

Modeling Logistics and Supportability for Crewed Missions Beyond Low Earth Orbit

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NASA's future missions aim to establish a sustained human presence on the lunar surface and send humans to Mars. These missions will send crews farther from home than previous missions, limiting the opportunities for resupply missions. Additionally, the use of multiple launches and reusable elements will increase mission and campaign complexity. Logistics and supportability analysis evaluates the link between mission and system characteristics and key metrics such as logistics and spares mass and volume, crew time, and risk. As missions become increasingly complex and crews are logistically isolated for longer periods of time, logistics and supportability will become more powerful drivers of risk and cost and, therefore, more important considerations during system and mission development. When logistics and supportability are considered from the beginning of system and mission development, opportunities arise to create more efficient, lower-risk systems. Design choices made without detailed consideration of logistics and supportability have the potential to result in greater risks and increased costs as all options may not have been analyzed. This paper provides an overview of a methodology used for space mission logistics and supportability analysis, including key metrics, assumptions, and required inputs. Example applications of this methodology to explore the impacts of system architecture, dormancy, and synergies between lunar and Mars missions are also presented. Conducting these holistic analyses enables informed decision-making for mission planning and system design, which can help mitigate the risk of loss of mission, vehicle, or crew. Using the knowledge of historical missions, experiences gained on the lunar surface, and logistics and supportability analyses, NASA can examine and optimize supportability characteristics for safer and more effective operations for future lunar and Mars missions.

Acronyms & Nomenclature

AIAA	American Institute of Aeronautics and Astronautics
CTB	Cargo Transfer Bag
CTBE	Cargo Transfer Bag Equivalent
ECLSS	Environmental Control and Life Support System
EVA	Extravehicular Activity
ISS	International Space Station
ISM	In-Space Manufacturing
ISRU	In-Situ Resource Utilization
IVA	Intravehicular Activity
LEO	Low Earth Orbit

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LoC	Loss of Crew
LoM	Loss of Mission
LoV	Loss of Vehicle
MADS	Maintenance and Analysis Data Set
MDC	Maintenance Data Collection
MTBF	Mean Time Between Failures
ORU	Orbital Replacement Unit
PART	Problem Analysis Report Tool
PLoC	Probability Loss of Crew
PLoM	Probability Loss of Mission
PLoV	Probability Loss of Vehicle
POS	Probability of Sufficiency
PRA	Probabilistic Risk Assessment
R&R	Remove and Replace
SME	Subject Matter Expert

I. Introduction

All human spaceflight experience has been relatively short or has had regular resupply opportunities. As a result, past missions have had short endurance periods, where endurance is defined as the time that a system must sustain a crew without resupply.^{1,2} Future crewed missions beyond Low Earth Orbit (LEO) will stay in space longer without resupply events or the option for a timely abort in the event of an emergency. A longer endurance can result in a higher probability of failure between resupply events, whereas the inability to abort the mission in an emergency can lead to a higher consequence of failure. NASA's Artemis missions will be longer than historical LEO and lunar missions, but the endurance will be similar to an average International Space Station (ISS) mission.^{1,2} Mars missions, on the other hand, will likely be about 3.8 to 6.5 times longer than any past human spaceflight experience with limited to no resupply opportunities.^{2,3} Current mission planning and system design requires different mental models and conceptual approaches than are used for more deterministic aspects of space systems.⁴ This will allow stakeholders to make to informed decisions as campaigns are developed.

A. Supportability

Supportability is a measure indicating how easily a specific system can be supported within a given context.⁵ Supportability is comprised of a set of characteristics stemming from design and operational decisions made during system and mission development. It is determined by a wide range of system attributes that influence the level of logistical and support resources needed for safe and efficient system operations. Supportability analyses characterize trade-offs between mission metrics and their relationship to system architecture and design choices. Mission metrics include mass, volume, cost, performance, schedule, and risk. Supportability analyses include models that relate system architecture and design choices to those mission metrics. The system and mission design decisions define the supportability of a system. The supportability strategy of a mission is comprised of the following supportability characteristics:

- *Reliability*: the probability that a system will perform its intended function for a given duration under given conditions.⁶⁻⁹
- *Availability*: the percentage of time that a system is operational, considering maintenance downtime.¹⁰
- *Maintainability*: the level of ease to perform maintenance operations and restore a system to an operational state after a failure.^{5,8-11}
- *Resupply Capability*: the frequency and difficulty of providing logistics resupplies.^{1,10}
- *Commonality*: the similarity of spares and maintenance items across multiple systems.¹⁰
- *Redundancy*: The incorporation of multiple copies of a system element (which can be of similar or dissimilar design, as long as they accomplish the same function) in order to mitigate the impact of a failure on system operations.⁸
- *Level of Repair*: the level in the parts hierarchy at which repair actions are executed.^{8,12}

A main goal of supportability analysis is to enable informed decision-making in the early stages of mission and system design. Systems that neglect supportability and logistics during the system architecture and design process may, in application, be significantly and potentially unexpectedly more expensive to operate than systems that consider supportability during those phases of the project lifecycle.¹³

Supportability analyses are conducted to observe the differences in mission metrics from various system architecture and design choices. When supportability is considered, decision makers can confidently make mission plans and system designs as they are aware of the many possible options, how the systems are expected to perform, and the known risks associated with each one.

The remainder of this paper is outlined as follows. Section I.B discusses risk, its relationship with supportability, and how it is accounted for in our analyses. Section II details the methodology and modeling of probabilistic spares, consumable logistics, and maintenance crew time in supportability analyses. Section III describes the impacts of system dormancy and the similarities between lunar and Mars missions in the context of logistics and crew time. Section IV provides insight on how to utilize supportability analysis in the design and planning phase. Lastly, Section V addresses the conclusions of this paper.

B. Risk

Risk is the combination of the probability that an event will occur and the impact that will result if that event does occur. When assessing risk for human spaceflight missions, a Probabilistic Risk Assessment (PRA) is used to estimate the probability associated with a set of outcomes. A PRA is a comprehensive, structured, and logical analysis method aimed at identifying and assessing risks in complex technological systems for the purpose of cost-effectively improving their safety and performance.¹⁴ PRAs primarily focus on, but are not limited to, events such as Loss of Mission (LoM), Loss of Vehicle (LoV), and Loss of Crew (LoC). Probability of Loss of Mission (PLOM), Probability of Loss of Vehicle (PLOV), and Probability of Loss of Crew (PLOC) are the associated probabilities that supply key risk metrics for the mission.¹³ These probabilities are then used to create requirements missions must satisfy, as described in NASA-STD-3001.¹⁵

Uncertainty is a facet of risk and can be included when conducting supportability analyses. Major types of uncertainty, aleatory and epistemic, drive risk associated with supportability. Aleatory uncertainty results from randomness that is inherent to the process being examined. Epistemic uncertainty results from a lack of knowledge about the process being examined. Through experience and testing, epistemic uncertainty can be reduced whereas aleatory is intrinsic and irreducible. Distributions on the values of failure rates or other parameters can be used to account for some of this uncertainty, but there is still the possibility of some unexpected and unpredictable failure. Unknown or unanticipated effects can have significant implications for system supportability and that must be kept in mind during system development.¹³ The role of uncertainty in supportability analysis is addressed further in Section II.

Supportability risk is primarily focused on the allocation of resources such as spares, maintenance items, consumables, and maintenance and repair crew time. It is important to point out that supportability analysis itself does not increase or decrease risk. Supportability analysis aids in characterizing the levels of risk in missions and system options, which is why conducting these analyses is critical. Knowing the risks associated with the mission and system choices will facilitate research to prepare for, or even mitigate, those situations in the mission.

II. Modeling

Supportability modeling aims to produce accurate estimates of mission logistics and crew time. Figure 1 shows the relationship between key supportability inputs, parameters, and metrics. The spares analysis outputs maintenance and spares mass requirements. Consumable logistics analysis estimates the mass and volume requirements of solid goods consumables and gases and liquids. Similar probabilistic assessments of failures produce the scheduled and corrective maintenance crew time requirements. Each of the models characterize a portion of the puzzle, and together they can provide sufficient information to better understand the tradeoff of required resources versus risks associated with the campaign.

A. Logistics Modeling

Logistics models were used to forecast the mass and volumes of over 130 tons of logistics delivered to the ISS from 2017 to 2023.¹⁶ Logistics are the items like food and clothing that are not part of the vehicle or habitat yet are required by the crew to complete the mission.¹⁷ These items are important for the health of the crew and the vehicle and to support mission operations. Logistics may be sub-divided into the following, as defined by Lynch et al.¹⁸

- *Consumables*: Consumables are comprised of all commodities that support the conduct of mission activities, often related to mission crew needs, that are not related to a specific payload or research activity and do not include propellant. In some cases, this category also includes consumables driven by non-crew activities (e.g., air leakage, vestibule re-pressurizations, etc.). Examples of specific consumable items

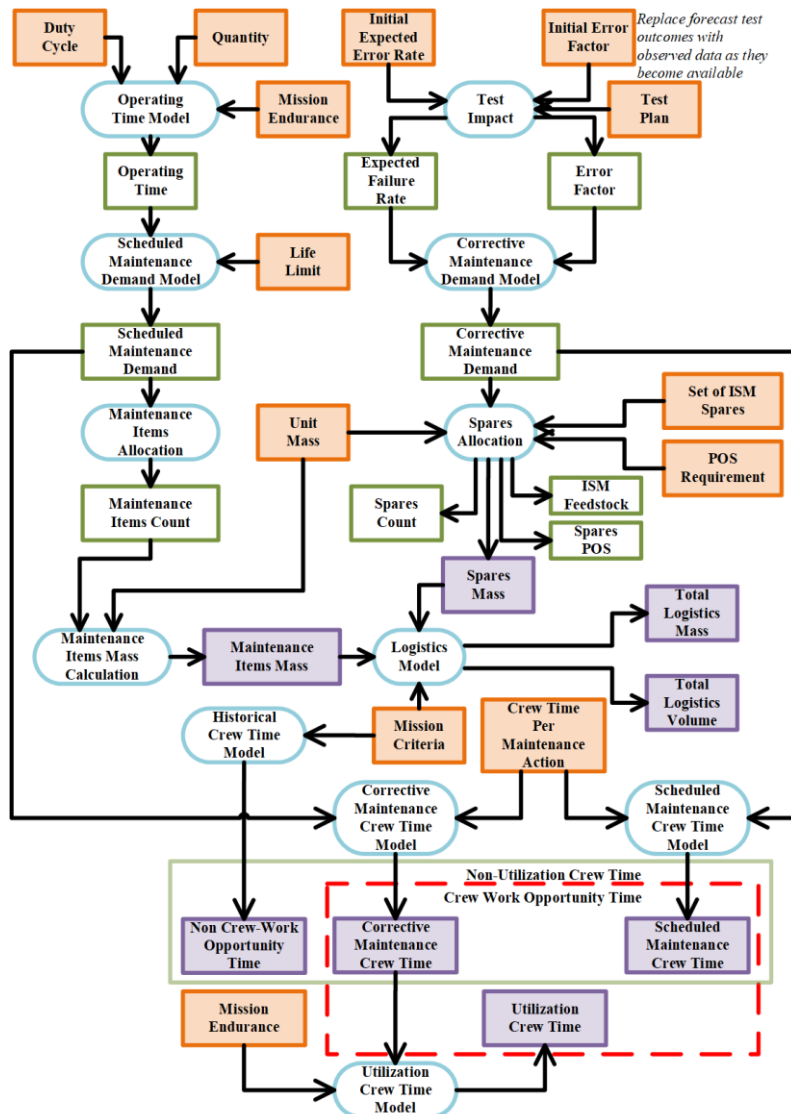


Figure 1. Supportability overview flowchart comprised of all the models (blue) and values (green) from the inputs (orange) to all outputs (purple) and all intermediate steps.

schedule, so key systems are delivered on alternate flights. Outfitting estimates are mission dependent.

- *Packaging:* Packaging refers to the materials required to safely and effectively transport and store each of the logistics items. This may include loose packaging or soft carriers, or pressurized carriers that are delivered to support the mission. This category does not include any spacecraft secondary structures required to house or contain logistics.

Characterization of logistics mass and volume enables informed decisions related to spacecraft mass and volume capacity. To get the logistics mass and volume estimates, supportability analysis employs the use of probabilistic spares analysis and deterministic analysis of consumables.

1. Spares Modeling

Spares analysis is one facet of the broader examination of physical resources within supportability analyses. Spares and maintenance items are required to enable safe and effective operations of the systems for the duration of the mission. Due to limited resupply opportunities, crews must be provided with sufficient spares to account for planned

include food, clothing, personal items, operational supplies, hygiene items, trash and human waste collection containers, towels, extravehicular activity (EVA) consumables, and gases and liquids.

- *Maintenance Items:* Maintenance items refer to all scheduled replacement hardware and associated tools for required replaceable system components that have known limited lifetimes and have a scheduled replacement plan.

- *Spares:* Spares are the components or orbital replacement units (ORUs) that address corrective maintenance for unexpected or unplanned failures of systems' hardware.

- *Utilization:* Utilization supplies are the additional hardware and items (e.g., science, research, capability demonstration, and outreach) that take advantage of the space-based architecture but are not required for vehicle operation. For early mission planning, mass and volume allocations are typically defined rather than specific utilization hardware as the latter is often mission dependent.

- *Outfitting:* Outfitting supplies are subsystem hardware or components that are flown after the initial module delivery for permanent installation or use. As items are identified for outfitting, they are expected to be tracked as part of the integrated logistics plan. Outfitting is often driven by insufficient resources to implement all the desired functions within the initial launch mass or

and unplanned failures to ensure safety throughout the mission. The importance of a detailed spares analysis increases as the opportunity for resupply decreases. This section includes an overview of how spares are modeled.

From a supportability standpoint, spares information is crucial to the story. Spares are influenced by the following supportability characteristics: reliability, availability, commonality, redundancy, and level of repair. Systems with higher reliability tend to last longer between maintenance activities. As for availability, the chance of failure is more likely as duty cycles are increased. Duty cycle is the percentage of time in a day that a system is active.¹⁰ Systems should be designed to be maintainable so that spares can easily be installed when a failure occurs. Commonality of spares is an important factor to consider and relates to the reduction of different types of spares, not necessarily the number of spares. Redundancy is important because it provides a fail-safe in the event of a failure so that the whole system can still function. Level of repair is how small or large a repair needs to be. In other words, level of repair refers to repairing or replacing an entire system versus only a small component within a system. Spares needs are dependent on system architecture and risk acceptance levels and are not based on a standard rate.

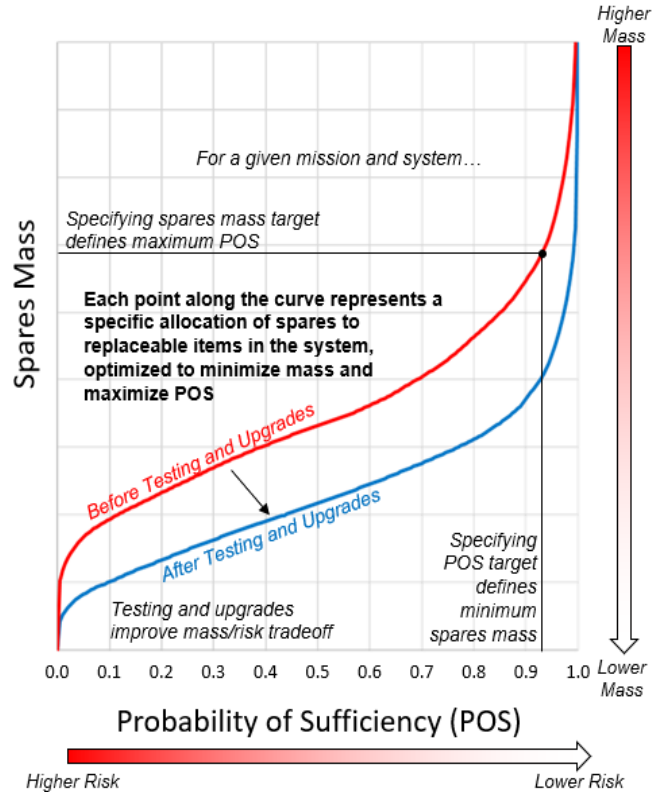


Figure 2. Spares Mass vs POS with the effects of testing and upgrades.

Assumptions must be made to forecast the number of spares and maintenance items required for a mission. The spares model assumes that redundancy is implemented at the ORU level and that failures occur during both crewed and dormant periods. Crewed periods are the periods during which the crew is actively on site. Dormant periods are the periods during which the crew is not actively on site. The duration of each dormant period is the time between crew departure and the arrival of a new crew. Since the returning crew must repair any failures that occur during a dormant period, the model accounts for the spares needed to restore the systems to an operational state. Spares requirements are modeled using ORU data, mission characteristics, and testing conditions. The mission characteristics include crewed and uncrewed durations, as well as crewed and uncrewed Probability of Sufficiency (POS). The ORU specific data include systems, duty cycles, life limits, error factors, and expected failure rates. Error factor is the ratio of the 95th and 50th percentiles of the uncertainty distribution.¹⁰ Finally, a set of planned tests, testing duty cycles, and start and end times are determined for the system.

POS is defined as the probability that the amount of maintenance resources provided for a given mission are sufficient to cover all maintenance demands during a mission and is the key risk metric that determines required spares allocations.^{12,19} The POS of a system is the product of the POS for each ORU associated with that system. Spares allocation optimization can be used to determine the number of spares to provide for each item in order to achieve a desired POS target while minimizing mass. Alternatively, optimization can be used to maximize POS based on a spares mass target. Figure 2 shows the tradeoff between POS, spares mass, and the effects of testing. As spares mass is increased, POS also increases; however, the total mass also increases. As described by Piontek et al., testing is used to reduce uncertainty and reveal previously hidden risks.⁴

Planned replacements are determined using an ORU's operating time and life limit. The data sources for the spares analyses are ISS ORU and maintenance data from NASA studies, the Maintenance and Analysis Data Set (MADS), Maintenance Data Collection (MDC), ISS Problem Analysis Reporting Tool (PART), and subject-matter experts (SMEs). Failure rate estimation is difficult. Historical analysis of ISS data shows that initial failure rate estimates are often inaccurate when compared to observed failure rates.²⁰ Therefore, data from testing and flight experience are critical. Through ORU testing and historical data, failure rates and other parameters are refined. The refined failure

rates are a result of reduced epistemic uncertainty, which is reduced by analyzing historical data. This process is called Bayesian analysis and is described in further detail by Owens et al.^{10,21-22}

Additionally, In-Space Manufacturing (ISM) can reduce spares mass, provide risk coverage, and enable resilient systems that can adapt and mitigate risks associated with unanticipated circumstances.¹⁹ ISM requires less overhead spares mass and volume because feedstock is used instead of the spares themselves. This is because raw materials provided for ISM do not need to be specialized to a specific spare part until a demand is known (“just-in-time” manufacturing).²³⁻²⁸ ISM allows the risk of several different items to be covered by the same raw materials as long as the items can be manufactured from common feedstock.

For supportability analysis, the key input for ISM analysis is the set of spares that can be manufactured on demand from common feedstock. Feedstocks are the raw materials that are used for ISM and can be used for a set of common spares.¹⁹ For each set of items that can be manufactured using common feedstock, the spares model multiplies the corrective maintenance demand of each spare in that set by the mass of that spare. This process converts a distribution of the number of spares required for that item to a distribution of the mass of spares required for that item. All item distributions that can be manufactured from common feedstock are added together to create a single distribution representing the total mass of feedstock required to manufacture spares for those items. If there are multiple sets of items each manufactured using different feedstock, then this process can be repeated multiple times for those distributions. These distributions are analyzed alongside spares demand distributions during the spares optimization process. The outputs of ISM modeling are feedstock mass, feedstock allocation, and feedstock POS. Feedstock mass is the mass of raw material. Feedstock allocation is a distribution of items that common feedstock will be used for. Finally, feedstock POS is the probability that the amount of raw materials are sufficient to cover the spares and maintenance items the feedstock has been allocated to.²³

Feedstock mass can be reduced through In-Situ Resource Utilization (ISRU). Materials recycling could “close the loop” on spare parts and allow the same raw material to be used multiple times, significantly reducing logistics requirements. If ISM capabilities are available, the spares mass and risk can both be reduced further than if only traditional spares are used.²⁹

All of the inputs and assumptions are compiled and processed through the spares model to generate spares and ISM feedstock demand distributions, which are then used to determine the spares and ISM feedstock allocations that achieve a desired POS while minimizing mass. Random failures are modeled as a gamma-Poisson process, and the number of random failures an ORU experiences is represented as a negative binomial distribution based on the estimated failure rate, error factor, and operating time of the ORU.¹⁰ The spares model returns the required spares and ISM feedstock allocations and the redundancy needed for the mission duration. The redundancy is determined for uncrewed periods since the crew is not present to do maintenance. The spares model separates the number of maintenance items that are used for planned maintenance and the total spares used for unplanned maintenance. Supportability analysis of spares provides a clear insight into the spares necessities for a logistics analysis.

2. Consumable Logistics Modeling

Consumable logistics are the commodities that attend to the needs of the crew and support the conduct of mission activities. Consumable logistics are broken into two categories: solid goods and gases and liquids. Solid good consumables are items such as food, clothing, personal items, operational supplies, hygiene items, waste collection, towels, and EVA consumables. Gas and liquid consumables include water, oxygen, and nitrogen. Logistics analysis employs the logistics model which produces the mass and volume allocations for consumable logistics.

To accurately plan for the required consumable logistics, assumptions must be made as mission details are yet to be decided upon. For most consumables, the demand is influenced by the crew size and makeup. Currently, the model operates under the assumption that half of the crew is male, and half is female, with each crewmember being of nominal size.³⁰ Some consumable logistics items are sex specific, such as feminine hygiene being reserved for female crew and electric razors being reserved for male crew. The crewmember metabolic rates used in the model are derived from studies on ISS and Shuttle crew.³¹ Depending on the mission studied, these assumptions are subject to change, and the model has the capability to be updated to reflect those changes. For an accurate mass and volume calculation, module leakage, EVA airlock pressurizations, and gas losses from Environmental Control and Life Support System (ECLSS) operation must be included in this analysis.

The inputs for the logistics model include mission characteristics such as duration and crew size, element characteristics such as internal volume and atmospheric composition, ECLSS architecture, number of EVAs and their respective durations, consumable transfers between mission elements, and crew transfers between mission elements. These inputs are the mission criteria seen in Figure 1. As documented by Lynch et al., the inputs are then able to produce an estimate of the total mass required to sustain the crew for that mission.¹⁸ The values, rates, and assumptions

utilized in logistics analysis have been compiled from a variety of NASA studies, historical data, and SMEs as documented by Lynch et al. and Ewert and Stromgren.^{18,31} The rates are reevaluated regularly as new data and information become available.

There are three different types of functions used for item mass calculations in the logistics model: continuous, discrete, and piecewise. Continuous logistics are consumable masses whose required amount is determined by a continuous rate multiplied by the crew size and mission duration. These types of logistics allocate items assuming the amount needed will be directly proportional to the size of the crew and duration of the mission. Discrete logistics determine consumable item masses by determining demand, in units, and multiplying by the unit mass and a mass growth allowance as defined by AIAA.³² The number of units is calculated with item-specific allocation criteria, mission duration, and crew size. Consumable items that are determined by piecewise functions use specific mass allocations per crew member for a set of mission duration ranges. Gas and liquid demands are calculated on a continuous logistics rate basis while considering the mission characteristics that govern the crew and the ECLSS, as well as their interactions. The total mass of consumable logistics is the sum of every solid good item and gases and liquid. The total logistics mass is the sum of both the spares mass from the spares analysis and the total consumable logistics.

The logistics model also determines the volume of the required mass of solid good consumables. The logistics model assumes that all solid good consumables of the same category have the same density. To simplify tracking the volume of solid goods, analysts use the volume unit of Cargo Transfer Bag Equivalent (CTBE). A CTBE is a unit of volume corresponding to one fully packed Cargo Transfer Bag (CTB). A CTB is a standardized bag used for transferring consumables cargo to the ISS and organizing it on board.¹⁸ To not exceed the mass limit of a CTB, the volumes are calculated with an imposed maximum packing density. The volume for each solid good is the total item mass divided by the item density and the internal volume of a CTB. Gasses and liquids are not handled by the logistics model because they are compressible and have many packaging options. The choice of packaging option is outside of the scope of supportability analysis. The total volume of all consumables is the sum of CTBEs for the solid goods.

When given mission criteria, the logistics model can be used to determine the required consumable logistics. Additionally, the logistics model can be used to determine which combination of fixed and variable inputs will output a total mass or volume requirement below a pre-defined threshold. As described by Piontek et al., inputs to a model are distinct from the model itself and mission logistics can be modeled even if the mission criteria are not fully understood.⁴ When calculating logistics estimates, additional mass margins can be included on the overall estimate to account for missing items and reduce risk from aleatory and epistemic uncertainty.

B. Crew Time Modeling

Crew time is finite, constrained by the mission duration and crew size, and needs to be properly allocated to ensure there is adequate time for the health of the crew, health of spacecraft systems, and completion of mission objectives. In supportability analysis, all the available crew time is allocated to specific operation type categories. The crew operations most critical to supportability risk analysis are utilization and the time available for maintenance and repair. Utilization crew time is the crew time associated with the mission objectives, such as science, research, and outreach activities. The crew work opportunity time refers to the total time available for both utilization activities and maintenance and repair activities. The goal of the crew time model is to take a mission scenario with a defined supportability strategy and output the distribution of crew time among the operation and the corresponding POS. Most crew time is allocated with fixed rates per time in mission or crew time per event. These crew times are relatively constant and constrained by the mission criteria, the type of mission segment (e.g., in-space transit, lunar or Mars surface operations, etc.), crew size, duration, and number of expected events. Outside of these operation types, the crew time allocated for maintenance and repair is probabilistic, depending on the corrective and scheduled maintenance demands. The crew time allocated for utilization is assumed to be the remainder of available crew time after all crew time for fixed operations and the appropriate repair and maintenance time demand is estimated. Crew time spent on maintenance and repair cannot be used for utilization. Therefore, reduction in maintenance crew time enables an increase in crew time available for utilization.

1. Crew Activity Categories

Crew activities are the specific activities performed by the crew during the mission. During a mission, the crew's recorded actions are unique to the mission goals and the exact equipment they use. These describe what the crew members are exactly doing with the specific systems; these raw data are too specific for direct use in supportability analysis. To apply this data to the supportability strategy, these actions are generalized by category. For example, a concise crew action such as cleaning food residue off of the water heater aboard the ISS is recorded as routine

Table 1. Categories of Crew Time.³³

Category	Sub-Category	Activity	Sub-Activity	Operation Type		
Work	Scheduled Operations	Vehicle Ops	Traffic	Standup/Closeout		
				Docking/Undocking		
				Berthing/Unberthing		
						Vehicle Relocation
		Upkeep Ops	Maintenance	Routine Operations		
				Corrective Repair		
				Scheduled Preventative		
				Outfitting		
				Medical		
		EVA		Pre-EVA		
				EVA		
				Post-EVA		
		Logistics		Vehicle Loading/Unloading		
				Routine Logistics Operations		
				Training		
			Exercise			
			Utilization			
	Operations Prep and Conference		Work Prep			
			Public Relations			
			Conference			
		Tag-Ups				
		Personal				
Non-Work		Sleep				
		Meals				

operations. Categorizing crew activities by operation type simplifies historical crew tasking data so that it can be applied to supportability analysis in the early phases of mission development, where the exact systems and mission goals have not been decided. Most categories of crew time are allocated based on defined requirements or historical crew time spent on the similar tasks applied to the new mission profile. The difference in the total crew time available and the discrete crew time allocations is the crew work opportunity time, time left for maintenance and repair actions and utilization. Table 1 shows all operation types with the crew work opportunity time operation types highlighted.

The maintenance time and utilization time compose the crew work opportunity time and are the

only components of the schedule affected by the probabilistic assessment. While EVAs have the potential to be used for maintenance and repair or utilization, no allocation is made for corrective or scheduled maintenance during an EVA. EVA time is explicitly allocated with user inputs for EVA hours and the corresponding time requirements for pre-EVA and post-EVA activities.

2. Non-Crew Work Opportunity Time

The categories not highlighted yellow in Table 1 are the crew time excluded from the crew work opportunity time. These are produced by the historical crew time model based on the mission criteria. These estimates are produced with a daily crew time requirement per crew member or a crew time per action produced by analysis of historical data. To apply these crew time rates to an entire mission scenario, the mission criteria specify the endurance and the number of events resulting in crew actions for crew activities with a rate per action. Some crew time operations occur less frequently than a day-to-day basis but still have a required rate of occurrence, described in detail later in this section.

Crew operations with a requirement of time per crew per day are outlined in the ISS's Safety Requirement Document Space Station Program, including the non-work category, exercise time, and operations prep and conference sub-category time.³⁴ Exercise time is used from this ISS data for in-space segments but altered for surface mission segments. The crew time per crew member per day of the mission is multiplied by the crew size and the mission duration to produce the total amount of crew time allocated for these categories during the mission.

Vehicle operations, logistics, and EVA crew time allocations are produced by assigning a crew time per event and multiplying by the number of events defined in the mission criteria. Vehicle operations activities are only included in in-space missions and not surface missions. Logistics time allocations are included for both in-space and surface missions. EVA times are defined in the mission criteria providing the number of EVAs, their respective duration, and the number of crew members participating. A fixed crew time is associated with both the pre-EVA and post-EVA phases.

Outfitting is the process of bringing systems online after a dormancy period and preparing for a dormancy period before leaving a spacecraft. Outfitting occurs at the beginning and end of each instance of crew ingress and crew egress from an element and is assumed to require a fixed amount of crew time. Medical activities are personal medical conferences that occur at a frequency of every 5 days after the first week and once before and immediately following an EVA.³³

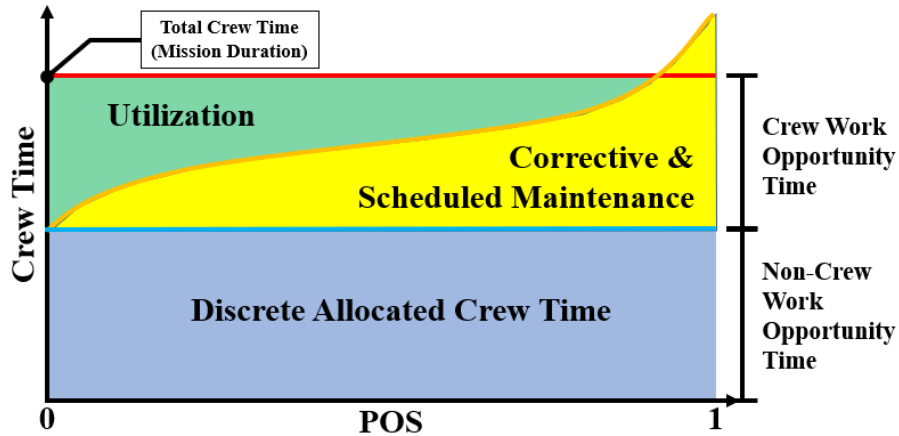


Figure 3. Visualization of the relationship between crew time types and POS.

3. Maintenance and Repair Crew Time

Maintenance and repair activities are both scheduled and unscheduled and include Remove and Replace (R&R) activities and non-R&R activities (e.g., inspecting, cleaning, and troubleshooting) to maintain the spacecraft. The crew time required for R&R and non-R&R activities is determined probabilistically and based on historical data and the maintenance demand described in the spares model in Section II.A.1, which produces the corrective and scheduled maintenance demand as shown in Table 1. The demands are a distribution of the number of maintenance actions during the mission duration and the corresponding probability that the specified number of failures will occur. For each ORU, a maintenance event has a corresponding crew time per maintenance action based on the historical crew time for the ORU type. The results of the maintenance and repair crew time assessment is a distribution of the amount of crew time required for maintenance and repair.

4. Utilization Crew Time

The distribution of maintenance and repair time with corresponding POS is compared to the total work opportunity time available, which is defined as the remainder of crew time available after allocation for the other crew operation types for the mission, as outlined in Section II.B.1. This is shown in Figure 3 where the utilization time decreases as the time for scheduled and corrective maintenance increases. For any part of the distribution where the time required for maintenance and repair is greater than the crew work opportunity time, this indicates the probability that the crew will not have enough time for necessary upkeep of spacecraft systems or responding to critical failures with this supportability strategy, risking LoM, LoV, or LoC. When the crew work opportunity time is larger than the maintenance and repair time, the remaining time is time for utilization. The utilization crew time model constrains the provided distribution of corrective maintenance crew time, per POS, with the mission endurance to produce the amount of crew time available for utilization and the corresponding POS.

III. Dormancy and Mission Considerations

Dormancy presents many challenges and increases epistemic uncertainty due to the unknown state systems will be in upon return. Similarly, lunar and Mars missions present unique supportability challenges due to differing environments and communications delays. These challenges can be better informed through supportability analysis.

A. Dormancy Impacts

Dormancy is a period during which the crew is not present within the vehicle. During dormancy, systems are put into a dormant state with potentially different duty cycles. It is assumed that maintenance and repair actions are not possible during dormancy. Systems in operation can experience failures, which will eventually need to be repaired during a subsequent crewed phase. These supportability needs are accounted for in supportability analysis. Dormancy presents three new operational phases, preparation for dormancy, possible problems during dormancy that might require crew presence, and restoration of operations.³⁵ Supportability analysis is conducted on the dormancy period

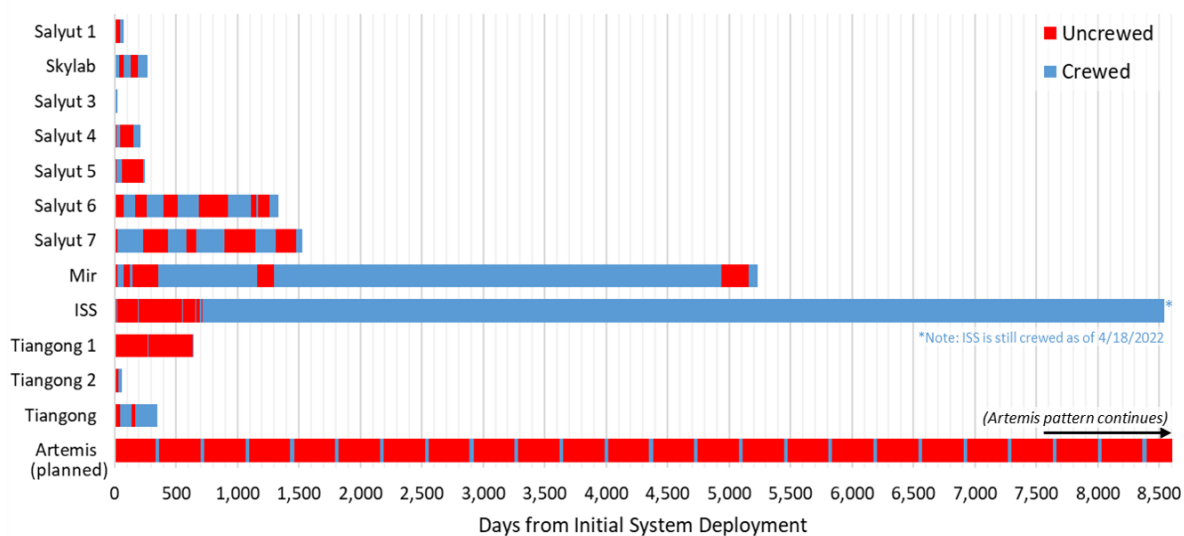


Figure 4. Crewed and uncrewed durations of human spaceflight.²

to better inform what additional logistics and crew time will be required to prepare the systems for dormancy and restore operations.

As shown in Figure 4, previous LEO missions have experienced dormancy, primarily in short bursts of time.² The ISS, for example, had dormant periods during the initial construction. However, the Artemis missions' dormant periods will occur frequently during steady-state operations. Frequent dormancy periods offer challenges in the early phases of mission development. However, frequent dormant periods will refine supportability models for future missions by reducing epistemic uncertainty and potentially identifying unknown unknowns.

Current supportability models assume that any failures that occur during a dormant period are repaired during the next crewed period. The probabilistic nature of failures means there is a chance the failures could require more crew time than available upon crew arrival. Systems that are vital to sustaining the crew can fail during dormancy and require immediate maintenance and repair action to restore the spacecraft systems. If there is not enough time available to restore operations before they are needed to sustain the crew, this could result in LoM. The crew time model only considers maintenance and repair required for the mission duration and not the time required for this urgent maintenance and repair scenario following dormancy. The crew's capability to address all dormancy failures at the beginning of the mission is a risk associated with dormancy. The following are considerations that can be explored with the supportability model to evaluate this specific dormancy risk.

There is a tradeoff between the benefits of keeping a specific system operating during dormancy and the resulting failures expected to occur during those operations. Systems that are not operational during dormancy are assumed to not experience failures during dormancy. This is not to say that there is no risk that a system will fail to turn back on after being turned off for dormancy, but the assumption that systems will not fail when they are not active is the same assumption used in the supportability analysis during the crewed portions.

Redundant systems, or backup systems, do not reduce the rate of failure for a system but reduce the impact of the failures that occur. While some failures may lead to loss of functionality, not all the failures of a redundant system will. After a failure, a redundant system will take over and maintain the systems operations. This reduces risk and acts as a safety net for the systems. The drawbacks of redundancy are that the additional systems add vehicle mass. Through supportability analysis, this tradeoff can be analyzed to determine the level of redundancy best suited for mission objective satisfaction.

B. Similarities and Differences of Lunar and Mars Missions

Lunar and Mars missions will have differences in mission planning and design which will affect the consumables and crew time allocations required and the corresponding risks. This section outlines the effects of the mission duration and similarity of systems on logistics mass requirements. Additionally, challenges posed by the larger communications delay for Mars compared to lunar missions and the changing of mission segments and the resultant effect on the crew time allocations will be examined. Data gained from lunar missions will help reduce epistemic uncertainty for components in subsequent Mars mission supportability analyses. A general overview of the similarities and differences outlined in this section can be seen in Table 2.

A key difference in lunar and Mars missions is the mission duration and endurance. Mars crews are expected to travel for approximately 700 to 1200 days with little resupply and abort opportunities, whereas lunar missions are comparable to historical LEO missions.² The spares demand is much higher on Mars missions because a Mars mission duration is a single long endurance mission, as opposed to a series of short endurance periods like the ISS experiences. Figure 5 shows that the record for spaceflight endurance currently sits at 182 days.³ The larger durances that are required for Mars missions put a heavier emphasis on accurate spares, logistics, and crew time analyses to ensure the health and safety of the crew and systems.

A similarity between lunar and Mars missions is the use of similar spares and maintenance items, as the current ECLSS and other systems can be used for both missions. Similarity of systems and spares between lunar and Mars missions will result in better data for spares analysis due to the historical data provided from lunar and ISS missions. Due to the different conditions faced on the lunar and Martian surfaces, some spares will not be used in both environments. In the case of dissimilar items, new items must be tested to reduce epistemic uncertainty in the spares analysis. Additionally, ISM can reduce overhead mass since spares can be manufactured on demand for both environments.

ORU testing is crucial to better understand the failure rates and life limits affecting spares during a mission, resulting in a more effective spares analysis. Testing enables uncertainty reduction by better understanding how ORUs perform in an in-space, lunar, or Mars environment, which helps reduce spares mass. Additionally, system reliability can be improved by implementing design upgrades to address failure modes identified during testing.

Trash accumulation is a factor that must be considered when analyzing logistics mass. Tracking of trash is important because the mass and volume of trash on board at each point in the mission can affect stowage and propellant requirements. This is not as important for lunar missions as for Mars missions because the distance and endurance of lunar missions are much smaller; however, it is important to consider trash accumulation in a comprehensive supportability analysis. Another difference between lunar and Mars missions is the communications delay that must be accounted for when talking to the ground during maintenance events. Oftentimes, a diagnosis of the problem and a plan of action can take time to formulate on the ISS. The lunar missions have a time delay of about 5 to 14 seconds roundtrip whereas for Mars missions there will be about 22 minutes of delay each way.³⁶ Besides the time delay to get the transmission to the ground or the crew, there will also be a period of discussion on either side. Overall, if this

Table 2. Lunar and Mars Missions Similarities and Differences.

Similarities	Differences
Sparing and Maintenance Items	Communications Delay
Consumable Items	Environmental Factors
Testing	Duration and Endurance
Trash Accumulation	Crew Time Allocations
Systems	Mission Segments
	Resupply and Abort Capabilities
	Spares, Maintenance, and Consumable Item Demands

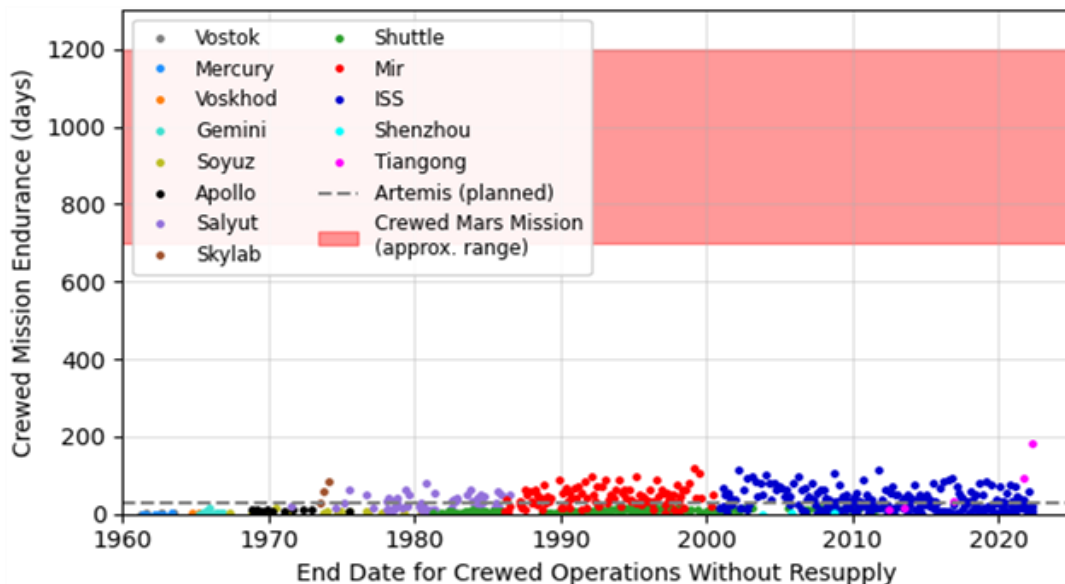


Figure 5. Timeline of human spaceflight mission endurance.²

discussion time takes an average of 15 minutes, then transmissions between the ground and the crew could take up to an hour for two transmissions. This will likely increase the amount of crew time necessary to complete maintenance actions; however, the crew may be able to perform other tasks while waiting for a response.

Mission segments are a driver of the crew time for operation types not in the crew work opportunity types. Lunar missions will have a short in-space transit period whereas Mars missions will have hundreds of days of in-space transit. Requirements for crew health not affected by microgravity, such as sleep and mealtimes, across all phases of lunar and Mars missions are constant. Exercise times across different gravity environments will vary slightly but likely tend to decrease in higher gravity environments, requiring less work to maintain Earth gravity bone density and muscle.³³ EVAs in microgravity historically have been for maintenance and repair of spacecraft systems that are not capable of being serviced with intra-vehicular activity (IVA). Historically during surface operations, the EVA cadence has been maximized to capitalize on the limited surface time. The different mission segments demanding different allocations for these operation types alter the amount of crew work opportunity time available. With the probabilistic distribution of maintenance and repair time being constrained by the crew work opportunity time, these changes to the non-crew work opportunity time will drive the risk associated with the maintenance and repair crew time.

As for future work on these models, the crew time model could account for communication delays and the difference in mission segments. Additionally, the mission segments are analyzed with total allocations distributed over the whole time period and the model does not account for sudden spikes in demand of activities such as EVA, logistics, or outfitting as noted by Lynch et al.¹⁶ Increases in workload for time-sensitive activities make crew not available for critical maintenance and repair. Experience and testing data, however, are crucial to better understanding the similarities and differences faced by crews on the lunar and Mars surfaces.

IV. Designing Systems with Supportability in Mind

Supportability analysis enables informed system design. A thorough supportability analysis can provide mass and volume estimates from the spares analysis and consumables logistics modeling, and crew time allocations for maintenance and utilization activities. With that information, decisions can be made on several design and system options. A spares analysis provides decision makers with the spares mass and volume necessary for a mission depending on the supportability strategy. Logistics mass and volume estimates allow decision makers to determine the size of the pressurized carriers, element stowage capacity and infrastructure, available capacity for utilization and outfitting goods, and the associated costs. Lastly, with results from crew time analysis the distribution of crew time for various tasking categories compared to various POS allows for informed decision making in the selection of the driving mission criteria to select an architecture and mission design that has adequately acceptable projected risk posture. Supportability analysis helps provide an estimate of available utilization time, which can enable preliminary analysis into prioritizing and scheduling mission science objectives through development. The results from logistics planning and crew time analysis both provide valuable insight into the trade-off of resources and risks, facilitating informed decision making as the mission is developed.

Supportability analysis can be combined with other engineering disciplines to iteratively develop and refine system and mission designs. In the beginning of the development process, system requirements should be formulated to reflect the challenges discovered in supportability. Aptly, the probabilistic nature of failures needs to be presented in the requirements to provide an adequate path of requirement validation, discussed further by Piontek et al.⁴ From the initial assessments, supportability strategies can be applied to show their impacts on logistics, crew time, and the overall mission. For example, adding regenerative ECLSS elements to the spacecraft can reduce the consumable logistics but drive up the spares mass and crew time required to maintain those systems. Additionally, it is important to consider the mass of the systems themselves as those can reduce the mass capacity available for utilization logistics. Adding layers of redundancy may reduce those spares but further drive up the systems mass. Incorporating reliable and maintainable systems would reduce the crew time necessary to conduct repairs after dormancy periods and throughout the mission. Further, identifying risks posed by certain systems incorporated into the architecture early on in the mission development allows for research into potential mitigation strategies. Each of these supportability strategies can be combined and incorporated throughout the system architectures to achieve an acceptable level of risk, resources, and objective satisfaction.

V. Conclusion

Supportability analysis provides insight into the tradeoffs of risks and resources associated with a system and architecture design of a mission. Supportability analyses are important to inform decision makers of the impacts of incorporating supportability characteristics as the systems and mission develop. During mission development, the data

gathered from spares, logistics, and crew time analyses facilitate informed decision-making. Supportability analysis alone does not reduce risk, but it can identify risks to facilitate research into mitigation strategies as the mission develops. Knowing the risks early on in mission development enables early investigation into risk mitigation strategies. These analyses can be updated and refined as more information is discovered from other trade studies being conducted. Supportability analysis characterizes the relationship between system design, mission design, risk, and resource requirements, and can help guide system development and mission planning to help achieve human spaceflight objectives beyond LEO.

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