Space Logistics Modeling and Simulation Analysis using SpaceNet: Four Application Cases

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The future of space exploration will not be limited to sortie-style missions to single destinations. Even in present exploration taking place at the International Space Station in low-Earth orbit, logistics is complicated by flights arriving from five launch sites on Earth. The future challenges of space logistics given complex campaigns of interconnected missions in deep space will require innovative tools to aid planning and conceptual design. This paper presents a modeling framework to evaluate the propulsive and logistics feasibility of space exploration from the macro-logistics perspective, which covers the delivery of elements and resources to support demands generated during exploration. The modeling framework is implemented in a versatile and unifying software tool, SpaceNet, for general space exploration scenario analysis. Four space exploration scenarios are presented as application cases to highlight the applicability of the framework across vastly different scenarios. The first case investigates the resupply of the International Space Station between 2010 and 2015 using 77 missions combining NASA, European Space Agency, Japanese Space Agency, Russian Space Agency, and commercial space transportation. The second case models a lunar outpost build-up consisting of 17 flights to achieve continuous human presence over eight years. The third case models and evaluates a conceptual sortie-style mission to a near-Earth object, 1999 AO10. Finally, the fourth case models a flexible path type human exploration in the vicinity of Mars using a combination of human and tele-operated exploration. Taken together these cases demonstrate the challenges and logistical requirements of future human space exploration campaigns during the period from 2010-2050 and illustrate the ability of SpaceNet to model and simulate the feasibility of meeting these requirements.

I. Introduction

LOGISTICS plays an important role in human exploration of remote locations. The context of space exploration logistics is especially challenging due to the combination of infrequent and long duration transports, high cost and limited cargo capacity aboard vehicles, and critical resource requirements. As space exploration transitions from single sortie-style missions to integrated campaigns, the complexity of logistics will grow as missions become interdependent, requiring new techniques and tools to support analysis.

Within the context of space logistics, there are two levels of analysis: micro-logistics and macro-logistics.[1] Micro-logistics covers the "handling, usage, and disposal of goods at the destination" and considers topics such as placement and retrieval of supply items within confined volumes, containment of resources by environment (pressurized, unpressurized) or type (solid, liquid, or gas), generation, storage, and processing of waste, contingency operations, movement and timing of elements during operations, and detailed maintenance and repair activities. Macro-logistics on the other hand covers the timely "delivery of goods [resources] and elements to a destination," and, for the most part, assumes that the micro-logistics are handled separately.

The macro-logistics problem can be divided into two interrelated aspects – propulsive and logistical feasibility – to analyze a space exploration mission. Propulsive feasibility models the consumption of propellant to achieve required delta-v to complete launches, in-space trajectories, or other required burns (e.g. station-keeping or midcourse corrections). In the case of mature transportation architectures in which propulsive feasibility is

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established it is sufficient to apply a maximum payload mass to a transport rather than perform a detailed burn-by-burn. Logistics feasibility models the generation of demands for resources during an exploration mission or campaign by consuming resources from cargo. This may be accomplished by checking for sufficient capacity of a pre-specified cargo manifest or creating a derived cargo manifest based on estimated demands.

This paper investigates the macro-logistics problem of space exploration using a unified modeling framework and discrete event simulation tool to analyze the transport, delivery, and consumption of resources during exploration campaigns. This builds on past research including quantifying the logistics requirements of lunar exploration and the impact of performance, affordability, and risk for strategic analysis.[2, 3] As an extension from past research, however, this paper presents a generic mission analysis tool capable of modeling a wide range of interesting mission concepts with destinations ranging from Earth orbit, the Moon, near-Earth objects, Mars, and beyond. Towards this goal, this paper provides a brief overview of the space logistics modeling framework and introduces a set of application cases showcasing the flexibility of the tool across widely-varying mission concepts. The main purpose of this paper is to demonstrate that it is possible to model a wide range of vastly different exploration scenarios based on a relatively small set of core principles and concepts as embodied in the SpaceNet software environment.

II. Space Logistics Modeling Framework and SpaceNet Tool

SpaceNet is an implementation of the space logistics modeling framework in the form of a discrete event simulation tool. It is one of several research areas within the MIT-NASA Space Logistics Project which researches innovations in space exploration logistics.[*] The first versions of SpaceNet were programmed as MATLAB applications and used for Constellation Program trade studies and analysis. SpaceNet 1.3 was first publicly released and distributed in 2007.[4]

One of the goals for development of the subsequent versions of SpaceNet – under the version 2.X umbrella – was to analyze the "ilities" of exploration, including reconfigurability, repairability, commonality, and reusability.[5] Within the context of space logistics, reconfigurability is the ability for elements to change operational state during an exploration, repairability is the ability to use crew time and lower-level resources rather than providing spare parts, commonality is the ability to use shared components to repair and/or spare multiple elements, and reusability is the ability to use elements across multiple missions. In addition to quantifying the "ilities" of space exploration, SpaceNet 2.5 also made the transition from single-mission lunar explorations to general-purpose, multi-mission campaigns at a variety of destinations. SpaceNet 2.5 was first released in October 2009 as an open source Java executable, followed by additional releases in December 2010, May 2011, and September 2011.[†]

The target audience for SpaceNet users are mission architects and logistics planners in national space agencies, commercial space transportation analysts, academic researchers, as well as knowledgeable space enthusiasts. The target analysis for SpaceNet is early conceptual missions working at a low-fidelity (high abstraction) to medium-fidelity level, characteristic of macro-logistics. SpaceNet and its underlying modeling framework are intended as a long-term platform from which future development and research for space logistics can be derived.

A. Overview and Modeling Framework

SpaceNet uses a space logistics framework with several core components to construct and evaluate space exploration scenarios. The network model captures spatial connectivity between locations using a combination of nodes and edges. The resource model captures the substances that are supplied and demanded during simulation. The element model captures the attributes of objects generating demands in the simulation. The event model captures the actions to guide simulation execution. The network, resource, and element models persist in a database connected to SpaceNet and can be easily added or removed from a particular space exploration campaign. The event models are generated by the user while constructing a campaign definition.

Network Model

The network model is comprised of a set of nodes and edges with the key simplification of time-invariance allowing a single network to be used across an entire exploration scenario. Nodes define time-invariant locations at which resources and elements can exist. Nodes exist in three classifications: surface nodes corresponding to locations on planetary bodies, orbital nodes corresponding to stable orbits (note: time-invariant orbits do not include an anomaly orbital element), and Lagrange nodes corresponding to stationary points between two bodies.

[*] For more information on the MIT Space Logistics Project, see http://spacelogistics.mit.edu
[†] For SpaceNet source code and executable downloads, see http://spacenet.mit.edu

Edges represent time-invariant connections ("trajectories") between nodes, traversable during simulation by certain elements. Edges also exist in three classifications: surface edges correspond to paths between two surface nodes, space edges correspond to trajectories requiring propulsion, and flight edges correspond to abstracted space edges traversable with known transportation architectures. Although fundamentally physics-based, space edges use pre-specified delta-v requirements to accommodate atmospheric effects (e.g. during launch, re-entry, or aerobraking) and optimal trajectory timing given time-invariant locations. Time-dependent space edges accessing a database of values and/or physics-based calculations are an active area of research.

Resource Model

Resources are substances consumed to satisfy demands during simulation. All resources are assigned a functional class of supply (COS) based on military and NASA techniques for classifying cargo by its function, as shown in Table 1.[7] Classes of supply are used to abstract and group similar resources to simplify demand models and visualizations. Resources must be contained within specific elements (resource containers), and may either be continuous or discrete (quantized).

Table 1. Common classes and subclasses of supply.

COS	Description and Sub-Classes
1	Propellants and Fuels 101: Cryogens, 102: Hypergols, 103: Nuclear Fuel, 104: Petroleum Fuels, 105: Other Fuels, 106: Green Propellants
2	Crew Provisions 201: Water & Support Equipment, 202: Food & Support Equipment, 203: Gases, 204: Hygiene Items, 205: Clothing, 206: Personal Items
3	Crew Operations 301: Office Equipment & Supplies, 302: EVA Equipment & Consumables, 303: Health Equipment & Consumables, 304: Safety Equipment, 305: Communications Equipment, 306: Computers & Support Equipment
4	Maintenance and Upkeep 401: Spares & Repair Parts, 4011: Pressurized Spares, 4012: Unpressurized Spares, 4013: Repair Parts, 402: Maintenance Tools, 403: Lubricants & Bulk Chemicals, 404: Batteries, 405: Cleaning Equipment & Consumables
5	Stowage and Restraint 501: Cargo Containers & Restraints, 502: Inventory Management Equipment
6	Exploration and Research 601: Science Payloads & Instruments, 602: Field Equipment, 603: Samples
7	Waste and Disposal 701: Waste, 702: Waste Management Equipment, 703: Failed Parts
8	Habitation and Infrastructure 801: Habitation Facilities, 802: Surface Mobility Systems, 803: Power Systems, 804: Robotic Systems, 805: Resource Utilization Systems, 806: Orbiting Service Systems
9	Transportation and Carriers 901: Carriers, Non-propulsive Elements, 902: Propulsive Elements

Element Model

Elements are unique objects that persist during simulation executions and may generate demands for resources (they may also carry resources within). Similar to resources they are also assigned a class of supply (COS) however elements are not the target of demands. Elements may contain several reconfigurable states corresponding to alternative demand models as well as resources corresponding to parts and supplies.

Elements are structured in a hierarchy to provide different capabilities, shown in Figure 1. Resource tanks and containers hold resources for transport or storage during simulation. Human and robotic agents can perform certain tasks such as repair and influence measures of effectiveness. Carrier elements can contain nested elements (e.g. human agents inside a habitat), and may additionally be classified as a surface vehicle capable of surface edge traversal, or a propulsive vehicle capable of space edge traversal.

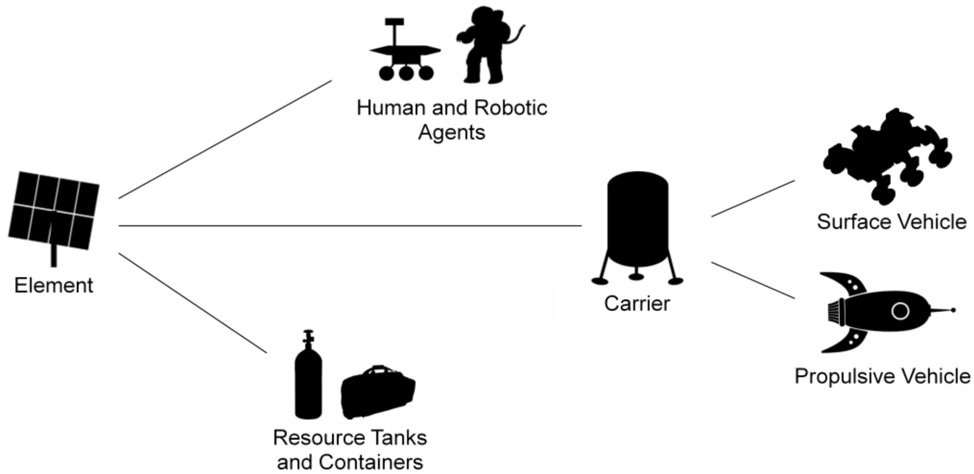

Figure 1. Element model hierarchy. *A hierarchy of elements provides a common set of inherited properties along with specialized capabilities extensible for future expansion*.

Event Model

The missions and campaigns defined in SpaceNet are comprised of events which define the actions that take place during simulation. There are seven core "instantaneous" events:

1. Initialize elements – creates elements at a node or nested within a carrier
2. Move elements – moves elements between carriers or nodes
3. Remove elements – removes elements from the scope of the simulation
4. Reconfigure elements – changes the operational state of elements
5. Add resources – adds resources to a tank or container
6. Transfer resources – transfers resources between tanks or containers
7. Demand resources – consumes resources from tanks or containers

Higher-level events are comprised of combinations of the core events over finite durations including: propulsive burn, space transport, surface transport, flight transport, extravehicular activity (EVA), and exploration.

A typical space exploration mission will start by initializing elements, followed by a sequence of space or flight transports to reach the destination location. During in-space or exploration operations, elements may be moved or reconfigured, resources may be demanded or transferred, and EVAs, exploration, and surface transports take place. After the exploration period, space or flight transports return the crew to Earth where they are removed from the scope of the simulation to prevent additional demands.

B. Key Flexibility Features

The space logistics modeling framework and SpaceNet tool provide several features that promote flexibility in modeling and simulating space explorations.

Multi-level Resource Models

In a detailed logistics analysis many resource models are desired to add depth and realism to demand models. In the extreme case the analysis fidelity may reach the individual supply item level, modeling instances of items such as spare parts, hygiene items, and science components in discrete, fixed-mass and fixed-volume resources. In less detailed cases, continuously-variable masses of resources identified by COS can be used as a placeholder for the underlying discrete items they may represent. In the least-detailed logistics analysis, generic resources may be aggregated only by base COS, for example COS 2 represents any sort of crew provisions.

By both enabling additional detail if available and providing an abstraction mechanism for comparing scenarios of varying analysis fidelities, this multi-level resource modeling technique allows a coordinated method of analyzing space exploration scenarios. It helps to enable conceptual mission evaluation without staunch data requirements while allowing the detailed analysis if the data is present.

Multi-level Demand Models

Closely tied to the level of resource modeling, a detailed logistics analysis will specify detailed demand models. The most detailed models can be custom-coded via a programming interface to produce simulation state-dependent demands on a per-element level, similar to agent-based modeling techniques. Mid-level demand models use linear functions to produce operational state-dependent demands for elements, which, even across a moderate number of elements and a few operational states, generate complex composite demands. Finally, there is also support for aggregated mission-level demand models which are parameterized by quantities such as the number and type of agents (e.g. astronauts), exploration duration, number of EVAs, etc.

Low-level Event Definitions

All simulation events are defined in a format compatible with a wide range of exploration scenarios. In particular, the core seven events can be combined in interesting ways to model nearly any scenario. For example transfer resource events have been used to model propellant depots and disposable fuel tanks. By enumerating the essential actions that can take place within the simulation, the simulation inherently is flexible to model a wide range of exploration scenarios. One of the main advantages of SpaceNet is that these low-level events are clearly defined and some are pre-packed into higher-level composite events that can easily be invoked during exploration planning and modeling. This saves time and frees mission planners to focus on the essential logic and feasibility of a particular mission or campaign.

Abstracted Flight Transports

Some space exploration scenarios focus on the logistics feasibility problem rather than the propulsive feasibility question (i.e. the launch or in-space vehicle architecture is treated as fixed), particularly for explorations with established launch vehicle architectures. In these cases, the modeling burden of verifying propulsive feasibility is unproductive and can be omitted by using the concept of abstracted flights. Abstracted flights provide transport between two or more nodes for cargo up to a mass limit and greatly simplify the modeling of space exploration. Use of flight transports is equivalent to space transports with propulsive burns through all portions of the analysis.

C. Application Cases

The following sections present four application cases illustrating the use of the space logistics modeling framework within the SpaceNet tool. The first case investigates the resupply of the International Space Station between 2010 and 2015 using 77 missions combining NASA, European Space Agency, Japanese Space Agency, Russian Space Agency, and commercial space transportation. The second case models a lunar outpost build-up consisting of 17 flights to achieve continuous human presence over eight years. The third case models and evaluates a conceptual sortie-style mission to a near-Earth object, 1999 AO10. Finally, the fourth case models a flexible path type human exploration in the vicinity of Mars using a combination of human and tele-operated exploration. These application cases exhibit a wide variety in mission concepts and scenarios.

III. International Space Station Resupply Campaign[‡]

The space shuttle, or more formally Space Transportation System (STS), served as the workhorse for assembling the International Space Station (ISS). After its retirement in 2011, a combination of commercial and government vehicles will continue to maintain the crew and science operations aboard the ISS.

This first application case builds a model of the planned resupply operations between September 2010 and December 2015. It models the final assembly and subsequent resupply of the ISS using a combination of the remaining STS missions and the Orbital Science Cygnus, SpaceX Dragon, European Space Agency (ESA) Automated Transfer Vehicle (ATV), Japanese Space Agency (JAXA) H-II Transfer Vehicle (HTV), and Russian Space Agency (RKA) Progress and Soyuz vehicles. This case is a proof of concept for internationally integrated ISS resupply logistics campaign modeling. For a more detailed discussion of this scenario, please see Ref. 6.

A. Network and Elements

The network model shown in Figure 2 is comprised of the launching and landing locations for each of the included launch vehicles as well as the ISS in orbit. Flight transports are used in this case as the propulsive feasibility for each type of vehicle has been clearly established. For each launch vehicle, a representative flight edge indicates the amount of cargo (including accommodation mass) that may be carried as payload (including the mass of the in-space vehicle where appropriate).

[‡] This scenario is available for download at http://spacenet.mit.edu/applications.php#iss-resupply

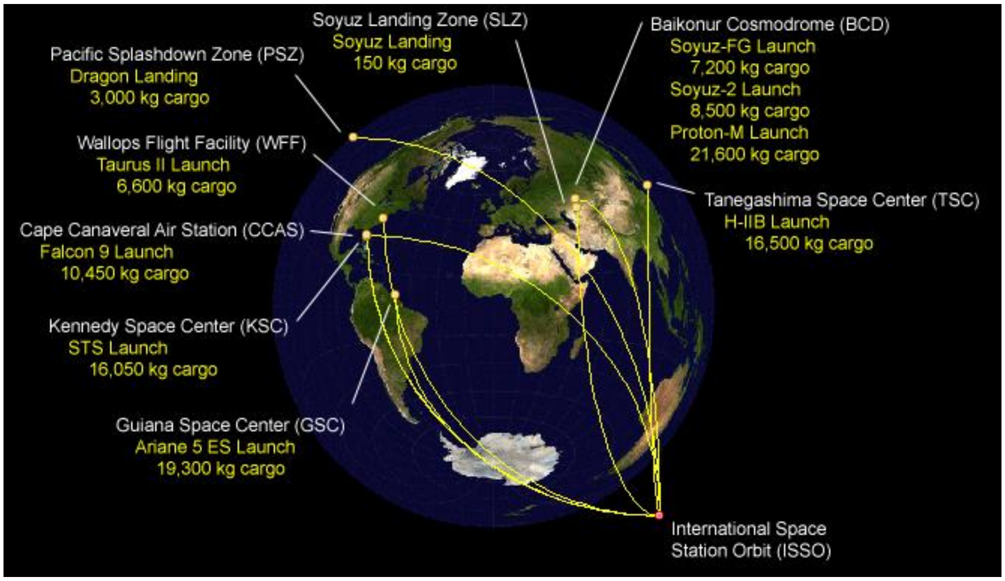

Figure 2. ISS resupply network. *Visualization of the launch and landing sites on Earth and the ISS's orbit. Yellow curves indicate flight transport edges with annotated cargo/payload capacities.*

The elements specified in Table 2 correspond to the spacecraft carrying crew and cargo to the ISS including infrastructure and logistics containers. Model inputs for this case were derived from spacecraft datasheets where available or from publicly-available online databases. All values are approximate due to modeling simplifications and assumptions, multiple vehicle configurations, and design evolution.

Table 2. ISS resupply elements (adapted from Ref. 6).

Name	Empty Mass [kg]	Crew Capacity	Cargo Capacity [kg]	Description
Progress-M	4,900	0	2,350	RKA Progress (M Configuration)
Soyuz-TMA	6,085	3	100	RKA Soyuz (TMA Configuration)
Dragon	4,200	0	6,000	SpaceX Dragon
Cygnus	3,500	0	2,000	Orbital Cygnus
Cygnus-M	3,500	0	2,700	Orbital Cygnus (Improved)
HTV	8,100	0	6,000	JAXA H-II Transfer Vehicle
ATV	11,700	0	7,600	ESA Automated Transfer Vehicle
STS Shuttle*	0	7	16,050	NASA Space Transportation System Shuttle
MLM	20,300	0	0	RKA Multifunctional Laboratory Module
ELC	4,400	0	2,000	EXPRESS Logistics Carrier
PMM	4,080	0	9,070	Pressurized Multipurpose Module
AMS	6,700	-	-	Atomic Magnetic Spectrometer
ISS	335,000	6	35,000	International Space Station

* STS Shuttle mass is accounted for in its flight transport capacity as it is a component of the launch vehicle.

Both the ISS and its crew of six produce demands that are modeled as linear functions of time. Annual ISS demands, including packaging mass, are estimated at 10 tons of spares and maintenance (COS 4) and 15 tons of science (COS 6). This is equivalent to 27.38 kilograms of COS 4 and 41.07 kilograms of COS 6 daily. Daily crew demands are estimated at 3.5 kilograms of water (COS 201), 2 kilograms of food (COS 202), 1 kilogram of gases (COS 203), 0.5 kilogram of hygiene items (COS 204), and 0.5 kilogram of waste disposal items (COS 7) per crew member. This results in a maximum total yearly demand for crew consumables (not taking into account water recycling) of about 16.4 metric tons (COS 2) for a full complement of six crewmembers. Thus, a rough estimate is that it takes 40-45 metric tons of up-mass cargo per year to maintain and operate the ISS. This corresponds to about 3 STS shuttle flights or about 17 Progress-M flights per year. In reality this total cargo mass is provided by a mix of various vehicles (see Table 2) with carefully coordinated flight schedules as discussed in the next section.

B. Missions and Events

A mission manifest from September 2010 through December 2015 was created using unofficial launch and mission manifests provided by Orbital, SpaceX, JAXA, and ESA, as well as extrapolating launch rates for Progress and Soyuz as of July 2010 (see Figure 3, below). The missions are comprised of 2 STS, 22 Progress, 22 Soyuz, 12 Dragon, 8 Cygnus, 5 HTV, and 4 ATV resupply missions and 1 assembly mission to replace the *Pirs* module with *Nauka*. In addition to the resupply missions, the first virtual "mission" initializes the ISS and its crew in orbit to start the demand generation process.

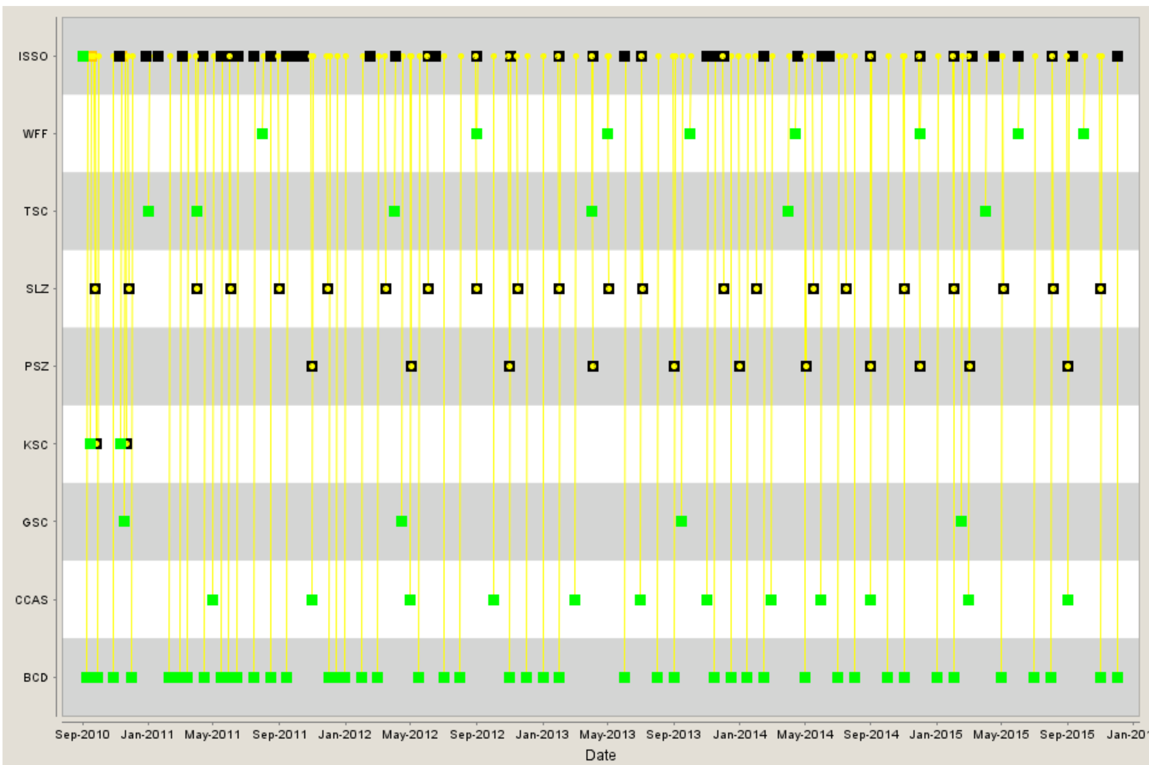

Figure 3. ISS resupply bat chart. *77 missions, comprised of 2 STS, 22 Progress, 22 Soyuz, 12 Dragon, 8 Cygnus, 5 HTV, and 4 ATV resupply the ISS between September 2010 and December 2015. Yellow lines indicate flight transports, green squares element instantiations, and black squares element removal events.*

Although it is not important for demands analysis, it is assumed that each Soyuz spacecraft spends 180 days docked at the ISS before the subsequent return to Earth. Other spacecraft (ATV, HTV, Dragon, Cygnus, and Progress) spend 60 days docked at the ISS before de-orbiting or return to Earth. Docking activities at the ISS will require action for 18 arrivals per year on average, or one arrival every 20 days. Docking port availability constraints were not taken into account in this analysis, but could be included in future analysis.

C. Analysis and Discussion

Figure 4 illustrates the cumulative raw capacity (total up-mass capacity of all vehicles), net capacity (raw capacity less manifested elements, e.g. ELC, AMS, etc.), and estimated demands for the ISS resupply scenario. The total raw capacity to ISS over the simulation is 245 tons, with 225 tons remaining for resources to satisfy demands. The demands over the same time period total 217 tons, of which 80 tons are for crew provision items (COS 2), 77 tons are scientific payloads for exploration and research (COS 6), 52 tons are for maintenance and upkeep (COS 4), and 6 tons are for waste and disposal (COS 7). Although not modeled, any pre-positioned resources at ISS would effectively shift the estimated demands curve down by a fixed amount no more than the maximum estimated capacity of 35 tons. Analysis without considering these pre-positioned resources focuses on the steady-state supply and demand. Of note, the demands nearly match the remaining capacity during this time period, indicating the projected resupply operations to the ISS maintain a steady stockpile of resources.

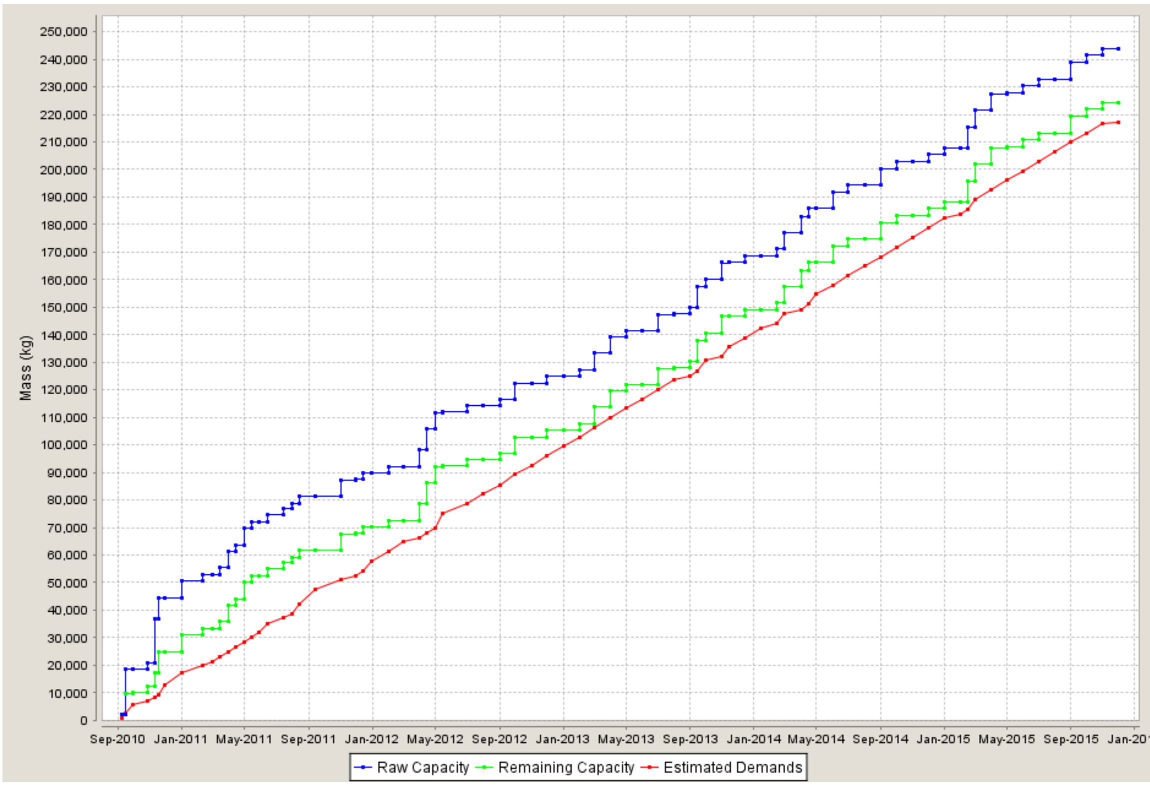

Figure 4. ISS resupply cumulative demands and supply capacity. *Between September 2010 and December 2015, resource demands nearly match the supply capacity of all resupply vehicles. Note: demands are aggregated for each launch and do not appear perfectly linear.*

Even from a high-level analysis the resupply of the ISS through 2015 warrants significant additional research. As modeled, there is limited supply capacity margin in steady-state, indicating undersupplies of critical resources may be a realistic concern. Steady-state infeasibilities could start to occur with the delay or cancellation of just one of the six resupply spacecraft, however advanced planning given the pre-positioned resources would probably not warrant an emergency. This situation may indeed be realized with the recent (at the time of writing) launch failure of a Progress spacecraft, although immediate focus is on the safety of crew rather than supply of resources for which the existing stockpile is expected to last for many months.[8]

More detailed analysis should include additional demands for propellant required for orbital re-boost and station keeping and differentiate between pressurized, unpressurized and liquid cargo, including the multiple spacecraft configurations supporting differing capacities of each type.

IV. Lunar Outpost Campaign[§]

An extended lunar exploration leading to continuous human presence was one potential goal of NASA's Constellation program and a driving application case throughout the majority of the development of SpaceNet between 2005 and 2010. Although exploration plans have since shifted with the cancellation of the Constellation program, an extended lunar exploration serves as an excellent case study of a campaign with significant element

[§] This scenario is available for download at http://spacenet.mit.edu/applications.php#lunar-outpost reuse and surface operations. In addition, due to the maturity of the campaign architecture, the modeled exploration benefits from detailed and realistic element models based on data developed with a reasonable amount of analysis.

As of late 2009 the working lunar surface architecture was Scenario 12, developed by the NASA Lunar Surface Systems Project Office (LSSPO) and the Constellation Architecture Team – Lunar (CxAT-Lunar). Scenario 12 evolved from the confluence of three scenarios: Scenario 4 (Optimized Exploration), Scenario 5 (Fission Surface Power System), and Scenario 8 (Initial Extensive Mobility).[9,10] In Scenario 12, successive missions at a rate of about three per year deliver infrastructure components to an outpost, building up to full capability within six years.

The primary surface mobility elements include the lunar electric rover (LER) and tri-ATHLETE. The LER is capable of traveling up to 200 kilometers on one charge, but when not exploring, it is attached to the crew habitat to provide private sleeping quarters and radiation protection. The tri-ATHLETE is capable of traveling alone, but when combined with a second tri-ATHLETE, can traverse terrain while carrying a habitat module as payload.

This case models an extended lunar surface exploration similar to Scenario 12. As the existing scenario is well-researched, this analysis focuses on validation of the modeling framework rather than explicitly evaluating feasibility. Only the build-up of outpost elements at the Lunar South Pole will be modeled (omitting sortie missions to independent locations) with two surface excursions to nearby locations.

A. Network and Elements

The network model includes the launch and landing sites on Earth as well as the exploration locations on the lunar surface. All elements arrive at the Lunar South Pole and surface excursions reach Malapert Crater and Schrödinger Basin. Abstracted flight transports are used in this scenario to provide a set amount of cargo capacity to and from the Lunar South Pole under three configurations: a sortie flight for self-sufficient exploration (i.e. no habitat), an outpost flight for crew supported by a habitat, and a cargo flight for uncrewed missions. Surface transports are modeled with approximate distances between the sites of interest.

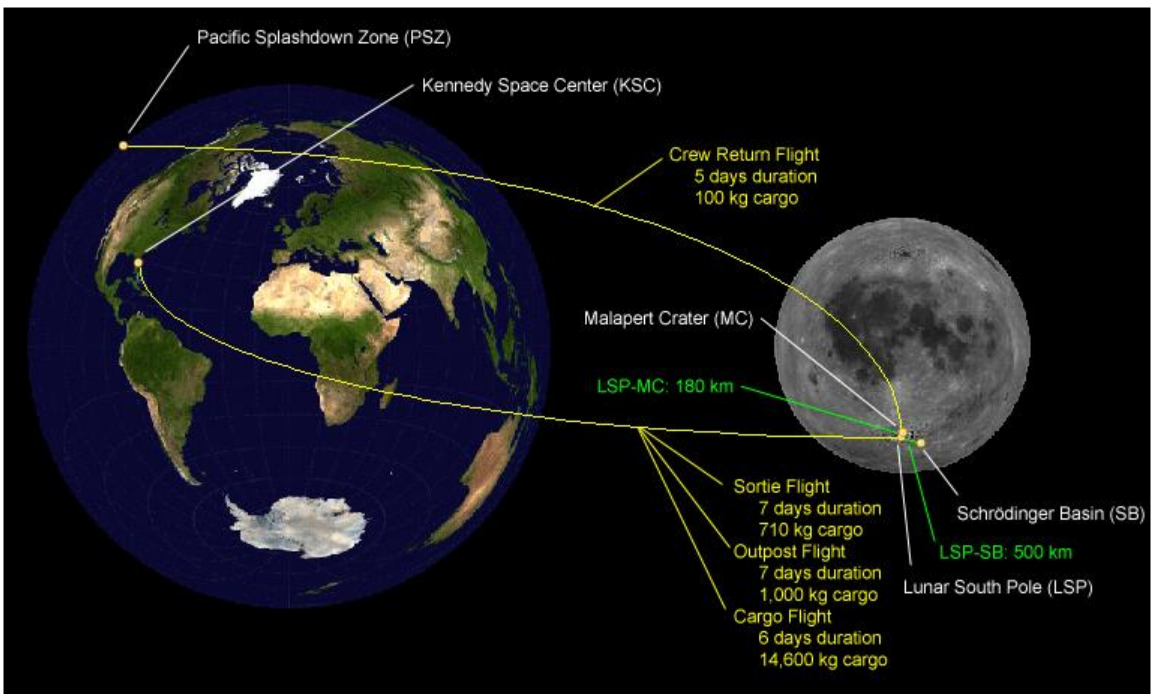

Figure 5. Lunar outpost network. *Visualization of the Earth-moon network. Yellow curves indicate flight transport edges with notated cargo/payload capacities. Green lines indicate surface transport edges with notated distances*.

In line with the abstracted nature of space transportation, the element models focus on surface operations. The primary elements, listed in Table 3, include ascent and descent modules, rovers, crew habitats, and logistics carriers. All primary elements generate demands for spares (generic COS 4) at a rate of 10% element mass per year during crewed periods and 5% element mass per year during uncrewed (dormant) periods. Two *in-situ* resource utilization (ISRU) plants are delivered in later missions to generate oxygen (generic COS 203) at a rate of 1,000 kilograms per year, stored aboard the plant until demanded by the crew.

Crew members generate demands during surface exploration only (in-space transport demands are omitted), at a rate of 2.0 kilograms of food (generic COS 201), 3.5 kilograms water (generic COS 202), 1.0 kilogram gases (generic COS 203), 0.5 kilograms of hygiene items (generic COS 204) and 0.5 kilograms of waste disposal items (generic COS 7) per day. After the delivery of the surface habitat, crew water demands are decreased from 3.5 to 0.5 kilograms per person per day to account for a greater water recovery rate.

Table 3. Primary lunar outpost elements (adapted from Ref. 6).

Name	Empty Mass [kg]	Max Crew	Max Cargo [kg]	Description
Sortie Descent Module (SDM)*	13,000	0	710	Descent module with airlock.
Sortie Consumables Container (SCC)	0	-	210	Container for resources during sortie exploration.
Cargo Descent Module (CDM)	12,000	0	14,600	Descent module for cargo delivery.
Outpost Descent Module (ODM)	12,000	0	1,000	Descent module w/o airlock (req. habitat).
Ascent Module (AM)	3,000	4	100	Ascent module for crew return.
Unpressurized Rover (CUR)	230	2	0	Unpressurized basic rover.
Lunar Electric Rover (LER)	4,000	4	1,000	Pressurized rover for excursions.
Portable Utilities Pallet (PUP)	650	-	-	Provides utilities.
In-situ Resource Utilization (ISRU)**	275	-	1,000	Processes lunar regolith to produce oxygen
Tri-ATHLETE (ATH)	1,200	0	10,000	Mobile surface vehicle.
Power and Support Unit (PSU)	2,800	-	-	Provides power and support.
Pressurized Excursion Module (PEM)	6,000	4	10,000	Habitat module.
Pressurized Core Module (PCM)	7,800	4	10,000	Central habitat module.
Pressurized Logistics Module (PLM)	3,400	0	17,500	Logistics module to contain resources.
Fission Surface Power System (FSPS)	9,500	-	-	Power plant for surface operations.

* Baseline cargo is 500 kilograms, plus 210 kilograms to support a four-crew, seven-day sortie-style exploration.
** ISRU plants are modeled as capable of storing up to one year's production. Any excess production is discarded.

Secondary element models, listed in Table 4, are simplified to mass estimates without demand models.

Table 4. Secondary lunar outpost elements (adapted from Ref. 6).

Name	Empty Mass [kg]	Max Cargo [kg]	Name	Empty Mass [kg]	Max Cargo [kg]
Airlock-derived Logistics Carrier (ALC)	400	500	Robotic Assistant (RA)	110	-
Solar Array (SA)	50	-	Lunar Outpost Manipulator System (LOMS)	190	-
Small Offloading Device (SOD)	10	-	Suit Port Transfer Module (STM)	50	-
Portable Communications Terminal (PCT)	170	-	Mobility Chassis Tool Kit (MCK)	210	-
Active-Active Mating Adapter (AAMA)	270	-	Battery (BT)	85	-
Chassis Blade (CB)	100	-	Structural Support Unit (SSU)	600	-
Chassis A (CA)	100	-			

B. Missions and Events

Table 5 lists the missions modeled for the lunar outpost build-up including two sortie-style missions (one uncrewed), eight cargo missions, and seven outpost-style missions. In addition, two excursions from the outpost are modeled in detail, one short-distance excursion to the Malapert crater using two LERs over approximately one week, and one long-distance excursion to the Schrödinger Basin using two ATHLETEs over approximately 60 days.

Table 5. Lunar outpost missions (adapted from Ref. 6).

#	Date	Flight(s)	Element(s)	Description
1	5/1/2021	Sortie to LSP	SDM (CUR, SA, SOD, PCT), AM (*empty*)	Uncrewed test flight with pre-positioning of some surface infrastructure.
2	11/1/2021 11/14/2021	Sortie to LSP Return to PSZ	SDM (CUR, SA, SOD), AM (4 Astronauts)	7-day crewed exploration mission with 180 kg of science payload.
3	11/1/2022	Cargo to LSP	CDM (2 LER, 2 PUP, AAMA, RA, CB, CA, LSMS, STM, 2 BT)	Cargo delivery with 820 kg of science payload.
4	2/1/2023 2/21/2023	Outpost to LSP Return to PSZ	ODM (MCT), AM (4 Astronauts)	14-day crewed exploration mission in LERs with 660 kg of science payload.
5	10/1/2023	Cargo to LSP	CDM (2 LER, 3 AAMA, LSMS, 2 PUP, STM)	Cargo delivery with 710 kg of science payload.
6	12/1/2023 12/16/2023 12/23/2023 1/4/2024	Outpost to LSP LSP → MC MC → LSP Return to PSZ	ODM (ISRU), AM (4 Astronauts)	28-day crewed exploration mission in LERs with 190 kg of science payload; 4-day Malapert Crater excursion.
7	10/1/2024	Cargo to LSP	CDM (2 ATH, PSU, AAMA, 2 BT, ALC)	Cargo delivery with 1,800 kg of science payload.
8	11/1/2024 12/3/2024	Outpost to LSP Return to PSZ	ODM (PCT), AM (4 Astronauts)	28-day crewed exploration mission in LERs with 320 kg of science payload.
9	10/1/2025	Cargo to LSP	CDM (ATH, PEM, PSU)	Cargo delivery with 60 kg of science payload.
10	11/1/2025 12/28/2025	Outpost to LSP Return to PSZ	ODM, AM (4 Astronauts)	50-day crewed exploration mission in PEM with 420 kg of science payload.
11	10/1/2026	Cargo to LSP	CDM (ATH, PCM, PSU, ISRU)	Cargo delivery with 0 kg of science payload.
12	12/1/2026 3/28/2027	Outpost to LSP Return to PSZ	ODM, AM (4 Astronauts)	110-day crewed exploration mission in PCM/PEM with 130 kg of science payload.
13	2/1/2027	Cargo to LSP	CDM (AAMA, PLM, SSU)	Cargo delivery with 780 kg of science payload.
14	7/1/2027 1/4/2028	Outpost to LSP Return to PSZ	ODM, AM (4 Astronauts)	180-day crewed exploration mission in PCM/PEM with 280 kg of science payload.
15	10/1/2027	Cargo to LSP	CDM (FSPS, ALC)	Cargo delivery with 980 kg of science payload.
16	1/1/2028 1/26/2028 3/5/2028 6/30/2028	Outpost to LSP LSP → SB SB → LSP Return to PSZ	ODM, AM (4 Astronauts)	180-day crewed exploration mission in PCM/PEM with 70 kg of science payload; 60-day Schrödinger Basin excursion.
17	5/1/2028	Cargo to LSP	CDM (PLM, SSU)	Cargo delivery with 1,760 kg of science payload.

Each mission includes events to instantiate the required elements at KSC and transport to LSP using the appropriate flight edge. Crewed missions include events to offload elements from the delivering vehicle upon arrival on the lunar surface and move crew to their surface habitat. Finally, events are used to remove the crew from the scope of the simulation after each respective crewed mission.

Elements are reconfigured between states for many of the missions to highlight different operational conditions. Upon crew arrival, all primary surface elements are reconfigured to an active state to generate increased demands. The elements are later reconfigured to a quiescent state upon the crew departure. Both unpressurized rovers (CURs) are decommissioned (but not scavenged) after mission 4, which delivers more capable LER surface mobility elements. The ISRU plants and the fission power plant are not reconfigured are assumed to operate continuously.

Mission 7 includes an excursion to Malapert Crater (MC) using one logistics LER for prepositioning and two crewed LERs. Three days are required for transit and exploration lasts four days at MC. Continuous human presence is achieved by mission 14. Mission 20 includes an excursion to Schrödinger Basin (SB) using a “Lunabago” concept, in which two ATHLETE systems carrying the pressurized excursion module (PEM) and a pressurized logistics module (PLM) travel with the crew in two LERs. Surface transport takes 25 days to arrive at SB, exploration lasts for 14 days, and 45 days are provided for the return surface transport to the outpost.

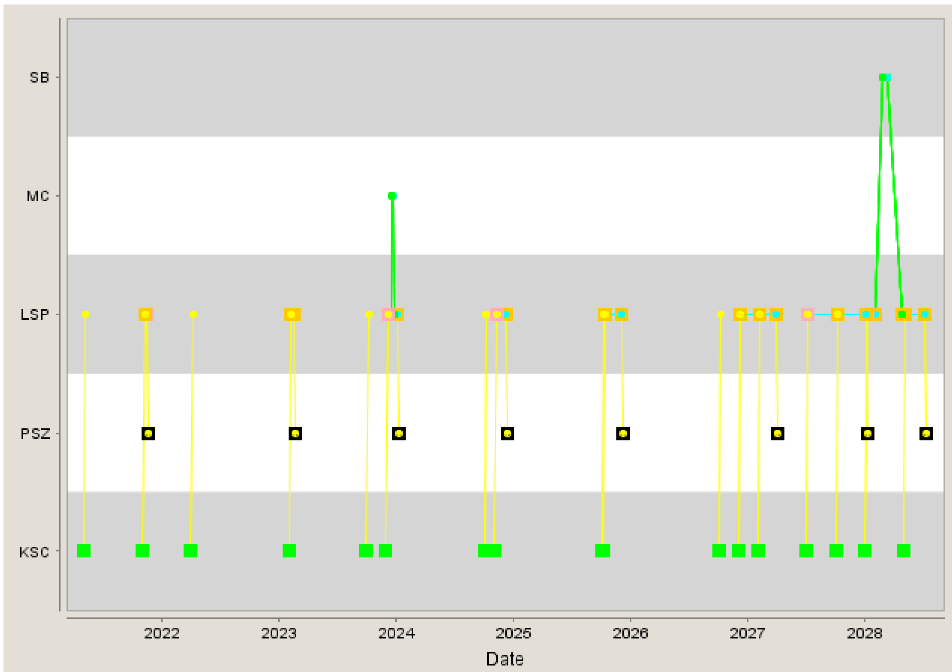

Figure 6. Lunar outpost bat chart. *17 missions executed between September 2021 and 2029. Yellow lines indicate flight transports, green lines surface transports, green squares element instantiations, orange squares element movements, pink squares element state changes, and black squares element removals.*

C. Analysis and Discussion

Figure 7 shows the logistical feasibility at LSP given the raw and remaining capacity of landers (after specified infrastructure elements have been accommodated) and total aggregated demands. Logistics containers are included using packing factors of 50% for water, 100% for gases, and 120% for all other non-science pressurized items.

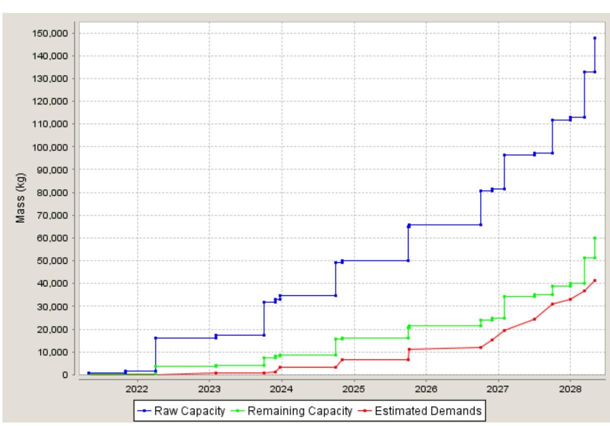

Figure 7. Lunar outpost feasibility. *The mission is feasible because the total demands (41.3 metric tons) are below the remaining cargo capacity at all times.*

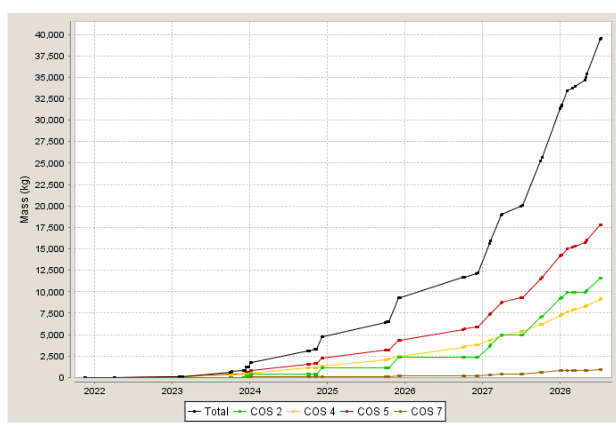

Figure 8. Demands at LSP. *The 39.5 metric tons of demands at LSP are mostly crew provisions (COS 2), maintenance and repair (COS 4), and stowage and restraint (COS 5).*

As expected, the campaign is logistically feasible. Stowage and restraints (COS 5) exhibit the highest demands, followed by crew provisions (COS 2) and spares and maintenance (COS 4). Close inspection illustrates the change in spares rates corresponding to crewed periods. An interesting observation is that there is a crossover during the year 2027 between COS 4 and COS 2 (see Figure 8) in a way that crew consumables become the second largest source of cargo demand once permanent human presence is established at LSP. This illustrates that demand models can become quite non-linear once elements are allowed to persist in different operational states.

This case study modeled an extended lunar surface exploration campaign based on existing architectural studies. Modeling details include ISRU oxygen production, dynamic spares rates for crewed versus un-crewed periods, surface transportation for excursions, and improved water recovery rates in crew habitats. As expected with a matured design, the aggregated demands for crew consumables and spares and maintenance indicate it is a logistically feasible campaign. Additional analysis for a lunar surface exploration campaign should introduce micro-logistics aspects such as a detailed inspection of the excursions to Malapert Crater and Schrödinger Basin.

V. Near-Earth Object Sortie[**]

Concepts for human exploration to asteroids and other objects having similar orbits to Earth (collectively called near-Earth objects, or NEOs) have existed since as early as 1966.[11] NEO mission concepts more recently gained attention as a way to improve technical readiness levels for advanced propulsion, in-space habitats and *in-situ* resource utilization systems while performing worthwhile scientific research.[12,13]

This scenario investigates the feasibility of a two-crew, five-day exploration at NEO 1999-AO10. This particular NEO has a favorable launch opportunity within a conceivable timeline (2025). Furthermore, prior research has explored the implementation of such a mission using a modified crew exploration vehicle and Ares V heavy-lift launch vehicle. [13] The goal of this scenario is to provide a high-level evaluation of the feasibility of such a mission.

A. Network and Elements

The network model captures the launch site from Earth, a parking orbit in low-Earth orbit, the NEO destination, and the return site in the Pacific Ocean. Space transports are used to traverse edges, requiring impulsive burns to achieve required changes in velocity (delta-v).

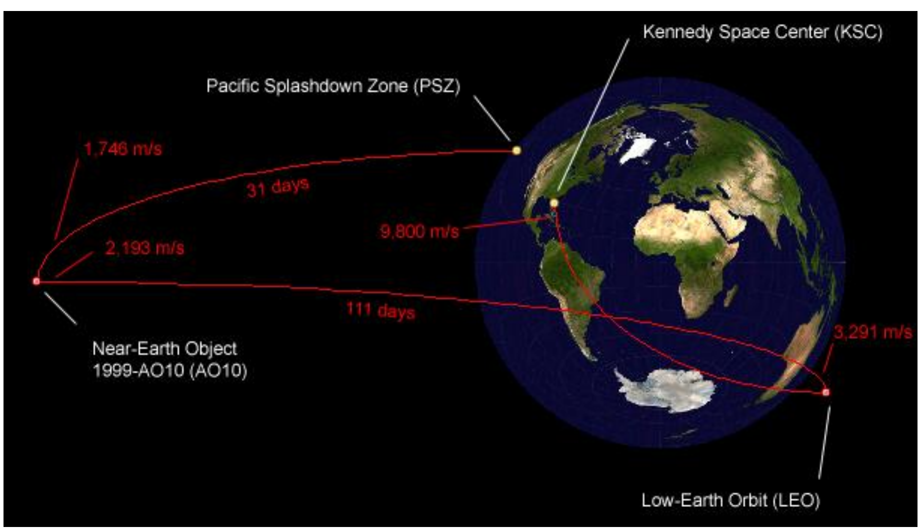

Figure 9. NEO sortie network. *Visualization of the Earth-NEO network including space transport edges (red curves). Required delta-v values to complete transports and durations are indicated.*

The elements used in this mission include a heavy-lift style launch vehicle and an in-space crew vehicle. The models are roughly based on Constellation program components (Ares V launch vehicle and Orion crew exploration vehicle) with slightly larger propellant capacities for the heavy-lift upper stage (increased from 253,000 kilograms to 305,000 kilograms) and service module (increased from 10,000 kilograms to 10,500 kilograms).

Some of the assumptions required to complete the mission include:

[**] This scenario is available for download at http://spacenet.mit.edu/applications.php#neo-sortie

- Crew demands of 7.5 kilograms per person per day include all provisions and operations resources.
- No waste is accumulated by consuming resources (i.e. any waste is jettisoned).
- Required logistics containers and spares are included in the base mass of each element.
- The heavy-lift upper stage can be restarted and has no cryogenic propellant losses while in transit.
- All exploration at the NEO is assumed to be tele-operated (i.e. no airlock is included).
- The crew module is of sufficient size to sustain the two astronauts for the long duration mission.

Table 6. NEO sortie elements (adapted from Ref. 6).

Name	Empty Mass [kg]	Crew Capacity	Cargo Capacity [kg]	Fuel [kg] (Type)	Isp [s]	Description
Boosters	213,000	0	0	1,370,000 PBAN	269	First stage of launch vehicle.
Core Stage	173,680	0	0	1,587,000 LOX/LH2	414	Second stage of launch vehicle.
Interstage	9190	-	-	-	-	Connects the core stage to the upper stage.
Upper Stage	26,390	0	0	305,000 LOX/LH2	449	Third stage of launch vehicle; also used for in-space propulsion.
Crew Module	8,600	2	2,500	-	-	In-space crew habitat and re-entry vehicle.
Service Module	3,000	0	0	10,500 MMH/N2O4	301	In-space propulsion.
LAS	3,700	0	0	2,500 HTPB	250	Used to abort launch, if necessary.
SA	500	-	-	-	-	Connects crew and service modules to the upper stage.

B. Missions and Events

This scenario features one sortie mission to 1999-AO10 starting on September 19, 2025, outlined in Figure 10. The launch from Kennedy Space Center uses a staging of the boosters, the core stage, and the upper stage to achieve low-Earth orbit. During the launch sequence the launch abort system is staged after the boosters and the interstage is staged after the core. Once in low-Earth orbit, the upper stage is burned to depart from Earth orbit and, 111 days later, again to arrive at 1999 AO10. The exploration operations take place over five days followed by a direct return to the Pacific Ocean by burning and staging the service module.

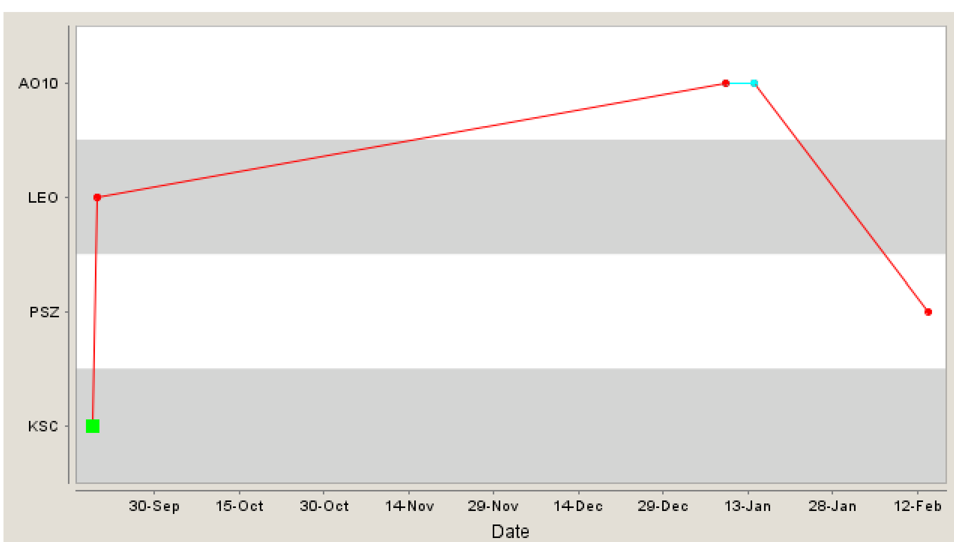

Figure 10. NEO sortie bat chart. *Red lines indicate space transports, the green square is the instantiation of elements at Kennedy Space Center, and the blue line is the exploration at 1999 AO10.*

C. Analysis and Discussion

The baseline mission is logistically feasible, with 2,220 kilograms of demands (primarily generated during the transit to 1999-AO10) satisfied by the 2,500 kilogram cargo capacity of the crew module, as shown in Figure 11. However, this does not explicitly take into consideration the considerable mass of logistics and packaging containers and any desired science and exploration resources. The demands could be reduced with the addition of closed-loop life support systems; however the limited space within the crew module may limit its application in this case.

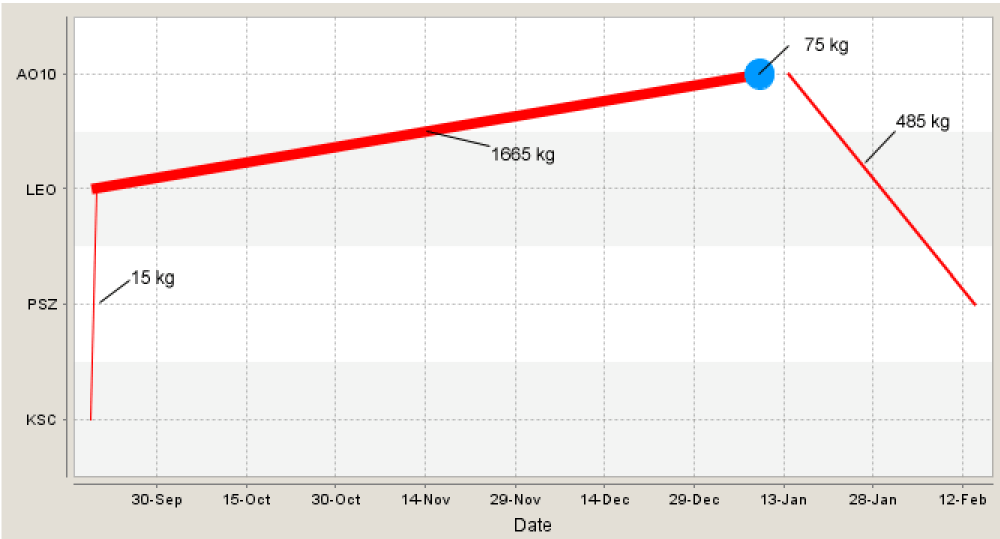

Figure 11. Near-Earth object sortie demands. *A total of 2,220 kilograms of demands are generated by the crew of two during the mission, which can be satisfied given the 2,500 kilogram cargo capacity of the crew module.*

The baseline mission is also propulsively feasible. At the end of life, upper stage has 370 kilograms (0.1%) of residual propellant (shown in Figure 12) and the service module has 25 kilograms (0.2%). Although acceptable within the context of this conceptual analysis (in part due to increases in baseline propellant capacities), these narrow propellant margins are likely insufficient to support an operational mission. Additionally, the assumption of a restartable upper stage with no cryogenic propellant losses is a stretch for current technology.

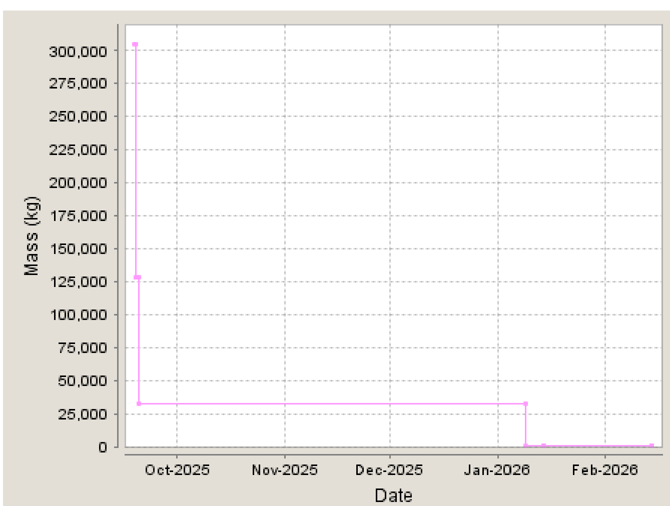

Figure 12. NEO upper stage propellant history. *The upper stage has 127,850 kilograms of propellant remaining after launch, 33,150 kilograms after Earth departure, and 370 kilograms after arrival at 1999 AO10.*

Although feasible as defined in this conceptual outline, a mission to a near-Earth object such as 1999 AO10 is challenging to accomplish due to the large delta-v values (relative to low-Earth orbit or lunar explorations) required and long durations experienced. A more plausible mission outline would include a dedicated in-space habitat with closed-loop life support systems to recycle water, the addition of an airlock, and a larger in-space propulsion system to perform the arrival burn (rather than the upper stage, which relies on cryogenic propellants).

VI. Mars Exploration Campaign††

The "Flexible Path to Mars" is a concept outlined by Ref. 14 as a philosophy for structuring a campaign to explore the inner solar system while building up human experience and capability in deep space with the ultimate goal of landing humans on the surface of Mars. The particular locations and the sequence in which they are visited depend on uncertain factors such as future technological capabilities, scientific impetus, and political direction. This case focuses on the final stages of the exploration campaign, analyzing four possible missions which culminate in the ultimate goal of landing humans on the Martian surface. More detail on this case can be found in Ref. 15.

A. Network and Elements

A graphical representation of the exploration network is shown in Figure 13. Not all nodes are visited in each mission, though all nodes are visited at least once throughout the course of the Martian exploration campaign. The target explorations sites include the two moons of Mars, Phobos and Deimos, and three surface sites, Mawrth Vallis, Holden Crater Fan, and Gale Crater, identified as potential sites of high scientific value.[16] The transportation network uses a combination of propulsive trajectories between the low Earth orbit and Martian orbit, and abstracted flight transports for launch to low Earth orbit and between orbital and surface locations in the Martian system.

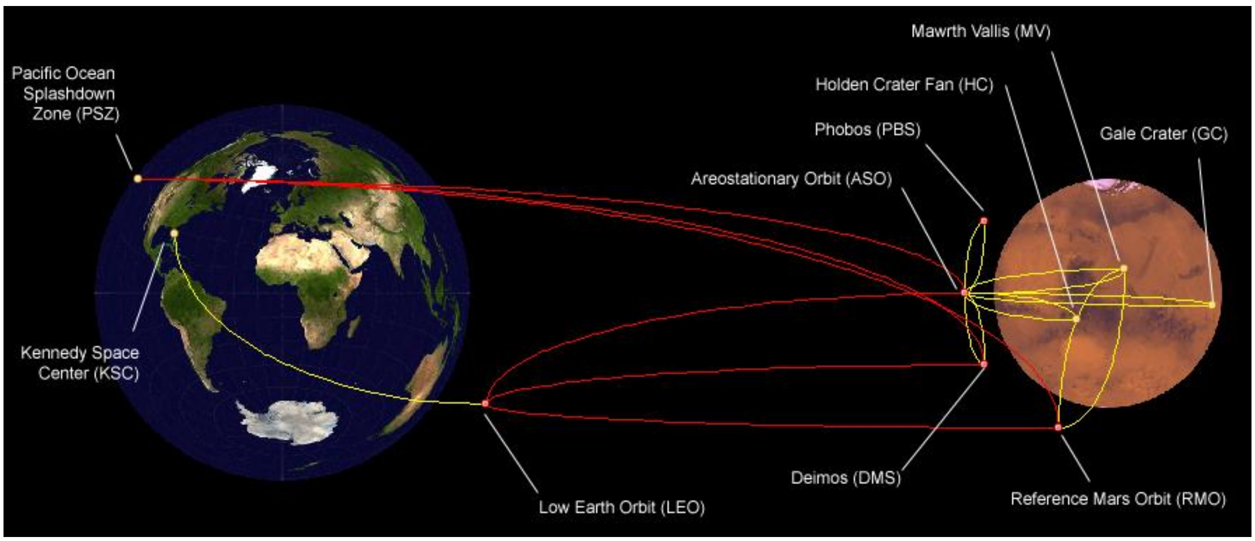

Figure 13. Mars exploration campaign network. *Red curves indicate propulsive transports, yellow curves indicate abstracted flight transports. Phobos and Deimos positions are selected for ease of visualization.*

Table 7 lists the vehicle elements modeled for the Mars exploration campaign. Most elements are based on NASA Design Reference Architecture (DRA) 5.0 with a few additions specific to the missions conducted.[16] For example, the *Pirogue* exploration vehicle allows humans to explore the Martian system without moving the massive Mars transit vehicle. Additionally, propellant depots hold stores of propellant to ensure the feasibility of the missions. One particular modification is the use of the Earth Departure Stage and propellant depots as the primary means of in-space transportation, precluding the use of nuclear thermal rocket technology.

B. Missions and Events

The Mars exploration campaign includes several missions building up to a human surface mission. A prominent aspect of all four missions is the use of propellant depots, both in Earth orbit and in Martian orbit, to supply the energy necessary to position the mission infrastructure and payloads. While other means of in-space transportation are viable, this choice allows the demonstration of the ability to model refueling in SpaceNet.

†† This scenario is available for download at http://spacenet.mit.edu/applications.php#mars-exploration

Table 7. Mars exploration campaign elements (adapted from Ref. 15).

Name	Mass (mT)	Max Crew	Max Cargo (mT)	Fuel Mass (mT)	I_{sp} (s)	Description
Ares V SRB	106.5	0	0.0	685	269	Ares V Solid Rocket Booster
Ares V Core	173.7	0	0.0	1,587	414	Ares V Core Stage
Ares V Interstage	9.2	0	0.0	0	-	Ares V Interstage
Ares V EDS	26.4	0	0.0	253	449	Ares V Earth Departure Stage
Ares V PLF	9.0	0	0.0	0	-	Ares V Payload Fairing
MTH	27.5	6	5.3	0	-	Mars Transfer Habitat
CEV	6.0	6	0.5	0	-	Orion Crew Exploration Vehicle
CFC	1.9	0	7.9	0	-	Contingency Food Canister
SM	4.0	0	0.0	0	-	Orion Service Module
Pirogue*	3.9	2	0.5	0	0	Pirogue Exploration Vehicle
Hopper/MAV* Team	1.8	0	1.0	0	0	Two hopping robotic explorers with a Mars Ascent Vehicle
MDAV	102.0	0	4.5	0	0	Mars Descent-Ascent Vehicle Cargo Lander with Aeroshell
SHAB	105.6	6	1.5	0	0	Surface Habitat with Aeroshell
Human MAV**	21.5	6	0.3	0	0	Human Mars Ascent Vehicle
LEO PD	17.4	0	85.0	0	0	Low Earth Orbit Propellant Depot
ASO PD	11.1	0	54.3	0	0	Areostationary Orbit Propellant Depot
PRM	38.2	0	85.0	0	0	Propellant Depot Refueling Module

*Events involving this vehicle are modeled as a flight transport. Propulsive feasibility is analyzed in Ref. 17.
**Events involving this vehicle are modeled as a flight transport. Propulsive feasibility is assumed from Ref. 16.

The Mars Tele-exploration Mission (MTM) delivers three pairs of hopping robotic explorers to the Martian surface which are remotely supervised by astronauts orbiting in areostationary orbit (analogous to Earth's geostationary orbit). The first Martian samples, on the order of a few kilograms, are gathered via small Mars Ascent Vehicles and returned with the astronauts to Earth after approximately 60 days in orbit.

The Phobos and Deimos Sorties (PDS) send two astronauts to aerostationary orbit with a small exploration vehicle, the *Pirogue*, designed to rendezvous with Phobos and Deimos. The astronauts spend seven days at each of the moons performing extravehicular exploration and gathering samples on the order of 10s of kilograms to be returned to Earth with the astronauts after approximately 60 days in the Martian vicinity.

The Phobos Exploration Mission (PEM) is conducted from orbit where astronauts spend approximately 60 days in the vicinity of Phobos. Dedicated extravehicular exploration of Phobos is performed and samples on the order of 100s of kilograms are gathered and returned to Earth.

Finally, the Mars Surface Mission (MSM) lands astronauts on the Martian surface, using a conjunction-class trajectory to spend approximately 500 days exploring on the Martian surface.

The four missions are nominally sequenced in a manner that would allow the gradual buildup of experience in long-term deep space travel, operations in the Martian neighborhood, and human exploration of extraterrestrial bodies. There is no overarching reason why any of the missions cannot be altered, repeated, delayed, rearranged, or cancelled entirely with exception of the initial prepositioning of necessary fuel depots. Instead, missions can be molded to suit the prevailing capabilities and desires at the time of launch and lessons learned and new knowledge acquired. That is the spirit of the Flexible Path to Mars.

Figure 14 shows the bat chart of the Mars exploration campaign. The campaign is divided into the four missions outlined above, including a preliminary phase, LPD Construction, of propellant depot construction. The bat chart is particularly apt at showing the range of locations explored during the exploration campaign and the subsequent repeat visits to certain locations.

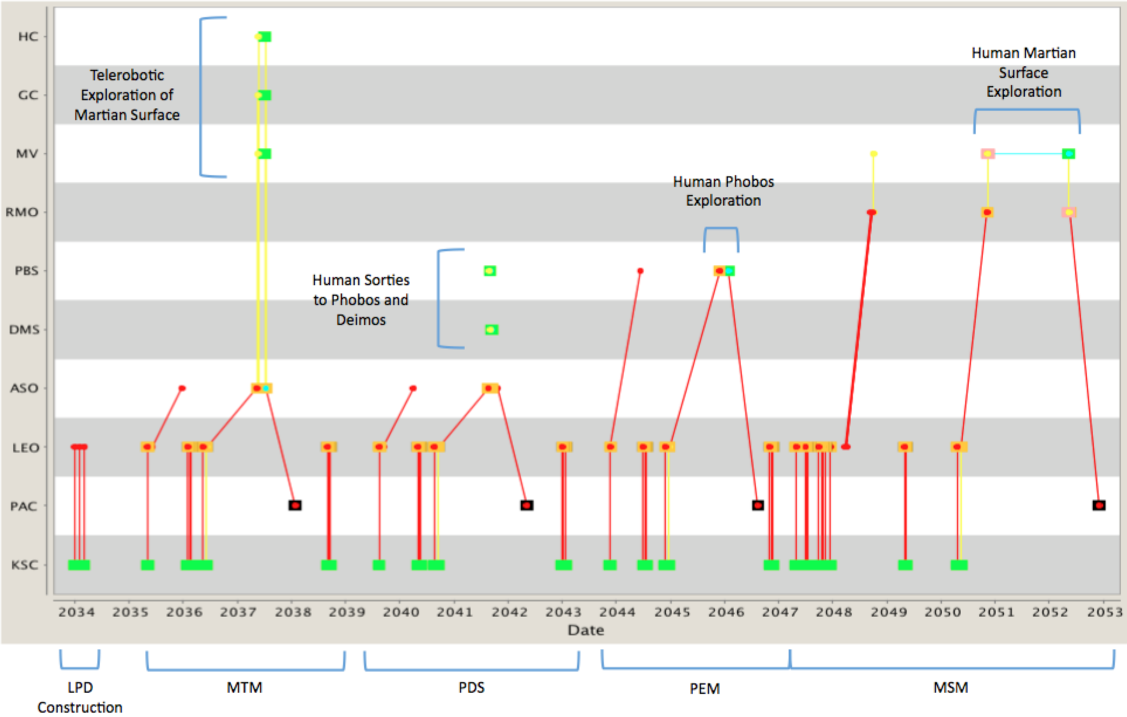

Figure 14. Mars exploration campaign bat chart. *Illustrates space transports (red lines) and flight transports (yellow lines), explorations (blue lines), element initialization events (green squares), element movement events (yellow squares), and element removal events (black squares), (adapted from Ref. 15).*

C. Analysis

Table 8 is a sample of the figures of interest for the Mars exploration campaign. It shows the progression of the missions from lighter, simpler ones, at first requiring relatively few Ares V launches, propellant, and consumables, to MSM which while heavier, allows for significantly more human exploration days and sample return. The buildup, from a resource demand, operational experience, and scientific return perspective, is clearly conveyed.

Table 8: Mars exploration campaign figures of interest (adapted from Ref. 15).

Figure of Interest	MTM	PDS	PEM	MSM	*Campaign Totals*
Ares V launches (mission payloads)	2	2	2	4	*10*
Ares V launches (PRM payload)*	6	6	6	11	*29*
Crew launches	1	1	1	1	*4*
Total mass in LEO** (mT)	681.7	681.7	681.3	1,448.7	*3,493.4*
Number of sites sampled	3	2	1	1	*5*
Returned sample mass (kg)	3	150	150	250	*553*
EDS propellant usage (mT)	510.9	510.9	511.9	1,019.1	*2,552.8*
EDS propellant remaining (mT)	4.7	4.7	4.8	47.3	*61.5*
Crew consumables demand (mT)	12.5	12.5	12.5	15.3	*52.8*
Crew consumables remaining (mT)	1.2	1.2	1.2	12.3	*15.9*
Robotic-days of exploration (robot-days)	360	0	0	1,060	*1,420*
Human-days of exploration (human-days)	0	28	360	2,120	*3,568*

*Includes launches required construct LPD
**Includes mass of stack immediately before TMI

VII. Conclusion

This paper presents a framework for generalized space exploration modeling and simulation consisting of a time-invariant network, elements, resources, and events. The modeling framework is implemented in the open source SpaceNet software tool. The network, element, and resource models persist in an integrated database while the user-specified events are defined uniquely for each scenario.

Four application cases showcase the variety of exploration scenarios capable of being modeled using this framework. The International Space Station resupply campaign illustrates the capacity to simulate a large number of missions (77) using abstracted flight transportation. The lunar outpost campaign illustrates a complex surface exploration operating over 8 years and 17 missions, highlighting element-level demand models, in-situ resource utilization, and surface transportation and excursions. The near-Earth object sortie mission illustrates the simplicity for which conceptual missions can be created and analyzed for new mission concepts. Finally, the Mars exploration campaign scenario explored a combination of flexible path missions to push the boundaries of human exploration. Table 9 provides an overview of the four case studies in terms of key characteristics. This comparison shows the bandwidth of SpaceNet to not only handle a wide spectrum of destinations and campaigns but also the ability to model and simulated very complex scenarios involving dozens of coordinated flights over many years.

Table 9. Summary of application cases.

Figure of Interest	ISS Resupply	Lunar Outpost	NEO Sortie	Mars Exploration Campaign
Nodes	9	5	4	10
Edges	13	6	3	23
Missions	78	17	1	21
Events	271	156	6	337
Elements Types	14	30	11	32
Elements	90	140	12	234
Duration (days)	1,920	2,628	148	6,911

Future research seeks to strengthen the modeling details of the SpaceNet tool. Although rudimentary capability exists for modeling advanced logistics, more work is needed to separate resources by environment – pressurized versus unpressurized, liquid versus solid versus gaseous – and enforce additional constraints such as volume, which is a primary driver for habitation components. Additionally, a probabilistic modeling capability both to support uncertain demand models but also element failure scenarios that may impact campaign robustness and resilience would improve research into the numerous contingency scenarios required for detailed mission design.

Acknowledgments

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