Logistics Information Systems for Human Space Exploration: State of the Art and Emerging Technologies

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Space agencies around the world are gearing up for new human space exploration missions. In order to ensure that such programs are sustainable, it is worthwhile to examine the lessons learned from past experiences with space logistics and supply chain management. This paper offers an overview of the current state of the art in logistics management for space exploration focused on information systems, and highlights some emerging technologies that have the potential to significantly improve both the study and operation of space logistics systems.

I. Introduction

One of the major difficulties in mission planning for interplanetary human space exploration is logistics management. The International Space Station (ISS) program, for example, has experienced difficulties predicting spares requirements, tracking and storing tools and equipment, and even shipping appropriate amounts of crew provisions. These difficulties are predicted to be significantly compounded for programs that venture outside Earth orbit, where the complexity of sending on-demand shipments is even greater. It seems clear from this experience that sustainable space exploration operations are not possible without appropriate logistics management.

The current state of the art in asset tracking for space exploration relies on a barcode based system interfacing with an Inventory Management System (IMS) database. Using a barcode based system for inventory management is very labor intensive and occasionally an update is missed and an item's status becomes unknown. On average 3% of the U.S. items in the IMS database are listed as “lost”, meaning that the item was not in the location that it was showing in the IMS the last time the crew looked for it. If a critical item is listed as lost, the mission control team has to decide whether to allocate critical crew time to continue looking for the item or, if there is a spare on the ground, to launch a replacement on an upcoming mission; both of these options are very costly. A barcode based system is also extremely time-consuming for both the crew and ground personnel. The ISS crew is allotted 20 minutes every day to make updates to the IMS but in reality a much larger portion of their day is dedicated to this task.

As humans plan for a return to the moon and travel on to Mars, innovative technologies should be utilized to improve upon current methods of interplanetary supply chain management. One of these emerging technologies is radio frequency identification (RFID). RFID has been in use since World War II but has only recently become a topic of discussion. The recent interest in RFID stems from several factors: one is the post-9/11 interest in using RFID for homeland security purposes; another is mandates from large commercial product retailers that suppliers must start using RFID at the pallet level to help automate inventory management and supply chain visibility. RFID shows great promise in space exploration to allow nearly autonomous tracking of commodities.

Another capability that is lacking in current practices of space logistics is the ability to perform integrated logistics modeling for multiple missions. When supplies are tracked across multiple missions, reuse from one mission to the next, risk pooling and space depots become important, but are presently poorly understood concepts. In order to satisfy this need, a space exploration logistics model has been developed. This tool, named SpaceNet, has the capability to model various types of surface missions on the Moon and Mars, various ‘logistics carriers’ or

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spacecraft, and any shipment paths or trajectories required (such as logistics hubs at Lagrange points or fuel depots in low lunar orbits). This complex modeling effort aims to build upon experience gained modeling analogous systems on Earth.

This paper presents observations and data on logistics management and operations in support of human space flight to date and discusses innovative approaches that can be utilized to improve asset management and perform integrated modeling for human missions to the Moon, Mars and beyond.

II. Current Practices

The current state-of-the-art in asset management for the International Space Station (ISS) is a barcode based system that interfaces to the Inventory Management System (IMS) database. All commodities that fly to the ISS are barcoded before launch. When U.S. items are being prepared for launch, the attributes of each item are carefully recorded on an excel spreadsheet and given to the Inventory and Stowage Officer (ISO) team to be entered into the IMS database. Item attributes include: official item name, part number, serial number, owner (NASA, Russia, etc.), barcode number, mass, dimensions, and category (Maintenance, Crew Health Care, EVA, etc.). As items are entered into the IMS, a location must also be listed for the item. For launch possible locations include the space shuttle mid-deck, the Multi-Purpose Logistics Module (MPLM), a SpaceHab cargo carrier, a Progress or a Soyuz. In the near future the Automated Transfer Vehicle (ATV) and H-II Transfer Vehicle (HTV) will also be viable launch options.

Once the commodities reach the ISS and transfer operations have begun, the crew uses hand-held barcode readers (Figure 1) to update the location of each item. All approved stowage locations on the ISS are labeled with a barcode so that the crew can scan the location, scan the items to be moved into that location, select "move" and the IMS database will be updated. This system is fairly user friendly and very accurate. A small display on the hand-held barcode reader allows the crew to visually verify that their scans are being recorded. The crew also has the option to update the IMS database manually on one of the ISS laptops.

For day-to-day operations, the task of performing IMS updates is split between the on-board crew and the ground control team. The exact work breakdown is left to crew preference, with most crews choosing to let the ground controllers perform the majority of the database updates. In the NASA Mission Control Center in Houston (MCC-H), the ISO console position is responsible for daily inventory management. A similar position, the Russian Inventory and Stowage Specialist (RISS) exists in the Mission Control Center in Moscow (MCC-M). It is envisioned that similar console positions will exist in the European Space Agency (ESA) and Japan Aerospace Exploration Agency (JAXA) Mission Control Centers once their modules join the ISS. IMS updates made at each control center and on-board the ISS are synchronized daily while the ISS crew is asleep. This assures that all of the IMS clients' house identical information at the start of each crew day.

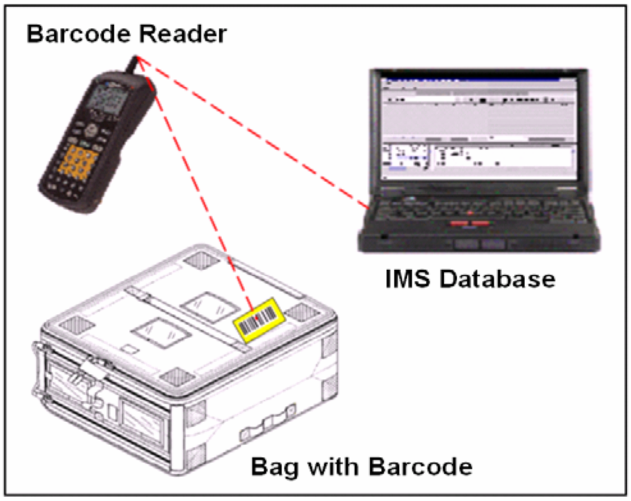


Figure 1: ISS Inventory Management System (IMS)

It should be noted that many consumable items (food, clothing, office supplies, etc.) are barcoded only at the bag-level. Items such as individual food items, individual pieces of clothing, individual printer cartridges are not assigned their own barcode, rather the bag that they are stored in is given a barcode and the contents is resupplied based on an assumed usage rate. This low-resolution system for tracking consumables can lead to large discrepancies between the actual quantities remaining on-board and what the standard usage rates predict to be remaining. When a discrepancy is suspected, the ground control team is forced to schedule an audit of the item believed to be out of sync. Audits are very time consuming, extremely tedious and reduce crew time available for scientific purposes.

Each day the ISS crew generates "common trash". Common trash is defined as food waste, used wipes, dirty clothes, and used hygiene items. This common trash is collected into trash bags. Solid and liquid human waste is collected into special containers. Common trash is then staged in the aft portion of the Service Module for future packing into a departing Progress vehicle. When an item that is not considered common trash has reached the end of its useful lifetime and is slated to be disposed of, a Waste Manifest Request (WMR) must be submitted. Approved WMRs are then collected into a change request (CR) and approved by the community. Similar to the complex transfer operations involved in unpacking new cargo when it reaches the ISS, the packing of items for disposal is also a well orchestrated process. All items with approved WMRs are carefully recorded on a trash packing list, which is sent to the crew so that they can pack them into the vehicle for disposal. Most of the trash on the ISS is disposed of in the Progress cargo vehicles. Approximately one week prior to the planned undock of the Progress vehicle, the crew begins packing the trash items into the vehicle. The Progress vehicle burns-up during reentry into the Earth's atmosphere so the trash is truly disposed of. Trash can also be returned on the space shuttle if the return manifest has extra space. As the crew loads trash into any vehicle they are instructed to use either the barcode reader or IMS database to update the location of all discarded items. Items will remain in the IMS database after disposal to maintain a historical record of the item.

III. Lessons Learned

In order for future human spaceflight programs not to repeat the shortcomings of previous programs, it is important that the lessons learned from current and past space programs are brought to the attention of those designing future missions. The following are some logistics related lessons learned that should be taken into consideration in the development of future human space missions.

Lessons Learned across Past and Present Programs

To consider a wider perspective on logistics lessons, it is necessary to draw upon the extensive research that has been performed in conjunction with United Space Alliance[1]. Lessons learned were collected from several sources within NASA, including crew debriefs, the John Commonsense lessons repository for the Mission Operations Directorate, Lessons Learned from Phase 1/MIR and the Johnson Space Center (JSC) and Marshall Space Flight Center (MSFC) Skylab Lessons Learned[1].

Once the lessons had been compiled, an analysis of the resulting data was performed, first sorting it by keyword, then finding duplication and root cause, and finally sorting by root cause. The data was then distilled into the top seven lessons learned across programs, center, and activities. Several of these top seven lessons learned have close ties to the inventory management lessons detailed in this paper, these are[1]:

Figure 2: Overflow of Stowage in the ISS Joint Airlock [http://spaceflight.nasa.gov/gallery/index.html]

1) *There should be design influence or specification to provide for **stowage** volume. Resulting problems from lack of stowage specification may include growing time demands for the crew, loss of accountability, loss of access to operational space, limits to housekeeping, weakened morale, and an increased requirement for resupply.*

From Figure 2 it should be apparent why stowage space should be considered early in the design process. Currently on the ISS, stowage space is over-crowded and many functional areas that were not originally intended for stowage, such as the joint airlock and the pressurized mating adapters (PMAs) are now being used extensively for stowage. As you can imagine from the image in Figure 2, finding items stowed in this non-traditional stowage space is very time consuming. The fact that non-tethered items can drift in three dimensions further increases the difficulty of asset management in a microgravity environment. The use of modules such as the joint airlock for stowage also adds a great deal of extra time to activities typically scheduled in these locations, such as preparation for Extravehicular Activity (EVA). When an EVA activity is scheduled several hours must be allocated before the activity for the crew to remove the items being stowed in the airlock. A similar block of time must also be reserved after the EVA activities for the crew to return the stowed items back to the airlock.

2) *The* ***inventory system*** *should be based on a common logistics system, shared by multiple organizations, to decrease the problem of differing values for like items across systems.*

The lack of a common database to handle manifesting, inventory management on the ground, and on-orbit inventory management is another weakness of the current ISS logistics system. Presently there are separate databases/applications to do manifesting, ground tracking, manage the parts catalog, on-orbit inventory management, etc. Very few, if any, of these databases can interact with each other, causing a lot of extra work for personnel who need to transfer information between the systems. This extra human intervention also expands the chance that an error is made.

3) ***Packing lists and manifests*** *do not make good manual accounting systems. Parent-child relationships are fluid and need to be intuitively handled by a system updated by the movement of both parents and children.*

A barcode based system such as the one in place on the ISS is very labor intensive and occasionally IMS updates are missed by both the crew and the ground controllers. There are presently ~20,000 U.S. and Russian items being tracked in the IMS system. Of these items approximately 3% (or 600 items) are typically listed as “lost” in the IMS. This is significantly better than for many commercial warehouses on Earth where missing inventory can be above 20%, but can still lead to problems, particularly if safety critical items are lost. An item is moved to “lost” when the crew goes looking for it and cannot locate it in the location given by the IMS database. The database also maintains a history for each item, so the first step in locating a lost item is usually to look in the previous few places that the IMS history states it was in recently. If the item is still not located, it is moved to “lost” in the database and the ground control team has to decide whether to allocate additional crew time to look for this item, fly a replacement item on a future mission, or just live without it. There have been several occasions when a “critical” item has been lost and valuable crew time or costly up-mass have been used to either find the item or fly a replacement.

4) *Include* ***return logistics*** *requirements in the design specification. Understand and model packaging requirements, pressurization, and reparability/disposability for the return or destructive re-entry of items ahead of time.*

With the grounding of the Space Shuttle fleet following the Columbia accident, the ability to return large pieces of failed hardware to Earth was lost and the amount of “trash” on ISS drastically increased. Previous to the Columbia accident, U.S. hardware owners enjoyed the luxury of returning their failed hardware on the Space Shuttle, examining the hardware to determine the cause and mode of the failure and then refurbishing or disposing of it. With the loss of that capability, the need to consider return logistics in the design of hardware was brought to the forefront of concern. As NASA returns to the Moon and eventually on to Mars, it is predicted that the capability to return hardware to Earth will be very limited and if return logistics are not considered, complications will arise.

IV. Emerging Technologies

As humans plan for a return to the moon and travel on to Mars, innovative technologies should be utilized to improve upon current methods of interplanetary supply chain management. The following section introduces a few emerging technologies that should be given consideration for incorporation in the logistics architectures of future manned spaceflight programs.

A. RFID[2, 3]

Radio Frequency Identification (RFID) shows great promise for addressing several of the logistics lessons learned mentioned above by providing nearly autonomous inventory management. RFID is a generic term for technologies that use radio waves to automatically identify objects. There are several methods of identification, but the most common is to store a number that uniquely identifies an object on a microchip that is attached to an antenna, which in turn is attached to the object. The chip, which is typically less than 5 mm across, activates a signal when it approaches an electronic reader. Though RFID technology has been around since World War II, when it helped ground soldiers identify fighter airplanes as friend or foe, the cost of developing it has been prohibitive. Now, thanks to advances in technology, the cost of RFID is declining and its usage is on the rise. Business experts predict that RFID chips will be found in thousands of products by 2010, and that the technology will revolutionize supply chain management, manufacturing, and retail efficiency.

An RFID system consists of tags and readers. RFID tags are small devices containing a chip and an antenna that store the information for object identification. Tags can be applied to containers, pallets, cases, or individual items. The primary difference between RFID and the barcodes used on ISS today is that RFID does not require line-of-sight. Barcodes must be scanned at specific orientations to establish line-of-sight between the barcode and the reader, while RFID tags theoretically need only be within the range of a reader to be read. With no line-of-sight requirement, the tag transmits information to the reader, and the reader converts the incoming radio waves into a form that can be read by a computer system. An RFID tag can be active (with a battery) or passive (powered solely by the signal strength emitted by the reader). RFID systems must be supported by an advanced software architecture that enables the collection and distribution of location-based information in real time

B. Surface Acoustic Wave (SAW)

Another emerging technology that shows great promise for use in asset management for human spaceflight is Surface Acoustic Wave (SAW) RFID tags. RFSAW Inc., based in Richardson, TX, has invented and patented an asset management system that utilizes SAW technology[4]. Their system operates by converting the radio waves emitted by a reader into nano-scale surface acoustic waves on the SAW RFID tag. These waves then travel past a set of wave reflectors on the tag producing a unique set of wave pulses. The pulse set is then converted into an encoded radio wave and sent back to the reader.

SAW tags offer several advantages for spaceflight applications over traditional RFID tags including the ability to operate at very low signal levels. RFSAW states that their tags can operate when receiving only a fraction of a microwatt from the reader[4]. In a space station environment, where metal and liquid are prevalent, the ability for SAW tags to operate at low signal levels will be a tremendous asset. Another advantage of the SAW tags lies in their simplicity. The minimal components used in the SAW tags allow it to be able to withstand a large temperature range. (RFSAW claims that their tags can operate at temperatures between -100 to +200 degC.[4])

C. The Future of Asset Management for Spaceflight

In order to fulfill the vision for space exploration in a sustainable manner, space agencies around the world should seek to improve their systems of asset management. The investment in an RFID/SAW based asset management infrastructure is one such improvement. Envision, as many large commercial retailers are today, a system of end-to-end asset management, where an item is tracked throughout its lifecycle using the same RFID/SAW tag. For NASA this means that the system of ground and on-orbit hardware tracking could be unified. As soon as NASA takes ownership of an item, an RFID/SAW tag could be applied and used to track the item before launch. Once in space, that same tag would allow the item to be tracked around the space station, Lunar or Mars base. As astronauts are loading or unloading a vehicle, RFID/SAW tags are continuously being sensed as they pass between elements. Through a basic software framework these RFID/SAW reads could be fed into a relational database (similar to the IMS database) and with very little human intervention, the location of all items would be known at all times (Figure 3).

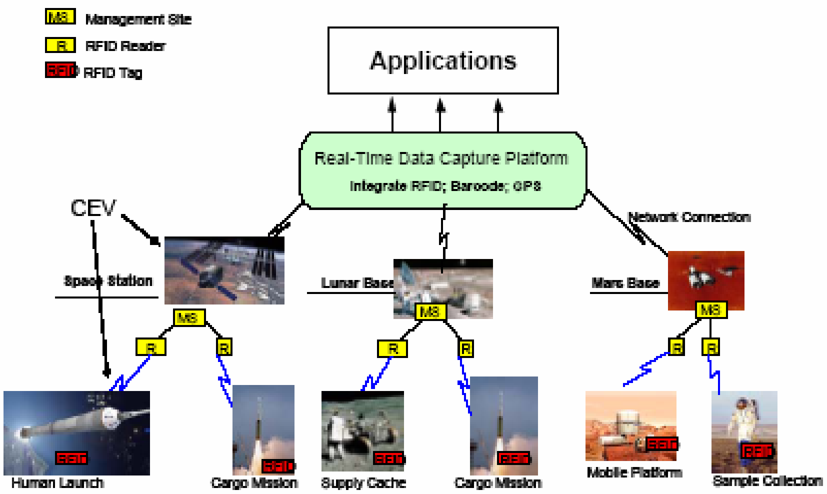


Figure 3: A Sample RFID-based Asset Management System for Space Operations

As the size and cost of passive RFID/SAW tags continues to decrease, these tags could feasibly be placed on all consumable items (food packets, individual pieces of clothing, office supplies, etc). This would allow ground controllers access to precise data on remaining quantities of consumable items and eliminate the need for time consuming audits.

It is easy to see how RFID/SAW has the potential to become indispensable for a wide range of automated data collection and identification applications. With the distinct advantages of RFID/SAW technology, however, comes an inevitably higher hardware and software cost. In a high cost arena, such as human spaceflight, where saving crew time and decreasing mass to orbit equate to large cost savings, the extra up-front cost investment in RFID/SAW may well be worth the savings over the lifecycle of a program.

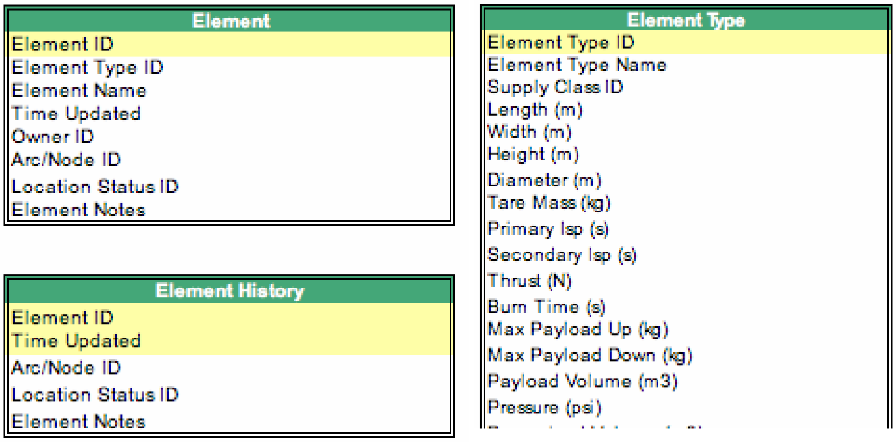
V. Integrated Modeling

Another capability that is lacking in current practices of space logistics is the ability to perform integrated logistics modeling for campaigns of missions. In order to satisfy this need, a space exploration logistics model has been developed. This tool, named SpaceNet, has the capability to model various types of surface missions on the Moon and Mars, various 'logistics carriers' or spacecraft, and any shipment paths or trajectories required (such as logistics hubs at Lagrange points or fuel depots in low lunar orbits). This complex modeling effort aims to build upon experience gained modeling analogous systems on Earth.

A. Relational Database

The backbone of this integrated modeling capability is the relational database. This database incorporates the inventory management features of the IMS database described above and adds extensive capabilities for manifesting, spares requirements planning and mission planning. Information maintained in the relational database includes astrodynamics data, element data, commodities data, spares data and node and arc data. (Note: An element is defined as a major end item in SpaceNet and includes launch vehicles, habitats, pressurized rovers, etc.)

For each commodity or element tracked in the integrated database numerous attributes are recorded. Figure 4 illustrates the types of attributes associated with each element in the database. From this figure, it should also be noted that the database is structured such that a time history is always maintained of each element/commodity.



Element
Element ID
Element Type ID
Element Name
Time Updated
Owner ID
Arc/Node ID
Location Status ID
Element Notes

Element History
Element ID
Time Updated
Arc/Node ID
Location Status ID
Element Notes

Element Type
Element Type ID
Element Type Name
Supply Class ID
Length (m)
Width (m)
Height (m)
Diameter (m)
Tare Mass (kg)
Primary Isp (s)
Secondary Isp (s)
Thrust (N)
Burn Time (s)
Max Payload Up (kg)
Max Payload Down (kg)
Payload Volume (m3)
Pressure (psi)

Figure 4: Attributes Recorded in Integrated Database for Each Element

The integrated database seeks to serve the needs of a variety of users including astronauts, mission controllers, ground processors, and loadmasters. Using the integrated database this diverse group of users is able to run queries to answer questions relevant to their area of interest. For the Inventory and Stowage Officer in MCC-H, these questions could include:

- Where is a supply item 'X' now?
- What's the current status (expired, failed, etc.) of this item?
- Where has the supply item been?
- What's the usage rate of a certain supply type?
- How many supply items are at the research station?

- How many supply items of supply class type ‘Y’ are at the research station?
- Find all the supply items with less than ‘#’ units at the research station?

The integrated database underlying SpaceNet addresses one of the four key lessons learned mentioned above, namely that the inventory system should be based on a common logistics system, shared by multiple organizations, to decrease the problem of differing values for like items across systems. While it is not practical to envision that one integrated database will replace the numerous separate databases used in spaceflight logistics today, NASA and its international partners should strive to limit the complexity of logistics systems for future human spaceflight programs.

B. SpaceNet v1.0

SpaceNet is a computational environment that supports the design, analysis and optimization of interplanetary supply chain (Figure 5). The SpaceNet software is a simulation and optimization tool that captures the concepts and ideas related to interplanetary supply chain management and logistics architectures. The software models interplanetary space logistics as a network, allowing the user to input scenarios, simulate them, and compute values for measures of effectiveness (MOE). Optimization can be used to find the best logistics network for a given set of surface missions, and trade studies can be carried out to evaluate various types of logistics architectures against one another.

The key engine of SpaceNet is a discrete event simulator that applies three fundamental processes (transporting, waiting and transferring) to elements (launch vehicles and major end-items) in the context of a time-expanded network. SpaceNet uses an event-driven simulation methodology. In SpaceNet, we are not interested in what happens “during” the process (e.g. transporting from one node to another or waiting at one node). Rather, the important questions for the users are: what are the states before a specific process, what are the characteristics of the process, and what are the states after the process?

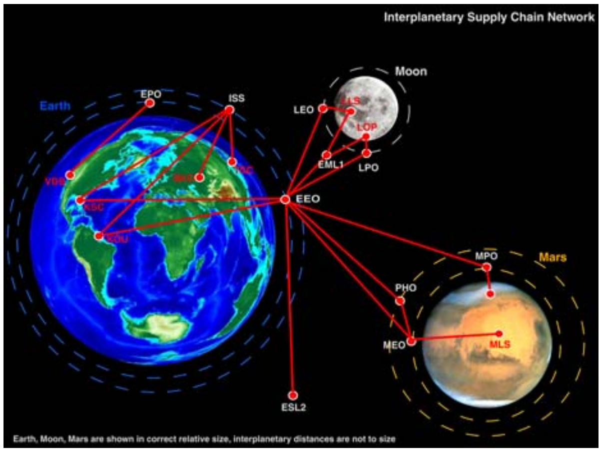


Figure 5: The Interplanetary Supply Chain

SpaceNet is currently written in Matlab, but it interacts with other programs through Excel as well as ASCII text files. The capabilities of SpaceNet presently include: modeling both individual sortie missions and campaigns and evaluation of those scenarios SpaceNet has the potential to support a diverse user base, including mission and system architects (especially in the conceptual design stage), mission planners and logisticians, and even real-time operations personnel. SpaceNet supports both short- and long-term architectural and operational decisions, including answering questions about the effect of various design decisions on long-term operations costs. In addition, SpaceNet is a flexible computational environment that can be used in several other ways:

- SpaceNet provides the capability to simulate the operations of any type of manned and unmanned missions provided the user enters trajectories and nodes
- By analyzing surface missions, SpaceNet could be used to define requirements for lunar systems such as the Lunar Surface Access Module (LSAM)
- SpaceNet can be utilized for virtual systems integration and testing during development and design
- SpaceNet can serve as a tool for integration of operational planning and system design (concurrent engineering)

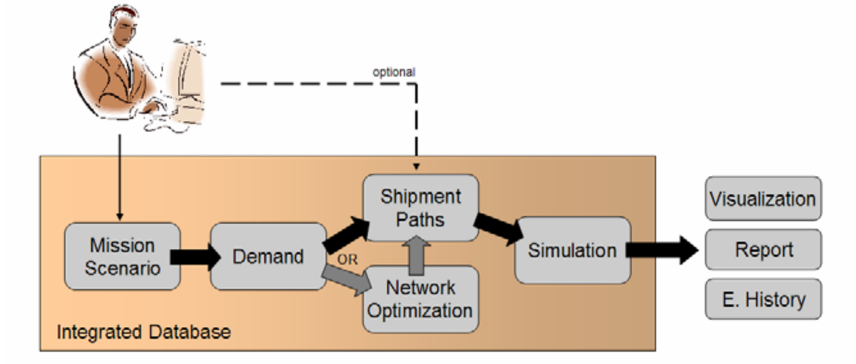
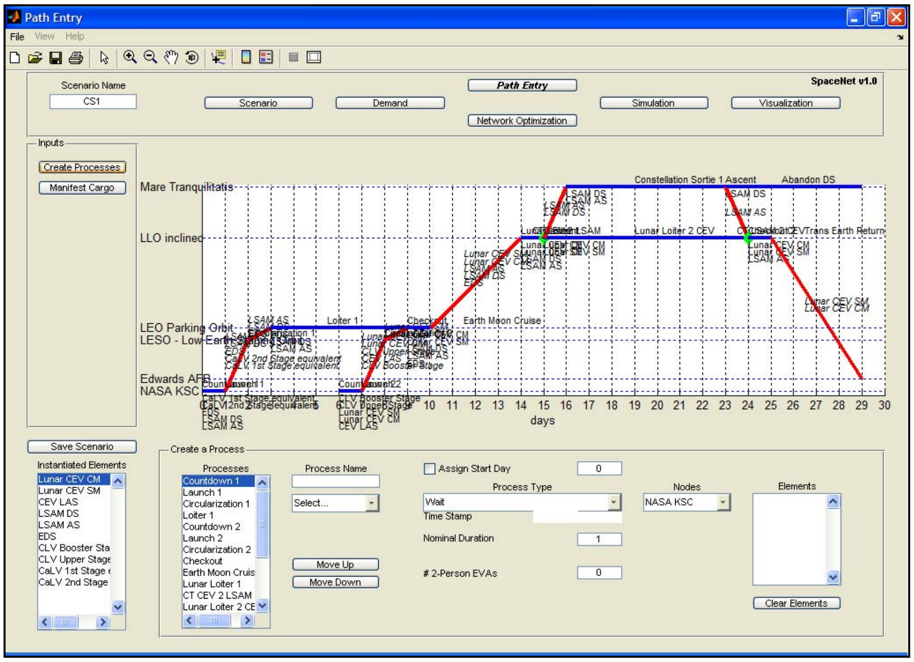


Figure 6: SpaceNet Flow Diagram

Figure 6 provides an overview of the SpaceNet software architecture. Using a graphical user interface (GUI) the parameters of a surface mission are entered. The SpaceNet software then calculates the demand for that surface mission. Demand is calculated based on a number of parameters that the user has specified, including mission duration, number of crew, number of EVAs and mission science objectives. Next, in order to satisfy the demand, the user can either enter the elements and shipment paths himself/herself, or ask the software to find the optimal set of shipment paths and elements for the given demand. Figure 7 shows a screenshot of the path entry screen of the SpaceNet GUI. In the figure time is shown as the x-axis, the nodes in the interplanetary supply chain are shown as the y-axis and the processes are shown using blue horizontal lines (waiting), red diagonal lines (transporting) and green diamonds (transfers), respectively.



Scenario Name: CS1

Instantiated Elements: Lunar CEV CM, Lunar CEV SM, CEV LAS, LSAM DS, LSAM AS, EDS, CLV Booster Sta, CLV Upper Stage, CaLV 1st Stage e, CaLV 2nd Stage

Processes: Countdown 1, Launch 1, Circularization 1, Loiter 1, Countdown 2, Launch 2, Circularization 2, Checkout, Earth Moon Cruis, Lunar Loiter 1, CT CEV 2 LSAM, Lunar Loiter 2 CE

Process Name: Select...

☐ Assign Start Day: 0

Process Type: Wait

Time Stamp

Nominal Duration: 1

2-Person EVAs: 0

Nodes: NASA KSC

Elements

Figure 7: Path Entry Screenshot from SpaceNet

Finally, the user simulates the scenario defined in the earlier steps and examines the outputs. The simulation runs through the events outlined in the mission definition and checks the mission feasibility, including propellant sufficiency (given ΔV of each maneuver), consumables undersupply and transport capacity constraints. It detects various types of errors, such as insufficient propellant to complete a transport given current payload. The simulation also generates the "measures of effectiveness", a set of metrics for evaluating mission performance. (The mathematics underlying SpaceNet are discussed in a separate paper[5].)

Other outputs of SpaceNet include a visualization of the discrete event scenario and a detailed spreadsheet of the history of all elements and commodities throughout the scenario. SpaceNet's visualization capability is intended to provide an intuitive understanding of the entire mission. The two types of visualization built into SpaceNet are the network animation, which shows the movement of cargo and elements along the static network (similar to that shown in Figure 5) and the bat diagram, a commonly used NASA visualization technique. The history spreadsheet generated by SpaceNet saves detailed time histories of the elements, nodes, and crew/cargo in the mission. At each time step, one can view these histories from a number of different perspectives: one can examine the element locations and cargo, the cargo and elements at each node, or the locations and elements that hold crew/cargo. This information can be plotted to view such things as the build-up of equipment at a lunar base, or the consumption of consumables and build-up of waste as a mission progresses.

C. Scenarios

At a high level SpaceNet can model two types of scenarios. The first type is a single mission, also known as a "sortie" missions. Examples of single missions that we have modeled in SpaceNet include: Apollo 11, Apollo 17 and a Constellation sortie mission (as detailed in the Exploration Systems Architecture Study (ESAS) final report[6]). We have also created variants of this basic sortie scenario for lunar exploration, including one where the Earth departure stage is refueled in low Earth orbit and one where the LSAM ascent stage is refueled with liquid oxygen generated by in-situ resource utilization (ISRU) on the lunar surface. The second modeling capability of SpaceNet, which is a unique capability, is the ability of SpaceNet to model and simulate entire campaigns. To date we have modeled two campaigns in an end-to-end fashion. The first is the Constellation lunar outpost buildup in the 2020-2022 timeframe. The second is the initial history of ISS assembly and operations. With the capability to simulate these two types of scenarios, SpaceNet is a very valuable tool for performing space exploration mission trade studies.

VI. Conclusions

The current state of the art in logistics management systems for human space flight is a barcode based system interfacing with an inventory management database. This system has been sufficient for ISS operations but should be rethought for lunar and interplanetary missions. Semi-autonomous technologies such as RFID and SAW show great promise for increasing accuracy and decreasing human workload associated with inventory management. The ability to perform integrated logistics modeling for spaceflight missions and campaigns will add tremendous value to many aspects of the mission design process. The integrated modeling framework we have developed, SpaceNet, has been used to model the logistics of numerous types of space missions including Apollo, ISS, lunar sortie, lunar outpost, on-orbit refueling and in-situ resource utilization. Using these scenarios, we have been able to run trade studies for NASA that quantify the logistics impact of various design trades.

Acknowledgments

S. Shull would like to thank her colleagues in the Cargo Integration and Operations Branch at NASA Johnson Space Center for teaching her everything she needs to know about ISS logistics. This work was completed as part of the Interplanetary Supply Chain Management & Logistics Architectures project financially supported by NASA under contract NNK05OA50C. Prof. Olivier de Weck and Prof. David Simchi-Levi, Massachusetts Institute of Technology, serve as the principal investigators, with Dr. Martin Steele from NASA's Kennedy Space Center as COTR Co-investigators are Dr. Robert Shishko (JPL), Mr. Joe Parrish (Payload Systems Inc.) and Mr. Andy Evans (United Space Alliance LLC).

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