Logistics is a Key Enabler of Sustainable Human Missions to Mars

Sydney Do¹, Robert Shishko¹, Dominic Antonelli², Timothy Cichan², Robert Collom³, Pan Conrad, Victoria Coverstone⁴, Richard M. Davis³, Christine M. Edwards², Michael Fuller⁵, Kandyce E. Goodliff⁶, Stephen J. Hoffman⁷, Sarag Saikia⁸, Paul Sheppard⁹, Sarah Shull¹⁰, Dennis Stone¹⁰, Charles Whetsel¹

¹NASA Jet Propulsion Laboratory, California Institute of Technology, ²Lockheed Martin, ³NASA Headquarters, ⁴University of Miami, ⁵Orbital ATK, ⁶NASA Langley Research Center, ⁷Aerospace Corporation, ⁸Purdue University, ⁹National Science Foundation, ¹⁰NASA Johnson Space Center

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Executive Summary

Logistics supply chains are a critical component of any sustained human operations occurring over large distances in unfamiliar environments. The importance of these supply chains has historically been demonstrated by military campaigns as well as all major exploration efforts from the Lewis and Clark Expedition, to Antarctic expeditions, to the multiple long duration space stations that have flown in low Earth orbit. This White Paper explores the question: What does the logistics supply chain for a sustainable human presence on Mars look like?

As a starting point, we review two particularly relevant present-day examples of robust exploration logistics supply chains, namely, those supporting the Amundsen-Scott South Pole Station (SPS) on the Antarctic continent, and the International Space Station (ISS) in low Earth orbit. At these two locations, continuous human presence has been enabled by a combination of: (1). multimodal logistics systems that facilitate multiple delivery pathways to the end-user; (2). generous stores of contingency supplies accessible from different locations within the logistics network; and (3). the exploitation of locally available resources through direct extraction and/or waste product recycling. Over time, the implementation of these strategies has been refined to operate reliably in their respective exploration environments.

Accomplishing continuous human presence on Mars will likely be far more challenging than what has been achieved in the Antarctic South Pole and low Earth orbit environments, due to the increased travel distances, diminished opportunities for crew abort, and greater energy needed to transfer crew and cargo to and from the Martian surface. Regardless, our review finds persistent logistics lessons and strategies learned from the SPS and ISS programs that are applicable to sustaining human presence on Mars. Based on these insights, we explore the various decisions that govern the Mars logistics tradespace, and propose a set of specific follow-on tasks needed to better inform the development of a future Mars logistics system. These tasks seek to:

- determine baseline logistics requirements for transits to/from Mars, and for various classes of surface missions up to and including permanent human presence, employing different levels of in-situ resource utilization;
- determine the implications of introducing logistics nodes in cislunar space (such as the Lunar Orbiting Platform - Gateway currently under development by NASA) and/or in Martian orbit, to create a the foundations of a logistics supply network to Mars; and to
- understand the impacts of landing site selection on in situ water availability, surface system architecture, and accessibility to a potential Mars orbital logistics node
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I. Introduction

The history of the human exploration of new territories – ranging from the Lewis and Clark Expedition of the western United States, to the “Heroic Age of Antarctic Exploration”, and the ongoing human exploration of space – has taught us that logistics supply chains play a critical role in ensuring crew safety and enabling mission success. Today, as NASA continues working towards its long-term goal of establishing a continuous human presence on the surface of Mars, building off the logistics lessons of the past has become more important than ever.

The challenging environment, vast distances, and scarce abort opportunities inherent to human Mars exploration magnify the challenge of sustaining human presence beyond any endeavor previously attempted. Fortunately, our experience in transitioning from initial exploration towards sustained presence in environments closer to home provides valuable insights as to how this might be accomplished on Mars. Two relevant present-day examples of such logistics architectures are those supporting continuous human presence at the Amundsen-Scott South Pole Station on the Antarctic continent, and on the International Space Station in low Earth orbit (see Figure 1).

This White Paper reviews the key logistics lessons learned from our operational experience in these two environments, and explores how these lessons might be applied to the early human exploration of Mars. From this, a set of specific studies are proposed to better inform the architecture of a future, robust, and evolvable Mars logistics system.

II. Historical Overview of Logistics System Architectures

As a first step in understanding potential strategies for sustaining future human crews on Mars, we look to the evolution of the logistics architectures and supply chains that today, enable people to live continuously at the Antarctic South Pole and in low Earth orbit. In particular, we focus on strategies that after their adoption, increased the period of time in which people were able to spend in a given exploration environment, and/or maintained their safety throughout life-threatening emergencies.

II.A. Antarctic South Pole

Early exploration of the Antarctic continent was enabled by a growing transcontinental shipping industry that led to whalers, sealers, and explorers venturing progressively farther south in search of new hunting grounds and lands to claim. By the late 19th century, growing recognition of the scientific discoveries and national prestige that could be achieved from exploring the continent led to the dawn of the “Heroic Age of Antarctic Exploration”, where ten countries conducted 17 major expeditions over a 25-year period. As each expedition probed deeper into the continent, crew survival became increasingly dependent on the strategic placement of well-stocked caches of supplies along predetermined traverse routes, the hunting of local seals and penguins for food and oil, and the cannibalization of discarded equipment for needed supplies.
The importance of these logistics strategies is well illustrated in the “Race to the South Pole” where Roald Amundsen’s South Pole Expedition beat Robert Falcon Scott’s Terra Nova Expedition to the South Pole by 34 days, even though the Scott team had arrived in the Antarctic 10 days earlier. By prepositioning generously margined supplies of food and oil at well-marked depots on his outbound journey, and exploiting the flexibility of dog-hauling and the efficiency of skis as his means of propulsion, Amundsen and his crew were able to return safely from the South Pole, ten days earlier than planned. In fact, Amundsen’s strategy was so effective that his party gained weight upon returning from the Pole[1]. Conversely, Scott’s team died of starvation on their return traverse from the South Pole. They had relied on manually pushing sledges for the vast majority of their traverse, after their other means of propulsion (early diesel-powered sledges that were found to be unreliable, and ponies that proved ineffective in the Antarctic environment) had failed. Scott’s approach of man-hauling required a significantly higher energy expenditure, with each of his crewmembers expending approximately 6000 kilocalories per day, compared to the 4500 kilocalories consumed by each member of Amundsen’s team on skis. This, combined with Scott’s depots being placed farther apart and containing little extra margin in supplies, resulted in the death of his crew as they struggled to reach their “One Ton Depot” towards the end of their return journey[1].

To successfully thrive on the Antarctic continent, Amundsen learned to live and operate in the environment, both from his time spent with the Arctic Inuit and Native Alaskan communities, and from his ability to repair, upgrade and modify equipment in situ. In the winter months prior to embarking on his South Pole traverse, he and his team worked tirelessly to improve their equipment based on their experiences throughout the previous season’s depot-laying journeys. Items ranging from snow boots, to ski bindings, snow goggles, dog harnesses, cooking equipment, tents, sledges, and the containers on the sledges themselves were modified to improve their performance and reduce their mass[1].

These practices of pre-emplacing well-stocked supply depots and improving upon equipment in situ have persisted to today, where the emergence of motorized snow transport and heavy-lift aircraft support the robust logistics networks that have enabled the continuous presence of humans at the South Pole since 1956. Today, the Amundsen-Scott South Pole Station (SPS) sustains an annual population ranging from a few dozen during the winter months to approximately 150 throughout the summer. To ensure the safety of the crew, particularly during the winter months when the weather conditions render the station inaccessible, the SPS stockpiles more than 430,000 gallons of AN8 fuel, 16 months’ supply of food, and an inventory of supplies and spare parts to maintain the operation of its power and water production equipment over multiple seasons. This stockpile is replenished regularly throughout the summer months by LC-130 cargo transport flights and periodic overland tractor-hauling traverses originating from McMurdo Station, the world’s southern-most deep-water port and the aggregation point for all crew and cargo prior to their delivery to the SPS[2].

To support the populations at both the South Pole and McMurdo Stations, McMurdo itself stockpiles 8 million gallons of fuel and 11 million pounds of supplies, and receives and processes 600 twenty-foot equivalent units (TEU) of supplies per year from a combination of military and commercially contracted ships, tankers, and aircraft. These vehicles depart from Christchurch, New Zealand, which acts as the last temperate-climate aggregation node prior to entry into the Antarctic Circle (see Figure 1(a)). Here, the various logistics transportation modes of aircraft, trucks, trains, and ships can all be exploited and merged for the final leg of re-supply to Antarctica[2].
In addition to stockpiling supplies, both the South Pole and McMurdo Stations have heavy equipment repair shops that are capable of servicing critical equipment. This capability is particularly important in maintaining the stations’ power plants and heating systems, as well as the tractors that are critical to supplying the SPS’s fuel supplies. For instance, detailed tracking of the degradation history of tractors used to haul fuel across the 1000 mile journey between McMurdo and SPS has enabled the accurate prediction of their failure rates, and the just-in-time air delivery of required spare parts to the SPS repair shop for tractor servicing prior to their return journey to McMurdo. To further ensure resource availability during this traverse, the practice of depoting supplies that was pioneered by Amundsen and Scott is also adopted. Here, multiple caches of pre-positioned equipment, including entire functioning tractors, are strategically placed along the McMurdo-South Pole Highway that connects the two stations.

This “entire system” level of redundancy is also adopted at the crew facilities level, where recreational areas at both stations can be converted into safe haven facilities in the case of an emergency. These buildings are physically separated from the main station facilities and stockpile their own independent power, medical, and food supplies, to support the population well through the Antarctic winter. All together, these logistics strategies have ensured the safe operation of the U.S. Antarctic Program since its inception in 1956.

Figure 1: Comparison of Logistics Supply Chains (a). Amundsen-Scott South Pole Station (b). International Space Station
II.B. Low Earth Orbit

In line with our Antarctic experience, the evolution of human presence in low Earth orbit, from suborbital sorties in the Vostok and Mercury spacecraft to sustained presence on the International Space Station (ISS), has also relied on the maturation of logistics strategies and the growth of a global multimodal logistics supply chain. The major logistics strategies in place today on the ISS can be traced back to the lessons learned from the Apollo and early Soviet space station programs, where near-misses and accidents led to lessons learned and standardized practices.

The actions taken to save the Apollo 13 crew are perhaps the most well-known illustration of the importance of logistics and supportability strategies in ensuring crew safety in off-nominal conditions. The combination of the lifeboat capability of the Apollo Lunar Module (LM), and the ability of the crew to scavenge in situ materials to build a square-to-cylindrical CO$_2$ removal cartridge adapter are famous examples of the importance of integrating safe haven, in situ fabrication and repair, and system interoperability capabilities into a flight system architecture$^{[3]}$.

One year after Apollo 13, a new era in spaceflight began, with the launch of the first of six Soviet Salyut space stations over the subsequent 15 years. Over the course of the Salyut program, the period of time continuously occupied by cosmonaut crews increased ten-fold from 23 days to 237 days. This significant increase coincided with the implementation of a second docking port on Salyut 6, which allowed for the simultaneous docking of the Soyuz crew transport and Progress logistics resupply vehicles with the space station. This, in turn, introduced the capability for consumables and spares parts to be periodically delivered to the station, thus enabling crewed expeditions of increasing duration and facilitating the upgrade and expansion of the complex over time$^{[4]}$.

This latter capability became a major feature of the subsequent Mir space station, which over a 15 year timeframe, grew from a single module space station to one with six modules that sustained two- to three-person expeditions in a near-continuous manner. During the latter stages of its life, the U.S. Space Shuttle transported crew and cargo to and from Mir on nine separate occasions, thus providing another logistics resupply pathway for the station$^{[4,5]}$.

This multimodal logistics supply chain became particularly critical when the two Elektron oxygen generation units onboard Mir became inoperable in early March 1997, forcing the crew to rely on the backup Vika system that had failed and caused a fire inside the station less than two weeks earlier. Without the arrival of a Progress resupply vehicle within the month, the crew would have run out of oxygen supplies and been forced to evacuate the station. Instead, the delivery of spare parts and additional oxygen stores enabled the crew to complete their expedition and successfully hand over Mir operations to the next crew. Moreover, the significant downmass capability offered by the later visiting Space Shuttle enabled the failed systems to be returned to the ground for diagnosis and repair. The lessons learned from these activities subsequently informed the design of the upgraded Elektron and Vika systems currently in operation today on the Russian Segment of the ISS$^{[5]}$.

Later the same year, the Mir multimodal logistics supply chain coupled with its multimodular structure again played a critical role in ensuring crew safety throughout a major in-flight accident. During a docking experiment on June 25, 1997, control of the Progress-M34 vehicle was lost, causing the seven tonne spacecraft to crash into the Mir Spektr module, significantly deforming one of its solar panels and puncturing its hull, causing a slow loss of cabin atmosphere. The crew responded by closing the hatch to
the Spektr module to contain the leak, taking advantage of the rest of the station as a safe haven location.

In the process of sealing off Spektr, power cables connecting the module’s solar panels to Mir’s main power system had to be cut, resulting in a loss of almost half the station’s power. This forced the crew to shut down all systems to prevent the complete discharge of the station’s batteries, and to use the thrusters on the docked Soyuz spacecraft to point the now-drifting station in a sun-facing orientation to fully recharge its batteries. Over the next three months, through the delivery of backup life support consumables and repair equipment from multiple Progress vehicles and a visiting Space Shuttle, the crew was able to reconnect Spektr’s solar arrays to the remainder of the station’s power system, and restore the life support systems that had remained dormant since their immediate shutdown after the accident. The location of the puncture on the Spektr hull, however, was never found, even after multiple attempts employing different leak detection techniques. Thus, Spektr remained uninhabited for the remainder of the life of the space station[5]. The recovery of Mir after this major accident would not have been possible without its robust logistics supply chain and the multiple safe haven options that were built into its architecture.

The lessons learned from these early space station experiences have since been expanded on throughout the development and operations of the International Space Station. Today, commercial- and government-developed logistics vehicles regularly deliver equipment, spares, propellants, and crew consumables to the station from five different launch sites around the world (see Figure 1(b)). In addition, the ISS stockpiles generous supplies of water and food onboard, and maintains a pool of spare parts both inside the station (mostly within the Permanent Multipurpose Module), as well as outside the station on External Stowage Platforms and ExPRESS Logistics Carriers. Through this robust supply chain and sparing philosophy, the ISS has sustained a continuous human presence since November 2000, even as multiple resupply vehicle launch failures in the period spanning 2014 to 2016 and the ending of the Space Shuttle program have delayed various deliveries to the station. During such events, the supply chain was able to adapt accordingly, thereby allowing the ISS crew to remain in place. Through over two decades of ISS operational experience, NASA has gathered and documented a number of logistics lessons to inform future programs. A number of these lessons are summarized in Appendix B[6].

III. The Challenge of Mars Surface Logistics

While the Antarctic South Pole and low Earth orbit are distinct environments with their own unique challenges, they share a number of common characteristics that make them appropriate analogs for a human Mars exploration logistics architecture. Namely, these are:

- an extreme environment hazardous to human life that requires the presence of highly reliable habitat systems;
- remoteness, requiring specialized systems for transportation to and from their locations;
- limited opportunities for forward delivery of supplemental resources and for evacuation, should a medical or other emergency arise; and
- limitations on naturally available resources for crew sustenance and health, necessitating some combination of supplementary resources to be periodically resupplied, systems to enable in situ resource recovery from waste products, and/or systems to process local materials into usable resources

The logistics systems that evolved to reliably sustain human presence at the South Pole and in low Earth orbit were built to ensure the continuous availability of critical supplies while subject to these
environmentally-induced constraints. As highlighted in Table 1, a future logistics system at Mars will need to manage these same constraints, but at more difficult levels across all dimensions. The longer transit times, increasingly constrained opportunities for evacuation, increased energetics associated with moving into and out of the Martian gravity well, and uniquely difficult operational environment of Mars create a logistics overhead not previously seen in the Antarctic and low Earth orbit contexts. Regardless, our extensive experience in sustaining human exploration in extreme environments closer to home provides a strong foundation from which we can begin to develop a future Mars logistics system. In the following sections, we explore how past logistics lessons learned can be used to architect logistics system that will enable future continuous human presence on the surface of Mars.

**Table 1: Comparison of Logistics Challenges and Constraints**

<table>
<thead>
<tr>
<th>Location</th>
<th>Environment</th>
<th>Resupply/Return Time</th>
<th>Crew Evacuation Opportunities</th>
<th>In Situ Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antarctic South Pole</strong></td>
<td>1-g, cold, dry, windy, dark six months out of the year</td>
<td>Air* Hours</td>
<td>Austral summer only, i.e., up to 6 months wait</td>
<td>Water, sunlight, wind, snow, ice</td>
</tr>
<tr>
<td>Low Earth Orbit</td>
<td>μ-g, cold, no air, no water, orbital periods of sunlight/darkness</td>
<td>Resupply from multiple launch sites 6 hours to a few days</td>
<td>Anytime</td>
<td>Sunlight, vacuum, microgravity</td>
</tr>
<tr>
<td>Mars Surface</td>
<td>3/8-g, cold, low pressure, low solar insolation, periodic dust storms, diurnal cycle similar to Earth</td>
<td>Chemical propulsion 6 to 9 months</td>
<td>Up to 18 months wait, depending on mission class</td>
<td>CO₂, water in the form of subsurface ice or hydrated minerals, sunlight, regolith</td>
</tr>
<tr>
<td></td>
<td>Solar electric propulsion 3 to 4.5 years</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*From McMurdo Station, which is open ~10 weeks each year

**IV. Applying Lessons Learned from the South Pole and Low Earth Orbit to a Human Mars Logistics Architecture**

Throughout their multi-decadal periods of operation, the Amundsen-Scott South Pole Station and the International Space Stations have adopted and advanced a number of logistics strategies that have enabled them to successfully sustain continuously crewed operations within their respective extreme environments (see Section III), and mitigate the near-misses and accidents that were experienced in their precursor programs (see Section II).

While their operational environments differ in a number of ways, the strategies employed to ensure the availability of critical resources to the crews of these two stations are largely common. These strategies include: (1) stocking generous supplies of consumables and equipment at their point of use, based on parts reliability values predicted from testing and long-term operations; (2) deploying supply chains with multiple delivery pathways to the exploration site; and (3) locally generating useful materiel through in situ resource extraction, waste product recycling, and/or parts cannibalization.
<table>
<thead>
<tr>
<th>Logistics Strategy</th>
<th>Amundsen-Scott South Pole Station</th>
<th>International Space Station</th>
<th>Potential Mars Surface Outpost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diversity of Supply Chains / Channels</strong></td>
<td>Continental System (military/commercial) Peninsula System (commercial)</td>
<td>Multiple Launch Sites/Vehicles: Baikonur Cosmodrome Kazakhstan (BCK), Kennedy Space Center (KSC), Wallops Flight Facility (WFF), Tanegashima Space Center (TSC)</td>
<td>Multiple Launch Sites/Vehicles</td>
</tr>
<tr>
<td><strong>Diversity in Delivery Modes</strong></td>
<td>Crew: Aircraft</td>
<td>Crew: Soyuz, for now; Commercial Crew post-2018</td>
<td>Crew: Fast Deep Space Transport</td>
</tr>
<tr>
<td></td>
<td>Bulk Cargo (Fuel): Ship, then Overland Tractors</td>
<td>Propellant: Progress</td>
<td>Propellant and Spares/Science Equipment/Consumables: Prepositioned at a Mars orbital ARRC node using SEP-delivered logistics modules</td>
</tr>
<tr>
<td></td>
<td>Spares/Science Equipment/Consumables: Aircraft</td>
<td>Spares/Science Equipment/Consumables: Progress, Cygnus, Dragon</td>
<td></td>
</tr>
<tr>
<td><strong>Generous Stores of Contingency Supplies</strong></td>
<td>Stores of fuel, spares, food, and medicine; spares based on manufacturer’s MTBF estimates, modified by multi-year field testing</td>
<td>Stores of spares, food, medicine, O₂ candles, EVA consumables; spares based on functional availability using NASA MTBF estimates, modified by multi-year experience</td>
<td>Same as ISS</td>
</tr>
<tr>
<td><strong>Intermediate Aggregation Nodes</strong></td>
<td>Port Hueneme, CA; Christchurch, NZ; McMurdo Station, Antarctica</td>
<td>Launch Sites: Baikonur, Kennedy Space Center, Wallops Flight Facility, Tanegashima Space Center</td>
<td>Launch sites; cislunar orbit (e.g., HEO), possible LEO; possible Mars orbit (e.g., HMO)</td>
</tr>
<tr>
<td><strong>Interoperability</strong></td>
<td>Single fuel type, TEU shipping containers</td>
<td>International Docking System Standard (IDSS), Common Berthing Mechanism, International Standard Payload Rack, Crew Transfer Bags, Contingency Water Containers</td>
<td>Possible standards for rendezvous and docking systems and resource transfer systems; Class of Supply (CoS) standards; standard shipping containers; standard habitat water and atmospheric composition and quality; other standards</td>
</tr>
<tr>
<td><strong>“Safe Havens”</strong></td>
<td>At SPS, segment within elevated building; distributed emergency generators; at McMurdo, gym</td>
<td>Modules can be sealed off; multiple Soyuz spacecraft used for emergency evacuation</td>
<td>Multiple habitat modules; Mars Ascent Vehicle (MAV) for evacuation to Mars Deep Space Transport or possible Mars orbital ARRC node</td>
</tr>
<tr>
<td><strong>Use of In Situ Resources</strong></td>
<td>Water from Rodriguez wells, solar and wind power to supplement fuel use; cannibalization of parts from older tractors, support equipment; wastewater processing and recovery plant at McMurdo</td>
<td>Energy from solar arrays, recovery of potable water from crew urine and perspiration, recovery of oxygen from crew-expired CO₂, reuse of Crew Transfer Bags as sound absorbing blankets, privacy partitions, and radiation shielding</td>
<td>Possible ISRU production of propellant, O₂, H₂O, metals for additive manufacturing (AM); energy from solar arrays; regolith for civil engineering structures (landing pads, berms, roads), and radiation shielding; in-situ food production; heat melt compaction of waste materials into radiation shielding</td>
</tr>
<tr>
<td><strong>In Situ Maintenance and Repair Capability</strong></td>
<td>Maintenance and repair facilities at McMurdo and South Pole to maintain aircraft, ground vehicles, and power systems</td>
<td>Systems designed to be composed of Orbital Replacement Units (ORUs) for quick subsystem removal and replacement. Detailed repairs supported by subject matter experts on the ground. Current experimentation with 3D printing tools and spare parts</td>
<td>Will likely be an evolved version of ISS with a lower level of repair (part or component level replacement rather than subsystem level, to minimize total mass of spares). May utilize AI for system self-diagnosis and partial repair, and AM for some parts</td>
</tr>
<tr>
<td><strong>Waste Management</strong></td>
<td>Metabolic wastewater processed at a treatment facility at McMurdo Station. All other waste shipped back to California (Antarctic Treaty requires the environment to be kept clean)</td>
<td>Urine and humidity condensate processed to recover potable water. Oxygen recovered from crew expired CO₂. Solid metabolic waste and general trash is disposed of on departing logistics vehicles</td>
<td>Like Antarctica, Mars will likely need to be kept clean (i.e., to planetary protection concerns). Shipping waste off-planet is likely infeasible. Will likely be ISS-like with some combination of quarantined surface storage, pyrolysis, and anaerobic digestion</td>
</tr>
</tbody>
</table>
The persistence of these strategies across different exploration contexts makes them suitable candidates for infusion into a future Mars logistics architecture. Table 2 summarizes the major logistics strategies that have emerged from the considerable experience previously gained in the SPS and ISS programs, and suggests how these strategies might be employed in the context of a Mars surface outpost.

The following sections explore the multitude of options for applying the strategies listed in Table 2 to the Martian context, and highlight open questions that require further study.

IV.A. Logistics Nodes for the Human Journey to Mars

One of the most critical driving decisions of any logistics system is the function and structure of the network of waypoints and transportation pathways deployed to deliver and return crew and cargo to and from the exploration site. Indeed, it was intelligent “depoting” that made the difference between Amundsen’s successful South Pole traverse and the Scott team’s demise, and it was the diversity in delivery modes that enabled Space Station Mir to continue operations throughout the Vika system fire and the Spektr module accidents. Even today, the large stockpile of spares situated at strategic locations along the routes to the SPS, and the diverse options for transporting goods to the ISS illustrate the importance of a well-architected logistics network in ensuring crew safety in long periods of physical isolation. These observations naturally point to the immediate question: “What does a well-architected Mars logistics system look like?”

As we have seen from the discussion in Section II and from a number of strategies outlined in Table 2, the answer to this question relies on the strategic selection of the locations and functions of a set of logistics nodes situated on the pathway between Earth and the final destination node located on the surface of Mars. The constraints imposed by celestial mechanics on this “interplanetary supply chain” limit the location of such nodes to be in either cisunar space, and/or the Martian system, as shown in Figure 2.

As is the case with Christchurch and McMurdo Station for the SPS, and the multiple launch sites that support the ISS, it is expected that each logistics node within the Martian interplanetary supply chain will provide some subset of the Aggregation, Refueling and Resupply Capabilities (ARRC). These capabilities include the caching of supplies and spare parts, the aggregation and refueling of multiple system elements, the resupply and refurbishment of used systems, and the local production and/or processing of resources consumed or produced by the crew. At each potential node location, the most appropriate set of capabilities implemented will be dependent on the capabilities of other nodes within the logistics network, and the transportation options available to move between these nodes. This

![Figure 2: Potential Logistics Nodes between Earth and Mars (not to scale). Dashed lines indicate potential exploration pathways in addition to Earth-Mars Surface](image)
dependency results in a number of coupled decisions that shape the architecture of a Mars logistics system. To better characterize the competing options for each of these decisions, we further examine how an ARRC node positioned in various locations within the Earth-Moon-Mars system might operate. This investigation is discussed in the following subsections.

We note here that regardless of where ARRC nodes are placed, any capabilities and associated equipment will have initial development and then continuing operations and maintenance costs. A supply of propellant will also be needed to maintain (or change) ARRC node orbits. Rendezvous and docking with a fixed asset will also entail orbital plane changes, particularly at Mars with the greater tilt of its polar axis (relative to Earth), and, while such plane changes can be managed, the actual propellant costs need to be fully understood.

**Selecting the Optimal Cislunar ARRC Node Orbit**

For a variety of reasons, we envision an ARRC node in cislunar space serving as a jumping off point for human missions to Mars. This concept has been studied before by NASA and others\(^{[8-11]}\), and has recently garnered widespread interest across the spaceflight community with the development of the Lunar Orbiting Platform-Gateway. The Gateway will be an evolvable, flexible, and modular space platform located in a lunar orbit that may potentially evolve into a Mars-enabling ARRC node.

The current NASA Mars exploration architecture assumes that a Deep Space Transport (DST) would rendezvous and dock with an ARRC node located in cislunar space, such as the Gateway. Here, in much the same way that McMurdo Station in Antarctica services aircraft and tractors that travel to and from the South Pole Station, the DST would be prepared for its journey to Mars and be received upon its return for refurbishment and resupply prior to embarking on subsequent missions back to Mars (see Figure 2).

Multiple locations in cislunar space have been proposed for such a node, ranging from various high Earth orbits to various halo orbits in the Earth-Moon system. The main criteria for the selection of the location of this cislunar ARRC node are: (1) its accessibility to multiple launch providers (including commercial and international entities) to maximize supply chain robustness, and (2) the efficiency of propulsive transfers from the ARRC location to and from Mars, both to reduce the total propellant demand of the mission, and to enable the return of the DST to the cislunar ARRC for refurbishment and reuse in subsequent missions.

As we have observed with the Antarctic context, the selection of a widely accessible location for an aggregation node that is conducive to forward transportation to more remote depots/nodes is a critical first step in establishing a reliable logistics supply chain. Previous studies suggest that a high Earth orbit (HEO) would be the most appropriate location for a departure node for a Humans-to-Mars focused architecture, primarily due to its lower energy requirements for transferring into a Mars-bound trajectory compared to other potential staging locations. However, further study is needed to understand how different ARRC node candidate locations in cislunar space can best balance these needs. One option might be to implement a robust propulsion system on the aforementioned Gateway to enable it to move between different orbit locations to suit different mission needs. After serving its initial mission in its currently baselined location of lunar Near Rectilinear Halo Orbit (NHRO), the Gateway could use its baselined solar-electric propulsion (SEP) to move between orbits with similar energies and be repositioned to the best location to service Mars missions. In this way, the lessons learned from its first mission in support of lunar operations could be directly applied to its use as a key ARRC node in a Mars-focused logistics chain.
Using Solar Electric Propulsion for Resupply at Mars

More cost-effective options for moving large amounts of cargo may be possible in the near future, as new propulsion technologies such as solar electric propulsion (SEP)\(^1\) mature. Such technologies are particularly attractive for supporting human missions to Mars due to the large amount of cargo required to support such expeditions (and the associated large quantities of propellant needed to transport this cargo). A typical Concept of Operations (ConOps) for SEP cargo missions to Mars involves a tug waiting at an ARRC node in cislunar space, where it is refueled and serviced as needed. Cargo elements and a fuel (Xenon) tanker rendezvous with the tug at the ARRC node. The cargo is then pushed out to the Martian system. For an orbital resupply at Mars, the tug spirals into the Mars gravity well, drops off the cargo, then spirals out and returns to the cislunar ARRC node. For a Mars surface resupply, the tug performs a hyperbolic flyby of Mars, drops off the cargo (with lander), and returns to the ARRC node\(^{[12]}\).

This ConOps is analogous to using “slow” ships to efficiently deliver large amounts of cargo from Christchurch to McMurdo Station in Antarctica. Again, the optimal location for a SEP-supporting ARRC node needs to be assessed, taking into account the cargo (mass) to be moved and the rate at which it can be delivered. While it is advantageous to use SEP for cargo, chemical propulsion is better suited for crewed missions. In our Antarctic analogy, while bulk cargo is delivered via ship, people are sent via airplanes.

The Possible Role of Low Earth Orbit (LEO)

Low Earth Orbit (LEO) represents a special location in cislunar space as the “least common denominator” access point for space. Incorporating an in-space logistics transfer capability between LEO and the location of the ARRC node in cislunar space could be an extremely valuable service (potentially commercial) that would open participation in Mars exploration to any organization (international or commercial entity) that can access LEO. Combined with the development of other standards (docking/grappling approaches, standardized cargo containers, etc., discussed in Section IV.C), the use of LEO as a “bus stop” on the way to a larger ARRC node could greatly increase the number of providers who are able to contribute to the overall supply chain to Mars.

A Dual ARRC Node-Safe Haven in Mars Orbit

The case for a logistics ARRC node in Mars orbit, likely high Mars orbit (HMO) based on prior mission design studies, needs to be studied more extensively, particularly from the perspective of serving as an aggregation point and possible refueling location on the way to and from the Martian surface. An appropriately designed ARRC node, which could be a copy of (or a sparse version of) the one in cislunar space, would serve as the node for the transfer of the crew from the arriving DST to the pre-positioned (in Mars orbit) human surface lander.

An ARRC node in Mars orbit could also serve as a safe haven for crews on their missions to and on Mars, in a similar manner to the role of the dual-use safe haven facilities at the South Pole Station (see Section II.A). By providing a back-up location for crews to perform needed repairs and/or to wait for rescue, a safe haven in Mars orbit could potentially increase overall mission safety, and may obviate the need to develop certain technologies prior to embarking on the first human missions to Mars.

\(^1\)SEP is significantly more efficient than chemical propulsion, but has much lower levels of thrust and therefore much longer transit times. A typical orbital resupply can be accomplished in about 4 to 6 years for a round-trip, and a typical surface resupply in 3 to 3 ½ years, with roughly 2/3 of that being on the outbound leg. The maximum drop-off mass is only achieved near the optimal alignment dates for each opportunity. However, the SEP tug and its cargo can loiter at the departure ARRC node awaiting a favorable alignment.\(^{[25]}\)
For instance, an initial ARRC node in Mars orbit might contain such critical supplies/consumables and spare parts, and have the capability to dock additional arriving logistics modules\(^2\). These pre-positioned spares could supplement the pool of spares carried along with the outbound DST\(^3\). If an off-nominal condition occurs during the surface mission, the crew could return to the DST docked to an adequately provisioned ARRC node rather than remain in place. This ConOps mirrors the evacuation of the ISS using the Soyuz, and soon, commercially-provided “lifeboats” that would provide the return trip to Earth. For Mars, however, the limitations in abort opportunities imposed by celestial mechanics necessitate the adoption of multiple safe havens in addition to the Earth alone. Over time, a network of safe havens at multiple logistics nodes could be built up to facilitate the management of a broad range of unexpected events.

The safe haven approach fundamentally allows one to divide a Mars mission into segments where the management of the segments and the equipment designs begin to look more like ISS length missions. As a result, we may not need all the significant advances in all systems; instead, we may contemplate using systems that are incremental improvements over what we already use on ISS, with the attendant savings in development cost and time. If done aggressively and creatively with adequate attention to risk, this may improve the overall cost-risk balance of Mars missions.

**Potential Tradeoffs**

One trade that needs to be considered is the relationship between DST “size” and its capability for keeping the crew safe. A larger size permits a greater amount of supplies/consumables and spare parts to be carried with the crew, but results in greater direct (e.g., development) and indirect (e.g., the need to launch more propellant) costs.

A related trade concerns the functional availability and inherent reliability requirements of the DST systems, especially the Environmental Control and Life Support System (ECLSS). With an ARRC node in HMO and the use of high-efficiency SEP to deliver large amounts of cargo, mission-level crew safety requirements may be met by alternative means; and while the total IMLEO may be higher, the launch packages may be more manageable.

**Other Potential Uses of a Mars Orbit ARRC Node**

Besides being an aggregation point for logistics and safety reasons, having an ARRC node in Mars orbit provides other benefits. Crewed sortie missions to one or both of the Martian moons from the aggregation point could be enabled depending on the orbit selected. Exploring the moons can achieve science, and potentially, ISRU objectives. Tele-operation of rovers, and maybe even aircraft, from orbit would increase the amount of science these assets could return. The facility itself could be a platform for science instruments and experiments during both crewed and un-crewed operations. Additionally, an ARRC node in HMO could act as an integral component of the overall communications network, utilizing the power rich infrastructure that is required to support a logistics node/safe haven. Orbital mechanics and mission coverage may determine the importance of an ARRC node in a communications network, but the possible inclusion of this capability should not be overlooked.

\(^2\)Having multiple entities (commercial or international) delivering logistics modules to the HMO ARRC node may be enabling. As with other ARRC nodes, standard docking adapters would be instrumental in supporting this concept.

\(^3\)This overall capability can also be augmented by additive manufacturing (3D printing) capabilities. Significant gains in additive manufacturing by the time we execute the first human Mars mission is a very reasonable assumption.
Establishing a Logistics Node on the Surface of Mars

Ultimately, the goal of any future human Mars exploration effort will be to establish a permanent outpost on the surface of Mars. In many respects, the Mars outpost is akin to the South Pole Station at the end of a very long supply chain. Because Mars presents significant hazards, environmental challenges, and inaccessibility, it will take a considerable amount of local infrastructure and development of logistics capabilities before humans can safely live there. Having said that, we envision a Mars surface outpost developing into a robust logistics node over time as a result of the delivery of infrastructure, cargo, and crews by commercial entities and international partners.

Where the permanent outpost is to be located has yet to be determined. Multiple factors will need to be considered such as thermal conditions, power availability, terrain, and landing accessibility. One of the most critical factors in site selection will be the availability of in situ resources, especially water. One trade that needs to be examined is the relationship between the permanent outpost location (and its accessibility to and from a potential Mars orbit ARRC node) and the water source location—that is, whether it is more cost-effective and safer to extract water from a low-content source (e.g., hydrated minerals) nearby or from a distant high-content source (e.g., sub-surface ice)\(^4\). Such a trade involves multiple issues of risk, cost, and supply chain reliability and maintainability.

Another strategic issue is the interaction between the overall Mars architecture and the deployment of various ISRU systems to the surface outpost. Specifically, the impact of introducing alternative forms of ISRU on the overall Mars architecture over multiple missions needs to be better understood. Such impacts can range from affecting the design of specific mission elements (such as landers, surface power, in-space transportation, new logistics nodes, etc.) and the type and sequence of missions to be flown.

IV.B. Managing Supply and Demand Uncertainty

Diversity Cost versus Risk Reduction Trades

In any exploration endeavor, there is an inherent tradeoff between cost and risk to mission and crew. The correct balance between cost and risk is critical to the sustainment of any exploration program. While this was intuitively understood by early explorers, it was not until the late 1980s, during the Space Station Freedom and post-Challenger accident era, that more formal methods were developed to quantify these two competing objectives. Since then, the Probability of Loss of Mission (PLOM) and Probability of Loss of Crew (PLOC) metrics have been widely adopted as quantitative measures of risk. At the same time, program lifecycle cost has been widely recognized as the best measure of cost.

The tradeoff between these two metrics can be measured by the amount of risk reduction—decreases in the risk probabilities—that can be bought for the next increment of cost. Nominally, these probabilities can be reduced by investments that increase the functional availability of our systems, or add diversity and robustness to the supply chain\(^5\). Not surprisingly, the tradeoff is most likely subject to diminishing returns, so choosing the right balance is often difficult. In the context of human missions to (and eventual permanent presence on) Mars, this tradeoff has not been studied in sufficient detail to warrant conclusions about the right balance.

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\(^4\)The trade must also consider the accessibility of the permanent outpost both to and from a potential ARRC node in HMO, and the accessibility of the ARRC node from cislunar space.

\(^5\)Increases in functional availability can mean adding redundancy to the system or raising the level of contingency supplies at various logistics nodes. Adding diversity can mean providing alternative logistics channels, and/or introducing ISRU capabilities.
One approach that has been successful in mitigating risk and spreading cost in both the Antarctic and low Earth orbit exploration domains is the implementation of diverse participants and systems in the logistics supply chain. The SPS and ISS have both been supplied by a combination of government, commercial, and internationally operated transportation providers throughout their operational lifetimes. This diversity has ensured a steady stream of supplies during both nominal and off-nominal situations. The recovery of the Mir space station from its multiple accidents (described in Section II.B) would not have been possible without the combined capabilities of the U.S. Space Shuttle and the Soviet Progress vehicles. Similarly, reliable access to and delivery of goods to McMurdo station in Antarctica would not be possible without the multiple options for heavy icebreakers, tankers, and cargo ships that have been made available from the U.S. military, commercial providers, and international Antarctic treaty partners as various mechanical failures have taken primary transportation vehicles offline[2].

In much the same manner, one expects several different logistics channels will be used to deliver supplies to a continuously crewed Mars research station. However, maintaining different logistics channels within the Mars outpost supply chain in order to mitigate against resupply failures is not without cost. This trade on the number and type of supply vehicles needs to be performed as well.

The Role of Contingency Supplies

While diversity of the supply chain is important, it cannot be the only means of protecting Mars crews and missions. Caches of supplies at forward logistics nodes can serve to mitigate against unexpected losses, such as a missed resupply missions, or statistical variation in the demand for particular items. The rate of demand for some supplies like food can be accurately predicted, but for spare parts, the demand is stochastic. To deal with this kind of uncertainty, the usual approach taken in previous work for ISS and the Constellation Program employs an availability objective function[6], which is then maximized subject to a variety of potential constraints on total budget, mass, volume, etc. This is the same approach used in military logistics planning. Raising the number of nearby spares for any component[7] increases the calculated availability. The trick is to be able to pick the best combination of spares that also meets all of the constraints.

This was never more important for ISS than when the Shuttle Program ended, since there were critical external spares that could only be delivered in the cargo bay of the Shuttle. These spares had to be selected and then pre-positioned using the few remaining Shuttle missions to the ISS. The selection of which parts to pre-position and how many would be needed for the remaining operational life of the Station was accomplished through a careful analysis of MTBFs based on actual flight experience[8]. For human missions to Mars, understanding the logistics requirements will be even more crucial, since evacuation and return of the crew to Earth prior to the scheduled departure window will not be possible. Contingency supplies also played a role following a string of failures in ISS resupply missions from late 2014 to late 2016[9]. The ISS was able to maintain normal operations throughout this period due to the excess water stored onboard. This water was previously processed by the Water Processor Assembly

6Availability is usually defined as the percent of system (or function) “up time” to total time. In the context of spares analysis, availability is typically determined by the probability of always having a spare locally available to cover random failures—that is, a condition in which there are no “backorders” for that part.

7Components are commonly termed Orbital Replacement Units (ORUs), or at a lower level of indenture, Shop Replaceable Units (SRUs). For random failures, MTBF characterizes the failure probability distribution.

8This analysis used Bayesian updating of prior MTBF estimates from Logistics Support Analysis Records (LSARs). LSARs contain the basic standardized component-level data used by logisticians for logistics planning.

9Cygnus CRS Orb-3 failure (occurred 28 October 2014); Dragon CRS-7 failure (occurred 28 June 2015); Progress MS-04 failure (occurred 1 December 2016).
(WPA) and stored in Contingency Water Containers (CWCs) for later use. Ground controllers also managed to operate the WPA in a degraded capacity during this period to generate some level of potable water; however, this degraded mode was short-lived.

IV.C. The Need for Logistics Standards

A Standardized Shipping Container for Space

Across the surface of the Earth, global supply chains have been established around intermodal transportation standards that enable a wide variety of commodities to be efficiently transported by a diverse set of carriers. One key standard that has revolutionized the global supply chain is the standard shipping container. Shipping container standards, such as the twenty-foot equivalent unit (TEU), shown in Figure 5, and forty-foot equivalent unit (FEU), are utilized by ships, trains, trucks, and aircraft as the canonical “denominations” of cargo delivery. Part of the planning associated with logistics nodes to support sustainable human missions to Mars needs to involve developing concepts for how the materiel can be efficiently moved between logistics nodes wherever they happen to be located. One idea about how to do so, worthy of further examination, centers on the concept of standardized shipping containers for in-space logistics[13].

Figure 5: A Standard Twenty-Foot Equivalent

Standardized Classes of Supply for Space Logistics

A requirement of nearly any asset management system is a robust method of classifying supplies and assets. Supply classification serves to collect logistics items of a similar nature within groups with similar attributes. These attributes permit consistent management of supply items within a logistics system. ISS operations currently use two Class of Supply (CoS) schemes—one called the Cargo Category Allocation Rates Table (CCART), is used by U.S. logisticians and another, is used by their Russian counterparts. Certainly, as we pursue deep space exploration, a common CoS standard would improve communication, interoperability of asset management systems, and the estimation of commodity demands[14].

The CCART itself has several deficiencies when logistics for a permanent outpost on Mars is considered. For instance, there are no categories in the CCART that would allow for classifying propellants, habitation and other infrastructure systems (e.g., ISRU systems), or surface exploration equipment. A new, function-based generic CoS classification standard, such as the one proposed in Figure 6, would better serve the requirements of an interplanetary exploration supply chain10. Ideally, such a standard would emanate from stakeholder organizations and be published by a recognized standards organization.

Figure 6: A Proposed Functional Classification for Inventory Management and Demand Modeling for Human Spaceflight Missions

10The ten major categories shown are based largely on the functional groupings and nomenclature from the CCART breakdown. The proposed CoS classification has 44 subclasses at the second level of indenture; subclasses serve to refine asset/inventory management processes and demand modeling.
Standardized Interfaces for Docking and Berthing, and Resource Transfers

The ISS uses the International Docking System Standard (IDSS) to accommodate different visiting vehicles\textsuperscript{15}. It is also intended to enable crew rescue and to support exploration missions beyond LEO. The IDSS umbilical connectors transfer resources between two docked vehicles, but currently, these connectors are only defined for power, data, and a ground safety wire. Future revisions may include the capability to transfer water, fuel, tank pressurization, and oxidizer. This would in turn require the establishment of standards for the composition and storage conditions of these consumables. For example, the U.S. Antarctic Program standardized the type of fuel used across systems, enabling logistics flexibility. Similar standardization of consumables composition and storage can benefit deep-space logistics. As we pursue deep space exploration, continued improvement in physical and resource interface standards would serve safety and interoperability goals.

V. Summary and Next Steps

Our experience in sustaining human crews in the Antarctic and low Earth orbit environments has provided valuable lessons on system supportability, supply chain robustness, and how the implementation of these features drive the system architecture, increase crew safety, and impact life cycle cost. Quoting the former Chief of Logistics and Maintenance at the ISS Program Office:

“History has shown that if proper attention and emphasis is not placed on supportability concerns and issues, particularly early in a program, the potential impacts can be significant. Those impacts can range from hardware designs that are difficult and expensive to operate and maintain, schedule slips due to longer-than-expected turn-around times, degraded system effectiveness, and even loss of a mission or loss of life.”\textsuperscript{16}

First, we must appreciate the sheer magnitude of the mass (and volume) of infrastructure and supplies that is needed to sustain humans transiting to and living on Mars. Combine that with the limited ability to return to Earth and the inherent uncertainty in the reliability of the complex systems needed, it is clear that logistics and supply chain considerations are significant overall mission architecture drivers. Architecting a cost-effective and robust supply chain for long-duration Mars missions is much more challenging than for previous exploration campaigns to the Antarctic and cis-lunar space\textsuperscript{17}.

However, there may be logistics architectures that can meet the challenges of long duration and lack of reactive resupply opportunities. Supply chains involving the use of multiple logistics channels as with the SPS and ISS, and approaches such as caching or prepositioning of consumables and spares at key nodal locations (i.e., at orbital ARRC nodes and the Martian surface) combined with additive manufacturing technologies will most likely be needed to achieve the levels of system availability required to maintain key systems and crew survival. The number and location of these ARRC nodes needs to be studied in more detail. Currently, the added cost of these ARRC nodes is unclear, but such increases would need to be weighed against the net value of having a robust interplanetary supply chain, having safe havens for our crews in contingency scenarios, and potentially removing the burden of technology development in other areas. Lastly, because of the synergies between the initial design of key systems and the long-term operations and maintenance, habitation (in particular, ECLSS) design, transportation, and ISRU decisions cannot be made independent of logistics life cycle considerations.
V.A Next Steps

With the discussion described throughout this White Paper in mind, the following tasks are proposed as critical next steps in furthering our understanding of the Mars mission logistics tradespace.

**Task #1: Determine the logistics requirements by Class of Supply for a range of Mars orbital and surface mission campaigns, including opposition-class (short-stay), conjunction-class (long-stay), and sustained human presence.**

Discussion: This task builds upon previous work developed for the Constellation Program and long-duration crewed deep-space missions to produce a parametric model to estimate the mass, volume, and composition of supplies needed to support both the round-trip journey to Mars and its related surface activities. The task investigates existing rate tables for consumables and develops demand models for spares, and maintenance and operations items needed to ensure crew survival with high confidence. Inputs to the parametric model include (but are not limited to) travel times and surface stay time, crew size, habitat/ECLSS/ISRU/waste management/power system technologies, crew surface activities and operation cycles, and desired spares availability (i.e., contingency supply levels based on predefined risk thresholds).

**Task #2: Assuming the Gateway as an ARRC node in cislunar space and one at a particular location on the surface of Mars, determine the logistics implications of an ARRC node in Mars orbit, and determine the most advantageous orbit(s).**

Discussion: This task addresses the implications of using the Gateway as the cislunar logistics node and introducing an ARRC node in Mars orbit, creating a realignment of logistics pathways and a redistribution of logistics supplies. Building on Task #1, this task determines the effect of alternative ARRC node orbital parameters and alternative Mars surface outpost locations on logistics demands, in-space crew and cargo transportation vehicles, and MAV size. For the cislunar node, this task investigates how the Gateway can perform that function, either in its planned orbit or moved into another orbit, and the services it can provide. In addition, this task explores the relative impacts of the safe haven capability provided by a Mars orbit ARRC node on crew safety under off-nominal conditions.

**Task #3: Analyze logistics tradeoffs in selecting the location of the Mars permanent outpost with respect to ISRU water locations.**

Discussion: This task investigates the tradespace for the location of the Mars outpost considering the impacts of that selection on the Mars architecture systems (e.g., surface transportation, habitats, power, etc.) This task results in a model of the Mars outpost that determines system quantities needed to support transportation to/from Mars orbit and nominal surface activities.

References


[2] Discussion with Paul Sheppard, Chief Program Officer, Antarctic Infrastructure and Logistics Section, Office of Polar Programs, National Science Foundation


Appendix A — Glossary of Interplanetary Supply Chain and Logistics Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Cislunar</td>
<td>Lying between the Earth and the moon or the moon's orbit. For the purposes of this White Paper, this includes Near Rectilinear Halo Orbits (NRHOs), High Earth Orbits (HEOs), Distant Retrograde Lunar Orbits (DRLOs), etc.</td>
</tr>
<tr>
<td>Classes of Supply</td>
<td>Categories into which supplies are grouped in order to facilitate supply management and planning.</td>
</tr>
</tbody>
</table>
Network of all participants in a supply chain engaged in the receiving, handling, storage, transportation, and communications functions. http://www.businessdictionary.com/definition/logistics-channel.html |
| Space Logistics    | The theory and practice of driving space system design for operability and managing the flow of materiel, services, and information needed throughout the system lifecycle. https://info.aiaa.org/tac/SMG/SLTC/Web%20Pages/Definitions.aspx |
| Sparing-to-        | A mathematical modeling technique that seeks to select an optimal set of system spares by maximizing a measure of system availability subject to a variety of constraints, for example, on mass, volume, or budget. |
| Availability       |                                                                                                                                          |
| Supportability     | A system characteristic that encompassing reliability, maintainability, reparability, redundancy and sparing philosophy, and potentially, manufacturing base, level-of-repair, and transportability considerations. |

Appendix B — Supportability Lessons Learned from the ISS Program[6]

- “Supportability advocates must work with both design and operations.”
- “Where supportability wasn’t designed in, the penalty is increased life cycle cost.”
- “Supportability planning must analyze [the system] design regarding spares, maintenance planning, technical data, shipping, warehousing, facilities, automation, etc.”
- “Give designers incentive for designing supportability into their systems.”
- “Ensure requirements for supportability, maintainability and reliability start with the highest level program document and flow down to the lowest level specification.”
- “Functional Availability requirements integrate the inherent reliability of the design with the planned support resources.”
- “[A future] program must get predictive tools early, and use or create early representative data in order to conduct trades between different design options.”
- “Modularity requirements early in design pay off in life cycle cost.”
- “Require commonality and standardization across architecture elements.”
- “Integrate [international partners] through negotiation of requirements.”
Appendix C — From ISS to Mars: Recent Logistics Research

One can trace a direct line from the ISS lessons learned in Appendix B to the logistics research efforts that began in the Constellation Program era, when a permanently occupied lunar outpost was the goal. That research, largely performed at NASA and MIT, sought to formalize the concepts involved in interplanetary supply chains and space logistics in ways that would permit quantitative analyses beyond simply “manifesting the next Shuttle mission”\(^{18}\). Quantitative analyses of terrestrial supply chains typically use simulation and/or optimization methods to address both planning and operations issues. Adapting these methods to interplanetary supply chains has fostered an on-going program of research that continues to the present day\(^{11}\).

Early in this research, the concept of a node, in particular a logistics node, proved to be a fundamental element in the analysis and modeling of interplanetary supply chains. A node has several principal properties worthy of further discussion: type, location, and primary function. Type is determined by whether the node is on the surface of a planetary body, is an orbit, or a Lagrange Point. Location provides the particulars of that node. For example, KSC is of the first type, and is located at a particular latitude and longitude on Earth. An Exploration Zone permanent outpost is also of the first type, with its location specified by latitude and longitude on Mars. High Earth Orbit (HEO) is of the second type and its “location” is specified by its central body and the usual orbital parameters. Lastly, primary function is described by the node’s intended operational purpose within the overall architecture’s Concept of Operations (ConOps). Some examples of “operational intent” are long-term habitation, exemplified by the ISS, and aggregation, refuel, and resupply, exemplified by the proposed Lunar Orbital Platform-Gateway\(^{12}\).

Implementing an operational intent at a node, often, but not always, requires the placement at that node of systems that may themselves require long-term logistics support\(^{13}\). These systems need to be engineered to provide a level of capability (or capabilities) implied by the ConOps. If cost efficiency and operational success are important, it then makes sense to carefully architect the logistics supply chain— that is, to select the optimal set of logistics nodes and determine what level of capability is needed at each\(^{14}\). However, that is only part of the challenge. The other part is operationally how to ensure mission success and crew survival by the selection of what supplies and what quantities are to be cached at each node, and what supplies and how much should travel along with the crew, taking into account mass, volume, and other constraints. This requires a detailed understanding of the demands likely to occur. In other words, another fundamental element in the design and analysis of interplanetary supply chains is the characterization of demands. Previous research has shown how important this is to crew survival in the context of a Mars outpost\(^{20}\).

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\(^{11}\)One of the primary products of the Constellation era work was a publically available web-based simulation tool called SpaceNet\(^{19}\).

\(^{12}\)Supplies and crews move within the Earth-Moon-Mars system—that is, from one logistics node to another—in accordance with the laws of orbital mechanics. Supplies and crews may move along different pathways in the logistics network to reach the final node, the Mars outpost; and various classes of supply may take different pathways from each other, bypassing some nodes.

\(^{13}\)The low lunar orbits used for rendezvous and docking by the Apollo missions are examples of logistics nodes that did not have in-place systems.

\(^{14}\)In terrestrial supply chain analysis, this is equivalent to the problem of selecting the optimal locations for warehouses and the capacity at each such location in order to best fulfill customer demands.
Previous research on the optimal location of logistics nodes for Mars missions has largely been based on reducing IMLEO (Initial Mass to Low Earth Orbit) through the use of lunar-derived propellant—that is, through the use of in situ resources delivered to the right location at the right time. This implied the establishment of a lunar surface logistics node for extracting useful quantities of water and another logistics node in cislunar space as a propellant depot. Other studies have indicated that water from asteroids could also serve the same purpose. In designing these ISRU-driven supply chains, several factors were considered including launch sequencing, ISRU efficiency, aggregation locations, propulsion technology, mission design, staging, rendezvous, timelines, etc. Collectively, these increasingly sophisticated studies have shown a significant reduction in IMLEO against a baseline NASA Mars architecture[21-24]. However, these results are still preliminary and not conclusive with regard to cost-effectiveness.

Other recent research has focused on using Mars resources, in particular, producing LOX from the Martian atmosphere and extracting water for human consumption and possibly for propellant manufacturing, as a way of reducing IMLEO. These architectures implied the establishment of a logistics node within close proximity to the permanent human outpost and perhaps other logistics nodes at some distance away. These studies suggest strong returns, pending significant technological breakthroughs[25].

Previous in-space supply chains have successfully dealt with spares issues through a mixed strategy of carry-along (pre-manufactured) and/or pre-positioned units plus resupply on demand. Recent research has shown that in the future, capabilities for in-space additive manufacturing have the potential to reduce overall carry-along and resupply mass at the cost of increased system mass, while potentially providing access to a much broader range of resupply items that have a low, but non-zero, probability of being needed[26].