Integrated Modeling and Simulation of Lunar Exploration Campaign Logistics

by

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Abstract

As NASA prepares to establish a manned outpost on the lunar surface, it is essential to consider the logistics of both the construction and operation of this outpost. This thesis presents an interplanetary supply chain management and logistics planning and simulation software tool, SpaceNet, developed to assist mission architects, planners, systems engineers and logisticians in performing analysis on what will be needed to support future human exploration missions, primarily in the Earth-Moon-Mars system. Also presented in this thesis are the results of numerous trade studies performed using SpaceNet to determining the best mix of mission types (pre-positioning, carry-along and resupply) to achieve sustainable, robust space exploration. These trade studies focus on analyzing notional mission architectures in terms of scientific benefit, logistical overhead and robustness to campaign level risks such as flight delays, flight cancellations and uncertain demand parameters.

The significant findings presented in this thesis broadly fall into three categories: a demonstration of the value of integrated modeling and simulation of campaign logistics, the best logistics strategy for the establishment of a lunar outpost, and suggestions to reduce campaign level risk. The development of SpaceNet has made several key contributions to the field of space logistics, primarily in the creation of a set of ten function-based classes of supply for human space exploration, the detailed modeling of demand parameters at the supply class level, and the ability to model entire campaigns of missions and to compare these campaigns using the measures of effectiveness developed. Through the campaign analysis it is shown that the Lunar Architecture Team (LAT) Option 1 lunar mission architecture is ~11,500 kg short of being able to support four crewmembers for the proposed durations. It is also shown that the inclusion of at least two unmanned cargo missions makes the architecture sustainable. The campaign level risk analysis research performed demonstrates that the best way to protect against schedule and demand uncertainty is to maintain at least a 90-day safety stock of consumables at the lunar base (~2100 kg for a crew of four).

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"The best of all things is to learn. Money can be lost or stolen, health and strength may fail, but whatever you have committed to your mind is yours forever." --Louis L'Amour

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"To Infinity and Beyond!" --Buzz Lightyear

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1 Introduction

1.1 Motivation

As this document is being written, space agencies around the world are gearing up for new human space exploration missions. These missions will take some nations into orbit for the first time, will return humans to the Moon, and strive to eventually put human footprints on Mars. In order to ensure that such programs are sustainable, it is worthwhile to examine the lessons learned from past experiences with space logistics and to analyze current plans for human space exploration campaigns in terms of their logistical footprint and robustness to campaign level risks.

1.1.1 The U.S. Vision for Space Exploration

In January of 2004, President Bush announced an ambitious vision that committed the United States to a long-term human and robotic program to further explore the Moon, with the ultimate goal of sending humans to Mars and beyond. This aspiration has given NASA a new focus and has outlined specific objectives that must be met prior to lunar return and Martian exploration. The near-term focus of NASA as outlined in this vision is for humans to return to the Moon no later than 2020.

The mission architecture that NASA will decide to pursue to achieve this vision has been the focus of several recent studies including the Exploration Systems Architecture Study (ESAS) completed in 2005 and the Lunar Architecture Team (LAT) study of which Phase I was completed in the fall of 2006 and Phase II is slated to be completed in the fall of 2007.

1.1.2 The ESAS Study

According to NASA's Exploration Systems Architecture Study (ESAS), a series of short-

duration lunar sortie missions will start in 2018, leading up to the deployment and permanent habitation of a lunar outpost beginning in 2022 [1]. This mission sequence is depicted in Figure 1. In the figure a mix of sortie missions, unmanned logistics missions (referred to as Pre-Deploy or Logistics/Resupply missions) and crewed outpost missions can be seen. Each sortie mission will consist of 4 crew members living and working on the lunar surface for seven days. The unmanned pre-deploy missions deliver critical elements and supplies for the buildup of the lunar outpost. Each lunar base expedition will consist of four crew members living and working for 180 consecutive days on the lunar surface.

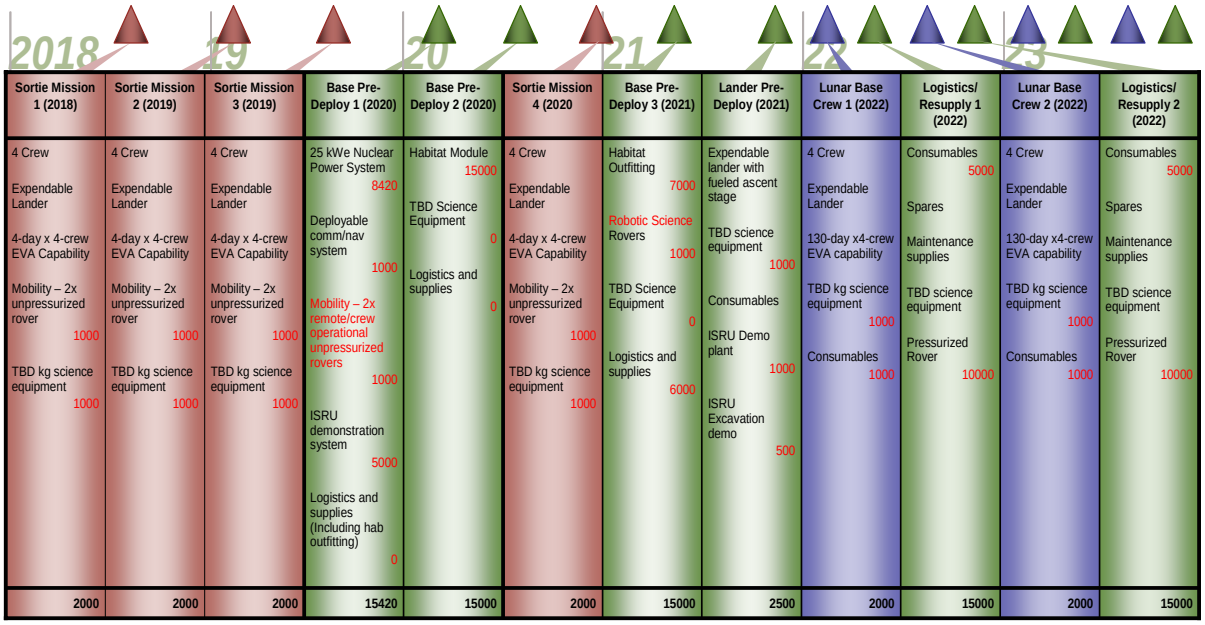

Figure 1 ESAS Lunar Mission Profile [1]

The ESAS final report states that this mission profile "was chosen to enable early missions to test the transportation systems and to allow short scientific sorties to a small number of diverse sites and extended development time lines for high-cost outpost systems" [1]. This same report also acknowledged that the strategy outlined above was just one of many mission profile options and that this strategy should be revised as better data becomes available.

The ESAS mission profile utilizes two new launch vehicles being developed by NASA,

the Ares I and the Ares V. The Ares I is a human rated launch vehicle designed to launch the Crew Exploration Vehicle (CEV) into low Earth orbit (LEO). The Ares V is a heavy-lift launch vehicle designed to launch all of the other required elements (habitats, lunar landers, rovers, cargo carriers, etc.) and the Earth departure stage (EDS) into LEO. For crewed missions, the Ares V would be launched first followed within 14 days by the Ares I. A rendezvous will then occur in LEO and the EDS will be utilized to push the stack through trans-lunar injection (TLI). For uncrewed cargo missions, only the Ares V will be utilized.

1.1.3 NASA's New Focus: the Global Exploration Strategy

On December 4, 2006 NASA's Constellation Program announced the results of Phase I of the Lunar Architecture Study conducted by the Lunar Architecture Team (LAT). This study was a follow on to the ESAS study and had as its goal to "understand what are the key drivers and how then does one develop a capability and implement an architecture that leads us to a sustained lunar presence, lunar base, while through commercial endeavors, international participation, discovery in science, while we prepare to send people to Mars and explore" [2]. The outcome of this study is what NASA has termed the *Global Exploration Strategy*. This strategy has the following six themes: establishing a sustained human presence on the Moon, fostering international collaboration, using the Moon as a unique laboratory to gain scientific knowledge, preparing for human exploration further out into the solar system, namely to Mars, promoting the economic advancement for all nations involved and engaging the interest of the public [2].

One of the major outcomes of the Lunar Architecture Study was the development of a proposed lunar architecture. In this document the term 'lunar architecture' refers to a specific series of missions that fulfill the lunar exploration elements of The President's Vision for U.S. Space Exploration. The fundamental difference between the lunar architecture recommended by the LAT team and that of the ESAS study is that the LAT architecture is an 'outpost centric' architecture. The LAT architecture suggests that the

best lunar exploration strategy would be for NASA to commence directly with building a base at one of the lunar poles, rather than starting with sortie missions to various locations, choosing a base location and then beginning construction of a base. Using data obtained from the Lunar Reconnaissance Orbiter, NASA will determine whether the North or South Pole is the most favorable location for a manned lunar outpost.

A representative lunar mission sequence for the Global Exploration Strategy is shown in Table 1 below. From this table it can be noted that the mission sequence starts off with ten buildup flights, nine of which land a crew on the lunar surface. The surface stays for each crew of four increase gradually from 7-30 days as the campaign progresses. Following the ten outpost buildup flights, a sustained human presence at the lunar outpost would begin with teams of four crewmembers conducting six month stays at the base [3], similar to the current six month increments on the International Space Station (ISS).

Table 1 : Notional Global Exploration Stragey Lunar Mission Profile

Year	Launch Vehicle	Crewed (Y/N)	Surface Duration (days)	Outpost Elements Delivered
2019	Aries V + Aries I	Y	0*	Power Units, Unpressurized Rover, Communications Terminal
2020	Aries V + Aries I	Y	7	Habitat Module
2020	Aries V + Aries I	Y	7	Power Unit, Unpressurized Rover, Mobility Carrier
2021	Aries V + Aries I	Y	7	Habitat Module
2021	Aries V + Aries I	Y	7	Power Units
2022	Aries V + Aries I	Y	14	Habitat Module
2022	Aries V + Aries I	Y	14	Power Units
2023	Aries V + Aries I	Y	25	Habitat Module
2023	Aries V + Aries I	Y	30	In-Situ Resource Utilization (ISRU) Unit
2024	Aries V + Aries I	Y	30	Logistics Supplies
2024+	Aries V + Aries I	Y	180	Logistics Supplies

* The crew for the 2019 mission does not travel to the lunar surface but instead remains in lunar orbit to monitor the LSAM tests.

The logistics of both the ESAS and the Global Exploration Strategy architectures will be

analyzed in detail in this thesis. The purpose of this analysis is to evaluate variations of these initial strategies in terms of scientific benefit, logistical overhead and robustness to campaign level risks.

1.2 Literature Survey

There exists a wealth of literature on terrestrial supply chains and logistics strategies but very little about the application of these methodologies to the field of space exploration. An attempt to summarize all the literature on terrestrial supply chains that may be applicable to the research described in this document would be an overwhelming task for very little value added. Instead, it is more appropriate to strive to capture just a sampling of the relevant articles, with an emphasis on only those that have directly influenced this research.

In an attempt to summarize a fraction of the wide expanse of terrestrial supply chain literature, a paper by Beamon [4] provides a concise review of the literature on terrestrial multi-stage supply chain modeling. In his textbook on designing and managing the supply chain, Simchi-Levi et al. [5] offer an overview of terrestrial supply chain concepts, strategies and models tailored for university students, MBA-level management courses and consultants. For his PhD dissertation Snyder [6] presented several models and algorithms for determining supply chain robustness and reliability.

Lying somewhere between terrestrial and interplanetary supply chain research exists a subset of articles that discuss the logistical aspect of exploration of remote environments here on Earth. In their articles about using Antarctic Exploration as a proxy for Exploration of the Moon and Mars, Ardanuy et al. [7] and Boehne et al. [8] discuss the potential to study the intercontinental supply chain in support of the remote science operations in Antarctica as a precursor to the logistical challenges of lunar and Mars exploration. At the opposite end of the Earth, de Weck et al. [9] and Gralla et al. [10] detail their research on the use of the Haughton-Mars Project Research Station in the high Artic as a logistical proxy for human exploration of the Moon and Mars.

In the context of the supply chain for future human space exploration missions, much of the publicly available literature is focused on lessons learned during long duration human spaceflight on the ISS. Drawing from his experience working in the Mission Control Center (MCC) for the ISS, Peek [11] emphasizes the need to consider both the forward and the reverse portion of logistics when designing future space vehicles. Peek also stresses the importance of considering the available stowage space as a critical design variable. Sanchez and Voss [12], of which Voss is a former ISS astronaut, discuss the importance of resupply and logistics to the ISS as well as the limitations seen with the current ISS supply chain and inventory management strategy. Furthering the idea of using ISS as a test bed for lunar and Mars exploration, Walz, also a former ISS astronaut, et al. [13] discuss the importance of turning lessons learned on the ISS into mission requirements for future lunar and Mars exploration programs.

The idea of incorporating logistics lessons learned from not only ISS but from the Apollo, Skylab, MIR and Space Shuttle Programs is expressed in the NASA Technical Publication by Evans et al. [14]. This publication lays out the top 7 logistics lessons learned across these programs as:

1. Resulting problems from lack of stowage specification may include growing time demands for the crew, loss of accountability, loss of access to operational space, limits to housekeeping, weakened morale, and an increased requirement for resupply. Therefore, include **stowage requirements** (volume, mass, reconfigurability, etc.) in the design specification.
2. A **common logistics/inventory system**, shared by multiple organizations would decrease the problem of differing values for like items across systems.
3. **Packing lists and manifests** do not make good manual accounting systems. Parent-child relationships are fluid and need to be intuitively handled by a system updated by the movement of both parents and children.
4. **Commonality** is a prime consideration for all vehicles, systems, components, and software in order to minimize training requirements, optimize maintainability, reduce development and sparing costs, and increase operational flexibility.
5. **Design for maintenance** is a primary consideration in reducing the logistics

footprint. An optimization is preferable, taking into account tools, time, packaging, stowage, and lifecycle cost.

6. **Plan for and apply standards** to system development. A simple example of this is standard and metric tools. In most cases, where there are multiple standards, there is an interface required, and the interface then requires support.
7. Include **return logistics** requirements in the design specification. Understand and model packaging requirements, pressurization, and reparability/disposability for the return or destructive reentry of items ahead of time.

This publication also discusses results from a survey sent out in 2005 to a subset of the space logistics community; namely that the survey results mirror the lessons learned mentioned above and therefore stress their importance.

The American Institute of Aeronautics and Astronautics (AIAA) has a technical committee dedicated to Space Logistics whose vision is described as to focus on "Innovative, near-term space logistics to establish safe, affordable and routine human and robotics spacefaring operations throughout the Earth-Moon System & Beyond" [15]. This technical committee is working to release a committee position paper in 2007.

The International Society of Logistics (SOLE) publishes the magazine *Logistics Spectrum* several times a year. The January-March 2006 issue was focused entirely on space logistics and included articles discussing the logistics of ISS Maintenance [16], the logistical aspects of repair and operation of the Hubble Space Telescope [17], and an article describing designs for potential in-space logistics facilities by the then Chair of the Space Logistics Technical Committee, J.M. Snead [18].

The American Astronautical Society (AAS) also publishes a space-themed magazine entitled *Space Times.* The July/August 2005 issue featured an article by Sietzen [19] briefly describing the logistics infrastructure of the Apollo Program and posing logistics questions to be answered by the Constellation program.

In their paper Galluzzi et al. [20] discuss the application of fundamental terrestrial supply

chain management (SCM) principles to NASA's future space exploration supply chain. It is the hope of the authors of their paper to "motivate the aerospace community in deploying the fundamentals of SCM along with simulation and modeling breakthroughs with the objective of growing a risk shared endeavor between customer and contractor that utilizes an integrated and cost effective supply chain through collaborative demand planning."

There are also several publications which discuss tools that can be used to model space logistics. Reynerson [21] discusses his methodology in developing a tool to perform engineering and cost modeling for lunar and Mars exploration missions. Gralla et al. [22] and Shull et al. [23] both discuss an interplanetary supply chain modeling tool jointly developed by personnel at MIT and JPL. This tool, named SpaceNet, is a computational environment for modeling exploration from a logistics perspective. It includes discrete event simulation at the individual mission level (e.g. sortie, pre-positioning, or resupply) or at the campaign level (i.e. a set of missions). It also allows for the evaluation of manually generated exploration scenarios with respect to measures of effectiveness and feasibility, as well as the visualization of the flow of elements and supply items through the interplanetary supply chain. Finally, it includes an optimization capability and acts as a software tool to support trade studies and architecture analyses. (For further information about SpaceNet see Chapter 2.)

1.3 Logistics in Past and Current Spaceflight Programs

Human space exploration programs to date have followed different types of logistics paradigms. The following sections introduce the logistics methodologies and mission types employed by past human spaceflight programs as well as those under consideration for inclusion in the Constellation Program. This chapter also offers an analysis of the logistic strategies used by the Apollo Program, the Space Shuttle Program, the International Space Station Program, and a terrestrial example of logistics for the Haughton-Mars Project Research Station in the high Canadian Artic.

1.4 Logistic Methodologies

In order to evaluate current and past logistics strategies, it is first necessary to understand the possible mission types from a logistician's perspective. For the purposes of this analysis, we have devised four different classifications of logistics methodologies: pre-position, carry-along, resupply and depot. The following sections give a brief explanation of each of these strategies along with a terrestrial example for each.

1.4.1 Pre-positioning

The propositioning methodology refers to the idea that a large percentage of the needed cargo is sent ahead of the crew. Propositioning can be achieved in a variety of ways including dedicated cargo flights that deliver a large mass of supplies to a designated base or a more gradual stockpiling of supplies over a series of flights.

Propositioning has been used extensively by the U.S. Military in support of their operations around the world. A specialized division of the U.S. Department of Defense, the Military Sealift Command, presently operates 35 ships around the world to support the Army, Marines, Navy and Air Force. These ships are loaded with military equipment and supplies and strategically positioned so as to be able to deploy on short notice to support military forces when needed [24]. Propositioning such as this is critical to the success and safety of U.S. military troops. The pre-positioning methodology has been used extensively on the ISS as will be described in Section 1.6.3.

1.4.2 Carry-Along

The carry-along methodology, as the name suggests, implies that all the cargo needed for that mission is carried-along on that mission. This methodology assumes that the vehicles that are being used to perform a given mission are capable of holding all the needed supplies for that mission. As supplies are consumed throughout the mission, waste is generated and either disposed of or stored for return to the point of origin.

On Earth, a very simple example of carry-along can be seen when anyone embarks on a backpacking trip into the wilderness or a picnic in the park. Generally for these types of

trips all needed supplies are literally carried by the people who will need them.

A disadvantage of the carry-along philosophy is that it does not allow for future missions to utilize the cargo brought to a node by a previous mission; each mission is in essence self-contained. The carry-along strategy was utilized on all Apollo and all Space Shuttle mission to date, as will be described in Section 1.6.2.

1.4.3 Resupply

The resupply methodology describes the process of sending a limited subset of cargo with the crew and then resupplying the remaining cargo as needed. Resupply can be of two types: scheduled and need-based. Scheduled resupply refers to the practice of determining resupply needs for an entire campaign of missions prior to the launch of the first mission and then setting a resupply schedule to meet the predicted needs. To determine the needs for the campaign. demand models based upon historical data are often used. Once the resupply schedule is fixed, the cargo to be flown on each mission may vary based upon the actual demand.

Need-based resupply, on the other hand, relies on the philosophy that resupply will only be scheduled once the crew begins to run low on necessary supplies or when the supply reaches a re-order point. Need-based resupply has the advantage that the amount of supplies flown can exactly match the actual demand for these supplies rather than having to rely on historical demand models. The disadvantage of need-based resupply is that it isn't very easy to "launch on demand" in the space business. Launch planning takes months and the manifests for shuttle flights are often set several months ahead of launch.

Examples of resupply are very prevalent on Earth. Nearly every retail store (grocery, clothing, hardware, etc.) operates on this paradigm where an initial stock of each sales item is purchased when the store opens and then is resupplied on either a schedule or need basis. The ISS relies heavily on resupply flights as will be described in Section 1.6.3.

1.4.4 Depot

The depot methodology stems from the terrestrial concept of a multi-echelon supply chain where inventory is held in a depot until it is demanded by the retailers or customers. The idea of a depot simply refers to an intermediate distribution center somewhere between where the cargo originates and where it is demanded.

In terrestrial logistics, most large retailers have depots (a.k.a. distribution centers or warehouses) where inventory is held between production and sales. The practice of determining where depots should be located and how much inventory should be held at these depots has been a major area of study in terrestrial supply chain management. Figure 2 shows a screen shot from a commercial product, LogicNet, designed to model and analyze terrestrial supply chain networks [25]. In this figure, potential depots can be seen as dark triangles while demand is shown as circles.

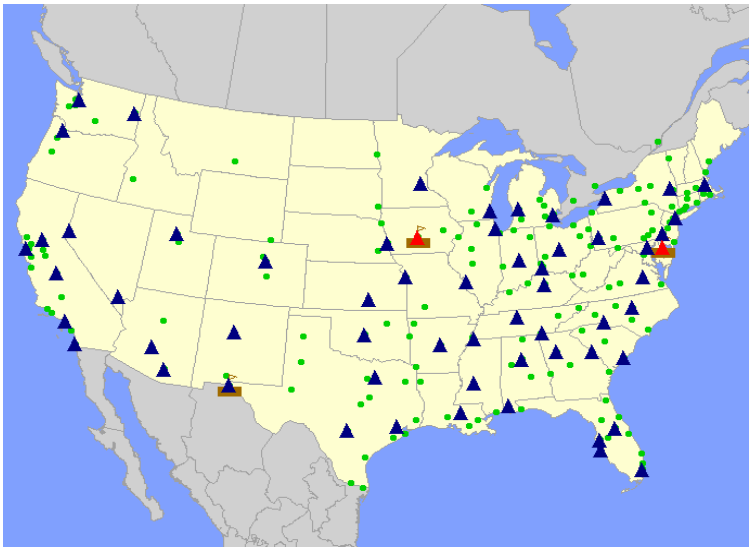

Figure 2 : Sample Terrestrial Supply Chain showing Distributon Centers and Customers [25]

The depot concept has yet to be implemented for human space exploration but there have been a few conceptual studies suggesting that depots may be a very attractive option for storing supplies in space as humans return to the Moon and on to Mars. A common suggestion is the proposal to store propellants in either Earth orbit, lunar orbit or at a Lagrange point. A fuel depot at the first Earth-Moon Lagrange Point (EM-L1) is a

common recommendation made to support the new vision for space exploration. Studies such as [26] imply that an EM-L1 fuel depot can greatly improve the logistics of the space exploration supply chain under certain assumptions.

A summary of the advantages and disadvantages as well as some terrestrial and in-space applications of the four logistics strategies is given in Table 2.

Table 2 : Logistic Strategy Summary

Logistics Strategy	Advantages	Disadvantages	Terrestrial Example(s)	Space Example(s)
Pre-Positioning	• Cargo is there waiting for the crew when they arrive • Can send non-perishable cargo on a cheaper (but slower) low thrust trajectory ahead of the crew	• Requires up front planning and financial investment	• U.S. Military • Appalachian Trail	• ISS Assembly Flights
Carry-Along	• Easy to plan • Mission success does not depend on other launches	• Does not protect for contingencies • Limited up mass may limit mission duration • Must manifest based on forecasted demand	• Backpacking	• Apollo Missions • Space Shuttle Flights
Resupply	• Can resupply non-perishable cargo with a cheaper (but slower) low thrust trajectory or unmanned mission • Can tailor manifest to meet actual demands	• Mission success is contingent on success of resupply flights	• Military • Retail Stores	• ISS Resupply Flights (Progress, MPLM)
Depot	• Risk-pooling • Can resupply the depot with cheaper low thrust trajectory missions	• Requires up front planning and financial investment	• Commercial Distribution Centers	• None

1.5 Mission Types

As was mentioned earlier in the chapter several types of lunar missions have been proposed for inclusion in the Constellation Program. These include unmanned cargo missions, Apollo-style sortie missions and ISS-style Lunar Outpost operations. Each of

these mission types is described below.

1.5.1 Unmanned Cargo

Unmanned cargo missions, as the name implies, are missions conducted with non-crewed vehicles strictly for the purpose of transporting necessary cargo from Earth to a node in space. For the constellation program, the unmanned cargo missions (referred to as pre-deploy missions in Figure 1-1) consist of a single Ares V launch. The Ares V as it is currently envisioned is capable of delivering 55,000 kg to trans-lunar injection (TLI) [1]. Depending on the design of the lunar lander this capability is predicted to equate to ~15,000 kg of cargo delivered to the lunar surface on an unmanned mission. As will be seen in Chapter 3, unmanned cargo missions are critical to the sustainment of a manned lunar outpost.

1.5.2 Sortie

The term sortie originates from its usage in the military to mean "one mission or attack by a single plane" [27]. When applied to the context of space exploration a sortie is meant to be a stand-alone mission of a relatively short duration (typically 2 weeks or less). All of the Apollo missions and most of the Space Shuttle missions have been sortie-style missions.

When sortie missions are performed, the astronauts typically live out of the vehicle they travel in. For the Apollo and Constellation programs, this means that the lunar lander is also the crew quarters for the mission while on the surface. For Space Shuttle missions, the middeck serves as the crew living quarters. Sortie missions are an effective way to explore a variety of locations without having to set up any infrastructure.

1.5.3 Outpost

Outpost missions imply a series of missions of a longer duration (typically 1-6 months) to the same location. Due to the extended length of these missions, the crew habitation for these missions should not be the same as the transportation vehicle. In Chapter 6 of Human Spaceflight Mission Analysis and Design (HSMAD) [28] a graph of total habitable module volume per crewmember versus mission duration is shown. From this

graph, it is noted that the optimal habitable volume per crewmember for a 6 month mission is ~19 m^3. This volume is significantly larger than can be provided by the transportation vehicles.

The assembly of the ISS is in fact the build up of an outpost in LEO. Both the ESAS and the LAT architectures have as their final outcome the establishment of a lunar outpost capable of supporting teams of four astronauts for 180-days.

1.6 Case Studies

The following sections detail which logistics methodologies (Section 1.4) and mission types (Section 1.5) have been utilized in past and current human space exploration programs.

1.6.1 Apollo

Under the Apollo program, six manned sortie missions to the lunar surface were successfully conducted between 1969 and 1972 [29]. (Apollo 13 is not counted due to the fact that it failed to reach the lunar surface.) Each mission was self-contained; in other words, no space logistics network existed to support each mission. Instead, all the supplies were carried with the astronauts to their destinations. Forecasts predicted the number and type of supplies that would be needed on the lunar surface to support the short duration missions and these supplies were loaded into the Apollo command module and lunar module prior to launch.

As was described earlier in this Chapter, the Apollo logistics strategy can be termed the 'backpack model' or carry-along because of its resemblance to hikers carrying all their equipment in backpacks and discarding or consuming supplies along the way. This type of strategy is clearly practical and perhaps even optimal for short-term sortie missions like those of the Apollo program. The Apollo missions that landed men on the Moon ranged in total duration from 8 days and 3 hours (Apollo 11) to 12 days and 14 hours (Apollo 17) [30]. For these short missions only a small amount of cargo was required so all of the cargo could easily be transported with the crew making the carry along

methodology ideal for these sortie-style missions.

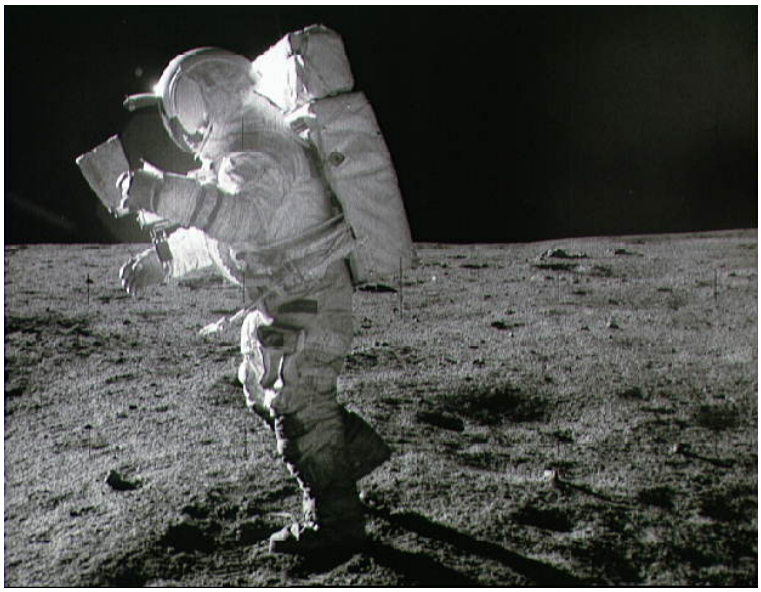

Figure 3 : Apollo Astronaut 'Backpacking' on the Lunar Surface
[NASA Image AS14-64-9089]

1.6.2 The Space Shuttle

The U.S. Space Transportation System (STS), commonly referred to as the Space Shuttle, has been in operation since 1981. During this time the space shuttle has flown well over 100 missions to low Earth orbit [31]. The Space Shuttle has the capability to carry seven astronauts and ~17,055 kg of payload to a 51.6 degree inclination low Earth Orbit [14]. The Space Shuttle orbiter is fully reusable and has a significant return payload capability.

When the Space Shuttle was developed, NASA planned to reach a point of "routine operations" with the Space Shuttle flying on the order of 25-60 missions per year (approximately one launch every one to two weeks) [32]. In reality NASA has never come close to reaching this goal. As Figure 4 shows, the highest annual flight rate achieved to date is 8 flights per year and the average flight rate over the program lifetime from 1981-2006 is 4.4 missions per year [31]. This dramatic decrease in flight rate between the predicted and the actual is due to a combination of several factors including budgetary limitations, the technical complexity of the vehicle and a lack of customers.

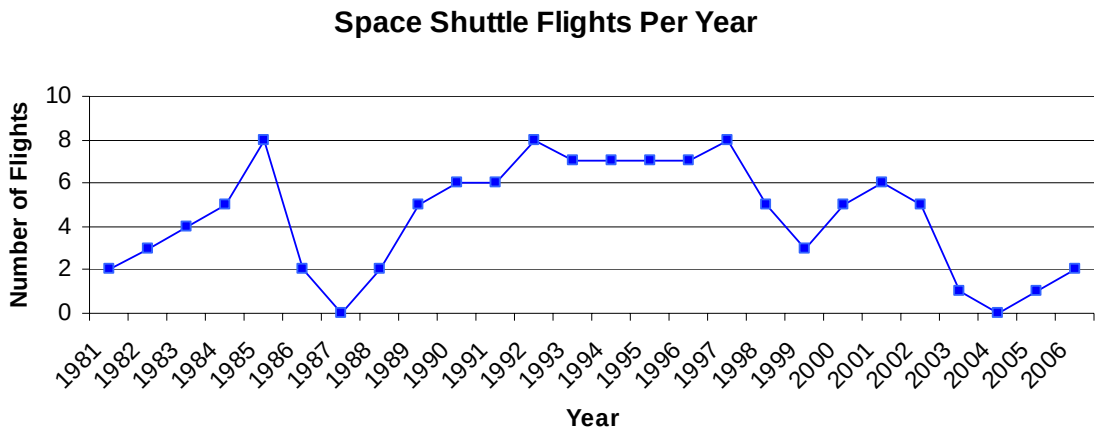

Figure 4 : Space Shuttle Flights per Year, 1981 – 2006

Similar to the Apollo missions, all of the Space Shuttle missions to date have utilized the carry-along logistics methodology. This statement is true for both standalone STS missions and those going to the ISS. Although the cargo bay of the space shuttle is used for pre-positioning and resupplying the ISS, the seven shuttle crewmembers live out of the space shuttle orbiter mid-deck, so the STS missions are considered carry-along. Prior to the scheduled launch date the Space Shuttle orbiter middeck is loaded with the necessary equipment to carry out the 7-14 day mission along with some contingency supplies. As the mission is conducted, the space shuttle crew members use the cargo they have brought with them and accumulate waste to be brought back to Earth upon the completion on their mission. As with the Apollo program the carry-along paradigm has been well suited to the short duration missions undertaken by the Space Shuttle; as will become apparent in the next few sections though, this paradigm cannot sustain longer duration space travel.

1.6.3 The International Space Station

Construction of the International Space Station (ISS) began in 1998 with the launch of the Russian Functional Cargo Block (FGB). As of November 2006, 2 Proton rockets, 1 Soyuz rocket and 15 Space Shuttle flights have launched ISS elements to continue ISS assembly [33]. ISS assembly is slated to be completed between 2010 and 2012,

coinciding with the retirement of the Space Shuttle [34]. ISS operations are predicted to continue until at least 2015. When assembly of the ISS is complete, it is predicted that the ISS will weigh ~390,000 kg and will cover an area roughly the size of two football fields [35].

The ISS logistics strategy is a combination of carry along, pre-positioning and resupply (Figure 5). For the ISS program, a "carry-along only" logistics strategy was extremely impractical because of the long duration (6 months) of each expedition. It is not possible to launch 6 months of supplies on the Russian Soyuz vehicle, the vehicle responsible for ~50% of the crew transportation to and from the ISS. The pre-positioning methodology was employed during the early ISS assembly flights (1998-2000) when elements and supplies were launched on Proton Rockets, Soyuz Rockets and the Space Shuttle prior to the arrival of the first ISS crew on November 2, 2000. The first 8 flights to the ISS, which launched the Functional Cargo Block, Node 1, the Service Module, Z1, the Pressurized Mating Adapter 3 and a large amount of equipment and supplies can all be considered propositioning flights. When the first ISS crew arrived in the Soyuz on the ninth mission all the equipment and supplies needed for their 6 month stay were already awaiting them. Pre-positioning continues to be utilized on the ISS for consumables such as food, clothing and water and necessary equipment such as spares. This strategy allows NASA and the Russian Space Agency to maintain a safety stock of these critical items on the ISS.

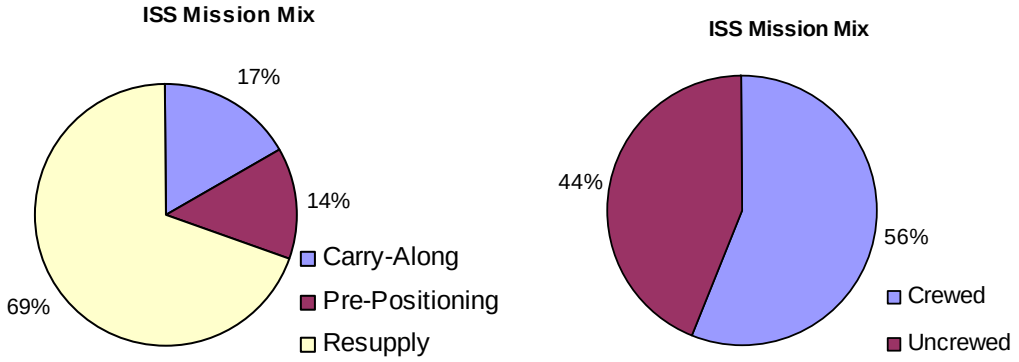

Figure 5 : ISS Mission Breakdown, 1998-2006

Since November of 2000 there has been a continuous human presence on the ISS and the needs of these humans have been met with regularly scheduled resupply flights provided by various vehicles, including the American Space Shuttle, the Russian Progress and the Russian Soyuz. The number and type of supplies shipped is generally based on the actual demand generated on the ISS, rather than forecasts predicting supply requirements. This strategy can be termed "scheduled resupply," the same strategy used by people the world over who replenish their pantries from the grocery store once a week. This type of strategy is appropriate for long-term missions located relatively near a resupply source (i.e. grocery store). Note that in the case of the ISS the resupply schedule is generally fixed, while the exact manifest of what is being resupplied is dynamic.

The ISS relies heavily on the resupply capabilities provided by the Russian Progress and the U.S. Space Shuttle. The Progress operates as a scheduled resupply vehicle. Since 2000, a Progress has launched every 3-4 months bringing ~2,350 kg of critical cargo to the ISS on each flight [36]. The space shuttle resupply schedule has been less regular over the history of the ISS. A complete listing of all flights to the ISS from 1998-2006 can be found in Appendix A. Figure 6 shows an estimation of the cumulative mass of the ISS from 1998-2006 based upon the data in Appendix A. From the figure, it can be seen that the Columbia Accident in early 2003 disrupted the aggressive mass buildup pattern seen from 1998-2003 and the years following have seen very little gain in total ISS mass. If one were to linearize and extrapolate the slope of the graph from 1998 until 2003, one could infer that the 390,000 kg final assembly mass (shown as the dashed line in the figure) would have been reached sometime in 2006. (Recall that as it stands right now, the ISS is slated to be fully assembled between 2010 and 2012.) Also worthy of note is the fact that this graph takes into account both the up and down mass flows to and from the ISS. This means that utilization flights, such as STS-114 and STS-121, in mid-2005 and mid-2006 respectively, which return nearly as much cargo as they launch, show only a minor contribution to the cumulative mass of the ISS.

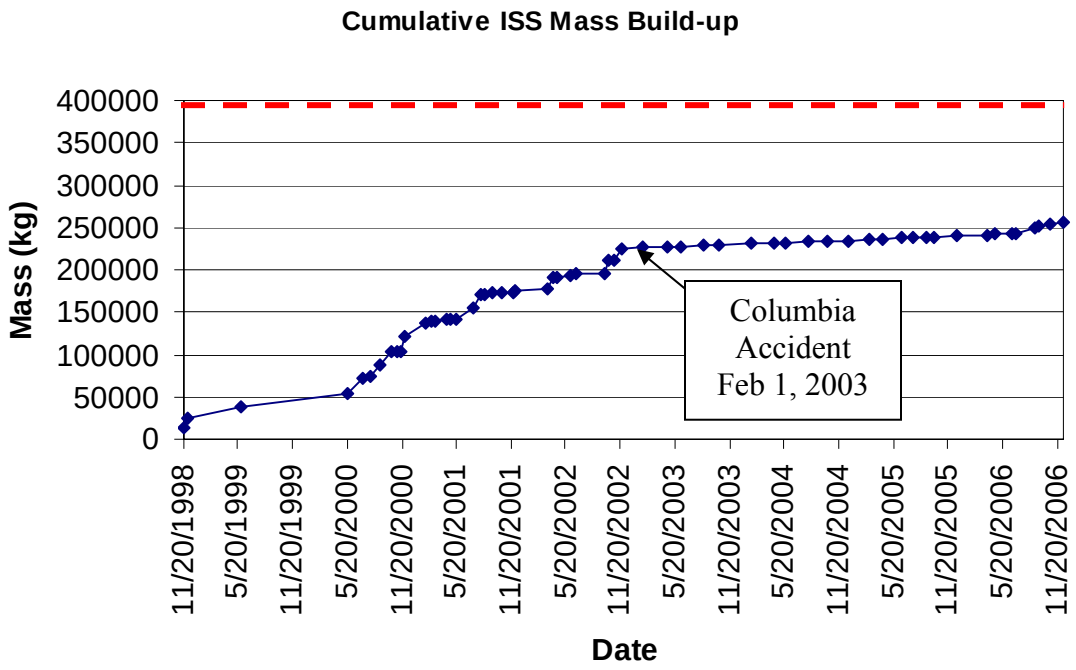

Figure 6 : Approximation of ISS Mass Buildup, 1998-2006

As the ISS continues to grow, so too will its supply chain. Within the next two years the European Space Agency (ESA) Ariane Transfer Vehicle (ATV) and the Japanese Aerospace Exploration Agency (JAXA) H-II Transfer Vehicle (HTV) are expected to begin providing additional resupply capabilities for the ISS [37]. NASA is also looking into the possibility of paying a commercial company to provide cargo resupply (upmass) and payload return to Earth (non-destructive downmass) capability to the ISS following the retirement of the Space Shuttle in the 2010-2012 timeframe [38]. Without this commercial cargo vehicle the non-destructive downmass capability from ISS will be limited to the ~100 kg payload capability of the Soyuz.

The ISS program has and will continue to serve as a learning experience for the logistics required to assemble large facilities and support humans for long durations in space. It is important that the logistics lessons learned from the ISS and other past programs are documented and incorporated into future programs. Lessons learned from the ISS can be found in several public sources including the NASA Public Lesson Learned Database

[39] and documents such as *Logistics Lessons Learned in NASA Space Flight* [14].

1.7 Research Goals

Figure 7 depicts the basic networks behind each of the space logistics paradigms described above, and also includes the growing network that will be needed to support the next-generation space exploration programs now in the planning stages. Relatively simple logistics strategies functioned well for the two major U.S. spaceflight programs that have been operated to date, but the next-generation network appears much more complex.

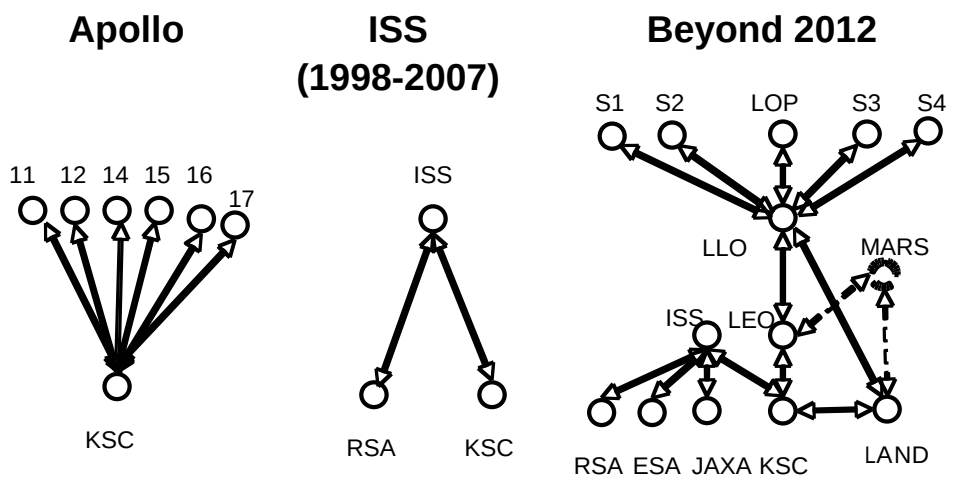

Figure 7 : Space Logistics Supply Chains

This leads to one of the major questions that we are string to answer through this research: What is the best logistics paradigm for next-generation space missions? The hypothesis is that the Constellation Architecture will utilize a combination of all three mission types (Unmanned Cargo, Sortie and Outpost) described in Section 1.5. The logistics methodologies therefore will be a blend of the pre-positioning, carry-along and resupply models described in Section 1.4, though it is unclear exactly what combination of these strategies will provide the most affordable, most robust supply chain for next-generation programs.

This research investigates the sustainability of NASA's current lunar mission architecture as well as its robustness to campaign level risk.

1.8 Thesis Organization

This thesis consists of five chapters. The remainder of Chapter 1 is dedicated to a terrestrial case study of logistics at the Haughton-Mars Project Research Station.

Chapter 2 gives an introduction to SpaceNet, an interplanetary supply chain modeling and simulation tool. This tool is based upon the logistics methodologies described in Chapter 1 and was developed as part of this research with assistance from personnel at MIT and the Jet Propulsion Laboratory (JPL).

Chapter 3 uses SpaceNet to perform trade studies on the baseline lunar exploration architectures introduced in Chapter 1. A comparison between the ESAS and Global Exploration Strategy (LAT) architectures is performed. SpaceNet is then used to determine whether the architectures are sustainable and if they are not, to determine whether there exists a simple modification that will make them sustainable.

Chapter 4 analyzes the robustness of the Global Exploration Strategy to campaign level risks. The risks analyzed include flight cancellation, flight delay and stochastic demand predictions. This chapter also includes a discussion of how to determine the "best" mix of classes of supply to be propositioned at the outpost.

Finally, Chapter 5 summarizes the key findings of this work and presents recommendations to NASA's Constellation Program based upon these findings. A roadmap of this thesis can be found in Figure 8.

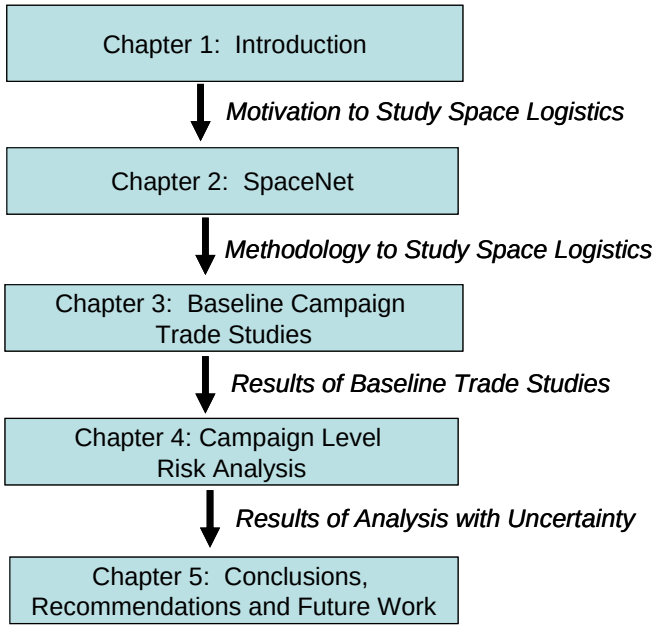

Figure 8 : Thesis Roadmap

1.9 The Haughton-Mars Project Research Station

While the study of past and current human space exploration programs provides a good foundation for beginning to lay out the logistics of future human space exploration, it must be noted that the challenges associated with establishing a permanently manned outpost on the Moon is in many ways uncharted waters. As such, a growing community of space professionals is beginning to appreciate the value of lessons learned from remote research bases here on Earth. These "analog sites" as they are commonly referred to offer a wealth of lessons learned on the logistics of human survival in harsh, remote environments.

During the summer of 2005, a team of nine researchers from the Massachusetts Institute of Technology (MIT) participated in an expedition to the Haughton-Mars Project Research Station (HMP RS) located near the Haughton Crater on Devon Island, Nunavut in the High Artic (Figure 9). During this expedition, we investigated the applicability of the HMP research station as an analogue for planetary macro- and micro-logistics to the Moon and Mars, and began collecting data for modeling purposes. We also tested new technologies and procedures to enhance the ability of humans and robots to jointly

explore remote environments.

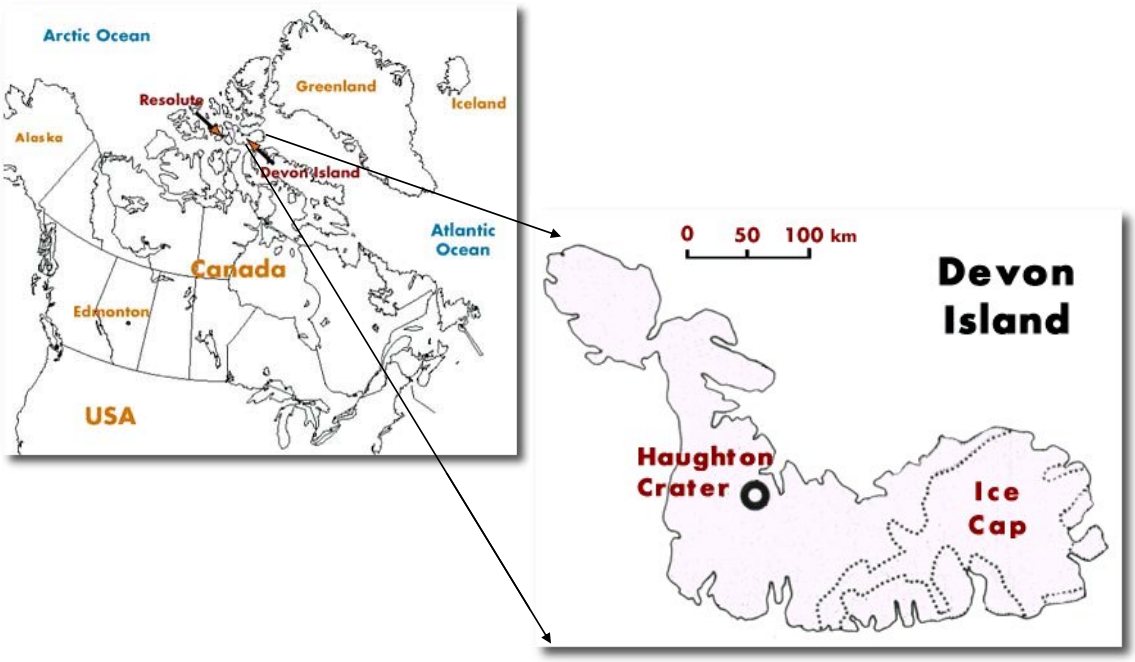

Figure 9 : HMP RS Location [40]

The Haughton-Mars Project is an international, multidisciplinary, scientific field research project centered on the exploration of the Haughton impact crater site, viewed as an analogue for Mars. The HMP research program has two components: Science and Exploration. The HMP Science Program includes investigations in planetary sciences, geology, astrobiology, microbiology, and environmental sciences and is aimed at advancing our understanding of the formation and evolution of the Earth and other planets, the adaptations of life in extreme environments, and the possibilities and limits of life elsewhere in the universe. The HMP Exploration Program focuses on advancing the development of new technologies and operational strategies for the future exploration of the Moon, Mars, and other planetary bodies by robotic systems and humans.

The HMP was established in 1997 by Dr. Pascal Lee as a small pilot study with initial support from NASA, the U.S. National Research Council (NRC), and the Geological Survey of Canada. Based at NASA Ames Research Center, the project has grown over

the years to become the largest, most integrated, planetary analogue field research program in the world. The HMP now hosts up to sixty field participants each year and represents the research interests of a variety of international partners including government agencies from the United States and Canada, as well as private organizations, academic institutions (including MIT), industrial partners, and nonprofit groups. Funding for the HMP research program is provided mainly by NASA and the Canadian Space Agency. The project is managed jointly by the Mars Institute and the SETI Institute, in collaboration with Simon Fraser University (BC, Canada). The Mars Institute manages and operates the HMP Research Station (HMP RS) [40].

The HMP RS offered us an excellent opportunity to study potential logistics strategies for future human exploration of the Moon and Mars. Due to the fact that the HMP RS is located in such a harsh, remote environment it has employed a combination of all four of the logistics strategies described earlier in the chapter (pre-positioning, carry-along, resupply and depot) since its inception in 1997.

As the HMP RS was first being established a pre-position strategy was utilized to ensure timely and affordable delivery of cargo to the base. In 1997 a shipment of non-perishable supplies with a large mass and volume, such as building materials, were loaded on a barge in Quebec for transportation to Resolute Bay. This mode of transportation was deemed the least expensive way to transport a large quantity of supplies to the research station prior to the arrival of the researchers. The main drawback of transportation by barge is that it involves a long lead time as the timeframe from initiation of the shipment to arrival at Devon Island was several months. A second drawback is the large upfront cost required at the time of shipment. This logistics strategy is analogous to the idea of sending non-perishable supplies to Mars on a low thrust, long duration trajectory to arrive prior to the arrival of the first crew. Another example of propositioning at the HMP RS occurs occasionally when HMP supplies are flown directly in a C-130 aircraft from Moffet Field, CA to be air-dropped at the HMP RS through interagency agreements between the NASA HMP and the United States Marine Corps.

Every summer, the HMP RS employs a hybrid of the carry-along, resupply and depot logistics strategies. Figure 10 below shows a simplified diagram of the HMP RS supply chain for the summer of 2005. The nodes in this supply chain include multiple origins around the world, Ottawa, Edmonton, Resolute Bay, and the HMP RS. As teams of researchers plan for their stay at the HMP RS, many of them choose to send supplies to Resolute Bay prior to their arrival. These supplies are then stored in a warehouse at Resolute Bay Airfield to await transport to Devon Island; this warehouse can be considered a depot for the HMP RS. Supplies of fuel, spare parts, building materials and even some consumables are maintained at the depot and transported to the HMP RS only when needed.

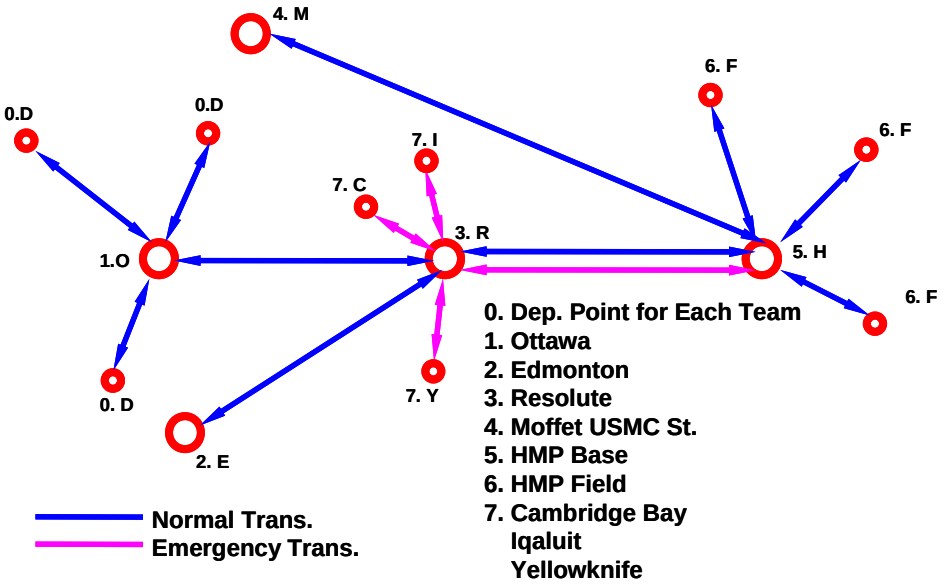

Figure 10 : HMP RS Supply Chain 2005

As researchers travel from their point of origin to Resolute Bay (via commercial flights through Ottawa or Edmonton) they are expected to bring all the personal items (clothing, sleeping bags, laptops, etc) that they will need for their stay at the HMP RS with them. This portion of the logistics is classified as carry-along.

In most instances once supplies and personnel reach Resolute Bay, they are shipped via Twin Otter airplane chartered via the Polar Continental Shelf Project (PCSP), a Canadian

Government Arctic science logistics support program. Dr. Lee secures annual logistical support from PCSP to support the HMP field campaign. The Twin Otter flights provide both carry-along and resupply logistical capability for the HMP RS. Each Twin Otter flight can safely carry 2400-2800 lbs of cargo from Resolute Bay to the HMP RS [9].

Scheduling of crew and cargo transportation between Resolute Bay and the HMP RS is typically carried out by the HMP core team, based on a tentative field season schedule. The planner collects information from each team about the team members, cargo weight and expected crew stay duration. With this information, the planner makes a pre-season schedule which hopefully satisfies all the research teams' carry-along and resupply requirements. Occasionally teams are requested to change their duration of stay or arrival and departure dates to improve overall scheduling. Once the field season is underway, transportation of the crew and cargo is carried out according to the pre-determined schedule. However, inclement weather, cargo estimation errors, priority usage by other field parties, and personal emergencies often act as disturbances to the transportation plan, such that actual flight schedules are dynamically changed to adjust to these factors. Due to this rescheduling process, the total actual number of flights then typically exceeds the initial plan. This rescheduling process was apparent during the 2005 field season, where 19 twin otter flights were originally planned between Resolute Bay and the HMP RS and 29 were actually conducted (Table 3). This dynamic schedule is very similar to that experienced by NASA in past programs such as Apollo, the Space Shuttle and ISS, where schedule changes, technical problems or congressional discretion have caused changes to the original plan.

Table 3 : HMP Flight Log 2005

Flight #	***No. of Passengers In***	***Approx. Mass of Cargo In# (lbs)***	***No. of Passengers Out***	***Approx. Mass of Cargo Out# (lbs)***
0*	1	2300	1	300
1	4	2200	0	0
2	3	1900	0	0
3	3	1900	0	0
4	5	2350	0	0
5	2	1800	0	0
6	0	2410	0	0

Flight #	*No. of Passengers In*	*Approx. Mass of Cargo In# (lbs)*	*No. of Passengers Out*	*Approx. Mass of Cargo Out# (lbs)*
7	2	3050	2	1200
8	2	1770	0	0
9	2	1800	0	0
10	2	1400	0	0
11	6	2300	0	0
12	2	1640	0	0
13	0	2000	0	0
14	2	2380	0	0
15	5	2560	3	900
16	2	2240	0	750
17	2	2100	0	1200
18	3	900	0	1600
Helicopter	0	0	2	600
19	0	2350	8	2400
20	0	2400	7	2100
21	5	2610	2	2100
22	0	0	6	1800
23	4	1200	0	2470
24	0	0	6	1800
25	0	2410	6	2185
26	0	0	8	2625
27	0	0	3	2400
28	0	0	3	2400
TOTAL	**57**	**49,970**	**57**	**28,830**

Cargo mass includes 300 lbs per person which is the estimated average mass of one person with their personal cargo (clothing, sleeping bags, etc.)
* Flight 0 was a reconnaissance/pre-positioning flight.

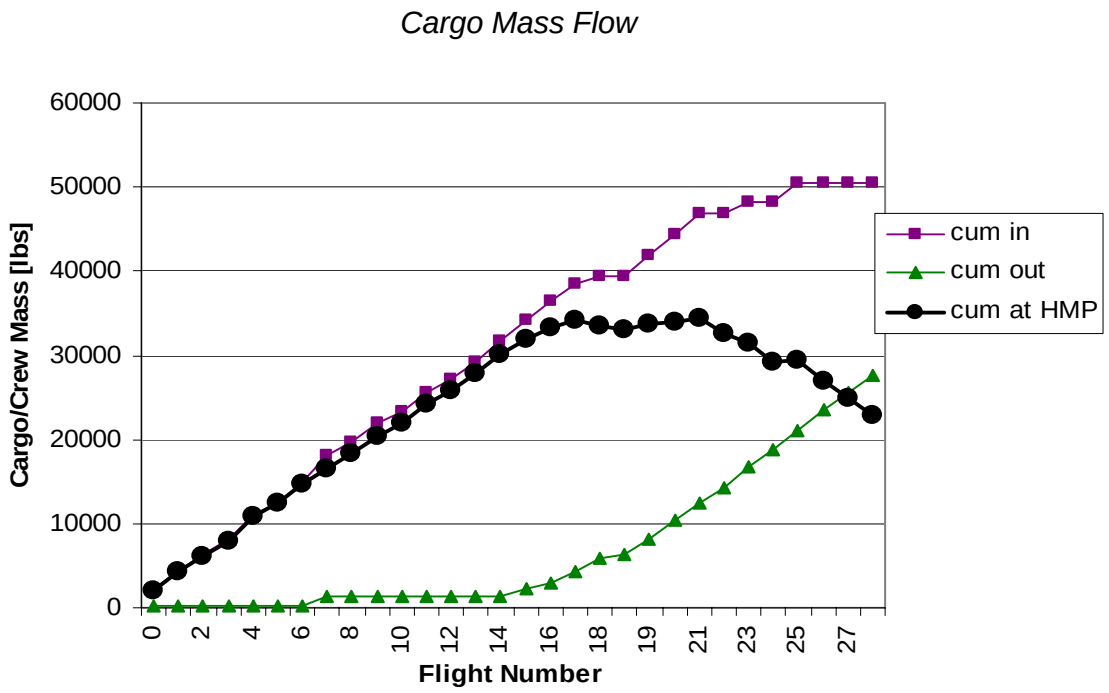

Figure 11 : HMP Cargo Mass Flow 2005

Since the twin otter flights are the primary means of transportation to and from the HMP RS, these flights serve the multi-faceted role of providing pre-positioning, carry along and resupply capabilities for the base. Pre-positioning at the research station is minimal but some maintenance supplies, building materials and food are pre-positioned at the beginning of each field season. Carry-along occurs on each twin otter flight that brings new researchers to the base as these personnel bring with them all personal items (tents, clothing, sleeping bags, etc.) that they will need for their stay. Resupply of consumable items such as food and gasoline also occurs on most of the twin otter flights. In general, any excess cargo capacity on an inbound twin otter flight will be filled with resupply items from the depot maintained at the Resolute Bay Airfield (described earlier in this section). The cumulative cargo flow for the HMP RS during the 2005 field season is shown in Figure 11. From the figure and the data in the table above it, it can be seen that the total growth of cargo at the HMP RS over this field season was ~21,000 lbs.

While at the research station, teams of two or more researchers often explore away from

the base on All Terrain Vehicles (ATVs) or in the Humvee to explore sites of scientific interest away from the camp. The duration of these expeditions can range from a few hours to an overnight stay, depending on the objectives and distance to be traveled. Each of these excursions depends on the carry-along paradigm where participants bring all food, clothing, science equipment and fuel with them.

The HMP RS offered an excellent opportunity to examine the combination of various logistics paradigms in use. Of the case studies presented in this chapter, it comes closest to resembling what is predicted to be the nominal lunar outpost supply chain.

2 SpaceNet

This chapter describes the framework of SpaceNet as well as its capabilities and intended uses. SpaceNet is an integrated interplanetary supply chain management and logistics planning and simulation software tool. The goal of SpaceNet is to assist mission architects, planners, systems engineers and logisticians to focus on what will be needed to support future crewed exploration missions, primarily in the Earth-Moon-Mars system. Instead of helping to design the elements (vehicles) themselves in terms of propulsive and pressurized/un-pressurized cargo carrying capability, SpaceNet evaluates such vehicles in the context of a particular mission architecture and supply chain strategy. The emphasis is on ensuring logistical feasibility of a given scenario as well as a prediction of the resulting logistics measures of effectiveness (MOEs).

2.1 Introduction to SpaceNet

One of the major challenges in the development of a generic space logistics model is defining the model components. A complete framework for interplanetary logistics has not been previously modeled, so the scope of such a model must be defined. The basic elements of the model are: Transportation (shipment of people, cargo, and vehicles), Demand (by supply class), Information Architecture, Simulation and Evaluation. Exploration architectures are modeled as a set of nodes (locations) and arcs (trajectories between these locations). Demand is generated at nodes; for example, a mission at a lunar surface node would generate demand for crew provisions, science equipment, etc. Vehicles traverse arcs carrying supplies to satisfy the demand. Users can then simulate their campaign of missions and evaluate this campaign for feasibility and logistics performance. This framework provides an integrated planning and simulation tool for space logistics.

The challenge of integrating these components into a cohesive end-to-end logistics and operations model is discussed in the next sections. First, we describe the basic building blocks of our modeling framework (nodes, elements, and supplies), along with two

concepts which enable us to tie these together: the time-expanded network and processes for movement through the network. Collectively, this framework allows us to describe and model both the demand and the movement of items in the logistics scenario. Finally, we describe the remaining layers which enable the effective utilization of this modeling framework: the ability to simulate and evaluate various architectures, and even to apply optimization techniques.

2.2 Building Blocks

The basic building blocks in the modeling framework (nodes, supplies, and elements) were derived from terrestrial supply chain management and from past practices in space logistics [4] [5].

2.2.1 Nodes

Nodes are spatial locations in the solar system. Contrary to some usages of the term, the existence of a node does not necessarily indicate that a facility exists at that location or that a node is ever used or visited. A node is simply a way to refer to locations in space. Nodes can be of three basic types: Surface nodes, Orbital nodes, and Lagrangian nodes

Surface nodes are fairly straightforward. They exist on the surface of a central body such as the Earth, the Moon, or Mars, and they are further characterized by their latitude and longitude on that central body. Examples of surface nodes include Kennedy Space Center (KSC) and the Apollo 11 landing site at Mare Tranquilitatis.

Orbital nodes are also characterized by their central body (e.g. Earth, Moon, Mars, or Sun), as well as other characteristics describing the orbit itself: apoapsis, periapsis, and inclination. Therefore, the ISS orbit could be an orbital node located around Earth at an altitude of 400 km and an inclination of 51.6 degrees. Similarly, a low lunar orbit (LLO) is a commonly used orbital node in lunar exploration missions. LLO is typically located 100 km above the lunar surface.

Lagrangian nodes are located at any of the Lagrange points in the solar system. They are

characterized by the two bodies and the number of the Lagrange point. One commonly considered Lagrange point is the Earth-Moon L1 (EML1) point, which lies between the Earth and the Moon at the point where the two bodies' gravitational pulls are balanced. Examples of all three types of nodes can be seen in Figure 12.

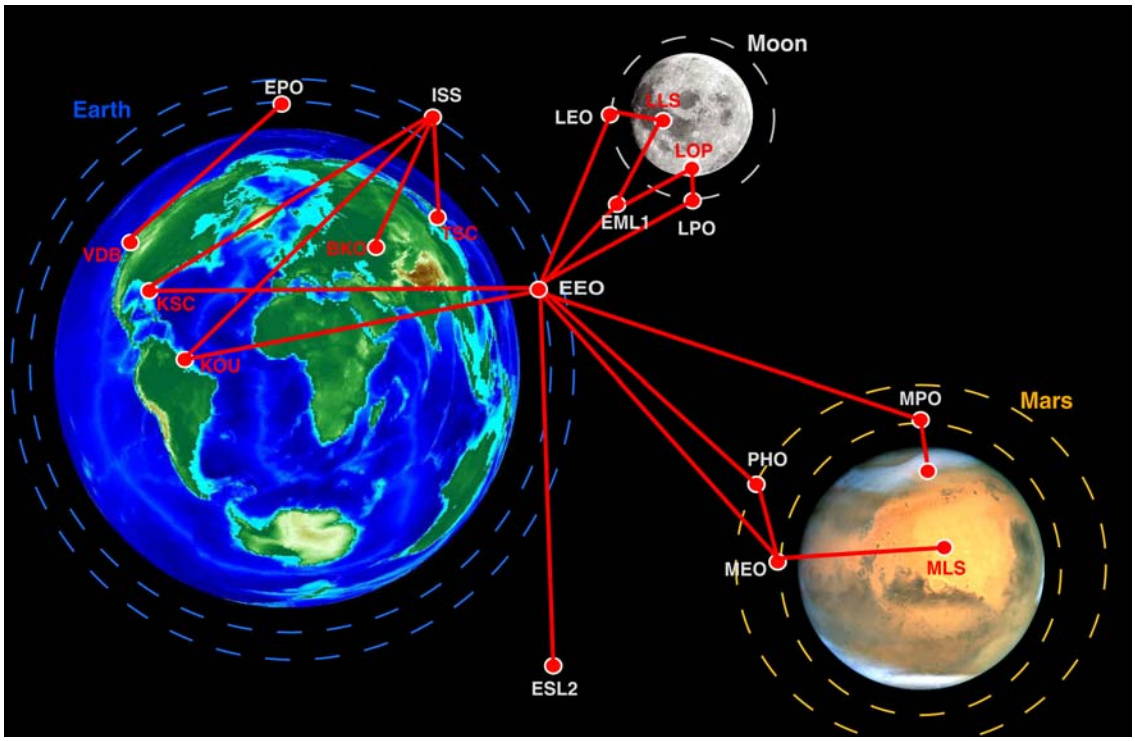

Figure 12 : Illustration of Several Nodes in the Earth-Moon-Mars Network

We reiterate that labeling a location as a *node* does not necessarily mean a permanent facility exists at that location. Rather, it means that some part of the logistics architecture for a space mission might make use of that location as a transit or waiting point. For example, if a spacecraft is launched from KSC to LEO, then propelled toward lunar equatorial orbit, it has passed through one surface node and two orbital nodes. The nomenclature developed around nodes allows us to build up a potential transportation network and thus to formalize description of logistics architectures.

2.2.2 Supplies

Supplies are the items that move through the network, from node to node. Generally,

supplies should include all the items needed at the planetary base, or during the journeys to and from the base. Examples include consumables, science equipment, surface vehicles, and spares. In order to track and to model the extraordinary variety of supplies that could be required, they must be classified into larger categories. This study spent a great deal of effort analyzing various ways to classify supplies (see [41] for more details), and concluded that the best method was to develop a set of *functional* classes of supply, organized regardless of material or owner. The classes are therefore based on the essential functions of a planetary base, or the tasks that need to be accomplished, such as research, habitation, transportation, etc. The final set of ten classes of supply (COS) is shown in Figure 13. (It should be noted that NASA's Cargo Category Allocation Rate Table (CCART) classification system, presently in use for ISS logistics, was evaluated for use in this context, but it was occasionally inconsistent and was missing a number of categories required for surface exploration.)

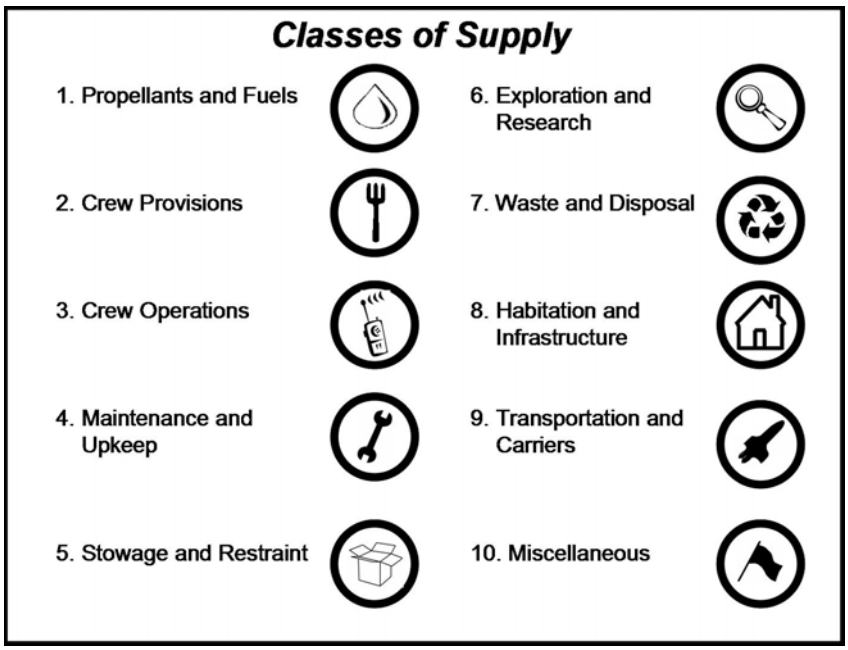

Figure 13: Functional Class of Supply for Human Space Exploration

These classes of supply then form the basis for the modeling of supply items. Recall that the impetus behind the development of these supply classes was the need for a manageable modeling framework for supplies moving through a transportation network. With these ten supply classes we can model demand for various types of items at the

supply class level. In addition, we can more easily simulate and track the movement of these aggregate supply items through the transportation network, using a unified relational database for exploration [41]. For example, a planetary base might require 10 units of crew provisions, rather than certain amounts of water, dried food, drink mix, eating utensils, etc. With these classes of supply, the modeling problem can be reduced to a manageable size.

2.2.3 Elements

Elements are defined as the indivisible physical objects that travel through the network and (in general) can hold or transport supplies. Most elements are what we generally think of as "vehicles" – the crew exploration vehicle (CEV), propulsion stages, etc. Here, we also include other major end items such as surface habitats and pressurized rovers. Elements, then, are characterized by a wide set of characteristics: they can:

- hold other supply items (e.g. fuel or cargo)
- be propulsive or non-propulsive
- carry crew or not carry crew
- be launched from Earth
- be reused, refueled, disposed of (staged), pre-deployed
- be "docked" with other elements to form a stack

In general, an element has defined capacities for three types of items: crew, cargo, and propellant. These capacities determine what types of supplies can be assigned to that element for transport, and whether the element is propulsive. Thus, elements can transport supplies and crew between the various nodes of the transportation network. Figure 14 illustrates the maximum payload capacity and maximum delta-v for some of the elements used in SpaceNet. Three distinct groupings of elements (carriers, propulsion stages and multi-use vehicles) can be seen in the figure.

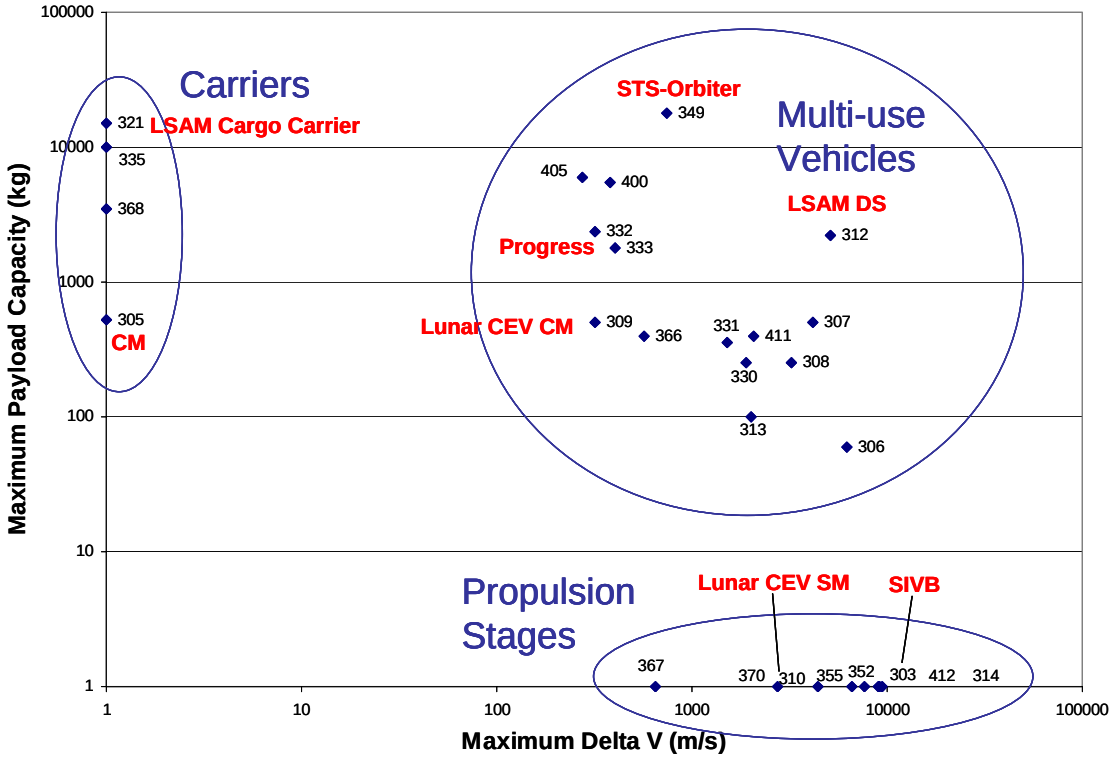

Figure 14 : Groupings of Elements in SpaceNet

2.3 Tying it all Together

With the preceding definitions of nodes, supplies, and elements, we have defined the basic building blocks of a modeling framework for space logistics. We can create a network of nodes, and define elements capable of traversing that network between nodes, carry supplies. Two remaining concepts are needed to tie these ideas together: the time-expanded network (to account for changes in trajectories over time) and processes that describe how elements and supplies move through the network.

2.3.1 Time-Expanded Network

A time-expanded network is a concept that builds on the idea of a static network. We have discussed the creation of a static network based on nodes like Kennedy Space Center (KSC), Low Earth Orbit (LEO), and Low Lunar Orbit (LLO). Now suppose one takes that static network and expand it over time, to account for changes in the network

over time, what one has then is a simple time-expanded network (Figure 15). The *static network* is made up of the three nodes along the left-hand side of the figure, labeled 'KSC,1', 'LEO,1', and 'LLO,1'. We then use a time step Δt and expand these three nodes forward in time. At time step two, therefore, we copy each of the static nodes, so that the middle column in Figure 15 is labeled 'KSC,2', 'LEO,2', and 'LLO,2'. We copy these nodes again for time step three, creating the right-most column. The next step is to define the allowable transitions – called *arcs* – between the nodes. It is always possible to remain or wait at a given node through the next time step. Therefore we can define all of the horizontal arcs (represented by dashed arrows) shown in Figure 15. Next, we look at the allowable transitions from KSC to LEO. The vertical arrow from 'KSC,1' to 'LEO,1' is crossed out because it is impossible to make an instantaneous transition from KSC to LEO. In this example, it takes one time step to make that transition, so arrows are drawn from 'KSC,1' to 'LEO,2' and 'KSC,2' to 'LEO,3'. The reverse arcs from LEO to KSC are also added. Finally, the transition from LEO to LLO (in this notional example) takes longer: two times steps are required, so the arcs are drawn as shown in Figure 15. This completes the definition of the time-expanded network in our simple example; we have defined time-expanded nodes, waiting arcs, and feasible transport arcs (filtered by the astrodynamic constraints). Now, we can define paths through the network; Figure 15 highlights in blue a path through KSC,1 to LEO,2 to LEO,3 (illustrating a transfer from KSC to LEO and a wait at LEO).

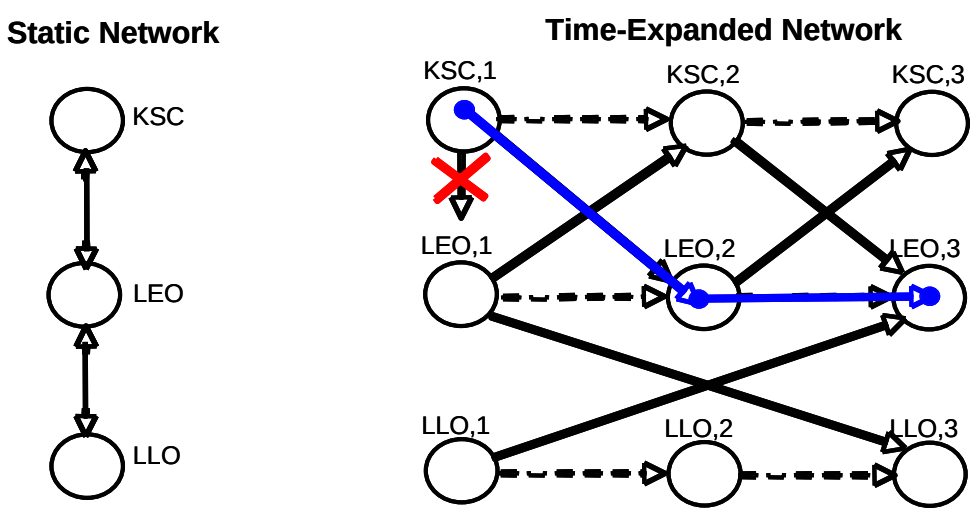

Figure 15 : Left: Static Network, Right: Time Expanded Network

Notice that arcs are only defined in the forward direction, because it is impossible to traverse backward in time (non-causal paths are forbidden). Note also that while this network is relatively simple, the construction of such a network is nontrivial for large time horizons or large static networks. A realistic time expanded network with a 3-year scenario (about 1000 days), a time step of 1 Earth day and 10 nodes will have 10,000 nodes once expanded in time. The advantages of this type of network construction are that it makes time explicit and enables simulation and optimization of time-varying transportation problems, such as the launch windows to Mars.

2.3.2 Processes

With the time-expanded network defined, the only remaining step is to describe how elements and supplies are allowed to move among the nodes of the time-expanded network. There are five essential processes that describe this movement: Wait, Transport, Transfer, Exploration and Proximity Operations. The implementation of each of these processes will be described in Section 2.4.2.

At this point, with the building blocks, the network, and the processes defined, we can model the flow of supplies, elements, and crew through the logistics network.

2.4 Implementation in SpaceNet

This section describes an implementation of our modeling framework in the form of a logistics planning tool called SpaceNet. SpaceNet is a computation environment for modeling exploration from a logistics perspective. It includes discrete event simulation at the individual mission level (e.g. sortie, propositioning, or resupply) or at the campaign level (i.e. set of missions). It also allows for the evaluation of manually generated exploration scenarios with respect to measures of effectiveness and feasibility, as well as the visualization of the flow of elements and supply items through the interplanetary supply chain. A brief explanation of SpaceNet is included here, significantly more details can be found in the *SpaceNet v1.3 User's Guide* [42].

SpaceNet is built on the modeling framework described earlier in this paper. The current version of SpaceNet, v. 1.3, is implemented in Matlab and exports its results directly to the user through a Graphical User Interface (GUI) and to an Excel file that can be used for post-processing analysis. The GUI allows analysts to describe complex space logistics architectures using the basic concepts of nodes, elements, and supplies. Missions are modeled as a series of processes on a network of nodes and arcs, with elements carrying supplies through the network.

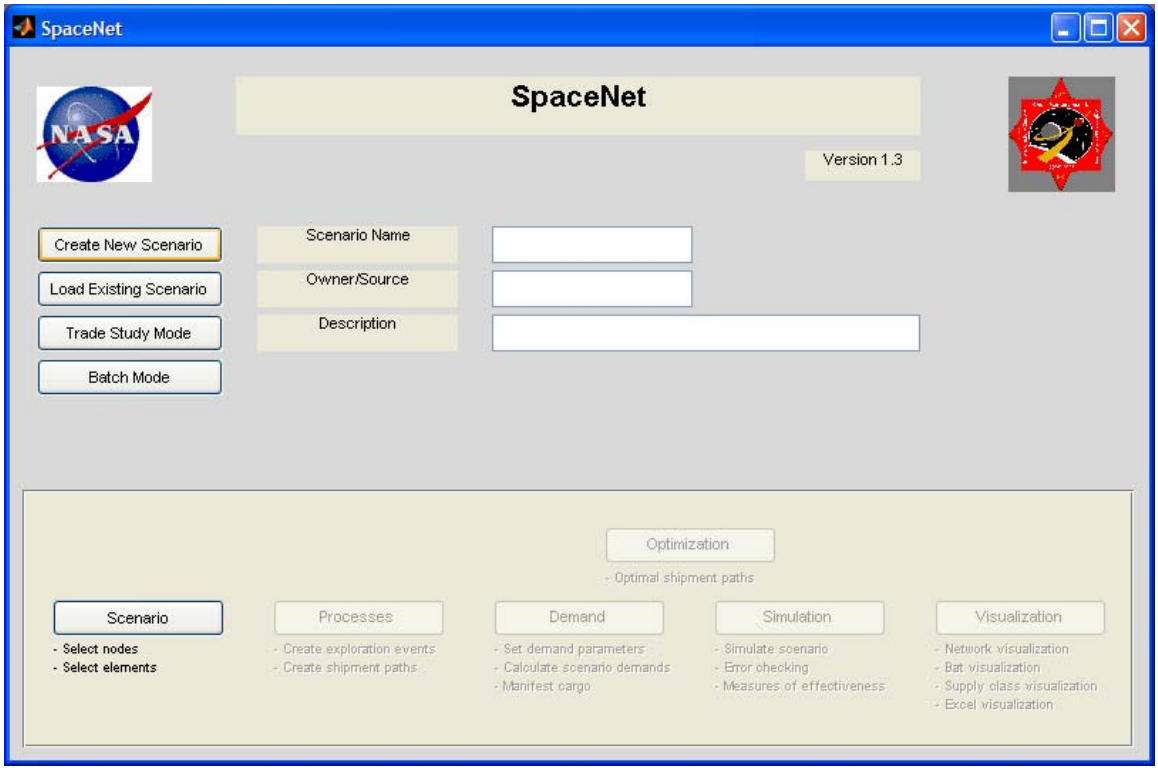

Figure 16 : SpaceNet Title GUI

From the title GUI (Figure 16) the user can choose to create a new scenario or load an existing scenario. The user can also perform analyses using trade study mode or batch mode for previously created scenarios. If the user chooses to create a new scenario, the folling six groupings describe the sequential steps required to create a scenario: Describe Scenario, Specify Processes, Calculate Demand, Simulate, Evaluate and Visualize. Each of these tasks will be described in detail in the following sections.

2.4.1 Describe Scenario

The task of describing the scenario to be modeled in SpaceNet is very straightforward and involves only the following three tasks:

- *Specify Global Parameters :* Specify the start date, end date and time discretization for the scenario.
- *Select Nodes*: Select nodes from the integrated database and create the static network
- *Select Elements*: Select elements (e.g. CEV) from the integrated database and instantiate them

2.4.2 Specify Processes

The user must then specify the process involved in the scenario. These processes will define how elements and supplies move in the network as well as when and where the exploration will take place. As was stated earlier in the chapter, there are five process types from which the user can choose: Wait, Transport, Transfer, Exploration and Proximity Operations. Each process has several parameters that must be defined by the user (see [42] for more details).

The **Wait** process is the act of remaining at the same node for a specified amount of time. The **Transport** process moves one or more elements to a new node along an allowable arc. The **Transfer** process specifies a transfer of crew and/or supplies between two different elements, from a node to an element, or from an element to a node. The **Exploration** process is the process that defines the main exploration and science activity of the scenario at a specified node (typically a surface node, but not always as exploration can take place at multiple nodes). The **Proximity Ops** process is used to describe rendezvous/docking, undocking/ separation, and transposition events.

2.4.3 Calculate Demand

Once the processes have been specified, the scenario demand can be calculated as followed :

- *Set Demand Parameters*: Specify demand parameters for each class of supply to be used in the demand models or choose to use the default parameters
- *Calculate Scenario Demands*: Calculate the demand for the scenario by class of supply
- *Manifest Cargo*: Set the initial conditions at launch for each element by class of supply

If the user chooses to use the default demand parameters in SpaceNet, the following built-in demand models are used to calculate the demand for the scenario specified by the user. The supply classes for which demand models have been defined to date are:

- *Crew Provisions (COS 2)* → *water, gases, food, clothing, …*
- *Crew Operations (COS 3)* → *EVA equipment, computers, …*
- *Maintenance/Upkeep (COS 4)* → *tools, spares*
- *Exploration/Research (COS 6)* → *science tools, surface exploration items*
- *Waste/Disposal (COS 7)* → *trash bags, waste containment system*
- *Stowage/Restraint (COS 5)* → *containers, bags,…*

Each demand model above takes as input the process parameters specified by the user (crew size, durations, number of EVAs, etc.) and the input parameters and calculates a mass and volume needed for the entire scenario. (The input parameters for COS 2, 3, 5, 6 and 7 can be found in Appendix C.) Each demand model will calculate and sum the process demands to yield a total scenario demand. Stowage (COS 5) is calculated last because it depends on results from the other classes of supply. The following is an overview of how each demand parameter is calculated. Additional details as well as the mathematical equations that are used to generate the demand for the various classes of supply can be found in Appendix C of [42].

The **Crew Provisions** model is split up into a "consumed" and "demand" model. The "demand" model computes a mass and volume of demand for every subclass of crew provision: water, food and support equipment, gasses, hygiene items, clothing, and personal items based on the parameters in the Crew Provisions table along with crew

size, arc duration, contingency duration, and number of EVAs. The “demands” are computed before the simulation is run. The “consumed” crew provisions are computed only during the simulation, such as the mass and volume of water consumed on an arc. The mass and volume data come from the Model for Estimation of Space Station Operations Cost (MESSOC), developed by personnel at the Jet Propulsion Laboratory [43].

The **Crew Operations** model computes a mass and volume of demand for every subclass of crew operations: Office equipment, EVA equipment, CHeCS equipment, Safety equipment and communications equipment based on input parameters and user specified parameters such as the crew size, mission duration and number of EVAs. The mass data for the Crew Operations demand model comes from Human Spaceflight Mission Analysis and Design (HSMAD) [28], the ESAS final report [1], and engineering judgment. Using a sub-set of Space Station data, average densities were calculated for each of the Crew Operations sub-classes. The volume data was then calculated by dividing the mass data by these densities.

The **Maintenance and Upkeep** model calculates a "buylist” of spares needed to meet a desired system availability specified by the user. The total mass and volume of spares required is then obtained by multiplying the quantity of each ORU in the buylist by its mass or volume respectively. The user also has the option to specify a mass or volume constraint (e.g. 1000 kg or 5 m^3) and a target availability (e.g., 95%). In this case the algorithm returns an optimal set of spares, the buylist, that meets the target availability and that does not violate the resource constraint. If the target availability is set too high, then the SpaceNet algorithm returns a buylist that meets the resource constraint, and it reports the achieved availability. The user can also select a threshold (minimum desired) availability, e.g., 65%. The SpaceNet algorithm always returns a buylist that meets the threshold availability, even if it means violating the resource constraint.

The **Exploration and Research** model allows the user the option of choosing exploration items from a library of supplies or calculating a mass and volume of exploration items by

entering a weighting factor for the following four baseline planetary science programs:

- Life (look for biological agents, fossils, carbon-based molecules…)
- Climate (analyze atmospheric properties, weather phenomena…)
- Geology (obtain rock and soil samples, take images, analyze strata…)
- Resources (look for useful minerals, ISRU feed stock, water/ice…)

The weights of each of the four objectives above should sum to 1.0 as they reflect the relative mix of science objectives that are to be achieved during an exploration process. The model determines the quantity of exploration items from a baseline Moon/Mars exploration mission with a defined set of equipment required to satisfy some defined science exploration objectives. Based on the baseline case, and using the given weights for the four exploration types (Life, Climate, Geology and Resouces), the normalized weights for each item are calculated then used for determining the quantity for each item to be used in the mission defined by the user. Depending on the sub-class of supply the weight may also be scaled with the number of teams (for concurrent EVAs) and the mission duration.

The final demand model, the **Stowage and Restraint** model, packs the mass and volume demands from the other demand models into either half Cargo Transfer Bags (CTBs), single CTBs, Crew Water Containers (CWCs), or oversized items. Bags are functionally divided by supply class and sub-supply class. In the cases of crew provisions and crew operations where lump masses and volumes are calculated, the stowage model uses the limiting constraint (usually volume) to calculate the number of bags. In the cases of maintenance and upkeep and exploration and research where the individual supply item types are calculated, the stowage model uses a packing efficiency parameter to specify when to start a new bag. Items that exceed single CTB mass and volume constraints are manifested individually as oversized items. A summary of the packing results is then presented to the user (Figure 17).

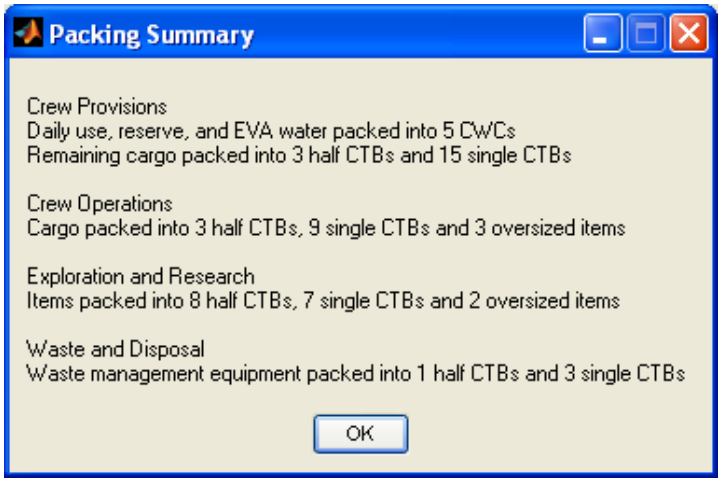

Figure 17 : SpaceNet Packing Summary

The last step in the demand calculations is to assign the individuals bags and containers of supply items to elements with non-zero cargo capacity at the time of their first launch. This process is commonly referred to as manifesting. **Cargo manifesting** in SpaceNet can be done either manually by the user or automatically by an algorithm. If the user elects to manifest cargo manually, he/she will need to select each element and assign cargo to it for launch by class of supply until the total scenario demands have been satisfied.

If the user elects to use auto manifesting, SpaceNet will run an algorithm that seeks to generating a feasible cargo manifest that will satisfy all element capacity limitations. This algorithm automatically assigns bags/containers containing supply items to instantiated elements before launch. The objective function is to maximize the "reward" of the scenario manifest. The reward matrix allows the user to prioritize some supply classes over others in particular elements. For example, it is critical that any elements carrying crew always have sufficient crew provisions.

2.5 Simulation

A logistics architecture can be described using the modeling elements discussed above, however, in order to determine the effectiveness of the architecture, it must be simulated so that it can be evaluated in relation to others. The simulation ties together all other

components of the modeling framework, taking the mission scenario as an input and producing the output information to fully describe and evaluate the mission scenario. The major steps of simulation in SpaceNet are:

- *Simulate Scenario*: Create time histories for each element in the scenario
- *Error Checking*: Errors are reported and logged in a text file. This step checks for feasibility violations of a scenario

Once the user has specified several preferences, such as whether to terminate the simulation if an error is received, the simulation carries out the defined processes for the scenario in order. Rather than specifying the times that each element performs actions, each element has a list of actions that are carried out sequentially. This means that the simulation is event-driven rather than time-driven. The models will calculate the consumption for their respective classes of supply and update the element histories accordingly.

If an **error** is discovered with a process, the user will be visually notified and the error will be logged in the scenario log file. These errors can include user logic errors in creating processes, such as a transfer process between two elements when they are not at the same node. The errors also include calculated infeasibilities, such as elements that do not have enough propellant to perform specified burns during a transport process. Typical errors include:

- Insufficient propellant to execute a burn
- Running out of crew provisions or crew operations in a crewed element
- Attempting to transfer supply items into an element that has insufficient capacity to accept the incoming item(s).

Generally it is up to the user to resolve errors in an iterative fashion by going through a number of simulate-edit-simulate-edit cycles in a particular scenario. SpaceNet v1.3 does not contain a detailed “wizard” that would automatically resolve errors (since there might be multiple non-unique ways in which an error can be resolved), but instead relies on the user’s experience and domain knowledge to repair infeasible scenarios.

2.6 Evaluation: Measures of Effectiveness

As was described by Beamon [4] for the terrestrial case, an important final step in supply chain design and analysis is the ability to process the simulation output in such a way that architectures can be evaluated and compared. Here, we discuss the metrics (termed measures of effectiveness or MOEs) developed hand-in-hand with our modeling framework to enable the comparative evaluation of logistics architectures [54]. These MOEs provide a quantitative way to evaluate specific space exploration scenarios and interplanetary supply chains in general. While we believe that these MOEs are important and relevant for space exploration logistics, they are only proxy metrics for comparative purposes, not for absolute forecasting. For example, the current benefit metrics do not take into account benefits derived from the presence of robots on planetary surfaces or from orbiting spacecraft.

2.6.1 Basic Logistics Performance MOEs

The value of planetary space exploration research comes primarily from healthy, motivated, and qualified explorers and scientists being able to spend a certain amount of time at one or more planetary surface locations (nodes). To first order, the exploration benefit should scale linearly with both the number of people (crew size) as well as the duration of their stay. In order to do productive research, the crew needs to have with them specific exploration equipment and scientific instruments, such as cameras, rock hammers and so forth. Also, surface infrastructure items (habitation facilities, surface mobility systems, etc.) act as enablers and multipliers for exploration productivity. Thus we define the concept of "exploration mass," which includes both science equipment and infrastructure mass. Based on these ideas, we propose five *basic logistics performance* measures of effectiveness:

Crew Surface Days (CSD) [crew-days]: The total number of crew-days over all surface nodes for the entire scenario.

$$CSD_{tot} = \Delta T \sum_{i=1}^{T} \sum_{j=1}^{S} N_{crew,i,j} \qquad (1)$$

ΔT = Earth days per *SpaceNet* time period

T = total number of *SpaceNet* time periods in a scenario[1]

S = number of planetary exploration nodes visited in a scenario

$N_{crew,i,j}$ = number of crew present at exploration node j during time period i

CSD_{tot} is the total cumulative number of crew surface days spent over an entire scenario over all S nodes explored. We can also compute the total number of crew surface days accumulated up to a certain time in a campaign as:

$$CSD(k) = \Delta T \sum_{i=1}^{k} \sum_{j=1}^{S} N_{crew,i,j} \quad \text{whereby } k < T \tag{2}$$

Similarly, *SpaceNet* defines the cumulative number of crew surface days spent over the entire scenario at a particular surface node as:

$$CSD_{tot}(j) = \Delta T \sum_{i=1}^{T} N_{crew,i,j} \tag{3}$$

The units of these metrics are [crew-days].

Exploration Mass Delivered (EMD) [kg]**:** The total mass of exploration items and surface infrastructure delivered over all surface nodes for the entire scenario. *SpaceNet* computes the total amount of exploration mass delivered to all surface nodes over the course of a campaign (scenario). Exploration mass contains all items that are characterized as COS 6 and COS 8. *SpaceNet* counts COS 6 and 8 as exploration mass because these *directly* (explicitly) contribute to exploration capability and can therefore be counted as a benefit. The other COSs are all *indirect* enablers (e.g., propellants, crew consumables, spares, etc.).

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[1] A scenario can include a single "sortie" style mission or an entire campaign, containing multiple missions.

$$EMD_{tot} = \sum_{i=1}^{T} \sum_{j=1}^{S} [\Delta m_{COS6,i,j} + \Delta m_{COS8,i,j}] \tag{4}$$

T = total number of time periods in a scenario

S = number of planetary surface nodes visited in a scenario[2]

$\Delta m_{COS6,i,j}$ = additional (new) exploration items mass delivered at time period i to node j

$\Delta m_{COS8,i,j}$ = additional (new) infrastructure mass delivered at time period i to node j

In Eq. (4), only mass additions are counted, i.e., removal of exploration mass from a surface node is ignored even though such an action causes a Δm_{COS} from one period to another. As with crew surface days, the cumulative *EMD* up to a certain time in the campaign can be defined as:

$$EMD(k) = \sum_{i=1}^{k} \sum_{j=1}^{S} [\Delta m_{COS6,i,j} + \Delta m_{COS8,i,j}] \qquad \text{where } k < T \tag{5}$$

Similarly, *SpaceNet* defines the cumulative EMD over the entire scenario at a particular surface node as:

$$EMD_{tot}(j) = \sum_{i=1}^{T} [\Delta m_{COS6,i,j} + \Delta m_{COS8,i,j}] \tag{6}$$

The units of these metrics are [kg].

Total Launch Mass (TLM) [kg]: The total launch mass (including crew, elements, and all other COS) lifted off from the surface of the Earth to accomplish a particular exploration scenario. *SpaceNet* calculates this metric as:

---

[2] For programming purposes, planetary surface nodes can be identified based on the node number in *SpaceNet*. Lunar surface nodes are all nodes from 2001 to 2500.

$$TLM = \sum_{v=1}^{N_f}\sum_{e=1}^{E} m_{empty,e} N_{e,v} + \sum_{k\neq 0,8,9} m_{COSk} + \sum_{v=1}^{N_f}\sum_{e=1}^{E} m_{crew} N_{crew,e} N_{e,v} \quad (7)$$

where

N_f = total number of launches in a scenario

E = number of element types in a scenario[3]

$m_{empty,e}$ = empty mass (= dry (tare) mass + accommodation mass) of element type e

$N_{e,v}$ = number of type e elements on launch v

$m_{COS,k}$ = total mass launched for class of supply k (includes k= COS 1 (propellant) and excludes COS 0, 8, and 9)

$N_{crew,e}$ = number of crew present on type e elements

m_{crew} = nominal mass of a crew member (usually taken to be ~220 lbs = 100 kg)

This calculation is important because each component is needed to develop the mass fractions used in Eq. (13). The first term in Eq. (7) divided by *TLM* contains the mass fractions for COS 8 and COS 9, the individual masses in the second term divided by *TLM* are the mass fractions for COS 1 through 7 and 10, and the last term divided by *TLM* is the mass fraction for the crew (COS 0).

The units of this metric are [kg]. The total launch mass for Apollo 17 was approximately 2,930 metric tons, about 3 million kilograms.

Upmass Capacity Utilization (UCU) [0, 1]: The fraction of the upmass capacity (from Earth) used by all COS (excluding crew, propellants, and elements) for the entire scenario. Ideally, this should always equal 1.

A key metric to understand exploration logistics efficiency is that of cargo *capacity utilization*. Each propulsive and non-propulsive element (COS 9) has a cargo capacity (in terms of mass and volume) associated with it. In some cases for propulsive elements such

[3] Note that this is not the same as the number of instantiated elements in the scenario. Elements in COS 9 include both propulsive and non-propulsive (carrier) elements.

as the Earth Departure Stage[4] (EDS), this capacity is zero, but for non-propulsive elements, the cargo capacity is usually non-zero.[5]

SpaceNet quantifies the fraction of available up-mass (launched from Earth) cargo capacity that is actually used for all classes-of-supply other than infrastructure (COS 8), transportation and carriers (COS 9), propellant (COS 1), and crew (COS 0). An efficient transportation system has a capacity utilization of *unity*. For a variety of reasons, this number is commonly lower in actuality. One such reason is that a volume constraint may come into play before the cargo mass capacity is reached.

$$UCU = \frac{\sum_{e=1}^{EI} \sum_{k=2,3,4,5,6,7,10} m_{COSk,e}}{\sum_{e=1}^{EI} (m_{cap,e} - m_{accom,e})} \tag{8}$$

$m_{COS,k,e}$ = total mass of class of supply k carried in instantiated element e at Earth launch
EI = number of instantiated elements in a scenario
$m_{cap,e}$ = up-mass cargo capacity of instantiated element e (from element type)
$m_{accom,e}$ = accommodation mass of instantiated element e (from element type)

Eq. (8) states that the upmass capacity utilization in a scenario is the ratio of the mass of tracked supply classes launched over all elements, divided by the total usable cargo mass capacity (= maximum cargo up-mass capacity less accommodation mass). *SpaceNet* performs a check to ensure that only elements, e, that are launched from Earth are counted in the summation. *UCU* will always be a number between zero and one.[6] A *UCU* of zero means that all elements are being launched empty, while a *UCU* of 1.0 indicates that the cargo up-mass capacity of the system is being fully utilized.

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[4] The EDS, as presented in NASA's ESAS architecture, fulfills a role similar to the S-IVB in Apollo.

[5] Fuel capacity (COS 1) is treated separately in *SpaceNet*.

[6] The reason that UCU cannot exceed 1 is that if the analyst tries to allocate more than an element can hold, an error message is issued in *SpaceNet*.

Computing the *UCU* for a scenario as a whole is useful, especially during iterative scenario definition. If *UCU* is less than 1.0, additional supply items such as spares, consumables or exploration items can be loaded (if volume constraints are not exceeded) with only a small impact on *TLM*. These additional items will eitherimprove *EC,* improve *system availability* or decrease the probability of under-supply situations due to a lack of consumables or spares. Another potential source of up-mass capacity utilization loss occurs when the launch vehicle capability is the binding constraint, not the carrier's cargo capacity. This is handled in *SpaceNet* as follows: if the analyst has manifested cargo up to the carrier's cargo capacity, but the stack is too massive to launch, an error message is issued. The analyst may try to overcome this by offloading some cargo until a feasible launch mass is achieved. An alternative would be to create another launch to carry the excess cargo.

Return-Mass Capacity Utilization (RCU) [0, 1]: Another important metric to quantify is the fraction of available non-destructive return-mass (returned to Earth) cargo capacity that is actually used for all classes of supply other than infrastructure (COS 8), transportation and carriers (COS 9), propellant (COS 1), and crew (COS 0). *SpaceNet* calculates this fraction using Eq. (9).

$$RCU = \frac{\sum_{e=1}^{EI} \sum_{k=2,3,4,5,6,7,10} m^{r}_{COSk,e}}{\sum_{e=1}^{EI} (m_{returncap,e} - m_{accom,e})} \tag{9}$$

$m^{r}_{COS,k,e}$ = total mass of class of supply k carried in instantiated element e at Earth return

EI = number of instantiated elements in a scenario

$m_{returncap,e}$ = non-destructive return-mass cargo capacity of instantiated element e (from element type)

$m_{accom,e}$ = accommodation mass of instantiated element e (from element type)

Eq. (9) states that the non-destructive return-mass capacity utilization in a scenario is the ratio of the mass of tracked supply classes returned to Earth over all elements, divided by

the total usable cargo return-mass capacity (= maximum cargo return-mass capacity less accommodation mass). *SpaceNet* performs a check to ensure that only elements, *e*, that are launched from Earth and then return to Earth are counted in the summation. *RCU* will always be a number between zero and one.[7] An *RCU* of zero means that all elements launch from and returning to the Earth are empty upon return, while a *RCU* of 1.0 indicates that the non-destructive return-mass cargo capacity of the system is being fully utilized.

Computing *RCU* for a scenario as a whole is important, since it reflects that benefits obtained by being able to return samples (COS 603) or failed equipment back (COS 703) for inspection on Earth.

2.6.2 Exploration Capability MOEs

The next set of MOEs attempts to capture the exploration capability of a given logistics architecture. To first order, the exploration capability is the amount of time the crew gets to spend doing exploration and research at a surface node, multiplied by the amount of total exploration mass they have to do the job at each node visited during the scenario. The amount of time the crew can spend doing exploration and research is limited by a number of factors. These sources of crew non-availability include: housekeeping activities, maintenance and repair, in-situ crew activity planning/scheduling, medical, EVA preparation, and physiological (exercise, sleep, eating, etc.). In general, the fraction of non-available crew-hours may vary with the size of the crew at the surface node and the length of the surface stay. The following set of *exploration capability* MOEs captures these ideas:

Exploration Capability (EC) [kg*crew-days]: The dot product of crew surface days and exploration mass (exploration items plus surface infrastructure) over all surface nodes for the entire scenario. Therefore, exploration capability is only accrued when crew and exploration mass are present at a surface node together (co-located).

---

[7] The reason that RCU cannot exceed 1 is that if the analyst tries to allocate more than an element can hold, an error message is issued in *SpaceNet*.

To first order, the exploration capability is the amount of time the crew gets to spend doing exploration and research at a surface node, multiplied by the amount of total exploration mass they have to do the job at each node visited during the scenario. The amount of time the crew can spend doing exploration and research while at a surface node is limited by a number of factors. These sources of crew non-availability include: housekeeping activities, maintenance and repair, in-situ crew activity planning/scheduling, medical, EVA preparation, and physiological (exercise, sleep/rest, eating). In general, the fraction of non-available crew-hours may vary with the size of the crew at the surface node and the length of the surface stay. *SpaceNet* defines exploration capability as:

$$EC_{tot} = \Delta T \sum_{i=1}^{T} \sum_{j=1}^{S} f_{i,j}(N_{crew,i,j})[m_{COS6,i,j} + m_{COS8,i,j}] \qquad (10)$$

ΔT = Earth days per *SpaceNet* time period

T = total number of time periods in a scenario

S = number of exploration nodes visited in a scenario

$N_{crew,i,j}$ = number of crew present at node j during time period i

$m_{COS6,i,j}$ = total exploration items mass present during time period i at node j

$m_{COS8,i,j}$ = total infrastructure mass present during time period i at node j

To account for crew non-available time in the simplest way, rewrite Eq. (10) as:

$$EC_{tot} = \Delta T \sum_{i=1}^{T} \sum_{j=1}^{S} (1-\alpha_{ij}) N_{crew,i,j}[m_{COS6,i,j} + m_{COS8,i,j}] \qquad (10')$$

where α_{ij} = fraction of non-available crew time at node j during period i. The units of this metric are [kg • crew-days].

Note that, even when α_{ij} = 0, the exploration capability is generally *not* the same as

simply the product of total exploration mass delivered and total crew surface days in the entire scenario.

$$EC_{tot} \neq EMD_{tot} \times CSD_{tot} \tag{11}$$

In order to provide exploration capability, crew and exploration equipment have to be *co-located* at the same node concurrently. Crew at a surface node without exploration equipment does not produce benefit (*SpaceNet* does not account for the productivity of robotic agents), and conversely exploration equipment at a node without crew to operate that equipment does not provide any benefit either. However, when both crew and exploration mass always travel together, as during the Apollo missions, then Eq. (11) holds with equality.

Relative Exploration Capability (REC) [0, inf): The relative exploration capability is a normalized measure of *exploration logistics efficiency*. It measures the amount of productive exploration that can be done for each kilogram of mass launched from the Earth's surface, relative to Apollo 17. Apollo 17 is used as the reference case because it can be argued that of all the Apollo lunar surface missions, Apollo 17 was the most productive in terms of exploration and science and also the one that came closest to approaching the constraints imposed by flight hardware elements and operational capabilities at that time.

The relative exploration capability metric is based on well-established theory of "linked" index numbers, used to measure changes in economic productivity due to technology improvements.[8] The exploration capability metric, Eq. (10'), is *explicitly* a function of the number of crew and the exploration mass present at each node. It is also implicitly a function of all classes of supply since crew provisions, crew operations equipment, propellants, carriers, spares etc. are needed to "produce" crew at the surface node. A relative exploration capability metric needs to account for the necessary use and

[8] Also called Divisia index numbers. See [53] for more information.

consumption of these resources as well in establishing overall logistics efficiency. *SpaceNet* uses Eq. (12), a commonly computed linked index number, as the relative exploration capability metric using Apollo 17 as the basis for normalization (i.e., *REC* =1 for Apollo 17).

$$REC_b = \frac{EC_{tot}^{b} / EC_{tot}^{a17}}{\prod_k \left(\frac{m_{COSk}^{b}}{m_{COSk}^{a17}} \right)^{\beta_k}} \tag{12}$$

where

$$\beta_k = \frac{1}{2}\left(\omega_k^{a17} + \omega_k^{b}\right) \tag{13}$$

EC^{b}_{tot} = exploration capability metric for scenario (campaign) *b* according to Eq. (10').
m^{b}_{COSk} = total class of supply *k* mass delivered in scenario (campaign) *b*.[9]
ω^{b}_{k} = mass fraction for class of supply *k* in scenario (campaign) *b*.

The *REC* metric is dimensionless. Specific numbers for Apollo 17 were derived from data at [44].

The relative exploration capability (REC) is a powerful metric for supply chain comparison. An interplanetary supply chain with a *REC* >1 would indicate a more efficient supply chain technology than Apollo 17 because more exploration capability is being provided for each unit of mass launched from Earth. Conversely a *REC* < 1 would indicate a less efficient supply chain technology than Apollo 17. Clearly, the value of the *REC* metric will be influenced by a number of factors such as:

- the chosen mission/transportation architecture
- the use of various propulsion (and other) technologies

[9] Class of Supply 0 (the crew itself) must be included in Eq. (11). The nominal mass of a crew member is usually taken to be ~220 lbs = 100 kg without a space suit, but with indoor clothing.

- various supply chain strategies implemented (e.g., on orbit depots)
- the application of various ISRU technologies.

For example, *REC* would be able to capture the effect of using in-situ resources (ISRU) as a supply chain strategy. If no ISRU is applied, a certain amount of consumables must be carried along to supply the missions in a particular scenario. These consumables directly contribute to the denominator of Eq. (12), making the value of *REC* less. If ISRU is used, the consumables mass over an entire scenario might be reduced, but the upfront mass penalty for transporting the ISRU (and related power) equipment to a node in the first place would be automatically captured as well. Whether or not an investment in ISRU would be worthwhile for a particular scenario, could then be assessed by comparing the *REC* of both alternatives.

2.6.3 Relative Cost and Risk MOEs

We attempt to capture the *relative cost and risk* of various logistics scenarios through two relatively simple measures of effectiveness (below). Note that these are by no means absolute measures of the cost or risk of any given scenario, but should serve to show which scenarios are more or less costly/risky than others.

Relative Scenario Cost (RSC) [0, inf): The weighted sum of the total launch mass and the number of element active days for the entire scenario, using weights such that relative scenario cost for Apollo 17 is unity.

The cost of a space mission or scenario typically involves three main components: DDT&E (Design, Development, Test, and Evaluation), launch cost (production and pre-launch processing), and mission operations costs (planning, training, and flight control). *SpaceNet* assumes that all instantiated elements are available for use and therefore ignores DDT&E. *SpaceNet* is not a spacecraft/vehicle design tool, but analyzes the implications of using vehicles (elements) with certain specified capabilities. In other words, estimating DDT&E costs of flight hardware elements is outside the scope of *SpaceNet.*

Launch costs, however, are included and are assumed to be a direct function of *TLM*. The main driver of mission operations costs are labor-hours spent on mission planning and during a mission supervising or actively operating the instantiated elements, which reflects both the total mission time and the mission complexity. For each vehicle (= element) *SpaceNet* assumes an operating profile, whereby $\Gamma_{e,i}$ =1 if instantiated element *e* is operating during time period *i* and $\Gamma_{e,i}$ =0 otherwise. An element is non-active if it is *not* associated with at least one of the five *SpaceNet* processes (waiting, transporting, proximity operations, transferring crew/cargo, exploring) during a time period. An instantiated element can be active, i.e., $\Gamma_{e,i}$ =1, even when no crew is in that element or when crew is co-located in another element at the same node. The assumption for *RSC* is that an element will still have to be monitored and will therefore cause operations costs, even when it is waiting or pre-positioned. Lacking element specifications or another adequate measure of complexity, *SpaceNet* normalizes these two major cost components using weighting "prices" γ and δ. The relative scenario cost (*RSC*) equation is then a linear function of *TLM* and the temporal element operating profiles, Γ, as follows:

$$RSC = \gamma TLM + \delta \Delta T \sum_{e=1}^{EI} \sum_{i=1}^{T} \Gamma_{e,i} \qquad (13)$$

TLM = total launch mass [kg] for the entire scenario from Eq. (11)

ΔT = Earth days per *SpaceNet* time period

EI = number of instantiated elements in a scenario

T = total number of time periods in the scenario

$\Gamma_{e,i}$ = 1 if the instantiated element *e* is "active" during time period *i*

γ = normalizing multiplier for *TLM*

δ = normalizing multiplier for operations complexity and time

The estimation of total scenario costs in terms of current monetary units ($) is outside the scope of *SpaceNet*. *RSC* can be used for a relative comparison of supply chain costs between exploration scenarios, but it is not suitable for budgetary planning purposes.

When used in this manner, *RSC* is actually a *Laspeyres* quantity index with γ and δ serving as base period "prices." We again chose to normalize to Apollo 17—that is, specific values for γ and δ were established such that the *RSC* for Apollo 17 equals 1. These multiplier values are calculated assuming that launch costs and operations cost each contribute about half of the scenario costs. The resulting values are:

$$\gamma = 1.706 \cdot 10^{-7}$$
$$\delta = 0.0077$$

Total Scenario Risk (TSR) [0, 1]: TSR is defined as 1 minus the probability that there are no failures in all launches, rendezvous-and-dockings, and landing for the entire scenario.

Risk is a critical, if difficult to quantify, metric for evaluation of exploration scenarios. Detailed risk calculations should include probabilities of failure for different mission operations processes and elements, resulting in a mission risk cumulative distribution function (cdf), expected mission risk, and a time-phased risk profile. As a first iteration, however, *SpaceNet* uses known quantities readily computable using *SpaceNet* outputs to get a first-order measure of total scenario risk (*TSR*). This metric uses the probabilities of failure associated with each *SpaceNet* process.

SpaceNet produces a rough measure of risk for scenario *S* using Eq. (14).

$$TSR = 1 - \prod_{i \in S} (1 - P_i) \qquad (14)$$

P_i = Probability of failure during *SpaceNet* process *i*

The probabilities of failure of each mission event will depend in part on the particular elements used in the scenario. Transport processes (e.g., launch, and descent and landing) and proximity operations processes (e.g., rendezvous and docking, undocking and separation, and transposition) contribute significantly to overall campaign (scenario) risk.

It is intended that these probabilities eventually come from formal PRAs (Probabilistic Risk Assessments) such as those performed for Shuttle and ISS [45], but initially the *SpaceNet* user must provide such values for each instantiated process through the user interface. Refinements of *TSR* can be made by distinguishing among the probabilities of failure involving the loss of mission (LOM) and/or loss of crew (LOC).

2.7 Visualization

An important part of any supply chain management and logistics planning and simulation tool is the ability to visualize both overview and detailed information about the supply chain. In commercial terrestrial supply chain software this typically involves a network view of the system, showing the locations of manufacturing plants, warehouses, distributors and retail stores along with the active transportation routes connecting them (recall Figure 1-2). For individual nodes in the network inventory levels are often also shown using a variety of symbols. In an analogous fashion SpaceNet provides a number of visualizations to help users better understand the scenarios which they are creating or analyzing.

The user can visualize the scenario simulation results in four different ways:

- *Network Visualization*: Animate elements from a network perspective
- *Bat Visualization*: Animate elements over time in a "bat" diagram
- *COS Visualization*: Create plots of time history of any class of supply in any element
- *Excel Visualization*: Create plots of the element, node and supply class time histories in Excel using Visual Basic.

The **Network Visualization** allows the user to visualize the scenario they just created by animating the scenario over a view of the Earth-Moon network. The (physical) nodes and arcs in the scenario are displayed in the network visualization. The positions of surface nodes in the figure are determined by their respective latitude/longitude information. The positions of orbit nodes are determined by their inclination/altitude

information. The 4-digit number beneath the circle representing the node is the unique node ID, corresponding to that node in the integrated database.

The instantiated elements in the scenario are also displayed in the network visualization. There are two colors/shapes that represent the element type. Red squares generally depict propulsive elements that cannot carry crew and blue diamonds depict elements that can carry crew. The name and current status for each element in the scenario is also displayed. TRA is the abbreviation for "transporting." So for each element in transit, "X" is marked in the TRA column. The ACT ("active element") column shows if an element is executing a burn in the current process. The DIS ("disposed") column shows if an element is disposed after/before the current process. The CRW ("crew") column shows the number of crew inside the element. The scenario MOEs are displayed both after the simulation and continuously updated during the visualization.

A traditional way in which mission architects at NASA (an in other organizations) depict transportation architectures is using so called **bat diagrams**. A bat diagram shows time on the x-axis and different nodes are represented as horizontal lines intersecting the y-axis. Earth is typically shown at the bottom, while the node(s) to be visited (ISS, Moon, Mars) is shown on top. When elements (vehicles) arrive at their destination on top they are often shown "hanging upside down" like bats at rest, thus the name of this representation.

The **COS Visualization** displays the nodal time history of a single element at a time as selected by the user. It can also display plots of the time history of each class of supply for the element selected. This form of visualization is very useful when troubleshooting errors that involve the over consumption of a certain class of supply or an infeasible transfer. An example of the type of plot generated by the COS visualization is shown in Figure 18.

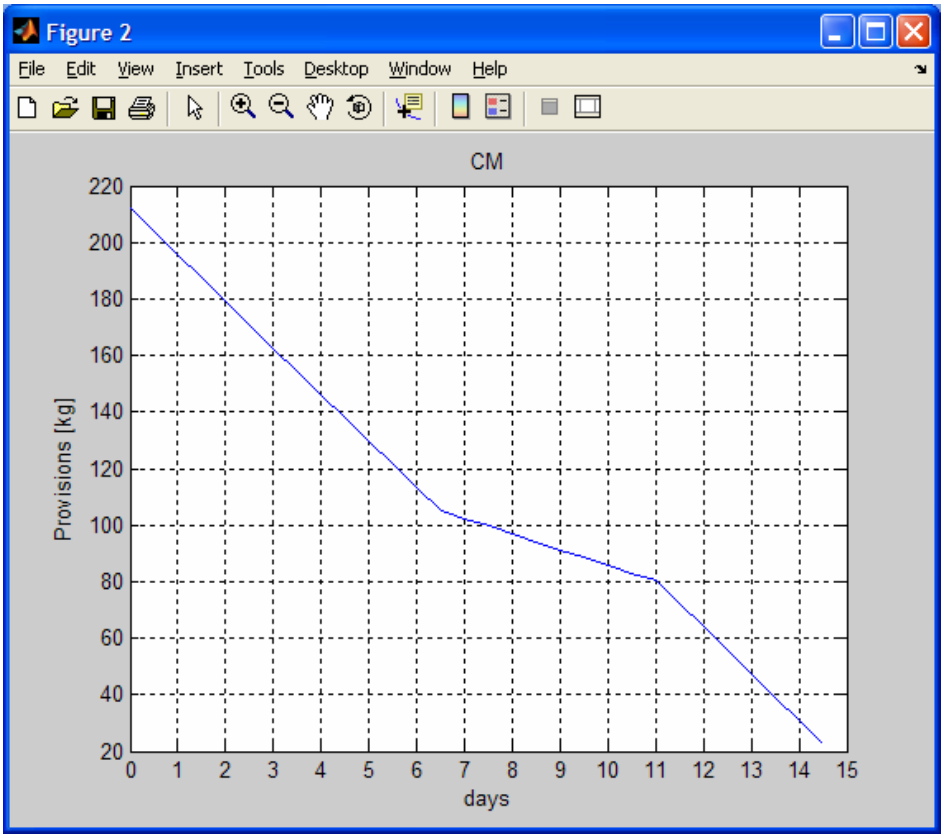

Figure 18 : COS Visualization – Crew Provisions in the Comand Module (CM)

The **Excel History File** saves the scenario element history data from the simulation for easy data interpretation, post-processing and visualization. The element history data is rearranged into six different types of history tables with the data organized by element, node, or class of supply (COS). The Excel History File has a built-in history plotter (programmed in Visual Basic) that can read the data from the history tables and generate mass tracking diagrams (Figure 19). This visualization capability is very powerful and can help view the interplanetary supply chain from a nodal, element or supply class perspective over time.

The figure below illustrates the use of the History Plotter. The default axes for a mass tracking plot are: time on the x-axis, nodes on the y-axis, elements on the color-axis, and classes of supply on the plot-axis. In this box plot, each box represents the total mass of fuel at a given node at a given time. The colors show how that fuel is distributed among

the elements at that node at that time. The size of each square shows the relative amounts. Any combination of history variable axes assignments and observed history variables can be plotted with the History Plotter.

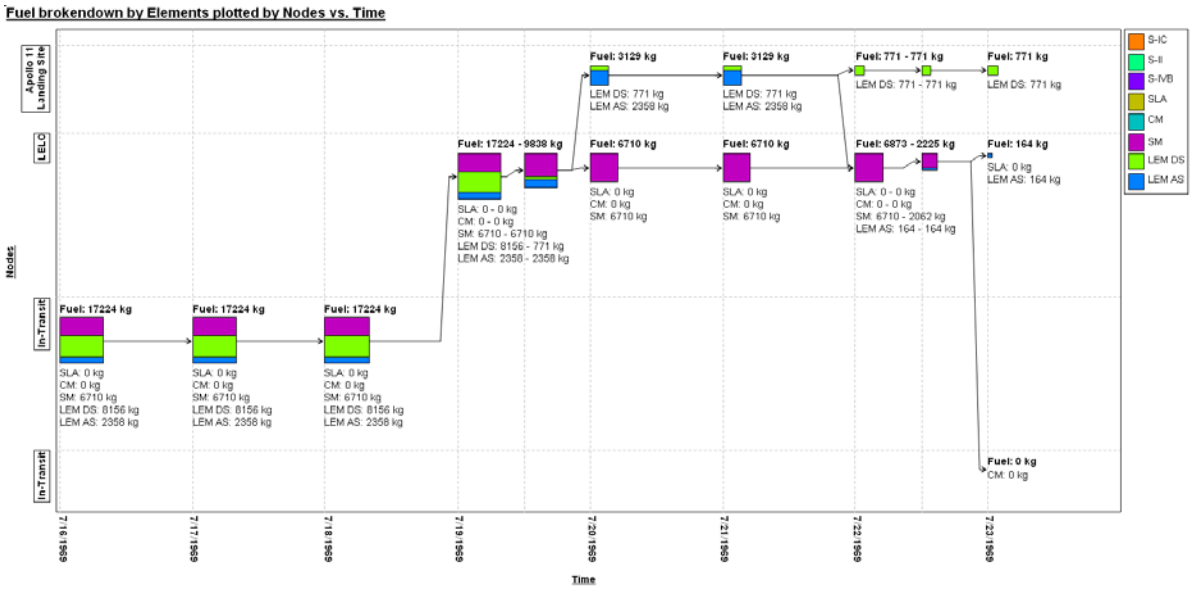

Figure 19 : History Plotter

This section has provided an overview of the framework and features of SpaceNet. The following section will discuss potential users and use cases for SpaceNet.

2.8 SpaceNet Users and Use Cases

SpaceNet can model virtually any manned exploration architecture in the Earth-Moon-Mars system, and simulate the flow of cargo, vehicles, and crew. The software evaluates logistics and transportation architectures for feasibility and sustainability. As such, it supports architecture-level trade studies for space logistics, and can act as an integrated planning and simulation tool.

SpaceNet was designed to accommodate the needs of a diverse group of users including mission and system architects, mission planners and space logisticians. SpaceNet supports both short and long-term architectural and operational decisions, including answering questions about the effect of various design decisions on long-term operations

costs.

In addition, SpaceNet is a flexible computational environment that can be used in several other ways:

- SpaceNet provides the capability simulate the operations of any type crewed or uncrewed missions provided the user enters nodes, trajectories and processes
- By analyzing surface missions, SpaceNet could be used to define requirements for lunar systems (e.g. the Lunar Lander)
- SpaceNet can be utilized for virtual systems integration and testing during development and design
- SpaceNet serves as a tool for integration of operational planning and system design (concurrent engineering)

At a high level SpaceNet was designed to model two types of scenarios. The first type is essentially single missions, which can be sortie style missions or longer expedition type missions. Examples of sortie style missions include any of the Apollo mission, any Space Shuttle mission and a single International Space Station Expedition. The more interesting and unique capability of SpaceNet is the ability to model and simulate entire campaigns of missions. Examples of campaigns include a scenario that models all of the Apollo missions, an ISS Buildup scenario and a Lunar Outpost Buildup scenario. As will be come apparent in Chapters 3 and 4, most of the analysis in this thesis centers on the modeling of campaigns of missions in SpaceNet.

2.9 Summary of Chapter 2

This chapter has described an interplanetary logistics modeling and simulation tool, SpaceNet, developed by systems engineers at JPL and MIT. The goal of SpaceNet is to allow mission architects, planners, systems engineers and logisticians to focus on what will be needed to support future crewed exploration missions, primarily in the Earth-Moon-Mars system. Instead of helping to design the elements (vehicles) themselves in terms of propulsive and pressurized/un-pressurized cargo carrying capability, SpaceNet evaluates such vehicles in the context of a particular mission architecture and supply

chain strategy. The software allows the user to specify how the transportation and inventory holding capacity resulting from particular mission architectures will be used in terms of various classes of supply. The most important classes of supply in space exploration are: consumables, spares and exploration items. SpaceNet allows simulating the time-varying flow of elements (vehicles), crew and supply items through the nodes and arcs (trajectories) of a supply network in space, while taking into account feasibility (ΔVs, fuel levels) as well as consumption and supply. One of the unique features of SpaceNet is that it supports not only single sortie-style missions but also detailed analysis of multi-year campaigns, where some items may be pre-positioned or re-supplied by one set of elements or crew while being used by other elements or crew. The emphasis is on ensuring logistical feasibility of a given scenario as well as a prediction of the resulting logistics measures of effectiveness (MOEs).

The following chapters will detail analysis performed on campaigns of lunar missions using SpaceNet.

3 Baseline Campaign Trade Studies

As was described in Chapter 2, SpaceNet was designed to assist in the performance of trade studies for NASA's Constellation Program. The following chapter describes some of the lunar architecture trades studies performed using SpaceNet.

3.1 Evaluation of Several ESAS Derived Architectures

The first trade study performed was an analysis of the Exploration Systems Architecture Study (ESAS) lunar architecture described in Chapter 1. Recall that this architecture is a mixture of carry along, pre-positioning and resupply flights and involves a series of four sortie missions, four pre-deploy missions and then altering crew rotation and logistics resupply flights [1]. The details of the ESAS mission architecture can be seen in Table 4.

Table 4: Baseline ESAS Mission Profile

Mission	Launch Vehicle	Crewed (Y/N)	Surface Duration (days)	Elements Delivered	Cargo Delivered (kg)
Sortie 1	Aries V + Aries I	Y	7		2000
Sortie 2	Aries V + Aries I	Y	7		2000
Sortie 3	Aries V + Aries I	Y	7		2000
Base Pre-Deploy 1	Aries V	N	N/A	Unpressurized Rovers, ISRU Demo System	0
Base Pre-Deploy 2	Aries V	N	N/A	Habitat	0
Sortie 4	Aries V + Aries I	Y	7		2000
Base Pre-Deploy 3	Aries V	N	N/A		7000
Lander Pre-Deploy	Aries V	N	N/A	ISRU Excavation System	4500
Lunar Base Crew 1	Aries V + Aries I	Y	180		2000
Logistics/Resupply 1	Aries V	N	N/A	Pressurized Rover	5000
Lunar Base Crew 2	Aries V + Aries I	Y	180		2000
Logistics/Resupply 2	Aries V	N	N/A	Pressurized Rover	5000

As was described in Chapter 2, SpaceNet outputs Measures of Effectiveness (MOE) for

all simulated scenarios. These MOEs are a convenient way to compare scenarios in terms of their capability for the crew to do exploration and their relative cost. The MOEs for the baseline ESAS architecture are shown in Table 5. It should be noted that the first four MOEs, Crew Surface Days (CSD), Total Launch Mass (TLM), Exploration Mass Delivered (EMD) and Exploration Capability (EC), are only useful when comparing multiple scenarios. The last two, Relative Exploration Capability (REC) and Relative Scenario Cost (RSC), compare the current scenario to Apollo 17 and so can be easily interpreted on their own. From the table it can be observed that the ESAS baseline provides 2,223 times the exploration capability of the Apollo 17 mission for 111 times the cost. The large increase in exploration capability is due to many factors including advances in technology, the extended crew surface durations in the campaign and the fact that the latter missions all build upon each other.

Table 5: ESAS Baseline Measures of Effectiveness

MOE	***Value***
Crew Surface Days (man-day)	2,406
Total Launch Mass (mT)	44,722
Exploration Mass Delivered (kg)	31,622
Exploration Capability (man-day-kg)	68,010,015
Relative Exploration Capability	2,223
Relative Scenario Cost	111

3.1.1 Variations of the ESAS Baseline Scenario

An analysis of several variations of the ESAS baseline scenario was then performed. The first trade examines how the MOEs would be impacted if the sorties were removed from the campaign. The second and third trades analyze the variation in the MOEs when the number of launches is restricted to 18 and the mission type is varied between all sortie missions and all outpost missions. The choice to use 18 launches is based on the fact that there are 18 launches required to complete the ESAS baseline campaign (see Table 4).

3.1.2 Trade 1 - No Sortie Missions

In order to baseline the ESAS architecture without the sortie missions a scenario was

created in SpaceNet consisting of the following series of missions: Base Pre-Deploy 1, Base Pre-Deploy 2, Pre-Deploy 3, Lander Pre-Deploy, Lunar Base Crew 1, Logistics/ Resupply 1, Lunar Base Crew 2, and Logistics/Resupply 2. The MOEs calculated by SpaceNet for this scenario are shown in Table 6. From these values it can be noted that the ESAS campaign without sortie missions has an exploration capability 2,208 times that of the Apollo 17 mission at a cost of 106 times the Apollo 17 mission. This result shows that removal of the four sortie missions reduces the relative exploration capability (REC) by <1% but reduces the relative scenario cost (RSC) by ~4.5%. This result alludes to the fact that, due to the short surface duration, sortie missions in general have a lower exploration capability than other crewed mission types.

Table 6: No Sortie ESAS Measures of Effectiveness

MOE	***Value***
Crew Surface Days (man-day)	2,294
Total Launch Mass (mT)	28,222
Exploration Mass Delivered (kg)	29,622
Exploration Capability (man-day-kg)	67,954,015
Relative Exploration Capability	2,208
Relative Scenario Cost	106

3.1.3 Trade 2 - All Sortie, 18 Launches

The second analysis was to hold the number of launches constant at 18 and vary the mixture of mission types to see how the MOEs change. The first trade performed was to examine how the MOEs change when only sorties are performed. With 18 launches it is possible to perform 9 sortie missions to various locations on the Moon, as is shown in Table 7.

Table 7: Sortie Only ESAS 18 Launch Mission Profile

Mission	**Launch Vehicle**	**Crewed (Y/N)**	**Surface Duration (Days)**
Sortie 1	Ares V + Ares I	Y	7
Sortie 2	Ares V + Ares I	Y	7
Sortie 3	Ares V + Ares I	Y	7

Mission	Launch Vehicle	Crewed (Y/N)	Surface Duration (Days)
Sortie 4	Ares V + Ares I	Y	7
Sortie 5	Ares V + Ares I	Y	7
Sortie 6	Ares V + Ares I	Y	7
Sortie 7	Ares V + Ares I	Y	7
Sortie 8	Ares V + Ares I	Y	7
Sortie 9	Ares V + Ares I	Y	7

The MOEs when 9 sorties are performed are shown in Table 8. From this table it can be observed that when only sorties are performed, both the relative exploration capability and the relative scenario cost drop dramatically due to the large decrease in crew surface days. The REC decreases by ~98%, while the RSC decreases by ~89%.

Table 8: Sortie Only ESAS Measures of Effectiveness

MOE	***Value***
Crew Surface Days (man-day)	252
Total Launch Mass (mT)	37,125
Exploration Mass Delivered (kg)	4,500
Exploration Capability (man-day-kg)	126,000
Relative Exploration Capability	35
Relative Scenario Cost	12

3.1.4 Trade 3 - All Outpost, 18 Launches

If the number of launches is held constant at 18 and the mission type is restricted to only missions that prepare for, supply and resupply a lunar base, the mission profile shown in

Table 9 can be performed. This profile allows for the buildup of a lunar outpost followed by 2.5 years of continuous crew presence at the outpost (made up of five 6-month 4-person crew expeditions).

Table 9: Outpost Only ESAS 18 Launch Mission Profile

Mission	Launch Vehicle	Crewed (Y/N)	Surface Duration (Days)
Base Pre-Deploy 1	Ares V	N	N/A
Base Pre-Deploy 2	Ares V	N	N/A
Base Pre-Deploy 3	Ares V	N	N/A
Lander Pre-Deploy 4	Ares V	N	N/A
Lunar Base Crew 1	Ares V + Ares I	Y	180
Logistics/Resupply 1	Ares V	N	N/A
Lunar Base Crew 2	Ares V + Ares I	Y	180
Logistics/Resupply 2	Ares V	N	N/A
Lunar Base Crew 3	Ares V + Ares I	Y	180
Logistics/Resupply 3	Ares V	N	N/A
Lunar Base Crew 4	Ares V + Ares I	Y	180
Logistics/Resupply 4	Ares V	N	N/A
Lunar Base Crew 5	Ares V + Ares I	Y	180

The MOEs for this scenario are shown in Table 10. These results show a dramatic increase in the relative exploration capability as compared to the previous campaigns that were simulated. The REC of the all-outpost scenario is more than double that of the ESAS baseline scenario, while the cost is only 12% higher. The following section will compare the MOEs from the baseline, trade 2 and trade 3.

Table 10: Outpost Only Measures of Effectiveness

MOE	***Value***
Crew Surface Days (man-day)	3,600
Total Launch Mass (mT)	47,366
Exploration Mass Delivered (kg)	42,500
Exploration Capability (man-day-kg)	260,355,000
Relative Exploration Capability	5,042
Relative Scenario Cost	124

3.1.5 Discussion of Results

When the MOEs from the baseline, all sortie and all outpost scenarios are compared, the results shown in Figure 20 are obtained. From these results it can be observed that the all outpost scenario is superior in all categories except relative scenario cost (RSC), where it is observed to be the most expensive scenario (12% more costly than the baseline). From the figure, it should also be noted that the all outpost scenario offers a significant increase in exploration capability (EC) over the other two scenarios. When compared to the baseline, the all outpost scenario offers 283% more exploration capability due to the combination of longer crew surface durations and the increase in exploration mass delivered to the lunar surface. This 283% increase in EC comes at an only 12% increase in scenario cost, reinforcing the notion that outpost campaigns provide the highest ratio of relative exploration capability to relative scenario cost. For this scenario this ratio is 5042 ÷ 124 or ~40:1.

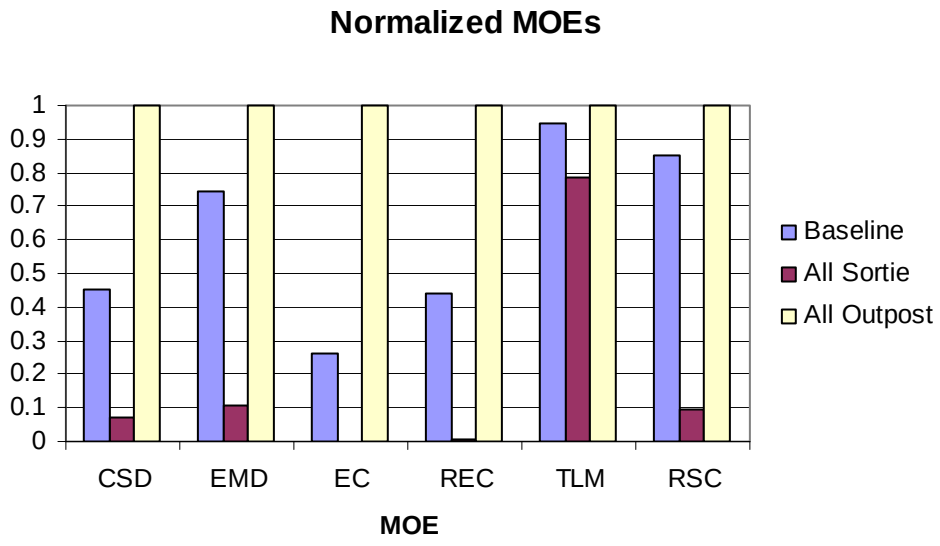

Figure 20: Normalized ESAS MOEs for Scenario Comparison

3.2 Evaluation of the Global Exploration Strategy Derived Architecture

The second analysis performed was an evaluation of the global exploration strategy architecture presented by NASA's Lunar Architecture Team (LAT) on December 4, 2006 and described in Chapter 1. This architecture consists of several phases, two of which have been modeled in detail in SpaceNet. The first phase that has been modeled will be referred to herein as the *Buildup Phase*, consisting of the first 10 flights described in Table 1-1. This phase utilizes the pre-position methodology to deliver the necessary elements and supplies to buildup the outpost at the Lunar South Pole in preparation for continuous human presence starting in 2024. A notional outpost configuration following the completion of the buildup phase is shown in Figure 21.

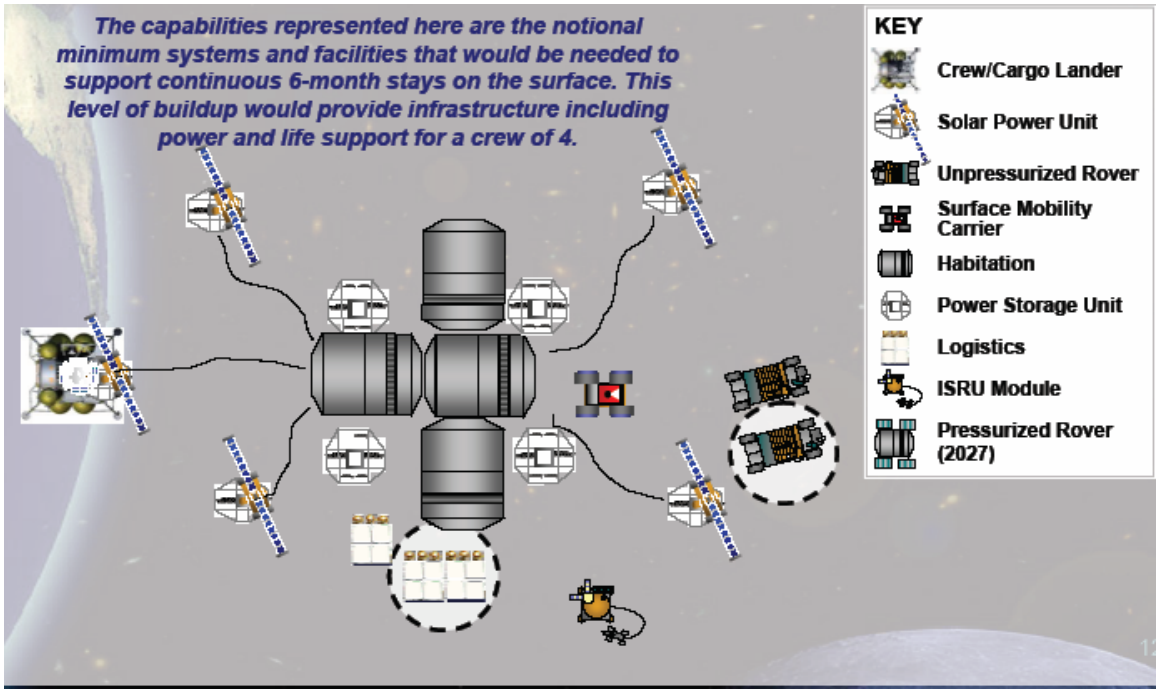

Figure 21: Notional Lunar Outpost at the South Pole [3]

The second phase, herein referred to as the *Sustainment Phase*, consists of the five manned mission starting in 2024. Each of these missions allows a crew of four 180 days at the lunar outpost. Together these five increments allow for a 2.5 year continuous human presence at the outpost and the ability to simulate the 2.5 year timeframe required

to carry-out a human mission to Mars.

3.2.1 The Buildup Phase

As was mentioned above, the buildup phase consists of the first 10 missions, each of which delivers critical outpost elements and supplies to the lunar surface. The details of the buildup phase can be seen in Table 11. Each mission in the buildup phase has a four person crew, with surface durations ranging from 0-30 days.

Table 11: LAT Buildup Phase Mission Summary

Mission	Launch Vehicle	Crewed (Y/N)	Surface Duration (days)	Outpost Elements Delivered	Cargo Delivered (kg)
2019A	Aries V + Aries I	Y	0*	Power Units, Unpressurized Rover, Communications Terminal	540
2020A	Aries V + Aries I	Y	7	Habitat Module	830
2020B	Aries V + Aries I	Y	7	Power Unit, Unpressurized Rover, Mobility Carrier	330
2021A	Aries V + Aries I	Y	7	Habitat Module	830
2021B	Aries V + Aries I	Y	14	Power Units	740
2022A	Aries V + Aries I	Y	14	Habitat Module	830
2022B	Aries V + Aries I	Y	14	Power Units	980
2023A	Aries V + Aries I	Y	25	Habitat Module	830
2023B	Aries V + Aries I	Y	30	In-Situ Resource Utilization (ISRU) Unit	3660
2024A	Aries V + Aries I	Y	30	Logistics Supplies	5790

* The crew for the 2019 mission does not travel to the lunar surface but instead remains in lunar orbit to monitor the LSAM tests.

The MOEs for the buildup phase are shown in Table 12. Due to the short surface durations of most of the missions in the buildup phase, it can be observed that the relative exploration capability and the ratio of relative exploration capability to relative scenario cost are both very low. The REC is only 416, while the ratio of REC to RSC is only 1.4:1.

Table 12: LAT Buildup Phase Measures of Effectiveness

MOE	*Value*
Crew Surface Days (man-day)	592
Total Launch Mass (mT)	46,768
Exploration Mass Delivered (kg)	41,823
Exploration Capability (man-day-kg)	21,220,520
Relative Exploration Capability	416
Relative Scenario Cost	292

3.2.2 The Sustainment Phase

Using the final conditions of the buildup phase as the initial conditions of the sustainment phase, a model of the sustainment phase was built in SpaceNet. As was mentioned above, the sustainment phase consists of five 180-day missions for a crew of four. The details of the sustainment phase missions can be seen in Table 13.

The final conditions of the build up scenario, which are used as the initial conditions of the sustainment phase, consist of the following elements remaining at the lunar outpost:

- 5 Surface Power Units
- 4 Habitat Modules
- 4 Makeup Power Units
- 2 Unpressurized Rovers
- 1 Communications Terminal
- 1 Surface Mobility Carrier
- 1 ISRU O2/H2O Production Unit

A stockpile of ~7300 kg of supplies is also remaining following the 2024A mission. A detailed discussion about what classes of supply should be pre-positioned in this stockpile can be found in Chapter 4.

Table 13: LAT Sustainment Phase Mission Summary

Mission	Launch Vehicle	Crewed (Y/N)	Surface Duration (days)	Elements Delivered	Cargo Delivered (kg)
2024B	Aries V + Aries I	Y	180	Unpressurized Rover	5190
2025A	Aries V + Aries I	Y	180		5860
2025B	Aries V + Aries I	Y	180	Unpressurized Rover	5190
2026A	Aries V + Aries I	Y	180		5580
2026B	Aries V + Aries I	Y	180		6000

The MOEs for the sustainment phase are shown in Table 14. Upon examination of this table a few interesting observations can be made. The first is that this data reinforces the results of Section 3.1.5 that long duration outpost missions have the highest ratio of relative exploration capability to relative scenario cost. For the sustainment phase, this ratio is 157:1. This high ratio is not surprising due to the fact that these five missions all provide long surface durations and are able to utilize the elements and supplies brought to the lunar surface by the buildup phase. The intent of the buildup phase is to deliver the elements and cargo that are then utilized during the sustainment phase.

Table 14: LAT Sustainment Phase Measures of Effectiveness

MOE	***Value***
Crew Surface Days (man-day)	3,600
Total Launch Mass (mT)	23,831
Exploration Mass Delivered (kg)	40,510
Exploration Capability (man-day-kg)	145,696,140
Relative Exploration Capability	23,806
Relative Scenario Cost	151

Figure 22 shows the cumulative mass build-up of the lunar outpost over both the buildup and sustainment phases. This mass includes both the elements and the cargo delivered to the lunar surface. From the figure it can be seen that the mass accumulation is nearly linear with a final value close to 90 mT. This linearity is due to the fact that each of the 15 missions are manned and can deliver ~6 mT to the lunar surface [46] (15 missions × 6 mT/mission = 90 mT).

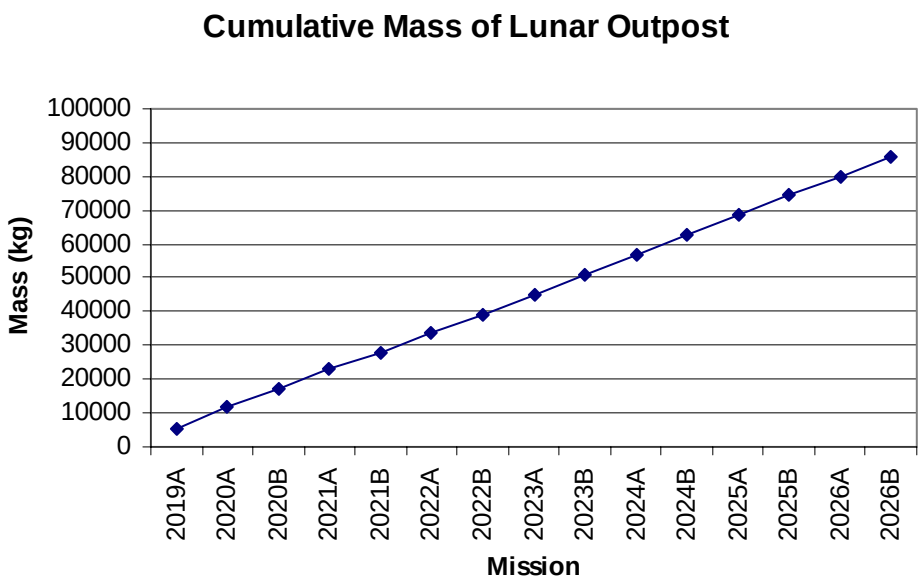

Figure 22 : Cumulative Mass (Elements + Cargo) of LAT Lunar Outpost, 2019-2026

3.3 Comparison of ESAS and Global Exploration Strategies

Another interesting comparison that can be made is to contrast the MOEs obtained from the ESAS and LAT inspired architectures. To make this comparison fair, the number of flights in both architectures must be the same. Recall from earlier in this chapter that the number of flights in the ESAS architecture is 12. To perform an impartial comparison, a 12 flight LAT-like scenario was created in SpaceNet. This scenario included the 10 flights of the buildup phase and the first two flights of the sustainment phase. The results of the comparison can be seen in Figure 23.

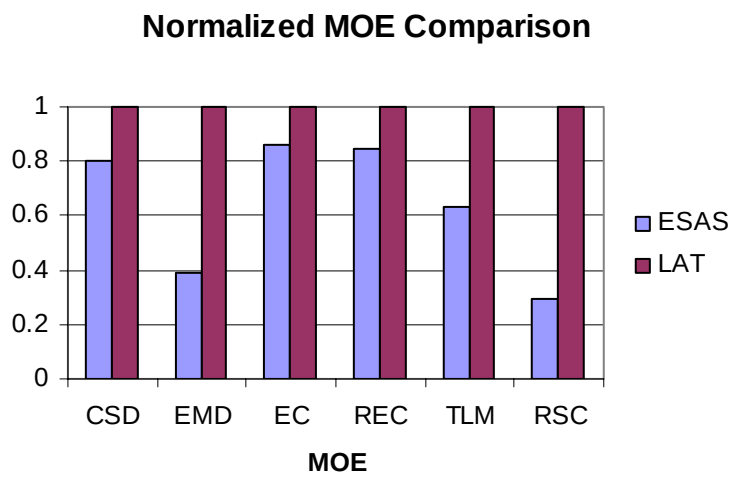

Figure 23: Normalized MOE Comparison ESAS vs. LAT

Several interesting observations can be made from this comparison. The first is that the LAT architecture is superior to the ESAS architecture in all categories except for cost (RSC), where it was found that the LAT architecture is far more costly. The second, and perhaps more thought provoking observation is that the ESAS architecture is able to provide 86% of the exploration capability (EC) of the LAT architecture for only 30% of the cost. The major contributor to this difference is the fact that the ESAS campaign includes four unmanned pre-positioning flights. These flights deliver a large mass of elements and cargo to the lunar surface (which contribute to the exploration capability of the scenario) but cost far less than manned missions.

A comparison of the cumulative crew surface days by mission is shown in Figure 24. From the figure it can be observed that although each architecture takes a different approach to building up the surface duration, the pattern is quite similar until the last mission when the LAT architecture surpasses the ESAS architecture and ends up with ~20% more crew surface days over the campaign.

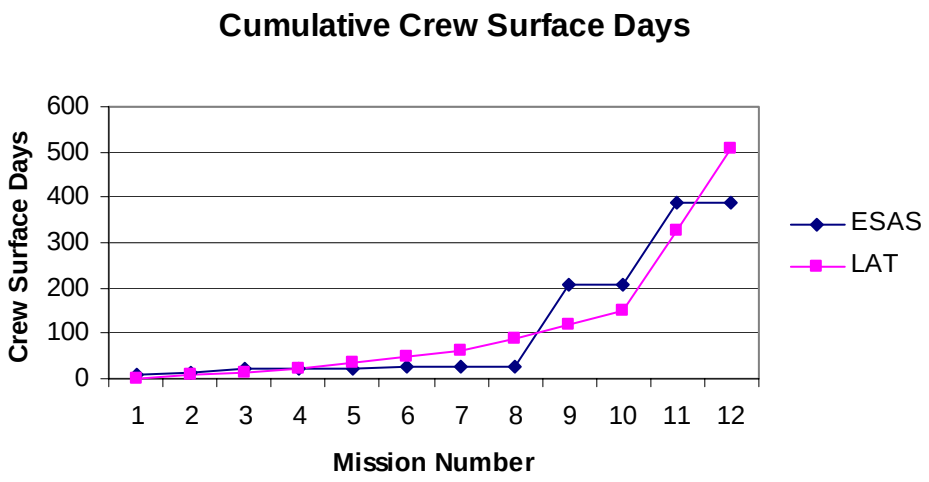

Figure 24: Crew Surface Day Comparison

3.4 Global Exploration Strategy Architecture Closure

In addition to analyzing the MOEs for the ESAS and global exploration strategy (LAT) it is also important to consider the cargo capability to the surface that each architecture allows and to ensure that the architecture "closes". A closed architecture means that the cargo capacity to the surface is sufficient to support the planned number of crew over the planned duration of the entire campaign of missions.

To perform this study, several key assumptions had to be made. The first is that this analysis will focus only on the LAT inspired architectures, since this architecture supersedes the ESAS architecture and represents the current strategy within the constellation program. The second assumption is that this analysis is only looking at the cargo requirements and capabilities on the lunar surface. All cargo that is needed by the crew for the 3+ day journey to and from the Moon must be carried along with the crew in the crew exploration vehicle (CEV) and will not be considered as part of this analysis. The cargo capacity to the surface is therefore only what can be landed on the surface by the lunar surface access module (LSAM). For this analysis it is assumed that the LSAM can land 6,000 kg of cargo at the lunar south pole for a manned mission and 15,000 kg

for an unmanned mission[10] [46].

To determine the available cargo mass capacity to the surface, the mass of any elements (Habitats, Rovers, etc.) delivered on each flight must be subtracted from the cargo capacities stated above. The details of the mass of each element are considered sensitive information and so will not be listed in this thesis but once these masses are considered, the results in Table 15 are obtained. The demand on the surface was calculated using SpaceNet. The excess capacity is the cargo capacity minus the demand. This excess represents the capacity available for the pre-positioning of cargo on the lunar surface.

Table 15: Surface Cargo Capacity and Demand by Mission Phase

LAT Mission Phase	*Cargo Capacity to Surface (kg)*	*Demand on Surface (kg)*	*Excess Capacity (kg)*
Buildup	15,360	8,072	7,288
Sustainment	27,820	46,661	-18,841
Total	43,180	54,733	-11,533

From the table it can be seen that although the architecture is capable of pre-positioning ~7,300 kg of cargo during the buildup phase this is not enough to make up for the ~18,800 kg shortage during the sustainment phase. This finding that the surface demand exceeds the capacity by more than 11,500 kg clearly indicates that the proposed architecture does not close. The following sections will discuss possible modifications to the initial architecture that were considered in an attempt to close the architecture.

[10] The difference in landed cargo capacity is due to the fact that unmanned missions do not require an ascent stage.

3.5 *Variations to the Initial Scenarios*

Following the conclusion that as it stands right now the LAT inspired lunar architecture is not sustainable; several trade studies were performed to evaluate simple variations to this architecture in an attempt to make it close.

3.5.1 Crew Size Reduction

The first trade performed was an analysis of the impact of reducing the crew size from four to three in both phases. This trade sought to determine if cargo shortfall seen in the baseline case could be eliminated by simply decreasing the crew size. For this trade the only change was the reduction in crew size, the mission architecture, surface duration, etc. remained as was specified in the baseline case.

Table 16: Surface Cargo Capacity and Demand for 3 Crew

LAT Mission Phase	*Cargo Capacity to Surface (kg)*	*Demand on Surface (kg)*	*Excess Capacity (kg)*
Buildup	15,360	6,953	8,407
Sustainment	27,820	40,404	-12,584
Total	43,180	47,357	-4,177

When the crew size was reduced to three the results in Table 16 are obtained. From the table it can be seen that the surplus of cargo delivered to the surface by the buildup scenario increased ~1,100 kg from 7,288 to 8,407. With the cargo capacity to the surface of the sustainment phase remaining at 27,820 kg and the demand for three crew over the five 180-day increments at 40,404, the sustainment phase is 12,584 kg short. If the surplus from the 3-crew buildup phase is applied to this shortage, the campaign is still 4,177 kg short! So simply decreasing the crew size will not fix the cargo shortfall.

Also worthy of note is that fact that decreasing the crew size by 25% has the effect of decreasing the exploration capability by 25% as can be seen in Figure 25. Arguably the exploration capability would actually be reduced by a percentage greater than 25% since the amount of maintenance and housekeeping tasks that need to be performed by a

reduced crew does not scale linearly with crew size and with only three crew to perform these tasks a larger portion of each crew member's day will need to be allocated to these duties. Also, the number of EVAs a three person crew is able to perform would be significantly lower then that of a four person crew, which would further decrease the exploration capability of the campaign.

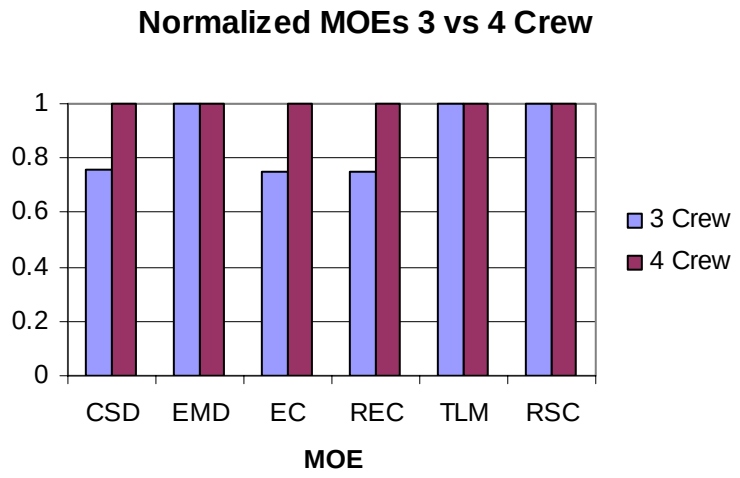

Figure 25: MOE Comparison for the Sustainment Phase with 3 vs. 4 Crew

3.5.2 Surface Duration

The second trade performed was an analysis of whether the cargo undersupply could be eliminated by decreasing the surface durations of the buildup phase missions to all be seven days. As can be seen in Table 17, this modification to the architecture decreases the surface cargo demand to 3,656 kg and leaves one with a reserve of 11,704 kg. Unfortunately this is still not a large enough reserve to meet the demand shortfall of 18,841 kg during the sustainment phase.

Table 17: Surface Cargo Capacity and Demand with 7 Day Buildup Missions

LAT Mission Phase	*Cargo Capacity to Surface (kg)*	*Demand on Surface (kg)*	*Excess Capacity (kg)*
Buildup	15,360	3,656	11,704
Sustainment	27,820	46,661	-18,841
Total	43,180	47,357	-7,137

By decreasing the surface duration one also substantially decreases the exploration capability as is shown in Figure 26 below. From the graph it should also be noted that this large (>60%) decrease in exploration capability is only accompanied by a very small (~2%) decrease in relative scenario cost. The ratio of exploration capability to cost is significantly lowered from the baseline case when the surface duration of each mission is limited to seven days; making this strategy not a very attractive option.

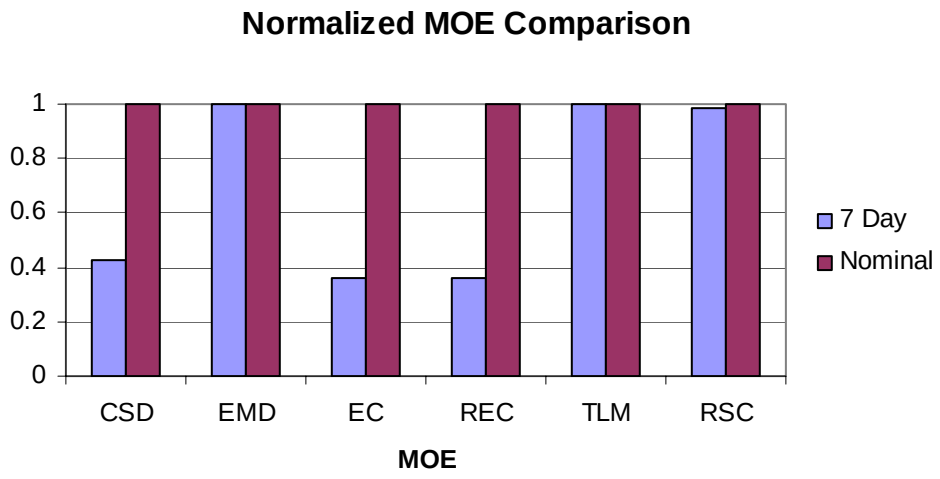

Figure 26: MOE Comparison between All 7 Day Surface Durations and Nominal Buildup

3.5.3 Substitute a Dedicated Cargo Flight

With the completion of the analysis above, it has become apparent that the cargo shortfall predicted in the nominal campaign is large enough that minor changes such as decreasing the number of crew by one or decreasing the surface duration are not going to close the architecture. Instead it is worthy to consider a more effective action, such as substituting one or more of the crewed flights for an uncrewed cargo flight. Recall that while the crewed flights are capable of delivering 6 metric tons of cargo to the lunar surface it is predicted that the uncrewed cargo flights will be able to deliver 15 metric tons to the surface.

In choosing which flight to substitute, it seems logical to choose one of the later flights so

that the large mass of cargo that is pre-positioned does not have to remain on the lunar surface for years. That said the most likely flights to substitute would be the 2023A, 2023B or 2024A flights (refer to Table 11 for the details of these missions). For the first analysis the 2023A flight was chosen. This flight was originally slated to deliver the fourth habitat and a minimal amount of cargo. When changed to an uncrewed cargo flight, 2023A will still deliver the fourth habitat but will also deliver 9,830 kg of cargo. This added cargo, plus the decrease in demand from removing 100 crew surface days from the campaign leads to a surplus of ~13,000 kg in the buildup phase. This surplus is not enough to close the 18,841 kg sustainment gap.

Since it appears that adding one dedicated cargo flight to the architecture is not adequate to close the architecture, the next trade performed was to add a second dedicated cargo flight. This time the 2024A mission was chosen to be replaced. As was shown in Section 3.2.1, this mission is not slated to deliver any elements to the lunar surface, only cargo. When this mission is changed to an uncrewed cargo mission, an additional 9,210 kg of cargo is delivered to the lunar surface (in addition to the extra cargo delivered on the 2023A mission discussed above). This additional cargo plus the decrease in demand due to the removal of 120 (30×4) crew days means that the buildup phase is now capable of pre-positioning 23,500 kg of cargo for the sustainment phase. This capability is sufficient to close the architecture! This capacity also allows for the pre-positioning of 4,659 kg of contingency supplies on the lunar surface. These supplies are critical for sustaining the crew in the event of a flight delay or cancellation, as will be discussed in Chapter 4.

Figure 27 compares the cumulative cargo delivered to the lunar surface for each of the three buildup scenarios: the LAT Phase I Baseline, the LAT Baseline with one dedicated cargo flight and the LAT Baseline with two dedicated cargo flights. From the figure, it can be seen that the campaign with two dedicated cargo flights more than doubles the baseline cargo capacity to the lunar surface.

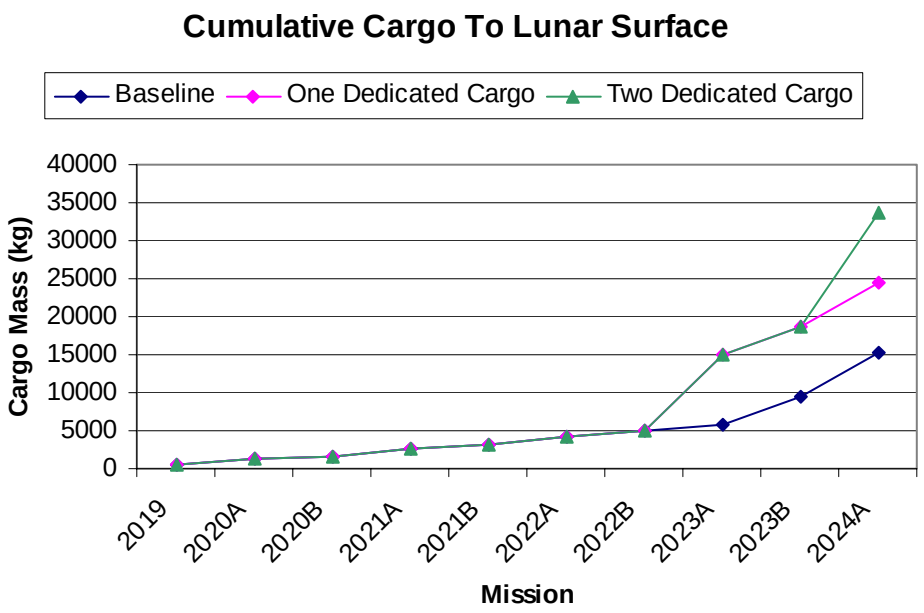

Figure 27: Cumulative Cargo Mass to the Lunar Surface

3.6 Summary of Chapter 3

This chapter presented the results of several trades studies performed on the baseline ESAS and LAT inspired lunar campaigns. The following section will summarize these results and present some conclusions that can be drawn from these results.

The first conclusion is that architectures that lead to the direct establishment of an outpost provide a significantly larger exploration capability than those that engage in sortie missions first and then begin construction of the outpost. The increase in exploration capability for "outpost centric" architectures stems partially from the increase in crew surface duration afforded by these architectures and partially from the re-use of components across missions as each mission builds upon the previous ones.

Figure 28 shows the overall trade space of the campaigns discussed in this chapter. The x-axis represents the total launch mass (TLM) in metric tons. The y-axis shows exploration capability (EC) in man-day-kg on a logarithmic scale. The graph has been

augmented by showing the lines of constant relative exploration capability (REC)[11]. The REC lines are parallel lines in this plot with iso-REC lines of higher efficiency providing more EC for the same TLM.

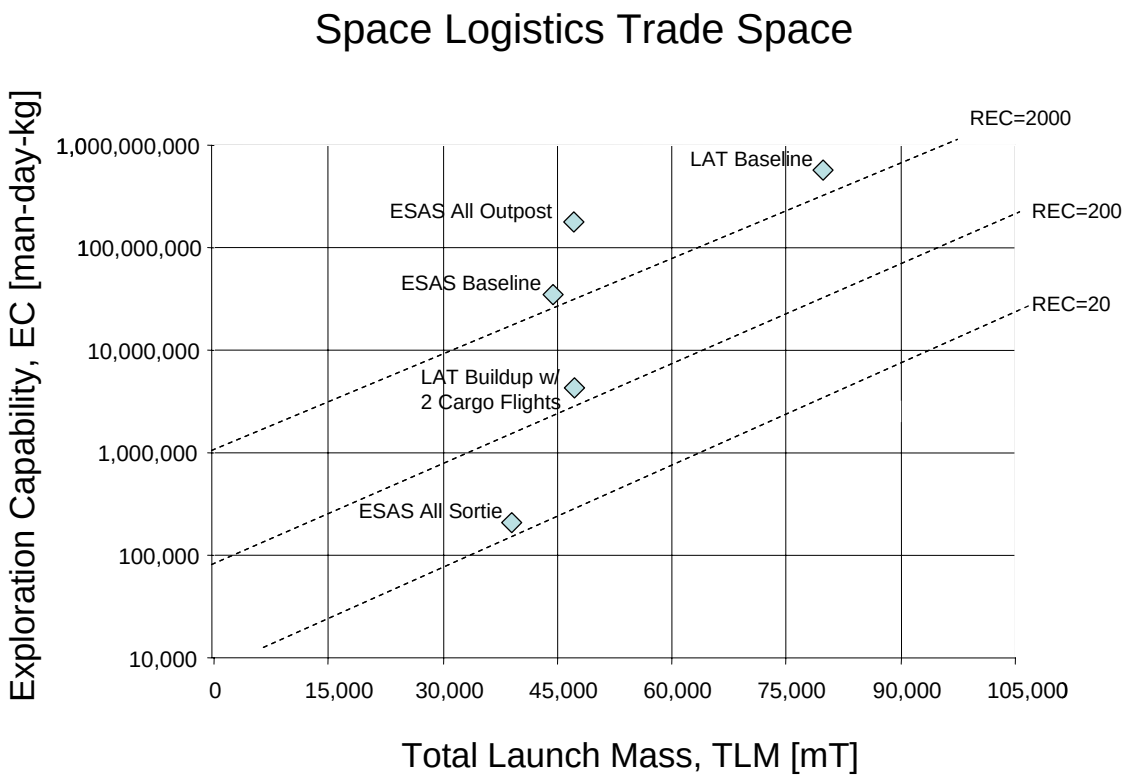

Figure 28: Trade Space Diagram

The ESAS all-sortie campaign is shown in the lower left corner, the ESAS baseline and ESAS all-outpost are in the middle upper portion of the chart, the LAT buildup with 2 dedicated cargo flights is in the center of the graph and the LAT baseline campaign is in the upper right. Several interesting insights can be obtained from this chart:

1. A set of sortie missions that all use the same transportation architecture, elements and technology will always fall onto or below the same iso-REC line
2. The LAT and ESAS baseline campaigns are about 100 times more efficient than a

[11] The REC lines shown on this graph are actually slightly curved due to the fact that the plot is semi-log; for simplicity they are represented as straight lines here.

campaign with an equivalent number of launches that performs only sorties.

3. The highest logistics efficiency is obtained in the ESAS all-outpost campaign. This is due to the fact that this campaign starts off with four unmanned pre-positioning missions. These single launch missions reduce the total launch mass of the scenario (as compared to the LAT baseline) while keeping the exploration capability high. This

One factor that is not reflected in this figure is the relative cost of each campaign. As has been mentioned several times in this chapter an interesting way of comparing campaigns is to look at the ratio of relative exploration capability (REC) to relative scenario cost (RSC). This ratio can be thought of as the benefit to cost ratio for the campaign. The REC to RSC ratio for seven of the campaigns analyzed in this chapter is shown in Table 18. The data in this table reinforce the idea that outpost-only campaigns such as the ESAS All Outpost and the LAT Sustainment offer higher ratios of benefit to cost.

Table 18: Benefit to Cost Comparison by Campaign

Campaign	*REC*	*RSC*	*REC:RSC*
ESAS Baseline, 18 Launches	2,223	111	20:1
ESAS All Sortie, 18 Launches	35	12	3:1
ESAS All Outpost, 18 Launches	5,042	124	41:1
LAT Buildup	416	292	>1:1
LAT Sustainment*	23,806	151	157:1
LAT Baseline, 18 Launches	2,633	359	7:1
LAT Buildup w/2 Dedicated Cargo	233	289	<1:1

*The REC:RSC of this campaign is high due to the fact that this campaign benefits from pre-positioning during the LAT Buildup phase

Another major conclusion that can be drawn from this chapter is the fact that the LAT Phase I architecture lacks sufficient cargo capacity to support four crew for the intended durations. Preliminary analysis indicates that the substitution of two unmanned cargo mission late in the buildup phase may be enough to close the architecture. Further analysis is necessary to determine which manned missions should be replaced with unmanned cargo missions and whether the surface durations of the remaining manned

missions should be adjusted to maximize exploration capability.

The next chapter builds upon the results obtained in this chapter by examining the robustness of the LAT architecture to campaign level risks. It also presents several strategies for risk mitigation such as pre-positioning critical cargo at the outpost. A methodology for determining the best mixture of crew provisions, spares and exploration items to pre-position at the lunar outpost to maximize endurance, system availability and exploration capability is also presented.

4 Campaign Level Risk Analysis

As was mentioned in the case studies of Chapter 1, all previous and current human spaceflight programs have faced challenges due to uncertainty in schedule, budget, etc. That said it is unrealistic to think that the Constellation program will not face similar sources of uncertainty. Building upon the analysis described in Chapter 3, this chapter will examine the robustness of the LAT architecture to campaign level risks such as uncertainty in demand, flight delay and flight cancellation.

Chapter 8 of the ESAS Final Report [1] deals entirely with the risk and reliability of the ESAS lunar architecture. While this chapter gives a nice summary of what the ESAS team considered the top 10 risks drivers in their architecture (see Table 19), it fails to address the logistical impacts as a key category of risk, which will be referred to in this thesis as *campaign level risk*. In our analysis, campaign level risk refers to a high-level source of risk that has the potential to cause disruptions to the logistics not of only one mission but of the entire campaign.

Table 19: Top Ten ESAS Risk Drivers [1]

• LOX/methane engine development;
• Air start of the SSME;
• Lunar-Earth reentry risk;
• Crew escape during launch;
• Liquid Acquisition Devices (LADs) in the CEV service propulsion system;
• Lunar vehicle LOX/hydrogen throttling on descent;
• Integration of the booster stage for the Heavy-Lift Vehicle (HLV);
• J–2S development for the Earth Departure Stage (EDS);
• Unmanned CEV system in lunar orbit;
• Automated Rendezvous and Docking (AR&D).

This chapter strives to be a supplement to previous work on risk mitigation for the proposed lunar architectures by addressing risk in terms of its impact on a campaign of missions, instead of the more immediate impacts (loss of crew, loss of mission, schedule delay, cost overrun, etc.) commonly thought of when one hears the term risk in reference to human spaceflight.

As is stated in NASA's document on Risk Management Procedures and Guidelines [47], "the first step in the risk management process is to identify the risks (technical and programmatic) specific to a program/project…this entails identifying individual risks and clearly describing those risks in terms of both the undesirable event the risk presents as well as the consequences of that event to the program/project." When seeking to identify risks one should seek to answer the following questions:

- What can go wrong?
- What would be the consequences (to safety, mission objectives, schedule, cost) if it does go wrong?

After these risks have been identified one should seek to develop a risk mitigation strategy. For the purposes of our analysis, the questions we seek to answer are:

- What can go wrong?
- What are the consequences (to the **campaign, schedule**) if it does go wrong?
- What responses/mitigations should be considered?

4.1 Sources of Risk in the Lunar Architecture

The first step in our risk analysis was to identify possible sources of campaign level risk. The following list contains several sources of campaign level risk we have identified in the Constellation mission architecture:

1. Vehicle Failure – Ares V
2. Vehicle Failure – Ares I
3. Flight Delay
4. Flight Cancellation
5. Stochastic Demand Predictions
6. Failed Rendezvous in Low Earth Orbit (LEO)
7. Failed Rendezvous in Low Lunar Orbit (LLO)

The next step in the analysis is to identify what the consequences are to the campaign for each of these risks. For the first risk, the Ares V failure, the consequences are a loss of cargo and resultant loss of mission. Analysis performed in 2005 by B. Nadir et al. shows

that the historical stand down time for an unmanned U.S. launch vehicle following a launch failure ranges from 7-13 months [48]. The question posed in our robustness analysis then becomes can the mission architecture survive a flight delay of this magnitude or will the disruption cause major problems? The results of this analysis are presented in Section 4.5.

The second source of risk, an Ares I failure, has as its worst case consequences the potential for a loss of crew. The Ares I is designed to provide a crew abort capability in case of a launch failure but in reality no system provides a 100% guarantee of crew safety. Assuming that the crew is able to abort to safety, the second consequence of an Ares I failure is a loss of mission. For crewed missions, historical data shows that the average stand down time for crewed U.S. vehicles is 28 months [48]. This long stand down time has had a large impact on past programs, especially in the prolonging of the assembly of the ISS following the Columbia accident as was discussed in Chapter 1. The impacts of a flight delay can vary widely depending on the length of the delay and the point in the campaign when the delay occurs. A simplistic analysis of the robustness of the notional LAT Phase I architecture to a flight delay is presented in Section 4.5.

The fourth source of risk, a flight cancellation, can also have varied impacts on a campaign. The extent of the impacts depends not only on which flight in the campaign was cancelled but also on what re-planning is done as a result of the cancellation. It also depends on how much pre-positioning was done before the launch failure occurred (i.e. what are the safety stock levels). The effects of a flight cancellation on the notional LAT Phase I architecture are discussed in Section 4.4.

The fifth source of risk, stochastic demand predictions, is probably the source of risk given the least amount of thought when designing a campaign of missions. This lack of attention is understandable as this source of risk has consequences of a much more subtle nature than the other sources of risk listed above. This source of risk can pose serious problems however, as was illustrated in December of 2004 when NASA ran the risk of having to bring the Expedition 10 crew home early, due to a shortage of food on the ISS

[49]. If the Progress docking scheduled for December 25th did not succeed the ISS would have had to have been (temporarily) abandoned due to this critical shortage. An analysis of the impact of stochastic demand predictions on the notional LAT Phase I architecture is presented in Section 4.2.1.

The last two sources of risk, a failed rendezvous in either LEO or LLO, can have several consequences. A failed rendezvous in LEO will result in a mission abort and return to Earth of the crew. If the failure was due to a fault with the docking system on any of the elements, it is possible depending on the failure that a duplicate element could be launched in a reasonable time and the mission would only be delayed. The effects of this type of risk on the campaign will not be addressed explicitly in this thesis because the impacts will be similar to that of a flight delay or flight cancellation.

4.2 Trade Studies

In an effort to evaluate the robustness of the LAT Phase I inspired architecture to some of the risks mentioned above, several trade studies were performed. The details of these trade studies are described in the following sections.

4.2.1 Demand Sensitivity

A major source of uncertainty in the lunar campaign is the demand parameters. As was mentioned in Chapter 3, the demand models in SpaceNet are based upon data gathered from ISS and textbooks such as Human Spaceflight Mission Analysis and Design [28]. (A table of the nominal demand parameters in SpaceNet v1.3 can be found in Appendix C.) While this data represents the best known demand parameters, there is certainly some uncertainty in the data that should not be ignored. The following sections present the results of several trade studies performed to highlight the impact that uncertain demand can have on a space supply chain.

4.2.2 ECLSS Closure

The first trade performed was to vary the rate of Environmental Control and Life Support

System (ECLSS) closure during both the buildup and the sustainment phase from 0% to 100% in increments of 20%. ECLSS closure refers to the percentage of water and gases that are reclaimed after their initial usage to be used again. An ECLSS closure of 50% means that half of the waste water and gases produced everyday are reclaimed and made available for reuse. This trade will analyze the effect of ECLSS water (not gas) closure on the crew provisions demand. The amount of ECLSS closure feasible in the lunar outpost is unknown at this time. SpaceNet uses a nominal ECLSS water closure rate of 0.42 (42%) based upon ISS data. For the establishment of a lunar outpost it is desirable to have a higher ECLSS closure rate to decrease the mass of water that needs to be transported from the Earth to the Moon.

The results of the ECLSS closure trade are shown in Table 20. From this table the effect on crew provisions mass required on the surface for both phases can be seen. Several observations can be made from this data. The first is that with no ECLSS closure ~42,200 kg of crew provisions is required to support a crew of four through both mission phases. This number represents an extremely large fraction (97.8%) of the total capacity to the surface 43,180 (15,360 during buildup + 27,820 kg during sustainment). On the other hand, if 100% ECLSS closure is achieved the required mass of crew provisions drops to ~26,700 kg, which represents a more reasonable 61.9% of the total capacity to the surface.

Table 20: ECLSS Closure Rate Effect on Crew Provision Mass

Demand Masses (kg)	*ECLSS Closure*					
	0%	20%	Nominal= 42%	60%	80%	100%
Buildup Crew Provisions	5,819	5,393	4,967	4,540	4,114	3,688
Sustainment Crew Provisions	36,400	33,720	30,780	28,380	25,710	23,030
Total	**42,219**	**39,113**	**35,747**	**32,920**	**29,824**	**26,718**

Another way to interpret these results is to look at the effect on the buildup cargo surplus for various ECLSS closure rates. Figure 29 shows the variation in buildup surplus as the ECLSS closure is varied from 0 to 100% for the buildup phase only. The buildup

surplus varies from a low of 6,356 kg with a 0% closure to a high of 8,576 kg with a full closure. This figure illustrates the feasible manifest planes for the pre-positioning of cargo (as will be discussed in Section 4.3.1) for the best and worst case ECLSS closure.

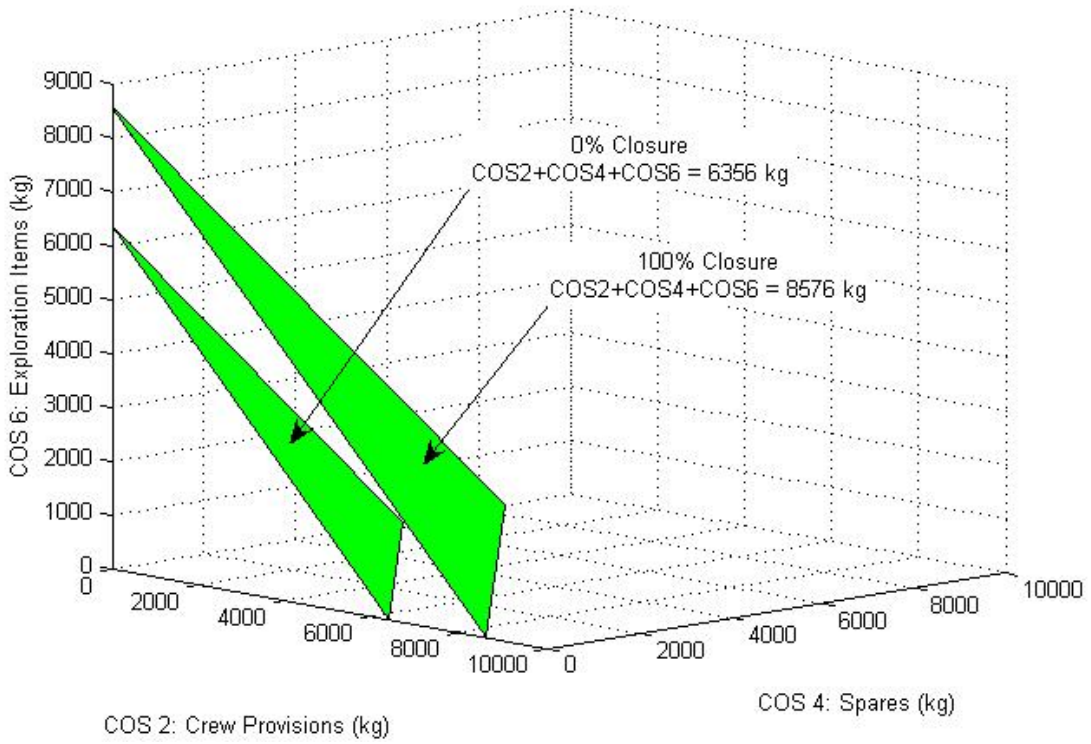

Figure 29: ECLSS Trade Buildup Surplus at End of Buildup Phase

This trade stresses the importance of investing in technologies that increase the ECLSS closure. It also highlights a potential source of risk in the architecture; regardless of the initial ECLSS closure rate, if this system were to malfunction, the mass required to support the crew could increase by as much as 15,500 kg (42,219-26,718). This mass is large enough that a dedicated cargo flight would need to be added to the architecture, potentially causing schedule and cost overruns.

4.2.3 Multiple Parameter Mass Sensitivity

In order to really evaluate the effects of uncertain demand on the lunar campaign, it is necessary to vary several factors in combination to determine a range of impacts. When one thinks of the parameters that could be varied there are numerous combinations. In

order to make the problem manageable, three factors where chosen to be varied for this analysis: ECLSS closure, Water + Food consumption and mean time between failures (MTBF) for the Habitat spares. Each of these three parameters was evaluated at five different levels as specified in Table 21.

If a full factorial analysis was run on these three factors the number of test cases would have been $5^3 = 125$. Instead, the number of test cases was reduced to 25 using a design of experiments (DOE) technique called Orthogonality [50]. Two additional test cases, #26 and Baseline, were added to evaluate the best case and the baseline case for comparison purposes. The 27 test cases that were run are shown in Table 22 below.

Table 21: Stochastic Demand Sensitivity Factors

Factor		
A: ECLSS Closure	**B: H2O+Food Consumption**	**C: MTBF for Habitat Spares**
A1: 0%	B1: 6 kg/person/day	C1: Nominal ÷ 2
A2: 25%	B2: 5.5 kg/person/day	C2: Nominal ÷ 1.5
A3: Nominal: 42%	B3: Nominal: 5.2 kg/person/day	C3: Nominal
A4: 75%	B4: 4.5 kg/person/day	C4: Nominal × 1.5
A5: 100%	B5: 4 kg/person/day	C5: Nominal × 2

Table 22: Stochastic Demand Parameter Study

Test Case Number	**Factor**		
	A: ECLSS Closure	**B: H2O+Food Consumption**	**C: MTBF for Habitat Spares**
Baseline	A3	B3	C3
1 (Worst Case)	A1	B1	C1
2	A1	B2	C2
3	A1	B3	C3
4	A1	B4	C4
5	A1	B5	C5
6	A2	B1	C2
7	A2	B2	C3
8	A2	B3	C4
9	A2	B4	C5
10	A2	B5	C1
11	A3	B1	C3
12	A3	B2	C4
13	A3	B3	C5
14	A3	B4	C1
15	A3	B5	C2

Test Case Number	Factor		
	A: ECLSS Closure	**B: H2O+Food Consumption**	**C: MTBF for Habitat Spares**
16	A4	B1	C4
17	A4	B2	C5
18	A4	B3	C1
19	A4	B4	C2
20	A4	B5	C3
21	A5	B1	C5
22	A5	B2	C1
23	A5	B3	C2
24	A5	B4	C3
25	A5	B5	C4
26 (Best Case)	A5	B5	C5

Each test case was simulated through modification of the demand parameters in the sustainment scenario in SpaceNet. The outputs of interest for this trade are the required crew provisions mass and Habitat spares mass. The spares mass represents the mass required to achieve a system availability of 1.0 for all 4 habitat elements.

When these test cases were run on the Sustainment Scenario in SpaceNet, the results shown in Figure 30 were obtained. From these results it can be observed that Case 1 has the largest mass requirement and Case 26 has the lowest. This result was to be expected as Case 1 has an ECLSS closure of 0%, the largest Water/Food Consumption requirement and the lowest MTBF. On the other hand Case 26 has an ECLSS closure of 1.0, the smallest water/food consumption requirement and the highest MTBF, so it produces the most desirable results. The mass difference between Case 1 and Case 26 is 48,804 kg (76,668-27,864). The average total mass requirement across all 27 cases is 46,730 kg, the variance is 11,797 kg and the coefficient of variation is 0.25.

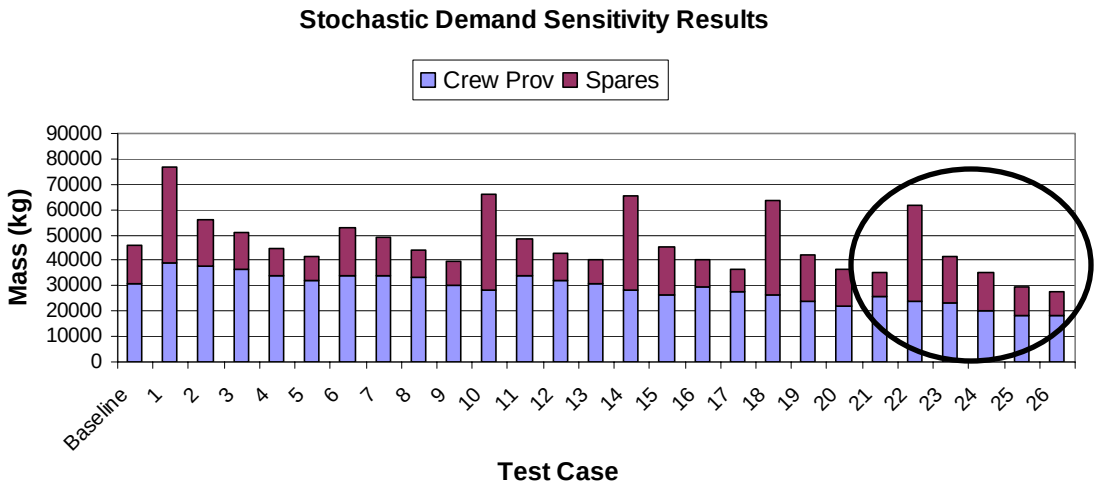

Figure 30: Stochastic Demand Sensitivity Results for Sustainment of a Lunar Base in Steady State (2.5 years)

Several other observations can be made from the results of this analysis. The first is that the fluctuation in spares mass is larger than the fluctuation in crew provisions mass. This is partially due to the large range of MTBFs used in this analysis. Varying the MTBF from 200% of nominal to 50% of nominal has a large impact on the mass of Habitat spares required to achieve a 50% system availability. The second and perhaps more useful observation is the effect of ECLSS closure on the demand. The family of results circled in Figure 30, show the results achieved with an ECLSS closure of 100%. These results, with the exception of case 22 where the MTBF was 50% of nominal, all represent positive outcomes; outcomes with relatively low mass requirements. This result reinforces the importance of investing in technologies to increase ECLSS closure.

4.2.4 Volume Sensitivity

As was mentioned in Chapter 2, SpaceNet was designed to calculate both mass and volume requirements for each class of supply. While mass data is readily available from sources such as data from the ISS and textbooks, volume data is scarcer and in reality many mission models do not even account for volume. This oversight is dangerous however as it is often the case that a manifest will satisfy mass limitations but will exceed volume limitations, making it infeasible.

While the demand models in SpaceNet presently compute a mass and volume demand by COS, only the mass capacities of most elements have been defined. The volume capacities of most of the LAT elements are not known at this time as their internal configuration has not yet been designed. This gap in capacity data makes it impractical to do a sensitivity analysis on the uncertainty surrounding the volume of cargo. This analysis will remain as future work once volume capacity data becomes available for the LAT elements.

4.3 Cargo Manifest Trades

The sections above have illustrated several examples of the possible fluctuation in required cargo mass to support a crew of four at the lunar outpost. This variation in demand can have enormous effects on a campaign and so should be guarded against. The easiest method of protecting against demand uncertainty is to pre-position a stockpile of contingency supplies at the lunar outpost. This method, however, can be expensive so another method is to carefully monitor actual usage and do adaptive re-planning. (A discussion of emerging technologies that can be utilized to monitor actual usage rates can be found in Chapter 5.)

The following sections discuss options for pre-positioning including which classes of supply should be included in a stockpile to provide maximum benefit. Specifically the trade off between crew provisions, spares and exploration items is examined. This trade off is a common problem in space logistics as elements typically have a given capacity and mission planners are forced to find the optimal allocation of classes of supply to fill this capacity.

As was mentioned in Section 3.2.2 the nominal buildup phase has the capability to pre-position 7,288 kg of cargo on the lunar surface. As we consider what supplies should be pre-positioned on the lunar surface during the buildup phase we must consider the trade off between crew provisions, which provide endurance to the campaign by allowing the crew to remain on the lunar surface for a longer duration, spares, which increase system

availability, and exploration items, which increase the amount of science/exploration that can be done. When these three variables are considered together, the feasible manifest forms a triangular plane in 3-D space, as is shown in Figure 31. The vertices of this triangle intersect each axis at the total stockpile mass, representing a manifest where all of the cargo is allocated to only one of the three classes of supply. Everywhere else on this plane is defined by the mass constraint given in Equation 15.

$$M_{crew\_provisions} + M_{spares} + M_{exploration\_items} = M_{total} \qquad (15)$$

The center point of the triangle would indicate a manifest where the cargo mass is allocated evenly between the three classes of supply. As the manifest moves away from the center point towards one of the vertices, one increases the capacity for endurance, exploration capability or system availability as is indicated in the figure. Finding the optimal manifest point on this triangle is the subject of Section 4.3.6.

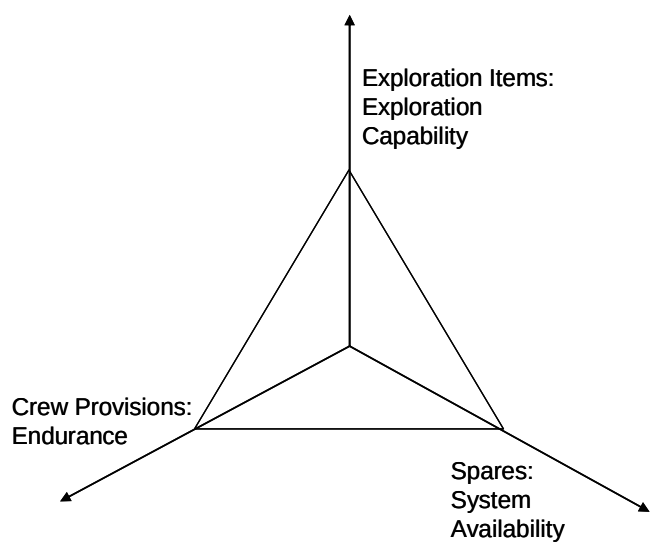

Figure 31: COS Trade-off Plane

4.3.1 The Base Case

Figure 32 shows the surplus manifest plane for the baseline buildup scenario described in Section 3.2.1. The vertices of this triangle intersect each axis at 7,288 kg, while the plane represents all manifest where Equation 15 is satisfied and the sum of the three classes of

supply is 7,288 kg.

The challenge of manifesting cargo then becomes the ability to decide where on the manifest plane one should be. For this analysis, we have considered four cases which will be described in the following sections. The location of each case on the manifest plane has been marked in Figure 32.

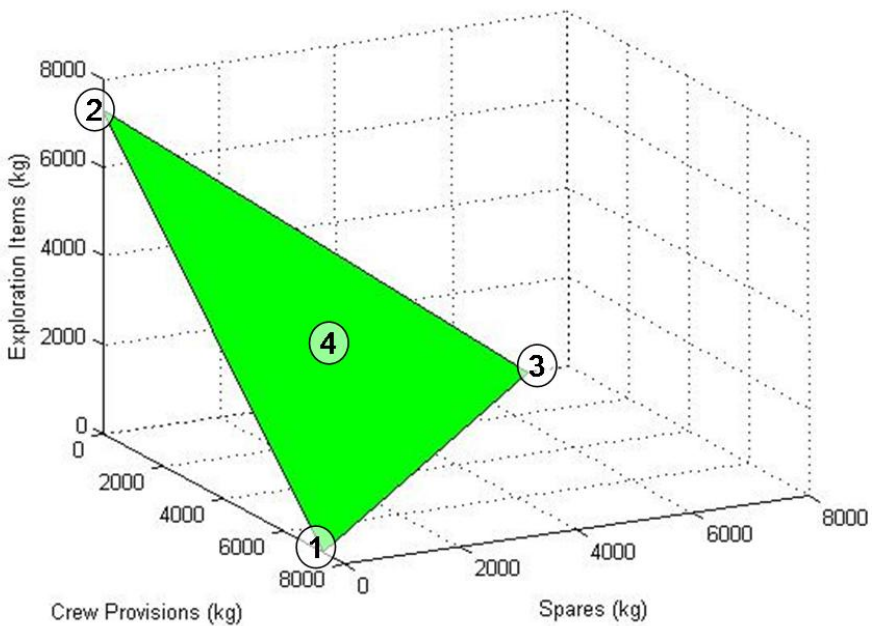

Figure 32: Feasible Manifest Plane for Buildup Surplus

4.3.2 Case 1: All Crew Provisions

The first case considered was to allocate all of the cargo to crew provisions to pre-position consumables on the lunar surface. This strategy seeks to provide a reserve for the crew in the event that a resupply flight is cancelled or delayed (as will be discussed in Sections 4.4 and 4.5) or to protect for uncertainty in the demand for crew provisions (as was discussed in Section 4.2.1). If all 7,288 kg are allocated to crew provisions, SpaceNet calculates that 326 days of consumables for four crewmembers can be stockpiled. With flights to the base scheduled every ~180 days, this stockpile could sufficiently sustain the lunar crew through an entire 6-month increment in the event of a

cancelled or delayed flight. With a bit of rationing this stockpile could potentially sustain the crew for two increments (a full year).

4.3.3 Case 2: All Exploration Items

The second case considered was to allocate the entire stockpile mass to Exploration Items and examine what effect that would have on the exploration capability of the campaign. Recall from Section 4.2.1 that the original Exploration Capability of the buildup phase was 21,220,520 man-day-kg. If this number is adjusted to exclude class of supply 8 infrastructure items, this number becomes 51,036 man-day-kg. With the additional 7,288 kg of capacity allocated entirely to exploration items, split evenly amongst the 10 missions, the revised exploration capability increases dramatically to 3,185,348 man-day-kg; a 62 fold increase! In reality the limited available crew time to perform exploration would prevent this increase from being realized; crew time limitations have not been considered in this analysis.

It should also be noted that instead of considering the increase in exploration capability one could consider instead the "days of science" one can buy. At the preferred manifesting rate of 3 kg of science equipment per surface day [3], the 7,288 kg would allow one to pre-position 2,429 days (6.66 years) of exploration items on the lunar surface. This means that with a bit of foresight, all of the science equipment for the entire Constellation Program could be pre-positioned during the buildup phase. (It may not be desirable to pre-position all of the science equipment so early in the program as this would limit ones ability to respond to new discoveries and adapt the science objectives accordingly.)

4.3.4 Case 3: All Spares

The third case to be considered is to allocate the entire surplus to spares and examine how that improves system availability. As has been mentioned in previous sections, the demand models in SpaceNet are based upon historical data and spares is no exception. Since the lunar outpost elements are not yet designed the spares list for these elements in uncertain. That said the data below is a best estimate based upon primarily ISS data.

As a conservative approximation, the spares mass to achieve a system availability of nearly 1.0 can be estimated as 10% of the element dry mass per year for each year the element is operational on the lunar surface. When calculated over both the buildup and sustainment phases the total spares mass required for the LAT architecture is on the order of 20,000 kg. Table 23 shows the breakdown of this mass by element type. From this table, it can be inferred that if one were to allocate the entire stockpile of 7,288 kg to spares, one could pre-position ~35% of the spares for the entire campaign (2019-2026).

Table 23: Estimate of Spares Mass by Element

Element {# to be Spared}	***Required Spares Mass for 2019-2026 (kg)***
Habitat {4}	11,374
Unpressurized Rover {4}	1,817
Surface Power Unit {5}	7,350
Surface Mobility Carrier {1}	1,593
Communications Terminal {1}	57
Makeup Power Unit {4}	1,700
ISRU Module {1}	880
Total	**20,933**

Included in SpaceNet is a complex demand model for spares estimation that strives to calculate system availability for each element by factoring in duty cycles, k-factors and mean time between failures for each orbital replacement unit (ORU) and shop replaceable unit (SRU) in the element. NASA defines system availability as "the ability of the system to operate whenever called upon to do so" [51]. System availability can be thought of as the opposite of downtime and is typically expressed as a number (or percentage) between 0 and 1 (0%-100%). (For more details on the calculations involved in the SpaceNet demand model, see Appendix C of [42].) This demand model is capable of producing system availability curves for the elements of interest over the life of the scenario. These curves show system availability as a function of the mass of spares required to achieve this availability.

System availability curves for the four unpressurized rovers and four habitat modules

over the life of the LAT campaign are shown in Figure 33 and Figure 34. These curves can be used to estimate the system availability obtainable for a given mass of spares. As an example, suppose it was decided to allocate all 7,288 kg of the surplus capacity to habitat spares. The dashed line in Figure 34 shows that this mass allocation would result in a 65% system availability for all 4 habitats over the campaign.

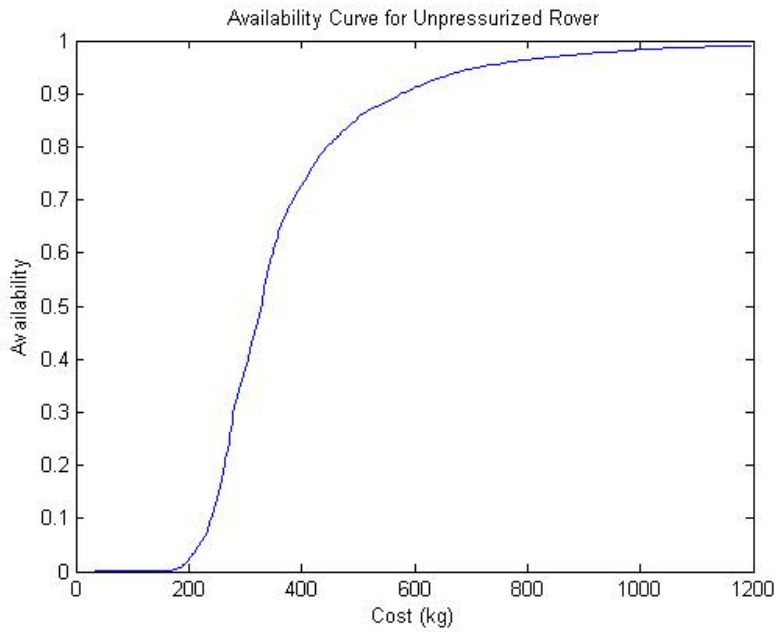

Figure 33: Unpressurized Rover System Availability Curve

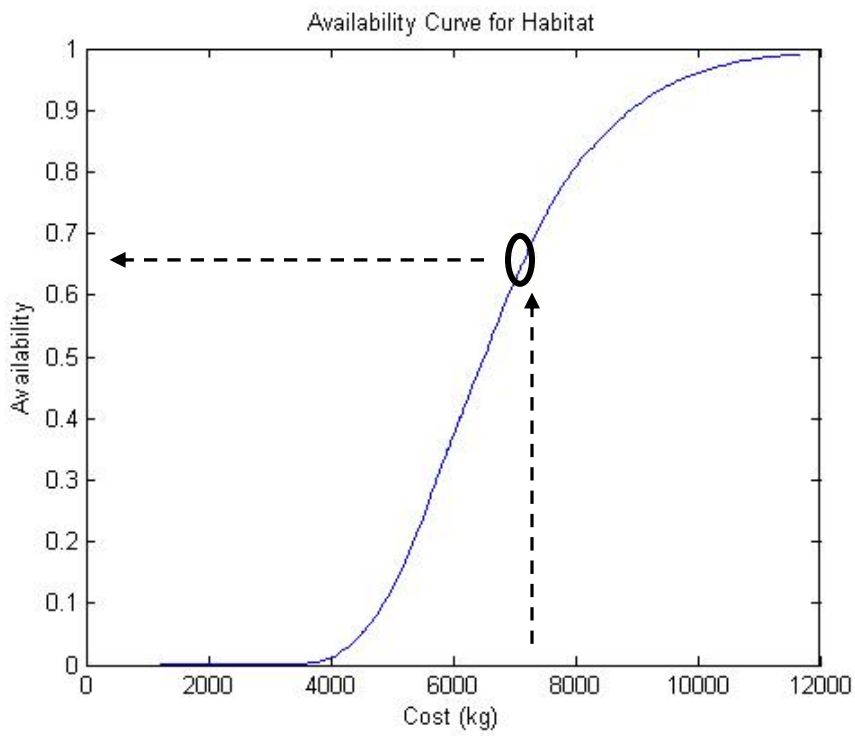

Figure 34: Mini-Habitat System Availability Curve

4.3.5 Case 4: Split the Cargo Evenly

The fourth case considered was to split the cargo surplus evenly between the three classes of supply. This case seeks to represent a desire to find a balance between providing a consumables reserve, increasing exploration capability and increasing system availability. When the surplus is split evenly, 2,429.3 kg will be allocated to each of the three classes of supply. This mass of cargo is sufficient to provide 108 days of crew provisions reserve, a 22-fold increase in Exploration Capability (again, this increase considers COS 6 mass only, not COS 8) and the ability to pre-position 11% of the predicted spares needed for the LAT campaign.

4.3.6 The "Best" Solution

The four cases above represent the simplest solutions to deciding what to manifest when one is faced with the ability to pre-position cargo. In reality, the "ideal" manifest will fall somewhere on the triangular plane, not necessarily in the center and definitely not at one

of the vertices. Determining where on the manifest triangle gives the ideal mix of endurance, system availability and exploration capability is a non-trivial task. At first glance one might think that the ideal manifest would exist at the point that maximizes the following equation

$$\Psi = \alpha M_{CP} + \beta M_S + \gamma M_{EI} \quad (16)$$

Where Ψ is a weighted sum of crew surface days (calculated from crew provisions mass, M_{CP}), system availability (from spares mass, M_S) and exploration capability (from exploration items mass, M_{EI}).

The flaw with this equation is that the ideal solution might come out to be on one of the vertices of the triangle where one of the three parameters (crew surface days, exploration capability or system availability) would be maximized but the other two would be zero. This is problematic because an enormous mass of spares won't do one much good if the crew cannot be sustained and don't have any science equipment for them to use and a large supply of crew provisions won't help if critical systems fail. There needs to be a balance of all three parameters for mission success.

A better strategy then becomes to determine the manifest mix that maximizes the number of crew surface days that can be gained given the available mass of cargo. This is done by solving the following two equations for M_{CP}, M_S, and M_{EI}:

$$\alpha M_{CP} = \beta M_S = \gamma M_{EI} \quad (17)$$

$$M_{CP} + M_S + M_{EI} = M_{total} \quad (18)$$

The α, β and γ coefficients are defined as follows. Alpha, α, is the increase in crew surface duration for a fixed crew size gained by launching one additional kilogram of crew provisions mass. For the lunar campaign alpha is easy calculated as one divide by the mass of crew provisions needed to support a crew of four for one day.

$$\alpha = 1 \text{ kg} \div 23.34 \text{ kg/day} = 0.043 \text{ days/kg} \quad (19)$$

Beta, β, is the increase in surface duration gained by launching one additional kilogram of spares mass. Beta is not easily calculated but can be estimated from preliminary spares mass requirements (see Section 4.3.4). For the sustainment phase of the lunar campaign where all elements listed in Table 23 are operational on the lunar surface, beta

can be calculated as one divided by the estimated mass of spares required per day. Note that this beta is a conservative estimate that represents a desired system availability of 1.0 for all elements.

$$\beta = 1 \text{ kg} \div 14.3 \text{ kg/day} = 0.070 \text{ days/kg} \qquad (20)$$

Gamma, γ, is the increase in days of science gained by launching one additional kilogram of exploration items. As was mentioned earlier in this document, the current plan is to fly 3 kg of exploration items per mission day on the lunar surface [3]. Gamma can then easily be calculated as one divided by three.

$$\gamma = 1 \text{ kg} \div 3 \text{ kg/day} = 0.330 \text{ days/kg} \qquad (21)$$

Given a total cargo mass to be allocated and using the α, β and γ parameters described above, equations (17) and (18) can then be solved for the best crew provision mass (M_{CP}), spares mass (M_S) and exploration items mass (M_{EI}). The corresponding maximum surface duration to be gained can also be found by multiplying out any of the three terms in equation (17).

As an example if one were to determine the best way to allocate the 7,288 kg available to be pre-positioned from the buildup phase, the following set of equations would need to be solved:

$$0.043M_{CP} = 0.070M_S = 0.330M_{EI} \qquad (22)$$

$$M_{CP} + M_S + M_{EI} = 7{,}288 \qquad (23)$$

Using a computation tool such as Excel or Matlab, the best solution is found to be:

$$M_{CP} = 4{,}177.7 \text{ kg},$$

$$M_S = 2{,}566.16 \text{ kg},$$

$$M_{EI} = 544.14 \text{ kg},$$

and the surface duration gained = 179 days.

This result is illustrated in Figure 35. The 179 days of surface duration gained means that this stockpile is enough to sustain the crew for an entire 6-month increment in the event of a flight delay or cancellation.

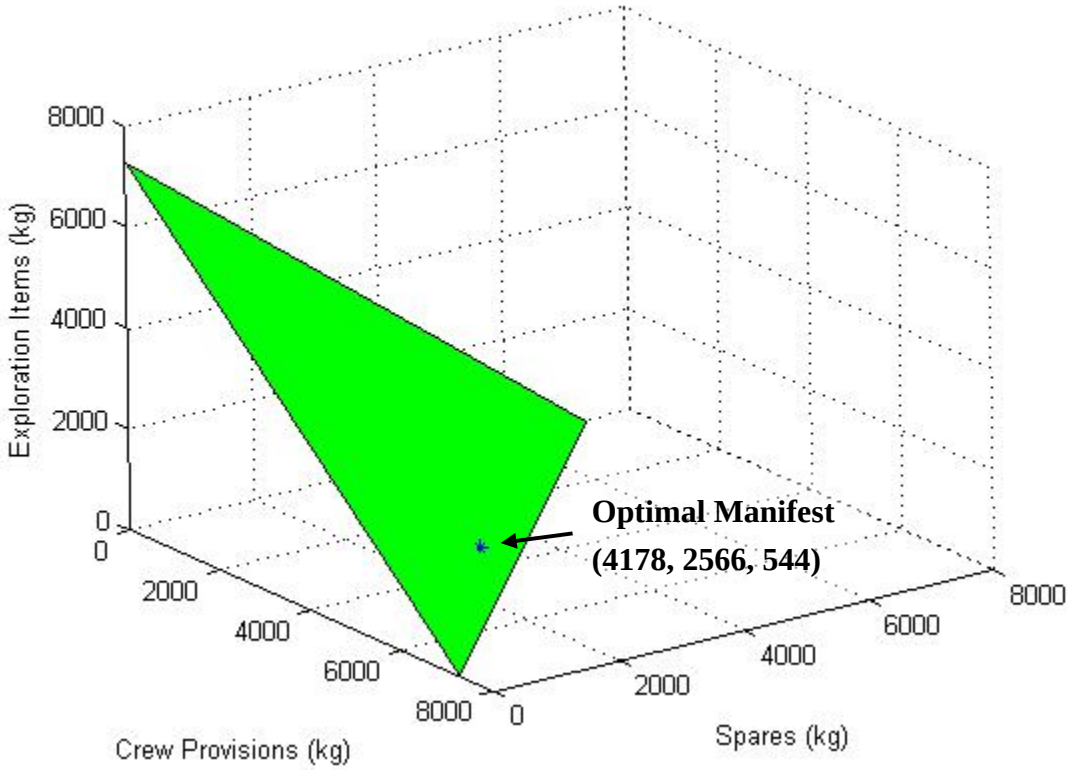

Figure 35: Best Solution for Pre-Positioning 7,288 kg

4.4 Flight Cancellation Sensitivity

4.4.1 The Buildup Phase

The next trade performed was an analysis of the impact of removing a flight from the baseline buildup architecture. This study seeks to quantify the robustness of the supply chain to disruptions in the flight schedule. To perform this study, each flight in the buildup phase was removed one at a time and the impact on the MOEs determined.

This trade study is a bit misleading because in reality if a flight were to be cancelled for technical, budgetary or other reasons, a lot of discussion would need to occur to decide whether the campaign could go on without the elements and cargo slated to be delivered on this flight or whether these elements and cargo should be flown on a later flight. For this analysis, however, we were forced to take a more simplistic approach and assume

that if a flight is cancelled, the elements (rovers, habitats, etc.) originally slated to be on that flight are no longer a part of the campaign. Any critical cargo (food, water, etc.) slated to launch on that flight, would, however be re-manifested on the next flight.

To perform this trade, SpaceNet was used to systematically remove one flight at a time from the LAT buildup campaign. The effect on the relative exploration capability and cargo capacity to the surface was noted. The results are shown in Figure 36. Also shown is the baseline buildup case for comparison. In the figure the bar graph represents the REC of the buildup campaign without the flight listed on the x-axis. The line graph illustrates the decrease in cargo capacity to the surface when the flight on the x-axis is removed. In this study cargo capacity is meant to include all classes of supply except the elements (COS 8 and 9).

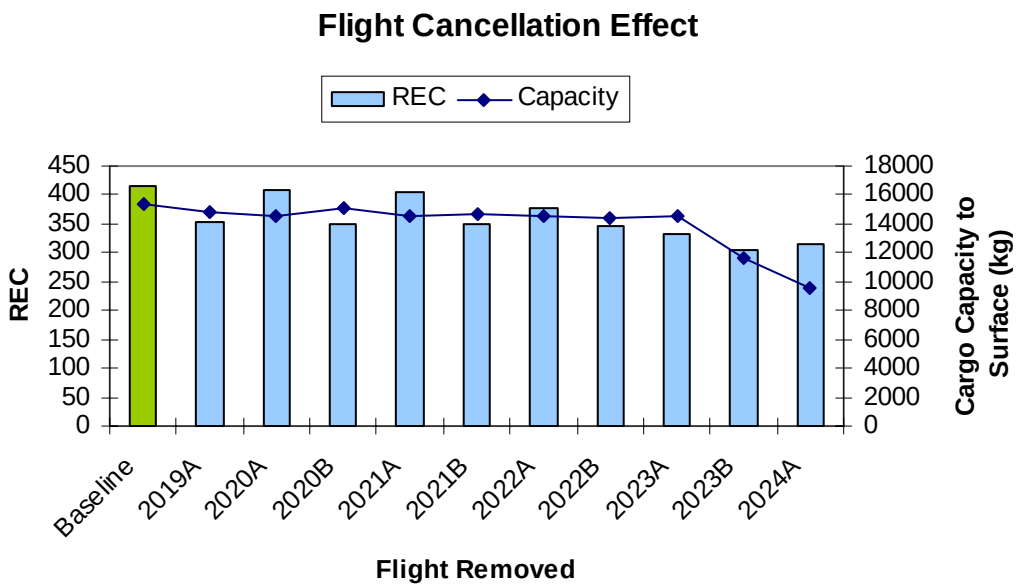

Figure 36: Effect of Flight Cancellation on REC and Buildup Phase Cargo Capacity to Surface

From the graph it can be observed that removing one flight from the campaign causes the REC to vary between the baseline high value of 419 and a low of 306, when the 2023B mission is removed. The REC for the removal of the 2023B mission is the lowest due to the fact that the removal of this mission not only removes 120 (30×4) crew surface days from the campaign, it also foregoes the delivery of the 2.2 metric ton in-situ resource utilization (ISRU) unit. Removal of the 2024A mission also takes away 120 crew surface

days but does not impact the delivery of any elements to the lunar surface as this flight delivers only crew and cargo; so its REC is not impacted quite as severely.

The cargo capacity to the surface varies between the baseline value of 15,360 kg and a low of 9,570 kg when the 2024A mission is removed. This mission has the largest impact on the cargo capacity because it is the only mission in the buildup phase that does not deliver any elements to the surface; only cargo.

4.4.2 The Sustainment Phase

The next trade study performed was to examine the robustness of the sustainment phase to the cancellation of a flight. The first thing to note is that one of the major goals of the sustainment phase was to simulate a 2.5 year Mars mission by having a continuous human presence at the lunar outpost for 5 back-to-back 180-day increments; if any of these 5 increments are cancelled this goal will not be achieved.

Using SpaceNet, each flight of the sustainment phase was removed one at a time and the resultant relative exploration capability and cargo capacity to the surface for the campaign was noted. The results are shown in Figure 37. From this figure it can be observed that because these 5 missions are almost identical (varying only in whether a rover is delivered on that mission or not), the removal of any one flight has nearly the same effect on REC and cargo capacity. Not surprisingly, each scenario resulted in a ~20% reduction of REC and a ~20% reduction in cargo capacity to the surface.

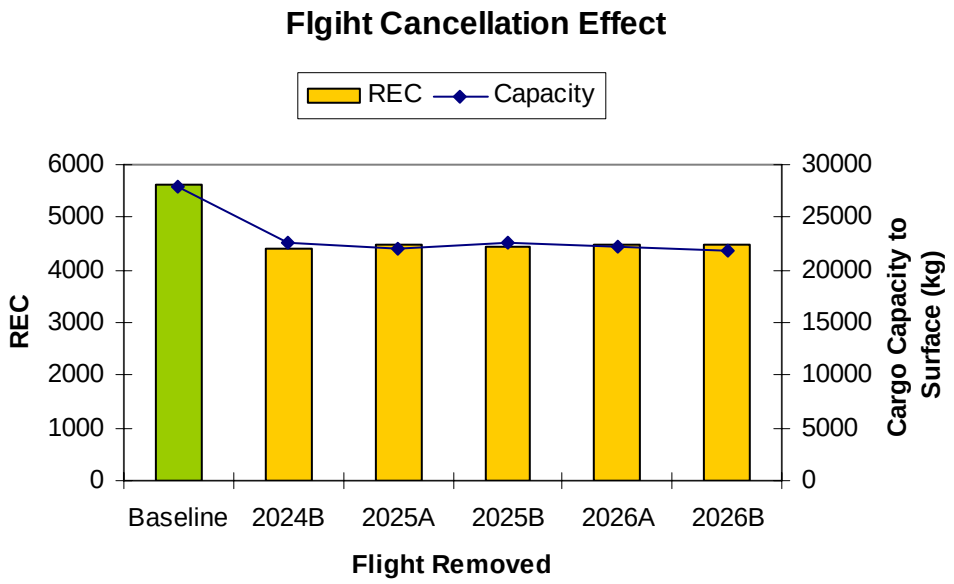

Figure 37: Effect of Flight Cancellation on REC and Sustainment Phase Cargo Capacity to Surface

This analysis has examined the vulnerability of the campaign to the removal of a single flight. It was found that removal of the 2023B or 2024A missions during the buildup phase has the largest effect on the campaign. If the 2024A mission is cancelled, the cargo capacity to the surface of the entire buildup phase is decrased by 38% and the campaign is severly hindered. It was also shown that removal of any one of the five flights in the sustainment phase has a nearly equivalent effect of decreasing both the cargo capacity and the REC of that phase by ~20%.

4.5 Flight Delay Sensitivity

Due to factors such as weather and technical delays the probability of the space shuttle launching on the first scheduled launch attempt has historically been low. Space shuttle launch data from 1981-1998 shows that out of 158 launch attempts, 67 (or 42%) were scrubbed [52]. While it is hoped that this number will be lower for future programs, it is unrealistic to think that the possibility of a launch scrub will be completely eliminated; thus it is important to study the effects of a delayed mission on the lunar campaign.

The effects of a flight delay on the campaign are best studied in the sustainment phase

when a permanent human presence is being maintained at the lunar base. This study therefore seeks to quantify the maximum delay that the sustainment phase can absorb without having to abandon the outpost. For this analysis the baseline LAT sustainment phase (Section 3.2.2) is used following an assumed successful completion of the buildup phase of the LAT Phase I architecture with two dedicated cargo flights. It was shown in Section 3.5.3 that this buildup phase is sufficient to close the architecture and pre-position 4,659 kg of contingency cargo at the outpost.

When considering the effects of a launch delay on the campaign it is important to consider both the effects of the delay of an Ares I and an Ares V, as the consequences may be very different. To begin this analysis it was first necessary to consider the decision process that would occur following the realization that the launch of either the Ares I or Ares V would be delayed. The resultant decision trees for these two cases are shown in Figure 38 and Figure 39. Each decision tree illustrates the consideration given for a launch delay of 30 days, 6 months and 1 year. In reality launch delays can be as short as one day or as long as a several years, depending on what caused the delay. The consequences of a launch delay of only a few days are usually minor and so will not be addressed in this analysis.

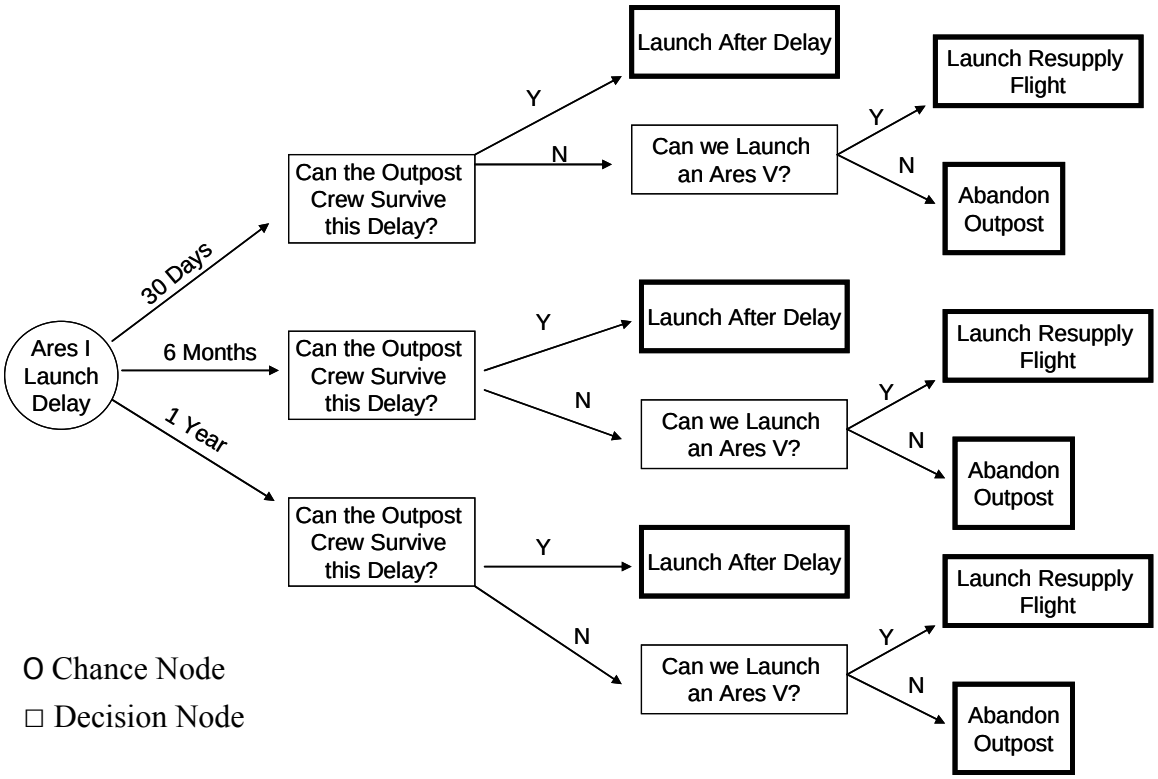

Figure 38: Decision Tree for Ares I Launch Delay

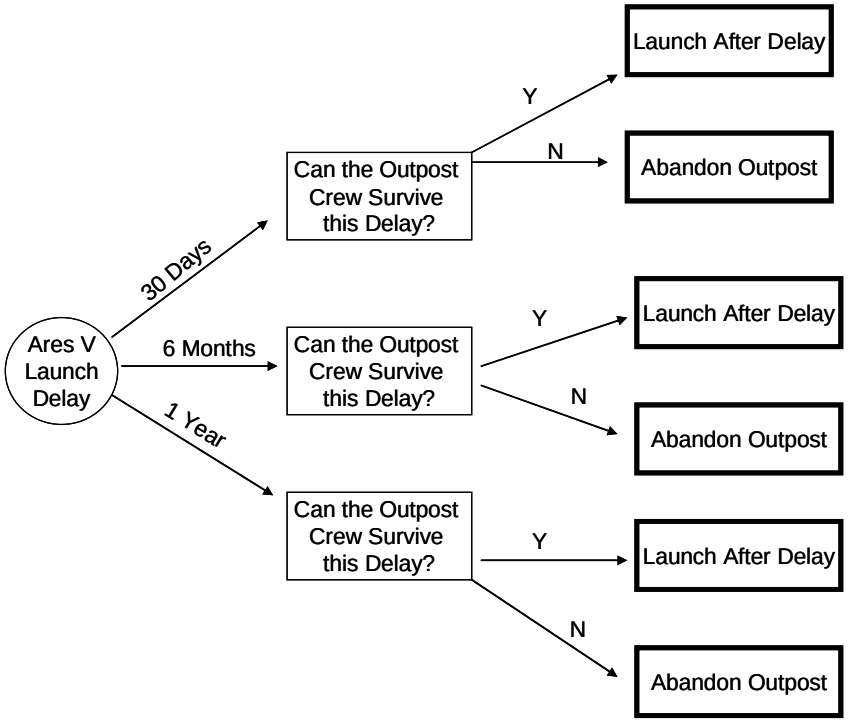

Figure 39: Decision Tree for Ares V Launch Delay

The underlying question when faced with a launch delay during the sustainment phase is "are there sufficient supplies at the lunar outpost for the crew to be able to remain at the outpost until the vehicle is able to launch?" If the answer to this question is "yes" then the impact to the campaign is minimal and the schedule simply shifts forward in time. If the answer is "no" then consideration must be given to whether there is any method of getting additional supplies to the crew or if the outpost must be (temporarily) abandoned. If the delay is with the Ares I, it is possible that an Ares V could still be launched or is already in LEO awaiting rendezvous with the CEV that was slated to be launched on the Ares I. Depending on the circumstances it may be possible to alter the mission plans to send an unmanned cargo mission to the outpost to sustain the crew that is already there. If not, the outpost crew will need to abandon the outpost once their supplies run out.

If the delay is with the Ares V, the options are limited to either waiting out the delay with the supplies stockpiled at the outpost or abandoning the outpost. Since the Ares I is designed specifically to launch the CEV to LEO, it is not capable of launching the Earth departure stage (EDS), the stage required to transport elements from Earth orbit to lunar orbit, and so the option to transport crew and cargo to the Moon is lost if the Ares V is grounded.

In order to determine the length of delay that can be absorbed into the sustainment phase, it is necessary to employ the methodology presented in Section 4.3.6. Using these equations one can determine the number of days of supplies that can be pre-positioned during the buildup phase with the 4,659 kg of available cargo. This leads to the following two equations:

$$0.043M_{CP} = 0.070M_S = 0.330M_{EI} \qquad (24)$$

$$M_{CP} + M_S + M_{EI} = 4{,}659 \qquad (25)$$

Which yields:

$$M_{CP} = 2{,}671 \text{ kg},$$

$$M_S = 1{,}640 \text{ kg},$$

$$M_{EI} = 348 \text{ kg},$$

$$\text{Surface Duration Gained} = 114 \text{ days.}$$

These results indicate that the outpost crew could sustain a delay of up to 114 days or almost four months.

Another consideration that could be made is whether it is more advantageous to maintain a safety stock comprised mostly of crew provisions and run the risk that system availability declines below 1.0 and that the crew runs short on exploration/science equipment. To perform this analysis, the coefficients for the spares and exploration items in equation (24) would need to be modified appropriately and the results re-calculated. As an example, suppose we were to decrease the safety stock of exploration items to provide 1.5 kg/day instead of the nominal 3 kg/day. Equation (24) then becomes:

$$0.043M_{CP} = 0.070M_S = 0.660M_{EI} \qquad (26)$$

and the solution becomes:

$$M_{CP} = 2{,}774 \text{ kg,}$$

$$M_S = 1{,}704 \text{ kg,}$$

$$M_{EI} = 181 \text{ kg,}$$

$$\text{Surface Duration} = 119 \text{ days.}$$

Notice from this solution that decreasing the safety stock of exploration items by 50% only increased the surface duration by 5 days. If one were to consider decreasing the safety stock of spares by 50% instead, equation (20) then becomes:

$$0.043M_{CP} = 0.140M_S = 0.330M_{EI} \qquad (27)$$

and the solution becomes:

$$M_{CP} = 3{,}241 \text{ kg,}$$

$$M_S = 996 \text{ kg,}$$

$$M_{EI} = 422 \text{ kg,}$$

$$\text{Surface Duration} = 139 \text{ days.}$$

This 50% reduction in the spares stockpile buys the crew an extra 25 surface days, with the understanding that there is a risk that the system availability may fall below 1.0 during the mission due to the reduction in the mass of spares maintained in the stockpile.

The relationship between the mass of the stockpile of crew provisions, spares and exploration items at the lunar outpost and the contingency duration this stockpile provides is linear as can be seen in Figure 40. For the nominal consumption rates shown in Equation 24, the slope of this line is ~41 kg/day for a crew of four.

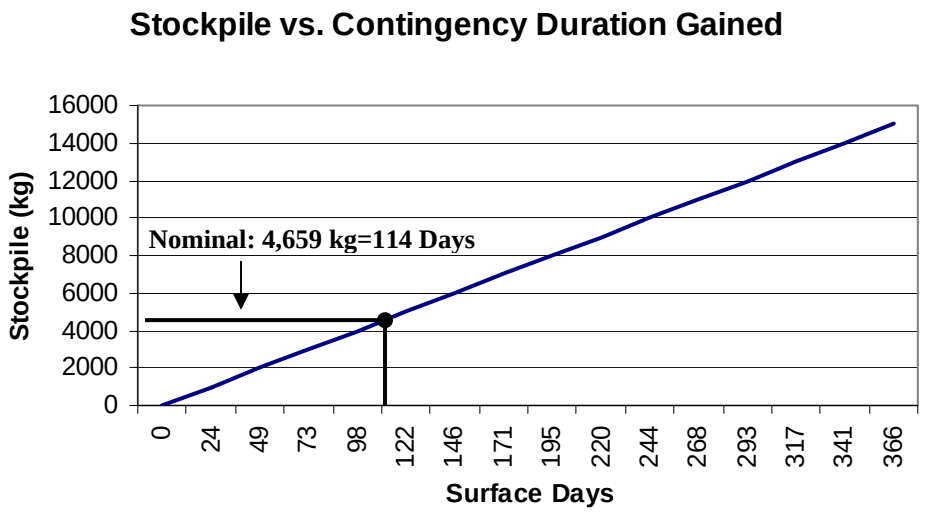

Figure 40 : Stockpile Mass vs. Contingency Duration for 4 Crew

4.6 Summary of Chapter 4

This chapter presented a discussion of campaign level risks that pose a threat to the human lunar exploration architecture. An analysis of the effects of a flight cancellation during the buildup phase, a flight delay during the sustainment phase and variations to the demand for several critical supply items was examined.

Following this analysis, a single recommendation can be made to reduce the potential effects of a campaign level risk on the architecture. The recommendation is to ensure that the lunar architecture has sufficient capacity to allow for the pre-positioning of critical supplies at the lunar outpost. It is recommended that an additional unmanned cargo flight be added to the architecture to meet this need. To determine the best mix of crew provision (which provide endurance to the campaign by allowing the crew to remain on the lunar surface for a longer duration), spares (which increase system availability), and exploration items (which increase the amount of science/exploration

that can be done) to pre-position, a methodology was presented in Section 4.3.6. This methodology is adaptable and can be easily modified as demand parameters are updated or priorities are re-evaluated.

The next chapter will summarize the significant findings of this work and will present several recommendations based upon these findings.

5 Conclusions and Recommendations

This chapter presents the important conclusions that can be drawn from the work summarized in this thesis as well as potential areas of future work. Several recommendations to NASA's Constellation Program are also presented based upon the results of this research. These recommendations seek to improve the logistics of returning humans to the Moon as well as to ensure that substantial forethought is given to ensuring that the mission architecture is robust to uncertainties in schedule and demand; which history has shown are bound to happen.

5.1 Significant Findings

The goal of this thesis is two-fold. The first is to explain the modeling framework, SpaceNet, which was developed to perform trade studies on the logistical aspects of campaigns of human spaceflight missions. The second goal is to present the results of several trade studies performed using SpaceNet. These trade studies focused on analyzing notional mission architectures in terms of scientific benefit, logistical overhead and robustness to campaign level risks. Several significant findings have been presented in the results of this research. These include:

- The Value of Integrated Modeling and Simulation of Campaign Logistics
- The Best Logistics Strategy for the Establishment of a Lunar Outpost
- Suggestions to Reduce Campaign Level Risk

Each of these findings will be discussed further in the following sections.

5.1.1 The Value of Modeling and Simulation

This thesis presented a modeling and simulation tool, SpaceNet, designed to evaluate the logistics of conducting campaigns of space missions. As the complexity of human spaceflight programs continues to grow the value of being able to model and simulate the logistics of campaigns of missions has become increasingly realized. As Chapter 2 described, SpaceNet is one of only a few modeling and simulation tools in existence that looks at the logistics of human spaceflight through methodologies commonly used in

terrestrial logistics.

Several key contributions to the field of space logistics have been made during the development of SpaceNet. These include:

- The development of a functional supply classification for human space exploration (Figure 13 and [41]). This classification is a robust high-level classification, independent of organizational boundaries and specific supply item or mission requirements.
- Detailed modeling of demand parameters at the supply class and sub-class level (Appendix C). This ability allows the user to quantify the needs of the scenario and to ensure that these needs can be satisfied by the proposed architecture.
- The development of nine measures of effectiveness (MOEs) that allow for easy comparison between scenarios (Section 2.6). By looking at the MOEs one can quickly determine whether one scenario is advantageous over another scenario in terms of exploration capability, relative cost, etc.
- The ability to model entire campaigns of space missions and to compare campaigns in terms of their exploration capability, relative cost, etc.

SpaceNet was used to conduct the research detailed in Chapters 3 and 4, the results of which will be summarized in the following sections.

5.1.2 The Best Logistics Strategy

An old military adage states that although tactics wins battles, logistics wins wars. While this notion seems to be well accepted in the domain of the U.S. Military, the importance of designing for logistics is still often overlooked in complex engineering projects such as those in support of human spaceflight. The work presented in this thesis has highlighted several important space logistics considerations. These include:

- The best mix of pre-positioning, carry along and resupply missions.
- The best mix of manned and unmanned missions.
- The importance of looking at the cargo capabilities of the campaign as a whole.

The analysis in Chapter 3 concluded that the establishment of a lunar outpost relies on a mix of manned (carry-along, pre-positioning) and unmanned (pre-positioning and resupply) missions. It was shown that the LAT Phase I architecture, which utilized solely manned missions, was ~11,500 kg short of "closing" and was therefore not a sustainable architecture. Inclusion of two unmanned cargo missions late in the buildup phase allowed the architecture to close and allowed for the pre-positioning of ~4,600 kg of contingency supplies at the outpost. The breakdown of mission types utilized in the closed LAT architecture is shown in Figure 41. From the figure, it can be seen that the 10 build-up phase missions (67% of the total number of missions) are considered pre-positioning missions, while the 5 sustainment phase missions can be considered a blend of the carry-along and resupply paradigms.

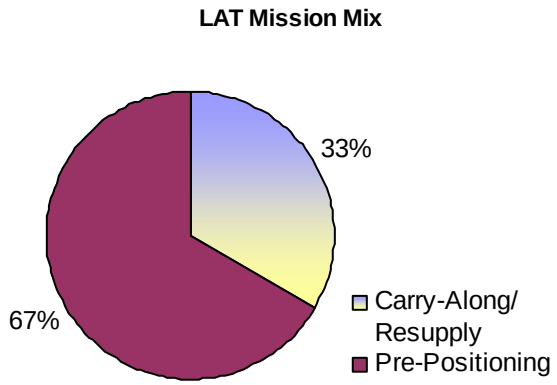

Figure 41 : LAT (Build-up + Sustainment) Mission Mix

When the MOEs from several different campaign architectures with an equal number of launches were compared, it was shown architecture that employ both manned and unmanned missions tend to have higher ratios of relative exploration capability (REC) to relative scenario cost (RSC). The current non-sustainable LAT architecture employs 15 manned missions, while the modified LAT architecture, which is sustainable, employs 13 manned missions and 2 unmanned missions. This mix of missions allows for the pre-positioning of additional supplies on the lunar surface and lowers the cost of the campaign as a whole.

The REC to RSC ratio is also depended on the surface duration of the buildup missions. Campaigns that have fewer manned missions with longer surface durations, such as the ESAS Baseline and ESAS All Outpost campaigns, tend to exhibit high ratios of REC to RSC due to the fact that the landed-mass investment is amortized over a longer duration. The high REC to RSC ratio makes this type of campaign very attractive.

5.1.3 Suggestions to Reduce Campaign Level Risk

Another important result presented in this thesis is the robustness of the proposed mission architecture to what has been referred to in Chapter 4 as *campaign level risk*. The three sources of campaign level risk analyzed were: uncertain mass demand, flight cancellation and flight delay.

The analysis presented earlier determined that the LAT architecture with two dedicated cargo flights is very susceptible to uncertainty in the demand parameters. This vulnerability is due to the fact that nearly all of the cargo capacity to the surface of the campaign is needed to sustain the crew leaving very little excess capacity to protect for uncertainty. The realization that the variation in ECLSS closure could end up requiring that an additional unmanned cargo flight be added to the architecture stresses the importance of investing in technologies to produce a high reliability ECLSS system with a closure as close to 1.0 as possible.

This research suggests that the best way to reduce the impact of these risk factors on the lunar campaign is to modify the campaign such that the capability to pre-position contingency supplies is increased. The addition of at least one additional unmanned cargo mission (above and beyond the two necessary to close the architecture) is recommended. In order to determine the best mix of cargo to include in this safety-stock, the methodology presented in Chapter 3 should be utilized to calculate the mass of crew provisions, spares and exploration items that will maximize the surface duration.

5.2 Recommendations to NASA's Constellation Program

Based upon the significant findings in this thesis the following recommendations are made to NASA's Constellation Program:

- As new lunar campaigns are presented, perform campaign level analysis to quantify the closure of the architecture, the capability of the architecture to maintain a safety-stock and the robustness to campaign level risk.
- Adopt the functional classification for space exploration supply classes (or one similar to it) for use by future human space exploration programs.
- Increase the surface duration of the early buildup flights to increase the ratio of exploration capability to cost.
- Add at least two dedicated cargo flights to the LAT Architecture to allow the architecture to close.
- Invest in technologies to improve ECLSS Closure.
- Maintain at least a 90-day safety stock of consumables at the lunar outpost to protect against uncertainty in launch scheduling and demand. A 90-day safety stock of consumables for a crew of 4 is ~2,100 kg.

5.3 Future Work

Several areas of future work are being proposed as follow-on work to this research. These areas broadly fall into two categories, improvements to SpaceNet and further analysis.

The following is a prioritized list of highly desired SpaceNet improvements:

- The ability to copy processes so that once the user defines a process (or an entire flight) he/she never has to define it again. (When a process (or flight) is copied, SpaceNet should know to use another instantiation of the same elements.)
- The ability to group processes so that one can add/delete an entire flight(s) easily and rerun the simulation.

- The ability to calculate demand and manifest flight by flight (flights would have to be defined as process groups by the user) <u>or</u> for the whole scenario (as is presently done)
- The ability for batch mode to be able to vary a lot more parameters, for instance demand parameters. As an example if one could have the ability to vary Crew Provisions: Water/crew/day or Food/crew/day and make a 3-D plot of the resultant total CP mass required for a certain scenario that would be very useful.
- Modify the exploration capability MOE to account for the fact that there is decreasing marginal benefit of always returning to the same node. This decrease in marginal benefit is not accounted for presently in any of the MOEs.
- Develop MOEs that take into account the robustness of the campaign to the types of campaign level risks described in Chapter 4.
- Develop a more user friendly way to save campaign histories to excel (right now this feature takes a really long time for long campaigns). Adding the option to save data in larger time increments (i.e. every 10 days) would make this process run faster.

The following is a list of follow-on analysis that should be performed to continue this work:

- Perform volume sensitivity analysis similar to the consumable mass sensitivity analysis in Section 4.2.3.
- Compare results received for the cargo demand and COS mix over the sustainment phase at the lunar outpost with those experienced on ISS.
- Rerun the analysis described in Chapters 3 and 4 on the latest Constellation Mission Architecture, once released.

Appendix A: ISS Flight Log 1998-2006

The following table shows the schedule of ISS flights from 1998-2006 [33] [31] [36].

Flight	Vehicle	Launch Date	Number of Crew	Est. Cargo Up Mass (kg)	Est. Cargo Down Mass (Kg)	Notes
1A/R	Proton	11/20/1998	0	13260	N/A	Launch of FGB
2A	Shuttle - Endeavour	12/4/1998	7	11600	0	Launch of Node 1
2A.1	Shuttle - Discovery	5/27/1999	7	14000	0	Supply Mission
2A.2a	Shuttle - Atlantis	5/19/2000	7	14000	0	Supply Mission
1R	Proton	7/12/2000	0	20000	N/A	Launch of Service Module. 14 day Rendezvous.
1P	Progress M1-3, #251	8/6/2000	0	2230	1000	Resupply
2A.2b	Shuttle - Atlantis	9/8/2000	7	14000	0	Supply Mission and Maintenance
3A	Shuttle - Discovery	10/11/2000	7	14800	0	Launch of Z1 and PMA 3
2R	Soyuz TM-31, #205	10/30/2000	3	255	255	First Soyuz Docking to ISS: Arrival of first 3 person crew (E1 Up)
2P	Progress M1-4, #253	11/15/2000	0	2230	1000	Resupply
4A	Shuttle - Endeavour	11/30/2000	7	18740	500	Launch of P6 Truss
5A	Shuttle - Atlantis	2/7/2001	7	15000	500	Launch of U.S. Lab
3P	Progress M-44, #244	2/26/2001	0	2350	1000	Resupply
5A.1	Shuttle - Discovery	3/8/2001	7	14000	12500	MPLM Resupply Mission (Leonardo), Crew Rotation (E2 up)
6A	Shuttle - Endeavour	4/19/2001	7	13744	12500	MPLM Resupply Mission (Raffaello), Launch of Canadarm2
2S	Soyuz-TM-32, #206	4/28/2001	3	255	255	Soyuz Changeout
4P	Progress-M1-6, #255	5/20/2001	0	2230	1000	Resupply
7A	Shuttle - Atlantis	7/12/2001	7	13872	500	Launch of Joint Airlock
7A.1	Shuttle - Discovery	8/10/2001	7	15107	500	Crew Rotation (E3 up)
5P	Progress-M45, #245	8/21/2001	0	2350	1000	Resupply

Flight	Vehicle	Launch Date	Number of Crew	Est. Cargo Up Mass (kg)	Est. Cargo Down Mass (Kg)	Notes
4R	Progress-M1-DC1	9/14/2001	0	2230	1000	Launch of cargo crane and Docking Compartment
3S	Soyuz TM-33, #207	10/21/2001	3	255	255	Soyuz Changeout
6P	Progress-M1-7, #256	11/26/2001	0	2230	1000	Resupply
UF-1	Shuttle - Endeavour	12/5/2001	7	14000	12500	Resupply Mission - MPLM. Crew Rotation (E4 Up)
7P	Progress-M1-8, #257	3/20/2002	0	2230	1000	Resupply
8A	Shuttle - Atlantis	4/8/2002	7	15193	500	Launch of S0 Truss and Mobile Transporter
4S	Soyuz-TM-34, #208	4/24/2002	3	255	255	Soyuz Changeout
UF-2	Shuttle - Endeavour	6/5/2002	7	14622	12500	Resupply Mission - MPLM. Crew Rotation (E5 Up)
8P	Progress-M46, #246	6/26/2002	0	2350	1000	Resupply
9P	Progress-M1-9, #258	9/26/2002	0	2230	1000	Resupply
9A	Shuttle - Atlantis	10/7/2002	7	15305	500	Launch of S1 Truss
5S	Soyuz-TMA-1, #211	10/29/2002	3	355	305	Soyuz Changeout
11A	Shuttle - Endeavour	11/23/2002	7	14934	500	Launch of P1 Truss. Crew Rotation (E6 Up)
10P	Progress M-47, #247	2/1/2003	0	2350	1000	Resupply
6S	Soyuz TMA-2, #212	4/26/2003	3	355	305	Crew Rotation (E7 Up)
11P	Progress M1-10, #259	6/8/2003	0	2230	1000	Resupply
12P	Progress M-48, #248	8/27/2003	0	2350	1000	Resupply
7S	Soyuz-TMA-3, #213	10/16/2003	3	355	305	Crew Rotation (E8 Up)
13P	Progress M1-11, #260	1/28/2004	0	2230	1000	Resupply
8S	Soyuz-TMA-4, #214	4/19/2004	3	355	305	Crew Rotation (E9 Up)
14P	Progress M-49, #249	5/24/2004	0	2350	1000	Resupply
15P	Progress M-50, #350	8/11/2004	0	2350	1000	Resupply
9S	Soyuz TMA-5, #215	10/13/2004	3	355	305	Crew Rotation (E10 Up)
16P	Progress M-51,	12/22/2004	0	2350	1000	Resupply

Flight	Vehicle	Launch Date	Number of Crew	Est. Cargo Up Mass (kg)	Est. Cargo Down Mass (Kg)	Notes
	#351					
17P	Progress M-52, #352	2/28/2005	0	2350	1000	Resupply
10S	Soyuz TMA-6, #216	4/14/2005	3	355	305	Crew Rotation (E11 Up)
18P	Progress M-53, #353	6/15/2005	0	2350	1000	Resupply
LF-1	Shuttle - Discovery	7/26/2005	7	15000	15000	Resupply mission - MPLM
19P	Progress M-54, #354	9/7/2005	0	2350	1000	Resupply
11S	Soyuz TMA-7, #276	10/1/2005	3	355	305	Crew Rotation (E12 Up)
20P	Progress M-55, #355	12/20/2005	0	2350	1000	Resupply
12S	Soyuz TMA-8	3/29/2006	3	355	305	Crew Rotation (E13 Up)
21P	Progress M-56 #365	4/23/2006	0	2350	1000	Resupply
22P	Progress M-57 #366	6/24/2006	0	2350	1000	Resupply
ULF1.1	Shuttle - Discovery	7/4/2006	7	15000	15000	Resupply mission - MPLM
12A	Shuttle - Atlantis	9/9/2006	7	7955	500	Launch of P3/P4 Truss
3S	Soyuz TMA-9	9/18/2006	3	355	305	Crew Rotation (E14 Up)
23P	Progress M-58 #367	10/26/2006	0	2400	1000	Resupply
12A.1	Shuttle - Discovery	12/10/2006	7	4045	2177	Launch of P5 Truss + SpaceHab

Appendix B: SpaceNet Scenarios

The following is a list of the SpaceNet scenarios created for this research.

Scenario Name (Description)	Scenario Date Range	# of Elements	# of Processes
Lunar_Base (ESAS Baseline)	1/1/20 – 12/31/23	55	78
Lunar_Sortie (Used for ESAS All Sortie)	7/1/18 – 7/18/18	10	18
Thesis_Base Only (ESAS All Outpost)	1/1/20 – 7/1/24	92	136
LATOutpostBuildFinal (LAT Buildup Phase)	1/1/19 – 12/31/24	113	147
LATMarsAnalog10 (LAT Sustainment Phase)	6/1/24 – 12/31/26	70	85
LATBuildupSurface (For Surface Demand Modeling)	1/1/24 – 6/1/24	3	1
LATSustainSurface (For Surface Demand Modeling)	1/1/26 – 9/1/28	3	1
LATBuildSurf3Crew (Demand Modeling with 3 Crew)	1/1/24 – 6/1/24	3	1
LATSustSurf3Crew (Demand Modeling with 3 Crew)	1/1/26 – 9/1/28	3	1
LATBuildupSurface7days (Buildup Phase with all 7 day missions)	1/1/24 – 3/10/24	3	1
LATBuildSurfDedCargo (LAT Buildup Phase w/ 1 Dedicated Cargo Mission)	1/1/24 – 6/1/24	3	1
LATOutpostBuildFinal2DedCargoA (LAT Buildup Phase w/ 2 Dedicated Cargo Missions)	1/1/19 – 12/31/24	113	125
LATOutpostBuildRem1 (Removal of Flights in Buildup Phase)	1/1/19 – 12/31/24	113	131
LATMarsCancel (Removal of Flights in Sustainment Phase)	6/1/24 – 12/31/26	70	56
LATSustainSurfStocDem (For Demand Uncertainty Analysis)	1/1/26 – 9/1/28	3	1

Appendix C: SpaceNet v1.3 Nominal Demand Parameters

The table below lists the nominal demand parameters in SpaceNet v1.3.

SpaceNet 1.3 Classes of Supply Breakdown					
Class of Supply	**Consumables**	**Value**	**Units**	**Value**	**Units**
COS 2 Crew Provisions					
Water and Support Equipment					
	Water (daily use) --Includes 42% Water Recovery Rate	2.088	kg/crew/day	2.088	liters/crew/day
	Water (EVAs)	5.500	kg/crew/EVA	5.5	liters/crew/EVA
	Sample Test/Biocide Kits	1.350	kg/kit		
Food and Support Equipment					
	Non-Food Items	0.056	kg/crew/day	0.000833	m^3/crew/day
	Ambient Food	0.764	kg/crew/day	0.0025	m^3/crew/day
	R/F (Refrigerated)\ Food	1.617	kg/crew/day	0.0075	m^3/crew/day
Gases					
	Oxygen (O2)	3.857	kg/crew/day		
	Nitrogen (N2)	2.214	kg/crew/day		
Hygiene Items					
	Daily Use	0.278	kg/crew/day	0.000833	m^3/crew/day
	Hygiene Kits	1.800	kg/crew	0.005	m^3/crew
Clothing		0.575	kg/crew/day	0.002	m^3/crew/day
Personal Items		10.000	kg/crew	0.02	m^3/crew
COS 3 Crew Operations					
Office Equipment		5.000	kg/crew	0.02619	m^3/crew
Extravehicular Activity (EVA) Equipment and Consumables					
	EVA Suit	107.000	kg/suit/crew	0.582	m^3/suit/crew
	EVA LiOH	2.900	kg/crew/EVA	0.009	m^3/crew/EVA
	EVA O2	0.630	kg/crew/EVA	9.00E-07	m^3/crew/EVA
Health Equipment and Consumables					
	Crew Health Care System (CHeCS) Equipment	20.000	kg	0.0865	m^3
	CHeCS Consumables	0.100	kg/crew/day	0.0004325	m^3/crew/day
Safety Equipment		25.000	kg	0.1	m^3
Communications Equipment		20.000	kg	0.07717	m^3
Computer Equipment		5.000	kg/crew	0.01243	m^3/crew
COS 7 Waste/Disposal					
	Trash bags	0.050	kg/crew/day	0.0013	m^3/crew/day
	Waste Containment System (WCS)	0.050	kg/crew/day	0.0013	m^3/crew/day
	Contingency WCS	0.230	kg/crew/day	0.008	m^3/crew/day

SpaceNet 1.3 Classes of Supply Breakdown Cont.					
COS 5 Stowage/Restraint					
CTB					
	Half Cargo Transfer Bag (CTB)	1.000	kg	0.0248	m^3
	Half CTB Capacity	27.220	kg	0.0248	m^3
	Single CTB	1.810	kg	0.0529	m^3
	Single CTB Capacity	45.360	kg	0.0529	m^3
	CTB % Capacity	95	%		
CWC					
	Contingency Water Container (CWC)	1.361	kg	0.0328	m^3
	CWC Capacity	32.800	kg	0.0328	m^3
COS 6 Exploration/Research					
				Sortie (7 days)	Lunar Outpost (180 days)
	GC-MS	75.000	kg/unit	1	1
	Optical Microscope	15.000	kg/unit	2	2
	APXS	5.000	kg/unit	2	2
	X-ray Fluorescence	15.000	kg/unit	2	2
	Raman Spectrometer	8.000	kg/unit	2	2
	Infrared Spectrometer	8.000	kg/unit	2	2
	Solubility wet/lab	20.000	kg/unit	1	1
	PI EXP -G	25.000	kg/unit	2	2
	PI EXP -R	25.000	kg/unit	4	4
	Monitoring Station	15.000	kg/unit	1	6
	Sieve	0.500	kg/unit	2	2
	Grinder	2.500	kg/unit	2	2
	Rock Saw	2.000	kg/unit	2	2
	Shovel	2.500	kg/unit	3	3
	Hammer	2.500	kg/unit	3	3
	Corer	2.500	kg/unit	3	3
	Laser Range Finder	7.000	kg/unit	2	2
	Hand lense	1.000	kg/unit	2	2
	Aeolian sediment trap	5.000	kg/unit	1	1
	Field Computer	7.000	kg/unit	2	2
	Still/Video Camera	4.000	kg/unit	4	4
	Drill_1_m	50.000	kg/unit	1	1
	Drill_10_m	250.000	kg/unit	0	2
	Rock Sample	1.000	kg/unit	2	39

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