Mass-Constrained Availability for Lunar Exploration

Susie Go[a*], Donovan L. Mathias[a], Fraser Thomson[b], and Balachandar Ramamurthy[c]
[a]NASA Ames Research Center, Moffett Field, CA, USA
[b]ELORET Corp., Sunnyvale, CA, USA
[c]Valador, Inc., Palo Alto, CA, USA

Abstract: This paper explores the definition and calculation of availability metrics for an example lunar outpost concept and the study of how different logistical supply capabilities would impact its functionality over time. First, some definitions of outpost availability are introduced to provide a metric that can be used to evaluate functionality. A Monte Carlo simulation model is used to integrate the functions of various lunar surface system elements and run their nominally-scheduled operations in a time-dependent manner. Using the definitions for availability, the impact of system failures can be tracked through time to observe the number of lunar outpost availability days that are actually achieved with respect to the planned outpost days. A series of simulation runs is performed using different mass levels to limit the ability to restore element functionality and, ultimately, the availability of the integrated system of outpost elements. The sensitivity analysis provides a mechanism for understanding how well the space transportation mass delivery capabilities align with the needs of the outpost.

Keywords: Reliability, availability, maintainability, lunar outpost.

1. INTRODUCTION

In 2004, NASA was chartered with the mission to return humans to the moon and enable a long-term lunar outpost capability. The Exploration Systems Architecture Study that followed resulted in the definition of a baseline space transportation system consisting of two vehicles [1]. Subsequently, the Lunar Surface Systems (LSS) Project was created to develop architecture concepts and approaches for establishing a lunar outpost capability. The LSS Project developed a collection of lunar architecture concepts and the accompanying suite of conceptual surface system elements—habitats, mobility units, power units and other critical systems—needed to support various objectives and capabilities.

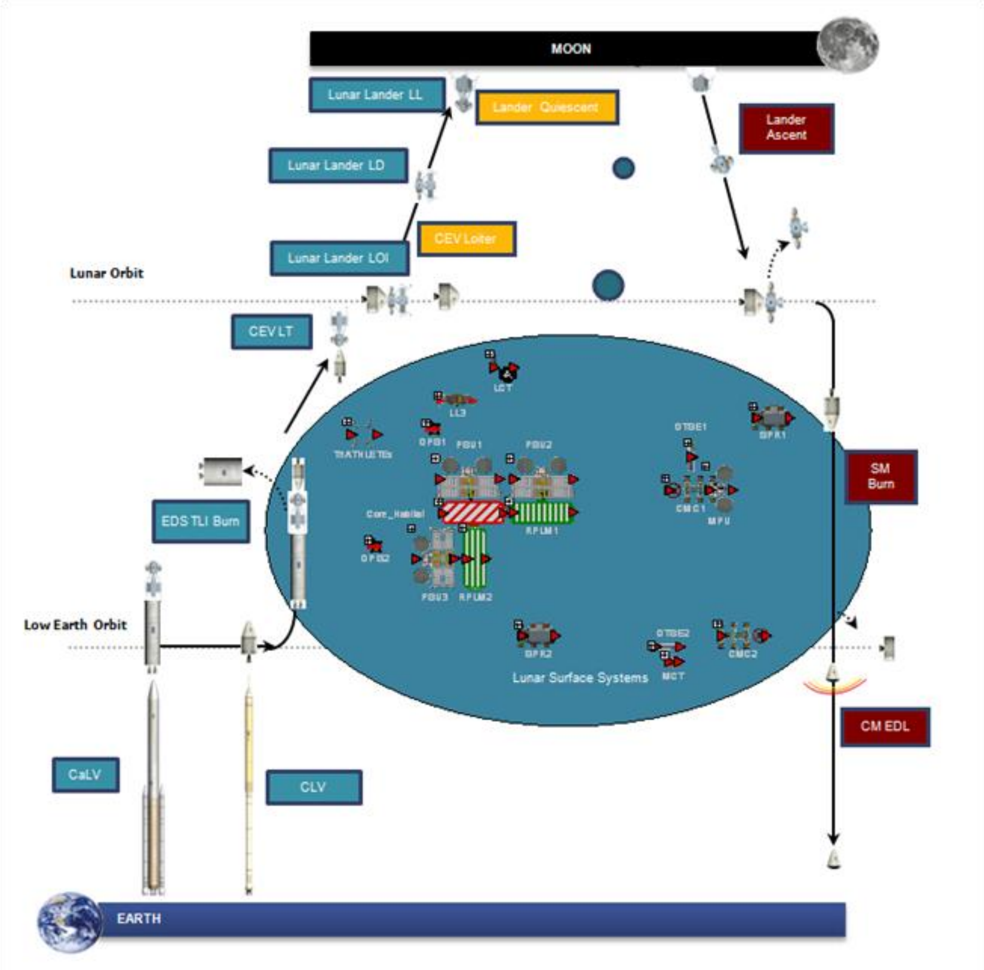
The study of lunar architecture concepts necessarily involves developing an early appreciation of the long-term sustainability characteristics and needs for each of the concepts. The establishment of a functional lunar outpost for long durations requires an understanding of the predominant failure scenarios that are likely to develop over time in order to understand the effectiveness of different long-term management strategies. Like traditional reliability studies, these analyses use failure data as an input. However, risk analyses for complex space launch systems focus on evaluating high reliability, one-shot systems, whereas analyses for long-term outposts must strike a proper balance between guiding the development of high reliability systems and planning for the sustainability of critical functions over the long term. Achieving long-term operations and productivity involves effective management of failures through direct mitigation strategies such as setting redundancy levels and defining contingency plans, and balancing them with operational strategies such as repair and routine maintenance activities for non-catastrophic failures. The latter two activities require the planning and delivery of appropriate logistical supplies that are compatible with the capabilities of the space transportation system. This paper describes a probabilistic approach for studying the first order functional behavior of an integrated lunar outpost.

* Susie.Go@nasa.gov

2. MOTIVATION

Component, element, and system reliability play major roles in the architecture-level design process, but are often studied independently. System reliability for complex systems is especially challenging to model because the definition of system interfaces—where the domain of influence of one element in a system ends and the other element begins—is generally fuzzy and debatable. While treating the reliability of the system elements as independent parts and using them to define element reliability requirements is not a trivial task, using this analysis approach could result in a loss of insight into the major interactive effects between systems and, subsequently, developing a system toward locally acceptable but globally non-optimal solutions. In the case of developing lunar surface systems for an extended lunar outpost capability, a system architecture that satisfies a local optimum in one area with a seemingly small effect in the short term to other critical systems could, in fact, have extremely negative consequences toward achieving long-term operational success or could lead to highly constrained down-stream mitigation strategies, particularly given the additional constraint of operating within the capabilities of a completely separate space transportation system (see Figure 1).

Figure 1: Example Lunar Mission Showing Transportation and Lunar Surface System Elements



Development of lunar outpost reliability requirements fundamentally differs from that of launch vehicles because the outpost system is a repairable system with a long operational lifetime, whereas the launch vehicle is a single-use system with necessarily high reliability requirements and no repair capability. A prerequisite for developing reliability requirements for a lunar outpost capability is to examine the long-term consequences of different repair and maintenance policies by including a thorough understanding of the tradeoffs between different reliability levels with associated repair and maintenance levels. This includes understanding the impact of downtimes for repair and maintenance levels, logistical supply requirements, and how different combinations might affect the overall long-term availability of the outpost. Critical systems with no tolerance for downtime might require higher reliability levels or more backup capability than systems with less strict downtime tolerances. Systems with multiple, alternate backups might have lower reliability requirements. The complement of surface system elements available at any time is also subject to potential transportation delays, however, so modelling the impact of time delays is necessary as well.

3. ANALYSIS APPROACH

In integrated system modelling, the individual elements within the system are coupled with external dependencies on other contributing elements in a time-dependent way. When the inherent reliabilities of the individual elements are added to the model, dynamic simulation can improve understanding of where operational dependencies may lead to non-robust designs.

In typical probabilistic risk analyses for space launch vehicles, the common metrics decision-makers use are the probabilities of loss of crew (LOC) and loss of mission (LOM). The definitions for these figures of merit are straightforward for a single mission with one distinct objective: deliver payload to target orbit. However, assessment of a long-term lunar outpost capability with multiple strategic objectives over multiple missions of varying durations requires measuring end states that are not defined by “fail” or “success” outcomes. Instead, metrics that define achievement of stated goals in non-binary quantities and relay how the outcome varies over time are needed. Additional metrics such as availability, utility, and throughput that are commonly used in planning new system designs should be included early in the design cycle to produce a richer understanding of the impact of various architecture-level design decisions and maintenance policies.

3.1. Lunar Surface Systems Concepts

Many example lunar campaigns were developed by the LSS Team [2,3], and a representative lunar outpost buildup concept spanning 10 years with multiple flights per year, was used in this paper. Each flight, or mission, performs different goals toward establishing a lunar outpost capability and delivers the various supporting hardware elements: some flights are test flights with just a lunar module to deliver crew, some support the construction of a lunar base and carry the required cranes and heavy lifting equipment, while others are exploratory, using a combination of pressurized and unpressurized rovers. The major lunar surface hardware elements were identified and included habitation modules, mobility elements, power distribution and supply elements, communication elements, and construction elements. In the early phases of the campaign, few elements are present on the lunar surface. However, as the outpost is built up, multiple habitation modules, mobility elements, and power suppliers are introduced to the integrated system. Each of these lunar surface elements performs some specialized and some generalized functions. Near the end of the buildup sequence, multiple elements may offer overlapping support toward a particular functional outpost need. Because there are many individual elements involved, the interactions among the elements become a dynamic modeling problem. Multiple element dependencies and complementary functionalities need to be tracked over time to understand how the overall establishment operates and to provide metrics to aid in developing suitable short- and long-term maintenance strategies.

3.2. Availability Metrics

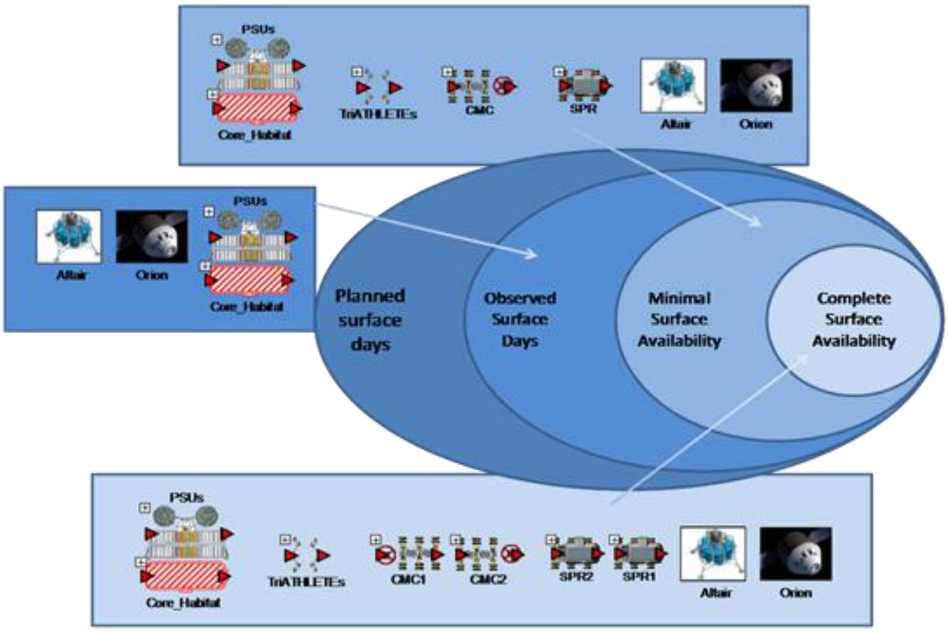
Our studies began with the following definitions of outpost availability to illustrate the potential analysis benefits of tracking these metrics [4,5]:

- **Observed lunar surface days** – the number of crewed days spent on the lunar surface. Early departures occur when a critical system fails, thus observed lunar surface days are a subset of the number of planned days spent on the lunar surface.
- **Minimal outpost availability days** – the number of observed lunar surface days with an operational transportation system and at least one of each major lunar surface element fully operational: at least one habitable volume, one mobility system, and the associated support systems such as power suppliers and communications systems.

• **Complete outpost availability days** – the number of observed lunar surface days with all major lunar surface elements that are delivered to be fully operational.

The diagram in Figure 2 summarizes some of the element-based metrics that were used in our early simulations.

Figure 2: Venn Diagram of Different Availability Metrics and the Surface Systems Required



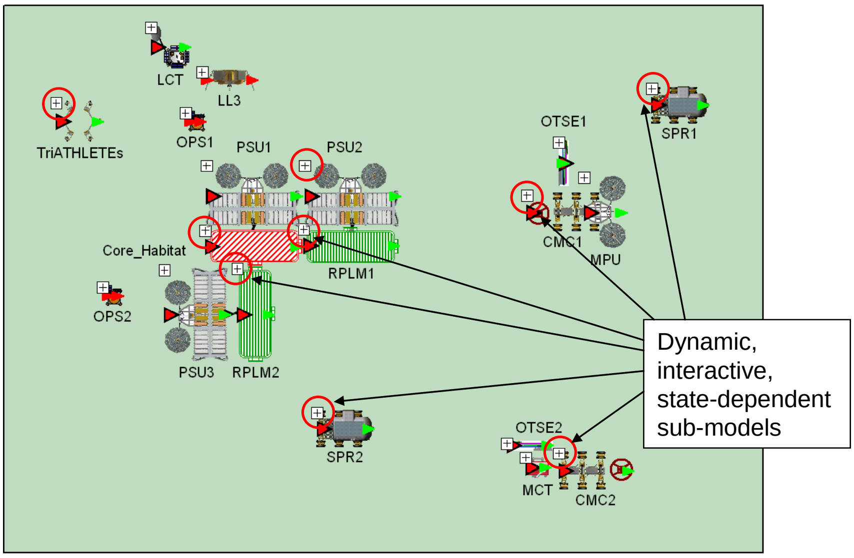
Statistics of the number of accumulated days of outpost system availability are reported instead of a probability of failure to complete 100% of the planned manifest. This approach offers many ways of defining benefit, providing decision-makers with more ways to interpret success. For example, when evaluating the likelihood of successful completion of a 180-day lunar surface stay, a simple, static definition might define the success of such a stay as having 180 days. In this case, a stay that is cut short by 5 days would count as a failure, even though it managed to achieve 175 full days of successful operation. Unless those last 5 days contained mission-critical activities, the utility of such a scenario would generally be considered extremely high. The availability of an outpost with 175 days of service out of 180, however, would be easy to define and would remove the need to define the specific requirements for "mission success" this early into the design process. The availability definitions that we use define outpost levels of availability using different subsets of the active elements that are required for various degrees of operations. The reliabilities of the individual element systems form the basis for these calculations, but the outpost availability definition considers the operability of the collection of elements in the global context of an integrated outpost system.

As more elements are delivered to the lunar surface toward the end of the buildup sequence, the ability to use diverse or multiple surface element backups becomes a dominant characteristic of a campaign. In order to better accommodate the notion of diverse backup lunar surface elements, the definition of availability was eventually extended from the element-based definition described above, to a functional-based definition within each element, and is described in further detail in [6]. In this enhanced definition of availability, each lunar surface element supports one or more high-level functions such as environmental protection, communications, mobility, waste management, storage, or ingress and egress. These functions are mapped to the corresponding hardware components, but not necessarily following the typical subsystem component hierarchy. Defining functional capabilities for each lunar surface element provides a way to express a functional outpost through a pooled collection of individual surface elements, where some elements may have suffered a failure but can still operate in a degraded state and contribute some of its functional capabilities to the outpost system. If multiple elements support a common function and not all of them are required to be operational in order to run the outpost, then a functional failure of an element does not constitute a loss of outpost availability. Using the previous element-based definition for outpost availability, a partial failure of an element would have resulted in the complete loss of that element to support the needs of the outpost.

3.3. Monte Carlo Simulation

We use Monte Carlo simulation to model the dynamic interactions between elements in an integrated system and track functional availabilities of the outpost. The Monte Carlo simulation allows failure-initiated interactions to evolve through simple response rules for specific failure modes by triggering the corresponding off-nominal response sequences in a time- and state-dependent manner. This method relieves the need to explicitly define all unique paths that lead to different end states. These off-nominal paths are uniquely defined by the condition of the system at the time of failure, thereby offering more realistic representations of the failure outcomes. We use a commercial simulation software package, GoldSim [7], which has discrete events superimposed in a time-continuous model, to track the system over time. Each major lunar surface element is defined by a reliability model that contains failure modes specific to that element. The failure modes in the reliability models are used to define fault tree or requirement tree rules for their operational states. In this way, each reliability model tracks its internal state of operation. Reliability models for each of the different lunar surface systems that are delivered are assembled in an overall campaign simulation model. The interactions between any two different surface systems and the necessary functions that each surface system provides to the overall outpost are tracked in the top level campaign simulation model in a time- and state-dependent manner (see Figure 3 below). In the figure below, each icon represents a reliability model for a surface system. The reliability models contain failure modes that are specific to that system and any external dependencies that are required. The top-level campaign model defines the required functions necessary for the outpost and queries the state of the reliability models that support them to determine if these requirements have been met.

Figure 3: Screenshot of Simulation Model Showing Multiple Lunar Surface System Elements



4. AVAILABILITY STUDY AND RESULTS

For a given a collection of lunar surface systems and their expected failure rates, we use the simulation model to look for sweet spots in the ability to maintain various functional outpost states, subject to constraint of the transportation system's ability to deliver the needed components for repair when they are needed. This constraint is currently modelled by a limit on the repair mass delivered per year.

Failures trigger the model to switch from nominal schedule simulation to off-nominal sequences that are dependent on the failure mode. Using the definitions for availability, the impact of system failures can be tracked through time to observe the number of lunar outpost availability days that are actually achieved with respect to the planned outpost days. Failures that trigger a repair or maintenance activity are the focus of this paper. The simulation tracks the required mass to restore functionality based on the component that has failed and assumes a repair success rate and the subsequent downtime expected for servicing, both of which, reduce the functional days of the system over time. In this study, a mean 90% repair success rate and mean 5 day repair downtime were assumed.

4.1. Mass-Constrained Availability Sensitivity Study

A series of simulation runs were performed to study the sensitivity of the outpost concept to different mass levels that further constrain the ability to restore element functionality and, ultimately, availability of the integrated system of outpost elements. The sensitivity analysis provides an understanding of how well the space transportation mass delivery capabilities align with the needs of the outpost. This study provides a mechanism for balancing outpost reliability with its required logistical supply mass, and the regions of feasibility for sustaining a long-term lunar outpost capability that are in line with the capabilities of the space transportation system currently in development.

4.2. Sensitivity Results

Figures 4-6 show how the repair mass limits impact availability of different lunar surface elements. In these charts, “availability” is presented in terms of specific functions that are supplied by the collection of elements. In the example lunar campaign, several pressurized habitation modules are brought to the lunar surface at various stages of the build-up sequence and assembled together to provide a large, stationary base with environmental protection, communications, consumables, storage, waste management, and ingress/egress accessibility functions. Several large, pressurized rovers provide similar functions but with the additional capability of providing mobility. Unless two different functions share a common piece of hardware, the loss of one particular piece of hardware does not affect any of the other functions supplied. Thus, a habitation module may have various degraded levels of functionality when a hardware failure occurs.

The chart in Figure 4 shows the percentage of lunar surface days with available environmental protection functionality from the collection of habitation modules present, as a function of elapsed time. An environmental protection availability day is defined to be any day in which all hardware contributing to environmental protection functionality is operating in at least one habitation module. The sensitivity parameter is maximum annual repair mass (in kg) provided by the transportation system for the outpost, and was run with a range from 0 kg of total repair mass per year to 500 kg of total repair mass per year. In this example, availability of environmental protection occurs intermittently, and for short periods of time in the first half of the campaign. As the campaign progresses, a continuous human presence is established and environmental protection is continuously available.

The level of availability to support an environmental protection capability starts off high, near 100% of observed days, but falls off as component failures occur and are not repaired. The repair mass limits the probability of successfully repairing a failure. A total repair mass limit of 0 kg/yr was run to show the availability days for a campaign without repair. In this case, the percentage of days with environmental protection capability decreases to 10% by the end of the 10 year campaign. The chart shows that a repair mass limit of 50-100 kg/yr yields a small improvement to environmental protection availability by the end of the campaign. However, increasing the repair mass limit from 100 kg/yr to 250 kg/yr provides a large increase in the percentage of days with environmental protection functionality, from 20% to 80% availability by the end of the campaign. Doubling the repair mass limit, from 250 kg/yr to 500 kg/yr, shows that full environmental protection availability can nearly be achieved, though the change is less dramatic, from 80% to 90% availability at the end of the campaign.

Figure 5, below, shows a similar plot for mobility functional availability days provided by the pressurized rovers. Near full mobility availability is achieved with 500 kg of total repair mass/yr. Here too, a large benefit is seen when the repair limit is increased from 100 kg/yr to 250 kg/yr.

Figure 4: Environmental Protection Functional Availability Days, as a Function of Elapsed Time and Maximum Annual Repair Mass

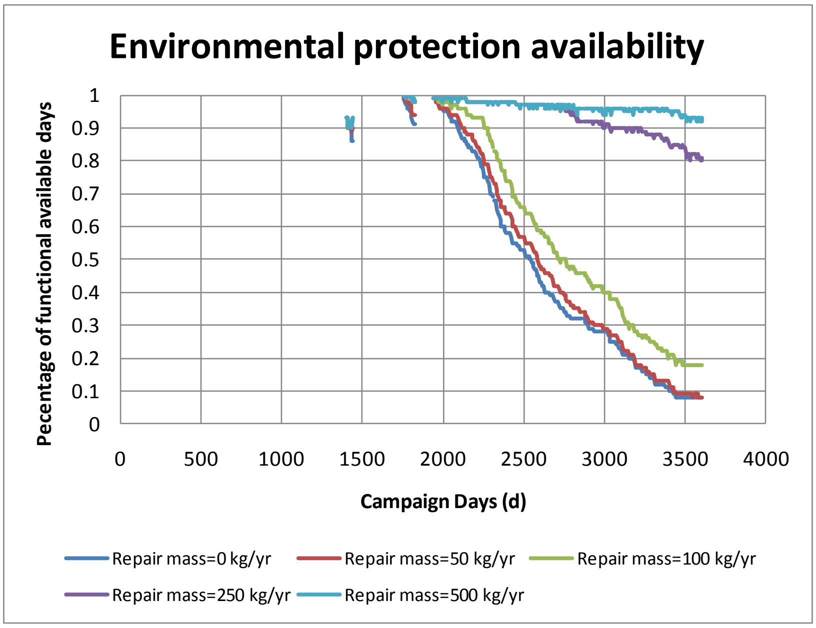


Figure 5: Mobility Functional Availability Days, as a Function of Elapsed Time and Maximum Annual Repair Mass

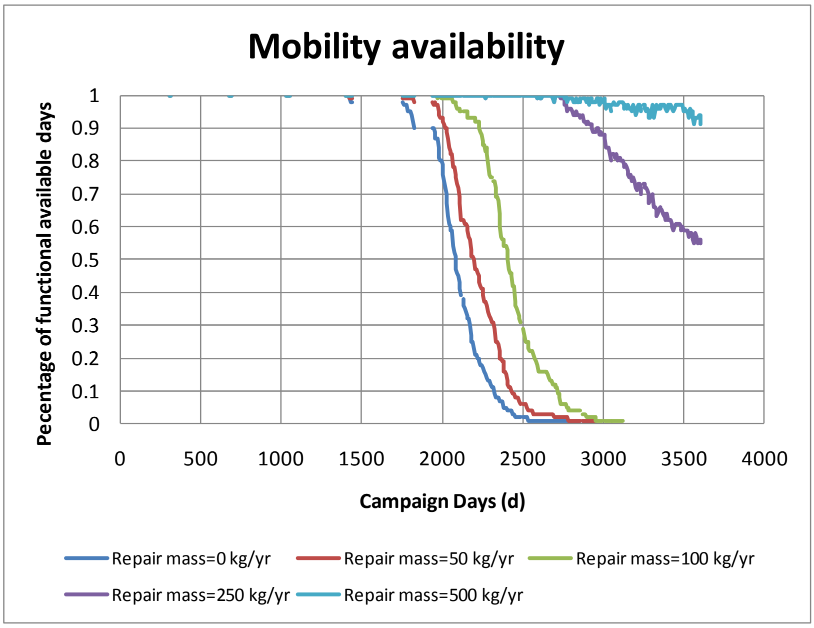
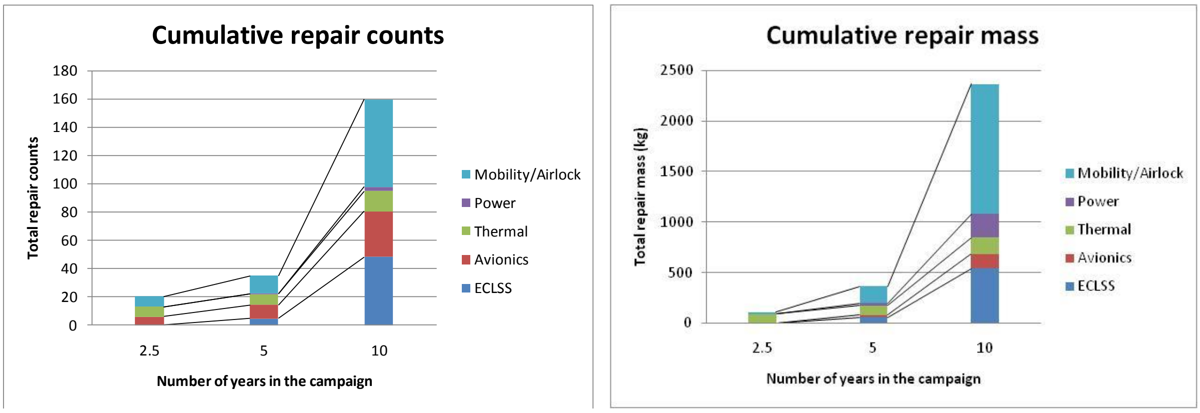


Figure 6 shows the total number of repair activities and repair mass required over different timeframes during the campaign. The mean number of repairs and mean repair mass required are shown at 2.5, 5, and 10 years into the campaign. The repair count metric could be used as a basis to establish an estimate for the number of planned repair activities. A very large number of repairs might motivate the development of more technologies that perform repairs robotically, freeing up crew time and lowering the risk of exposure due to excessive extra-vehicular repair activities. The repair count and mass breakdowns by subsystem are easily captured in the simulation model and show how the allocations vary with timeframe. In this example, the repair mass allocations shift from being weighted toward thermal system components in the early campaign years, to mobility and airlock system components in the later campaign years. This time-dependent tracking provides additional guidance on effectively supplying logistics and resources to the outpost over time.

Figure 6: Total Repair Counts and Repair Mass Breakdowns



5. CONCLUSION

This paper illustrates how new availability metrics can be defined and used to study the long-term behavior of lunar campaign concepts. Because an outpost includes a collection of individual systems with both unique and redundant functional roles, built up and introduced over many years, understanding the dynamics of the collection requires using simulation methods that can track each system's state and their meaning within a larger outpost context. Outpost availability, defined in terms of functional support to an overall outpost system, provides a more accurate representation of the total performance of the outpost over time. These calculations use simulation-based reliability techniques to provide a quantitative basis for establishing logistics requirements that can sustain different levels of operations over time. These approaches and techniques help develop a better understanding of the fluctuating needs of long-term quests such as establishing an extraterrestrial outpost. Future work includes using the Monte Carlo simulation results to show uncertainty levels.

Acknowledgements

The authors thank the NASA Lunar Surface Systems Project and team for supporting and collaborating on this work.

References

[1] Anon., *"NASA's Exploration Systems Architecture Study: Final Report"*, NASA Headquarters, Washington, D.C., NASA/TM-2005-214062, November 2005.
[2] D.D. Mazanek, P.A. Troutman, C.J. Culbert, M.J. Leonard, and G.R. Spexarth, *"Surface Buildup Scenarios and Outpost Architectures for Lunar Exploration,"* IEEE Aerospace Conference, 7-14 March 2009.
[3] K. Goodliff, W. Cirillo, K. Earle, J.D. Reeves, H. Shyface, M. Andraschko, R.G. Merrill, C. Stromgren, and C. Cirillo, *"Lunar Exploration Architecture Level Key Drivers and Sensitivities"*, IEEE Aerospace Conference, 7-14 March 2009.
[4] H. Nejad, S. Go, and D.L. Mathias, *"Risk Assessment Sensitivity Study for Lunar Surface*

Systems," AIAA-2009-6648, AIAA SPACE 2009 Conference & Exposition, Pasadena, California, 14 - 17 Sep 2009.
[5] S. Go, D.L. Mathias, and H. Nejad, *"Integrated Risk Sensitivity Study for Lunar Surface Systems,"* Proceedings of the 56th Annual Reliability & Maintainability Symposium (RAMS), San Jose, CA, 25-28 January 2010.
[6] F. Thomson, D.L. Mathias, S. Go, and H. Nejad, *"Functional Risk Modeling for Lunar Surface Systems,"* to appear in the Proceedings of the 10th International Probabilistic Safety Assessment & Management Conference (PSAM10), Seattle, WA, 7-11 June 2010.
[7] GoldSim Simulation Software, by GoldSim Technology Group, http://www.goldsim.com/.