

# SpaceNet: Modeling and Simulating Space Logistics

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**This paper summarizes the current state of the art in interplanetary supply chain modeling and discusses SpaceNet as one particular method and tool to address space logistics modeling and simulation challenges. Fundamental upgrades to the interplanetary supply chain framework such as process groups, nested elements, and cargo sharing, enabled SpaceNet to model an integrated set of missions as a campaign. The capabilities and uses of SpaceNet are demonstrated by a step-by-step modeling and simulation of a lunar campaign.**

## I. Introduction

THE term “supply chain” has traditionally been used to refer to terrestrial logistics and the flow of commodities in and out of manufacturing facilities, warehouses, and retail stores. Rather than focusing on local interests, optimizing the entire supply chain can reduce costs by using resources and performing operations as efficiently as possible. There is an increasing realization that future space missions, such as the buildup and sustainment of a lunar outpost, should not be treated as isolated missions but rather as an integrated supply chain. Supply chain management at the interplanetary level will maximize scientific return, minimize transportation costs, and reduce risk through increased system availability and robustness to failures.<sup>1,2</sup>

SpaceNet is a model with a graphical user interface (GUI) that allows a user to build, simulate, and evaluate exploration missions from a logistics perspective.<sup>3</sup> The goal of SpaceNet is to provide mission planners, logisticians, and system engineers with a software tool that focuses on *what* cargo is needed to support future space missions, *when* it is required, and *how* propulsive vehicles can be used to deliver that cargo. Users can model space missions as interplanetary supply chains to identify, quantify, and evaluate the key drivers and logistics strategies that impact their physical feasibility and performance effectiveness.

The space logistics modeling framework of nodes, processes, elements, and supplies was previously introduced in 2006<sup>1</sup> and has since evolved into functional versions of SpaceNet. SpaceNet v1.3, the last version officially documented in literature,<sup>3</sup> was used in the second Constellation Program (CxP) Integrated Design Analysis Cycle (IDAC-2).<sup>4,5</sup> The studies, trading launch architectures and propellant types, used a version of SpaceNet that was primarily developed to model individual, sortie-style missions.

When SpaceNet was proposed to analyze the lunar campaign from a logistics perspective in the CxP IDAC-3<sup>6</sup>, it required fundamental upgrades in order to model such campaigns and to evaluate trades of interest. The implementation of these upgrades, and the resulting expansion in modeling capabilities, yielded SpaceNet v1.4.

This paper provides a general overview of the SpaceNet v1.4 model, focuses on its current capabilities, application to campaign analysis, verification and validation status, and concludes with recommendations for future work.

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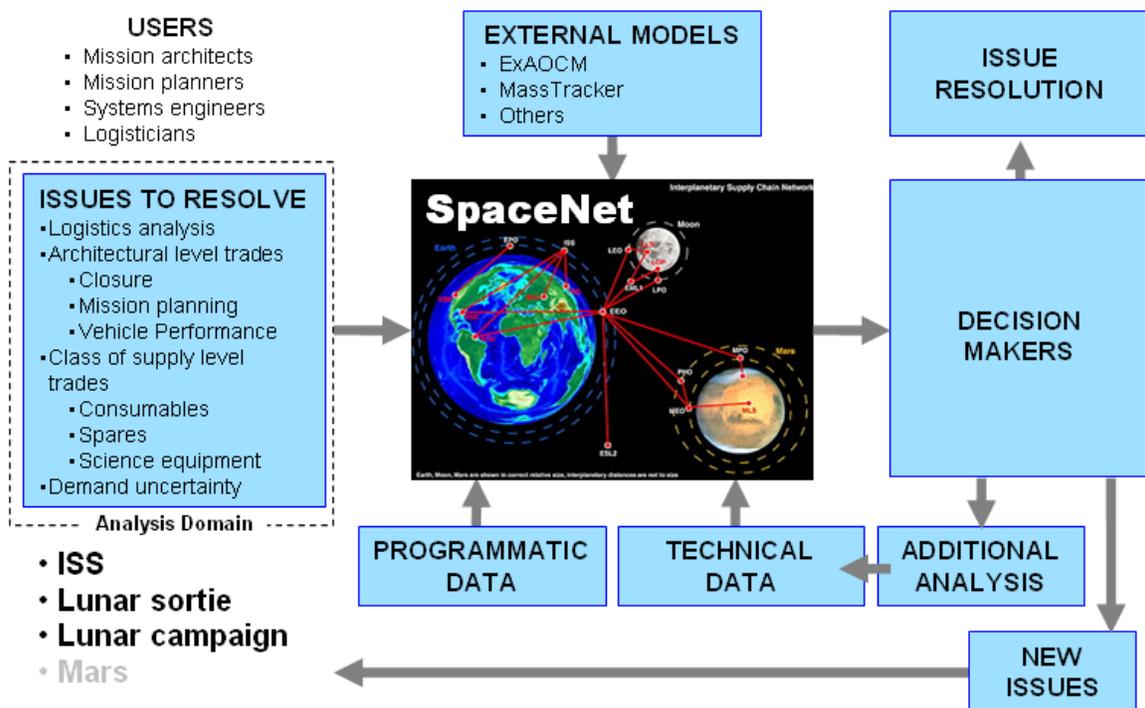
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## II. SpaceNet Overview

SpaceNet is a computational environment in MATLAB (supported by an Excel database) that enables users to visually construct exploration missions at both the sortie (individual mission, short duration) level and the campaign (set of missions, long duration) level. Interplanetary supply chains are modeled using a space logistics framework of nodes, arcs, elements, and supplies.<sup>1</sup> These building blocks are integrated via processes and process groups, which describe how elements and supplies move through a time-expanded network of nodes and arcs. The time-expanded network has the ability to capture the time-dependency of interplanetary trajectories, including launch windows and tradeoffs between fuel consumption and time-of-flight<sup>7</sup>. Surface missions and surface systems create cargo demands at the supply class level, where detailed models exist for functional classes of supply. These demands are then manifested on cargo carriers and delivered via a transportation architecture. A discrete event simulator tracks the flow of vehicles, infrastructure, crew, and supply items in conjunction with propellant and cargo consumption. The simulator provides for the evaluation of user generated missions with respect to feasibility and measures of effectiveness (MOEs). With this end-to-end analysis capability, SpaceNet is a planning and simulation tool that can perform architecture level trade studies for future space missions.

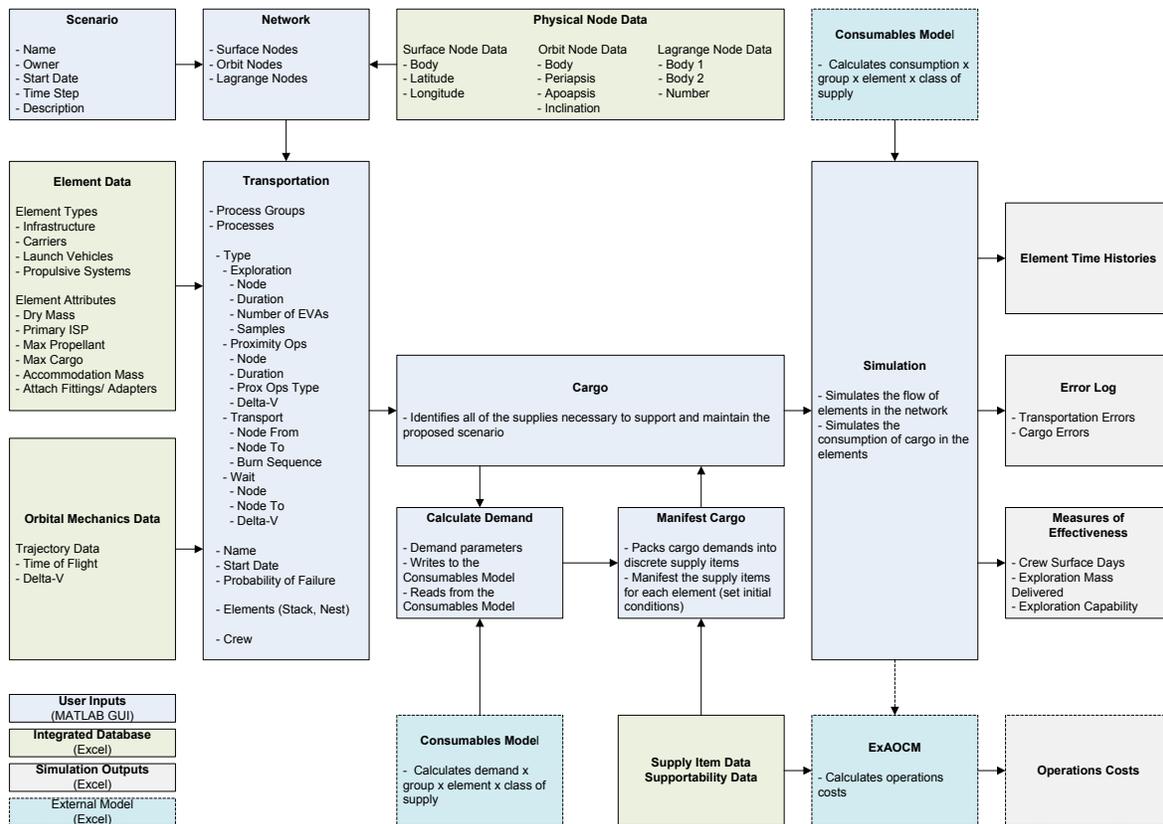
Figure 1 shows a logic diagram of how SpaceNet can be used to evaluate technical issues and trades.



**Figure 1. SpaceNet Use Case Diagram.** The dashed box to the left represents the analysis domain of SpaceNet and lists the types of issues SpaceNet can resolve. The types of users and campaigns are shown above and below the dashed box, respectively. Data and external models feed into SpaceNet as necessary. Decision makers take results from SpaceNet and decide whether issues are resolved, additional analyses are required, or new issues are created.

### A. Model Architecture

One of the major challenges in the development of a space logistics model lies not only in defining its underlying modules and the inputs, outputs, and relationships they share, but also how they are implemented in the context of a user-created exploration mission. Figure 2 shows a data flow diagram that illustrates the module functions, interfaces, and data dependencies within the overall SpaceNet model.



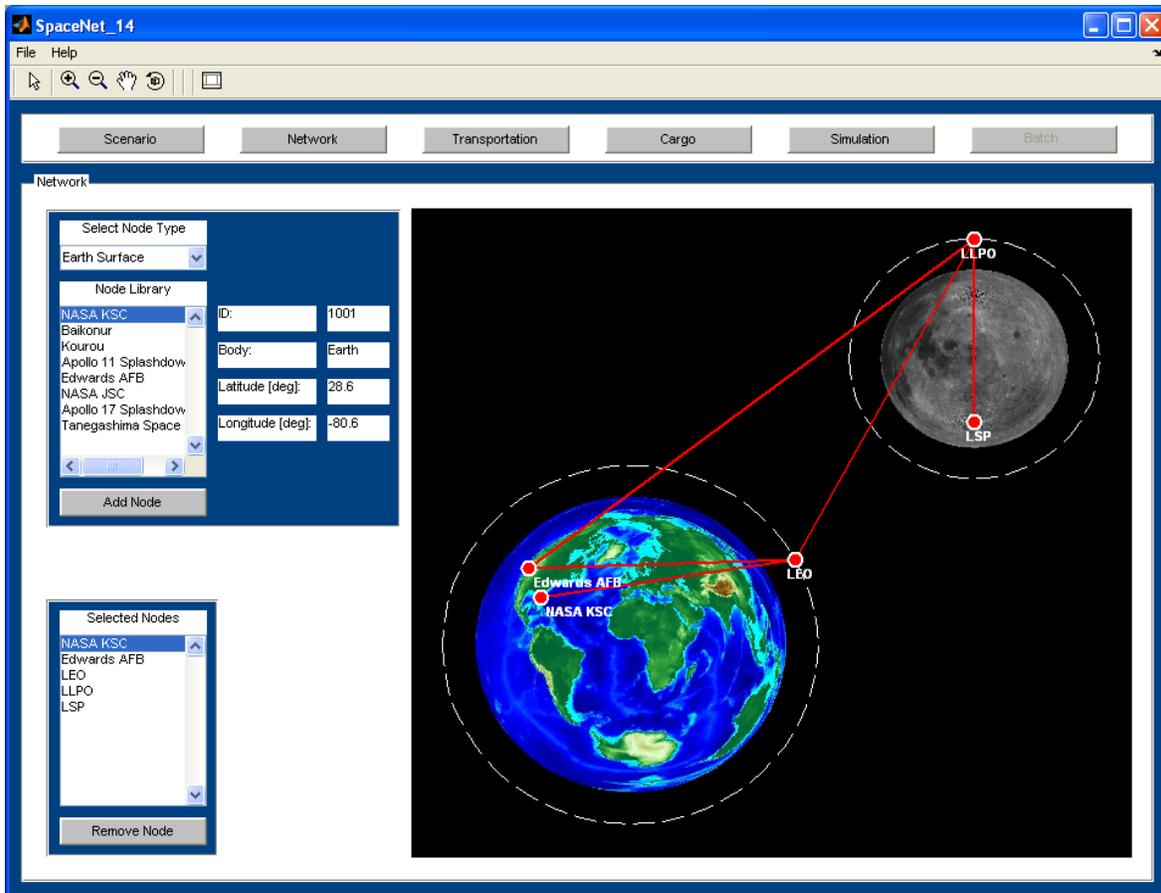
**Figure 2. SpaceNet Data Flow Diagram.** The information flow in this diagram is read from top-to-bottom and left-to-right. A user would follow the path outlined by the light purple blocks, starting with the creation of a scenario, building a network and transportation architecture, calculating and manifesting cargo demands, and ending with the simulation. The light olive covered blocks show the data types that feed into the modules. The light pink blocks are the simulation outputs. The dashed boxes represent the external models that interface with SpaceNet.

The best demonstration of the capabilities of SpaceNet, and how it can be used to answer key logistics questions for exploration, is to step through and describe each of the blocks while creating a scenario. A scenario is a representation of a space mission in the interplanetary supply chain framework. SpaceNet can model human and robotic missions as stand-alone sorties or integrated campaigns on Earth, to the Moon, and beyond.

## B. Network

The first step in creating a scenario beyond specifying a name, owner, start date, time step, and description, is to define a network of nodes. Nodes, as described in previous literature,<sup>1</sup> are spatial locations in the solar system that include surface locations, orbits, and Lagrangian points. Nodes connected together via arcs, or trajectories, form a network, and are governed by astrodynamic constraints.

Figure 3 shows a possible network for a lunar campaign at the South Pole.



**Figure 3. Network.** This network consists of surface and orbit nodes in the Earth-Moon system. The red circles correspond to nodes on a planetary body or an orbit. The red lines represent the allowable trajectories between the nodes.

### C. Elements

With the “where” in the supply chain defined by the network, the next step is to define the “what”, the elements that travel through the network. Elements, as modeled in SpaceNet, are indivisible physical objects with attributes that distinguish them as launch vehicles, propulsive stages, cargo carriers, and surface systems. Before discussing how elements are used in SpaceNet, a significant distinction must be made between element types and element instantiations.

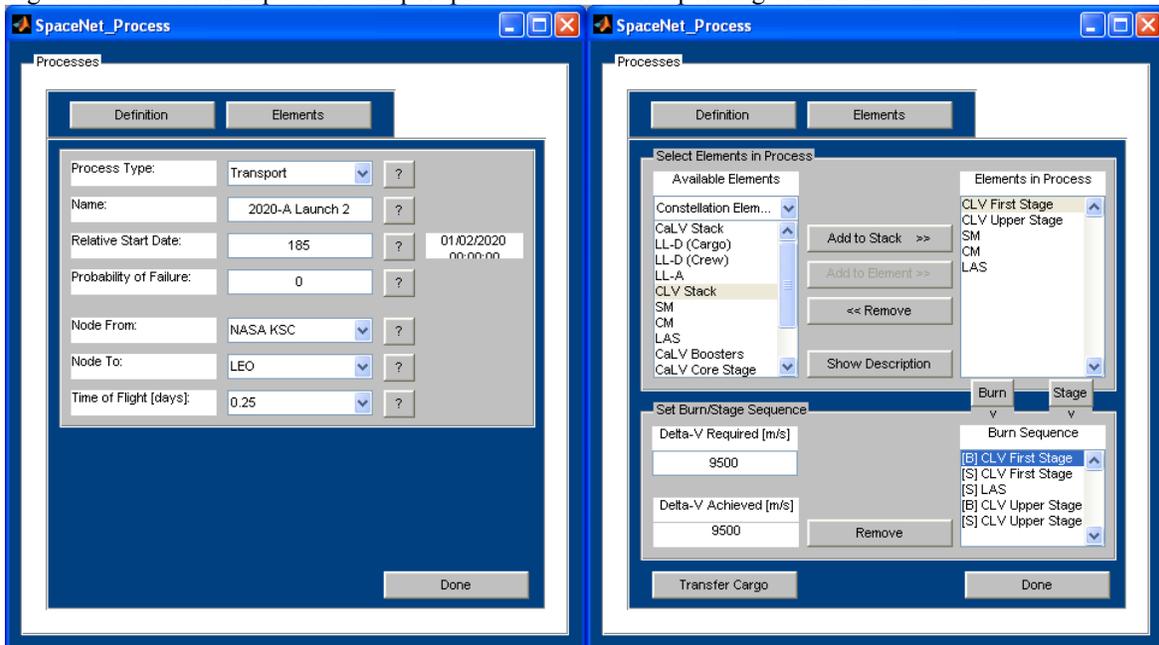
Element types, as read from a database, are a single representation of a particular element’s attributes, such as crew, cargo, and propellant capacity. Element instantiations, on the other hand, are created in SpaceNet by the user, where each instantiation represents an “instance” of how a particular vehicle or carrier is used in a scenario. The ability to create instances is critical to how SpaceNet models space logistics, by allowing the discrete event simulator to track when and where each element travels in the network, and what crew or cargo it delivers or consumes.

### D. Processes

Processes, the “how” and “when” in the supply chain, are what integrate the nodes and elements from a scenario into an architecture. The five basic process types are wait, transport, transfer, proximity operations, and exploration (surface missions) and are described in previous literature.<sup>1,3</sup>

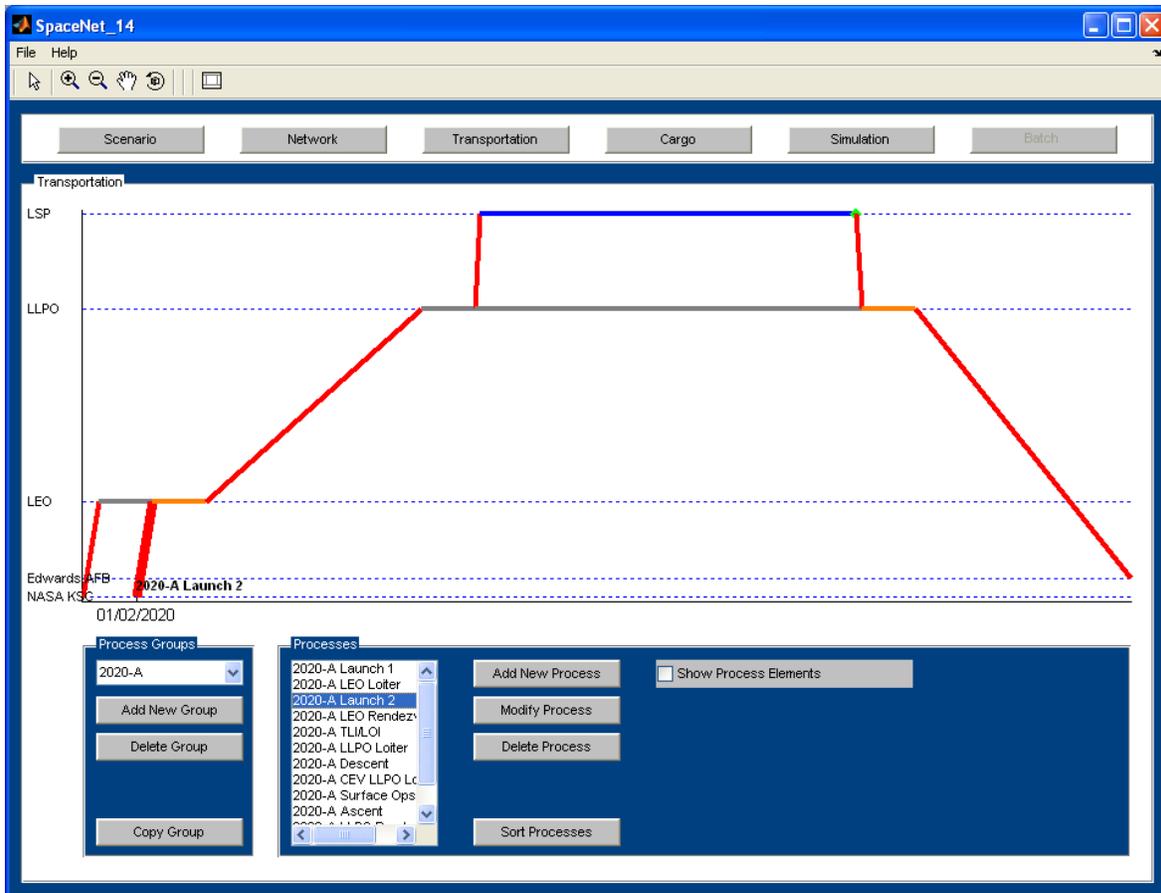
As opposed to previous versions of SpaceNet, elements and processes are now defined in conjunction. The user can select from a collection of elements, such as ISS and Constellation, and upon doing so, will dynamically create instantiations of them. Alternatively, the user can select from previously instantiated elements to continue using them throughout a scenario. Previously instantiated elements can include the propulsive stages and surface systems delivered to an orbit by a launch vehicle. These elements would then be used in future processes until they reach a surface location.

Figure 4 shows an example of a transport process and its corresponding element instantiations.



**Figure 4. Processes.** A transport process (left) and its instantiated elements (right) in a lunar campaign. The inputs to the process include the start date relative to the beginning of the scenario, the node the elements are leaving from, the node the elements are arriving to, and the trajectory. For transport processes, a burn sequence of the instantiated elements is required in order to simulate propellant consumption.

Figure 5 shows a graphical representation of a crewed flight as a collection of processes. The nodes are displayed on the vertical axis and time, increasing from left to right, is on the horizontal axis. Processes are represented by colored line segments: wait-gray horizontal, transport-red diagonal, transfer-green diamond, proximity operations-orange horizontal, and exploration (surface missions)-blue horizontal.

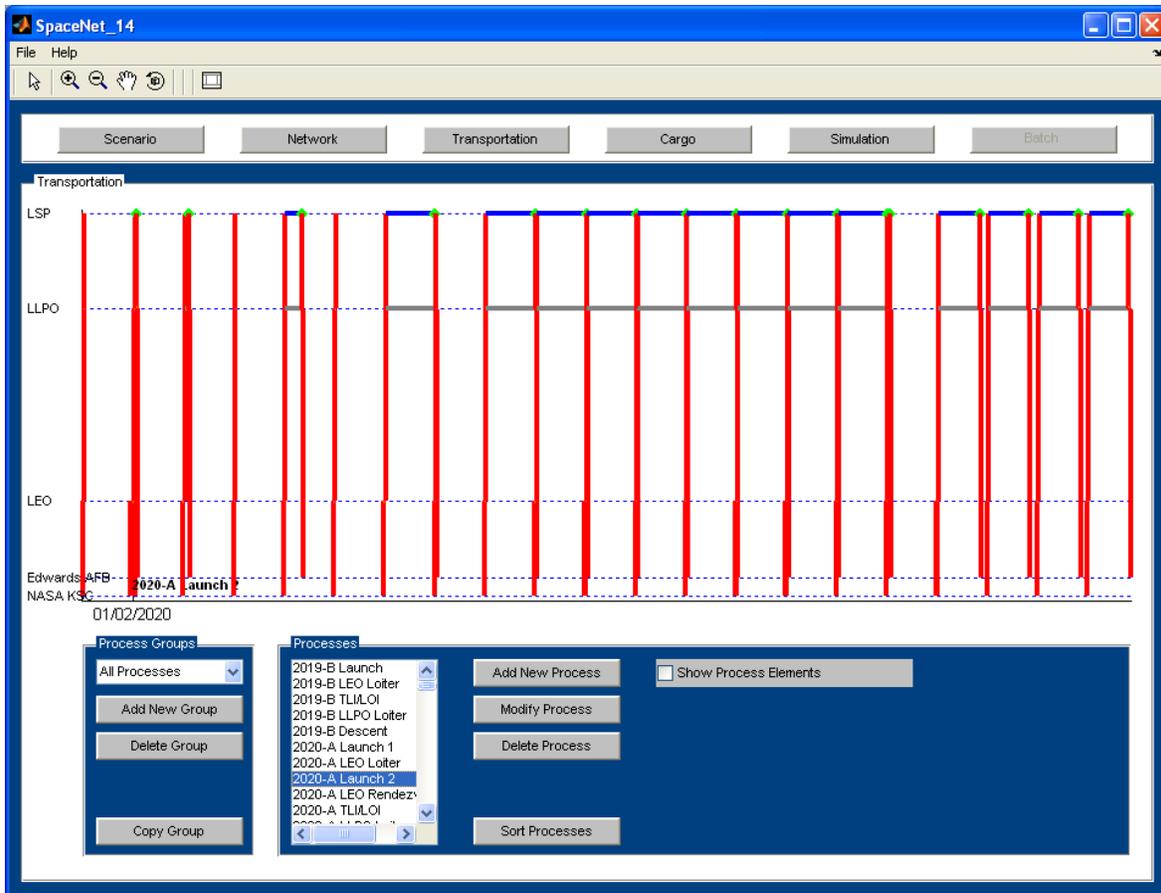


**Figure 5. Crewed Flight.** The transport process in Figure 4 is highlighted as the second (crewed) launch from Earth. The elements delivered by this launch rendezvous and dock with elements in LEO that were delivered by a preceding cargo launch. Upon a trans-lunar injection and cruise to a Low Lunar Polar Orbit (LLPO), some elements descend to the South Pole while the remainder loiter in orbit. After a surface mission and transfer of samples, elements ascend to LLPO, rendezvous and dock with the loitering elements, and return to Earth via a trans-Earth injection.

### E. Process Groups

A fundamental upgrade introduced in SpaceNet v1.4 is process groups, which are a collection of processes and their respective element types. Process groups are an essential step in defining a transportation architecture, the delivery system that supports the surface missions in a campaign scenario. Such groups can be used to copy and replicate flight types, such as the crewed flight above, cargo flights, or any other variation a user may define. When a group is copied, new instantiations of the same element types are created at a user specified time.

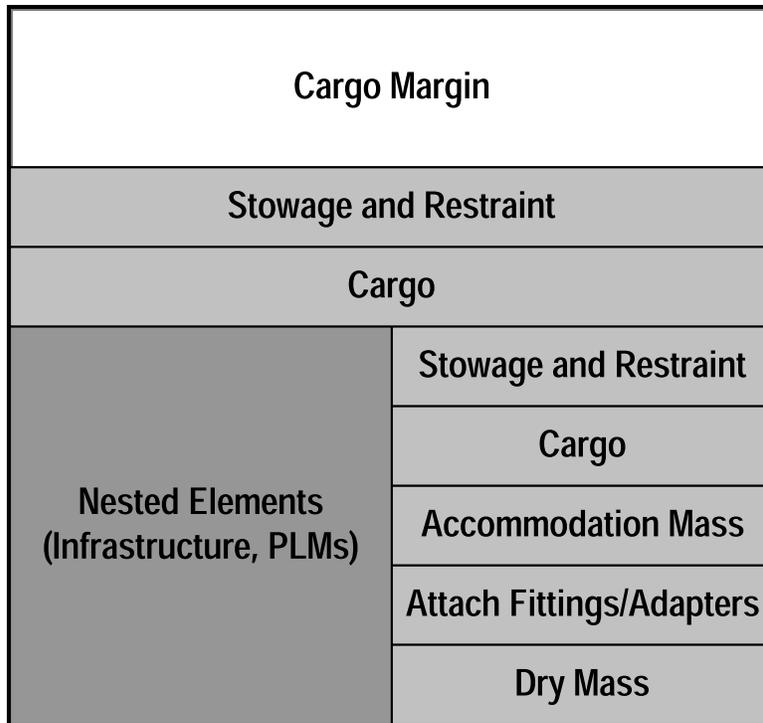
Figure 6 shows a transportation architecture for a lunar campaign, which includes a mixture of crewed flights of varying durations and cargo flights.



**Figure 6. Transportation Architecture.** *The process group in Figure 5 is highlighted as the second of 21 total flights in a lunar campaign. The campaign starts with short duration crewed flights and cargo flights to build-up infrastructure at the South Pole. Continuous 180 day exploration processes (surface missions) make up the body of the campaign. Surface mission duration decreases at the end of the campaign as cargo inventory levels are exhausted.*

## F. Nested Elements

Another fundamental upgrade from previous versions is the ability to nest elements. Elements with unpressurized cargo capacity can “hold” other elements, where “parent” elements include propulsive stages such as the descent stage of a lunar lander and “children” elements include cargo carriers and surface infrastructures. Nested elements, while allowing a user to specify what surface systems the transportation architecture delivers to a given location, also provide for the full accounting of cargo constraints and margins, when supply items are manifested in elements that are nested in other elements. An example of the full accounting in SpaceNet v1.4 is shown in Figure 7.



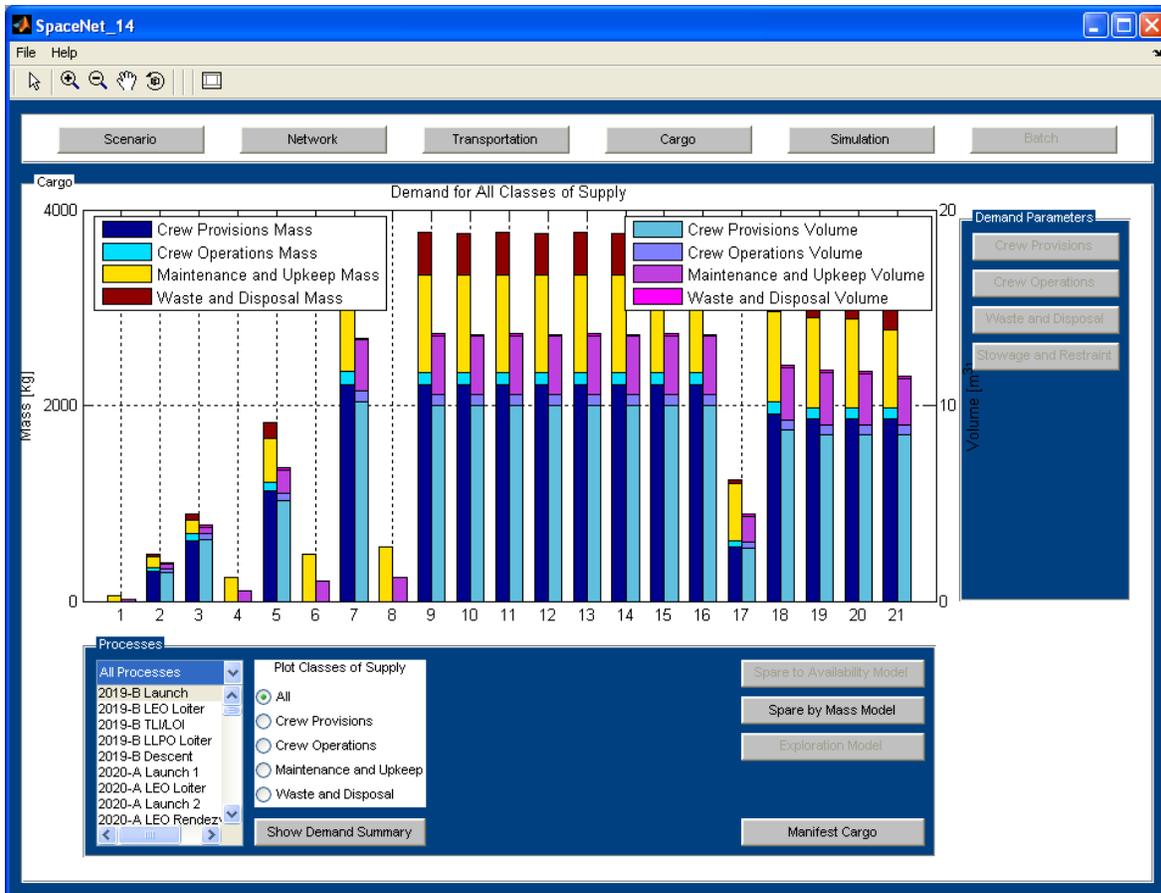
**Figure 7. Cargo Margin.** The total cargo capacity (mass in this example) of a parent element is represented by the large square. The five rectangles to the right of the dark gray box represent the total mass of a nested element. The components include the dry mass of the nested element, the attach fittings/adapters mass required to nest the element on the parent, the accommodation mass (racks/lockers) required to hold cargo, the cargo in the nested element, and the stowage and restraint (packaging) mass used to pack the cargo. The parent element can hold cargo itself, represented by the two rectangular boxes on top of the nested elements. Subtracting all of these components from the total cargo capacity yields the cargo margin.

Cargo margins are used both for feasibility (can the transportation architecture deliver the required cargo) and for performance metrics (how efficient and robust is the transportation architecture).

### G. Cargo Demands

The next step after defining what surface systems are delivered and when is to calculate the cargo demands for the surface missions. Supply items, along with elements, are the “what” in the supply chain. Supply items are created from demands generated by the elements and processes, such as consumables, spares, and science equipment.

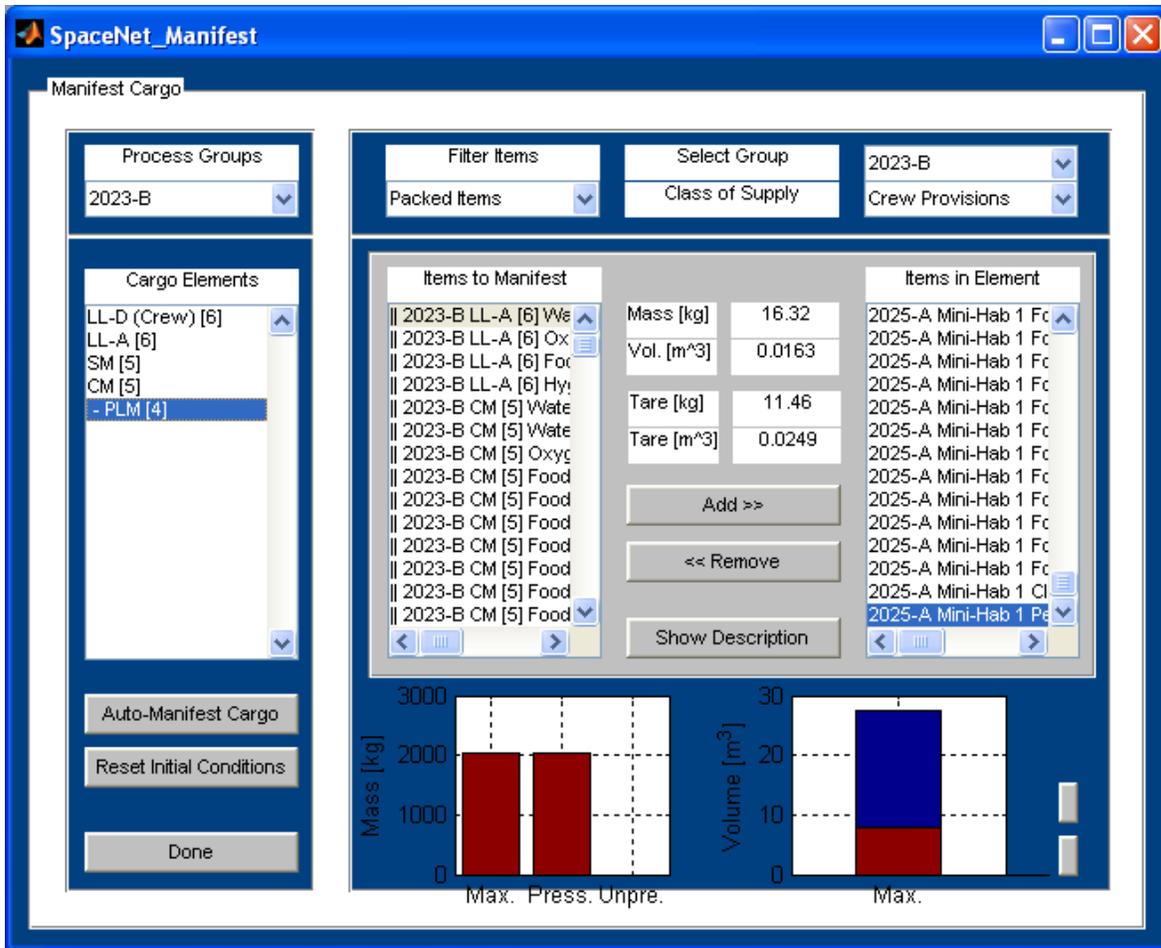
These demands are categorized into functional classes of supply,<sup>1</sup> where individual models determine the required mass and volume (by class of supply) for the surface missions defined in a campaign scenario. An updated consumables model was integrated in SpaceNet v1.4 as a stand-alone Excel application, which takes into account water recovery, oxygen produced by electrolysis, and in-situ resource utilization (ISRU). The parameters in the consumables model can be modified for trade studies, such as varying the percentage of water and solid waste recycling to reflect future technology investments. There are two options for calculating spares demands. The spare-by-mass model calculates the mass and volume of pressurized and unpressurized spares for an element as a function of its dry mass. The predicted demands may not accurately reflect the actual spares demands, but such a model can be used until data is available to support the higher fidelity sparing-to-availability model. The sparing-to-availability model calculates spares demands as a function of element orbital replacement units (ORUs) and shop replacement units (SRUs). Such demands are application-specific and rely on attributes such as mean-time-between-failure (MTBF) and duty cycle. While this model can calculate spares masses and volumes as a function of a target availability, it cannot be used until the element ORUs and SRUs are defined. Figure 8 shows the mass and volume of the cargo demands by class of supply for each process group in a lunar campaign.



**Figure 8. Cargo Demands.** Cargo demands (mass and volume) are calculated for each process group by class of supply. The demands are plotted as pairs of columns stacked by class of supply, where mass is on the left and volume is on the right. While uncrewed, cargo flights still have demands because the surface systems they deliver require spare parts.

## H. Manifesting Cargo

Calculating the demands determines the nominal amount of cargo required to support the surface missions and surface systems in a campaign. To understand if such a campaign is feasible, and to evaluate what the most effective delivery strategies are, the cargo demands are packed into individual supply items and then manifested on cargo carriers. Supply items, such as cargo transfer bags (CTBs), gas tanks, and liquid tanks, have respective mass and volume capacities and tares. The tare values are used to quantify the amount of packaging required to deliver the cargo demands for a campaign. Manifesting the discretized supply items into cargo carriers must satisfy multiple constraints. The cargo carrier must have the available pressurized or unpressurized mass and volume capacity for a given supply item. If the cargo carrier, such as a pressurized logistics module (PLM), is nested in another element such as a descent stage, then the cargo capacity of that parent element must be satisfied as well. In addition to the supply items created by the cargo demands from the surface missions and surface systems, a user can also manifest exploration items such as science instruments, and reserve supplies such as safety stocks. These reserves would serve to hedge against uncertainties in demand or flights that are delayed or cancelled. While the manifesting process can be performed by hand to optimize packing efficiency, it is also completely automated via a simple heuristic. This heuristic manifests the supply items that are to be consumed first in the first available elements that can deliver them. Figure 9 shows an example of Crew Provisions supply items manifested in a nested PLM in a particular group.



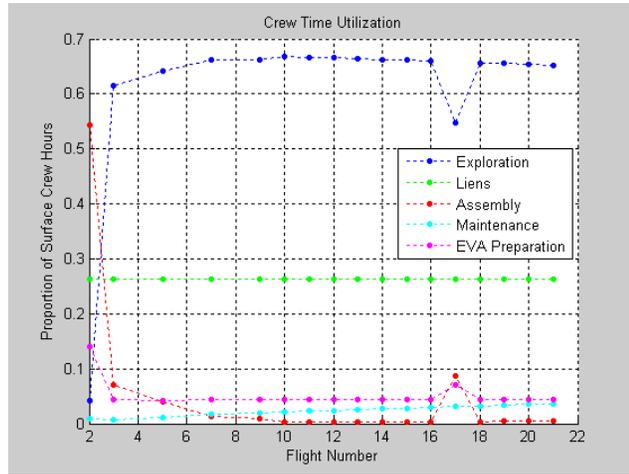
**Figure 9. Manifesting Cargo.** Cargo can only be manifested in elements with cargo capacity (left). Individual supply items are tagged with the process groups and elements that generated them (center). These packed items can be sorted by process group and class of supply. The supply items already manifested in an element determine how much pressurized or unpressurized mass and volume capacity it has remaining (right, bottom).

## I. Simulation

Once a scenario is complete with its network, transportation architecture, surface missions, surface systems, cargo demands, and cargo manifests, the last step is to evaluate such a scenario with respect to feasibility and performance metrics. The discrete event simulator simulates by process group, process, and element. Propellant consumption includes how much propellant is left over in a descent stage upon a transport process to a surface location. Cargo consumption includes, for example, how the mass and volume of food decreases (consumption) or increases (resupply) over time in a habitation module. A new capability in SpaceNet v1.4 is for the simulator to recognize cargo sharing among elements co-located at a node. For example, if crew resides in a habitation module and runs out of food to consume during a surface mission, the simulator will automatically allow the crew to consume food in another habitation module or PLM located at the same node. The purpose of the discrete event simulator is to capture and quantify the feasibility/infeasibility boundary of a campaign. Insufficient delta-v and propellant margins in the transportation architecture, or cargo shortages by class of supply will result in “errors” that are flagged in an output file.

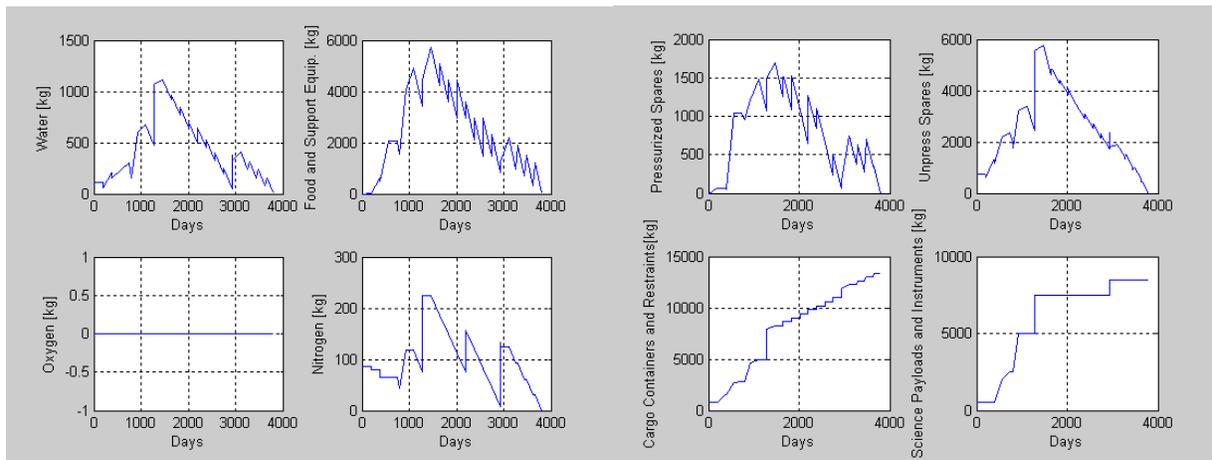
Another output of the simulation is a table of the MOEs of a scenario, which include Exploration Capability and Up-Mass Capacity Utilization. These and the rest of the SpaceNet MOEs are defined in.<sup>3</sup> For SpaceNet v1.4, a few new performance measures were introduced that relate to nested elements and pressurized and unpressurized cargo. Also included is crew time utilization history that tracks the time allocated to exploration versus maintenance activities. Figure 10 shows an example set of MOEs for a lunar campaign and a notional plot of crew time utilization.

Group Name	Total
Crew Surface Days [crew-day]	9158
Exploration Mass Delivered [kg]	59548.8
Exploration Capability [crew-day·kg]	486361087.4
Relative Exploration Capability	5216.771964
Total Launch Mass [kg]	85525512.74
Up-Mass Capacity Utilization	0.781203074
Return-Mass Capacity Utilization	0.97952008
Relative Scenario Cost	569.3590363
Total Scenario Risk	0
Parent Cargo Capacity Remaining [kg]	2678.499365
Max Pressurized Cargo Capacity Remaining [kg]	2220.675468
Max Unpressurized Cargo Capacity Remaining [kg]	41177.8239
Parent Volume Capacity Remaining [m <sup>3</sup> ]	110.9156938
Delivery-Mass Capacity Utilization	0.976391794
Max Cargo to Manifest [kg]	69438.90437
Max Pressurized Cargo to Manifest [kg]	41461.47827
Max Unpressurized Cargo to Manifest [kg]	27977.4261
Max Volume to Manifest [m <sup>3</sup> ]	265.3449582
Stowage Factor	0.146756972
Max Cargo that can be Delivered [kg]	16319
Number of EVAs (2-Person)	1636
Sample Mass Returned [kg]	1700



**Figure 10. MOEs and Crew Time Utilization.** The discrete event simulator calculates the MOEs for a lunar campaign (left). The crew time utilization shows how the total available crew time is distributed among each activity (right).

Time histories for every element in a scenario are written to Excel spreadsheets and include the time, node, and cargo by class of supply for each process the element was a part of. The cargo data in the time histories can be aggregated across a surface node by class of supply. This aggregation can provide insight into safety stocks and sustainability margins, thus enabling SpaceNet to quantify how effective a particular cargo delivery strategy is such as pre-position, carry along, or resupply. Figure 11 shows a plot of cargo consumption by class of supply against time for a lunar campaign.



**Figure 11. Cargo Inventory Levels at a Surface Node.** Each class of supply that is consumed generally exhibits the same behavior. There is a gradual build-up to a peak followed by a steady decline to zero (safety stocks were not manifested). This is an illustration of a pre-positioning logistics strategy, where cargo is stockpiled as early and as much as possible. While this strategy can hedge against disruptions in supply caused by a delayed or cancelled flight, it may not be practical from an accessibility, capacity, and shelf-life perspective.

Once an end-to-end campaign scenario is modeled and the discrete event simulator evaluates its feasibility, performance metrics, and time histories, a user can use SpaceNet to perform trades studies in order to identify key drivers and quantify their impacts on the scenario.

### III. SpaceNet Use

The goal of SpaceNet is to allow a user to model and evaluate an exploration mission as an interplanetary supply chain with the purpose of answering key logistics questions. Such questions include where the bottlenecks in the transportation architecture exist, how exploration capability can be maximized, and how uncertainties can impact logistics strategies. The fidelity at which SpaceNet models, such as processes, element instantiations, and supply items, enables it to respond to complex issues such as campaign robustness and contingency analysis. SpaceNet is unique in the respect that it captures this modeling fidelity within an end-to-end analysis capability. This allows a user to discover if there are any major holes in a transportation or surface architecture, to identify what parameters drive feasibility and MOEs, and to aid in decision making, such as whether future investments should be made in descent stage propulsive capability, PLM capacity and tare mass, or water-recycling and ISRU production.

SpaceNet v1.4 was used in the CxP IDAC-3 to analyze the lunar campaign from a logistics perspective.<sup>6</sup> In this analysis, SpaceNet evaluated campaign architectures to identify performance drivers and to quantify their impacts. Trades were categorized into mission planning, vehicle performance, and demand uncertainty parameters. A design of experiments (DOE) with orthogonal arrays was used to sample the trade matrix populated by the parameter values and to calculate their main effects on performance metrics.<sup>8</sup> Given the results of the DOE, follow-on studies evaluated the impact of modular PLMs, reduced PLM accommodation mass, and extra cargo flights. In addition to the performance trades, SpaceNet was used to quantify the logistical impacts of selecting a particular manifest strategy (cargo prioritization) and the contingency case of a skipped cargo flight.<sup>6</sup>

As architectural assumptions and system designs mature, supply chain and logistics analysis in SpaceNet should continue in order to provide decision makers with a current assessment of campaign scenarios with respect to performance, cost, risk, and schedule implications.

### IV. SpaceNet VV&A

A credibility assessment of SpaceNet v1.4 was performed in conjunction with the IDAC-3 trade study using the Recommended Practices Guide (RPG) for the CxP Modeling and Simulation (M&S) Verification, Validation, and Accreditation (VV&A) process.<sup>9</sup> The results suggested that SpaceNet is at a credibility level of 2.55 out of 4.0, where Level 2 represents development code and Level 3 represent production code. The credibility levels are further described in NASA's new standard for models and simulations (NASA-STD-(I)-7009).<sup>10</sup> A VV&A panel was assembled from CxP leadership in different programmatic and technical areas to understand what SpaceNet is, what it can do, what it is used for, to approve the accreditation criteria it was evaluated against, and to approve the credibility assessment. Following a presentation about the model, its use cases, and VV&A history, the panel accredited SpaceNet for its intended use of analyzing interplanetary campaigns from a logistics perspective.

### V. Conclusions and Recommendations

With the formal accreditation by the CxP and the confidence in its use based on the IDAC-3 trade study, SpaceNet has established itself as a logistics model with the capability to model and evaluate exploration campaigns. SpaceNet can be used to define/refine mission concepts, address issues/requirements, and aid in decision making as necessary for a user and a scenario. SpaceNet results can provide performance implications for a broad range of design alternatives, where such insights should be taken into account sooner rather than later when planning for a future space mission.

#### A. Assumptions and Limitations

SpaceNet v1.4 has a number of assumptions and limitations that are either a result of the abstraction used in the space logistics framework or for modeling simplification. A complete list of the limitations can be found in Ref. 11, Section 3.2, but a few are listed as follows:

- 1) Current limitations in trajectory data allow the creation of Earth and Earth-Moon only scenarios
- 2) SpaceNet models only the orbital maneuvering system (OMS) in propulsive vehicles
- 3) "Micro-logistics" are not considered for cargo sharing (co-location, not the layout and accessibility of elements at a node, matters)

It is the intention to remove the limitations in future releases of SpaceNet as applicable to analysis needs.

#### B. Future Work

There is an effort currently underway to upgrade the modeling capability of SpaceNet and to increase its relevance and application to exploration missions as part of the Jet Propulsion Laboratory (JPL) 2008 Strategic University Research Partnership. The upgrades include the ability to quantify the "-ilities" as part of an end-to-end

campaign scenario, such as the reconfigurability, reusability, commonality, and repairability of elements. While the implementation of these features will occur at a lower level than SpaceNet currently models, especially regarding surface missions, they will naturally fit within the space logistics framework of nodes, processes, elements, and supply items. Use cases ranging from ISS, lunar, and Mars campaigns will be developed to demonstrate how decisions made at the “-ility” level can propagate back to impact overall campaign effectiveness.

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