

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 campaign (strategic) analysis, with an emphasis on the logistics modeling and the impacts of logistics resupply on campaign 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 campaign is provided to tie the theories of campaign analysis to results generation capabilities.

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

1. INTRODUCTION

Space programs around the world are planning for extended human presence on the Moon (ESAS Final Report 2005; Cooke 2006; Cooke 2007); 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 a lunar transportation system, there is a balance that determines the amount of time that the crew can survive on the lunar surface 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, maintenance equipment; 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 campaign performance for extended duration missions is closely linked to - and driven by - the required element logistics and maintenance as well as crew consumables and their associated packaging and transportation methodology.

This paper will present an overview of the campaign analysis utilized for NASA Constellation Program’s with a focus on the logistics. In particular, the discussion will include the necessity of analyzing campaigns from both a deterministic and probabilistic perspective; a discussion of “macro-logistics,” “micro-logistics,” and the importance of studying both; and results of an example campaign and sensitivity analysis.

2. CAMPAIGN ANALYSIS OVERVIEW

One of the primary goals of campaign analysis is to provide an integrated assessment of the logistics system over the campaign 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. Campaign analysis supports strategic 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 campaigns which is aggregated into high-level value metrics and Figures of Merit (FOMs) that enable cost-benefit analysis.

The campaign analysis methodology is based on resource utilization analysis using predefined element data sets. The model does not perform element design or sizing. Rather, that data is provided by element experts from their design and sizing tools and analysis. The data is imported into a library for use in the campaign 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 campaign model does not perform any transportation system analysis itself. 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, Δv 's, in-space logistics use, etc. In most other cases, some amount of analysis is performed, but the level of detail is limited.

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

'Campaign Definition' is the process in which campaign architectures and approaches are defined. Flight rates, destinations, transportation system capability, and surface elements specify the campaign 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 campaign 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.

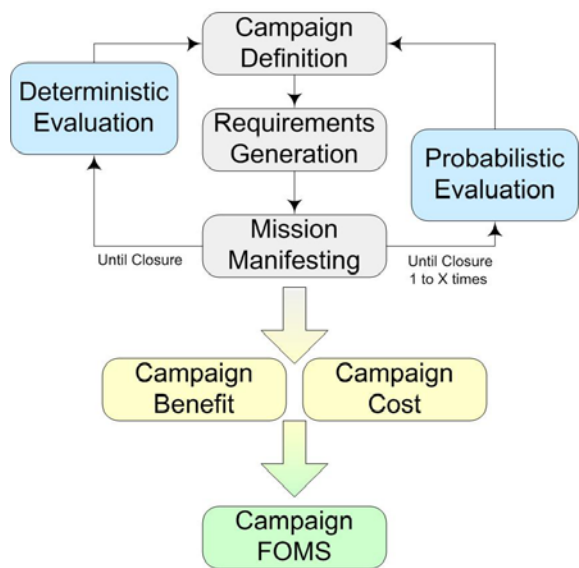


Figure 1: Campaign Analysis Flowchart

'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 'closing' the planned campaign. Parameters such as crew surface durations and the logistics container manifest are modified to achieve a balance between required goods and available mass and volume for logistics allocation.

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

'Campaign Benefit' determines which objectives can be satisfied in the given campaign and then weights by theme to determine an overall benefit.

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

'Campaign FOMS' are high-level Figures of Merit for a given campaign and are calculated based on campaign performance metrics produced by the campaign model.

3. DETERMINISTIC AND PROBABILITY ANALYSIS

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

Deterministic analysis alone allows for an evaluation of only the nominal performance of a lunar campaign. While this is a critical step in the development of the campaign, 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 a campaign. Campaign 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/campaign in a deterministic manner provides an initial assessment of the performance of the campaign, with the performance being largely driven by logistics resupply constraints for campaigns supporting extended lunar outpost crewed operations. Sensitivity analysis and trade studies conducted on candidate campaigns provide insight into the behavior of the nominal campaign 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. Campaigns are defined and analyzed deterministically prior to performing probabilistic assessments.

The deterministic model requires as input a campaign definition. This definition consists, primarily, of the parameters necessary to describe the set of missions that will constitute the campaign, 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 campaign 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. Campaign definition, logistics requirements calculation, and logistics loading are iteratively performed until the campaign is performed satisfactorily.

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

3.2. Probabilistic Analysis

The Campaign Analysis Team (CAT) has developed methodologies and tools to provide probabilistic analysis of lunar campaigns. These probabilistic tools are used to simulate the real-world outcome of campaigns, based upon the probability of occurrence for non-nominal events, the expected consequence and delays associated with those events, and established contingency operations policies. Using this data, the tools simulate a large number of possible campaigns, each a possible instantiation of the actual campaign.

Within each simulated campaign run, the probabilistic campaign analysis tool performs a mission-by-mission temporal simulation. At each mission step, the tool uses the deterministic campaign 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 campaign 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 in the campaign 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 campaign have been simulated, the overall campaign 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 campaign tool repeats this process many times, simulating a large number of possible campaign outcomes and collecting performance data for each. The performance data is then integrated into probabilistic distributions for expected campaign results. These distributions show the likelihood of achieving different levels of campaign performance based on the current reliability, control policies, and uncertainties within the system. The probability distributions can be compared to the nominal campaign performance, as predicted in the deterministic campaign analysis tools, to evaluate the robustness of the given campaign.

Campaigns 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. Campaigns that exhibit a sharp drop-off in expected performance are less robust.

Based on the results of the probabilistic analysis, revised campaigns may be developed to provide additional robustness against adverse events and to optimize contingency planning to better ensure a high level of expected campaign 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 campaign and its associated logistics support necessitate the inclusion of probabilistic analysis when defining a campaign.

4. MACRO-LOGISTICS

Depending on the overall lunar campaign architecture, 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 campaign performance and must be effectively modeled to reliably predict campaign performance.

The logistics model (Andraschko, Merrill, and Earle 2008) that is currently incorporated into the deterministic campaign 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 campaign, 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) model from subject matter experts at Johnson Space Center that takes 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, which 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. Current campaigns use both oxygen ISRU and water scavenging techniques to reduce logistics delivery requirements.

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 heritage Shuttle & ISS heritage and 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.

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 campaign. 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 they 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 campaign.

5. MICRO-LOGISTICS

The bulk of campaign 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 campaign. The local handling of goods at the destination, referred to as “micro-logistics” may also impose severe constraints on campaign 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 gasses 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 campaign 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: food, crew consumables, spares and maintenance items, science equipment and consumables, gasses, and liquids. As part of this tracking, the tool models the operation of the ECLSS, simulating the consumption and conversion of gasses and liquids.

The system dynamics model is run against a specific set of case results from the campaign manifest model. Consumption rates, as well as the goods delivery schedule for a specific campaign 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 CAMPAIGN RESULTS

Over the last decade this campaign analysis methodology has been applied to the Space Shuttle and International Space Station Programs and is now being applied to the development of the baseline Constellation Program lunar architecture. The following sections cover the Figures of Merit used to evaluate lunar architectures, an example campaign and sensitivity analysis, and architectural level observations resulting from the campaign analysis completed to date for the Constellation Program.

6.1. Figures of Merit

Figures of Merit (FOMs) are used to evaluate and compare the relative merits of differing campaign architectures, approaches, and executions. The FOMs should be discrete enough to compare relative value expected to be achieved by closely related campaigns (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 campaign. 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 a campaign 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 campaign 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.

6.2. Example Campaign and Sensitivity Analysis

The primary assumptions established for the example campaign include:

- 2019 start date, 2 missions per year, and 21 missions total (campaign end date of 2030)
- Outpost location at Lunar South Pole
- Emphasis on early outpost buildup
- Maximum crewed duration of 180 days
- Crewed operations only enabled during non-blackout periods given current power system design choices
- 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 campaign consist of the Core Habitat, power systems (PSU), mobility chasses (CMC), pressurized logistics carriers (RPLM & DPLM), ISRU oxygen production system (OPS) & tools, small pressurized rovers (SPR), tri-ATHLETES, and 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 campaign. 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 logistics requirements for the example campaign are shown in Figure 3 on a per mission basis. 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. Due to the constraint of the crew stay on the lunar surface during non eclipse periods, there is unallocated payload on the cargo missions. This additional payload capacity could be utilized to send additional elements, science, or other non-pressurized goods.

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

As spares and maintenance requirements are a significant driver of campaign performance, a sensitivity analysis was performed on the example campaign that explored variations in sparing and maintenance mass requirements. For this analysis, sparing and maintenance mass was varied by $\pm 10\%$, $\pm 25\%$, and $\pm 50\%$. 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. Campaign level analysis when combined with a “bottoms-up” element level assessment is required to yield a more refined spares and maintenance strategy.

6.3. Architectural Level Observations

Two key observations were determined as a result of all the campaigns 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 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 campaign behavior when a cargo lunar lander is available to deliver hardware (verified with crew lunar lander cargo payload performance from 0 t to 8 t). 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 campaign robustness. The second key observation is that logistics are a major campaign driver. The variability in logistics requirements and strategies remain a first order driver to campaign performance.

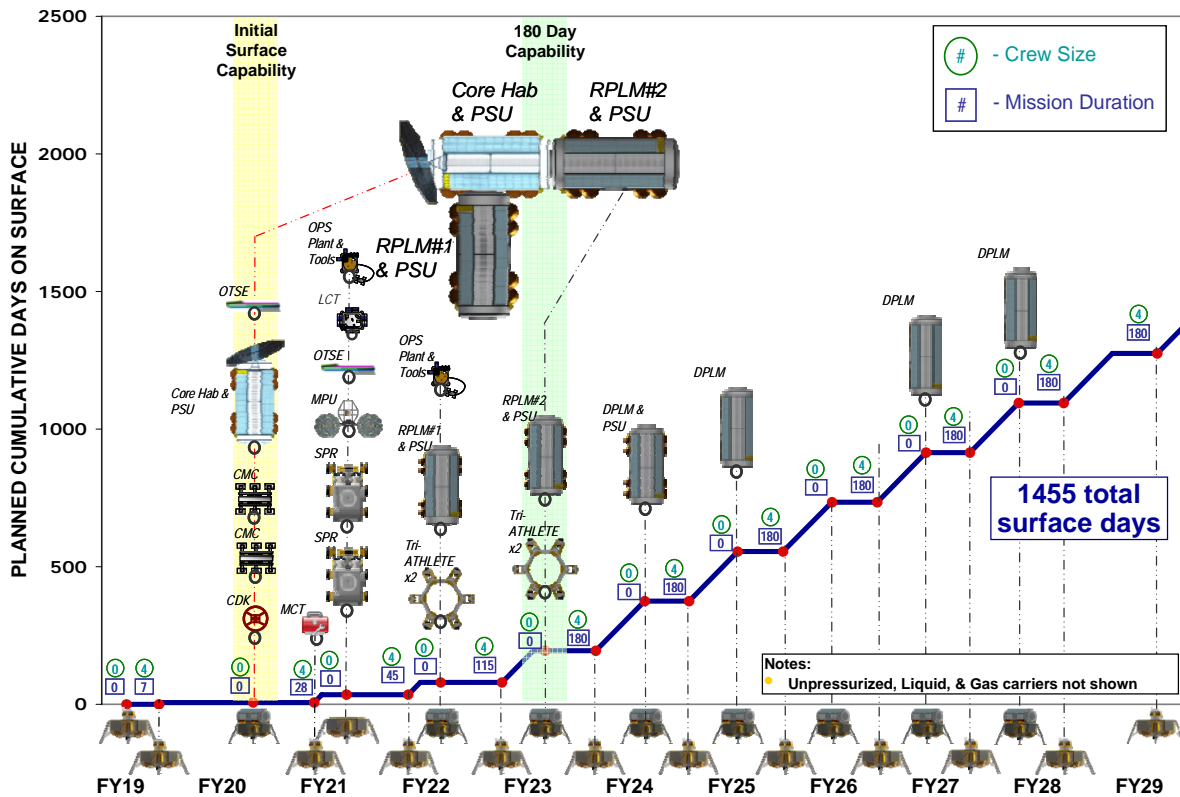


Figure 2: Deterministic Manifest of Example Campaign

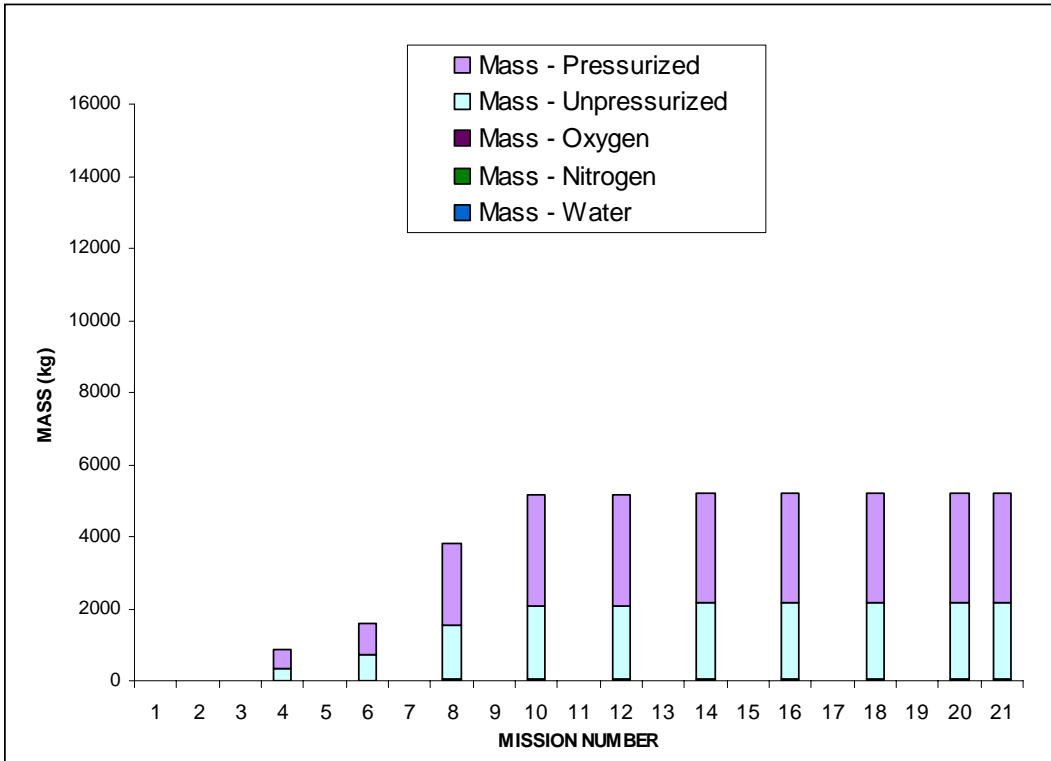


Figure 3: Required Logistics by Mission

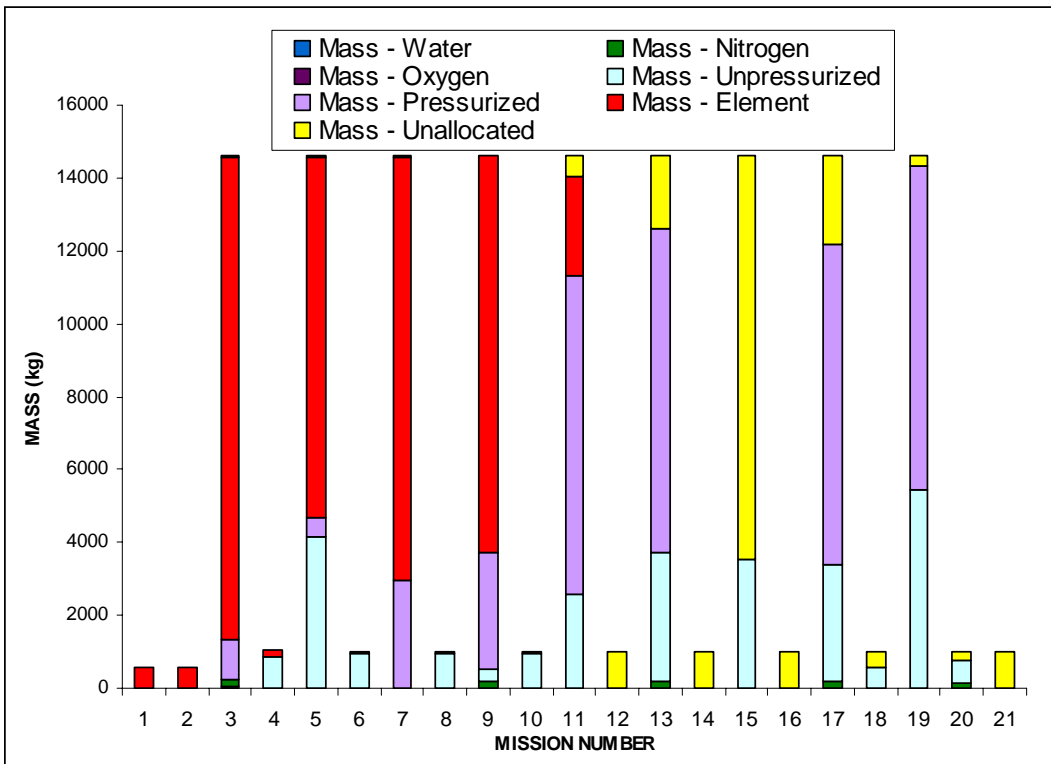
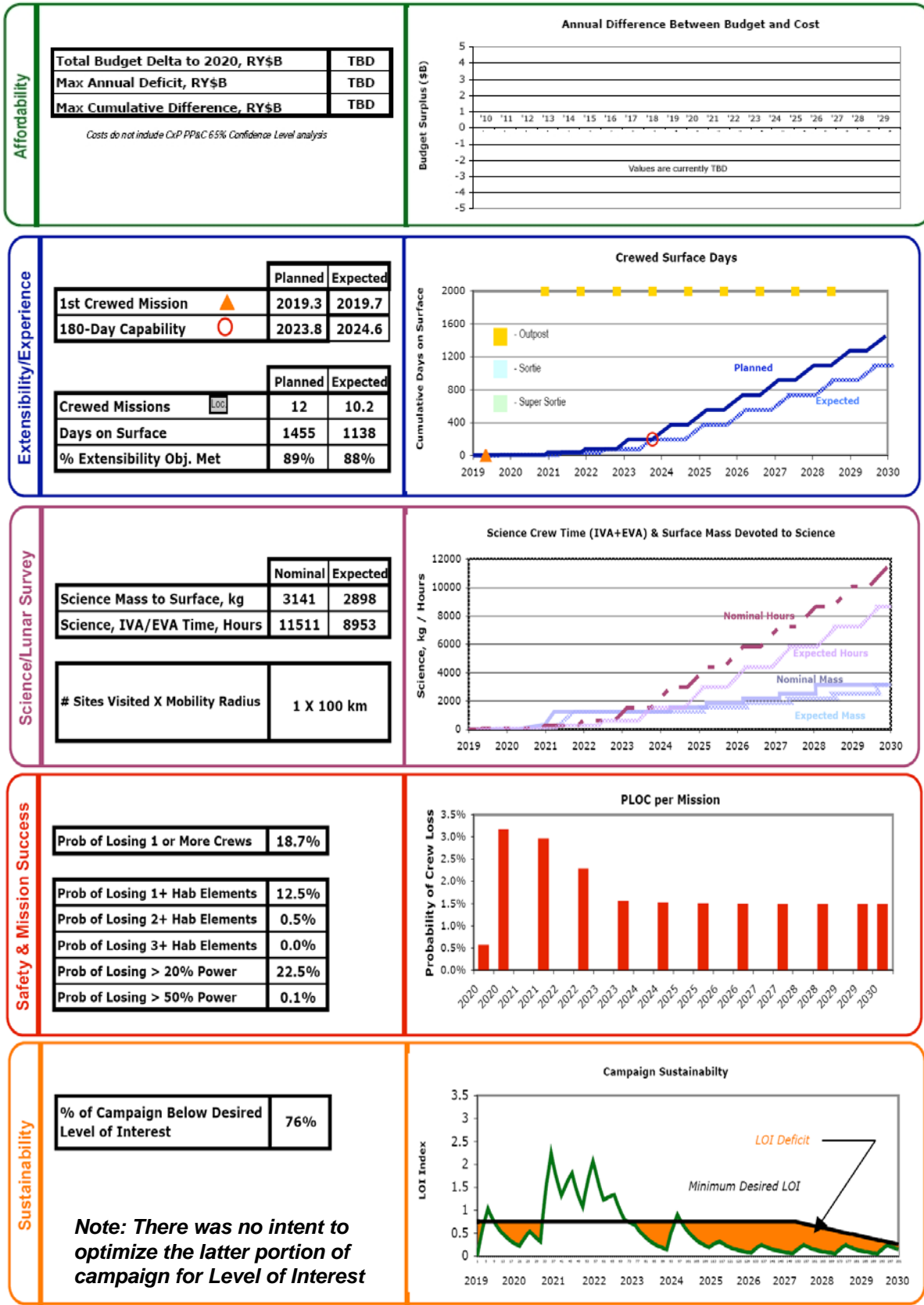


Figure 4: Delivered Mass by Mission



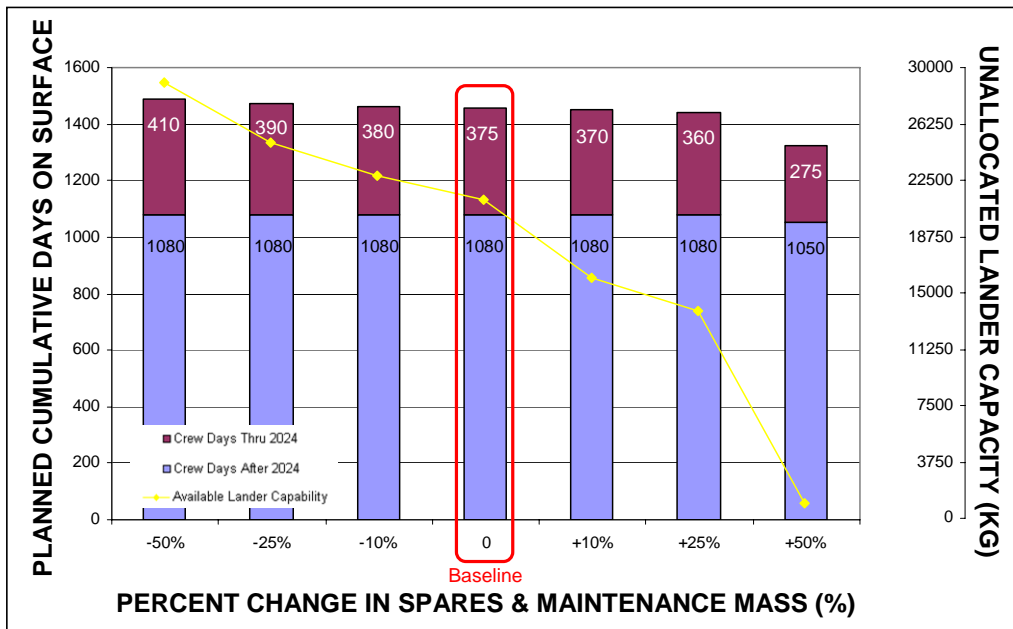


Figure 6: Spares & Maintenance Sensitivity

REFERENCES

- Andraschko, M., Merrill, R. G., Earle, K., 2008. Logistics Modeling for Lunar Campaigns. *Proceedings of AIAA SPACE 2008 Conference & Exposition*. September 9-11, 2008, San Diego, California, USA.
- Cirillo, W., Earle, K., Goodliff, K., Reeves, J.D., Andraschko, M., Merrill, R. G., Stromgren, C., 2008. Campaign Analysis Overview. *Proceedings of AIAA SPACE 2008 Conference & Exposition*. September 9-11, 2008, San Diego, California, USA.
- Cooke, D., 2006. *Exploration Strategy and Architecture*. National Aeronautics and Space Administration. Available from: http://www.nasa.gov/pdf/164310main_2nd_exp_conf_26_ExplorationStrategyArch_IntegratedLAT_CookeVolosinLavoie.pdf [Accessed date April 2008].
- Cooke, D., 2007. *Lunar Architecture Update*. National Aeronautics and Space Administration. Available from: http://www.nasa.gov/pdf/190083main_AIAA_ES_MD_finalSPACE2007.pdf [Accessed date April 2008].
- Exploration Systems Architecture Study -- Final Report, NASA-TM-2005-214062, Section 4, November 2005. Available from: http://www.nasa.gov/mission_pages/constellation/news/ESAS_report.html [Accessed date April 2008]
- Stromgren, C., Andraschko, M., Merrill, R. G., Cirillo, W., Earle, K., Goodliff, K., 2008. A Comparison of Probabilistic and Deterministic Campaign Analysis for Human Space Exploration.

Proceedings of AIAA SPACE 2008 Conference & Exposition. September 9-11, 2008, San Diego, California, USA.

- Stromgren, C., Galan, R., Cirillo, W., 2008. Micro-Logistics. *Proceedings of AIAA SPACE 2008 Conference & Exposition*. September 9-11, 2008, San Diego, California, USA.