ANALYSIS OF LOGISTICS IN SUPPORT OF A HUMAN LUNAR OUTPOST

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ABSTRACT
Strategic level analysis of the integrated behavior of lunar transportation system and lunar surface system architecture options is performed to inform NASA Constellation Program senior management on the benefit, viability, affordability, and robustness of system design choices. This paper presents an overview of the approach used to perform the strategic-level analysis, with an emphasis on the logistics modeling and the impacts of logistics resupply on system behavior. An overview of deterministic and probabilistic analysis approaches is provided, with a discussion of the importance of each approach to understanding the integrated system behavior. The logistics required to support lunar surface habitation are analyzed from both "macro-logistics" and "micro-logistics" perspectives, where macro-logistics focuses on the delivery of goods to a destination and micro-logistics focuses on local handling of re-supply goods at a destination. An example lunar exploration system scenario is provided to tie the theories of strategic analysis to results generation capabilities.

Keywords: strategic analysis, space logistics, lunar outpost, lunar architecture

1. INTRODUCTION

Over the past three years, an interest in establishing an extended human presence on the Moon has been rekindled by the world's space fairing nations. NASA's contribution to this exploration renewal was first formulated in the Exploration Systems Architecture Study (ESAS Final Report 2005) and subsequently refined through ongoing analysis (Cooke 2006; Cooke 2007), which taken together provides the basis of the current NASA Space Exploration Program. The overall value of a human lunar return and subsequent extended duration surface stays will be significantly driven by the logistics requirements, packaging design and re-supply methodology. Transportation and delivery of the resources required to support extended human presence at a lunar outpost is challenging and will involve significantly more risk and cost than delivery of goods to locations currently re-supplied in Earth orbit, i.e. the International Space Station (ISS). Given the constrained payload capability of currently envisioned lunar transportation systems, there is a balance that must be achieved in order to optimize the permissible crew surface stay time at a given location. In addition to delivery of elements for life support and scientific utilization on the lunar surface, logistics must also be delivered in order to support continued habitability and crew needs. These logistics include crew consumables, spares and maintenance equipment, liquids, and gases; all of which must be packaged, transported to the lunar surface, stored for some period of time before use, and finally disposed of in an appropriate way. Determination and optimization of these exploration system drivers required to support extended duration missions forms the basis of the analysis conducted under the Constellation Program by the Exploration Systems Analysis Team (ESAT).

This paper will present an overview of the strategic analysis conducted by the ESAT for utilization by NASA Constellation Program's decision-makers, with a focus on the influence of logistics on strategic-level Figures of Merit (FOMs). An overview of deterministic and probabilistic analysis approaches is provided, with a discussion of the importance of each approach to understanding the integrated system behavior. The logistics required to support lunar surface habitation are analyzed from both "macro-logistics" and "micro-logistics" perspectives, where macro-logistics focuses on the delivery of goods to a destination and micro-logistics focuses on local handling of re-supply goods at a destination. An example lunar exploration system scenario is provided to tie the theories of strategic analysis to results generation capabilities. This scenario presented is notional and is not representative of NASA's official position on lunar exploration.

2. STRATEGIC ANALYSIS OVERVIEW

One of the primary goals of strategic analysis is to provide an integrated assessment of the logistics over the exploration system life-cycle required to support strategic decision making. This integrated analysis encompasses not only performance, but also uncertainty, risk, and affordability, as well as capturing their associated linkages and feedbacks. Strategic analysis supports decision making by Constellation Program senior management through study of system robustness as well as alternate strategies. This is enabled by assessment of both the planned and expected benefit and cost of exploration systems, which is aggregated into high-level value metrics and FOMs that enable cost-benefit analysis.

The exploration systems analysis methodology is based on resource utilization analysis using predefined element data sets. The exploration system model does not perform element design or sizing. Rather, those data are provided by element experts from their design and sizing tools and analysis. The data are imported into a library for use in the exploration system analysis model.

The overall methodology is designed to simplify the analysis, while still capturing those details that have major impacts on system performance. For example, the exploration system model does not explicitly perform any transportation system analysis. Instead, it focuses on delivery of elements and goods to locations on the lunar surface. Delivery is driven largely by the amount of mass that a crewed or cargo lunar lander is capable of delivering to a given location. These cargo capacities are provided as inputs to the model from transportation system analysts, such that the model does not require the user to set up launches, in-space rendezvous, engine burns, etc and the model is not required to track propellant, delta-velocities, in-space logistics use, etc. In most other cases, some amount of analysis is performed, but the level of detail is limited.

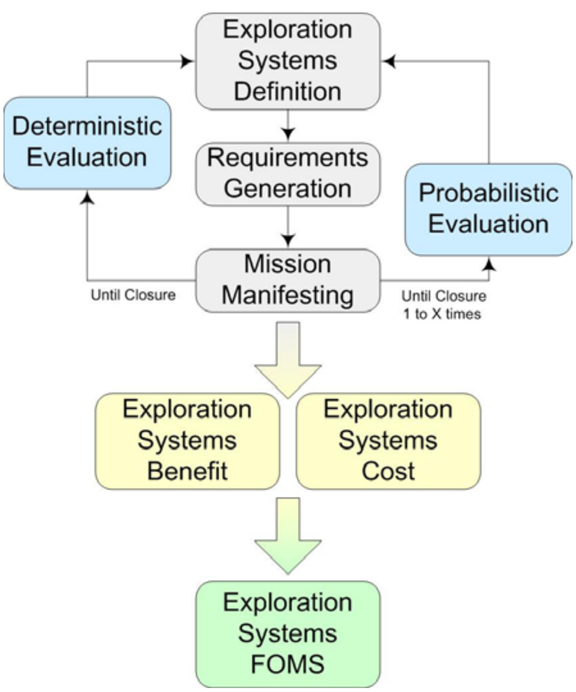

Figure 1: Strategic Analysis Flowchart

Figure 1 provides a high-level overview of the strategic analysis process. Each of these blocks will be briefly described in the following paragraphs (Cirillo, Earle, Goodliff, Reeves, Andraschko, Merrill, and Stromgren 2008).

'Exploration System Definition' is the process in which exploration system architectures and approaches are defined. Flight rates, destinations, transportation system capability, and surface elements specify the exploration system and drive the assumption sets for logistics requirements.

'Requirements Generation' is the calculation of the total mass of required cargo for delivery based on the exploration system definition. Logistics required include: crew resupply, habitat logistics and maintenance, surface element logistics and maintenance, Extra-Vehicular Activity (EVA) consumables, and leakage. The final step is categorization of each logistic by type; either pressurized, unpressurized, gas, or liquid.

'Mission Manifesting' is the optimization of the loading of each mission based on capabilities and requirements from the previous steps and on a set of input loading criteria. Goods are loaded by carrier, accounting for mass and volume limitations.

'Deterministic Evaluation' is the process of evaluating the viability of an exploration system scenario with respect to delivery mass and crew resupply capability. Inputs, such as crew surface durations and scheduling of pressurized logistics container delivery, are varied to maximize exploration system performance, while satisfying the ability to deliver the required exploration system logistics.

'Probabilistic Evaluation' is run after deterministic evaluation and incorporates exploration system risk and evaluates the robustness of the exploration system through Monte Carlo analysis. Exploration systems are adjusted and re-analyzed based on expected loss of mission, crew, rendezvous, and other programmatic risks (as specified).

'Exploration System Benefit' determines which objectives can be satisfied in the given exploration system and then weights can be assigned to determine an overall benefit. Objective weightings are left unassigned by the analyst, so as to allow the decision-maker the freedom to investigate the impact of alternative policy decisions.

'Exploration System Cost' is the calculation of the annual cost of all lunar architecture elements, including Design, Development, Test and Evaluation (DDT&E), Production, and Operations.

'Exploration System FOMs' are high-level Figures of Merit for a given exploration system scenario and are calculated based on scenario performance metrics produced by the exploration system model.

3. DETERMINISTIC AND PROBABALISTIC ANALYSIS

History has shown that complex space exploration systems rarely proceed exactly as planned. Unplanned, although not always unexpected or unanticipated, events intervene, changing the course of the planned exploration system.

Deterministic analysis alone allows for an evaluation of only the nominal performance of a lunar exploration system. While this is a critical step in the development of the exploration system, using this approach alone neglects the risk and uncertainty associated with human space exploration. Vehicle reliability, technology development risk, budgetary uncertainty, and launch uncertainty all contribute to stochasticity in an exploration system. Strategic analysis that allows for both deterministic and probabilistic modeling will lead to better understanding of the system's range of behaviors due to various modeled uncertainties (Stromgren, Andraschko, Merrill, Cirillo, Earle, and Goodliff 2008).

3.1. Deterministic Analysis

Analysis of the logistics and re-supply methodology of a human lunar outpost/exploration system in a deterministic manner provides an initial assessment of the performance of the exploration system, with the performance being largely driven by logistics resupply constraints for exploration systems supporting extended lunar outpost crewed operations. Sensitivity analysis and trade studies conducted on candidate exploration system scenarios provide insight into the behavior of the nominal exploration system when focused on key system parameters, such as the physical characteristics of the elements, their associated logistics, required crew consumables, and the logistics packaging methodology. Scenarios are defined and analyzed deterministically prior to performing probabilistic assessments.

The deterministic model requires as input an exploration system definition. This definition consists, primarily, of the parameters necessary to describe the set of missions that will constitute the exploration system, such as the number of crew delivered, the length of crewed surface duration, the delivery capacity of the transportation system, and the payloads delivered. Once the exploration system has been defined, the logistics requirements are calculated for each mission based on the mission parameters, the capabilities of the manifested elements, and a set of assumptions about crew consumption, Extra-Vehicular Activity (EVA), logistics, science requirements, and In-Situ Resource Utilization (ISRU). The required logistics are then loaded onto each mission within carriers for delivery prior to their date of use. Any cases in which the logistics could not be loaded due to limited capacity are flagged for further attention. Exploration system definition, logistics requirements calculation, and logistics loading are iteratively performed until the exploration system is performing satisfactorily.

Once the deterministic exploration system has been created, the defined exploration system can then be leveraged as an input into other analysis, to include probabilistic assessments, figures of merit assessment, and sensitivity/trade space analysis.

3.2. Probabilistic Analysis

Methodologies and tools have been developed to provide probabilistic analysis of lunar exploration systems. These probabilistic tools are used to simulate the real-world outcome of exploration systems, based upon the probability of occurrence for non-nominal events, the expected consequence and delays associated with those events, and established contingency operations polices. Using this data, the tools simulate a large number of possible exploration system scenarios, each a possible instantiation of the actual exploration system.

Within each simulated scenario run, the probabilistic exploration system analysis tool performs a mission-by-mission temporal simulation. At each mission step, the tool uses the deterministic exploration system tools to calculate a planned manifest for all remaining missions, including requirements, capacities, and loadings. The outcome of the current mission is then simulated based on probability distributions for all possible non-nominal events and mission event trees. Once the outcome of the mission has been determined, if the mission is successful, the tool tracks the additional material that is delivered to a site on the lunar surface and the amount of material that is consumed. In this manner a running inventory of surface deliverables is maintained. The consumption of material on the lunar surface can also be driven by probabilistic data. Failures of equipment use logistics and crew activity rates can be represented stochastically. If the current mission experiences a failure, then the consequences and resultant delays to the remaining missions are determined, based upon specified contingency operational policy. The remaining flights are reset based upon these consequences.

The tool then moves on to the next flight and repeats the simulation. This flight, and all the flights that follow, are therefore influenced by the events that have occurred cumulatively on all previous flights. After all the flights in a scenario have been simulated, the overall exploration system performance for that case is evaluated. The amount of potential science conducted, the extensibility objectives that are met, additional costs that are incurred, and the risk to the crew are determined.

The probabilistic exploration system tool repeats this process many times, simulating a large number of possible scenario outcomes and collecting performance data for each. The performance data is then integrated into probabilistic distributions for expected exploration system results. These distributions show the likelihood of achieving different levels of exploration system performance based on the current reliability, control policies, and uncertainties within the system. The probability distributions can be compared to the nominal exploration system performance, as predicted in the deterministic exploration system analysis tools, to evaluate the robustness of the given exploration system.

Exploration systems that provide a high level of expected performance across the range of possible probabilistic outcomes are identified as being more robust. That is, they are relatively insensitive to the real-world events that disrupt planned behavior. Exploration systems that exhibit a sharp drop-off in expected performance are less robust.

Based on the results of the probabilistic analysis, revised exploration systems may be developed to provide additional robustness against adverse events and to optimize contingency planning to better ensure a high level of expected exploration system performance. Typically, however, in order to improve the expected performance under probabilistic conditions, it is necessary to sacrifice some level of nominal performance. Nominal performance is typically traded for increased robustness through increased redundancy, contingency deliveries, schedule margin, or other mitigation techniques.

Probabilistic analysis tools allow mitigation techniques to be optimized and can demonstrate the ultimate values of these measures to decision-makers, who otherwise will tend to focus on nominal performance measures. This additional insight into mitigation of critical failures and the implications for the planned exploration system and its associated logistics support necessitate the inclusion of probabilistic analysis when defining an exploration system.

4. MACRO-LOGISTICS

Depending on the overall lunar exploration system, the mass of the logistics and the containers necessary to hold those logistics can account for half to two-thirds of the total mass delivered to the lunar surface by the transportation system. Thus, logistics is a primary driver of overall exploration system performance and must be effectively modeled to reliably predict exploration system performance.

The logistics model (Andraschko, Merrill, and Earle 2008) that is currently incorporated into the deterministic exploration system model tracks the requirements and delivery of logistics that fall into the following seven categories:

1. Pressurized crew consumables – food, clothing, etc.
2. Pressurized spares and maintenance – repair and replacement items for surface elements
3. Unpressurized spares and maintenance
4. Unpressurized science
5. Oxygen
6. Nitrogen
7. Water

The model takes a predefined exploration system, calculates the logistics requirements for each segment, and then manifests carriers and loads logistics onto the landers to ensure that all required logistics are delivered prior to the date they are needed. The model makes some effort to perform the loading efficiently while also accounting for requirements driven by multiple surface locations, element and crew transfers between those locations, and overlapping crew surface periods.

Requirements are calculated for each segment of each mission, by location. Pressurized crew supply requirements are primarily driven by the number of crew and the duration of their stay on the surface. Spares and maintenance requirements are driven by the amount of time each element is active, whether or not crew are present, and total duration on the surface. Science requirements are defined externally on a per mission basis, and incorporated directly into the requirements definition. Oxygen, nitrogen, and water requirements are all based on an Environmental Control & Life Support System (ECLSS) models from subject matter experts at NASA's Johnson Space Center and Marshall Space Flight Center that take as inputs the number of crew, the crew's time on surface, habitat volume, etc. Requirements are calculated for each mission segment and then assigned to the closest lander arrival prior to the start of that segment, to ensure that all required goods will exist at the appropriate location by the time they are needed.

There are additional factors that are currently modeled that affect the requirements calculations. If the ECLSS can electrolyze water, any oxygen requirements are converted to an equivalent water requirement, as water requires less packaging mass and volume to deliver. The model can account for consumables produced by In-Situ Resource Utilization (ISRU) systems, including the buildup of a stockpile over time that is used to reduce requirements on supply delivery. The model also has the capability to allow the crew to extract water from the propellant residuals in the lander descent stage tanks after landing. This value is allowed as a fixed amount per lander and assumes sufficient storage capacity exists and the hardware to convert the propellant residuals to water is in place. To date, exploration systems have utilized both oxygen ISRU and water scavenging techniques to reduce logistics delivery requirements. These options will be further assessed as additional data from actual technology performance evaluations becomes available.

Once the required logistics have been determined and assigned to specific missions, they must be loaded onto those landers or earlier landers traveling to the same location. Logistics must be loaded into logistics carriers, which are then manifested on a lander where space is available. With the exception of the pressurized logistics modules (PLMs), the currently modeled carriers are all derived from the actual carriers used on board the Space Shuttle for delivery to the ISS. Logistics are loaded in these containers up to specified carrier mass and volume limits. The PLM designs are provided by a team of surface habitat designers; however, the packaging for logistics delivered inside the PLMs uses Shuttle & ISS heritage techniques. The pressurized logistics are loaded slightly differently than the other logistics types. They are first loaded into

Cargo Transfer Bags (CTBs), up to the CTB mass and volume limits. The CTBs are then loaded onto the PLMs up to a specified CTB limit, while not violating the PLM mass limit. The manifesting of PLMs on missions is performed by the model user, whereas the manifesting of the unpressurized, oxygen, nitrogen, water carriers and the loading of the PLMs is performed automatically by a logistics loading algorithm.

The loading of logistics into carriers and the carriers onto landers is handled by a loading algorithm that attempts to minimize the unused capacity in each carrier, which therefore minimizes the number of carriers required over the course of the lunar exploration system. This algorithm performs the following set of steps to load the required logistics assigned to each lander, starting with the first mission and progressing to the last:

1. Load required logistics into available space on carriers that are already manifested on any earlier landers at the assigned landing location
2. Load remaining logistics onto the assigned or earlier landers at the assigned landing location, treating already-manifested carriers as if they were filled to capacity, and only manifesting additional carriers if the already-manifested carriers are completely filled
3. Load remaining logistics onto the assigned or earlier landers at the assigned landing location, treating already-manifested carriers as if they are filled to capacity, and manifesting carriers that are not completely filled, as needed
4. Load remaining logistics onto the assigned or earlier landers at the assigned landing location, not treating already-manifested carriers as if they are filled to capacity, and manifesting carriers that are not completely filled, as needed
5. Follow steps 1-4 to load remaining logistics onto landers at OTHER locations if there is a surface element transfer from there to the assigned landing location prior to the assigned landing date
6. If there are additional logistics required that could not be loaded on any previous lander, they are "overloaded" onto the assigned lander (using packaging mass multipliers, rather than actual carrier elements), which will exceed the lander's delivery capacity and cause it to be flagged as "broken"

After the loading has been performed, the user must adjust the element manifest, mission dates and durations, number of crew, or other assumptions and re-run the loading algorithm. This iteration is performed until all required logistics can be loaded into the available space on the landers in the defined exploration system.

5. MICRO-LOGISTICS

The bulk of exploration system manifest analysis has traditionally focused on the delivery of elements and goods to a destination. This focus on macro-logistics captures only a portion of the constraints that will apply to a lunar surface architecture. The local handling of goods at the destination, referred to as "micro-logistics" may also impose severe constraints on architecture operation.

The evaluation of micro-logistics includes a number of areas related to the storage and handling of goods at lunar sites, including: storage requirements for all goods, including system storage requirements for gases and liquids; the movement and storage of cargo carriers; and the collection and disposal of trash (Stromgren, Galan, and Cirillo 2008).

There are several key issues regarding the operation of a lunar outpost that can be analyzed using the micro-logistics models that have been developed for lunar exploration system analysis. Of particular concern is the storage volume required in lunar habitats for all of the consumables that must be accommodated. In addition, the availability of those consumables, particularly critical spares is of significant interest. Other issues include the storage time of goods on the surface, the amount of crew time required to move goods, and the availability of consumables in case of an emergency.

Micro-logistics analysis is conducted using a time-based system dynamics model. This model tracks the location and quantity of all goods at a lunar site over time. Specific items that are tracked include: crew consumables, spares and maintenance items, science equipment and consumables, gases, and liquids. As part of this tracking, the tool models the operation of the ECLSS, simulating the consumption and conversion of gases and liquids.

The system dynamics model is run against a specific set of case results from the exploration system manifest model. Consumption rates, as well as the goods delivery schedule for a specific exploration system are imported. The local storage, movement, and consumption of those goods are then evaluated.

The model simulates how each type of good is moved and used. Consumption rates are dynamic, reflecting real schedules and rates, and accounting for crew timelines and activities. The movement of goods reflects a concept of operations for how each type of good would be stored and positioned and how carriers would be manipulated on the lunar surface. In addition, the model relates crew times to each cargo movement activity simulated in the model and calculates total crew time requirements required to support micro-logistics.

Evaluation of micro-logistics allows analysts to develop logistics plans that can be accommodated using the storage capabilities that are available on the surface and that minimize the crew time required to reposition goods. In addition, this type of analysis provides a prediction for the availability of critical spares and consumables, which, in turn, can be used to predict the safety and productivity of key surface system elements.

6. EXAMPLE EXPLORATION SYSTEM RESULTS

Over the last decade this strategic analysis methodology has been applied to the Space Shuttle and International Space Station Programs and is now being applied to the development of various options for the planned Constellation Program lunar architecture. The following sections cover the FOMs used to evaluate proposed lunar architectures. Additionally, an example lunar exploration system scenario and sensitivity analysis are presented. Finally, architectural level observations resulting from the analysis of this example scenario are discussed.

6.1. Figures of Merit

Figures of Merit are used to evaluate and compare the relative merits of differing exploration systems, approaches, and executions. The FOMs should be discrete enough to compare relative value expected to be achieved by closely related exploration systems (i.e. capable of evaluating differences in delivered mass, crew time, etc.). For the lunar architecture analyses, a comprehensive set of high-level FOMs were used that covered five major areas: Affordability, Extensibility & Experience, Science & Lunar Survey, Safety & Mission Assurance, and Sustainability.

The Affordability FOMs capture an integrated representation of the ability of a planned budget to cover predicted costs over the life of the exploration system. Affordability results are generated using a combination of deterministic and probabilistic integration and cost estimating tools and models. The scope of affordability integration includes full life cycle costs; conceptual studies, system development, recurring system production, ground & mission operations support, logistics demands, communications infrastructures, prime contractor sustaining engineering, and government oversight costs. The Affordability FOMs consolidate all such information to demonstrate the overages and shortages (cumulative as well as annual) between predicted cost and planned budget profiles. Due to the sensitivity of cost projections and budget implications, only a notional example of Affordability FOM results is included within this paper.

Extensibility & Experience FOMs measure accomplishment in three objective areas: 1) development, testing, and demonstration of relevant technologies, processes, and components for extensibility to future exploration; 2) accumulated experience in living off the Earth, maintaining equipment, and performing useful exploration; and 3) accumulated experience in living on the Moon.

Science & Lunar Survey FOMs measure accomplishments in four objective areas: 1) conduct of fundamental science; 2) science conducted to support future exploration; 3) science/survey conducted to support future lunar exploration; and 4) science/survey conducted to determine opportunities for commercial endeavors.

Safety & Mission Assurance FOMs measure expected losses of the system. Safety FOMs capture the expected losses that are due to uncertainty or reliability. These include the expected loss of life and expected loss of missions. The primary Safety FOM measures total expected human loss. Mission Assurance FOMs capture expected losses to mission critical elements. FOMs measure probability of loss of these elements. The current risk model utilized was exclusive to transportation system. The surface elements architecture risk model is under development.

The Sustainability FOM measures perceived output of an exploration system and compares that to the minimal acceptable limit. To evaluate Sustainability, a “benchmark event” is established that defines Level of Interest (LOI) required to sustain budget (e.g. Spirit/Opportunity Landing) and a nominal LOI weight is assigned for that event. Next, a LOI weight is assigned to each potential exploration system event based on relative LOI that it will generate. Then, a reasonable “decay rate” is set, where the decay rate is the rate at which interest dissipates. Weights and decay rates are used to calculate a running LOI over the exploration system.

6.2. Example Exploration System Scenario and Sensitivity Analysis

The following section presents an example of strategic analysis. The exploration system scenario presented is notional and is not representative of NASA’s official position on lunar exploration. The results of the example scenario are focused on initial outpost buildup and achieving continued human presence. Future analyses will further explore the steady state behavior of the system in more depth. The primary assumptions established for the example scenario include:

- 2019 start date, maximum of 4 missions per year
- Outpost location at Lunar South Pole
- Emphasis on early outpost buildup
- Maximum crewed duration of 180 days
- Current Pressurized Logistics Module (PLM) sizing prioritized to maximize commonality with Core Habitat
- Transportation system performance to Lunar South Pole yields 14.6 t payload for a cargo lander, 0.5 t payload for a crewed sortie lander, and 1.0 t payload for a crewed outpost lander
- Residual propellant in the lander descent stages can be scavenged to generate 400 kg of water per lander

The surface system elements in the exploration system consist of the Core Habitat, power and support units (PSU), mobility chasses (CMC), reusable and disposable pressurized logistics carriers (RPLMs and DPLMs), ISRU oxygen production system (OPS) and tools, small pressurized rovers (SPRs), tri-ATHLETEs (ATHLETE is an acronym for All-Terrain Hex-Legged Extra-Terrestrial Explorer), and lunar communication terminals (LCT). These elements are strategically placed on specific missions to support the emphasis of early outpost buildup. Figure 2 shows the deterministic manifest for the example scenario. Only the surface system elements and pressurized logistics modules are shown in the figure. The unpressurized, gases, and liquid carriers are not shown for clarity. As seen in the figure, the delivery of habitation in 2020 allows for successive crews to stay longer on the lunar surface than a standard sortie mission of 7 days length. The elements are also placed on specific missions to get a balance between the capabilities the elements provide and the logistics required to support the crew for a given number of days. The figure only shows the first seventeen missions since the latter flights would be repeated to sustain continued human presence.

Scenario Description

Example Scenario	Description:	Habitability Emphasis 4 Flights per Year	Date:

Lander

Ref. Crewed Capacity	1000 kg
Cargo Lander Capacity	14600 kg
Launch Order	I-V
EDS Loiter	4 Days

Transportation System

Lander Mass	46765 kg
Shroud Diameter	10 m

ECLSS

Water Recovery	yes	93.5%
Brine Recovery	no	-
Solid Waste	no	-
O_2 Generation	yes	
Sabatier	no	
Sabatier+CFR	no	
EVA CO_2 Recovery	no	
Laundry	no	

Outpost Details

1 Core Hab + 2 RPLMs
1 Suitlock
ICP

#	Date	Mode	Location	Crew Size	Duration (days)	Delivered Surface Elements
1	3/30/19	Test	Equator	0	0	
2	6/28/19	Sortie	South Pole	4	7	
3	12/8/19	Cargo Outpost	South Pole	0	0	Core Hab, ICP, Chassis-C, CDK, OTSE
4	2/27/20	Crewed Outpost	South Pole	4	14	MCT
5	5/12/20	Crewed Outpost	South Pole	4	30	
6	9/15/20	Cargo Outpost	South Pole	0	0	RPLM #1, ICP, MPU, ATHLETE, LCT
7	11/24/20	Crewed Outpost	South Pole	4	60	
8	1/24/21	Cargo Outpost	South Pole	0	0	ICP, MPU, SPR, SPR, ISRU Module, ISRU Module
9	4/4/21	Crewed Outpost	South Pole	4	90	
10	6/13/21	Cargo Outpost	South Pole	0	0	RPLM #2, ICP, MPU, ATHLETE
11	10/11/21	Crewed Outpost	South Pole	4	120	
12	12/30/21	Cargo Outpost	South Pole	0	0	DPLM, ICP, MPU
13	2/28/22	Crewed Outpost	South Pole	4	180	
14	5/29/22	Cargo Outpost	South Pole	0	0	DPLM, ICP
15	10/16/22	Crewed Outpost	South Pole	4	180	
16	1/24/23	Cargo Outpost	South Pole	0	0	DPLM, ICP
17	4/14/23	Crewed Outpost	South Pole	4	180	
+	. . .	. . .	. . .	. . .	. . .	***Repeat flights (for continued human presence)***

Figure 2: Exploration System Description for Example Scenario

The logistics requirements for the example scenario are shown in Figure 3 on a per mission basis (again only through the first seventeen missions). The driving requirements are pressurized goods (i.e. crew consumables and element spares and maintenance mass) followed by unpressurized goods (i.e. element spares and maintenance mass and science). There is no oxygen delivered to the Moon, since the ECLSS has an electrolyzer and water is electrolyzed into hydrogen and oxygen. The water requirement is very close to zero due to the water scavenged from the lander propellant residuals and the ISRU processor producing 1000 kg of oxygen per year. Figure 4 shows how these logistics are delivered on each mission. Logistics are delivered on or before the flight that they are needed to support the crewed missions to the lunar surface. Current transportation system capabilities were primarily driven by a desire to achieve global lunar access. This global access requirement, coupled with current mission design choices that constrain the crew stay on the lunar surface to non eclipse periods, results in an unallocated payload capability on cargo missions during the later part of the scenario. This additional payload capacity could be utilized to send additional elements, science, or other non-pressurized goods.

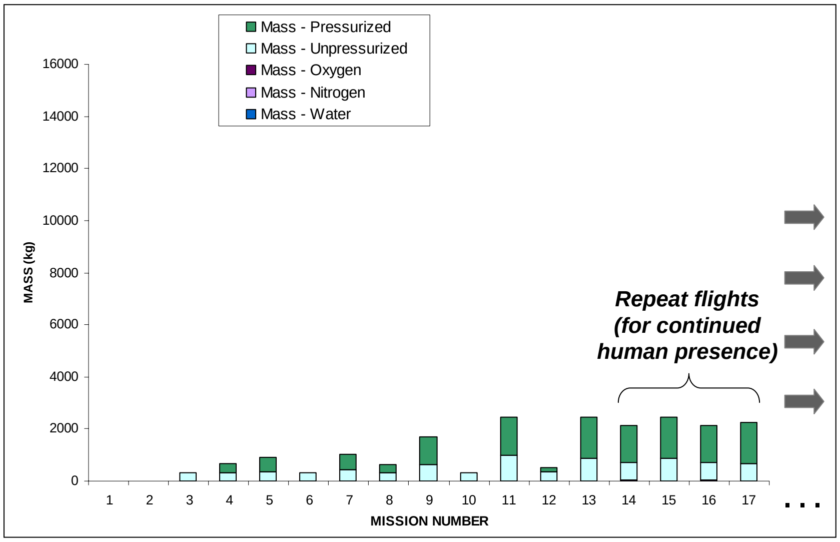

Figure 3: Required Logistics by Mission for Example Exploration System Scenario

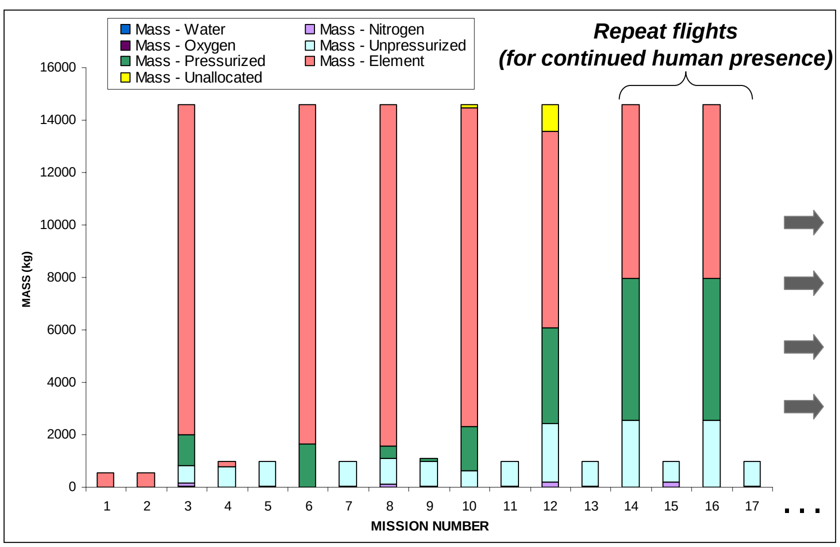

Figure 4: Delivered Mass by Mission for Example Exploration System Scenario

Figure 5 gives the FOMs results for the example scenario. Each of the FOMs gives a comparison of the planned/deterministic scenario and the expected/probabilistic scenario. For multiple exploration systems, the FOMs can be compared side-by-side or cross-plotted to determine the "best" exploration system based on a stakeholders' values and beliefs. For this example scenario, there was no intent to optimize the latter missions in order to improve the Sustainability FOM.

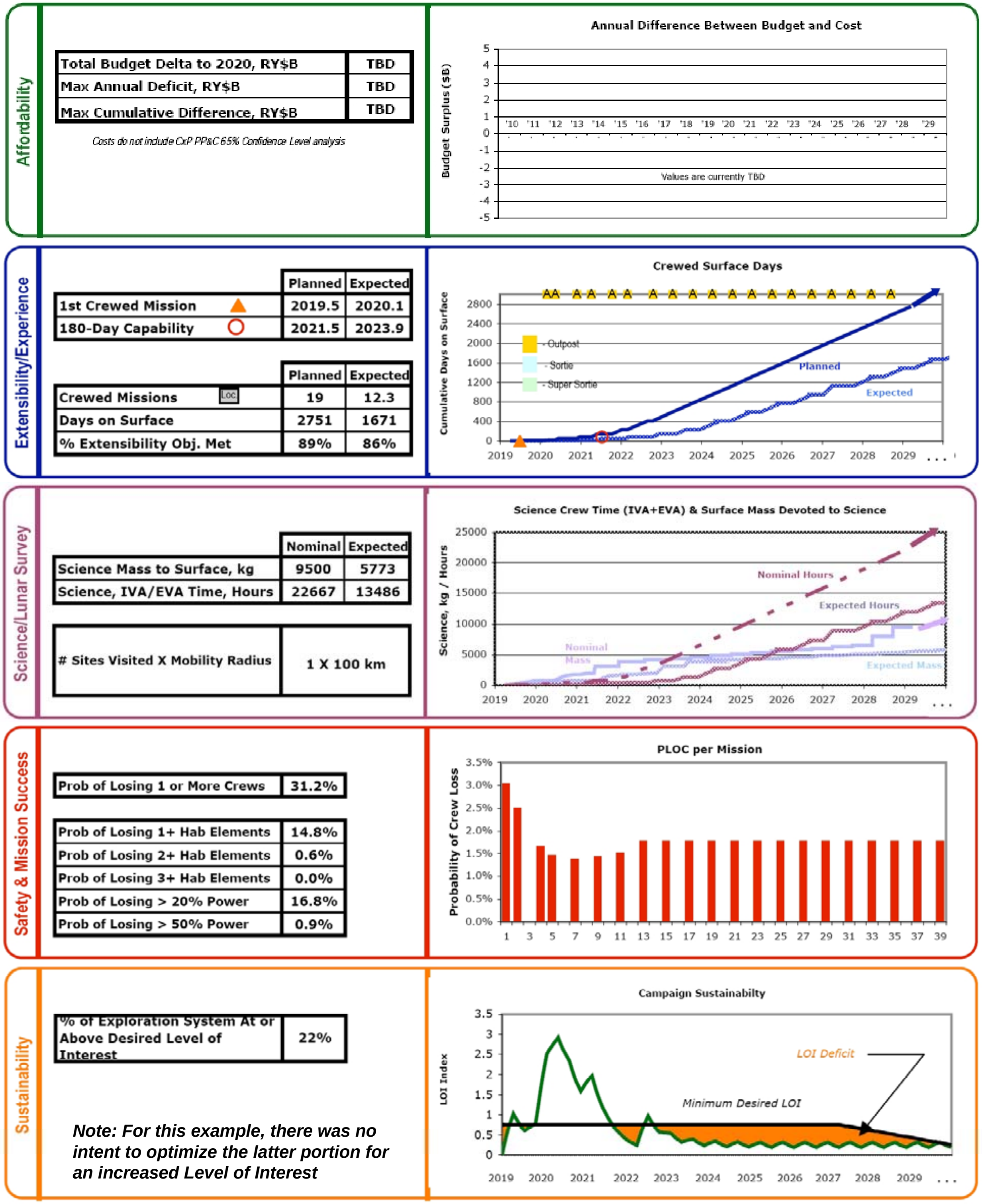

Figure 5: Example Figures of Merit through First Ten Years of Lunar Exploration

As spares and maintenance requirements are a significant driver of exploration system performance, a sensitivity analysis was performed on the example scenario that explored variations in sparing and maintenance mass requirements. For this analysis, sparing and maintenance mass was varied by ±10%, ±25%, and ±50%. The results of the sensitivity analysis are shown in Figure 6. As the figure shows, reduction in spares and maintenance mass required will allow slight increases in crew days, along with significant increases in available mass. Small increases in spares and maintenance requirements lead to slight losses of crew days and significant reduction in available mass. Large increases in spares and maintenance requirements result in significant loss of crew days and available mass. Strategic-level analysis when combined with a "bottoms-up" element level assessment is required to yield a more refined spares and maintenance strategy.

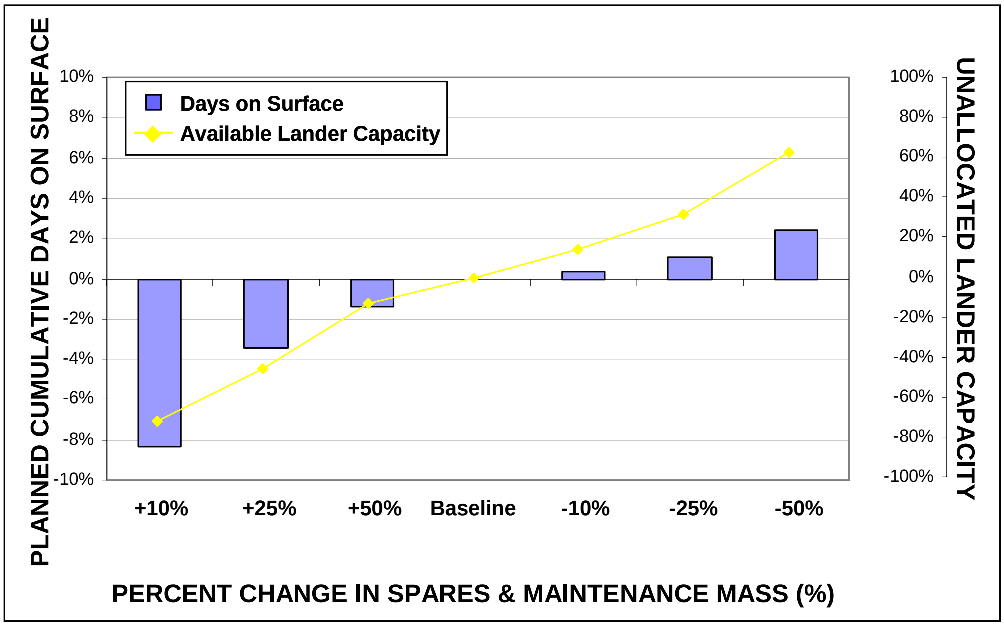

Figure 6: Spares & Maintenance Sensitivity

6.3. Architectural Level Observations

Two key observations were determined as a result of all the exploration systems and sensitivity analyses studied. The first key observation is that a cargo version of the lunar lander enables robustness. The analysis verified that inclusion of a cargo lunar lander is mandatory to enable outpost build-ups that are robust to changes in overall lunar lander performance. The analysis also showed that variations in crewed lunar lander cargo payload performance have secondary impacts on the exploration system behavior when a cargo lunar lander is available to deliver hardware (verified with crew lunar lander cargo payload performance from 0 to 8 metric tons). In addition, variations in cargo lunar lander payload performance have first-order effects on the rate of initial outpost build-up, but less of an impact on long-term exploration system robustness. The second key observation is that logistics are a major exploration system driver. The variability in logistics requirements and strategies remain a first-order driver to exploration system performance.

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