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Supportability Concepts for Crewed Deep Space Exploration

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Supportability—defined as the set of system characteristics that influence the logistics and support required to enable safe and effective operations—will be a much larger driver of mass, risk, and crew time for future human space exploration due to the more challenging mission context. For Mars, systems must operate in a logistically isolated environment for much longer durations than previous missions, which results in a higher probability of system failure and therefore an increased need for maintenance or contingency options. Mars missions also lack access to quick aborts, which increases the consequences of an unrecoverable system failure. Together, this higher likelihood and consequence of failure results in an increase in supportability-related risk. Supportability analysis is an important part of systems development that helps designers better understand the impacts of system and mission decisions on risk, mass, and crew time. The real-world processes that drive maintenance requirements and other supportability-related characteristics are probabilistic, and therefore they require different conceptual approaches and models than are used for more deterministic aspects of space systems. This paper provides an overview of supportability analysis, addresses key concepts, and provides examples of how supportability analysis can be incorporated into system development. Specifically, system supportability involves stochastic processes, and therefore must be evaluated using probabilistic models. These models can be used to perform sensitivity analysis even if system characteristics are not yet fully defined. Failure rates cannot be measured directly, but tests provide valuable data that can help refine those estimates. Human spaceflight architectures are complex, and exhibit coupled behavior that should be examined with integrated systems analysis that includes an assessment of supportability.

Acronyms

CDF = Cumulative Distribution Function
ECLSS = Environmental Control and Life Support Systems
ISS = International Space Station
MTBF = Mean Time Between Failures
ORU = Orbital Replacement Unit
PMF = Probability Mass Function
POS = Probability of Sufficiency
R&R = Remove and Replace

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I. Introduction

Supportability—defined as the set of system characteristics that influence the logistics and support required to enable safe and effective operations of systems[1,2]—will be a much larger driver of mass, risk, and crew time for future human space exploration due to the more challenging mission context. Supportability analysis characterizes the relationship between:

1. system characteristics such as level of repair, failure rates, uncertainties, and unit masses;
2. campaign characteristics such as mission endurance, resupply interval, risk posture, and test plan; and
3. supportability impacts on performance, cost, risk, and schedule.

Future missions to the Moon and Mars will expose crew and systems to environmental conditions such as dust, radiation, and dormancy that have not been as prevalent for past and current operations. Especially for Mars missions, systems must operate in a logistically isolated environment for longer than previous missions[1], which results in higher probability of system and subsystem failure and need for maintenance or contingency options such as abort. Lack of access to quick aborts means that the consequences of an unrecoverable system failure are higher.[3] Together, this higher likelihood and consequence of failure results in higher supportability-related risk. Supportability analysis is an important part of systems analysis and development that helps designers better understand the impacts of system and mission design decisions on risk, mass, and crew time.[4] The real-world processes that drive maintenance requirements and other supportability-related characteristics are probabilistic, and they therefore require different mental models and conceptual approaches than are used for more deterministic aspects of space systems.

Human spaceflight architectures are highly complex and can benefit from supportability analysis throughout the engineering design cycle, and this paper will highlight the major drivers behind supportability analyses and explore common misconceptions surrounding these drivers. This paper provides an overview of supportability analysis, addresses key concepts, and provides examples of how supportability analysis can be incorporated into system development with a case study at the end. The purpose of this paper is to aggregate and organize key concepts related to supportability that should be considered when evaluating spaceflight systems. Specific concepts include:

- Spares mass and crew time for maintenance are probabilistically driven and therefore should be modeled and evaluated in a probabilistic manner.
- Systems can be modeled even if their characteristics are not fully known. Sensitivity analysis can help analysts understand the impact of system characteristics on the integrated spares mass and crew time for maintenance.
- Space systems are complex with coupled interactions and limited resources, and therefore integrated analysis is needed to understand the system.
- Failure rates cannot be measured directly but they can be estimated.
- Testing is valuable regardless of the outcome.

Modeling of these concepts, as well as others, are described by Vega et al.[4]

II. Background

A. Supportability Affects the Relationship Between Risk and Resources

The purpose of supportability analysis is to characterize the relationship between risk and resources during system and mission development, enabling more informed decision-making. At a high level, supportability analysis addresses the uncertainties in mission operations and resource requirements and aims to find a balance between those uncertainties and the resources available. A large area of focus for supportability analysis is the random failures of systems, the associated risk, and the resources needed to repair those systems.

As defined by the NASA Risk Management Handbook, "risk is the potential for shortfalls, which may be realized in the future, with respect to achieving explicitly stated performance commitments. The performance shortfalls may be related to institutional support for mission execution or related to any one or more of the following mission execution domains: safety, technical, cost, schedule.

Risk is characterized as a set of triplets:

a. The scenario(s) leading to degraded performance in one or more performance measures,
b. The likelihood(s) or probability of failing to achieve a particular outcome, of those scenarios,
c. The consequence(s), impact, or severity of the impact on performance that would result if those scenarios were to occur."[5]

Both the number of spares provided for each item and the crew time spent on maintenance affect overall mission risk. There is a risk of not having enough spares or enough crew time. Supportability analysis characterizes the relationship between system characteristics, the number of spares provided for each item, the amount of crew time available for maintenance, and the risk of insufficient spares or maintenance crew time.

Spares and crew time are resources used to address random failures. A failure, in this context, is any event or state of a component that leads to off-nominal operations. Tied to these failures is the crew time spent on maintenance, which is associated with a probability distribution of time the crew may have to spend on maintenance during the mission. For this paper, crew time for maintenance can be divided into two categories: corrective and preventive maintenance. Corrective maintenance is maintenance in response to or in anticipation of a random failure. A random failure is a failure whose timing is not precisely known beforehand. On the other hand, preventive maintenance is maintenance that occurs on a regular schedule. The interval between preventive maintenance actions may be based on the passage of time (e.g., a filter replacement every 30 days) or on a different indicator (e.g., an exercise system cable replacement after 1,000 cycles).

B. Future Human Spaceflight Missions will be More Challenging than Past Experience

For Mars missions, systems must operate in a logistically isolated environment for longer than previous missions. Future missions to the Moon and Mars will expose crew and systems to environmental conditions such as dust, radiation, and dormancy to a much greater extent compared to past and current operations. For supportability analysis, some key elements for defining a mission are the mission duration and the mission endurance. Mission duration is defined as the time between crew launch and crew return. Mission endurance is defined as the amount of time that a system must sustain the crew without resupply,[6] as illustrated by Figure 1.

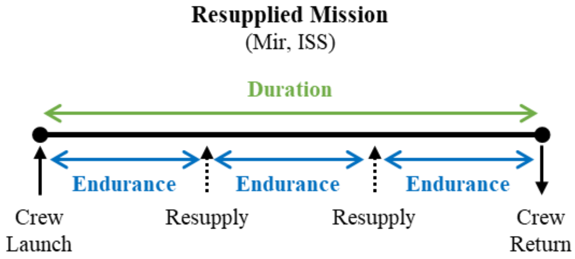

Figure 1. Comparison of mission duration and endurance.

Figure 2 shows a timeline of human spaceflight mission endurance from 1961 to 2022 described by Owens et al.[7] All past human spaceflight missions have had endurances less than 200 days. Meanwhile, the estimated duration of a Mars mission is 700-1,200 days (2-3 years) depending on the trajectory and propulsion system utilized.

It is likely that the mission endurance for a Mars mission is equal to the mission duration for early Mars missions. For a Mars mission there are different methods of ensuring the crew has sufficient supplies for the mission. One option is that all of the supplies needed for a mission are carried for the entire mission. Another is for the crew to rendezvous with another vehicle for supplies. Regardless of whether or not there is resupply, all the planning for what the crew will need has to be done prior to the start of the mission. For current International Space Station (ISS) missions, the planning time horizon is shorter, and with frequent resupply, planning can be reactive. In some cases, if something breaks aboard the ISS, it can be sent down to Earth to be refurbished and then sent back up to the ISS for installation and recovery of the system. For a Mars mission, there will not be an option for reactive resupply.

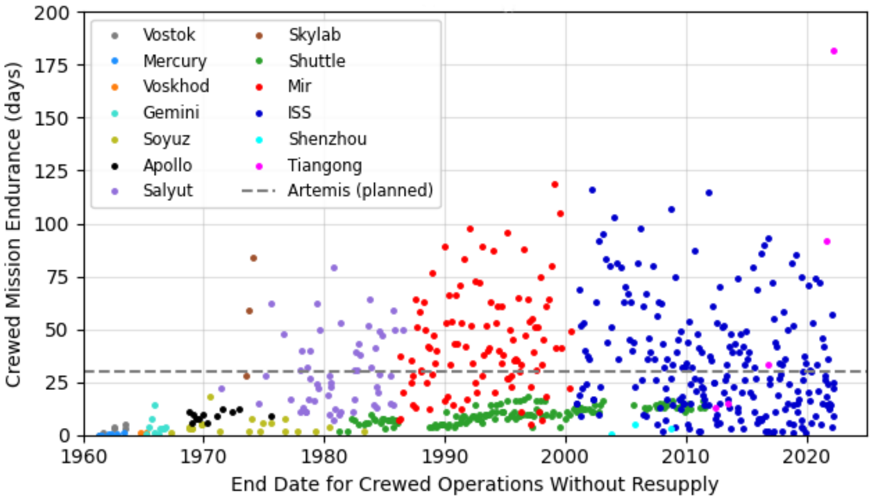

Figure 2. Timeline of human spaceflight mission endurance.

Extended endurance and duration missions result in higher probability of system and subsystem failure due to the extended time the system is operating, which increases the need for maintenance or contingency options such as abort. On the ISS, crew members can abort and return to Earth within hours if needed.

For future lunar missions, abort capabilities are on the order of days to return the crew to Earth. For Mars missions, the time required to abort and return to Earth is on the order of months or years once the crew are more than a week or two past Earth departure.[3] The lack of access to quick aborts for Mars missions means that the consequences of an unrecoverable system failure are higher.

III. Key Concepts for Supportability Analysis

A. Spares Mass and Crew Time for Maintenance are Probabilistically Driven

Risk is driven by uncertainty, which can be understood by probability. Supportability analysis optimizes resources that are driven by probabilistic processes. Understanding what demands are probabilistic compared to deterministic enables better modeling of the associated systems. Some resource demands are effectively deterministic, such as those related to life-limited maintenance items that are replaced on a regular schedule or consumables that are used at a known rate. Other demands, particularly those related to spare parts required to repair random failures, are stochastic.[8]

There are two main types of uncertainty, aleatory and epistemic. Aleatory uncertainty results from randomness that is inherent to the process being examined. Epistemic uncertainty, on the other hand, results from a lack of knowledge about the process being examined.[9] Whereas epistemic uncertainty can be reduced through experience as data are gathered and knowledge of the system is improved, aleatory uncertainty is intrinsic and irreducible.[10] Aleatory uncertainty only changes when the system itself changes via the identification and removal of failure modes. For example, testing a car engine can help to reduce the epistemic uncertainty in the failure rate of that engine by providing data to improve the failure rate estimate, but an upgrade to the engine to remove a failure mode discovered during the test would alter aleatory uncertainty by changing the likelihood of failure.

The likelihood of events can be described via two probability functions, a Probability Mass Function (PMF) and a Cumulative Distribution Function (CDF). As shown in Figure 3, a PMF shows the probability of a specific number of events occurring; for example, a 12% probability that exactly 3 events will occur. A CDF shows the probability of the total amount of events or less occurring. For example, a CDF may show an 80% probability that there will be 3 or less events. Supportability analysis utilizes both functions to describe the likelihood of events occurring during spaceflight. Mission analysts may need to be aware of the likelihood of a specific number of events occurring, via a PMF, or may need to know the likelihood of the maximum number of events when planning and evaluating overall mission risk.

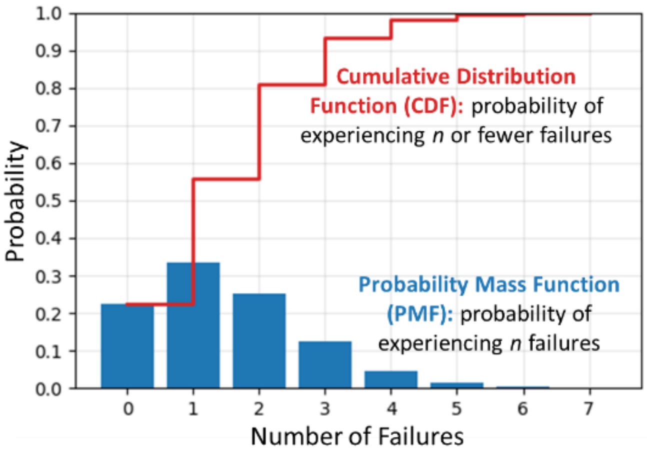

Figure 3. Example Probability Mass Function (PMF) and Cumulative Distribution Function (CDF) for a single component.

It is not possible to precisely predict probabilistic demands. Probabilistic demands referenced in this paper include spares mass demands and crew time spent on maintenance. While it is difficult to precisely predict maintenance events beforehand, analysis can be completed to model certain events as a probability of them occurring. A part of this modeling covers the uncertainties of mass and crew time demands. Supportability is driven by the probabilistic demands of systems. Probabilistic demands occur as a result of random failures. There is no way to know ahead of time precisely which items will fail, when, or how many times. However, failure distributions can be developed to show when failures are likely to occur during a given mission. The failure distribution for an item is estimated based on the total accumulated operating time during the mission and the rate at which failures occur. Items with longer operating times and higher failure rates have a higher likelihood of failure. Based on the failure distribution an expected number of failures can be generated. This does not mean one knows how many failures will occur over the course of a mission. However, probabilistic modeling allows us to understand the relationship between how many spares are taken and the associated risk, called Probability of Sufficiency (POS). POS is the probability that those spares are sufficient for the mission. For critical components, the overall POS for a particular spares allocation is the product of the POS for each individual component, because all critical items are needed for successful operations. The POS for crew time is calculated based on the distribution of the total crew time required for maintenance, which is derived from the sum of crew time demands associated with each ORU.

For example, water demand is deterministic, and the amount of water needed is based on the rate of consumption. For spares there is no way to know exactly how many will be needed because demand is probabilistic. However, the distribution of the number of spares that may be required can be characterized as a function of time. These distributions contain the number of spares that might be needed for the mission for a given probability. Ultimately, probabilistic modeling enables the evaluation of the relationship between resources and risk for better mission planning.

A specific example of why corrective maintenance must be considered probabilistically, rather than deterministically, can be seen when writing requirements for corrective maintenance. Corrective maintenance is stochastic in nature. As a result, goals or requirements relating to corrective maintenance must be expressed in terms of probabilities. Consider the example requirement "the system shall operate for 5 years without corrective maintenance." A system *might* operate for 5 years without corrective maintenance, but due to the stochastic nature of corrective maintenance there is always some probability that the system will require corrective maintenance within 5 years. Without a specified probability threshold, this requirement is unverifiable. Reliability analysis relates duration, probability, and failure rate, enabling verification of the requirement. For example, a probabilistic requirement that can be used to inform system design could be "the probability that the system will require corrective maintenance within the first 5 years of operation shall be less than 0.05." The new verbiage addresses the inherent probabilistic nature of the system and adds a bound on the uncertainty associated with the item's ability to last for 5 years.

B. Systems can be Modeled Even if Their Characteristics are Not Fully Known

A model is a relationship between parameters. The data that serve as inputs to the model are distinct from the model itself. Systems can be modeled even if their characteristics are not fully known. Failure rates cannot be measured directly (see Section III.D), but a model can be used to explore how failure rates affect other characteristics, such as mass and crew time.

Additionally, sensitivity analysis can help mission analysts and system designers better understand systems when dealing with uncertainty. Sensitivity analysis determines how different values of an independent variable affect a particular dependent variable under a given set of assumptions.[11] When considering systems that are still in the conceptual phases, engineering estimates can be used as placeholders and sensitivity analysis can help engineers better understand the impacts of changing a particular parameter. In instances where there is a change to an existing system, the associated epistemic uncertainty is increased since there has been a change to the system. However, past data can be leveraged to form initial estimates of system performance. Initial estimates can then be refined over time as more knowledge is gained about the system. Supportability analysis can evaluate the integrated impacts of that system upgrade by evaluating the total mission spares mass allocation with the reduced mass of an item, but with the increased uncertainty regarding its operations. Sensitivity analysis can be used to evaluate a range of upgrade options and estimate the overall mass savings or growth with the associated change. Sensitivity analysis can also show the point at which further changes would result in diminishing returns so investments can be more targeted.

C. Integrated Analysis is Needed to Understand the System

Spacecraft are complex systems with coupled interactions between subsystems that must operate with limited resources. To best allocate resources, it is necessary to consider space systems in an integrated fashion. To understand how a system will behave, it is useful to understand as much of the integrated system as possible. In supportability analysis, it is important to perform analysis in an integrated manner rather than for isolated components and subsystems.[12] The methodology used to determine a spares allocation for a mission is documented by Owens.[13]

Figure 4 compares the number of spares needed when considering an individual component's risk versus considering the integrated

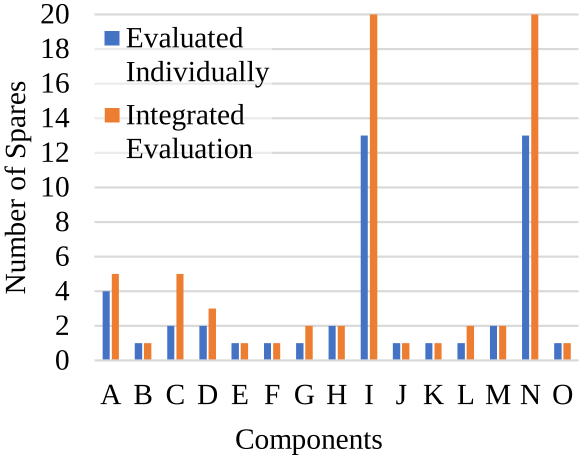

Figure 4. Comparison of spares allocations generated from individual and integrated analyses.

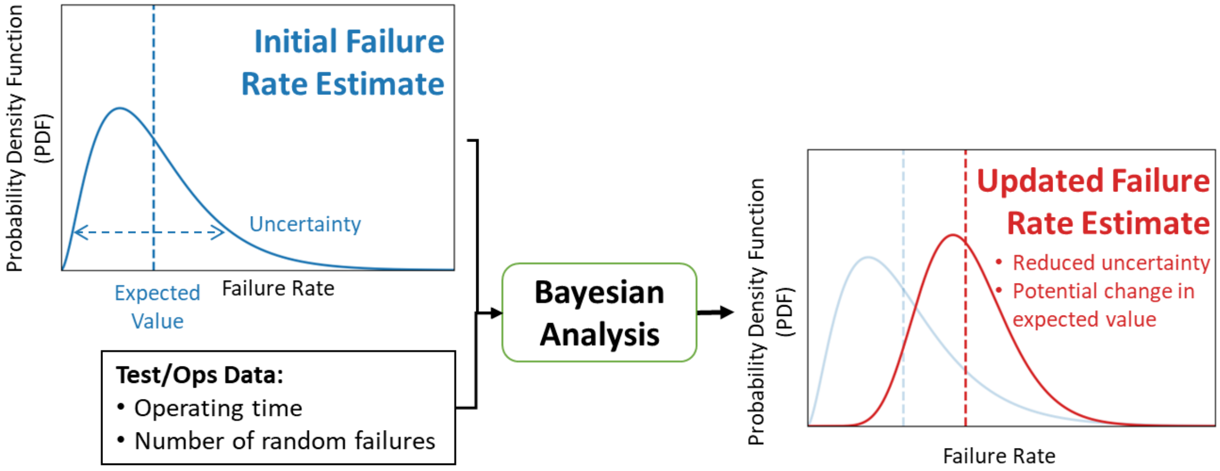

Figure 5. Initial failure rate estimated can be updated with test and operation data to refine the failure rate and reduce uncertainty.

system with a 0.99 Probability of Sufficiency (POS), or a 1-in-100 chance of insufficient spares to complete the mission. To evaluate the risk of an integrated system, the individual component probabilities are multiplied together. Considering components individually can lead to underestimating mission risk due to the cumulative nature of probabilities. Considering components in an integrated manner allows for more accurate predictions of mission risk and the optimization of the mass-risk relationship to enable the lowest mass solution to meet the risk posture.

D. Failure Rates Cannot Be Measured Directly, but Can Be Estimated

Up to this point, this paper has discussed how known maintenance data can be used to predict crew time and mass demands for spaceflight missions. However, some of the input data for supportability analysis are innately probabilistic and therefore require probabilistic analysis to predict. One example of a probabilistic input is a failure rate, which is the key parameter for random failure characterization. The inverse of failure rate is the Mean Time Between Failure (MTBF).

Mean Time Between Failure (MTBF) is the average amount of time that passes in between system failure, but MTBF is not a lifetime. Some systems will fail prior to the MTBF, while others will fail after their MTBF. Furthermore, MTBF is not an indication of exactly when a system will fail but an average of prior data. For example, if a system has a MTBF of 3 years, this does not mean that on exactly the 3-year mark the system will fail.

Failure rates cannot be measured directly. Instead, they must be estimated based on statistical analysis of test and operations data, analogy to existing systems, and subject matter expertise. Assessments that neglect failure rate uncertainty tend to underestimate risk.[14] As shown in Figure 5, data from tests and operations enable verification/refinement of failure rate estimates, which reduces risk of inaccurate spares allocations by correcting over- or underestimated reliability and enables more precise, lower mass spares allocations by reducing uncertainty.

E. Testing is Valuable Regardless of the Outcome

A main approach to reduce the uncertainty in the failure rates of systems is to perform tests. There are two main types of tests, uncertainty reduction and reliability growth. Uncertainty reduction testing focuses on gathering data to improve failure rate estimates and reduce uncertainty without implementing design changes. In contrast, reliability growth testing focuses on identifying failure modes to attempt to remove them via design changes. The outcome of a test cannot be known prior to doing the test. As shown in Table 1, if an initial failure rate estimate is too low, testing can help correct the underestimate and reveal previously hidden risks. On the other hand, if the initial failure rate estimate is too high, testing can help correct the overestimate and reduce spares mass.[15]

Table 1. The value of testing based on initial failure rate estimate accuracy.

Initial Failure Rate Estimate	Value of Testing
Accurate *System is as reliable as anticipated*	• Validate estimate • Reduce uncertainty • Reduce spares mass
Too High *System is more reliable than anticipated*	• Reveal and help correct overestimate • Reduce spares mass
Too Low *System is less reliable than anticipated*	• Reveal and help correct underestimate, mitigating previously hidden risk of insufficient spares • Enable identification and potential removal of failure modes to improve system reliability

IV. Supportability Analysis Inputs and Outputs

Supportability analysis can come in several different forms such as the evaluation of proposed upgrades,[8,15,16] spares and maintenance evaluation,[7,12,17] identification of high value investments,[16] maintenance crew time evaluation,[18,19] and more. To model system supportability, certain data are needed. **Table 2** describes key inputs for supportability analysis, and Table 3 defines key outputs. The next section presents a case study that utilizes the data explained here. For a more detailed explanation of the modeling involved in supportability analysis see Vega et al.[4]

Table 2. Supportability inputs, with definitions.

Input	Definition
System	A collection of software, hardware, or equipment within an element dedicated to performing a function of the element. System breakdowns (subsystems) are required as well as system/subsystem/ORU performance metrics.
Subsystem	A collection of software, hardware, or equipment within a system dedicated to performing a function of the element. Subsystem breakdowns (i.e., the lists of ORUs and components included in the system) are required as well as performance metrics.
ORU	Orbital Replacement Unit: a unique component or a collection of components that may be replaced or repaired during flight. A list of included ORUs/components are required as well as any performance metrics (i.e., processing efficiencies and processing rates).
Unit Mass	The mass of an individual component or ORU.
Unit Quantity	The quantity of an individual component or ORU on flight or mission.
Duty Cycle	The percentage of calendar hours that a system, subsystem, or ORU is operating.
Life Limit	The maximum operating hours that an ORU or component is designed for.
Expected Failure Rate	The expected value of the uncertain failure rate.
Error Factor	The ratio of the 95th and 50th percentiles of the uncertain failure rate distribution.
Crew Time for R&R	All crew time dedicated to a single Remove and Replace (R&R) of an ORU/component that has experienced an unplanned failure.
Crew Time for Non-R&Rs	All crew time dedicated to a single non-R&R activity of an ORU/component that has experienced an unplanned failure.
Non-R&R to R&R Event Ratio	The ratio of non-R&R events to R&R events.
Preventative Maintenance Schedule	Operating or calendar time between scheduled cleanings, inspections, or swaps of components that do not have an associated life limit.
Surface Elements	The amount and descriptions of elements on the surface that are included or associated with the supportability assessment.
Crew Concept of Operations (ConOps)	Crew duration, EVA events and durations, crew schedule in elements, crew transfers, and any other scheduled events for crew during the surface mission.
Uncrewed ConOps	Includes uncrewed duration and system events during uncrewed surface operations.

Table 3. Supportability outputs, with definitions and purpose.

Output	Definition and Purpose
Spares Mass	The required spares mass for given POS and mission endurance. Can be reported for individual ORUs and subsystems or totaled for all ORUs/components.
Corrective Maintenance Crew Time	The required crew time spent on corrective maintenance, which is maintenance following a random failure of an ORU. Corrective maintenance crew time is not a deterministic value, and as a result is typically reported in terms of an expected value and/or specific percentiles of the corrective maintenance crew time distribution. Can be reported for individual ORUs and subsystems or totaled for all ORUs/components.
Preventative Maintenance Crew Time	The required crew time spent on preventative maintenance. Preventative maintenance crew time can be reported for individual ORUs and subsystems or totaled for all ORUs/components.
Logistics Mass and Volume	The total mass and volume of logistics, including spares and maintenance items.

V. Case Study

The following case study will walk through a simplified example for one crew member on a mission to explore the Sahara Desert. As illustrated in Figure 6, the crew member will utilize one car composed of the following replaceable components: 4 wheels, 2 headlights, a radio, an engine, and a windshield. Table 4 shows the example supportability characteristics for spares assessments and crew time assessments. All the characteristics of the mission and the car are for illustrative purposes only. In addition, this illustrative calculation of the probability of failure does not account for epistemic uncertainty.

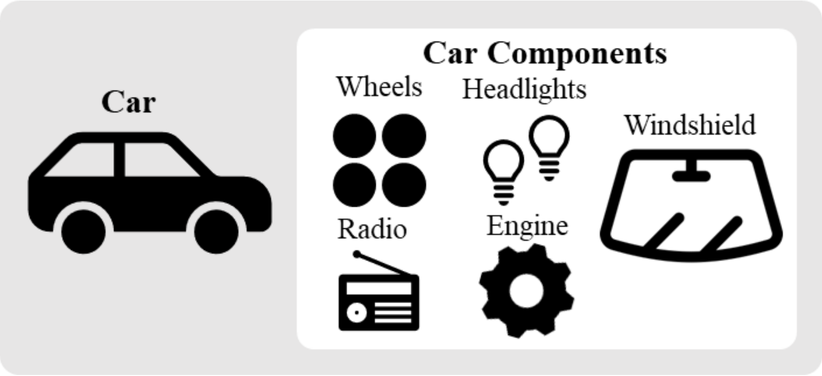

Figure 6. Example car system breakdown.

Understanding the likelihood and consequence of the system risks during a mission is critical for mission planning and system design. When evaluating scenarios, it is a best practice to define the levels of likelihood and consequence. Table 4 shows the probability of experiencing one or more failures in each notional car subsystem. Table 5 categorizes each of these potential failure modes in terms of likelihood and consequence. Engine failure results in a severe consequence because the car would be immobile, unable to transport the driver out of the Sahara Desert. In addition, without the engine, there would be no power to heat and cool the car effectively to keep the crew member safe from the harsh environment, which could lead to loss of crew. On the other hand, radio failure results in a negligible consequence of the loss of entertainment while driving.

Table 4. Example supportability characteristics for spares assessments and crew time assessments.

Subsystem	Quantity	Mass (kg)	Duty Cycle	Expected Failure Rate (1/hours)	Error Factor	Life Limit (hours)	Crew Time for R&R	Crew Time for Non-R&Rs	Non-R&R to R&R Event Ratio
Wheel	4	25	0.33	$1.00\text{x}10^{-4}$	1.0	1,800	2	0.25	5
Headlight	2	5	0.1	$1.00\text{x}10^{-5}$	3.0	-	0.5	0.33	0.5
Radio	1	2	0.33	$9.00\text{x}10^{-5}$	4.0	-	1.5	0.1	2
Windshield	1	13	0.33	$5.00\text{x}10^{-5}$	3.0	-	3	0.5	4
Engine	1	120	0.33	$8.33\text{x}10^{-6}$	2.0	-	7	1	1

Table 5. Likelihood and consequence of risk.

		Consequence →				
		Negligible *may cause slight discomfort but does not limit mission operations and still allows major objectives to be accomplished*	Minor *limits mission operations and still allows major objectives to be accomplished*	Moderate *limits mission operations and still allows major objectives to be accomplished and/or minor injury of crew member*	Significant *limits mission operations and major objectives cannot be accomplished and/or injury of crew member*	Severe *limits mission operations and major objectives cannot be accomplished and/or loss of crew*
Likelihood ↑	Very likely [1x10^{-3},5x10^{-4})	🟩	🟨	🟨	🟥 Wheel fails	🟥
	Likely [5x10^{-4},1x10^{-5})	🟩	🟩 Headlight fails	🟨	🟨	🟥
	Unlikely [1x10^{-5},5x10^{-6})	🟩 Radio fails	🟩	🟨 Windshield fails	🟨	🟨
	Very unlikely <5x10^{-6}	🟩	🟩	🟩	🟩	🟨 Engine fails

For a single component, a PMF and CDF can be generated to show the probability of experiencing a particular number of failures and the probability of experiencing that number or fewer failures, respectively. Individual components' failure distributions can be used in an integrated model to understand the overall risk of system failure and plan spares accordingly.[12] As discussed in section III.C it is important to perform analysis in an integrated manner rather than for isolated components and subsystems.[12] For this example, when comparing the number of spares needed based on an individual component's risk, even if all five components have an individual POS of 0.99, the combined system would have a POS of 0.99^5, which is ~0.95, or a 1-in-20 chance of insufficient spares. That is considerably different than evaluating the integrated system with a total 0.99 Probability of Sufficiency (POS), or a 1-in-100 chance of insufficient spares to complete the mission.

In order to evaluate the spares and maintenance demands to sustain a mission in the Sahara Dessert, the information displayed in Table 4 would be needed, specifically, the system, sub-system, quantity, mass, duty cycle, failure rate, error factor, and any life limits of the replaceable items. Figure 7 shows the total spares and maintenance mass needed to support a mission for a given duration and a set POS of 0.99, or 1-in-100 chance of insufficient spares. Total spares and maintenance mass is composed of the scheduled maintenance mass, which is deterministic based on the life limits of items, and the spares mass, which is probabilistically determined based on the failure rates of the items.

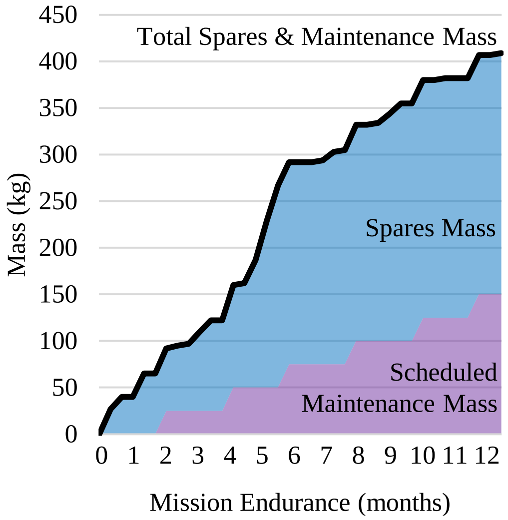

Figure 7. Spares mass for a car as a function of mission endurance for a 0.99 POS.

In addition to evaluating the spares needed to sustain a mission, it is important to understand the crew time associated with the maintenance actions. Specifically, the crew time for R&R, crew time for non-R&Rs, and the non-R&R to R&R event ratio as shown in Table 4. Corrective maintenance crew time is not a deterministic value, and as a result is typically reported in terms of an expected value and/or specific percentiles of the corrective maintenance crew time distribution. Corrective maintenance crew time is based on the distribution of the number of corrective maintenance actions an item will require and the amount of maintenance crew time required per event.

In this example, the crew member needs to sleep for 8 hours each day, eat for 3 hours each day, have 1 hour for personal hygiene and 4 hours of personal time, and will nominally spend the rest of the remaining 8 hours of each day driving. The amount of time needed for the mission to devote to corrective maintenance in a 1-year mission is shown in the CDF in Figure 8. There is a 50% chance the crew will need 5 or less hours to maintain the car throughout the trip. Since this is based on when random failures will occur, the exact day and time the failure will occur cannot be predicted, so it cannot be planned in the same way as the 8 hours of sleep can be. Corrective maintenance is anticipated maintenance, which is recognized as something that may be required during a mission and for which required resources (spares, crew time, tools, etc.) are allocated, but it is not directly incorporated into the mission timeline.

For a year, it is not realistic to drive 8 hours every day since the likelihood of the maintenance time demands is understood. Margin can be incorporated in the schedule to account for the need to respond to random failures. For example, on the days where there are no random failures, the crew member can follow the “ideal” schedule of driving 8 hours a day, but when the random failures occur, there is time left over to be able to make the repair and still achieve mission goals. In addition, preventative maintenance crew time demands can be planned, and the required crew time spent on preventative maintenance is known in advance of the mission. For example, if the wheels on the car need to be rotated every 6 months, this can be planned prior to the start of the mission.

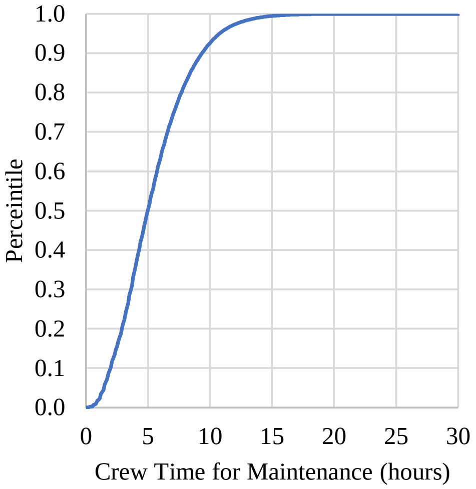

Figure 8. Example CDF of maintenance crew time required for a 1-year mission.

VI. Summary and Conclusions

Human spaceflight architectures are highly complex and can benefit from supportability analysis throughout the engineering design cycle. This paper provides an overview of supportability analysis, addresses key concepts, and provides examples of how supportability analysis can be incorporated into system development with a case study at the end. Key concepts related to supportability that should be considered when evaluating spaceflight systems include:

- Spares mass and crew time for maintenance are probabilistically driven, and therefore they should be modeled and evaluated in a probabilistic manner.
- Systems can be modeled even if their characteristics are not fully known. Sensitivity analysis can help analysts understand the impact of system characteristics on the integrated spares mass and crew time for maintenance.
- Space systems are complex with coupled interactions and limited resources, and therefore integrated analysis is needed to understand the system.
- Failure rates cannot be measured directly, but they can be estimated.
- Testing is valuable regardless of the outcome.

Supportability analysis concepts can be applied to any system or subsystem at any level of available data. The more data available to model an integrated system, the better resources can be allocated. For example, if multiple exploration missions reuse the same systems, the analyses described here could be applied to incorporate the data from each mission, improve failure rates, improve the accuracy and precision of POS estimates, and potentially reduce spares mass requirements. In addition, if items can be replaced at a lower level of maintenance, that could be modeled to show the reduction in mass required to support the system. As with any system, the ability to remove and replace an item is dependent on the crew time available to do so as well as the tools and knowledge to successfully complete the repair. Supportability analysis has been used, for example, to examine Environmental Control and Life Support Systems (ECLSS),[12] future Mars exploration missions,[12] and sustained lunar surface missions.[7,18,19]

Supportability will be a much larger driver of mass, risk, and crew time for future human exploration missions due to the more challenging mission context. Specifically, the new environmental conditions, the logistically isolated environment, and the lack of access to quick aborts results in higher supportability-related risk. Supportability analysis is an important part of systems analysis and system development that helps designers understand risk, mass, and crew time. The real-world processes that drive maintenance requirements and other supportability-related characteristics are probabilistic, and therefore they require different mental models and conceptual approaches than are used for more deterministic aspects of space systems.

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