |
| Median | 2 |
| Standard Deviation | 4.10 |

Table 1. Statistical parameters for the time to turn around the Space Shuttle after each mission.

(Derived from data available at: United States, National Aeronautics and Space Administration. NASA Space Shuttle: Past Missions Website)

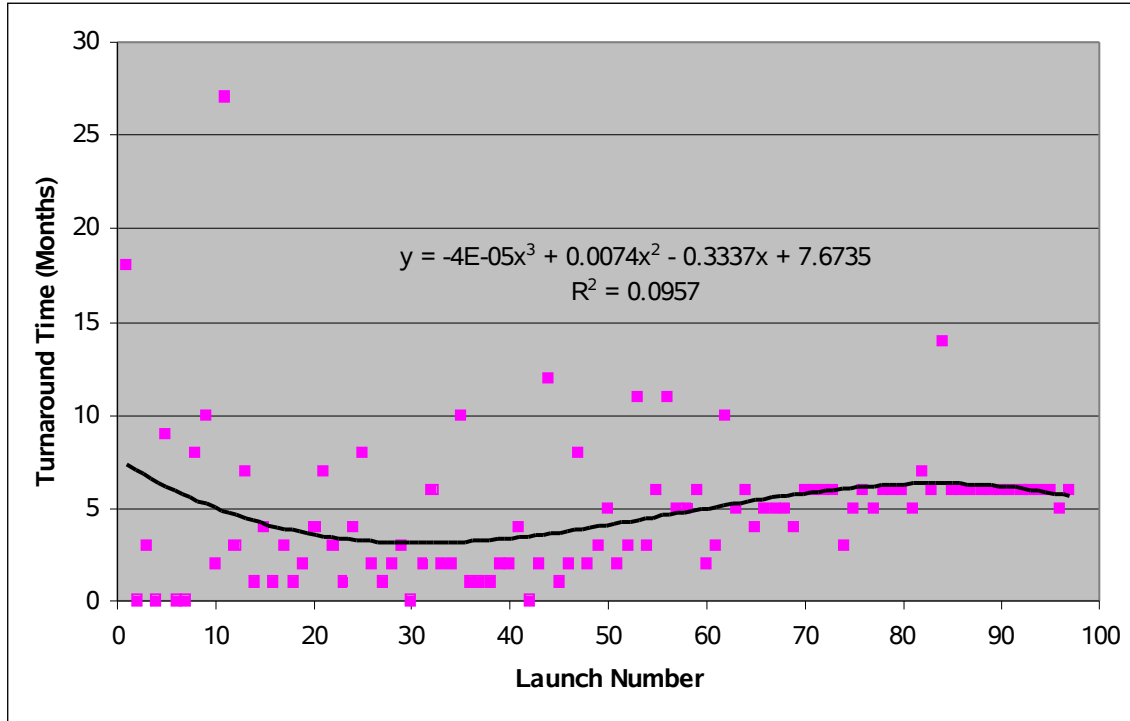


Figure 2. The historical turnaround time after each Soyuz flight.

(Derived from data available in Starsem, 2005)

| Statistical Parameter | Data (Months) |
|-----------------------|---------------|
| Average | 4.88 |
| Min | 0 |
| Max | 27 |
| Median | 5 |
| Standard Deviation | 3.92 |

Table 2. Statistical parameters for the time to turn around the Soyuz after each mission.

(Derived from data available in Starsem, 2005)

Launch Vehicle Success Rate:

The launch vehicle success rate is the overall percentage of missions that a launch vehicle successfully completes over a given time interval. In the assembly and supply of a space station, the requirements for mission success are much more stringent than they are for free-floating missions (i.e. satellite missions that do not require the rendezvous of multiple spacecraft). For example, if space station assembly and supply constraints were applied to the Space Shuttle mission STS-51F, the mission would be considered a failure because it did not achieve the proper orbit. However, since there were no requirements for a rendezvous during STS-51F, the failure to achieve the proper orbit did not hinder the accomplishment of the primary mission objectives and thus the mission was deemed a success.

Ultimately, if a launch vehicle failure prevents the docking of a spacecraft to the space station for the period of time necessary to complete the mission, the space station program will be negatively affected in terms of cost and schedule. At best, the failure will result in duplication of the effort necessary to complete the mission and at worst the failure will result in the destruction of the space station, a loss of the crew, and the cancellation of the program.

The lifetime success rates for the Space Shuttle, Soyuz, Proton, and Ariane V programs are 94.8%, 84.7%, 88.2%, and 85.7%, respectively (note: these success rates are based on the constraints that would be applied to space station assembly and supply and thus STS-51F is considered a failure along with several other missions that have been deemed successful in the context of their own requirements). Figure 3 and Figure 4 show the success rating—based on the criteria for a space station mission—of each Space Shuttle and Soyuz mission, respectively. These charts, along with those in Appendix 1 of the Proton and Ariane V success ratings, demonstrate that for some vehicles, many of the failures occurred at the beginning of that vehicle’s operating life and can probably be attributed to the learning curve inherent in the vehicle’s operation.

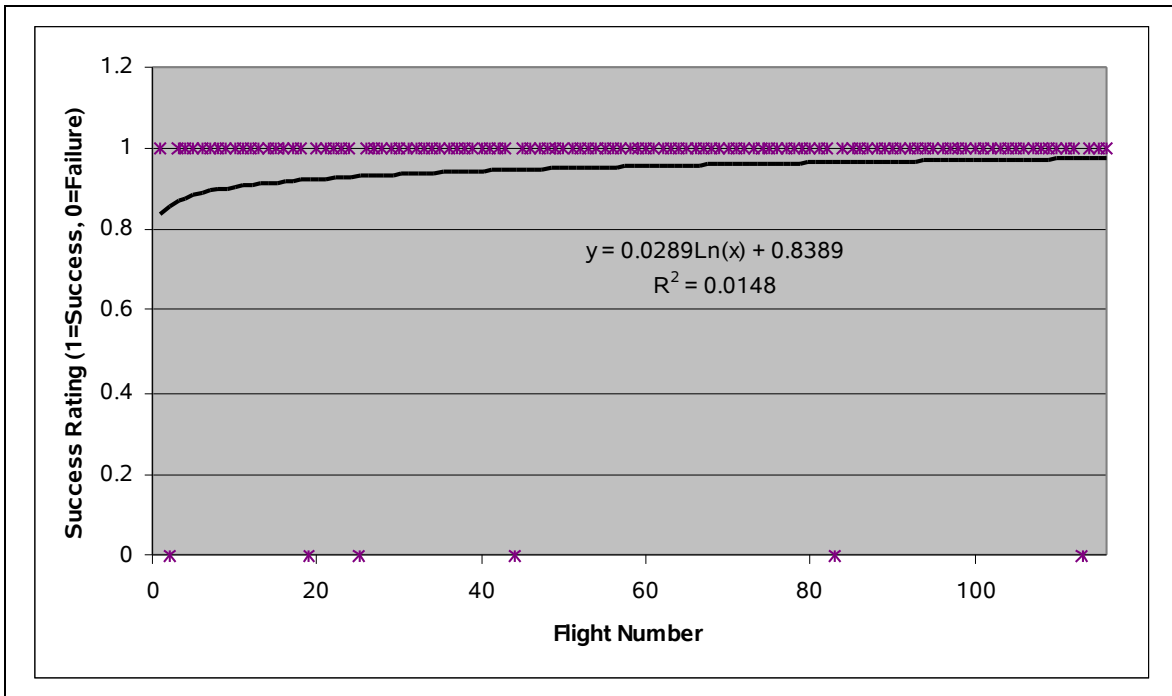


Figure 3. The historical success rating Space Shuttle missions.

(Derived from data available at: United States, National Aeronautics and Space Administration. NASA Space Shuttle: Past Missions Website)

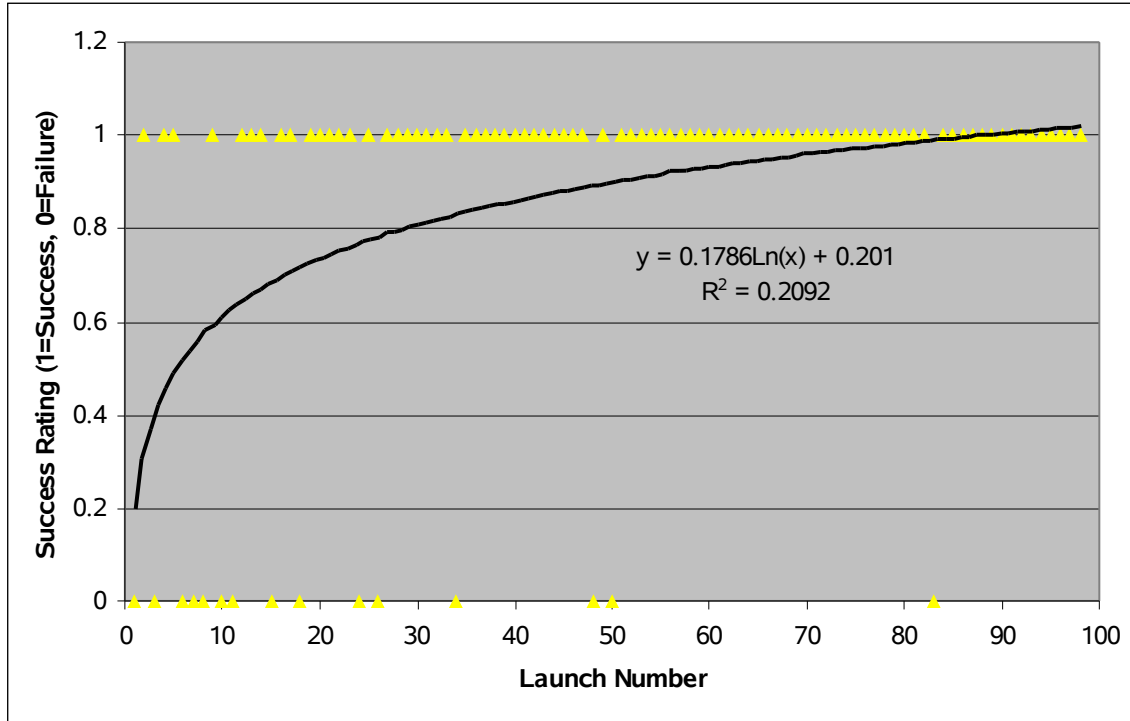


Figure 4. The historical success rating Soyuz missions.

(Derived from data available in Starsem, 2005)

Annual Space Station Assembly and Supply Budget:

The annual budget for the assembly and supply of a space station is the amount of money that the agency building and supplying it receives each year to procure the goods and services necessary to complete these tasks. In the case of NASA, the annual budget is proposed by the President of the United States and appropriated by the United States Congress. For planning purposes, the President provides annual budget forecasts for NASA several years into the future (available at NASA Budget Request Website). Unfortunately, these forecasts include a great deal of uncertainty as the President reserves the right to propose more or less than he/she forecast and in turn, Congress reserves the right to appropriate more or less than what the President proposes.

The data for historical differences in the Presidential budget proposals for NASA from both the forecasts and actual Congressional appropriations are available to the general public. A portion of this data is provided in Table 3.

| <i>Fiscal Year</i> | <i>President's Request to Congress</i> | <i>Congressional Appropriation</i> | <i>Change</i> | <i>NASA Operating Plan*</i> | <i>Change</i> |
|--------------------|--|------------------------------------|---------------|-----------------------------|---------------|
| 1993 | 4,128.0 | 4,078.0 | -50.0 | 4,052.9 | -25.1 |
| 1994 | 4,196.1 | 3,778.7 | -417.4** | 3,772.3 | -6.4 |
| 1995 | 3,324.0 | 3,155.1 | -168.9 | 3,155.1 | 0.0 |
| 1996 | 3,231.8 | 3,178.8 | -53.0 | 3,143.8 | -35.0 |
| 1997 | 3,150.9 | 3,150.9 | 0.0 | 2,960.9 | -190.0 |
| 1998 | 2,977.8 | 2,927.8 | -50.0 | 2,912.8 | -15.0 |
| 1999 | 3,059.0 | 3,028.0 | -31.0 | 2,998.3 | -29.7 |
| 2000 | 2,986.2 | 3,011.2 | +25.0 | 2,984.4 | -26.8 |
| 2001 | 3,165.7 | 3,125.7 | -40.0 | 3,118.8 | -6.9 |
| 2002 | 3,283.8 | 3,278.8 | -5.0 | 3,270.0 | -8.9 |
| 2003 | 3,208.0 | 3,252.8 | +44.8 | | |

Table 3. The Space Shuttle program budget FY1993-2003 (in millions of dollars).
(United States, Columbia Accident Investigation Board, 2003)

Externally Decreed Scope Changes:

The final primary uncertainty that could be considered in an analysis of design options for mitigating/exploiting uncertainty involves externally decreed changes in the space station scope. In the case of NASA, these changes are usually proposed by the President of the United States as a means to reduce cost and/or facilitate a specific political objective of the President. For example, at the beginning of the Clinton Administration, Bill Clinton—as part of his efforts to balance the federal budget—ordered a reduction of the operating lifetime of the proposed Space Station Freedom from 30 years to 10 years (Harland and Catchpole, 2002). Shortly thereafter, he ordered NASA to include Russia in the project to, among other things, ensure that Russian rocketry experts would not sell their expertise to terrorist groups and/or nations unfriendly to the U.S. (Harland and Catchpole, 2002 and Launis and McCurdy, 1997). In George W. Bush's first few months in office, he ordered NASA to halt work on the Habitation and Propulsion Modules of the International Space Station and the Crew Return Vehicle (Harland and Catchpole, 2002). Several years later, in response to the *Columbia* Space Shuttle accident, he declared that the Space Shuttle would be retired in 2010 (United States, National Aeronautics and Space Administration, NASA's Future: The Vision for Space Exploration Website).

While these events are largely anecdotal, they still provide the basis for plausible discrete event simulation scenarios. For instance, Clinton's reduction of the operational

lifetime of the International Space Station to a third of what it was proposed to be can be modeled as a discrete, 66% change in the operational lifetime of station occurring after a change in the Presidency. Thus, this event, along with historical Presidential election data could be used to include random changes in the station lifetime and/or size coinciding with Presidential elections where the incumbent's term expires or he/she is unseated. While this would be a very crude approximation of Presidential politics, it would have the potential to provide an interesting look into the effect of the political uncertainty that the system faces.

Decision Analysis of Space Station Assembly and Supply Alternatives

In designing a space station, one of the most important parameters to decide upon is the inclination of the orbit that it will be placed in. This parameter is defined as the angle between the plane of the orbit and the plane of the Equator. Thus, if a spacecraft/space station orbits the Earth, moving west to east directly over the equator at all times, it has an orbital inclination of 0° and if it passes directly over the North and South Poles in its orbit it has an orbital inclination of 90° . What makes the orbital inclination so important is the fact that the closer the inclination is to 0° , the more the vehicle that it was launched on is able to take advantage of the Earth's rotation (i.e. the vehicle will be able to carry more mass). Unfortunately, not every vehicle can be launched into an inclination of 0° due to a variety of constraints. The constraint that plays the biggest role in determining the inclination is the latitude of the launch site: no vehicle can be launched into an orbital inclination that is lower than the latitude of its launch site.² Thus, a vehicle launched from the Kennedy Space Center in Florida (KSC), which is located at 28.5° North latitude, must launch into an orbital inclination of at least 28.5° . Similarly, a vehicle launched from the Baikonur Cosmodrome in Kazakhstan (the launch site used by the Soviet Union/Russia for crewed flights), which is located near 51.6° North latitude, must launch into an orbital inclination of at least 51.6° (Wertz and Larson, 1999).³ This presents a problem in that if the U.S. decides to partner with Russia in the assembly and utilization of a space station, it must launch the station components into a 51.6° orbital inclination rather than a 28.5° inclination. This ultimately reduces the payload mass that can be carried up on each launch and prevents the use of the space station as a "way station" for missions to the Moon, Mars, and beyond.⁴

One of the major decision points in this analysis is whether or not to include the Russians in the assembly and utilization of the space station. Due to the constraints discussed above, this decision is driven by another decision: the inclination of the space

² Once a vehicle is in an orbit, its inclination can be changed, but such maneuvers are very costly in terms of propellant. For many spacecraft and most space stations it is not practical to carry enough propellant to change their inclination by a more than a few fractions of a degree.

³ While Baikonur is actually at 45.6° North latitude, launch vehicles cannot launch directly to the east because of populated areas and neighboring countries.

⁴ It would be a tremendous waste of fuel to stop at a space station at an orbital inclination of 51.6° on the way to and/or from the Moon, Mars, and beyond. It would however be reasonable if the inclination were close to 28.5° .

station's orbit. Thus, the following hypothetical alternatives are considered in this analysis:

1. Alternative 1 (A_1): The launch of a station requiring a crew of four astronauts into a 28.5° orbital inclination and the outfitting of the station with equipment that could only interface with U.S. vehicles (this would optimize U.S. launch vehicle performance while ruling out Russian involvement in the program),
2. Alternative 2 (A_2): The launch of a station requiring a crew of seven astronauts—four from the U.S. and three from Russia—into a 51.6° orbital inclination (this would lead to suboptimal U.S. launch vehicle performance and a U.S. dependence on Russia to provide three crewmembers and two Soyuz spacecraft each year),
3. Alternative 3 (A_3): The launch of the station mentioned in A_2 with the possibility of canceling Russian involvement in the operation of the space station (Alternative A_{3B}) five years after the start of assembly (this would lead to suboptimal U.S. launch vehicle performance while allowing the U.S. to utilize Russian crewmembers when they are needed). It is assumed that the Russians will provide this option for an additional charge of \$5M on each Soyuz flight.

The production function of the system is assumed to be as follows:

$$Y_{\text{payload returned}} = \text{MIN} [(\eta \times N_{\text{Shuttle Flights}} \times M_{\text{Shuttle return capacity at given inclination}}), P_{\text{crew}}]$$

where,

η = Space Shuttle efficiency factor (i.e. the payload mass delivered to the space station per Space Shuttle mission divided by the total mass delivered to the space station per mission)

$N_{\text{Shuttle Flights}}$ = Number of Space Shuttle flights to the space station

$M_{\text{Shuttle return capacity at given inclination}}$ = Maximum mass returnable from a given inclination

P_{crew} = annual mass of payload that can be processed by a crew of a given size.

This production function assumes path independence in the return of payload (i.e. the total amount of payload returned depends on the number of flights and not necessarily the sequence of flights). While this assumption is not necessary for this decision analysis, it is necessary for the binomial lattice analysis presented later in this document and thus, for the sake of comparing the results of the two methods it is made here. Appendix 2 provides details on how a decision analysis of this system can be conducted without the assumption of path independence.

The fixed costs of the Space Shuttle Program are the same for each alternative and Soyuz spacecraft are assumed to be procured at a per unit rate. Thus the overall fixed costs are same for each alternative. As a result, keeping track of the fixed costs adds little value to the decision process and it is therefore not considered in the input cost function, which is as follows:

$$C = C_{\text{Shuttle variable cost}} \times N_{\text{Shuttle Flights}} + C_{\text{Soyuz variable cost}} \times N_{\text{Soyuz Flights}}$$

where,

$N_{\text{Soyuz Flights}}$ = Number of Soyuz flights to the space station

$C_{\text{Shuttle variable cost}}$ = Variable cost of a Space Shuttle mission

$C_{\text{Soyuz variable cost}}$ = Variable cost of a Soyuz mission.

Thus, the annual cash flows are as follows:

$$\text{Cash Flow}_i = V \times (Y_{\text{payload returned}})_i - C_i \quad \text{for all } i$$

where “i” is an index variable for each year and,

V = Hypothetical value of payload.

Finally, the Net Present Value (NPV) of each alternative is as follows:

$$\text{NPV} = \sum \text{Cash Flow}_i / (1+r)^i \quad \text{for all } i$$

where,

r = Discount rate.

Table 4 below summarizes the assumed launch vehicle parameters necessary to perform these calculations for each alternative. One of the parameters in this table, η , is derived through the author’s subjective classifications of each of the ISS segments in Table 5.^{5,6}

⁵ A segment is defined here as a piece of the station that requires its own dedicated launch.

⁶ This classification is informed by the author’s internship experiences as a contractor for the Space Shuttle and ISS programs as well as descriptions of the modules in (Harland and Catchpole, 2002).

| PARAMETER | A ₁ | A ₂ | A ₃ |
|---|------------------------|------------------------|---------------------|
| Hypothetical Value of Payload (V) | \$21,000/ kg | \$21,000/ kg | \$21,000/k g |
| Maximum Number of Space Shuttle Launches During the 1 st Five Years | 25 | 25 | 25 |
| Maximum Number of Space Shuttle Launches During the 2 nd Five Years | 25 | 25 | 25 |
| Payload Processing Capability of 4 Person Crew (P _{crew} when crew size is 4) ⁷ | 1,800 kg/year | 1,800 kg/year | 1,800 kg/year |
| Payload Processing Capability of 7 Person Crew (P _{crew} when crew size is 4) ⁷ | N/A | 4,500 kg/year | 4,500 kg/year |
| Variable Cost for Shuttle Missions (C _{Shuttle variable cost}) ⁸ | \$92M per flight | \$92M per flight | \$92M per flight |
| Space Shuttle Payload Return Capability ⁹ | 4,500 kg | 3,200 kg | 3,200 kg |
| Space Shuttle Efficiency Factor (η) ¹⁰ | 0.3 | 0.3 | 0.3 |
| Discount Rate (r) ¹¹ | 12% | 12% | 12% |
| Maximum Number of Soyuz Launches During the 1 st Five Years | 0 | 10 | 10 |
| Minimum Number of Soyuz Launches During the 1 st Five Years | 0 | 10 | 10 |
| Maximum Number of Soyuz Launches During the 2 nd Five Years | 0 | 10 | 10 |

Table 4. (Part 1 of 2)

⁷ This capability is based on a hypothetical payload processing capability of 900 kg/(crewmember-year) with the assumption that two crewmember-years are spent each year on support (i.e. non-payload) operations such as space station maintenance.

⁸ (Isakowitz, 1995) estimated the variable or “marginal” cost of a Space Shuttle mission (i.e. the cost of adding another mission to the manifest in a given year) as ~\$63M for FY1988. (Jenkins, 2002) uses an inflation factor of 1.451 to convert FY1988 Space Shuttle Program expenditures into FY2002 dollars. Thus, the marginal cost of a Space Shuttle mission in FY2000 dollars is \$63M x 1.451 = \$92M.

⁹ According to (United States, National Aeronautics and Space Administration. NASA Space Shuttle: Past Missions Website, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/list_main.html) the Space Shuttle returned roughly 3,200 kg of payload in the Multi-Purpose Logistics Module (MPLM) on STS-114. Thus, it is assumed here that the maximum payload that can be returned is on a mission to a 51.6° inclination space station is 3,200 kg. According to (Isakowitz, 1995) the maximum ascent performance capability is 24,400 kg and 17,100 kg for launches to 28.5° and 51.6° inclinations, respectively. This means that the ascent performance is affected by a factor of 17,100/24,400. Thus, if the maximum payload returnable from a 51.6° orbit is assumed to be 3,200 kg, then the maximum payload returnable from a 28.5° orbit is 3,200kg x 24,400/17,100 ~4,500 kg.

¹⁰ This figure is derived in Table 5. The assumption is that the payload mass will simply be fraction of the total mass that the Space Shuttle delivers to the station on each mission. This fraction is equivalent to the fraction of the space station that is devoted to payload operations.

¹¹ (de Neufville, 1990) argued that government projects should use a discount rate similar to those used in the private sector because the government uses money taxed from the private sector. Thus, a discount rate of 12% is assumed here as it is on par with discount rates used in the private sector.

| PARAMETER | A ₁ | A ₂ | A ₃ |
|---|----------------|------------------|------------------|
| Minimum Number of Soyuz Launches During the 2 nd Five Years | 0 | 10 | 0 |
| Variable Cost for Soyuz Missions (C _{Soyuz variable cost}) ¹² | N/A | \$20M per flight | \$25M per flight |

Table 4. Assumed launch vehicle parameters for decision analysis.

| ISS Support Segments | ISS Payload Segments | Hybrid Segments |
|--|--|--|
| <ul style="list-style-type: none"> • Zarya Cargo Module • Node 1 • Z1 Truss • P6 Truss and Solar Arrays • SSRMS and other robotic equipment • Quest Airlock • Pirs Module • S0 Truss • S1 Truss • P1 Truss • P3/P4 Truss and Solar Arrays • P5 Truss and Solar Arrays • S5 Truss • Node 2 • S6 Truss and Solar Arrays | <ul style="list-style-type: none"> • Columbus Laboratory • Kibo ELM-PS • Kibo JEM-PM • Kibo JEM-EF • Multipurpose Russian Laboratory • Russian Research Module | <ul style="list-style-type: none"> • Zvezda Service Module • Destiny Laboratory • Node 3 and Cupola |
| Fraction of ISS Segments Devoted to Payload Operations = (# of Payload Segments + ½ # of Hybrid Segments) / (Total # of Segments) | | 0.3 |

Table 5. A classification of ISS segments.

As mentioned before, the uncertainty in the decision of which alternative to choose stems from the fact that the number of successful launches that will be achieved is in doubt. Thus, the uncertainty modeled in this decision analysis is the annual launch rate of the Space Shuttle. Over the history of the Space Shuttle Program, the annual launch rate has been as shown in Table 6 below.

¹² (Baker, 2006) estimated a Soyuz launch cost to be \$20M

| Year | # of Flights |
|------|--------------|
| 1981 | 2 |
| 1982 | 3 |
| 1983 | 4 |
| 1984 | 5 |
| 1985 | 9 |
| 1986 | 2 |
| 1987 | 0 |
| 1988 | 2 |
| 1989 | 5 |
| 1990 | 6 |
| 1991 | 6 |
| 1992 | 8 |
| 1993 | 7 |
| 1994 | 7 |
| 1995 | 7 |
| 1996 | 7 |
| 1997 | 8 |
| 1998 | 5 |
| 1999 | 3 |
| 2000 | 5 |
| 2001 | 6 |
| 2002 | 5 |
| 2003 | 1 |
| 2004 | 0 |
| 2005 | 1 |
| 2006 | 3 |

Table 6. The historical annual flight rate of the Space Shuttle.

(Derived from data available at: United States, National Aeronautics and Space Administration. NASA Space Shuttle: Past Missions Website)

Upon examination of these data, there appears to be several years with extremely low flight rates: 1981, 1982, 1986, 1987, 1988, 2003, 2004, and 2005. The low flight rates for these years are not coincidental; these are the years corresponding to the initial flight-testing of the Space Shuttle (1981-1982) and the grounding of the Space Shuttle due to the *Challenger* and *Columbia* accidents (1986-1988 and 2003-2005, respectively). For this analysis the annual flight rates for years after the initial learning curve of Space Shuttle operation are not considered because it is assumed that the time period analyzed is after the initial flight test period. Thus, the flight data to be considered is shown in Table 7 below.

| Year | # of Flights |
|-------------------------------|---------------------|
| 1983 | 4 |
| 1984 | 5 |
| 1985 | 9 |
| 1986 | 2 |
| 1987 | 0 |
| 1988 | 2 |
| 1989 | 5 |
| 1990 | 6 |
| 1991 | 6 |
| 1992 | 8 |
| 1993 | 7 |
| 1994 | 7 |
| 1995 | 7 |
| 1996 | 7 |
| 1997 | 8 |
| 1998 | 5 |
| 1999 | 3 |
| 2000 | 5 |
| 2001 | 6 |
| 2002 | 5 |
| 2003 | 1 |
| 2004 | 0 |
| 2005 | 1 |
| 2006 | 3 |
| Average | 4.67 |
| Min | 0 |
| Max | 9 |
| Median | 6 |
| Standard Deviation | 2.63 |
| Standard Deviation (%) | 56.40% |

Table 7. Flight data and statistical parameters of the annual Space Shuttle flight rate during “normal” years.

(Derived from data available at: United States, National Aeronautics and Space Administration.
NASA Space Shuttle: Past Missions Website)

Figure 5, which spans two pages of this document, contains a decision tree for this problem.

Outcomes



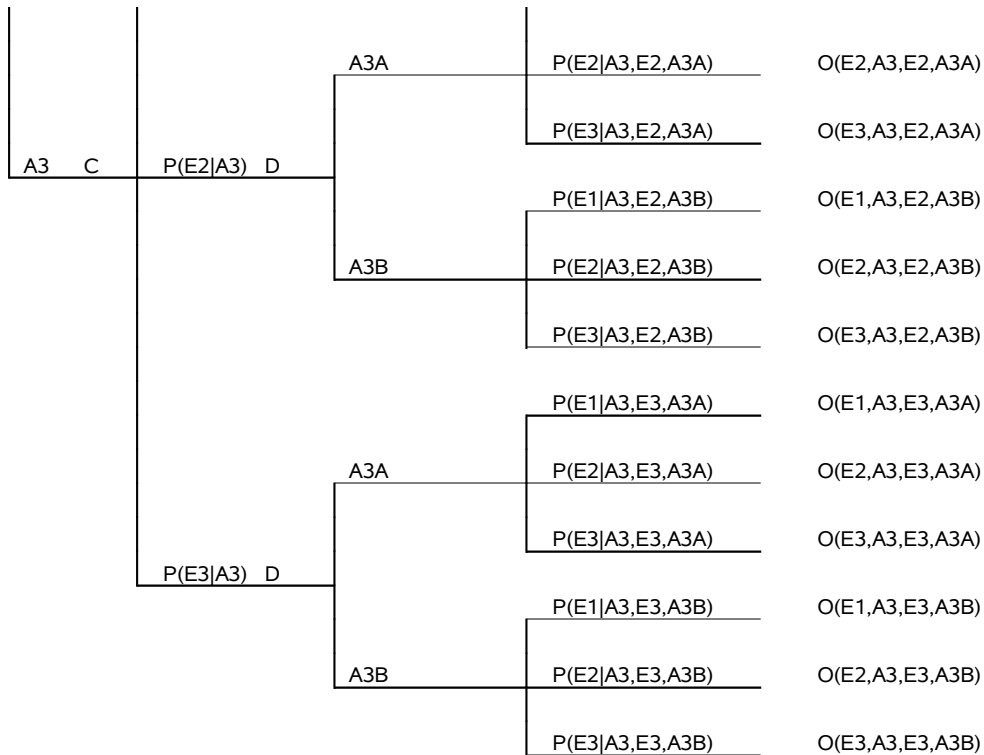


Figure 5. Decision Tree for the Space Station Assembly Alternatives.

For the purpose of this analysis, a simple model of launch success probability is used. The chance events are as follows:

- E_1 = The Space Shuttle averages 5 launches per year for five years.
- E_2 = The Space Shuttle averages 4 launches per year for five years.
- E_3 = The Space Shuttle averages 3 launches per year for five years.

The events are assumed to be independent over both five-year stages of the analysis and their probabilities are assumed to be as follows:

$P(E_1) = 0.625$
 $P(E_2) = 0.042$
 $P(E_3) = 0.333.$

These figures were derived from simply dividing the number of years in which there were three or less, four, and five or more Space Shuttle launches, respectively, by the total number of considered years in the history of Space Shuttle operation. This is admittedly a very unsophisticated model, but for this exercise it is assumed to be sufficient. Additionally, it is assumed that all Russian launches are successful.

With that said, Table 8 describes the number of launches corresponding to the various combinations of events that can occur in the simplified analysis in this section. Table 9 and Table 10 contain the values of all of the outcomes and the probabilities in the decision tree.

| Combination of Events | Resulting Number of Successful Space Shuttle Missions over the 10 Year Period |
|-----------------------------------|---|
| E ₁ and E ₁ | 50 |
| E ₁ and E ₂ | 45 |
| E ₁ and E ₃ | 40 |
| E ₂ and E ₂ | 40 |
| E ₂ and E ₃ | 35 |
| E ₃ and E ₃ | 30 |

Table 8. The number of missions resulting from each combination of events in the decision analysis.

| Outcomes | NPV |
|-----------------|--------------------|
| O(A1, E1, E1) | \$ (1,877,523,595) |
| O(A1, E1, E2) | \$ (1,729,415,906) |
| O(A1, E1, E3) | \$ (1,581,308,217) |
| O(A1, E2, E1) | \$ (1,616,507,241) |
| O(A1, E2, E2) | \$ (1,468,399,552) |
| O(A1, E2, E3) | \$ (1,320,291,864) |
| O(A1, E3, E1) | \$ (1,355,490,888) |
| O(A1, E3, E2) | \$ (1,207,383,199) |
| O(A1, E3, E3) | \$ (1,059,275,510) |
| O(A2, E1, E1) | \$ (1,803,258,687) |
| O(A2, E1, E2) | \$ (1,655,150,998) |
| O(A2, E1, E3) | \$ (1,507,043,309) |
| O(A2, E2, E1) | \$ (1,581,565,015) |
| O(A2, E2, E2) | \$ (1,433,457,326) |
| O(A2, E2, E3) | \$ (1,285,349,637) |
| O(A2, E3, E1) | \$ (1,377,745,288) |
| O(A2, E3, E2) | \$ (1,229,637,599) |
| O(A2, E3, E3) | \$ (1,081,529,910) |
| O(E1.A3,E1,A3A) | \$ (1,847,728,692) |
| O(E2.A3,E1,A3A) | \$ (1,699,621,003) |
| O(E3.A3,E1,A3A) | \$ (1,551,513,314) |
| O(E1.A3,E1,A3B) | \$ (1,858,514,795) |
| O(E2.A3,E1,A3B) | \$ (1,710,407,106) |
| O(E3.A3,E1,A3B) | \$ (1,562,299,418) |
| O(E1.A3,E2,A3A) | \$ (1,626,035,019) |
| O(E2.A3,E2,A3A) | \$ (1,477,927,330) |
| O(E3.A3,E2,A3A) | \$ (1,329,819,642) |
| O(E1.A3,E2,A3B) | \$ (1,636,821,123) |
| O(E2.A3,E2,A3B) | \$ (1,488,713,434) |
| O(E3.A3,E2,A3B) | \$ (1,340,605,745) |
| O(E1.A3,E3,A3A) | \$ (1,422,215,293) |
| O(E2.A3,E3,A3A) | \$ (1,274,107,604) |
| O(E3.A3,E3,A3A) | \$ (1,125,999,915) |
| O(E1.A3,E3,A3B) | \$ (1,433,001,396) |
| O(E2.A3,E3,A3B) | \$ (1,284,893,707) |
| O(E3.A3,E3,A3B) | \$ (1,136,786,018) |

Table 9. The possible outcomes in the decision analysis.

| Probability | Equivalent Expression of the Probability | Value of the Probability |
|-----------------|--|--------------------------|
| P(E1 A1) | P(E ₁) | 0.625 |
| P(E2 A1) | P(E ₂) | 0.042 |
| P(E3 A1) | P(E ₃) | 0.333 |
| P(E1 A2) | P(E ₁) | 0.625 |
| P(E2 A2) | P(E ₂) | 0.042 |
| P(E3 A2) | P(E ₃) | 0.333 |
| P(E1 A3) | P(E ₁) | 0.625 |
| P(E2 A3) | P(E ₂) | 0.042 |
| P(E3 A3) | P(E ₃) | 0.333 |
| P(E1 A1,E1) | P(E ₁) | 0.625 |
| P(E2 A1,E1) | P(E ₂) | 0.042 |
| P(E3 A1,E1) | P(E ₃) | 0.333 |
| P(E1 A1,E2) | P(E ₁) | 0.625 |
| P(E2 A1,E2) | P(E ₂) | 0.042 |
| P(E3 A1,E2) | P(E ₃) | 0.333 |
| P(E1 A1,E3) | P(E ₁) | 0.625 |
| P(E2 A1,E3) | P(E ₂) | 0.042 |
| P(E3 A1,E3) | P(E ₃) | 0.333 |
| P(E1 A2,E1) | P(E ₁) | 0.625 |
| P(E2 A2,E1) | P(E ₂) | 0.042 |
| P(E3 A2,E1) | P(E ₃) | 0.333 |
| P(E1 A2,E2) | P(E ₁) | 0.625 |
| P(E2 A2,E2) | P(E ₂) | 0.042 |
| P(E3 A2,E2) | P(E ₃) | 0.333 |
| P(E1 A2,E3) | P(E ₁) | 0.625 |
| P(E2 A2,E3) | P(E ₂) | 0.042 |
| P(E3 A2,E3) | P(E ₃) | 0.333 |
| P(E1 A3,E1,A3A) | P(E ₁) | 0.625 |
| P(E2 A3,E1,A3A) | P(E ₂) | 0.042 |
| P(E3 A3,E1,A3A) | P(E ₃) | 0.333 |
| P(E1 A3,E1,A3B) | P(E ₁) | 0.625 |
| P(E2 A3,E1,A3B) | P(E ₂) | 0.042 |
| P(E3 A3,E1,A3B) | P(E ₃) | 0.333 |
| P(E1 A3,E2,A3A) | P(E ₁) | 0.625 |
| P(E2 A3,E2,A3A) | P(E ₂) | 0.042 |
| P(E3 A3,E2,A3A) | P(E ₃) | 0.333 |
| P(E1 A3,E2,A3B) | P(E ₁) | 0.625 |
| P(E2 A3,E2,A3B) | P(E ₂) | 0.042 |
| P(E3 A3,E2,A3B) | P(E ₃) | 0.333 |
| P(E1 A3,E3,A3A) | P(E ₁) | 0.625 |
| P(E2 A3,E3,A3A) | P(E ₂) | 0.042 |
| P(E3 A3,E3,A3A) | P(E ₃) | 0.333 |
| P(E1 A3,E3,A3B) | P(E ₁) | 0.625 |
| P(E2 A3,E3,A3B) | P(E ₂) | 0.042 |
| P(E3 A3,E3,A3B) | P(E ₃) | 0.333 |

Table 10. The probabilities of each of the possible events in the decision analysis.

Thus, the expected NPVs of the alternatives are:

$$EV(A_1) = P(E1|A1) \times [P(E1|A1,E1) \times O(A1, E1, E1) + P(E2|A1,E1) \times O(A1, E1, E2) + P(E3|A1,E1) \times O(A1, E1, E3)] + P(E2|A1) \times [P(E1|A1,E2) \times O(A1, E2, E1) + P(E2|A1,E2)$$

$$\times O(A_1, E_2, E_2) + P(E_3|A_1, E_2) \times O(A_1, E_2, E_3)] + P(E_3|A_1) \times [P(E_1|A_1, E_3) \times O(A_1, E_3, E_1) + P(E_2|A_1, E_3) \times O(A_1, E_3, E_2) + P(E_3|A_1, E_3) \times O(A_1, E_3, E_3)] = \$1,588M,$$

$$EV(A_2) = P(E_1|A_2) \times [P(E_1|A_2, E_1) \times O(A_2, E_1, E_1) + P(E_2|A_2, E_1) \times O(A_2, E_1, E_2) + P(E_3|A_2, E_1) \times O(A_2, E_1, E_3)] + P(E_2|A_2) \times [P(E_1|A_2, E_2) \times O(A_2, E_2, E_1) + P(E_2|A_2, E_2) \times O(A_2, E_2, E_2) + P(E_3|A_2, E_2) \times O(A_2, E_2, E_3)] + P(E_3|A_2) \times [P(E_1|A_2, E_3) \times O(A_2, E_3, E_1) + P(E_2|A_2, E_3) \times O(A_2, E_3, E_2) + P(E_3|A_2, E_3) \times O(A_2, E_3, E_3)] = \$1,547M,$$

$$EV(A_{3A}|E_1, A_3) = P(E_1|A_3, E_1, A_{3A}) \times O(E_1, A_3, E_1, A_{3A}) + P(E_2|A_3, E_1, A_{3A}) \times O(E_2, A_3, E_1, A_{3A}) + P(E_3|A_3, E_1, A_{3A}) \times O(E_3, A_3, E_1, A_{3A}) = \$1,743M,$$

$$EV(A_{3B}|E_1, A_3) = P(E_1|A_3, E_1, A_{3B}) \times O(E_1, A_3, E_1, A_{3B}) + P(E_2|A_3, E_1, A_{3B}) \times O(E_2, A_3, E_1, A_{3B}) + P(E_3|A_3, E_1, A_{3B}) \times O(E_3, A_3, E_1, A_{3B}) = \$1,754M,$$

$$EV(A_{3A}|E_2, A_3) = P(E_1|A_3, E_2, A_{3A}) \times O(E_1, A_3, E_2, A_{3A}) + P(E_2|A_3, E_2, A_{3A}) \times O(E_2, A_3, E_2, A_{3A}) + P(E_3|A_3, E_2, A_{3A}) \times O(E_3, A_3, E_2, A_{3A}) = \$1,521M,$$

$$EV(A_{3B}|E_2, A_3) = P(E_1|A_3, E_2, A_{3B}) \times O(E_1, A_3, E_2, A_{3B}) + P(E_2|A_3, E_2, A_{3B}) \times O(E_2, A_3, E_2, A_{3B}) + P(E_3|A_3, E_2, A_{3B}) \times O(E_3, A_3, E_2, A_{3B}) = \$1,532M,$$

$$EV(A_{3A}|E_3, A_3) = P(E_1|A_3, E_3, A_{3A}) \times O(E_1, A_3, E_3, A_{3A}) + P(E_2|A_3, E_3, A_{3A}) \times O(E_2, A_3, E_3, A_{3A}) + P(E_3|A_3, E_3, A_{3A}) \times O(E_3, A_3, E_3, A_{3A}) = \$1,317M,$$

$$EV(A_{3B}|E_3, A_3) = P(E_1|A_3, E_3, A_{3B}) \times O(E_1, A_3, E_3, A_{3B}) + P(E_2|A_3, E_3, A_{3B}) \times O(E_2, A_3, E_3, A_{3B}) + P(E_3|A_3, E_3, A_{3B}) \times O(E_3, A_3, E_3, A_{3B}) = \$1,3280M.$$

$EV(A_{3A}|E_1, A_3) > EV(A_{3B}|E_1, A_3)$ so the decision-maker would choose A_{3A} if E_1 occurs

$EV(A_{3A}|E_2, A_3) > EV(A_{3B}|E_2, A_3)$ so the decision-maker would choose A_{3A} if E_2 occurs

$EV(A_{3A}|E_3, A_3) > EV(A_{3B}|E_3, A_3)$ so the decision-maker would choose A_{3A} if E_3 occurs

Thus,

$$EV(A_3) = P(E_1|A_3) \times EV(A_{3A}|E_1, A_3) + P(E_2|A_3) \times EV(A_{3A}|E_2, A_3) + P(E_3|A_3) \times EV(A_{3A}|E_3, A_3) = \$1,592M.$$

Table 11 below contains the expected values of the alternatives. Because $EV(A_2) > EV(A_1) > EV(A_3)$ the decision-maker would choose A_2 as it represents the optimal choice for the probabilities and outcomes that are predicted. However, it should be noted that the model of the probabilities and outcomes provided in this analysis is not very sophisticated and thus a more detailed analysis could lead to a different decision. As can be seen in the sensitivity analysis results in Table 12 and Table 13, the option is more attractive than Alternative 1 for high values of η and more attractive than Alternative 2 at extremely low values of η . Additionally, as can be seen in the sensitivity analysis results in Table 14, Table 15, and Table 16 Alternative 3 becomes more attractive than Alternative 1 as the probability of high launch rates increases.

| | | |
|--|--|--|
| Expected Value of A₁ | Expected Value of A₂ | Expected Value of A₃ |
| \$(1,588M) | \$(1,547M) | \$(1,592M) |

Table 11. The expected value of each alternative.

| Space Shuttle Efficiency Factor (η) | Value of Option vs. A1 (Expected Value of A3- Expected Value of A1) |
|--|--|
| Baseline | \$ (4,016,644.67) |
| 0.05 | \$ (168,595,460.81) |
| 0.10 | \$ (159,692,751.68) |
| 0.15 | \$ (119,259,743.13) |
| 0.20 | \$ (74,668,381.05) |
| 0.25 | \$ (33,756,904.75) |
| 0.30 | \$ (4,016,644.67) |
| 0.35 | \$ 7,104,921.70 |
| 0.40 | \$ 16,687,342.73 |
| 0.45 | \$ 26,220,113.90 |
| 0.50 | \$ 29,794,903.09 |
| 0.55 | \$ 29,794,903.09 |
| 0.60 | \$ 29,794,903.09 |
| 0.65 | \$ 29,794,903.09 |
| 0.70 | \$ 29,794,903.09 |
| 0.75 | \$ 29,794,903.09 |
| 0.80 | \$ 29,794,903.09 |
| 0.85 | \$ 29,794,903.09 |
| 0.90 | \$ 29,794,903.09 |
| 0.95 | \$ 29,794,903.09 |
| 1.00 | \$ 29,794,903.09 |

Table 12. The value of the option when compared to Alternative 1 over a range of Space Shuttle efficiency factors.

| Space Shuttle Efficiency Factor (η) | Value of Option vs. A2 (Expected Value of A3 – Expected Value of A2)) |
|-------------------------------------|--|
| Baseline | \$ (44,470,004.62) |
| 0.05 | \$ 36,023,304.53 |
| 0.10 | \$ (4,103,951.63) |
| 0.15 | \$ (43,247,847.87) |
| 0.20 | \$ (44,470,004.62) |
| 0.25 | \$ (44,470,004.62) |
| 0.30 | \$ (44,470,004.62) |
| 0.35 | \$ (44,470,004.62) |
| 0.40 | \$ (44,470,004.62) |
| 0.45 | \$ (44,470,004.62) |
| 0.50 | \$ (44,470,004.62) |
| 0.55 | \$ (44,470,004.62) |
| 0.60 | \$ (44,470,004.62) |
| 0.65 | \$ (44,470,004.62) |
| 0.70 | \$ (44,470,004.62) |
| 0.75 | \$ (44,470,004.62) |
| 0.80 | \$ (44,470,004.62) |
| 0.85 | \$ (44,470,004.62) |
| 0.90 | \$ (44,470,004.62) |
| 0.95 | \$ (44,470,004.62) |
| 1.00 | \$ (44,470,004.62) |

Table 13. The value for the option when compared to Alternative 2 over a range of Space Shuttle efficiency factors.

| | Expected Value Of A1 | P(E3) | | | | |
|-------|----------------------|-------------------|--------------------|--------------------|--------------------|-------------------|
| | | 1.00 | 0.75 | 0.50 | 0.25 | 0.00 |
| P(E1) | \$ (1,587,727,398) | | | | | |
| | 0.00 | \$(1,059,275,510) | \$ (1,161,556,521) | \$ (1,263,837,531) | \$ (1,366,118,542) | \$(1,468,399,552) |
| | 0.25 | | \$ (1,263,837,531) | \$ (1,366,118,542) | \$ (1,468,399,552) | \$(1,570,680,563) |
| | 0.50 | | | \$ (1,468,399,552) | \$ (1,570,680,563) | \$(1,672,961,574) |
| | 0.75 | | | | \$ (1,672,961,574) | \$(1,775,242,584) |
| | 1.00 | | | | | \$(1,877,523,595) |

Table 14. The expected value of Alternative 1 over a range of event probabilities.

| | Expected Value Of A2 | P(E3) | | | | |
|-------|---------------------------|-------------------|--------------------|--------------------|--------------------|-------------------|
| | | 1.00 | 0.75 | 0.50 | 0.25 | 0.00 |
| P(E1) | \$ (1,547,274,038) | | | | | |
| | 0.00 | \$(1,081,529,910) | \$ (1,169,511,764) | \$ (1,257,493,618) | \$ (1,345,475,472) | \$(1,433,457,326) |
| | 0.25 | | \$ (1,261,962,105) | \$ (1,349,943,958) | \$ (1,437,925,812) | \$(1,525,907,666) |
| | 0.50 | | | \$ (1,442,394,299) | \$ (1,530,376,153) | \$(1,618,358,006) |
| | 0.75 | | | | \$ (1,622,826,493) | \$(1,710,808,347) |
| | 1.00 | | | | | \$(1,803,258,687) |

Table 15. The expected value of Alternative 2 over a range of event probabilities.

| | Expected Value Of A3 | P(E3) | | | | |
|-------|---------------------------|-------------------|--------------------|--------------------|--------------------|-------------------|
| | | 1.00 | 0.75 | 0.50 | 0.25 | 0.00 |
| P(E1) | \$ (1,591,744,043) | | | | | |
| | 0.00 | \$(1,125,999,915) | \$ (1,213,981,769) | \$ (1,301,963,623) | \$ (1,389,945,477) | \$(1,477,927,330) |
| | 0.25 | | \$ (1,306,432,109) | \$ (1,394,413,963) | \$ (1,482,395,817) | \$(1,570,377,671) |
| | 0.50 | | | \$ (1,486,864,303) | \$ (1,574,846,157) | \$(1,662,828,011) |
| | 0.75 | | | | \$ (1,667,296,498) | \$(1,755,278,351) |
| | 1.00 | | | | | \$(1,847,728,692) |

Table 16. The expected value of Alternative 3 over a range of event probabilities.

Binomial Lattice Modeling of Space Shuttle Flight Rates and Payload Return

In this section, the annual launch rate of the Space Shuttle is modeled through a binomial lattice approach. The alternatives that are considered in this analysis are essentially the same as those in the previous section. The only differences of significance are that the probabilities of the annual launch rates are assumed to be governed by Geometric Brownian Motion and that there will be more than one opportunity to exercise the option in Alternative 3.

As shown in Table 7, the average flight rate is 4.67 flights per year and the standard deviation, σ , in terms of a percentage is:

$$\sigma = 2.62/4.67 \times 100\% = 56.4\%/year.$$

The time span of the space station’s operation is assumed to be ten years. However, in order to keep the lattices compact, only five time steps are used in this analysis and thus the change in time between each time step, ΔT , is 2 years.

An additional assumption that is made for this analysis is that the launch rate is initially expected to decay exponentially over time due to aging of the Space Shuttle fleet and infrastructure. Thus, the initially predicted launch rate at any given time can be found with the following function:

$$S_T = Se^{vT} \rightarrow \ln(S_T/S)/T = v$$

where,

T = Time in years.

S = Initial annual launch rate = 4.67 flights per year.

S_T = The launch rate at time, T.

v = The expected annual decrease in launch rate by percentage.

As a hypothetical assumption, the launch rate at the end of 10 years is expected to be 2.5 flights per year. Therefore, v is as follows:

$$v = \ln(S_T/S)/T = \ln(2.5/4.67)/10 \text{ years} = -0.0624/\text{year} = \underline{-6.24\%/year}$$

This value of v results in the decay trend shown in Figure 6.

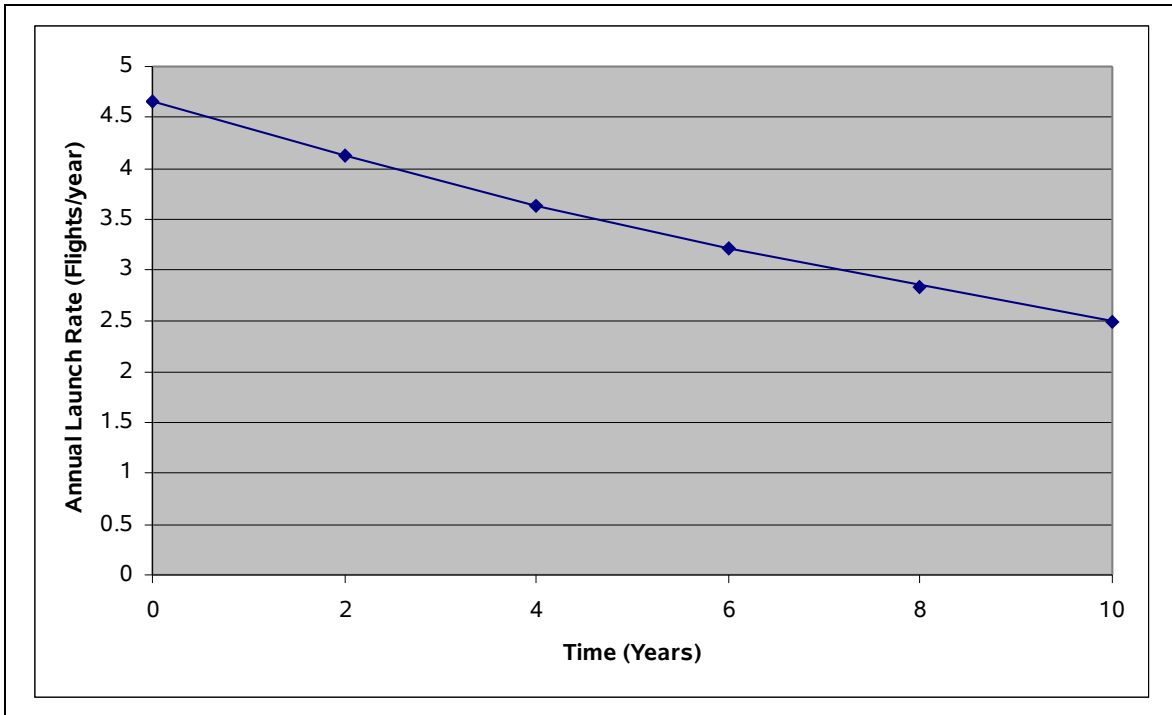


Figure 6. Expected launch rate throughout the time period analyzed.

Thus, the standard parameters for lattice modeling—u, d, and p—are as follows:

$$u = e^{(\sigma\sqrt{\Delta T})} = e^{(56.4\% \times \sqrt{2 \text{ year}})} = e^{(0.7976)} = \underline{2.22}$$

$$d = e^{(-\sigma\sqrt{\Delta T})} = 1/u = \underline{0.45}$$

$$p = 0.5 + 0.5(v/\sigma)\sqrt{\Delta T} = 0.5 + 0.5(-6.24\%/56.4\%)\sqrt{2 \text{ year}} = \underline{0.422}$$

These values result in the following outcome and probability lattices (Table 17 and Table 18) for the annual launch rate:

| OUTCOME LATTICE (Annual Launch Rate) | | | | | |
|--------------------------------------|-------------|-------------|-------------|-------------|-------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| 4.67 | 10.36 | 23.00 | 51.08 | 113.40 | 251.78 |
| | 2.10 | 4.67 | 10.36 | 23.00 | 51.08 |
| | | 0.95 | 2.10 | 4.67 | 10.36 |
| | | | 0.43 | 0.95 | 2.10 |
| | | | | 0.19 | 0.43 |
| | | | | | 0.09 |

Table 17. The outcome lattice for the annual Space Shuttle launch rate.

| PROBABILITY LATTICE | | | | | |
|---------------------|-------------|-------------|-------------|-------------|-------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| 1.00 | 0.422 | 0.178 | 0.075 | 0.032 | 0.013 |
| | 0.578 | 0.488 | 0.309 | 0.174 | 0.091 |
| | | 0.334 | 0.423 | 0.357 | 0.251 |
| | | | 0.193 | 0.326 | 0.344 |
| | | | | 0.112 | 0.236 |
| | | | | | 0.065 |

Table 18. The probability lattice for annual Space Shuttle launch rate outcomes.

Thus, the probability distribution function for launch rates is as shown in Figure 7.

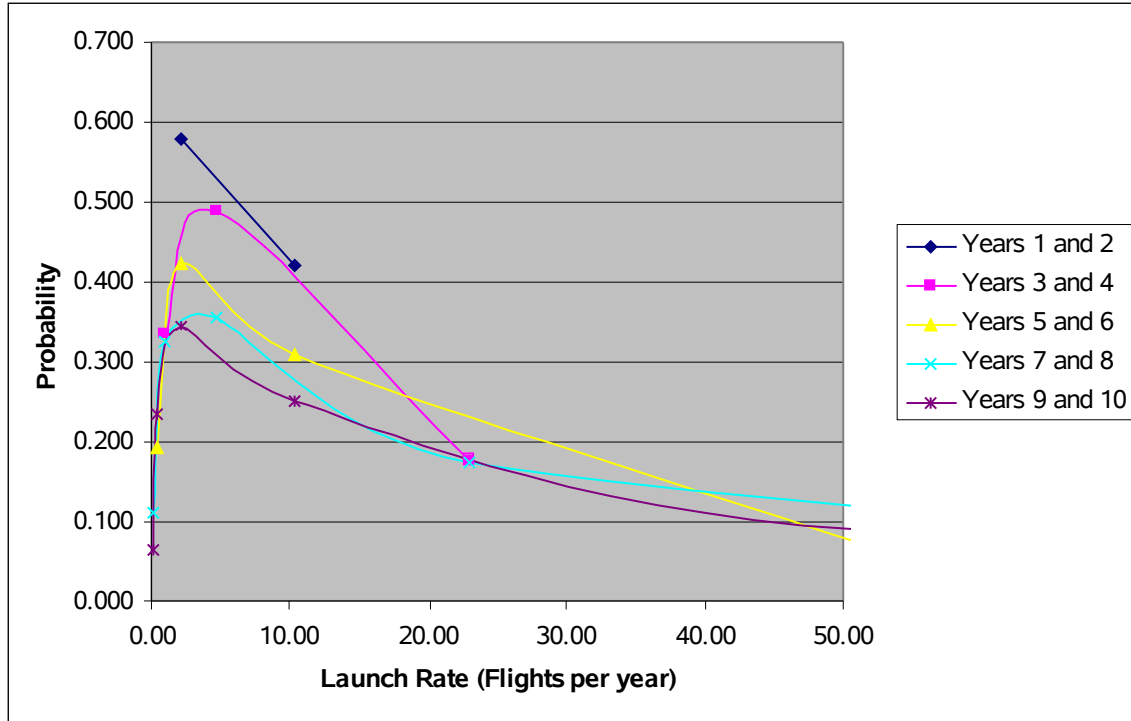


Figure 7. The probability distribution of outcomes for the annual Space Shuttle launch rate outcomes.

Realistically, an annual launch rate greater than 12 flights per year would probably be impossible without a major influx of funding and resources to the Space Shuttle Program. However, this model predicts that the likelihood of such launch rates will be fairly low and the overall amount of payload returned will be constrained by the size of the space station crew.

In order to compare the binomial lattice techniques with the decision analysis techniques, the production function, input cost function, cash flow formula and NPV formula are the same as those used in the previous section:

$$Y_{\text{payload returned}} = \text{MIN} [(\eta \times N_{\text{Shuttle Flights}} \times M_{\text{Shuttle return capacity at given inclination}}), P_{\text{crew}}]$$

$$C = C_{\text{Shuttle variable cost}} \times N_{\text{Shuttle Flights}} + C_{\text{Soyuz variable cost}} \times N_{\text{Soyuz Flights}}$$

$$\text{Cash Flow}_i = V \times (Y_{\text{payload returned}})_i - C_i$$

$$\text{NPV} = \sum \text{Cash Flow}_i / (1+r)^i \quad \text{for all } i.$$

Given the launch rates above in Table 17, the following lattices (Table 19 and Table 20) of returned payloads result if the crew size is held to four:

| RETURNED PAYLOAD LATTICE (Crew size = 4, Inclination = 28.5°) | | | | | |
|---|-------------|-------------|-------------|-------------|-------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| 0 | 3600 | 3600 | 3600 | 3600 | 3600 |
| | 2837.51 | 3600 | 3600 | 3600 | 3600 |
| | | 1278.01 | 2837.51 | 3600 | 3600 |
| | | | 575.61 | 1278.01 | 2837.51 |
| | | | | 259.26 | 575.61 |
| | | | | | 116.77 |

Table 19. A lattice of the possible amounts of payload returned (in kilograms) if Alternative 1 is chosen.

| RETURNED PAYLOAD LATTICE (Crew size = 4, Inclination = 51.6°) | | | | | |
|---|-------------|-------------|-------------|-------------|-------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| 0 | 3600 | 3600 | 3600 | 3600 | 3600 |
| | 2017.78 | 3600 | 3600 | 3600 | 3600 |
| | | 908.81 | 2017.78 | 3600 | 3600 |
| | | | 409.33 | 908.81 | 2017.78 |
| | | | | 184.36 | 409.33 |
| | | | | | 83.04 |

Table 20. A lattice of the possible amounts of payload returned (in kilograms) if Alternative 3 is chosen and the option is always exercised.

These payload returns lead to the lattices of undiscounted cash flows in Table 21 and Table 22.

| UNDISCOUNTED CASH FLOW LATTICE (Crew size = 4, Inclination = 28.5°) | | | | | |
|---|--------------------|--------------------|--------------------|---------------------|---------------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| \$ 0 | \$ (1,830,860,592) | \$ (4,157,232,286) | \$ (9,322,375,093) | \$ (20,790,319,054) | \$ (46,252,100,772) |
| | \$ (327,154,334) | \$ (783,066,667) | \$ (1,830,860,592) | \$ (4,157,232,286) | \$ (9,322,375,093) |
| | | \$ (147,349,765) | \$ (327,154,334) | \$ (783,066,667) | \$ (1,830,860,592) |
| | | | \$ (66,366,088) | \$ (147,349,765) | \$ (327,154,334) |
| | | | | \$ (29,891,175) | \$ (66,366,088) |
| | | | | | \$ (13,462,935) |

Table 21. A lattice of the possible cash flows if Alternative 1 is chosen.

| UNDISCOUNTED CASH FLOW LATTICE (Crew size = 4, Inclination = 51.6°) | | | | | |
|---|--------------------|--------------------|--------------------|---------------------|---------------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| \$ 0 | \$ (1,830,860,592) | \$ (4,157,232,286) | \$ (9,322,375,093) | \$ (20,790,319,054) | \$ (46,252,100,772) |
| | \$ (344,368,558) | \$ (783,066,667) | \$ (1,830,860,592) | \$ (4,157,232,286) | \$ (9,322,375,093) |
| | | \$ (155,103,023) | \$ (344,368,558) | \$ (783,066,667) | \$ (1,830,860,592) |
| | | | \$ (69,858,143) | \$ (155,103,023) | \$ (344,368,558) |
| | | | | \$ (31,463,991) | \$ (69,858,143) |
| | | | | | \$ (14,171,329) |

Table 22. A lattice of the possible cash flows if Alternative 3 is chosen and the option is always exercised.

Accordingly, the probability-weighted cash flow lattices and NPVs (Table 23 and Table 24) result if the crew size is held at 4:

| PROBABILITY WEIGHTED RETURN PAYLOAD LATTICE (Crew size = 4, Inclination = 28.5°) | | | | | |
|--|---------------------------|--------------------|--------------------|--------------------|--------------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| \$ 0 | \$ (772,162,154) | \$ (739,453,316) | \$ (699,336,631) | \$ (657,770,046) | \$ (617,159,809) |
| | \$ (189,177,583) | \$ (381,943,359) | \$ (564,936,970) | \$ (721,341,605) | \$ (852,759,392) |
| | | \$ (49,270,100) | \$ (138,407,989) | \$ (279,441,207) | \$ (459,249,796) |
| | | | \$ (12,832,084) | \$ (48,063,308) | \$ (112,514,925) |
| | | | | \$ (3,342,035) | \$ (15,647,229) |
| | | | | | \$ (870,412) |
| Subtotals = | \$ (961,339,737) | \$ (1,170,666,774) | \$ (1,415,513,674) | \$ (1,709,958,201) | \$ (2,058,201,562) |
| Discounted Subtotals = | \$ (766,374,152) | \$ (743,979,899) | \$ (717,143,280) | \$ (690,623,438) | \$ (662,685,819) |
| Total Expected NPV = | \$ (3,580,806,588) | | | | |

Table 23. A lattice of the expected cash flows and NPV if Alternative 1 is chosen.

| PROBABILITY WEIGHTED CASH FLOW LATTICE (Crew size = 4, Inclination = 51.6°) | | | | | |
|---|---------------------------|--------------------|--------------------|--------------------|--------------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| \$ 0 | \$ (772,162,154) | \$ (739,453,316) | \$ (699,336,631) | \$ (657,770,046) | \$ (617,159,809) |
| | \$ (199,131,739) | \$ (381,943,359) | \$ (564,936,970) | \$ (721,341,605) | \$ (852,759,392) |
| | | \$ (51,862,596) | \$ (145,690,748) | \$ (279,441,207) | \$ (459,249,796) |
| | | | \$ (13,507,284) | \$ (50,592,306) | \$ (118,435,241) |
| | | | | \$ (3,517,886) | \$ (16,470,556) |
| | | | | | \$ (916,211) |
| Subtotals = | \$ (971,293,893) | \$ (1,173,259,271) | \$ (1,423,471,632) | \$ (1,712,663,051) | \$ (2,064,991,005) |
| Discounted Subtotals = | \$ (774,309,545) | \$ (745,627,477) | \$ (721,175,029) | \$ (691,715,881) | \$ (664,871,837) |
| Total Expected NPV = | \$ (3,597,699,770) | | | | |

Table 24. A lattice of the expected cash flows and NPV if Alternative 3 is chosen and the option is always exercised.

Similarly, if the crew size is increased to seven, the returned payload lattice, undiscounted cash flow lattices, probability-weighted lattices, and NPVs in Table 25, Table 26, Table 27, Table 28, and Table 29 result.

| RETURNED PAYLOAD LATTICE (Crew size = 7, Inclination = 51.6°) | | | | | |
|---|-------------|-------------|-------------|-------------|-------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| 0 | 9000 | 9000 | 9000 | 9000 | 9000 |
| | 2017.78 | 4480 | 9000 | 9000 | 9000 |
| | | 908.81 | 2017.78 | 4480 | 9000 |
| | | | 409.33 | 908.81 | 2017.78 |
| | | | | 184.36 | 409.33 |
| | | | | | 83.04 |

Table 25. A lattice of the possible amounts of payload returned (in kilograms) if Alternative 2 is chosen or if Alternative 3 is chosen and the option is always exercised

| UNDISCOUNTED CASH FLOW LATTICE (Crew size = 7, Inclination = 51.6°, No option to terminate Russian participation) | | | | | |
|--|--------------------|--------------------|--------------------|---------------------|---------------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| \$ 0 | \$ (1,797,460,592) | \$ (4,123,832,286) | \$ (9,288,975,093) | \$ (20,756,919,054) | \$ (46,218,700,772) |
| | \$ (424,368,558) | \$ (844,586,667) | \$ (1,797,460,592) | \$ (4,123,832,286) | \$ (9,288,975,093) |
| | | \$ (235,103,023) | \$ (424,368,558) | \$ (844,586,667) | \$ (1,797,460,592) |
| | | | \$ (149,858,143) | \$ (235,103,023) | \$ (424,368,558) |
| | | | | \$ (111,463,991) | \$ (149,858,143) |
| | | | | | \$ (94,171,329) |

Table 26. A lattice of the possible cash flows if Alternative 2 is chosen.

| PROBABILITY WEIGHTED CASH FLOW LATTICE (Crew size = 7, Inclination = 51.6°, No option to terminate Russian participation) | | | | | |
|--|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| \$ 0 | \$ (758,075,764) | \$ (733,512,406) | \$ (696,831,063) | \$ (656,713,327) | \$ (616,714,140) |
| | \$ (245,391,884) | \$ (411,949,943) | \$ (554,630,945) | \$ (715,546,209) | \$ (849,704,144) |
| | | \$ (78,612,608) | \$ (179,536,055) | \$ (301,394,923) | \$ (450,871,800) |
| | | | \$ (28,975,526) | \$ (76,687,120) | \$ (145,948,842) |
| | | | | \$ (12,462,425) | \$ (35,332,272) |
| | | | | | \$ (6,088,407) |
| Subtotals = | \$ (1,003,467,647) | \$ (1,224,074,957) | \$ (1,459,973,590) | \$ (1,762,804,004) | \$ (2,104,659,605) |
| Discounted Subtotals = | \$ (799,958,265) | \$ (777,921,764) | \$ (739,668,057) | \$ (711,966,971) | \$ (677,644,065) |
| Total Expected NPV = | \$ (3,707,159,122) | | | | |

Table 27. A lattice of the expected cash flows and NPV if Alternative 2 is chosen.

| UNDISCOUNTED CASH FLOW LATTICE (Crew size = 7, Inclination = 51.6°, Option to terminate Russian participation) | | | | | |
|--|--------------------|--------------------|--------------------|---------------------|---------------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| \$ 0 | \$ (1,817,460,592) | \$ (4,143,832,286) | \$ (9,308,975,093) | \$ (20,776,919,054) | \$ (46,238,700,772) |
| | \$ (444,368,558) | \$ (864,586,667) | \$ (1,817,460,592) | \$ (4,143,832,286) | \$ (9,308,975,093) |
| | | \$ (255,103,023) | \$ (444,368,558) | \$ (864,586,667) | \$ (1,817,460,592) |
| | | | \$ (169,858,143) | \$ (255,103,023) | \$ (444,368,558) |
| | | | | \$ (131,463,991) | \$ (169,858,143) |
| | | | | | \$ (114,171,329) |

Table 28. A lattice of the possible cash flows if Alternative 3 is chosen and the option is never exercised.

| PROBABILITY WEIGHTED CASH FLOW LATTICE (Crew size = 7, Inclination = 51.6°, Option to terminate Russian participation) | | | | | |
|--|--------------------|--------------------|--------------------|--------------------|--------------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| \$ 0 | \$ (766,510,728) | \$ (737,069,837) | \$ (698,331,403) | \$ (657,346,093) | \$ (616,981,008) |
| | \$ (256,956,920) | \$ (421,705,009) | \$ (560,802,218) | \$ (719,016,506) | \$ (851,533,634) |
| | | \$ (85,300,111) | \$ (187,997,382) | \$ (308,532,021) | \$ (455,888,564) |
| | | | \$ (32,842,587) | \$ (83,210,823) | \$ (152,827,243) |
| | | | | \$ (14,698,560) | \$ (40,047,701) |
| | | | | | \$ (7,381,456) |
| Subtotals = | \$ (1,023,467,647) | \$ (1,244,074,957) | \$ (1,479,973,590) | \$ (1,782,804,004) | \$ (2,124,659,605) |
| Discounted Subtotals = | \$ (815,902,142) | \$ (790,632,126) | \$ (749,800,679) | \$ (720,044,636) | \$ (684,083,530) |
| Total Expected NPV = | \$ (3,760,463,113) | | | | |

Table 29. A lattice of the expected cash flows and NPV if Alternative 3 is chosen and the option is never exercised.

The expected value of being in any state of Alternative 3 is as follows:

$$EV(i) = \frac{\text{Cash Flow}_{in} + \text{MAX} [p \times EV(i_{ou}) + (1-p) \times EV(i_{od}), p \times EV(i_{nu}) + (1-p) \times EV(i_{nd})]}{(1+r)^{\Delta T}} \text{ for all } i$$

where,

i = The analyzed state

i_{ou} = The state following state i if the option is exercised and the launch rate goes up

i_{od} = The state following state i if the option is exercised and the launch rate goes down

i_{nu} = The state following state i if the option is not exercised and the launch rate goes up

i_{nd} = The state following state i if the option is not exercised and the launch rate goes down

r = The discount rate

ΔT = The time step

Cash Flow_{in} = Cash Flow of state i if the option is not exercised.

Table 30 below contains the expected value of each state. As indicated by the MAX function in the equation for the expected value of each state, the expected value depends

on the whether or not the option is executed in the following state. Table 31 shows, for each state analyzed, the crew size that will maximize the expected value of the following state. Notice that at Time Step 0 a crew size of four is suggested; this suggestion means that for the assumption made in this analysis, the option should be exercised at the beginning of the space station program if an orbital inclination of 51.6° is selected.

| OPTION VALUE LATTICE | | | | | |
|----------------------|--------------------|---------------------|---------------------|---------------------|---------------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| \$ (3,597,699,770) | \$ (8,450,479,442) | \$ (15,551,561,574) | \$ (26,703,329,307) | \$ (40,614,307,694) | \$ (46,238,700,772) |
| | \$ (1,731,345,881) | \$ (3,105,698,718) | \$ (5,270,670,347) | \$ (8,111,460,893) | \$ (9,308,975,093) |
| | | \$ (686,150,240) | \$ (1,107,699,090) | \$ (1,638,896,211) | \$ (1,817,460,592) |
| | | | \$ (300,103,751) | \$ (403,088,048) | \$ (444,368,558) |
| | | | | \$ (161,484,034) | \$ (169,858,143) |
| | | | | | \$ (114,171,329) |

Table 30. A lattice of the expected value of each state of Alternative 3.

| CREW SIZE LATTICE | | | | | |
|-------------------|-------------|-------------|-------------|-------------|-------------|
| Time Step 0 | Time Step 1 | Time Step 2 | Time Step 3 | Time Step 4 | Time Step 5 |
| 4 Crew | 4 Crew | 7 Crew | 7 Crew | 7 Crew | N/A |
| | 4 Crew | 4 Crew | 4 Crew | 7 Crew | N/A |
| | | 4 Crew | 4 Crew | 4 Crew | N/A |
| | | | 4 Crew | 4 Crew | N/A |
| | | | | 4 Crew | N/A |

Table 31. The strategy lattice for crew size.

As shown in Table 30, the option results in an expected value at the start of the space station program of roughly \$(3,598M). This is \$(3,598M) – \$(3,707M) = \$109M more than the expected return without the option if an inclination of 51.6° is selected. Thus, we can say that the value of the option is \$109M if Alternative 1 is not selected. However, if Alternative 1 is considered, the option is worth \$(3,598M) - \$(3,581M) = \$(17M) and thus would not be selected. The expected returns are summarized in Table 32 below. It should be noted that the expected values of the alternatives are much lower than they were in the decision analysis; this discrepancy is due to the fact that launch rates significantly greater than five flights per year are possible when Geometric Brownian Motion is assumed.

| Expected Value of A ₁ | Expected Value of A ₂ | Expected Value of A ₃ |
|----------------------------------|----------------------------------|----------------------------------|
| \$(3,581M) | \$(3,707M) | \$(3,598M) |

Table 32. The expected value of each alternative

As was the case with the decision analysis, the values of the alternatives are sensitive to the parameters assumed in this lattice analysis. As shown in Table 33, the option increases in attractiveness relative to Alternative 1 as η increases. Additionally, as illustrated by Table 34, the value of having an option if the space station is launched into a 51.6° inclination orbit decreases as η increases.

| Space Shuttle Efficiency Factor (η) | Value of Option vs. A1 (Expected Value of A3- Expected Value of A1)) |
|--|---|
| Baseline | \$ (16,893,182) |
| 0.05 | \$ (13,816,462) |
| 0.10 | \$ (14,840,554) |
| 0.15 | \$ (17,124,514) |
| 0.20 | \$ (17,110,978) |
| 0.25 | \$ (14,077,652) |
| 0.30 | \$ (16,893,182) |
| 0.35 | \$ (19,708,712) |
| 0.40 | \$ (19,497,740) |
| 0.45 | \$ (14,506,781) |
| 0.50 | \$ (9,515,822) |
| 0.55 | \$ (6,163,546) |
| 0.60 | \$ (6,723,868) |
| 0.65 | \$ (7,284,190) |
| 0.70 | \$ (7,844,513) |
| 0.75 | \$ (8,404,835) |
| 0.80 | \$ (8,965,157) |
| 0.85 | \$ (9,373,474) |
| 0.90 | \$ (8,393,989) |
| 0.95 | \$ (7,414,505) |
| 1.00 | \$ (6,435,021) |

Table 33. The value of the option when compared to Alternative 1 over a range of Space Shuttle efficiency factors.

| Space Shuttle Efficiency Factor (η) | Value of Option vs. A2 (Expected Value of A3 – Expected Value of A2) |
|---|---|
| Baseline | \$ 109,459,352.74 |
| 0.05 | \$ 204,492,282.37 |
| 0.10 | \$ 189,165,211.65 |
| 0.15 | \$ 166,329,455.83 |
| 0.20 | \$ 146,370,586.82 |
| 0.25 | \$ 125,140,227.24 |
| 0.30 | \$ 109,459,352.74 |
| 0.35 | \$ 102,339,005.61 |
| 0.40 | \$ 95,218,658.48 |
| 0.45 | \$ 88,098,311.35 |
| 0.50 | \$ 80,977,964.22 |
| 0.55 | \$ 72,218,934.69 |
| 0.60 | \$ 59,547,306.30 |
| 0.65 | \$ 53,614,577.87 |
| 0.70 | \$ 48,063,296.61 |
| 0.75 | \$ 42,512,015.35 |
| 0.80 | \$ 36,960,734.09 |
| 0.85 | \$ 31,409,452.83 |
| 0.90 | \$ 25,858,171.57 |
| 0.95 | \$ 20,306,890.30 |
| 1.00 | \$ 14,755,609.04 |

Table 34. The value of the option when compared to Alternative 2 over a range of Space Shuttle efficiency factors.

Conclusions

The methods employed in the above decision analysis and binomial lattice modeling of space station assembly and supply are useful for qualitatively illustrating key concepts in the mitigation and exploitation of uncertainty in the design and operation of complex systems. Both techniques demonstrated that the optimization of key performance parameters such as payload mass to orbit does not always lead to optimal system behavior—the value of Alternative 1 was not always the greatest of the three alternatives. Additionally, the analyses highlighted issues such as when it is appropriate to decrease the scope of the system if the designers/operators have the freedom to do so. However, the specific system chosen for this analysis—a space station in Low Earth Orbit—appears to be too complex and unique to gain reliable, quantitative insights through this type of analysis. Numerous assumptions were necessary to perform even the most trivial calculations and some of the results (e.g. an annual rate of 252 Space Shuttle launches) would not be taken seriously by anyone involved with the system.

Of the two techniques used, decision analysis offers the most promise in accurately modeling this system. Path-independence does not have to be assumed in decision analysis and realistic boundaries can be placed on variables such as the evolution of the annual launch rate. Moreover, the additional uncertainties discussed in this paper—launch success rate, annual budget, and externally decreed scope changes—can be modeled concurrently with the launch rate uncertainty in a decision analysis.

Overall, these analyses stress the importance of using the correct analytic tools to answer a research question. There are no tools available to provide the complete answer to every question of interest. More often than not, when a specific modeling approach is used to address a research question, the modeling approach dictates the portion of the questions that is ultimately answered. Accordingly, the results obtained could lack sufficient accuracy or intrigue to justify the modeling effort. Therefore, commitments should not be made to use certain quantitative tools until after the questions to answer have been clearly defined and the typical outputs derived from the proposed tools have been identified as the desired type of information.

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Appendix 1: Additional Launch Vehicle Statistics

As mentioned a previous section, this appendix contains launch vehicle statistics for the Progress, Proton, and Ariane V launch vehicles. Each of these vehicles has been or will be used in the assembly and supply of the ISS. While these vehicles were not considered in this analysis, future work could benefit from the statistics provided here.

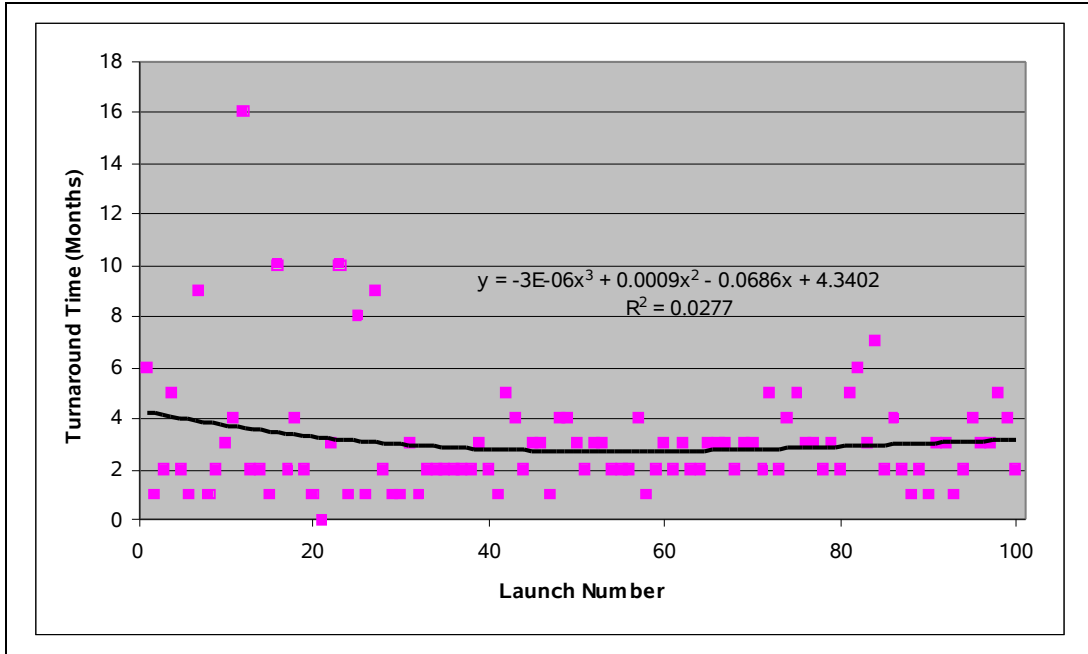


Figure 8. The historical turnaround time after each Progress flight.

(Derived from data available in Baker, 2006)

| Statistical Parameter | Data (Months) |
|-----------------------|---------------|
| Average | 3.07 |
| Min | 0 |
| Max | 16 |
| Median | 2 |
| Standard Deviation | 2.332272486 |

Table 35. Statistical parameters for the time to turn around the Progress after each mission.

(Derived from data available in Baker, 2006)

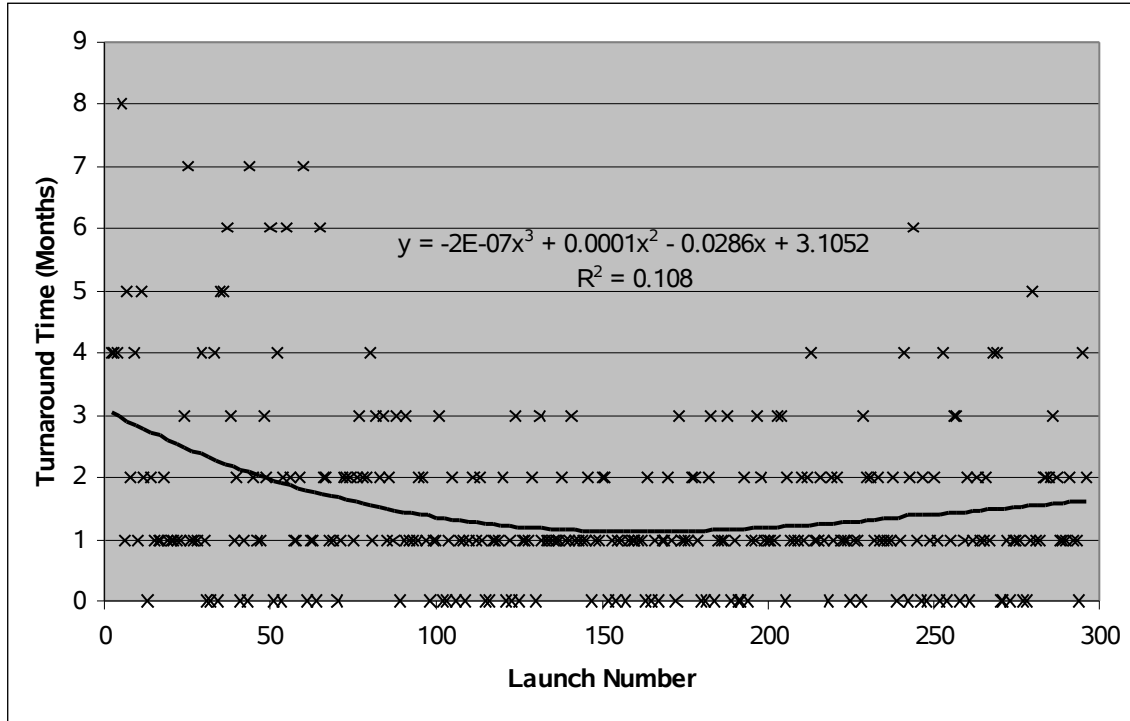


Figure 9. The historical turnaround time after each Proton flight.

(Derived from data available in Baker, 2006)

| Statistical Parameter | Data (Months) |
|-----------------------|---------------|
| Average | 1.542372881 |
| Min | 0 |
| Max | 8 |
| Median | 1 |
| Standard Deviation | 1.434772658 |

Table 36. Statistical parameters for the time to turn around the Proton after each mission.

(Derived from data available in Baker, 2006)

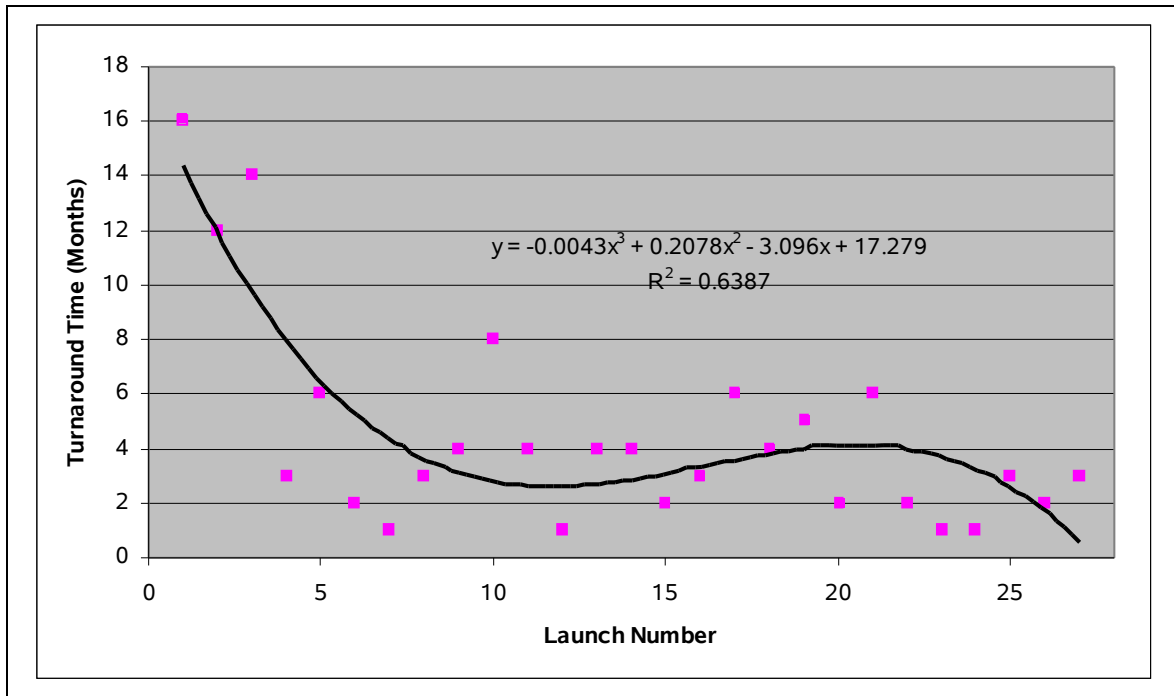


Figure 10. The historical turnaround time after each Ariane V flight.

(Derived from data available in Arianespace, 2004)

| Statistical Parameters | Data (Months) |
|------------------------|---------------|
| Average | 4.518518519 |
| Min | 1 |
| Max | 16 |
| Median | 3 |
| Standard Deviation | 3.876659648 |

Table 37. Statistical parameters for the time to turn around the Ariane V after each mission.

(Derived from data available in Arianespace, 2004)

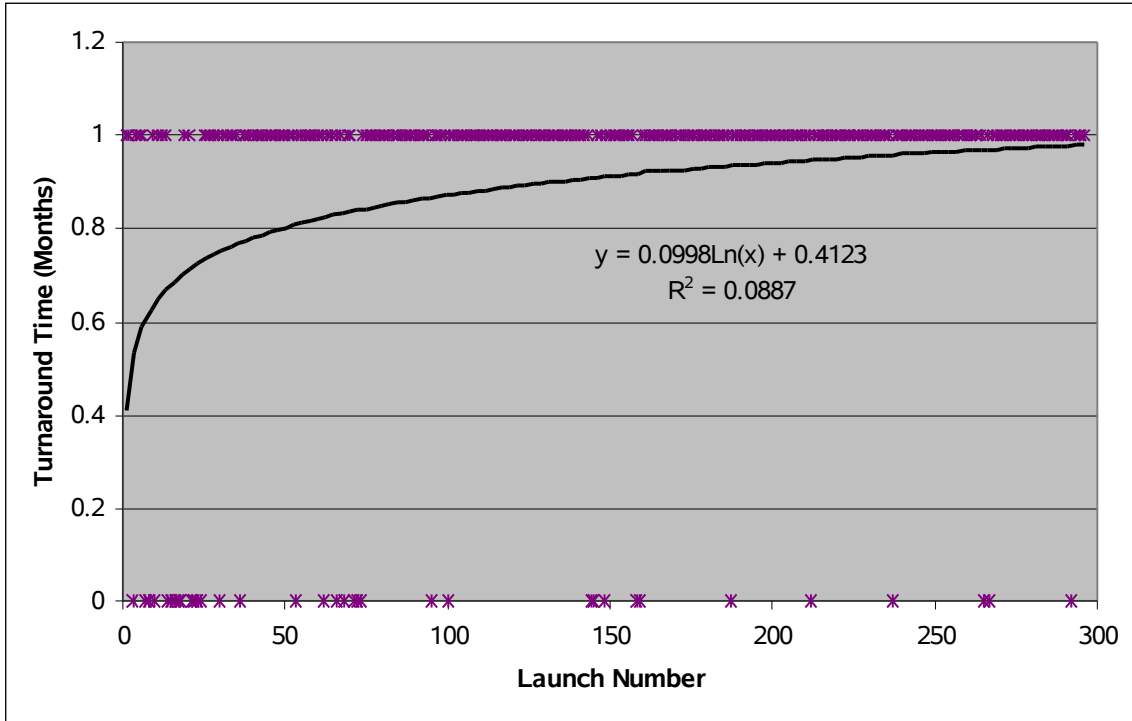


Figure 11. The historical success rating Proton missions.
(Derived from data available in Baker, 2006)

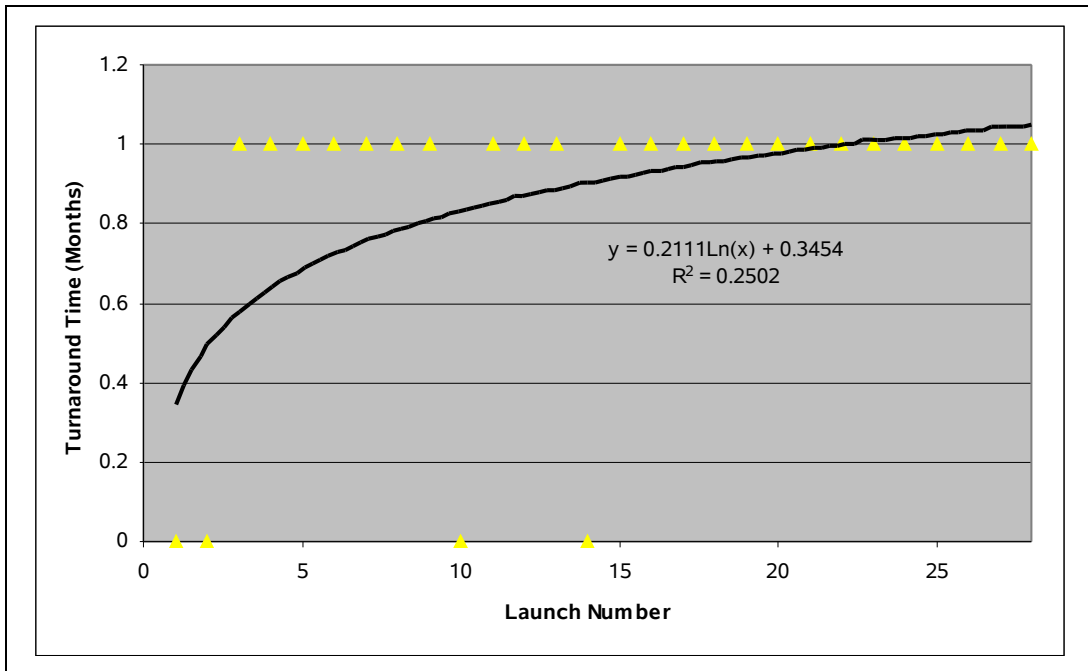


Figure 12. The historical success rating Ariane V missions.
(Derived from data available in Arianespace, 2004)

Appendix 2: Hypothetical Path-Dependent Outcomes

As mentioned in a previous section, one of the advantages of a decision analysis over a binomial lattice analysis is that path independence does not have to be assumed in a decision analysis. In this appendix several hypothetical, path-dependent outcomes for payload and crew return from a space station are derived to illustrate the effect of path dependence on the production function of such a system.

In this path-dependent analysis, the following assumptions are made:

- The Space Shuttle, Soyuz, Proton, and Progress launch vehicles are used for assembly and supply of the space station
- The Proton can only be used for assembly
- The payload returned on Soyuz launches is negligible
- On Shuttle flights where crew is transferred, the station will also be supplied
- Crew transfers on the Space Shuttle do not reduce the mass that Shuttle can transfer to the station
- No crew is returned on the first crew transfer flight (instead they are delivered to the station to return on a later flight)
- The maximum crew size is six people. The maximum number of crewmembers that can be delivered on any flight is three.
- The following alternatives are available:
 - Alternative 1 (A_1): The launch of the station into a 28.5° orbital inclination and the outfitting of the station with equipment that will only interface with U.S. vehicles (this will optimize U.S. launch vehicle performance while ruling out Russian involvement in the program),
 - Alternative 2 (A_2): The launch of the station into a 51.6° orbital inclination with Russian involvement in the assembly of critical station elements (this will lead to suboptimal U.S. launch vehicle performance and a U.S. dependence on Russia to deliver the key components while adding to the maximum possible number of launches to the station over a give time period.)
 - Alternative 3 (A_3): The launch of the station into a 51.6° orbital inclination with possibility of added non-critical Russian payload segments (Alternative A_{3B}) to the station five years after the start of assembly (this will lead to suboptimal U.S. launch vehicle performance while increasing the maximum possible number of launches to the station after the five-year mark).

The assumed launch vehicle parameters are summarized in Table 38.

| PARAMETER | A ₁ | A ₂ | A ₃ |
|---|------------------------|------------------------|------------------------|
| Maximum Number of Space Shuttle Launches During the 1st Five Years | 25 | 25 | 25 |
| Maximum Number of Space Shuttle Launches During the 2nd Five Years | 25 | 25 | 25 |
| Variable Cost for Shuttle Missions¹³ | \$92M per flight | \$92M per flight | \$92M per flight |
| Space Shuttle Payload Return Capability on Resupply Only Missions¹⁴ | 4,500 kg | 3,200 kg | 3,200 kg |
| Space Shuttle Payload Return Capability on Resupply Missions with Crew Transfer¹⁴ | 4,500 kg 3 crew | 3,200 kg 3 crew | 3,200 kg 3 crew |
| Space Shuttle Payload Return Capability on Assembly Only Missions | 0 kg 0 crew | 0 kg 0 crew | 0 kg 0 crew |
| Maximum Number of Soyuz Launches During the 1st Five Years | 0 | 10 | 0 |
| Maximum Number of Soyuz Launches During the 2nd Five Years | 0 | 10 | 10 |
| Soyuz Payload Return Capability on Crew Transfer Missions | 3 crew | 3 crew | 3 crew |
| Variable Cost for Soyuz Missions¹⁵ | N/A | \$20M per flight | \$20M per flight |
| Maximum Number of Proton Launches During the 1st Five Years | 0 | 5 | 0 |
| Maximum Number of Proton Launches During the 2nd Five Years | 0 | 0 | 5 |
| Proton Payload Return Capability on Assembly Only Missions | 0 kg | 0 kg | 0 kg |

Table 38. (Part 1 of 2)

¹³ (Isakowitz, 1995) estimated the variable or “marginal” cost of a Space Shuttle mission (i.e. the cost of adding another mission to the manifest in a given year) as ~\$63M for FY1988. (Jenkins, 2002) uses an inflation factor of 1.451 to convert FY1988 Space Shuttle Program expenditures into FY2002 dollars. Thus, the marginal cost of a Space Shuttle mission in FY2000 dollars is \$63M x 1.451 = \$92M.

¹⁴ According to (United States, National Aeronautics and Space Administration. NASA Space Shuttle: Past Missions Website, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/list_main.html) the Space Shuttle returned roughly 3,200 kg of payload in the Multi-Purpose Logistics Module (MPLM) on STS-114. Thus, it is assumed here that the maximum payload that can be returned is on a mission to a 51.6° inclination space station is 3,200 kg. According to (Isakowitz, 1995) the maximum ascent performance capability is 24,400 kg and 17,100 kg for launches to 28.5° and 51.6° inclinations, respectively. This means that the ascent performance is affected by a factor of 17,100/24,400. Thus, if the maximum payload returnable from a 51.6° orbit is assumed to be 3,200 kg, then the maximum payload returnable from a 28.5° orbit is 3,200kg x 24,400/17,100 ~4,500 kg.

¹⁵ (Baker, 2006) estimated Soyuz and Proton launch costs to be \$20M and \$40M, respectively. The Progress is essentially an unmanned version of the Soyuz and thus it is assumed to the cost the same as a Soyuz.

| PARAMETER | A ₁ | A ₂ | A ₃ |
|---|----------------|------------------|------------------|
| Variable Cost for Proton Missions ¹⁵ | N/A | \$40M per flight | \$40M per flight |
| Maximum Number of Progress Launches During the 1 st Five Years | 0 | 15 | 0 |
| Maximum Number of Progress Launches During the 1 st Five Years | 0 | 15 | 15 |
| Variable Cost for Progress Mission ¹⁵ | N/A | \$20M per flight | \$20M per flight |
| Progress Payload Return Capability on Resupply Missions ^{16,17} | N/A | 2,700 kg | 2,700 kg |

Table 38. Assumed launch vehicle parameters for a path-dependent decision analysis.

The production function for returned payload and the input cost function are as follows:

$$Y_{\text{payload returned}} = (N_{\text{Shuttle crew transfer flights}} + N_{\text{Shuttle resupply flights}}) \times M_{\text{Shuttle return capacity at given inclination}} + N_{\text{Progress flights}} \times M_{\text{Progress return capacity}}$$

$$C = (N_{\text{Shuttle crew transfer flights}} + N_{\text{Shuttle resupply flights}} + N_{\text{Shuttle assembly flights}}) \times C_{\text{Shuttle variable cost}} + N_{\text{Progress flights}} \times C_{\text{Progress variable cost}} + N_{\text{Soyuz flights}} \times C_{\text{Soyuz variable cost}} + N_{\text{Proton flights}} \times C_{\text{Proton variable cost}}$$

Unlike the production function in the path-independent decision analysis, a Space Shuttle efficiency factor is not used in this production function. In the assembly and supply of a space station, payload return per flight can increase as assembly of the station nears completion. This increase in efficiency could be due to a number of factors (e.g. fewer flights devoted to the delivery of space station hardware, increased station ability to process payloads, etc.). Thus, the use of an efficiency factor that does not vary as the station progresses through its assembly sequence is bound to decrease the accuracy of the analysis results. A more accurate approach is to model a sequence of flights and the payload returned on each flight.

As mentioned earlier in Table 5, there are slightly less than three “Support” segments for every “Payload” segment of the ISS.¹⁸ Thus, on the station considered in this analysis, the launch of each “Payload” segment is preceded by the launch of three “Support” segments. With that said, a hypothetical “best case” launch manifest for A₁ is represented by the values in Table 39. Furthermore, it is assumed that the sequence of launches must be adhered to (i.e. if the schedule slips for one flight or if a flight has to be repeated due to a failure, the schedule for all subsequent flights will slip). The key features of this manifest are:

¹⁶ (Baker, 2006) estimated the total cargo launch mass to be roughly 2,700kg.

¹⁷ It is assumed that the Progress cannot re-enter the Earth’s atmosphere and thus, the payload that it returns will be trash that would otherwise have to be carried back to Earth on the Space Shuttle.

¹⁸ A segment is defined here as a piece of the station that requires its own dedicated launch.

- Four “Payload” segments
- Twelve “Support” segments
- Only three crewmembers can be placed on the station at any given time.

| Launch # | Vehicle | Type of Segment | Crew Delivered | Crew Returned | Maximum Payload Returned (kg) | Maximum Cumulative Payload Returned (kg) | Cost of Launch (\$M) | Cumulative Variable Costs (\$M) |
|----------|---------|-----------------|----------------|---------------|-------------------------------|--|----------------------|---------------------------------|
| 1 | Shuttle | Support | 0 | 0 | 0 | 0 | 92 | 92 |
| 2 | Shuttle | Support | 0 | 0 | 0 | 0 | 92 | 184 |
| 3 | Shuttle | Support | 0 | 0 | 0 | 0 | 92 | 276 |
| 4 | Shuttle | Payload | 0 | 0 | 0 | 0 | 92 | 368 |
| 5 | Shuttle | Crew/Resupply | 3 | 0 | 3200 | 3200 | 92 | 460 |
| 6 | Shuttle | Support | 3 | 0 | 0 | 3200 | 92 | 552 |
| 7 | Shuttle | Support | 3 | 0 | 0 | 3200 | 92 | 644 |
| 8 | Shuttle | Crew/Resupply | 6 | 3 | 3200 | 6400 | 92 | 736 |
| 9 | Shuttle | Support | 6 | 3 | 0 | 6400 | 92 | 828 |
| 10 | Shuttle | Payload | 6 | 3 | 0 | 6400 | 92 | 920 |
| 11 | Shuttle | Crew/Resupply | 9 | 6 | 3200 | 9600 | 92 | 1012 |
| 12 | Shuttle | Support | 9 | 6 | 0 | 9600 | 92 | 1104 |
| 13 | Shuttle | Support | 9 | 6 | 0 | 9600 | 92 | 1196 |
| 14 | Shuttle | Crew/Resupply | 12 | 9 | 3200 | 12800 | 92 | 1288 |
| 15 | Shuttle | Support | 12 | 9 | 0 | 12800 | 92 | 1380 |
| 16 | Shuttle | Payload | 12 | 9 | 0 | 12800 | 92 | 1472 |
| 17 | Shuttle | Crew/Resupply | 15 | 12 | 3200 | 16000 | 92 | 1564 |
| 18 | Shuttle | Support | 15 | 12 | 0 | 16000 | 92 | 1656 |
| 19 | Shuttle | Support | 15 | 12 | 0 | 16000 | 92 | 1748 |
| 20 | Shuttle | Crew/Resupply | 18 | 15 | 3200 | 19200 | 92 | 1840 |
| 21 | Shuttle | Support | 18 | 15 | 0 | 19200 | 92 | 1932 |
| 22 | Shuttle | Payload | 18 | 15 | 0 | 19200 | 92 | 2024 |
| 23 | Shuttle | Crew/Resupply | 21 | 18 | 3200 | 22400 | 92 | 2116 |
| 24 | Shuttle | Crew/Resupply | 24 | 21 | 3200 | 25600 | 92 | 2208 |
| 25 | Shuttle | Resupply | 24 | 21 | 3200 | 28800 | 92 | 2300 |
| 26 | Shuttle | Crew/Resupply | 27 | 24 | 3200 | 32000 | 92 | 2392 |
| 27 | Shuttle | Crew/Resupply | 30 | 27 | 3200 | 35200 | 92 | 2484 |
| 28 | Shuttle | Resupply | 30 | 27 | 3200 | 38400 | 92 | 2576 |
| 29 | Shuttle | Crew/Resupply | 33 | 30 | 3200 | 41600 | 92 | 2668 |
| 30 | Shuttle | Crew/Resupply | 36 | 33 | 3200 | 44800 | 92 | 2760 |
| 31 | Shuttle | Resupply | 36 | 33 | 3200 | 48000 | 92 | 2852 |
| 32 | Shuttle | Crew/Resupply | 39 | 36 | 3200 | 51200 | 92 | 2944 |
| 33 | Shuttle | Crew/Resupply | 42 | 39 | 3200 | 54400 | 92 | 3036 |
| 34 | Shuttle | Resupply | 42 | 39 | 3200 | 57600 | 92 | 3128 |
| 35 | Shuttle | Crew/Resupply | 45 | 42 | 3200 | 60800 | 92 | 3220 |

Table 39. (Part 1 of 2)

| Launch # | Vehicle | Type of Segment | Crew Delivered | Crew Returned | Maximum Payload Returned (kg) | Maximum Cumulative Payload Returned (kg) | Cost of Launch (\$M) | Cumulative Variable Costs (\$M) |
|----------|---------|-----------------|----------------|---------------|-------------------------------|--|----------------------|---------------------------------|
| 36 | Shuttle | Crew/Resupply | 48 | 45 | 3200 | 64000 | 92 | 3312 |
| 37 | Shuttle | Resupply | 48 | 45 | 3200 | 67200 | 92 | 3404 |
| 38 | Shuttle | Crew/Resupply | 51 | 48 | 3200 | 70400 | 92 | 3496 |
| 39 | Shuttle | Crew/Resupply | 54 | 51 | 3200 | 73600 | 92 | 3588 |
| 40 | Shuttle | Resupply | 54 | 51 | 3200 | 76800 | 92 | 3680 |
| 41 | Shuttle | Crew/Resupply | 57 | 54 | 3200 | 80000 | 92 | 3772 |
| 42 | Shuttle | Crew/Resupply | 60 | 57 | 3200 | 83200 | 92 | 3864 |
| 43 | Shuttle | Resupply | 60 | 57 | 3200 | 86400 | 92 | 3956 |
| 44 | Shuttle | Crew/Resupply | 63 | 60 | 3200 | 89600 | 92 | 4048 |
| 45 | Shuttle | Crew/Resupply | 66 | 63 | 3200 | 92800 | 92 | 4140 |
| 46 | Shuttle | Resupply | 66 | 63 | 3200 | 96000 | 92 | 4232 |
| 47 | Shuttle | Crew/Resupply | 69 | 66 | 3200 | 99200 | 92 | 4324 |
| 48 | Shuttle | Crew/Resupply | 72 | 69 | 3200 | 102400 | 92 | 4416 |
| 49 | Shuttle | Resupply | 72 | 69 | 3200 | 105600 | 92 | 4508 |
| 50 | Shuttle | Crew/Resupply | 75 | 72 | 3200 | 108800 | 92 | 4600 |

Table 39. A hypothetical "best case" launch manifest for Alternative 1.

Similarly, a hypothetical “best case” launch manifest for A₂ is represented by the values in Table 40. This manifest has the following features:

- Five “Payload” segments
- Fifteen “Support” segments
- The Russians launch vehicles are involved in the assembly of the station throughout the first five years.
- Only six crewmembers can be placed on the station at any given time.

| Launch # | Vehicle | Type of Segment | Crew Delivered | Crew Returned | Maximum Payload Returned (kg) | Maximum Cumulative Payload Returned (kg) | Cost of Launch (\$M) | Cumulative Variable Costs (\$M) |
|----------|----------|-----------------|----------------|---------------|-------------------------------|--|----------------------|---------------------------------|
| 1 | Shuttle | Support | 0 | 0 | 0 | 0 | 92 | 92 |
| 2 | Proton | Support | 0 | 0 | 0 | 0 | 40 | 132 |
| 3 | Shuttle | Support | 0 | 0 | 0 | 0 | 92 | 224 |
| 4 | Progress | Resupply | 0 | 0 | 2700 | 2700 | 20 | 244 |
| 5 | Shuttle | Payload | 0 | 0 | 0 | 2700 | 92 | 336 |
| 6 | Soyuz | Crew/Resupply | 3 | 0 | 0 | 2700 | 20 | 356 |
| 7 | Progress | Resupply | 3 | 0 | 2700 | 5400 | 20 | 376 |
| 8 | Shuttle | Support | 3 | 0 | 0 | 5400 | 92 | 468 |
| 9 | Soyuz | Crew/Resupply | 6 | 0 | 0 | 5400 | 20 | 488 |
| 10 | Progress | Resupply | 6 | 0 | 2700 | 8100 | 20 | 508 |
| 11 | Shuttle | Crew/Resupply | 9 | 3 | 3200 | 11300 | 92 | 600 |
| 12 | Proton | Support | 9 | 3 | 0 | 11300 | 40 | 640 |
| 13 | Shuttle | Support | 9 | 3 | 0 | 11300 | 92 | 732 |
| 14 | Soyuz | Crew/Resupply | 12 | 6 | 0 | 11300 | 20 | 752 |
| 15 | Progress | Resupply | 12 | 6 | 2700 | 14000 | 20 | 772 |
| 16 | Shuttle | Payload | 12 | 6 | 0 | 14000 | 92 | 864 |
| 17 | Soyuz | Crew/Resupply | 15 | 9 | 0 | 14000 | 20 | 884 |
| 18 | Progress | Resupply | 15 | 9 | 2700 | 16700 | 20 | 904 |
| 19 | Shuttle | Crew/Resupply | 18 | 12 | 3200 | 19900 | 92 | 996 |
| 20 | Progress | Resupply | 18 | 12 | 2700 | 22600 | 20 | 1016 |
| 21 | Shuttle | Support | 18 | 12 | 0 | 22600 | 92 | 1108 |
| 22 | Shuttle | Support | 18 | 12 | 0 | 22600 | 92 | 1200 |
| 23 | Proton | Support | 18 | 12 | 0 | 22600 | 40 | 1240 |
| 24 | Shuttle | Crew/Resupply | 21 | 15 | 3200 | 25800 | 92 | 1332 |
| 25 | Progress | Resupply | 21 | 15 | 2700 | 28500 | 20 | 1352 |
| 26 | Shuttle | Payload | 21 | 15 | 0 | 28500 | 92 | 1444 |
| 27 | Soyuz | Crew/Resupply | 24 | 18 | 0 | 28500 | 20 | 1464 |
| 28 | Progress | Resupply | 24 | 18 | 2700 | 31200 | 20 | 1484 |
| 29 | Shuttle | Support | 24 | 18 | 0 | 31200 | 92 | 1576 |
| 30 | Shuttle | Crew/Resupply | 27 | 21 | 3200 | 34400 | 92 | 1668 |
| 31 | Shuttle | Support | 27 | 21 | 0 | 34400 | 92 | 1760 |
| 32 | Soyuz | Crew/Resupply | 30 | 24 | 0 | 34400 | 20 | 1780 |
| 33 | Progress | Resupply | 30 | 24 | 2700 | 37100 | 20 | 1800 |
| 34 | Proton | Support | 30 | 24 | 0 | 37100 | 40 | 1840 |
| 35 | Shuttle | Payload | 30 | 24 | 0 | 37100 | 92 | 1932 |
| 36 | Shuttle | Crew/Resupply | 33 | 27 | 3200 | 40300 | 92 | 2024 |
| 37 | Progress | Resupply | 33 | 27 | 2700 | 43000 | 20 | 2044 |
| 38 | Shuttle | Support | 33 | 27 | 0 | 43000 | 92 | 2136 |
| 39 | Soyuz | Crew/Resupply | 36 | 30 | 0 | 43000 | 20 | 2156 |
| 40 | Progress | Resupply | 36 | 30 | 2700 | 45700 | 20 | 2176 |
| 41 | Shuttle | Support | 36 | 30 | 0 | 45700 | 92 | 2268 |
| 42 | Soyuz | Crew/Resupply | 39 | 33 | 0 | 45700 | 20 | 2288 |
| 43 | Progress | Resupply | 39 | 33 | 2700 | 48400 | 20 | 2308 |
| 44 | Shuttle | Support | 39 | 33 | 0 | 48400 | 92 | 2400 |

Table 40. (Part 1 of 3)

| Launch # | Vehicle | Type of Segment | Crew Delivered | Crew Returned | Maximum Payload Returned (kg) | Maximum Cumulative Payload Returned (kg) | Cost of Launch (\$M) | Cumulative Variable Costs (\$M) |
|----------|----------|-----------------|----------------|---------------|-------------------------------|--|----------------------|---------------------------------|
| 45 | Proton | Support | 39 | 33 | 0 | 48400 | 40 | 2440 |
| 46 | Shuttle | Payload | 39 | 33 | 0 | 48400 | 92 | 2532 |
| 47 | Progress | Resupply | 39 | 33 | 2700 | 51100 | 20 | 2552 |
| 48 | Shuttle | Crew/Resupply | 42 | 36 | 0 | 51100 | 92 | 2644 |
| 49 | Shuttle | Resupply | 42 | 36 | 3200 | 54300 | 92 | 2736 |
| 50 | Soyuz | Crew/Resupply | 45 | 39 | 0 | 54300 | 20 | 2756 |
| 51 | Progress | Resupply | 45 | 39 | 2700 | 57000 | 20 | 2776 |
| 52 | Shuttle | Resupply | 45 | 39 | 3200 | 60200 | 92 | 2868 |
| 53 | Soyuz | Crew/Resupply | 48 | 42 | 0 | 60200 | 20 | 2888 |
| 54 | Progress | Resupply | 48 | 42 | 2700 | 62900 | 20 | 2908 |
| 55 | Shuttle | Resupply | 48 | 42 | 3200 | 66100 | 92 | 3000 |
| 56 | Shuttle | Crew/Resupply | 51 | 45 | 3200 | 69300 | 92 | 3092 |
| 57 | Progress | Resupply | 51 | 45 | 2700 | 72000 | 20 | 3112 |
| 58 | Shuttle | Resupply | 51 | 45 | 3200 | 75200 | 92 | 3204 |
| 59 | Soyuz | Crew/Resupply | 54 | 48 | 0 | 75200 | 20 | 3224 |
| 60 | Progress | Resupply | 54 | 48 | 2700 | 77900 | 20 | 3244 |
| 61 | Shuttle | Resupply | 54 | 48 | 3200 | 81100 | 92 | 3336 |
| 62 | Shuttle | Crew/Resupply | 57 | 51 | 3200 | 84300 | 92 | 3428 |
| 63 | Soyuz | Crew/Resupply | 60 | 54 | 0 | 84300 | 20 | 3448 |
| 64 | Progress | Resupply | 60 | 54 | 2700 | 87000 | 20 | 3468 |
| 65 | Shuttle | Resupply | 60 | 54 | 3200 | 90200 | 92 | 3560 |
| 66 | Shuttle | Crew/Resupply | 63 | 57 | 3200 | 93400 | 92 | 3652 |
| 67 | Progress | Resupply | 63 | 57 | 2700 | 96100 | 20 | 3672 |
| 68 | Shuttle | Resupply | 63 | 57 | 3200 | 99300 | 92 | 3764 |
| 69 | Soyuz | Crew/Resupply | 66 | 60 | 0 | 99300 | 20 | 3784 |
| 70 | Progress | Resupply | 66 | 60 | 2700 | 102000 | 20 | 3804 |
| 71 | Shuttle | Resupply | 66 | 60 | 3200 | 105200 | 92 | 3896 |
| 72 | Shuttle | Crew/Resupply | 69 | 63 | 3200 | 108400 | 92 | 3988 |
| 73 | Soyuz | Crew/Resupply | 72 | 66 | 0 | 108400 | 20 | 4008 |
| 74 | Progress | Resupply | 72 | 66 | 2700 | 111100 | 20 | 4028 |
| 75 | Shuttle | Resupply | 72 | 66 | 3200 | 114300 | 92 | 4120 |
| 76 | Shuttle | Crew/Resupply | 75 | 69 | 3200 | 117500 | 92 | 4212 |
| 77 | Progress | Resupply | 75 | 69 | 2700 | 120200 | 20 | 4232 |
| 78 | Shuttle | Resupply | 75 | 69 | 3200 | 123400 | 92 | 4324 |
| 79 | Soyuz | Crew/Resupply | 78 | 72 | 0 | 123400 | 20 | 4344 |
| 80 | Progress | Resupply | 78 | 72 | 2700 | 126100 | 20 | 4364 |
| 81 | Shuttle | Resupply | 78 | 72 | 3200 | 129300 | 92 | 4456 |
| 82 | Shuttle | Crew/Resupply | 81 | 75 | 3200 | 132500 | 92 | 4548 |
| 83 | Soyuz | Crew/Resupply | 84 | 78 | 0 | 132500 | 20 | 4568 |
| 84 | Progress | Resupply | 84 | 78 | 2700 | 135200 | 20 | 4588 |
| 85 | Shuttle | Resupply | 84 | 78 | 3200 | 138400 | 92 | 4680 |
| 86 | Shuttle | Crew/Resupply | 87 | 81 | 3200 | 141600 | 92 | 4772 |

Table 40. (Part 2 of 3)

| Launch # | Vehicle | Type of Segment | Crew Delivered | Crew Returned | Maximum Payload Returned (kg) | Maximum Cumulative Payload Returned (kg) | Cost of Launch (\$M) | Cumulative Variable Costs (\$M) |
|----------|----------|-----------------|----------------|---------------|-------------------------------|--|----------------------|---------------------------------|
| 87 | Progress | Resupply | 87 | 81 | 2700 | 144300 | 20 | 4792 |
| 88 | Shuttle | Resupply | 87 | 81 | 3200 | 147500 | 92 | 4884 |
| 89 | Soyuz | Crew/Resupply | 90 | 84 | 0 | 147500 | 20 | 4904 |
| 90 | Progress | Resupply | 90 | 84 | 2700 | 150200 | 20 | 4924 |
| 91 | Shuttle | Resupply | 90 | 84 | 3200 | 153400 | 92 | 5016 |
| 92 | Shuttle | Crew/Resupply | 93 | 87 | 3200 | 156600 | 92 | 5108 |
| 93 | Soyuz | Crew/Resupply | 96 | 90 | 0 | 156600 | 20 | 5128 |
| 94 | Progress | Resupply | 96 | 90 | 2700 | 159300 | 20 | 5148 |
| 95 | Shuttle | Resupply | 96 | 90 | 3200 | 162500 | 92 | 5240 |
| 96 | Shuttle | Crew/Resupply | 99 | 93 | 3200 | 165700 | 92 | 5332 |
| 97 | Progress | Resupply | 99 | 93 | 2700 | 168400 | 20 | 5352 |
| 98 | Shuttle | Resupply | 99 | 93 | 3200 | 171600 | 92 | 5444 |
| 99 | Soyuz | Crew/Resupply | 102 | 96 | 0 | 171600 | 20 | 5464 |
| 100 | Progress | Resupply | 102 | 96 | 2700 | 174300 | 20 | 5484 |
| 101 | Shuttle | Resupply | 102 | 96 | 3200 | 177500 | 92 | 5576 |
| 102 | Shuttle | Crew/Resupply | 105 | 99 | 3200 | 180700 | 92 | 5668 |
| 103 | Soyuz | Crew/Resupply | 108 | 102 | 0 | 180700 | 20 | 5688 |
| 104 | Progress | Resupply | 108 | 102 | 2700 | 183400 | 20 | 5708 |
| 105 | Shuttle | Resupply | 108 | 102 | 3200 | 186600 | 92 | 5800 |

Table 40. A hypothetical "best case" launch manifest for Alternative 2.

Next, a hypothetical “best case” launch manifest for A_{3A} is represented by the values in Table 41. This manifest has the following features:

- Four “Payload” segments
- Twelve “Support” segments
- Only three crewmembers can be placed on the station at any given time.

| Launch # | Vehicle | Type of Segment | Crew Delivered | Crew Returned | Maximum Payload Returned (kg) | Maximum Cumulative Payload Returned (kg) | Cost of Launch (\$M) | Cumulative Variable Costs (\$M) |
|----------|---------|-----------------|----------------|---------------|-------------------------------|--|----------------------|---------------------------------|
| 1 | Shuttle | Support | 0 | 0 | 0 | 0 | 92 | 92 |
| 2 | Shuttle | Support | 0 | 0 | 0 | 0 | 92 | 184 |
| 3 | Shuttle | Support | 0 | 0 | 0 | 0 | 92 | 276 |
| 4 | Shuttle | Payload | 0 | 0 | 0 | 0 | 92 | 368 |
| 5 | Shuttle | Crew/Resupply | 3 | 0 | 3200 | 3200 | 92 | 460 |
| 6 | Shuttle | Support | 3 | 0 | 0 | 3200 | 92 | 552 |
| 7 | Shuttle | Support | 3 | 0 | 0 | 3200 | 92 | 644 |
| 8 | Shuttle | Crew/Resupply | 6 | 3 | 3200 | 6400 | 92 | 736 |
| 9 | Shuttle | Support | 6 | 3 | 0 | 6400 | 92 | 828 |
| 10 | Shuttle | Payload | 6 | 3 | 0 | 6400 | 92 | 920 |
| 11 | Shuttle | Crew/Resupply | 9 | 6 | 3200 | 9600 | 92 | 1012 |
| 12 | Shuttle | Support | 9 | 6 | 0 | 9600 | 92 | 1104 |
| 13 | Shuttle | Support | 9 | 6 | 0 | 9600 | 92 | 1196 |
| 14 | Shuttle | Crew/Resupply | 12 | 9 | 3200 | 12800 | 92 | 1288 |
| 15 | Shuttle | Support | 12 | 9 | 0 | 12800 | 92 | 1380 |
| 16 | Shuttle | Payload | 12 | 9 | 0 | 12800 | 92 | 1472 |
| 17 | Shuttle | Crew/Resupply | 15 | 12 | 3200 | 16000 | 92 | 1564 |
| 18 | Shuttle | Support | 15 | 12 | 0 | 16000 | 92 | 1656 |
| 19 | Shuttle | Support | 15 | 12 | 0 | 16000 | 92 | 1748 |
| 20 | Shuttle | Crew/Resupply | 18 | 15 | 3200 | 19200 | 92 | 1840 |
| 21 | Shuttle | Support | 18 | 15 | 0 | 19200 | 92 | 1932 |
| 22 | Shuttle | Payload | 18 | 15 | 0 | 19200 | 92 | 2024 |
| 23 | Shuttle | Crew/Resupply | 21 | 18 | 3200 | 22400 | 92 | 2116 |
| 24 | Shuttle | Crew/Resupply | 24 | 21 | 3200 | 25600 | 92 | 2208 |
| 25 | Shuttle | Resupply | 24 | 21 | 3200 | 28800 | 92 | 2300 |
| 26 | Shuttle | Crew/Resupply | 27 | 24 | 3200 | 32000 | 92 | 2392 |
| 27 | Shuttle | Crew/Resupply | 30 | 27 | 3200 | 35200 | 92 | 2484 |
| 28 | Shuttle | Resupply | 30 | 27 | 3200 | 38400 | 92 | 2576 |
| 29 | Shuttle | Crew/Resupply | 33 | 30 | 3200 | 41600 | 92 | 2668 |
| 30 | Shuttle | Crew/Resupply | 36 | 33 | 3200 | 44800 | 92 | 2760 |
| 31 | Shuttle | Resupply | 36 | 33 | 3200 | 48000 | 92 | 2852 |
| 32 | Shuttle | Crew/Resupply | 39 | 36 | 3200 | 51200 | 92 | 2944 |
| 33 | Shuttle | Crew/Resupply | 42 | 39 | 3200 | 54400 | 92 | 3036 |
| 34 | Shuttle | Resupply | 42 | 39 | 3200 | 57600 | 92 | 3128 |
| 35 | Shuttle | Crew/Resupply | 45 | 42 | 3200 | 60800 | 92 | 3220 |
| 36 | Shuttle | Crew/Resupply | 48 | 45 | 3200 | 64000 | 92 | 3312 |
| 37 | Shuttle | Resupply | 48 | 45 | 3200 | 67200 | 92 | 3404 |
| 38 | Shuttle | Crew/Resupply | 51 | 48 | 3200 | 70400 | 92 | 3496 |
| 39 | Shuttle | Crew/Resupply | 54 | 51 | 3200 | 73600 | 92 | 3588 |
| 40 | Shuttle | Resupply | 54 | 51 | 3200 | 76800 | 92 | 3680 |
| 41 | Shuttle | Crew/Resupply | 57 | 54 | 3200 | 80000 | 92 | 3772 |
| 42 | Shuttle | Crew/Resupply | 60 | 57 | 3200 | 83200 | 92 | 3864 |
| 43 | Shuttle | Resupply | 60 | 57 | 3200 | 86400 | 92 | 3956 |
| 44 | Shuttle | Crew/Resupply | 63 | 60 | 3200 | 89600 | 92 | 4048 |

Table 41. (Part 1 of 2)

| Launch # | Vehicle | Type of Segment | Crew Delivered | Crew Returned | Maximum Payload Returned (kg) | Maximum Cumulative Payload Returned (kg) | Cost of Launch (\$M) | Cumulative Variable Costs (\$M) |
|----------|---------|-----------------|----------------|---------------|-------------------------------|--|----------------------|---------------------------------|
| 45 | Shuttle | Crew/Resupply | 66 | 63 | 3200 | 92800 | 92 | 4140 |
| 46 | Shuttle | Resupply | 66 | 63 | 3200 | 96000 | 92 | 4232 |
| 47 | Shuttle | Crew/Resupply | 69 | 66 | 3200 | 99200 | 92 | 4324 |
| 48 | Shuttle | Crew/Resupply | 72 | 69 | 3200 | 102400 | 92 | 4416 |
| 49 | Shuttle | Resupply | 72 | 69 | 3200 | 105600 | 92 | 4508 |
| 50 | Shuttle | Crew/Resupply | 75 | 72 | 3200 | 108800 | 92 | 4600 |

Table 41. A hypothetical "best case" launch manifest for Alternative 3A.

Finally, a hypothetical "best case" launch manifest for A_{3B} is represented by the values in Table 42. This manifest has the following features:

- Five "Payload" segments
- Fifteen "Support" segments
- The Russian launch vehicles are involved in the assembly of the station throughout the second five years.
 - Only two Proton launches are need
 - Two Shuttle assembly flights are required after the five-year mark
- Only three crewmembers can be placed on the station at any given time.

| Launch # | Vehicle | Type of Segment | Crew Delivered | Crew Returned | Maximum Payload Returned (kg) | Maximum Cumulative Payload Returned (kg) | Cost of Launch (\$M) | Cumulative Variable Costs (\$M) |
|----------|----------|-----------------|----------------|---------------|-------------------------------|--|----------------------|---------------------------------|
| 1 | Shuttle | Support | 0 | 0 | 0 | 0 | 92 | 92 |
| 2 | Shuttle | Support | 0 | 0 | 0 | 0 | 92 | 184 |
| 3 | Shuttle | Support | 0 | 0 | 0 | 0 | 92 | 276 |
| 4 | Shuttle | Payload | 0 | 0 | 0 | 0 | 92 | 368 |
| 5 | Shuttle | Crew/Resupply | 3 | 0 | 3200 | 3200 | 92 | 460 |
| 6 | Shuttle | Support | 3 | 0 | 0 | 3200 | 92 | 552 |
| 7 | Shuttle | Support | 3 | 0 | 0 | 3200 | 92 | 644 |
| 8 | Shuttle | Crew/Resupply | 6 | 3 | 3200 | 6400 | 92 | 736 |
| 9 | Shuttle | Support | 6 | 3 | 0 | 6400 | 92 | 828 |
| 10 | Shuttle | Payload | 6 | 3 | 0 | 6400 | 92 | 920 |
| 11 | Shuttle | Crew/Resupply | 9 | 6 | 3200 | 9600 | 92 | 1012 |
| 12 | Shuttle | Support | 9 | 6 | 0 | 9600 | 92 | 1104 |
| 13 | Shuttle | Support | 9 | 6 | 0 | 9600 | 92 | 1196 |
| 14 | Shuttle | Crew/Resupply | 12 | 9 | 3200 | 12800 | 92 | 1288 |
| 15 | Shuttle | Support | 12 | 9 | 0 | 12800 | 92 | 1380 |
| 16 | Shuttle | Payload | 12 | 9 | 0 | 12800 | 92 | 1472 |
| 17 | Shuttle | Crew/Resupply | 15 | 12 | 3200 | 16000 | 92 | 1564 |
| 18 | Shuttle | Support | 15 | 12 | 0 | 16000 | 92 | 1656 |
| 19 | Shuttle | Support | 15 | 12 | 0 | 16000 | 92 | 1748 |
| 20 | Shuttle | Crew/Resupply | 18 | 15 | 3200 | 19200 | 92 | 1840 |
| 21 | Shuttle | Support | 18 | 15 | 0 | 19200 | 92 | 1932 |
| 22 | Shuttle | Payload | 18 | 15 | 0 | 19200 | 92 | 2024 |
| 23 | Shuttle | Crew/Resupply | 21 | 18 | 3200 | 22400 | 92 | 2116 |
| 24 | Shuttle | Crew/Resupply | 24 | 21 | 3200 | 25600 | 92 | 2208 |
| 25 | Shuttle | Resupply | 24 | 21 | 3200 | 28800 | 92 | 2300 |
| 26 | Shuttle | Crew/Resupply | 27 | 24 | 3200 | 32000 | 92 | 2392 |
| 27 | Proton | Support | 27 | 24 | 0 | 32000 | 40 | 2432 |
| 28 | Shuttle | Support | 27 | 24 | 0 | 32000 | 92 | 2524 |
| 29 | Soyuz | Crew/Resupply | 30 | 27 | 0 | 32000 | 25 | 2549 |
| 30 | Progress | Resupply | 27 | 24 | 2700 | 34700 | 20 | 2569 |
| 31 | Shuttle | Support | 30 | 27 | 0 | 34700 | 92 | 2661 |
| 32 | Progress | Resupply | 27 | 24 | 2700 | 37400 | 20 | 2681 |
| 33 | Shuttle | Crew/Resupply | 33 | 30 | 3200 | 40600 | 92 | 2773 |
| 34 | Soyuz | Crew/Resupply | 30 | 27 | 0 | 40600 | 25 | 2798 |
| 35 | Progress | Resupply | 33 | 30 | 2700 | 43300 | 20 | 2818 |
| 36 | Shuttle | Resupply | 30 | 27 | 3200 | 46500 | 92 | 2910 |
| 37 | Proton | Payload | 33 | 30 | 0 | 46500 | 40 | 2950 |
| 38 | Shuttle | Resupply | 30 | 27 | 3200 | 49700 | 92 | 3042 |
| 39 | Soyuz | Crew/Resupply | 36 | 33 | 0 | 49700 | 25 | 3067 |
| 40 | Progress | Resupply | 30 | 27 | 2700 | 52400 | 20 | 3087 |
| 41 | Shuttle | Crew/Resupply | 39 | 36 | 3200 | 55600 | 92 | 3179 |
| 42 | Progress | Resupply | 30 | 27 | 2700 | 58300 | 20 | 3199 |
| 43 | Shuttle | Resupply | 39 | 36 | 3200 | 61500 | 92 | 3291 |
| 44 | Soyuz | Crew/Resupply | 33 | 30 | 0 | 61500 | 25 | 3316 |

Table 42. (Part 1 of 2)

| Launch # | Vehicle | Type of Segment | Crew Delivered | Crew Returned | Maximum Payload Returned (kg) | Maximum Cumulative Payload Returned (kg) | Cost of Launch (\$M) | Cumulative Variable Costs (\$M) |
|----------|----------|-----------------|----------------|---------------|-------------------------------|--|----------------------|---------------------------------|
| 45 | Progress | Resupply | 39 | 36 | 2700 | 64200 | 20 | 3336 |
| 46 | Shuttle | Resupply | 33 | 30 | 3200 | 67400 | 92 | 3428 |
| 47 | Shuttle | Crew/Resupply | 42 | 39 | 3200 | 70600 | 92 | 3520 |
| 48 | Shuttle | Resupply | 33 | 30 | 3200 | 73800 | 92 | 3612 |
| 49 | Soyuz | Crew/Resupply | 45 | 42 | 0 | 73800 | 25 | 3637 |
| 50 | Progress | Resupply | 33 | 30 | 2700 | 76500 | 20 | 3657 |
| 51 | Shuttle | Crew/Resupply | 48 | 45 | 3200 | 79700 | 92 | 3749 |
| 52 | Progress | Resupply | 33 | 30 | 2700 | 82400 | 20 | 3769 |
| 53 | Shuttle | Resupply | 48 | 45 | 3200 | 85600 | 92 | 3861 |
| 54 | Soyuz | Crew/Resupply | 36 | 33 | 0 | 85600 | 25 | 3886 |
| 55 | Progress | Resupply | 48 | 45 | 2700 | 88300 | 20 | 3906 |
| 56 | Shuttle | Resupply | 36 | 33 | 3200 | 91500 | 92 | 3998 |
| 57 | Shuttle | Crew/Resupply | 51 | 48 | 3200 | 94700 | 92 | 4090 |
| 58 | Shuttle | Resupply | 36 | 33 | 3200 | 97900 | 92 | 4182 |
| 59 | Soyuz | Crew/Resupply | 54 | 51 | 0 | 97900 | 25 | 4207 |
| 60 | Progress | Resupply | 36 | 33 | 2700 | 100600 | 20 | 4227 |
| 61 | Shuttle | Crew/Resupply | 57 | 54 | 3200 | 103800 | 92 | 4319 |
| 62 | Progress | Resupply | 36 | 33 | 2700 | 106500 | 20 | 4339 |
| 63 | Shuttle | Resupply | 57 | 54 | 3200 | 109700 | 92 | 4431 |
| 64 | Soyuz | Crew/Resupply | 39 | 36 | 0 | 109700 | 25 | 4456 |
| 65 | Progress | Resupply | 57 | 54 | 2700 | 112400 | 20 | 4476 |
| 66 | Shuttle | Resupply | 39 | 36 | 3200 | 115600 | 92 | 4568 |
| 67 | Shuttle | Crew/Resupply | 60 | 57 | 3200 | 118800 | 92 | 4660 |
| 68 | Shuttle | Resupply | 39 | 36 | 3200 | 122000 | 92 | 4752 |
| 69 | Soyuz | Crew/Resupply | 63 | 60 | 0 | 122000 | 25 | 4777 |
| 70 | Progress | Resupply | 39 | 36 | 2700 | 124700 | 20 | 4797 |
| 71 | Shuttle | Crew/Resupply | 66 | 63 | 3200 | 127900 | 92 | 4889 |
| 72 | Progress | Resupply | 39 | 36 | 2700 | 130600 | 20 | 4909 |
| 73 | Shuttle | Resupply | 66 | 63 | 3200 | 133800 | 92 | 5001 |
| 74 | Soyuz | Crew/Resupply | 42 | 39 | 0 | 133800 | 25 | 5026 |
| 75 | Progress | Resupply | 66 | 63 | 2700 | 136500 | 20 | 5046 |
| 76 | Shuttle | Resupply | 42 | 39 | 3200 | 139700 | 92 | 5138 |
| 77 | Shuttle | Crew/Resupply | 69 | 66 | 3200 | 142900 | 92 | 5230 |

Table 42. A hypothetical "best case" launch manifest for Alternative 3B.

If it is assumed that the “best case” launch manifest is always fulfilled, then it can be determined by inspection of the manifests that Alternative 2 is the best option. However, there is uncertainty over what the successful launch rate will be and thus, a probabilistic model of the likelihoods of the outcomes listed in these manifests is necessary to complete the decision analysis. Such a model is left to future work. Ultimately, the probabilities derived will effectively drive the decision on which alternative to choose.