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AN INTEGRATED MODELING TOOL FOR SUSTAINABLE SPACE EXPLORATION

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ABSTRACT

In order to ensure that future human lunar and Mars exploration programs are both affordable and sustainable, it is essential to consider the impact of logistics, especially for long-duration and multiple mission campaigns. It is important that logistics be taken into account at an early stage in the design process, because the exploration architecture and vehicle design undoubtedly impact logistics-related operations costs. In order to understand the specific logistics costs associated with various exploration architecture choices, a modeling framework and planning tool for interplanetary space logistics is required. Terrestrial logistics and supply chain management is a highly-developed field; techniques for efficient supply chain management have been proven very effective in the business case. The wealth of information in this area can be applied to the interplanetary problem in order to develop a model for understanding space logistics. This paper describes the space logistics model developed by personnel at Massachusetts Institute of Technology (MIT) and the Jet Propulsion Laboratory (JPL) to understand the supply chain management problem for human lunar and Mars exploration. This paper also discusses the results of several trade studies performed using this tool.

I. Introduction

Background

The term 'space logistics' might mean many different things to many different people. In this paper it is defined loosely as the movement, storage, and tracking of all crew and equipment necessary to carry out an exploration mission or campaign. With this definition, logistics encompasses nearly every aspect of space flight *operations*, but does not include the detailed design of the vehicles and equipment. In other words, throughout the work described in this paper, it is safe to assume that an initial set of vehicle characteristics and available equipment items are given. Such vehicle designs can (and should) be subjected to trade studies, evaluating their relative suitability for logistics. However, by the term space logistics, a more narrowed focus on the operations architecture for transportation and storage of cargo and crew is implied.

Furthermore, this paper is focused on what is termed 'interplanetary logistics', meaning that the ground-based component of the logistics architecture (e.g. transportation to and from the Kennedy Space Center (KSC)) is ignored, and consideration is given only to the transportation and storage of items *in space*, including launch. (It is acknowledged that ground operations are very important and a large contributor to overall costs and must be studied as well, but that study is outside the scope of this paper.) It is also worthwhile to note that the terms 'logistics' and 'supply chain management' are used interchangeably in this paper; Simchi-Levi et al. [1] does not find it necessary to define them separately, and the same model is followed here.

Logistics in Past Human Spaceflight Missions

Past human space exploration programs have followed different types of logistics paradigms. Under the Apollo program, six missions to the lunar surface were conducted between 1969 and 1972. 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-term lunar missions. This 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 missions like those of the Apollo program.

On the other hand, for the International Space Station (ISS) program, a "backpack model" logistics strategy was extremely impractical because of the long duration of the mission: supplies for several years of operations could not be stored on the station. Instead, the ISS logistics strategy is based on regular resupply flights by various vehicles, including the American Space Shuttle and the Russian Progress. The number and type of supplies shipped is generally based on the actual demand generated on the Space Station, 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 not.

Figure 1 depicts the basic networks behind each of these logistics paradigms, and also includes the growing network that may 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. This leads to the question that we are string to answer in our modeling: What is the best logistics paradigm for next-generation space missions? We hypothesize that it lies somewhere on the spectrum between the “backpack” and “resupply” models, perhaps including the more specialized idea of “pre-positioning” supplies for future use, but it is unclear exactly what combination of these strategies will provide the most affordable, most robust supply chain for next-generation programs.

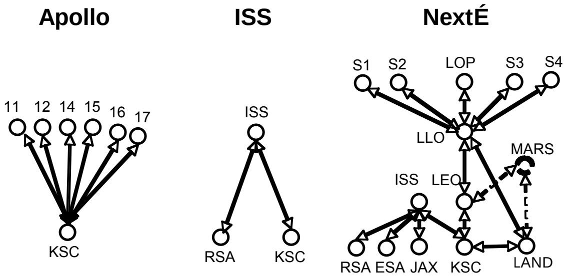

Figure 1 : Space Logistics Supply Chains

II. Modeling Framework

One of the major challenges in the development of a space logistics model is defining the model components. Interplanetary logistics has not been previously modeled, so the scope of such a model must be defined. The basic elements of the model are: Movement (shipment of people, cargo, and vehicles), Demand (by supply class), Information Architecture, Simulation and Optimization. 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 either manually define the shipment paths through the network, or use an optimization tool to find the best solution given a particular demand scenario. 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.

Building Blocks

This section describes the basic building blocks in our modeling framework: nodes, supplies, and elements. They are derived from terrestrial supply chain management and from past practices in space logistics.

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 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.

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 point, which lies between the

Earth and the Moon at the point where the two bodies' gravitational pulls are balanced.

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.

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 [2] 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 2. (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.)

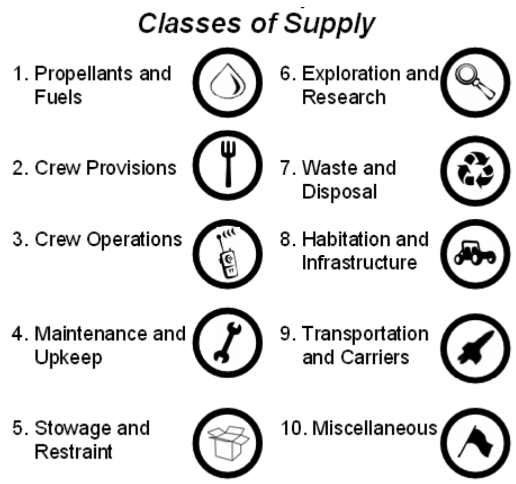

Figure 2: Functional Class of Supply for Human Space Exploration

These classes of supply can 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 [2]. 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.*

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) Orion, 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:

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* For more detailed demand forecasting, a total of 44 sub-classes of supply were developed, but these are subsequently aggregated into the ten classes shown in Figure 2.

- 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 (temporary) 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.

III. 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.

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 you take that static network and expand it over time, to account for changes in the network over time, what you then have is a simple time-expanded network (Figure 3). 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 ∆t 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 3 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 3. 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 3. 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 3 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).

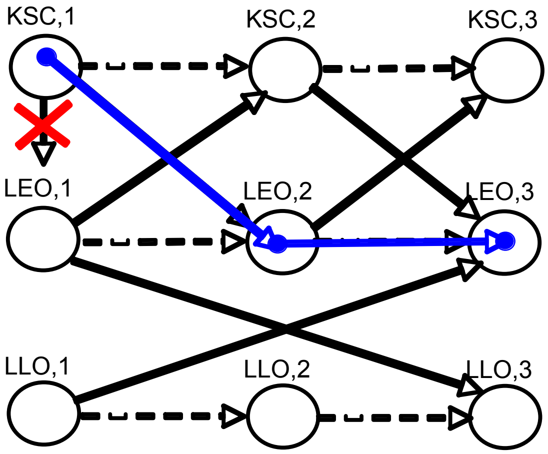

Figure 3 : Simple Time Expanded Network

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.

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 three essential processes that describe this movement:

- Waiting: remain at the same node
- Transporting: move to a new node along an allowable arc
- Transferring: transfer crew and/or supplies to a different element

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.

IV. Wrapping it Up: Optimization, Simulation, and Evaluation

The final step in building an effective modeling framework is to add wrappers that allow logistics architectures described by the model to be created, visualized, and evaluated. In the following sections, we first describe the development of an optimization capability which can return optimal logistics architectures within the modeling framework described above, based on a given demand scenario. Alternatively, logistics architectures could be created by hand. Second, we describe the essential simulation capability which takes a described architecture and simulates it to ensure demands are met, transport arcs have sufficient fuel, etc. Finally, the scenario can be visualized and evaluated using various types of tools built over the previously defined modeling framework.

Optimization

In some cases, we envision that pre-defined architectures will be evaluated against one another, resulting in a logistics trade study. In other cases, however, the best approach would be to calculate the demand for various supplies at a lunar base for example, and ask the software to find the optimal logistics architecture to supply that mission (or series of missions). This is the goal of the optimization layer. The modeling framework was specifically built to allow for optimization. The description of this capability is outside the scope of this paper; for further information refer to [3] and [4].

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.

This section describes an implementation of our modeling framework in the form of a logistics planning tool called SpaceNet. SpaceNet is a computation environment, coded in Matlab, for modeling exploration from a logistics perspective. It includes discrete event simulation at the individual mission level (e.g. sortie, pre-deploy, 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. Finally, it includes an optimization capability and acts as a software tool to support trade studies and architecture analyses.

SpaceNet is built on the modeling framework described earlier in this paper. SpaceNet provides a graphical user interface which allows analysts to describe complex space logistics architectures using the basic concepts of nodes, elements, and supplies Missions are modeled on a network of nodes and arcs, with elements carrying supplies through the network. Demand is generated based on the required length of surface stay and in-space transportation, and a simulation ensures that demands are met for a given scenario (undersupply situations are explicitly flagged as error conditions). . Built-in demand models, a unified database of nodes, vehicles, astrodynamics constraints and supplies, and an optimization capability assist the user in describing various types of supply chains. Such logistics scenarios can then be simulated and assessed for feasibility and performance.

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

Evaluation: Measures of Effectiveness

The final step is 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. 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.

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 four *basic logistics performance* measures of effectiveness:

- **Crew Surface Days [crew-days]:** The total number of crew-days over all surface nodes for the entire scenario.
- **Exploration Mass Delivered [kg]:** The total mass of exploration items and surface infrastructure delivered over all surface nodes for the entire scenario.
- **Total Launch Mass [kg]:** The total launch mass (including crew, elements, and all other COS) for the entire scenario.
- **Upmass Capacity Utilization [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.

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/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. The following set of ‘exploration capability’ MOEs captures these ideas:

- **Exploration Capability [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).
- **Relative Exploration Capability [0, inf):** A normalized measure of exploration logistics efficiency, which 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.[†] Technically, the calculation depends on the exploration capability divisia index [5] with Apollo 17 normalization.

The relative exploration capability (REC) is a powerful metric for supply chain comparison. A supply chain with a relative exploration capability greater than unity would appear to be more efficient than Apollo 17 because more exploration capability is provided for each unit of mass launched from Earth. The REC is influenced by a number of factors such as the chosen mission/transportation architecture, the use of various propulsion technologies, implemented supply chain strategies such as on-orbit depots, and the application of In-Situ Resource Utilization (ISRU) technologies. For example, the effects of ISRU can be captured: if no ISRU is applied, a certain amount of consumables directly contribute to the total launch masses. If ISRU is used, the consumables mass over the entire scenario might be reduced, but the upfront mass penalty for transporting ISRU equipment to a node in the first place would also be captured. Whether or not an investment in ISRU is worthwhile for a particular scenario can then be assessed by comparing the REC of both alternatives.

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 [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.
- **Scenario Risk [0,1]:** Defined as 1 minus the probability that there are no failures in all launches, rendezvous-and-dockings, and landing for the entire scenario.

This section has provided an overview of the measures of effectiveness that make up the evaluation portion of this modeling framework. Specific equations and significantly more detail can be found in [6].

V. Use Cases

With the modeling framework described above, we have modeled both single 'sortie' missions and entire campaigns such as the lunar outpost build-up. Specific sortie misisons we have modeled include Apollo 11, Apollo 17, and the basic Constellation sortie. The two major campaigns modeled in SpaceNet presently are the build-up and operation of the Constellation lunar base (four base pre-deploy missions and the crew/re-supply cycle), and a two-year historical ISS assembly and re-supply scenario.

Table 1 shows a comparison between the MOEs calculated for the Apollo 17, Constellation Sortie and Constellation Lunar Base scenarios. Apollo 17 serves as the baseline. We see that a single constellation sortie mission is expected to have a relative exploration capability that is about 9 times larger than that of Apollo 17. This means that for every kg of mass launched from Earth about 9 times more exploration capability is expected to be provided for a constellation sortie than an Apollo sortie. This is due to the combination of larger crew size, longer surface stay and more exploration mass taken along to the lunar surface. The total launch mass is also larger due to the split launch (1.5 launch) Earth Orbit Rendevous (EOR) architecture; but only about 25% more than a single Saturn V launch.

	Baseline: Apollo 17	*Constellation Sortie 1*	*Constellation Lunar Base*
Crew Surface Days (man-day)	6	28	1980
Exploration Mass Delivered (kg)	415	1171	4828[‡]

[†] 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.

[‡] Only reflects class of supply 6 (Exploration Items) does not yet reflect the mass of class of supply 8

	Baseline: Apollo 17	*Constellation Sortie 1*	*Constellation Lunar Base*
Exploration Capability (man-day-kg)	2490	32793	4,781,720
Relative Exploration Capability	1	9.7	201.3
Total Launch Mass (MT)	2928	3975	27119
Up Mass Capability Utilization	0.931	1.0	0.348[§]
Relative Scenario Cost	1	1.7	106.7
Scenario Risk	0.004	0.006	0.032

Table 1 : MOE Calculations for 3 SpaceNet Scenarios

It is also apparent from the table that the entire Constellation Lunar Base Scenario from 2020-2022 (3 years) has a relative exploration capability of about 200 more than Apollo. This is because delivered mass and infrastructure is being reused by subsequent missions. The relative scenario cost is significantly larger (about 63 times larger) than a single sortie mission, because it is dominated by the operational cost term; the Lunar Base Scenario has more elements and 36 months of operations versus only 1 month for a single sortie mission.

Figure 4 shows the overall tradespace of these space logistics scenarios. The x-axis represents total launch mass (TLM) in metric tons. The y-axis shows Exploration Capability (EC) in [man-day-kg]. Note that the y-axis is shown on a logarithmic scale.

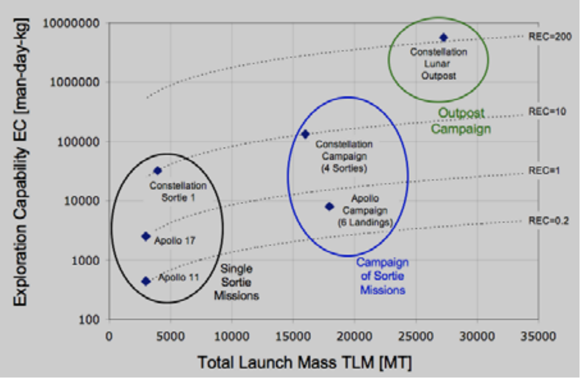

Figure 4 : Space Logistics Trade Space

Various scenarios that were simulated with SpaceNet are shown in this space. The graph can be augmented by showing the lines of constant relative exploration capability (REC), i.e. a measure of space logistics efficiency. The REC lines are parallel lines in this plot with iso-REC lines of higher efficiency providing more EC for the same TLM. Single sortie missions are shown in the lower left corner, campaigns of (disconnected) sortie missions are in the middle and outpost missions are in the upper right. It is clear that the Apollo and Constellation campaigns consisting of a series of sorties (center oval) have exploration capabilities equivalent to multiples of each single campaign. Thus, the relative exploration capability (REC) is the same. However, the lunar outpost mission builds upon the equipment and supplies left by previous missions, so it can gain in relative exploration capability. Such results prove that an early focus on the logistics strategy can help planners to enhance returned value (exploration capability).

In summary, several Interesting insights can be obtained from this chart:

- A set of sortie missions that all use the same transportation architecture, elements and technology will always fall unto the same iso-REC line
- The constellation sortie missions are about 10 times more efficient than the Apollo sortie missions. This is mainly due to advances in technologies (e.g. propulsion).
- Another order of magnitude in logistics efficiency can be gained by reusing previously delivered exploration mass in subsequent missions, as is done in the lunar outpost scenario (REC ~ 200). Thus, logistics strategies such as pre-

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(Habitation and Infrastructure) taken to the Moon as elements.

[§] The up mass capacity utilization for the lunar campaign is lower because we have not fully taken advantage of cargo capacity of the LSAM because some cargo has been modeled as elements (e.g. ISRU power plant, rovers etc.)

deployment can also improve logistics efficiency.

VI. Trade Studies

The previous section described scenarios built by the SpaceNet team mostly for internal testing of the model and demonstrative purposes. The next few sections will present results obtained when SpaceNet was used to perform trade studies for an external customer, NASA's Constellation Program. Personnel at MIT and JPL used SpaceNet in July and August of 2006 to perform trade studies for the Constellation Program's Integrated Design Analysis Cycle 2 (IDAC2). The details of two of these trade studies, along with some generalized results are presented here. Note that because of the sensitive nature of the data involved in these studies, many results are expressed verbally rather than numerically and/or have been normalized. The specific trades performed were:

A. CaLV/CLV Launch Architecture Trade
B. Integrated ISS Resupply Scenarios

A. CaLV/CLV Launch Architecture Trade

The purpose of this trade study was to assess launch architecture trades between a single (1) or dual (2) Cargo Launch Vehicle (CaLV) launch versus the baselined (1.5) Crew Launch Vehicle (CLV) + CaLV launch Earth orbit rendezvous-Lunar orbit rendezvous (EOR-LOR) architecture in terms of exploration capability and logistics for Lunar Surface missions. Other issues that were considered qualitatively include risk to crew and schedule, impact of LEO loiter time variations and launch scrub probabilities, delta recurring and non-recurring costs of development and operations.

Assumptions and Groundrules

The following assumptions and ground rules are critical to this study:

- Vehicle-launch masses for CaLV are updated from ESAS using the best available data from NASA JPL
- EOR-LOR architecture
- 2% element fuel margins
- Nominal moon surface duration: 7 days
- Nominal crew size: 4
- Architectures must provide global lunar access
- Architectures must provide anytime return capability
- Identical processes to the 1.5-launch baseline architecture whenever possible
- Modification of the minimum number of elements possible in 1-launch and 2-launch scenarios to achieve mass closure

Study Methodology

The first step in our analysis was to determine the delta-v requirements for lunar missions. Section 4 of the Exploration Systems Architecture Study (ESAS) final report [7] discusses the delta-V (ΔV) requirements for such missions in depth and arrives at the ΔV model shown in Figure 5. This model provides immediate access to about 84% of the moon (including the 10 major research sites as listed in the ESAS document) and global access with a maximum of 7 days of loiter. The 1450 m/s of ΔV from LLO to Edwards AFB includes a worst-case plane change and thereby enforces the anytime return capability requirement.

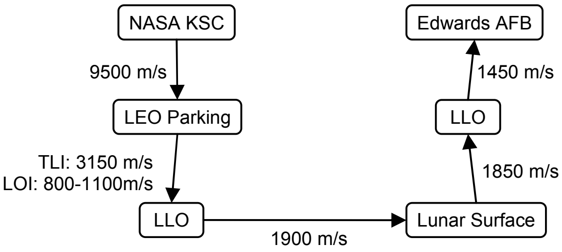

Figure 5 : Delta-V Requirements

For this trade study, four launch architectures were considered: the 1.5-launch baseline, the 1-launch equivalency, the 1-launch unmodified and the 2-launch architecture. The launch vehicle used for the 1-launch equivalency scenario is here-in referred to as the Ares V+ (or CaLV+) and is a larger version of the Ares V launch vehicle. The 1-launch equivalency scenario tries to achieve equivalent performance to the 1.5-launch baseline through modifying the Earth Departure Stage (EDS), Lunar Surface Acquisition Module (LSAM), and Crew Exploration Vehicle (CEV) propellant levels. The Ares V- (CaLV-) is a smaller version of the Ares V and is used for the 2-launch scenario. The 2-launch scenario features 2 nearly symmetric launches. The Ares V is used in the 1.5-launch baseline scenario as well as the 1-launch unmodified scenario.

The 1-launch unmodified scenario achieves mass closure by reducing mission duration and exploration mass. Figure 6 shows representations of the launch vehicles used for each launch architecture.

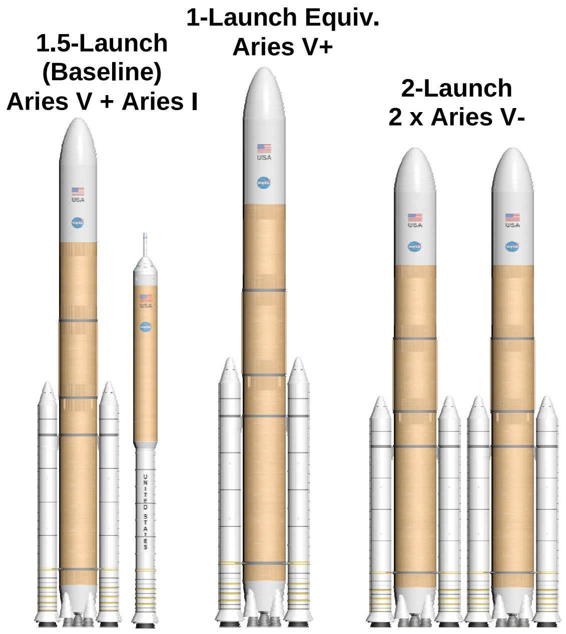

Figure 6 : Trade Study Launch Architectures

The nominal element masses and distributions used in this study were obtained both from the ESAS final report [7] and from personnel at JPL. It is important to note that blocks of elements were derived from a single source (i.e. both LSAM elements are derived from a single source, all CEV elements from a single source, and both LV elements from a single source) to produce the most consistent updated model possible.

1-LAUNCH UNMODIFIED ARCHITECTURE

The 1-launch unmodified scenario uses identical elements to the 1.5-launch baseline scenario; all of which now launch on a single Ares V. This scenario achieves mass closure by reducing crew size, mission duration and exploration mass (payload).

1-LAUNCH EQUIVALENCY ARCHITECTURE

For the 1-launch equivalency architecture, it was found that either increasing LSAM DS propellant mass, increasing EDS propellant mass or some hybrid of the two, was sufficient to achieve mass closure (while keeping cargo and operations mass constant). After careful analysis, it was determined that a hybrid option, in which EDS propellant mass was increased by 18% and the LSAM DS propellant mass by 17% over the baseline, offered the best solution. This option best combines the robustness of the EDS modification strategy with the relatively low launch mass and mass to LEO of the LSAM DS modification strategy. This option was henceforth carried forward as the representative of the 1-launch Equivalency architecture and formed the basis of the Ares V+ launch vehicle.

2-LAUNCH ARCHITECTURE

The best 2-launch option was found to be what is nominally a 2 x 80mT architecture. In reality it is an asymmetric 87mT + 70mT to LEO architecture in which both launches share common boosters and core stages. The reduced size Ares V- LVs were modeled as a 4 segment solid rocket booster (SRB) instead of a 5 segment used in the 1.5-launch specification plus a 1.5-launch specification core stage with a slightly reduced propellant load. The EDS was reduced in size due to less suborbital burn time, but contains the same amount of propellant in LEO as the baseline EDS.

Results

This section presents the results of the 1-launch and 2-launch architectures compared to the 1.5-launch baseline architecture. Most of these results are presented in the context of SpaceNet Measures of Effectiveness (MOEs), which, as stated above, provide a quantitative way to evaluate specific space exploration scenarios.

	1.5-launch Baseline	*1-launch Un-modified*	*1-launch Equiv.*	*2-launch*
Crew Surface Days (man-days)	28	20	28	28
Exploration Mass Delivered (kg)	1100	200	1100	2625
Exploration Capability (man-day-kg)	30799	4000	30799	73499
Relative Exploration Capability	8.367	1.375	10.432	15.149
Total-launch Mass (mT)	4202	3332	3370	5522
Relative	1.485	1.073	1.142	1.643

	1.5-launch Baseline	*1-launch Un-modified*	*1-launch Equiv.*	*2-launch*
Scenario Cost				
Total Scenario Risk	0.007	0.004	0.004	0.007
Net Mass to LEO (mT)	133 + 21	139	148	87 + 70
Gross Cargo to Surface (kg)	2085	1265	2085	3630
Total Mission Duration (days)	7	5	7	7

Table 2 : MOEs and Data for All Architectures

The key finding of this trade study is as follows: The data in Table 3 shows that the 1-launch equivalent and 2-launch architectures generally outperformed the 1.5-launch baseline in lunar surface missions. Despite this, it appears that *the best option is essentially dependent on the long-term distribution of ISS re-supply, Lunar Sortie, and Lunar Outpost activities* (mission mix):

- For lunar sorties, performance is extremely important since Exploration Mass Delivered (EMD) is primary determinant of single-mission capabilities. The 2-launch architecture delivers significantly more exploration mass than any other scenario.
- In contrast, for lunar outpost missions cost & risk are primary drivers. Given that crew can be delivered to the lunar surface, the amount of EMD is not hugely important assuming the outpost is already well-equipped and stocked.
- For ISS Resupply, performance is a primary driver as the number of ISS support flights looks to increase in the future. Ares V- could potentially deliver 3x Ares I payloads to ISS, greatly reducing the number of flights. These payloads would not all have to dock with ISS at the same time, but could be placed in a safe parking orbit until a compatible docking port opens up on ISS.

Thus the 2-launch architecture may be best suited to handle all 3 activities in an environment of uncertainty due to its low development costs, flexibility, and consistently high performance across mission types. However, the 1-launch solution is a relatively simple, low-cost architecture that essentially avoids boiloff issues all together. The Constellation traffic model needs to be more defined before the "best" option can truly be determined. However, based on the findings of this trade study, both the 1-launch equivalent and 2-launch architectures have better performance to cost ratios than the 1.5-launch baseline and should strongly be considered for use in Constellation.

B. Integrated ISS Resupply Scenarios

This assessment was performed to assess ISS resupply strategies beyond 2010 utilizing the Crew Exploration Vehicle (CEV), Ariane Transfer Vehicle (ATV), H-II Transfer Vehicle (HTV), Soyuz and Progress vehicles. This analysis supports the effort to determine "optimal" (minimum cost/ minimum number of flights) resupply scenarios.

The following assumptions were critical to this study:

- ISS assembly complete configuration per: NASA's *Reference Assembly Sequence Overview*, updated May 24, 2006.
- ISS Crew Size: 6
- Expedition Length: 6 months
- Nominal International Partner (IP) Flight Rate: ATV 0.5/year, HTV 2/year, Progress 4/year, Soyuz 2/year, CEV 3/year
- Cargo capacities of each vehicle as provided by NASA/JPL

Study Methodology

The ISS Resupply analysis was run in two different modes:

a) *Forward mode:* where the number of flights per year of each of the three CEV variants was pre-determined and the resulting cargo capacity was determined along with an appropriate cargo mix.
b) *Backward mode:* where the forecasted ISS cargo demand was determined and the minimum number of flights and appropriate mix of vehicles was determined to meet this demand.

Two tools were used in this analysis: The Model for Estimating Space Station Operations Costs (MESSOC), version 3.18, and SpaceNet, version 1.2. MESSOC is a tool developed and maintained at JPL to estimate ISS operations cost and performance. Version 3.18 adds a crewed CEV and pressurized cargo CEV to the available flight types within the Operations

Profile. MESSOC was used as the *forward mode* tool. SpaceNet was used as the *backward mode* tool.

For the **forward mode**, a standard baseline scenario for ISS (called the canonical scenario) was entered into MESSOC that included two crewed CEV flights per year from 2011 through 2020. This was consistent with the assumption of a six-month tour length for ISS crew. The canonical scenario also had three pressurized cargo CEV flights per year. Alternative scenarios were run in which the pressurized cargo CEV flights per year were two and four. Additional scenarios were run that varied the pressurized cargo CEV capacity to determine the sensitivity to that requirement. Lastly, additional scenarios were run in which IP flights were reduced or eliminated.

In the **backward mode** analysis, SpaceNet was used to model one year of ISS resupply (2012) with the vehicle capacity data specified by NASA and the following IP and crewed CEV flight rates: ATV 1/year[**], HTV 2/year, Progress 4/year, Soyuz 2/year, Crewed CEV 2/year. Given this scenario, SpaceNet calculated the demand required to support a crew of 6 on ISS for 1 year. For comparison purposes, the same scenario was entered into MESSOC and the resultant demand predictions calculated. With these demand numbers in hand, we were then able to vary the number of CEV and IP vehicle flights to determine possible flight mixes to satisfy this demand.

Results

Early runs suggested that a major constraint existed in the ability to return mass (e.g., failed ORUs, utilization payloads) safely to Earth, as the CEV (the pressurized cargo CEV, in particular) provides virtually all of the non-destructive downmass capability for ISS.

Testing to determine the effects of reducing or eliminating IP flights to ISS showed that reductions in IP flight rates do not affect available utilization non-destructive downmass, only available utilization upmass. Two scenarios were run to determine how many CEV flights per year would be needed in the absence of all IP flights. In these runs, the crewed CEV carried six crewpersons, which fulfilled the crew rotation requirement with two flights per year. Both MESSOC and SpaceNet agreed that between eleven and twelve pressurized cargo CEV flights per year would be needed to provide a positive amount of utilization upmass.

The key findings of this analysis are:

- For ISS resupply, two crewed CEV flights and three pressurized cargo CEV flights per year is a feasible scenario, if international partners (IPs) sustain nominal flight rates.
- Non-destructive utilization downmass is very limited with only three pressurized cargo CEV flights, but ISS can “buy back” some of this downmass by condemning-in-orbit failed parts (Orbital Replacement Units, ORUs) that would normally be returned in a pressurized carrier. (Note: Such ORUs may, in fact, be external in their application (installed location), so candidate ORUs could be both internal and external to the Station.)
- There is a need to determine economic criteria (e.g., price/kg) for selecting those ORUs to be returned and those to be condemned-in-orbit (i.e., selected for destructive re-entry). There was no attempt in the analysis to determine how much mass and volume would be available in IP vehicles for destructive reentry of U.S. parts.
- A pressurized cargo CEV capability of 3500 kg is marginally sufficient. A reduction by as little as ten percent, however, could have significant effect on non-destructive utilization downmass, if failed parts are also to be returned for repair.
- Stochastic variation in spares upmass demand per year was found to be on the order of one pressurized cargo CEV flight, validating a surge requirement of four flights per year. The surge capability would also be helpful in compensating for a failed or missed IP launch.
- A reduction by one or two flights in a year by a single IP is survivable as measured by utilization upmass and non-destructive downmass, but loss of IP support altogether will require significant

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[**] The predicted ATV flight rate is actually one flight every two years but since this analysis only modeled one year of ISS resupply, we were forced to round up and present a “best case” scenario.

increases in flight rates, and thus cost, for the U.S. Two six-person crewed CEV flights per year would be able to provide the full crew transfer capability, but on the order of eleven to twelve pressurized cargo CEV flights per year would be required to provide positive utilization upmass. (Note: This is approximately the same number of visiting vehicles as in the canonical scenario.)

Based on our initial analysis, key findings, and issues raised, we recommend the following:

1. The Constellation Program Office should engage ISS to establish an integrated plan for CEV use.
2. With that plan, conduct a further analysis to refine the quantitative relationship between cargo flight rates and ISS utilization upmass and non-destructive downmass.
3. To determine the minimum required CEV flight rate, obtain estimated ISS utilization upmass / non-destructive downmass requirements.
4. As non-destructive downmass is likely to be limited, establish economic criteria to determine which failed ORUs/SRUs should be returned for repair and which should be condemned-in-orbit. This most likely will include considerations of ease and cost of repair, supply availability and re-procurement price.
5. Explore the tradespace more fully, including alternative MTBF or service life assumptions, and changes in maintenance concepts (corrective maintenance by SRU replacement).

VII. Conclusions

This paper describes in detail a modeling framework for interplanetary supply chain management developed by building on the proven techniques of commercial supply chain management to model and evaluate logistics architectures. The framework is built on the basic concepts of nodes, supplies, and elements, tied together into a time-expanded network with a set of processes governing movement through the network. These elements enable coherent technical descriptions of logistics architectures, and a simulation layer provides feasibility assessments and various visual and data reporting outputs for further study by analysts. A set of logistics-related measures of effectiveness are proposed for comparative evaluation of logistics scenarios modeled with this framework.

SpaceNet is a software tool built around this modeling framework. It provides a graphical user interface, built-in demand models, an integrated database with libraries of nodes, vehicles, and supplies, and visualization and Excel reporting capabilities. The modeling framework proposed here (and its current implementation in SpaceNet) enables modeling the flow of crew, cargo, and vehicles through the Earth-Moon-Mars system. As is evident from the trade study results presented in this paper, SpaceNet can support both short- and long-term architectural trade studies, and highlight ways in which space logistics can be improved, enhancing the affordability and robustness of future manned space exploration missions.

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