Supportability Challenges, Metrics, and Key Decisions for Future Human Spaceflight

Andrew C. Owens[1] and Olivier L. de Weck[2]
Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Chel Stromgren[3]
Binera, Inc., Silver Spring, MD, 20910, USA

William Cirillo[4] and Kandyce Goodliff[5]
NASA Langley Research Center, Hampton, VA, 23681, USA

Future crewed missions beyond Low Earth Orbit (LEO) represent a logistical challenge that is unprecedented in human spaceflight. Astronauts will travel farther and stay in space for longer than any previous mission, far from timely abort or resupply from Earth. Under these conditions, supportability – defined as the set of system characteristics that influence the logistics and support required to enable safe and effective operations of systems – will be a much more significant driver of space system lifecycle properties than it has been in the past. This paper presents an overview of supportability for future human spaceflight. The particular challenges of future missions are discussed, with the differences between past, present, and future missions highlighted. The relationship between supportability metrics and mission cost, performance, schedule, and risk is also discussed. A set of proposed strategies for managing supportability is presented – including reliability growth, uncertainty reduction, level of repair, commonality, redundancy, In-Space Manufacturing (ISM) (including the use of material recycling and In-Situ Resource Utilization (ISRU) for spares and maintenance items), reduced complexity, and spares inventory decisions such as the use of predeployed or cached spares – along with a discussion of the potential impacts of each of those strategies. References are provided to various sources that describe these supportability metrics and strategies, as well as associated modeling and optimization techniques, in greater detail. Overall, supportability is an emergent system characteristic and a holistic challenge for future system development. System designers and mission planners must carefully consider and balance the supportability metrics and decisions described in this paper in order to enable safe and effective beyond-LEO human spaceflight.

Nomenclature

AM	Additive Manufacturing
CFR	Constant Failure Rate
ECLSS	Environmental Control and Life Support Systems
EDL	Entry, Descent, and Landing

[1]PhD Candidate and NASA Space Technology Research Fellow, Department of Aeronautics and Astronautics, 77 Massachusetts Ave. Bldg. 33-409 (AIAA Student Member)
[2]Professor of Aeronautics and Astronautics and Engineering Systems, Department of Aeronautics and Astronautics, 77 Massachusetts Ave. Bldg. 33-410 (AIAA Associate Fellow)
[3]Vice President and Chief Scientist, 8455 Colesville Rd. Suite 1075 (AIAA Member)
[4]Senior Researcher, Space Mission Analysis Branch, 1 NASA Drive, MS 462 (non-AIAA Member)
[5]Aerospace Engineer, Space Mission Analysis Branch, 1 NASA Drive, MS 462 (AIAA Senior Member)

EMTT	External Maintenance Task Team
FDM	Fused Deposition Modeling
IMLEO	Initial Mass in Low Earth Orbit
ISM	In-Space Manufacturing
ISRU	In-Situ Resource Utilization
ISS	International Space Station
LEO	Low Earth Orbit
LoC	Loss of Crew
LoM	Loss of Mission
LoV	Loss of Vehicle
LRU	Line Replaceable Unit
MADS	Maintenance and Analysis Data Set
MTBF	Mean Time Betwen Failures
MTTR	Mean Time To Repair
NRC	National Research Council
ORU	Orbital Replacement Unit
P(LoC)	Probability of Loss of Crew
P(LoM)	Probability of Loss of Mission
P(LoV)	Probability of Loss of Vehicle
PACT	Probability and Confidence Tradespace
POS	Probability of Sufficiency
PRA	Probabilistic Risk Assessment
S&MA	Safety and Mission Assurance
SRU	Shop Replaceable Unit
SSF	Space Station Freedom

I. Introduction

Future crewed missions beyond Low Earth Orbit (LEO) represent a logistical challenge that is unprecedented in human spaceflight. Astronauts will travel farther from Earth than ever before, and stay in space for longer without resupply from home or the option of timely abort in the event of an emergency. Under these conditions, supportability will be a much more significant driver of space system lifecycle properties – especially cost and risk – than it has been in the past.[1–8] This paper presents an overview of supportability, including a discussion of the challenges presented by future missions and the relationship of supportability metrics to mission-level cost, performance, schedule, and risk. In addition, the set of decisions that must be made to determine a system's supportability strategy are discussed, along with their potential impacts on supportability metrics and various couplings between them.

A. Supportability

Supportability is a metric describing the ease with which a particular system can be supported in a given context, as a function of a broad set of system characteristics that drive the amount of logistics and support resources required to enable safe and effective system operations.[1,9] Logistics and support resources include physical resources such as spares and consumables, as well as temporal resources such as maintenance crew hours. 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. As a result, supportability is fundamentally a trade between risk and resources. Specifically, a system's supportability defines the minimum amount of resources that must be allocated in order to achieve a desired level of risk mitigation in a given context.

The core challenge of system supportability management is balancing logistics mass, crew time, and risk in order to achieve mission and campaign objectives in a safe and cost-effective manner. Some broad supportability-related considerations include:

- *Reliability:* the probability that an item will perform its intended function for a given period of time, under a given set of operating conditions[1,10–12]
- *Maintainability:* the ease with which a system can be maintained, as a function of the set of system, component, and crew characteristics that allow for or reduce the cost and difficulty of maintenance activities during operations[1,2,9,12]
- *Repairability:*[a] the ease with which components can be repaired by the crew after a failure occurs[1]
- *Redundancy:* the incorporation of additional copies of a given system element in order to mitigate the impact of a failure[1,12]
- *Sparing Philosophy:* the set of decisions regarding the number and type of spare parts carried, including design decisions regarding commonality, level of repair, and other factors that determine the set of repairable items, as well as operational decisions such as spare parts allocations for pre-deployment and/or carry-along[1]

Each of these elements of supportability encompasses a set of interrelated design and operational decisions that must be made – explicitly or implicitly, consciously or unconsciously – during system development and deployment. These decisions, once made, define the supportability of the system.

While each of the characteristics described above – and each underlying decisions driving them – influences system supportability, it is important to note that no individual decision or characteristic fully encapsulates supportability. Supportability is a holistic, emergent characteristic of a system. It does not result from any single subsystem, nor any single system characteristic. Coupled, nonlinear interactions between risk/resource trades associated with all elements of a system drive overall supportability characteristics. Therefore, holistic systems analysis is required to understand the trade between logistics mass, crew time, and risk and assess supportability.

B. Importance of Including Supportability in Early Design and Architecture Decisions

Decisions made early in the development of a system can have a very strong impact on overall system cost. In general, it is estimated that 80% of total system lifecycle cost will be determined (i.e. "locked in") after only approximately 20% of that cost has been spent.[13] Montgomery[14] notes that operational support costs typically account for 60-80% of total program costs. By definition, these costs occur during operations, later in the system lifecycle; however, the decisions that defined these costs – or, more precisely, the cost-risk tradespace available to system operators – were made earlier, during concept development and 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. In addition, supportability issues may not become apparent until after hardware is manufactured and integrated, by which point design changes may be excessively expensive to implement and more complex and/or expensive operations strategies may be the only viable option to mitigate risk. For example, Space Shuttle operations and maintenance activities were made more complex and expensive due to a lack of interchangeability and accessibility for certain components. Partially as a result of those and other supportability lessons learned from the Shuttle program, logistics and supportability was included as a consideration during early International Space Station (ISS) concept development.[14]

One example of the application of supportability analysis during system development is the Space Station Freedom (SSF) External Maintenance Task Team (EMTT) Report, also known as the Fisher-Price study.[15] The EMTT was formed in 1990, when a preliminary analysis of external maintenance crew time demands for SSF (a precursor to the ISS) found that they may exceed planning allocations by an order of magnitude. The team performed an in-depth analysis of the expected number of failures and amount of maintenance crew time that could be expected for SSF, based on estimates of system characteristics. This analysis provided valuable results illustrating the prohibitively high crew time demands that the then-current design would

[a]Sometimes spelled "reparability"

have imposed, and informed a set of recommendations for changes to design and operations planning in order to reduce that demand.[15,16]

The conditions under which future systems will operate (described in greater detail in Section II) are unprecedented in human spaceflight. Astronauts will fly their systems far from home, staying in space for longer than ever before, with limited or no option for timely abort or resupply in the event of an emergency. Under these conditions, it is expected that supportability will be a much more significant driver of crewed space system lifecycle properties than it has been in the past. In addition, strategies that have been effective for past missions may not be as effective, or even feasible, for future missions. It is therefore critical that supportability be carefully considered early in campaign planning and system development for future missions.[1–6]

C. Outline

The remainder of this paper is organized as follows. Section II discusses supportability challenges for future human spaceflight missions, comparing the context of a mission to Mars to past and present human spaceflight experience. Section III describes key supportability metrics and how they influence mission-level cost, performance, schedule, and risk. Section IV discusses proposed strategies to improve supportability for future spaceflight missions and the potential impacts that they might have on the factors described in Section III. Section V discusses other considerations, including data needs for supportability analysis, and Section VI presents conclusions.

II. Future Supportability Challenges

Future human spaceflight missions beyond LEO will be unlike any previous human spaceflight experience. The horizon goal of human spaceflight is to land humans on Mars and return them safely to the Earth.[17] On missions such as this, crews will fly farther from home than ever before, and remain in space for longer. Resupply and abort options will be heavily constrained, if they are available at all. Without resupply options, mission endurance, defined as the amount of time that a system must sustain the crew without resupply,[18] will be significantly increased from that of past missions. When abort options are limited and the crew does not have a way to quickly return to Earth in the event of an emergency, the criticality of various system failure modes increases. The combination of these factors – long endurance missions without timely options for abort or resupply – creates an unprecedented supportability challenge for future missions. Strategies that have supported human spaceflight operations in LEO and on short trips to the Moon will not be effective for future missions to Mars or other beyond-LEO destinations. New approaches to supportability will need to be developed.[1–8]

The longest crewed mission beyond LEO to date – and the most recent instance of beyond-LEO human spaceflight – is Apollo 17, which lasted approximately 12.5 days in December 1972.[19] The longest Space Shuttle mission occurred at the end of 1996, when STS-80 spent over 17 days in LEO.[20] In both cases, there was no resupply during the mission. As a result, the mission endurance is equal to the duration. However, when resupply is used, endurance can be much shorter than duration; the overall long-endurance mission is broken up into a series of short-endurance segments. This is the case, for example, on the current state-of-the-art in long-duration human spaceflight, the ISS, which has sustained a continuous human presence in LEO for nearly 17 years, since November 2, 2000.[21] However, this exceptionally long mission duration has been supported by regular resupply missions that occur approximately every three months. As a result, station mission endurance is approximately 90 days. In addition, in all of these cases (Apollo, Shuttle, ISS, and all other previous human spaceflight programs) the crew had the ability to abort and return to Earth in a matter of days, if not hours.

In contrast, a Mars transit habitat must be able to support a crew in deep space – without resupply or timely abort – for 1,000 to 1,200 days.[22,23] While a 1,200 day mission is only approximately one fifth of the total ISS crewed mission duration to date, it is over 13.3 times longer than ISS endurance, and 96 times longer than Apollo 17. In short, the mission endurance required for Mars systems is an order of magnitude greater than that of LEO missions, and nearly two orders of magnitude greater than the longest period of time that any crew has ever spent beyond LEO.

The distinction between duration and endurance is important because endurance defines the planning time horizon for logistics. Many resource demands are driven by stochastic processes, and longer planning

Table 2. **Summary of supportability metrics and corresponding mission-level metrics.**

Mission-Level Metric	Supportability Metric
Cost	Logistics Mass
	Logistics Volume
	Logistics Procurement Costs
	Extent of Redesign for Maintainability
	Investment in Reliability Growth
	Investment in Uncertainty Reduction
Performance	Crew Time Required for Maintenance and Repair
Schedule	Test Time for Reliability Growth
	Test Time for Uncertainty Reduction
	Required Number of Launches
Risk	Probability of Sufficient Spares Maintenance Materials
	Probability of Sufficient Crew Time for Maintenance and Repair
	Probability of Crew Maintenance and Repair Time Saturation
	Confidence in Probability Assessments, Given Epistemic Uncertainty

time horizons result in greater uncertainty. As a result, more resources must be allocated on a long-endurance mission in order to mitigate risk than would be required for a mission of an equivalent duration broken up into segments of shorter endurance. On a long-duration, short-endurance mission such as the ISS, resupply can be used to replenish stores of spare parts and consumables as they are used, reducing uncertainty. This reduces logistics requirements, since a relatively small buffer of on-orbit spares can be used to cover potential failures in the short term, with new ones supplied from the ground as needed. In contrast, a long-endurance system must carry all spares to cover potential failures across a much longer time period. While the overall number of failures that will actually be experienced may be low, there is no way to know beforehand which items will fail, and how many times. For example, it is estimated that more than 95% of spares allocated to cover random failures on the ISS will not be used. However, a large number of spares must be carried for risk mitigation since it is unknown which specific ones will be needed.[1]

Endurance is also the key factor when considering the criticality of different failure modes. In LEO, the availability of rapid abort and resupply options means that the crew are well-protected in the event of an emergency. While a failure event that forces an abort may result in Loss of Mission (LoM), only a subset of potential failures – specifically, those with a short time to critical impact after failure, such as a loss of pressure event – are likely to result in Loss of Crew (LoC) in LEO. On long-endurance missions with limited abort capability, a much larger set of potential failures directly threaten crew survival, due to the lack of this contingency option. Under these circumstances, the ability of the crew to maintain spacecraft systems, and therefore the supportability of the system, will be much more critical.[1,3]

III. Supportability Metrics and Mission-Level Impacts

The purpose of supportability analysis, as with all other system architecture and design disciplines, is to support the creation of effective systems. Specifically, analysis efforts characterize tradeoffs between cost, performance, schedule, and risk – and, perhaps more importantly, how those metrics relate to architecture and design choices – in order to inform decision-making during system and mission development. Supportability influences overall mission cost, performance, schedule, and risk in several ways. This section outlines a set of key supportability metrics, summarized in Table 2, that influence mission-level metrics. The relationship between each supportability metric and its associated mission metric is also briefly described. This list should not be taken as an exhaustive enumeration of all system- and mission-level impacts of supportability, nor of all supportability metrics that may be valuable to track during system development; however, it may provide a good starting point and overview for supportability analysis planning.

It is important to note that in this discussion each supportability impact is examined independently.

This is effectively an "all else being equal" assessment of the effects of that specific factor. In practice, a change in one element that would have a particular impact on a mission-level metric could (and often would) be mitigated through a change in some other aspect of the mission. For example, though an increase in logistics requirements could affect mission schedules by requiring additional launches – which at a limited launch cadence would require an extended launch timeline – this effect could be mitigated by increasing the launch cadence, or accepting higher levels of risk to reduce logistics loads. However, all of these potential mitigations have impacts on other metrics. All of these factors are coupled in some way, and a change in any one of them typically has impacts that can ripple through an entire mission. However, for the purposes of understanding the impacts of each of these supportability metrics at a high level, each is considered in isolation.

A. Cost

One of the most direct impacts of supportability on cost comes in the form of logistics requirements. Supportability resources include consumables, spare parts, and other maintenance items. In this context, "maintenance items" refers to items with limited lifetime that are replaced on a regular schedule. "Spares," on the other hand, refers to items that are used to fill demands resulting from random failures.[22] Similarly, the activity associated with the use of a maintenance item is referred to as "maintenance," and "repair" refers to the use of a spare part after a random failure. The supportability characteristics of the system determine the amount of logistics that must be supplied in order to mitigate risk to a given level. Increased logistics requirements imply increased total mass and volume, as well as an increased infrastructure cost related to packaging, storing, and transporting these logistics items. As a result, supportability directly impacts launch costs.

Mass is a commonly-used proxy metric for cost in space mission development, due to the high cost associated with launch to and transportation in space.[24] Initial Mass in Low Earth Orbit (IMLEO) is typically used as a metric which captures the total mass that must be launched to LEO for a given mission, including not only logistics and equipment but also the fuel required to perform necessary maneuvers over the course of the mission, as well as infrastructure costs such as packaging material. However, it is important to note that mass is a proxy metric, and does not capture all aspects of cost.[25] For example, in addition to being launched, these supportability items must also be procured. For some resources, such as water, procurement costs may be low. Other items – particularly spare parts for complex systems – may have significantly higher costs. The cost of procuring resources for the mission, including storage and transportation costs on the ground, should also be considered.

Finally, supportability-related changes to a system may incur significant development costs. This includes both the design (and/or redesign) of systems for maintainability and reliability, as well as testing to confirm those characteristics. Testing – including both ground testing and on-orbit operational experience – is critical to understanding the supportability characteristics of a system. As discussed in Section III.D, component failure rates cannot be measured directly; test time is required to reduce epistemic uncertainty in failure rate estimates, as well as to confirm that predicted failure rates are accurate to within a certain level of confidence. In addition, reliability growth requires investment of both time and financial resources to perform tests, identify failure modes, and change designs or operational practices to mitigate them. The cost of reliability growth trends exponentially; that is, while early failure modes may be detected and corrected for relatively low cost, each additional increase in reliability (i.e. reduction in failure rate) incurs significantly increasing cost.[26–28]

Importantly, reliability growth and uncertainty reduction are two separate, yet strongly interrelated, activities. The former involves making changes to the system in order to mitigate failure modes; the latter consists of simply observing the system in order to learn more about its behavior. When changes are made to a system, the impact of those changes on uncertainty in system failure rates and other characteristics must be carefully considered. It may be the case that past observations are no longer as applicable, and failure rate estimates based on previous data should be discounted and uncertainty increased. However, these two activities may be performed concurrently for different parts of the system. For example, testing of a system that is focused on improving the reliability of a specific Orbital Replacement Unit (ORU) could also provide data that can be used to reduce failure rate uncertainty in other ORUs, even if uncertainty is increased or held constant for the ORU undergoing upgrades.

B. Performance

One core objective of human exploration missions is the safe delivery a crew to an exploration destination in order to perform utilization activities such as completing exploration objectives and scientific investigations. Utilization activities output is one metric for mission performance; the more utilization that can be done, the more productive and higher-performing the mission is. Utilization activities require time from the crew, and therefore the amount of crew time available for these activities, or utilization time, is a metric for the performance of a given mission. Missions with more utilization time can achieve higher performance through greater crew productivity, which results in higher scientific output. Conversely, a reduction in available utilization time corresponds to a reduction in mission performance due to a reduction in productivity.

Crew time is a valuable and limited resource on space missions. In addition to performing utilization activities, the crew must spend time maintaining their health via activities such as eating, sleeping, and exercise as well as maintaining spacecraft systems by performing required maintenance and repair. Since any time spent on maintenance and repair activities cannot be spent on utilization, this maintenance and repair time therefore reduces the productivity, or performance, of the mission. The supportability characteristics of a system, such as failure rates and maintenance crew time requirements (typically reported in terms of Mean Time To Repair (MTTR)), strongly influence how much time the crew must spend performing maintenance and repair activities. As with spares logistics, the amount of crew time that will actually be required over the course of the mission is uncertain, and therefore crew time allocation is a trade between the amount of crew time that is provided for maintenance and repair and the risk that not enough crew time will be available.[1,6,7,29,30]

Experience with maintenance and repair on LEO space stations has shown that maintenance and repair crew time is a significant challenge. In practice, maintenance and repair crew time demands have been higher than expected, and as a result system productivity has been lower.[7,29,30] For example, the amount of crew time associated with maintenance and repair of the ISS Environmental Control and Life Support Systems (ECLSS) during station operations has exceeded the amount specified in design documents by more than an order of magnitude; whereas it was initially estimated that only approximately 1 hour per week of crew time would be required, ISS ECLSS maintenance and repair has accounted for approximately 13 to 15 hours of crew time per week.[29,30]

The high maintenance and repair crew time demand experienced on the ISS is indicative of a particular challenge for future missions, given that the ISS supportability strategy was specifically designed to minimize crew time spent on maintenance and repair by packaging components into ORUs. This approach saves crew time by simplifying maintenance and repair activities, but it also increases logistics mass by reducing the mass efficiency of spare parts allocations.[7,31] When ORUs are used, each spare part replacement removes not only the specific item that failed, but also any other items packaged within the same ORU – items which may have a significant amount of useful lifetime remaining. Implementing repair at a lower level is a commonly-discussed supportability strategy that can enable more efficient maintenance and repair logistics, thereby reducing logistics mass; however, it also tends to have the effect of increasing the amount of crew time necessary for maintenance and repair activities.[1,32] Any new approaches to supportability must carefully consider their impact on crew time, and by extension their impact on mission productivity and performance.[1,6]

Supportability is also a strong driver of logistics requirements (see Section III.A). In addition to affecting costs, changes in logistics requirements can also affect the amount of cargo space that can be allocated to utilization for a given mission, given other transportation system or infrastructure constraints. A reduction in logistics may therefore allow a mission to carry more equipment for scientific investigation or other utilization purposes, thus increasing the performance of the mission.

C. Schedule

The supportability characteristics of a system, and the strategies used to improve them, can impact the development and operations schedule of a system in addition to its physical characteristics. As noted in Section III.D, a core driver of the supportability challenge is uncertainty, including both aleatory and epistemic sources. Test time and operational experience are critical factors in understanding this uncertainty and implementing changes to the system in order to improve reliability and potentially reduce logistics mass. In order to increase the reliability of a component (i.e. reduce its failure rate), failure modes must be observed and corrected. A significant amount of test time may be required to achieve significant reliability growth, however. Analysis of historical failure rates and efforts to improve them has shown that failure rate reduction tends to follow a power law relationship with time; each additional amount of time spent on reliability growth produces diminishing returns.[11,28,33–35]

Test time is also critical for reducing the epistemic uncertainty associated with failure rates, which is a critical factor in supportability assessment.[8,36] This uncertainty can be reduced by observing component behavior over time. The result of reduced uncertainty is increased precision in spares forecasting, which can reduce the amount of logistics mass required to achieve a desired level of risk mitigation for a mission. Unlike reliability growth efforts, uncertainty reduction can be performed without making changes to the system. Program planning must take into account the test time required to increase reliability or reduce uncertainty, especially when new or significantly upgraded systems are being deployed for the first time.

Supportability can also affect schedule during mission preparation and operations. Given a limited launch capability (in terms of cadence, launch vehicle capacity, and/or other factors), an increase in logistics mass or volume may result in the need for additional launches. These additional launches can extend the mission timeline and increase the amount of time needed to prepare for and deploy given mission. This extended timeline can affect hardware delivery dates and on-orbit waiting periods for other hardware, especially for missions to destinations such as Mars, which have limited launch windows.

D. Risk

Risk, defined as the combination of the probability that an event will occur and the impact that will result if that event does occur,[37] is at the core of supportability assessment and management. A typical approach to risk assessment for human spaceflight mission design is to estimate the probability associated with a set of particular events or outcomes using Probabilistic Risk Assessment (PRA). The three events most commonly examined for crewed mission PRA are LoM, Loss of Vehicle (LoV), and LoC. The corresponding probabilities for each event – Probability of Loss of Mission (P(LoM)), Probability of Loss of Vehicle (P(LoV)), and Probability of Loss of Crew (P(LoC)) – provide key risk metrics for that mission, usually used along with a given threshold value to define requirements.[38] For example, Apollo program risk requirements specified that P(LoM) be no greater than 0.01 and P(LoC) no greater than 0.001 on any given mission.[39] As noted in Section II, on a long-endurance mission with limited (or nonexistent) abort and resupply options, an inability to maintain critical systems such as ECLSS could result, depending on the circumstance, in LoM, LoV, or LoC. Therefore, supportability is a key contributor to overall mission risk. Specifically, system supportability characteristics define the risk-resource trade for a particular system in a given context, and key risk metrics are related to the probability that the amount of resources provided are sufficient for a given mission.

Two 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, on the other hand, results from a lack of knowledge about the process being examined.[38] While epistemic uncertainty can be reduced through experience as data are gathered and knowledge of the system is improved, aleatory uncertainty is intrinsic and irreducible.[40]

As an example, consider the roll of a die. The outcome of the roll, given known probabilities associated with each potential outcome, is associated with aleatory uncertainty. If the probabilities associated with particular outcomes are unknown – for instance, if the die has an unknown bias – then epistemic uncertainty is also present. This epistemic uncertainty can be reduced via measurement and analysis, for example by observing a series of die rolls. However, the aleatory uncertainty present in the outcome of the die roll itself will not be reduced by observing rolls, even once any bias present in the die is precisely characterized. In order to accurately forecast the the behavior of the die, both aleatory and epistemic uncertainty need to be taken into account.

Supportability risk is primarily associated with the allocation of resources, including physical resources such as spare parts and maintenance items as well as non-physical resources such as crew time allocated for maintenance and repair activities. In addition, past spaceflight experience has highlighted the impact of unanticipated effects, or "unknown unknowns," on system supportability. These risks are discussed in greater detail below.

1. *Spares and Maintenance Resources*

In the context of supportability, aleatory uncertainty typically relates to the number of failures that may be experienced by a particular item with a known failure rate over the course of a mission, which is a random variable. The distribution of the number of failures that may be experienced can be used to determine the number of spares that must be provided in order to achieve a desired Probability of Sufficiency (POS), a metric defined as the probability that the number of spares provided is sufficient to cover all maintenance demands during a given period of time.[40,41] POS is a function of a variety of factors, depending on the complexity of the model being used. These typically include mission endurance, item failure rates (or Mean Times Between Failures (MTBFs)), and the number of spares provided.

POS can be assessed using a wide variety of stochastic modeling techniques, including Poisson, Binomial, Markov, and Semi-Markov models, Monte Carlo mission simulation, or combinations of various methods.[42] Some models assess system-level POS directly, while others assess POS for each repairable item in the system independently, then multiply them together to obtain the system POS. While POS is typically applied in the context of traditional spare parts, it can also be adapted to consider more advanced supportability strategies such as In-Space Manufacturing (ISM). In this context, POS refers to the probability that the amount of raw materials, or feedstock, provided for ISM will be sufficient to manufacture all required items.[43,44] Overall, the probability that sufficient spare parts, feedstock, and other physical maintenance resources is a critical risk consideration for supportability. An in-depth discussion of risk, reliability, and POS modeling is beyond the scope of this paper; however, a selection of references is provided here that include more detailed descriptions of various modeling approaches.[1,2,8,15,16,27,32,37,38,40–59]

Epistemic uncertainty is also a critical consideration for spares and maintenance logistics.[8,36] When failure rates are (or, at least, are assumed to be) deterministically known, POS for a given item is a deterministic value. However, a component's failure rate cannot be directly measured. Instead, it must be estimated based on similarity to other components and/or statistical analysis of observed behavior. For example, the failure rate estimates for ISS ORUs are updated based on observed failures using a Bayesian approach, as described by Vitali and Lutomski[60] and Anderson et al.[40] An analysis by Stromgren et al.[8] found that, of the items in Maintenance and Analysis Data Set (MADS) – the data set used by ISS Safety and Mission Assurance (S&MA) to track reliability characteristics for all ISS ORUs – that have had their reliability estimates change as a result of Bayesian updates, approximately 85% of MTBF values were adjusted upwards (indicating higher than predicted reliability), while 15% were adjusted downwards. While Bayesian updating of failure rate estimates can reduce uncertainty in these estimates over time, some amount of epistemic uncertainty remains. If test/operational experience is relatively limited or the number of test articles is small – as is often the case for human spaceflight when compared to, for example, the aviation or automotive industries – a significant amount of epistemic uncertainty may be present in failure rate estimates.[40] This means that assessment of POS values (which are a function of failure rates) result in a distribution of possible values rather than a point estimate. To account for this epistemic uncertainty, analysts must consider not only POS but also confidence, a measure of fidelity of the estimate typically expressed in terms of the probability that the real-world POS value is greater than or equal to the estimated value.[40] Both aleatory and epistemic uncertainty are critical considerations for supportability analyses, especially for long-endurance missions. Previous analyses have shown that if epistemic uncertainty is not taken into account during supportability analyses, the results can severely underestimate risk and/or logistics mass requirements for long-endurance missions.[8,36]

2. Crew Time

The availability of required maintenance materials is necessary, but not sufficient, for successful maintenance. The crew must also have time to implement required repairs.[1,6,7,29,30] Therefore POS must also be extended to apply to crew time. Unlike spare parts, crew time is a general resource; that is, crew time is not specialized to a particular application, and can be used as needed. However, it is also a limited resource, both in terms of the total amount of crew time available (measured in crew-hours) and in terms of the number of simultaneous or overlapping demands for crew time that occur. The total amount of crew time that will be required over the course of a mission is stochastic, a function of the number of failures that will occur, as well as the amount of time required to implement repairs for each failure (expressed either as a repair time distribution or MTTR estimate). Some assessment approaches examine expected maintenance crew time requirements,[15,16,48] while others assess the distribution of the total amount of crew time required, and therefore the POS associated with a given allocation of crew time to maintenance activities.[6]

In addition to the risk that the total amount of crew time available for maintenance may be exceeded, there is also a risk that a cluster of maintenance demands may overwhelm the crew's maintenance capacity, especially for critical systems. When a critical system such as ECLSS fails, there is a limited time to perform maintenance before the loss of functionality results in LoM, LoV, or LoC. The crew must repair the failure before an unrecoverable hazard condition is reached. If multiple failures occur in quick succession, or if there is an ongoing high cadence of maintenance demands within the system, the crew's ability to implement repairs may be saturated and overwhelmed. Given the small crew size for a mission to Mars, the amount of maintenance crew time "bandwidth" may be very limited, especially when other mission critical activities such as docking, orbital maneuvers, Entry, Descent, and Landing (EDL), or launch/ascent are underway. As such, the probability that the crew's repair capacity will be overwhelmed at any given moment in the mission timeline must also be considered. As with spares and maintenance resources, both aleatory and epistemic uncertainty must be taken into account when assessing maintenance crew time demands.

3. Unknown Unknowns

The above risk factors are only some of the many contributions to overall system risk, and the assessment techniques that generate POS and confidence estimates are only as valid as the data that are used as inputs. However, these data can only account for known or anticipated factors. Unknown or unanticipated effects can have significant implications for system supportability that must be kept in mind during system development. For example, the ISS ECLSS system has experienced several instances of component failure and/or degraded performance due to unanticipated issues,[18,44] including significantly reduced component lifetimes due to dust and debris impingement,[61,62] seal material degradation,[63] component manufacturing and assembly errors,[63] or even changes in the concentration of calcium in crew urine due to physiological changes resulting from the microgravity environment.[63,64] Distributions on the values of failure rates or other parameters can be used to account for some of this uncertainty, but unknown risks will always remain.

For future missions to new destinations, unknowns resulting from the exploration destination itself – such as resource availabilities and/or environmental conditions and their effects on the crew and mission hardware – will be even more prevalent. These "unknown unknowns" are, by definition, unknown. However, historically they have had a detrimental impact on system supportability, introducing additional risk factors. Therefore, probabilistic assessments of risk should be seen as a bound, rather than a guarantee; when risk factors beyond the scope of the analysis (known and unknown) are included, the actual risk will almost certainly be higher.

IV. Supportability Strategy Decisions

A supportability strategy is the collection of architecture, design, and operational decisions that influence the supportability of a system and, by extension, the system characteristics described in Section III. These decisions each have different, often coupled, and sometimes conflicting impacts on mass, risk, crew time, and other characteristics of the system. They occur at various points in the system development timeline, from concept generation and architecture synthesis, through design and testing, all the way to operations. Key supportability strategy decisions for human spaceflight missions are listed and described below, based on descriptions in various sources and lessons learned from previous supportability analyses.[1,8,15,36,44,65] As with the metrics described in Section III, this list is not necessarily exhaustive. The potential impacts that each decision could have on high-level metrics is described briefly, as well as major couplings with other supportability strategy decisions.

A. Reliability Growth

Reliability growth is a commonly-discussed tactic to reduce logistics mass for long-endurance missions.[5] However, longer mission endurance results in increased probability that a failure will occur, even for high-reliability components.[27,51] On very long missions, such as a mission to Mars and back, an unrealistically high reliability would be required to provide high confidence that no spares are required.[28] Long-endurance missions will almost certainly experience failures during flight for any reasonable component MTBF values, and the crew will need to perform repairs in order to maintain system functions. The challenge, then, is not to attempt to ensure that failures do not occur, but rather to accept that they will and design the system to be able to recover from component failures via maintenance while minimizing the amount of resources required.[1,27,28,51]

Increasing the reliability of a given component (measured in terms of MTBF or failure rate) reduces the probability that the component will fail in a given period of time, thereby allowing the same POS to be achieved with fewer spares. However, spares mass for systems with many different repairable items is driven more by the number of potential failures than the reliability of any one item. As a result, the value of reliability growth for individual items, in terms of logistics mass reduction, may be limited.[1,28] In particular, since the overall POS for a set of repairable items is equal to the product of the POS for each individual item, two important factors influence the amount of spares required to achieve system-level POS objectives. First, the POS achieved by any individual item must significantly exceed the target system POS, since all POS values are probabilities that are by definition between 0 and 1. Second, the system POS will always be limited by the lowest item-level POS. As a result, while increased reliability for a subset of items may produce some logistics mass reduction, continued reliability growth produces diminishing returns. While the effect may be larger as more items experience increased reliability (even when all items are included), the amount of reliability growth required to reduce logistics mass by a given amount increases rapidly.[28]

Reliability growth can also incur significant costs. Failure modes must be identified through testing or operational experience, and the system or mission design must be changed to mitigate those failure modes. As reliability increases, the amount of operations time required to observe a failure also increases, since the failures occur at a lower rate. As a result, the amount of time required to increase the reliability of an item is superlinear as a function of the amount of increase in MTBF desired – each additional increase in reliability requires more testing time than the last to achieve.[11,33,34] In addition, cost tends to grow exponentially with higher MTBF targets.[26,27,66] As a result, reliability growth efforts tend to produce diminishing returns, in terms of logistics mass reduction per unit time or cost spent on reducing failure rates.[28]

This is not to say that improvements in reliability should not be pursued at all. On the contrary, during the early phases of reliability growth efforts significant improvements in reliability may be achievable relatively easily as major failure modes (i.e. ones associated with high failure rates) are identified and corrected. The correction of failures that occur at a very high rate can provide significant benefits in terms of overall system reliability and logistics mass. In addition, reliability also impacts crew time demands. A system comprised of more reliable components will tend to experience fewer failures and require less crew time for maintenance. Targeted reliability growth programs for specific, high-impact items – that is, items with high mass, crew time requirements, and/or failure rates – may provide more efficient use of test resources than broader efforts, since they can focus on items that are relatively early in the reliability-cost curve, before the impact of diminishing returns is too strong. However, at a certain point the benefits of additional reliability growth may no longer be worth the cost and time required. In addition, changes to system design to improve reliability may result in increased epistemic uncertainty, which could have a detrimental effect on logistics requirements (see Section IV.B).

Decisions regarding reliability growth efforts must balance the logistics mass and crew time reductions that may be achieved against the test time and cost required for those improvements, as well as the potential for increased uncertainty that may result from changes to the system design. Mission supportability analysis that examines the sensitivities of various metrics with regard to the reliability can help identify when and where reliability growth provides value and when it may be more cost-effective to pursue other strategies. A more detailed discussion of the costs and benefits of reliability for long-endurance systems is presented by Owens et al.[28]

A related consideration is component lifetime extension. Some items (e.g. filters) have logistics driven not by the need for spares to cover random failures, but by scheduled replacements of those items when they reach the end of their useful life. Increased lifetime for these components could also reduce logistics, but again test time and operational experience is required to validate these increased lifetimes. Shelf life is also a critical consideration in addition to operational lifetimes, particularly if spares are to be predeployed (discussed further in Section IV.H). As with reliability growth, the amount of redesign effort and time required to increase and validate a component lifetime must be weighed against the logistics mass and maintenance crew time reductions that could be achieved by longer lifetimes.

B. Uncertainty Reduction

Supportability analyses must consider not only the estimated failure rates for components within the system, but also epistemic uncertainty in those values. This epistemic uncertainty can have a very strong impact on logistics and risk, described in greater detail in Section III.D. Reducing the amount of epistemic uncertainty present in failure rate estimates can reduce the amount of logistics mass required to achieve a desired POS and confidence value. More information about the behavior of the system, in the form of component lifetimes and/or the number of repairs over a given period of time, enables more precise failure rate estimates, which in turn enable more precise forecasts of maintenance demands.[8,36]

For ISS logistics management, for example, failure rates and the associated uncertainty are tracked at the ORU level in MADS. Each ORU has two parameters associated with it to describe reliability: a failure rate estimate and an error factor. The failure rate estimate represents the mean failure rate, or the expected value of the distribution of possible failure rates. The failure rate uncertainty distribution is typically modeled as being lognormal, though a gamma distribution may also be used. The error factor, defined as the ratio between the 95^{th} and 50^{th} percentiles in the lognormal distribution, captures the amount of uncertainty present in the estimate. Together, the mean failure rate and error factor define the distribution of potential failure rates. As ORUs fail during ISS operations, the associated mean failure rate and error factor are updated using a Bayesian approach. Thus, as experience is gained the error factor tends to shrink and the mean failure rate estimate tends to approach the true value. A more detailed description of the ISS Bayesian update approach is presented by Anderson et al.[40] and Vitali and Lutomski,[60] and general approaches to PRA and Bayesian analysis for space missions are described in greater detail by Stamatelatos and Dezfuli[38] and Dezfuli et al.[67]

As with reliability growth (Section IV.A), the key to uncertainty reduction is test time and operational experience. Unlike reliability growth, however, uncertainty reduction can be achieved through simple observation of system behavior; no changes to system design, manufacturing process, or operational procedures are required. As a result, it is likely cheaper to reduce uncertainty than it is to increase reliability. Uncertainty reduction can also be achieved without the risk of introducing new failure modes into the system, since the system itself remains unchanged. However, reducing uncertainty around failure rate estimates does not improve the characteristics of the system itself; it only improves understanding of the systems for analysts and mission planners, enabling more effective supportability and logistics planning.[36]

Uncertainty reduction and reliability growth are not mutually exclusive. During all-up systems testing, for example, a subset of components can be focused on for reliability growth while data are gathered on others for uncertainty reduction. Failure modes discovered in items targeted for reliability growth are corrected, while others are allowed to remain and studied in order to reduce uncertainty. In this way the reliability of some components in the system can be improved, and the uncertainty in failure rate estimates for other components is reduced simultaneously. The determination of whether or not an item is targeted for reliability growth can be made based upon the impact of that item on logistics mass, crew time requirements, or other factors. Alternatively, failure modes can be selected for reliability improvement dynamically as they are discovered. For example, failure modes with associated failure rates below a given threshold could be targeted for correction, while those with rates above the threshold can be left unchanged and monitored for uncertainty reduction. The strategy used during testing and early "shakedown" operations depends upon the particular system and mission context.

Overall, decisions regarding uncertainty reduction efforts must balance the potential impact of reduced uncertainty on logistics and crew time requirements against the associated test time and cost. A more detailed discussion of epistemic uncertainty in failure rates and its impact on supportability is presented by Stromgren et al.[8] and Owens et al.[36]

C. Level of Repair

Level of repair, also known as indenture, refers to the level in the parts hierarchy (system, subsystem, assembly, component, etc.) at which repair actions are executed.[1,41] For example, the Air Force uses the terms Line Replaceable Unit (LRU) and Shop Replaceable Unit (SRU) to refer to items that are maintained on the flight line or in a maintenance shop, respectively.[41] Spaceflight applications typically refer to ORUs in the place of LRUs.

Grouping components into ORUs can result in a more maintainable system by simplifying maintenance activities and reducing the amount of time required for maintenance. This approach was used on the ISS, for example, in order to reduce maintenance crew time demands.[7,31] However, higher-level repair reduces the mass-efficiency of maintenance; when components are grouped together into ORUs, the failure of a single component within that ORU can force the replacement of all components when the entire ORU is replaced. Items that may still have a significant amount of useful lifetime remaining before they fail are replaced because of the failure of some other item in the same ORU. In contrast, lower-level repair can result in significant reductions in spares mass requirements. Lower-level repair is more mass-efficient; for example, when maintenance actions can be executed at the component rather than assembly level, all other components within the assembly that are still functioning can remain in service and the mass of elements that are replaced is lower than it would be in a higher-level repair paradigm.[1,32] In addition, there may be more potential for commonality between lower-level items such as valves, sensors, fans, hoses, and manifolds than there is between higher-level assemblies. Increased commonality enabled by lower level repair may provide additional benefits (see Section IV.D).

However, lower level repair can increase the complexity of system development and maintenance operations. In order to enable effective lower-level repair, systems must be designed to enable access to lower-level components, rather than collecting components into convenient boxes. Design for maintainability will place additional constraints on the physical design of the system from the perspective of crew access, tool clearances, potential hazards (sharp edges, containment for toxic materials, etc.), and sensing requirements for diagnostics. Crews must have the knowledge and tools to execute maintenance activities at a lower level, including diagnostic of system failures to identify failed components and removal/installation of those components. There may be additional risk to the crew during more complex maintenance operations, as well as an increased risk of unsuccessful maintenance. Increased complexity is also likely to increase the amount of crew time required for maintenance, just as reduced complexity resulting from the implementation of higher-level maintenance using ORUs is intended to reduce maintenance crew time. Decisions regarding level of repair must carefully balance their impact on logistics mass, crew time, and the challenges of design for lower-level maintenance.[1]

D. Commonality

Commonality is a maintenance strategy in which repairable items from different parts of the system are designed to be interchangeable, meaning that a single type of spare can cover multiple types of failures. The use of common components reduces the total number of spares that are required, since each additional spare covers multiple sources of risk. In addition, common components can enable scavenging or cannibalization of components from some systems to provide contingency spares for other, higher-criticality systems. Finally, commonality can simplify inventory management and maintenance procedures by reducing the number of different types of components that must be accounted for, as well as the number of different tools that may be required to perform maintenance.[1,68]

Common components do not have to be identical, but they do need to be interchangeable with regard to both form and function. Commonality can impose additional constraints on the component design process, forcing the component to conform to requirements associated with multiple locations in the system. As a result, the final design may not be as optimal in terms of local performance as it could be if it were specific to a single installation point. However, the overall system characteristics may be significantly improved as a result of the logistics benefits of commonality. In some cases, the loss of local optimality in component design is more than made up for by the global optimality enabled at the system level.[1]

Commonality can increase the risk of common cause failures, since the same design is used multiple times within the system. A common cause failure is a failure that occurs in different parts of a system for the same reason.[69] When the same design is reused, failure modes within that design – whether they arise from design flaws, manufacturing flaws, unanticipated interactions, or any other source – become common failure modes across multiple systems. As a result, failure modes within common components can be more critical than those in individualized components, since they may impact wide swaths of system functionality. This increased criticality should be taken into account during testing and evaluation of proposed common component designs. However, the use of commonality increases the population of a given type of component that is active in the system at a given time, providing more data for reliability growth and uncertainty reduction (see Sections IV.A and IV.B). As a result, improvements to system reliability and/or failure rate estimates may be achievable faster than they would be for a set of individual components. Therefore, while the impact of a failure mode within a common component may be greater, the ability of system designers to detect and understand/correct that failure mode is likely increased. Commonality also reduces the number of different types of components that must be designed and evaluated, which may simplify development and testing for the system. During system development, designers must carefully balance the impact of additional constraints and common cause risks against the logistics mass reduction and simplification of development, testing, and operations that may result from the implementation of commonality.

E. Redundancy

Redundancy addresses reliability issues in the same way as spare parts – additional copies of certain system elements are provided so that if one fails, another can take its place. However, with redundancy the replacement item is already within the system; no crew time is required to execute a maintenance action to install a new spare when failure occurs. This provides an additional benefit in that redundant components can recover system functionality without crew intervention, thus significantly lowering risks associated with loss of critical functions. Redundancy can be implemented at many levels within the system, from individual components all the way to entire redundant systems. Level of redundancy considerations have similar implications to level of repair, described in Section IV.C. Specifically, while high-level redundancy may provide the ability to switch over to an entirely different system or subsystem when a failure occurs, it is not a mass-efficient way to improve POS for the system.[32] In addition, redundancy may consist of identical copies of a system, or of different systems that accomplish the same function. The latter approach, known as dissimilar redundancy, has the benefit of reducing the potential for common cause failures.

Analysis shows that multiple spares are needed to mitigate risk for most components.[32,54] Since each redundant instance of a system or subsystem effectively supplies only one additional spare for all items within that system or subsystem, multiple redundant copies would be necessary to provide risk mitigation. Spare parts are typically implemented at a lower level than redundancy, and are therefore typically a more mass-efficient approach for risk mitigation. When combined with spare parts, however, redundancy can provide a backup capability to maintain system function while maintenance activities are completed, giving the crew more time to respond to failures. Thus, while redundancy may be valuable to preserve critical system functions during maintenance downtime, it is unlikely to eliminate the need for spare parts as an effective supportability strategy. Decisions regarding redundancy – including the level at which redundancy is to be implemented, whether it is similar or dissimilar, and how many redundant elements to include – impact system mass, risks associated with loss of function, and crew time required for maintenance.[1]

F. In-Space Manufacturing

ISM can enable the on-demand, in situ production of useful items from raw material feedstock and/or low-level components. “Just-in-time” manufacturing can significantly reduce logistics mass requirements by enabling the use of common raw materials to cover a variety of potential failures on-demand, eliminating the need to specialize spares and maintenance items to particular components.[43,44,70,71] This is effectively an extension of commonality (Section IV.D), and has similar effects in terms of broad risk coverage from common resources. However, a key difference is that where commonality of spare parts imposes interchangeability constraints on the design of the part itself, ISM imposes the need for common materials and for manufacturability within the constraints of ISM technology available to the mission. This commonality of material, rather than commonality of design, can enable the application of the benefits of commonality more flexibly than traditional implementation, especially as manufacturing technologies and capabilities advance.[43,44]

Recent technological advancements in Additive Manufacturing (AM), colloquially known as 3D printing, have opened the door to more advanced manufacturing capabilities in space than have previously been available, due to the fact that AM processes are automated (meaning they do not require excessive crew time) and relatively resource-efficient when compared to traditional, subtractive manufacturing techniques. However, it is important to note that ISM does not necessarily have to make use of AM, though there are many benefits to AM which make it an attractive option. An extensive review of potential applications of AM for spaceflight and the benefits that might result was published by the National Research Council (NRC) in 2014.[72] The first 3D printer in space, the 3D Printing in Zero-G Technology Demonstration Mission, was delivered to the ISS in 2014 and has demonstrated the feasibility of ISM using Fused Deposition Modeling (FDM) in a microgravity environment; initial results of this technology demonstration are reported by Prater et al.[73]

In addition to enabling commonality of material and the resulting savings in logistics mass, ISM can enable adaptable maintenance logistics. Traditional spare parts are specialized, covering specific failure modes (or sets of failure modes, for common components). In contrast, raw materials provided for an ISM system can be used to cover a wide variety of potential failure modes, and specific allocations of resources to specific failure modes do not have to be made before launch. When traditional, individualized spares are used, an unexpectedly high failure rate in a single component could exhaust the spares allocated to that item before the end of the mission (potentially resulting in LoC, LoM, or LoV), even if other items experience unexpectedly low failure rates and have a surplus of components. ISM enables the adaptive reallocation of maintenance resources, since raw materials are not specialized. If one item requires fewer spares than are expected, resources that might have been used for that item can be reallocated to cover demand from an item that requires more spares than expected. As a result, ISM helps mitigate the impact of epistemic uncertainty.[44] In addition, ISM provides the flexibility for the crew to manufacture items that may not have been planned for, providing a powerful contingency option.[44,74–76] ISM can also offer several other benefits, including simplified inventory management, reduced logistics stowage volume requirements, and opportunities to re-optimize system designs without launch packaging or loading constraints.[43,44,70,72,74,75]

One of the most significant benefits of ISM may be that it enables recycling and/or In-Situ Resource Utilization (ISRU) for maintenance logistics. Recycling has been used to great effect for the reduction of ECLSS consumables requirements on past spaceflight missions, and ISRU has the potential to reduce logistics demands even further for crewed missions to the Moon and Mars.[18,77–80] When ISM is available, recycling and ISRU can be applied to spare parts in the same way that it is currently applied to water, oxygen, and propellant. Failed components may be converted into raw materials that could be used to manufacture new components, and new components may be manufactured on site using local materials. This would be a revolutionary capability in maintenance logistics, drastically reducing the amount of mass required for long-endurance missions.[44,65,70–72,74,81–83]

ISM is still a relatively new capability, and a significant amount of development effort remains before ISM can be deployed in a mission-critical setting. This development and testing cost must be accounted for in future mission planning when ISM is considered. In addition, ISM introduces new risks that must be considered. For example, if ISM is to be used to manufacture critical components, then the ISM system may become a common failure mode across several systems. Thus, the reliability and maintainability of such a system is a critical consideration. In addition, the ISM system itself has mass and volume that must be accounted for, in terms of both the emplaced system and any logistics that it may require.

The manufacturing capability of any ISM system is a critical concern. This includes available materials, precision, surface finish, quality, and reliability of the manufacturing process. ISM capabilities place constraints on the type and quality of part that can be manufactured in space. However, it is important to bear in mind that the operational and logistical context of parts manufactured in space is different from that of parts manufactured on Earth and launched into space, and therefore the optimal design may change – especially if material recycling and/or ISRU are available. Therefore, component designs may change, adapting to the constraints of an ISM system or to the different context provided when material can be recycled or produced in situ.

Decisions regarding the implementation of ISM – including selection of specific components to produce in space, which manufacturing capability to develop, whether or not to use recycling/ISRU, and what changes to component and system design may be implemented to make full use of ISM – must carefully balance the cost of ISM/recycling/ISRU system development, the cost of any design changes to components to enable ISM, as well as additional logistics and risk against the potential logistics savings or risk mitigation provided by an ISM capability. A more in-depth discussion of ISM and its potential benefits for human exploration missions is presented by Owens and de Weck.[44]

G. Reduced Complexity

One of the primary drivers of spares mass for long-endurance missions is the large number of different types of items for which spares must be provided. While the probability of any individual failure mode occurring once (or multiple times) may be relatively low, the cumulative risk from all of them is relatively high, and it is that cumulative risk that drives the supportability challenge. Most of the spare parts that are carried on these future missions may never be used, but they are required for mitigation since there is no way to know beforehand which spares will be needed.[1] Reducing system complexity by lowering parts counts and using simpler, more robust components may alleviate this effect and allow a reduction in the amount of spares required for risk mitigation in addition to the reduction in spares resulting from the removal of items to spare for.[28] In addition, there is a need to balance the logistical benefits of spacecraft systems, especially for ECLSS, that reduce the mass of consumables like water and oxygen that need to be carried against the mass of spare parts required to maintain those systems to a desired POS and confidence. In some cases, the cost of additional spares/maintenance logistics and crew time associated with more complex systems may outweigh the benefits that those systems provide.[8,52,53,57] Reducing the complexity of systems may enable cost savings in development and testing in addition to logistics reduction, and simplification may also reduce risk. These potential benefits should be weighed carefully against performance increases or logistics reduction that could be achieved by more complex systems if they are implemented.

H. Spares Inventory Selection

Once a system and mission context are defined – that is, after many of the above decisions are made – a critical supportability decision remains: which, and how many, spares should be carried on the mission? A fully-defined system results in a list of repairable items, each associated with characteristics such as mass, failure rate (or failure rate distribution), and life limits. This list, along with mission characteristics such as endurance, enable the calculation of probabilities associated with various risks, described in Section III.D. Typically, a requirement will be set on POS and confidence or other risk metrics for a given mission, and supportability modeling and optimization will be used to determine the allocation of spare parts that meets that requirement for minimum mass. Optimization of spares allocations is a critical step – though there will be many spares allocations that fulfill mission risk requirements, only one will do so while requiring the minimum amount of logistics mass. Several discrete optimization approaches may be used to determine the minimum-mass spares inventory, which are beyond the scope of this paper; however, a selection of references that describe spares inventory optimization in greater detail is provided here.[2,32,36,40,41,45,48,50,53,54] When ISM is used, raw material for manufacturing is also included in the inventory optimization process.[43,44]

In addition to the selection of which and how many spares should be carried, inventory optimization may include decisions regarding predeployment of a subset of spare parts to an exploration destination. The use of slower, more efficient transit trajectories could reduce the propellant costs associated with logistics. If future missions will visit the same exploration destination, then leftover logistics may be cached, or left for future use. This approach could be particularly useful for spare parts; even though a large amount of spares must be carried to cover potential failures, only a small number of spares are likely to actually be used on the mission (though it is impossible to know which ones beforehand).[1] The unused spares could be cached for later use, thus reducing the amount of new spares that future missions must carry.[57] However, if cached spare parts are to be used on future missions, they must remain compatible with spacecraft systems. Any upgrades to the system must either maintain compatibility with previous spares, or mission planners must accept the additional logistics required to re-initialize the spares cache when a system changes. In addition, predeployed and/or cached spares and maintenance items may spend years in space or waiting at an exploration destination before use, and therefore the shelf life of these items must be taken into consideration during mission planning.

V. Discussion

A. "Mean Time Between Failures" Can Be Misleading

Component reliability is typically characterized in terms of MTBF, which is the inverse of failure rate. This term can be misleading, however. MTBF is not a direct description of the amount of time that a component will operate before failing, but rather a parameter used to characterize a probability distribution. The amount of time that a component will function, as well as the number of times a component may fail during a mission, is a random variable. The component may fail before its MTBF is reached, or it may last beyond it. Figure 1 shows the impact of MTBF and mission endurance on the probability of failure. The probability that an item fails before the end of the mission is shown in red, while the probability that it does not fail is shown in blue, as a function of the ratio of mission endurance to MTBF. These curves are generated assuming the Constant Failure Rate (CFR) model, a commonly-used model for random failures that assumes that component lifetimes are exponentially distributed.[84] If MTBF is equal to the mission endurance, the probability that a component will fail before the end of the mission is 0.63. Even if the MTBF is twice the mission endurance, the probability of failure before the end of the mission is 0.39. Supportability analysis that allocates spares using MTBF as an estimate for the deterministic lifetime of each item may significantly underestimate risk. It is critical that spares logistics planning and risk analysis use MTBF to characterize the probability of failure rather than use it interchangeably with component lifetimes.

B. Data Needs

To understand the supportability characteristics of a system, forecast logistics and crew time needs, and inform system development and mission planning, supportability analysts need data. Failure rate estimates for repairable items – ideally captured as probability distributions, characterized by a mean and error factor (see Section IV.B) – are critical to forecasting spares demands, and can be derived from similarity to well-

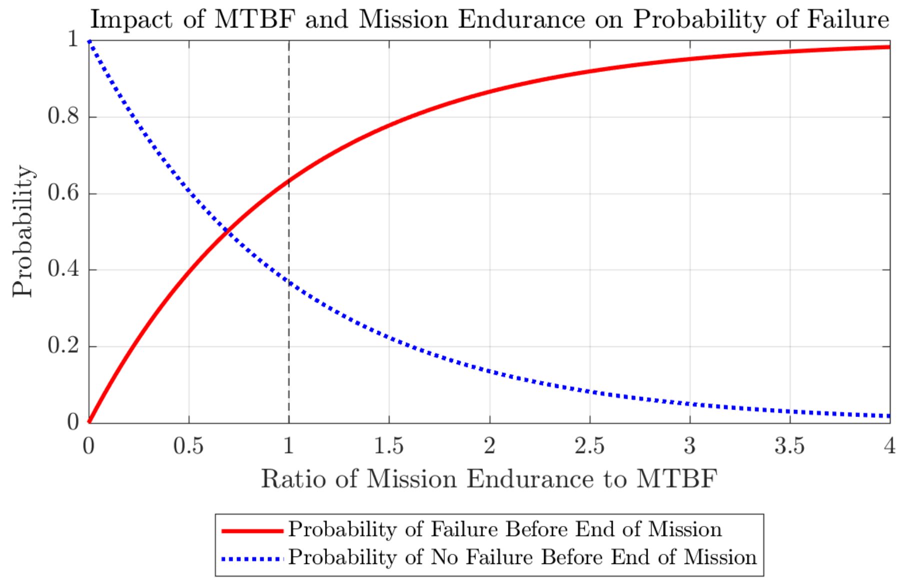

Figure 1. Probability that a component will (red) or will not (blue, dotted) fail before the end of the mission as a function of the ratio between the mission endurance and component MTBF

understood systems or through statistical analysis of component operating histories. If failure rate estimates are not readily available, failure histories consisting of either a set of component lifetimes or a count of the number of failures that have been experienced by a particular component over time can be used to derive those estimates. These component histories can also be used to generate trends and assess how much time and effort may be required for further improvements in reliability or reduction in uncertainty. Similarly, component life limit information is necessary to forecast maintenance demands. K-factors, multipliers on failure rates to account for induced failures, are also necessary, as well as any shelf life limitations that must be taken into account. Component mass and volume estimates are required to assess the cost of logistics. To forecast crew time demands, estimates of the amount of time required for maintenance of each item are necessary either as an MTTR estimate or a distribution with uncertainty. It is also important to understand tools requirements associated with various maintenance activities. In order to investigate design options such as lower levels of repair, these data must be available at multiple levels of repair (ORU, assembly, subassembly, component, etc.). In addition, opportunities for commonality, ISM, ISRU, and material recycling must be identified and characterized.

Mission experience is a critical source for these data. The ISS has provided and continues to provide essential knowledge of spacecraft system behavior and operational challenges that are necessary for the analysis of and planning for future missions. Data from continued ISS operations, commercial space stations, and initial missions to cislunar space or other destinations will be extremely valuable to the understanding of supportability for future space missions. Therefore, supportability data collection, organization, and dissemination is an important part of spaceflight operations.

C. The Value of Sensitivity Analysis

A common challenge for supportability assessment is that early in mission lifecycles, when it is most valuable, input data may not be available. It can be difficult to assess the mass or failure rate of components that have not yet been designed. However, it is often possible to bound these and other characteristics and provide a range of possible values, including perhaps a most likely estimate. Sensitivity analysis on the impact of those values can be used to guide system designers and identify targets and breakpoints for those values (e.g. reliability thresholds that must be achieved by a new component in order for it to provide a net benefit to the system). Supportability analysis is not a one-way computation, but a flexible, multifaceted method to forecast system behavior and inform mission design.

VI. Conclusion

Supportability is a critical consideration for future human spaceflight missions. The supportability characteristics of the systems that carry humans to Mars and back will be determined in part by decisions made in the near future, and will be strong drivers of system lifecycle cost and risk. This paper has outlined the many impacts that supportability has on cost, performance, schedule, and risk, as well as a set of strategies that have been proposed to address these impacts. New approaches for supportability will be required to enable safe and effective beyond-LEO human spaceflight. It is likely that no single supportability strategy will be sufficient to enable cost-effective long-endurance human spaceflight. Holistic analysis and trade studies of the supportability metrics and decisions that are described and assessed in this paper, as well as in the many papers referenced above, can help guide system development and mission planning to enable the human spaceflight goals of the future.

Acknowledgments

This research was supported by a NASA Space Technology Research Fellowship (NNX14AM42H).

References

[1]Cirillo, W., Aaseng, G., Goodliff, K., Stromgren, C., and Maxwell, A., "Supportability for Beyond Low Earth Orbit Missions," *AIAA SPACE 2011 Conference & Exposition*, American Institute of Aeronautics and Astronautics, Long Beach, CA, Sept. 2011, AIAA-2011-7231.

[2]Stromgren, C., Terry, M., Cirillo, W., Goodliff, K., and Maxwell, A., "Design and Application of the Exploration Maintainability Analysis Tool," *AIAA SPACE 2012 Conference & Exposition*, AIAA-2012-5323, Pasadena, CA, Sept. 2012, AIAA-2012-5323.

[3]Jones, H. W., Hodgson, E. W., and Kliss, M. H., "Life Support for Deep Space and Mars," *44th International Conference on Environmental Systems*, Tucson, AZ, July 2014, ICES-2014-074.

[4]Kennedy, K. J., Alexander, L., Landis, R., Linne, D., Mclemore, C., and Santiago-Maltonado, E., "Technology Area 07: Human Exploration Destination Systems Roadmap," Tech. rep., National Aeronautics and Space Administration, Washington, DC, April 2010.

[5]Hurlbert, K., Bagdigian, B., Carroll, C., Jeevarajan, A., Kliss, M., and Singh, B., "Technology Area 06: Human Health, Life Support and Habitation Systems," Tech. rep., National Aeronautics and Space Administration, Washington, DC, April 2012.

[6]Mattfeld, B., Stromgren, C., Shyface, H., Cirillo, W., and Goodliff, K., "Developing a crew time model for human exploration missions to Mars," *2015 IEEE Aerospace Conference*, March 2015.

[7]Bertels, C., "Crew Maintenance Lessons Learned from ISS and Considerations for Future Manned Missions," *SpaceOps 2006*, American Institute of Aeronautics and Astronautics, Rome, Italy, June 2006.

[8]Stromgren, C., Goodliff, K. E., Cirillo, W., and Owens, A., "The Threat of Uncertainty - Why Using Traditional Approaches for Evaluating Spacecraft Reliability Are Insufficient for Future Human Mars Missions," *AIAA SPACE 2016*, American Institute of Aeronautics and Astronautics, Long Beach, CA, Sept. 2016, AIAA-2016-5307.

[9]National Aeronautics and Space Administration, "NASA Systems Engineering Handbook," Handbook NASA/SP-2007-6105 Rev1, National Aeronautics and Space Administration, 2007.

[10]Birolini, A., *Reliability Engineering: Theory and Practice*, Springer, Berlin, Heidelberg, 2004.

[11]Department of Defense, "Department of Defense Handbook: Reliability Growth Management," Handbook MIL-HDBK-189C, United States Department of Defense, June 2011.

[12]National Aeronautics and Space Administration, "NASA Technical Standard: Planning, Developing and Managing an Effective Reliability and Maintainability (R&M) Program," NASA Technical Standard NASA-STD-8729.1, National Aeronautics and Space Administration, Dec. 1998.

[13]Haskins, C., "Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities," Tech. Rep. INCOSE-TP-2003-002-03.1, International Council on Systems Engineering, Aug. 2007.

[14]Montgomery, A. D., "Logistics: An Integral Part of Cost-Efficient Space Operations," *Space Mission Operations and Ground Data Systems - SpaceOps '96*, European Space Agency, Munich, Germany, Sept. 1996, S096.8.016.

[15]Fisher, W. F. and Price, C. R., "Space Station Freedom External Maintenance Task Team Final Report," Tech. rep., National Aeronautics and Space Administration, Houston, TX, July 1990.

[16]Fragola, J. R. and McFadden, R. H., "External Maintenance Rate Prediction and Design Concepts for High Reliability and Availability on Space Station Freedom," *Reliability Engineering & System Safety*, Vol. 49, No. 3, Jan. 1995, pp. 255–273.

[17]National Research Council, *Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration*, June 2014, DOI: 10.17226/18801.

[18]Do, S., *Towards Earth Independence - Tradespace Exploration of Long-Duration Crewed Mars Surface System Architectures*, Doctoral Thesis, Massachusetts Institute of Technology, 2016.

[19]Williams, D. R. and Bell II, E., "NASA Space Science Data Coordinated Archive," July 2017.

[20]Dunbar, B., "Space Shuttle Mission Archives," Aug. 2011.

[21] National Aeronautics and Space Administration, “Reference guide to the International Space Station,” Tech. Rep. NP-2010-09-682-HQ, National Aeronautics and Space Administration, Washington, DC, 2010.

[22] Goodliff, K., Stromgren, C., Ewert, M., Hill, J., and Moore, C., “Logistics Needs for Future Human Exploration Beyond Low Earth Orbit,” *AIAA SPACE 2017*, American Institute of Aeronautics and Astronautics, Orlando, FL, Sept. 2017, (Submitted for Publication).

[23] Simon, M. A., Wald, S. I., Howe, A. S., and Toups, L., “Evolvable Mars Campaign Long Duration Habitation Strategies: Architectural Approaches to Enable Human Exploration Missions,” *AIAA SPACE 2015 Conference and Exposition*, AIAA SPACE Forum, American Institute of Aeronautics and Astronautics, Pasadena, CA, Aug. 2015, AIAA-2015-4514.

[24] Everett, D. F., “Chapter 14: Overview of Spacecraft Design,” *Space Mission Engineering: the New SMAD*, edited by J. R. Wertz, D. F. Everett, and J. J. Puschell, Space Technology Library, Microcosm Press, Hawthorne, CA, 2011.

[25] Jones, H. and Anderson, G., “Need for Cost Optimization of Space Life Support Systems,” *47th International Conference on Environmental Systems*, International Conference on Environmental Systems, Charleston, SC, July 2017, ICES-2017-83.

[26] Mettas, A., “Reliability Allocation and Optimization for Complex Systems,” *Reliability and Maintainability Symposium*, IEEE, Los Angeles, CA, 2000, pp. 216–221.

[27] Agte, J., Borer, N., and de Weck, O., “Design of Long-Endurance Systems With Inherent Robustness to Partial Failures During Operations,” *Journal of Mechanical Design*, Vol. 134, No. 10, 2012, pp. 100903.

[28] Owens, A. and de Weck, O., “Limitations of Reliability for Long-Endurance Human Spaceflight,” *AIAA SPACE 2016*, American Institute of Aeronautics and Astronautics, Long Beach, CA, Sept. 2016, AIAA-2016-5308.

[29] Russell, J. F., Klaus, D. M., and Mosher, T. J., “Applying Analysis of International Space Station Crew-Time Utilization to Mission Design,” *Journal of Spacecraft and Rockets*, Vol. 43, No. 1, Jan. 2006, pp. 130–136.

[30] Russell, J. F. and Klaus, D. M., “Maintenance, reliability and policies for orbital space station life support systems,” *Reliability Engineering & System Safety*, Vol. 92, No. 6, June 2007, pp. 808–820.

[31] Leath, K. and Green, J., “A Comparison of Space Station Utilization and Operations Planning to Historical Experience,” *44th Congress of the International Astronautical Federation*, International Astronautical Federation, Graz, Austria, Oct. 1993, IAF-93-T.5.522.

[32] Owens, A. and de Weck, O., “Increasing the Fidelity of Maintenance Logistics Representation in Breakeven Plots,” *46th International Conference on Environmental Systems*, International Conference on Environmental Systems, Vienna, Austria, July 2016, ICES-2016-344.

[33] Duane, J. T., “Learning Curve Approach to Reliability Monitoring,” *IEEE Transactions on Aerospace*, Vol. 2, No. 2, 1964, pp. 563–566.

[34] Crow, L. H., “Planning a Reliability Growth Program Utilizing Historical Data,” *Reliability and Maintainability Symposium*, IEEE, Lake Buena Vista, FL, Jan. 2011, pp. 1–6.

[35] Department of Defense, “Department of Defense Handbook: Reliability Growth Management,” Handbook MIL-HDBK-189, United States Department of Defense, Feb. 1981.

[36] Owens, A. C., de Weck, O. L., Stromgren, C., Goodliff, K., and Cirillo, W., “Accounting for Epistemic Uncertainty in Mission Supportability Assessment: A Necessary Step in Understanding Risk and Logistics Requirements,” *47th International Conference on Environmental Systems*, International Conference on Environmental Systems, Charleston, SC, July 2017, ICES-2017-109.

[37] Wertz, J., “Chapter 24.2: Space System Risk Analysis,” *Space Mission Engineering: the New SMAD*, edited by J. R. Wertz, D. F. Everett, and J. J. Puschell, Space Technology Library, Microcosm Press, Hawthorne, CA, 2011.

[38] Stamatelatos, M. and Dezfuli, H., “Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners,” Technical Report NASA/SP-2011-3421, National Aeronautics and Space Administration, Washington, DC, Dec. 2011.

[39] Kelly, T. J., *Moon Lander: How We Developed the Apollo Lunar Module*, Smithsonian Institution Press, Washington, DC, 2001.

[40] Anderson, L., Carter-Journet, K., Box, N., DiFilippo, D., Harrington, S., Jackson, D., and Lutomski, M., “Challenges of Sustaining the International Space Station through 2020 and Beyond: Including Epistemic Uncertainty in Reassessing Confidence Targets,” *AIAA SPACE 2012 Conference & Exposition*, American Institute of Aeronautics and Astronautics, Pasadena, CA, Sept. 2012, AIAA-2012-5320.

[41] Sherbrooke, C. C., *Optimal Inventory Modeling of Systems: Multi-Echelon Techniques*, Kluwer Academic Publishers Group, London, 2nd ed., 2004.

[42] Owens, A., de Weck, O., Mattfeld, B., Stromgren, C., and Cirillo, W., “Comparison of Spares Logistics Analysis Techniques for Long Duration Human Spaceflight,” *45th International Conference on Environmental Systems*, International Conference on Environmental Systems, Bellevue, WA, July 2015, ICES-2015-288.

[43] Owens, A., Do, S., Kurtz, A., and de Weck, O., “Benefits of Additive Manufacturing for Human Exploration of Mars,” *45th International Conference on Environmental Systems*, International Conference on Environmental Systems, Bellevue, WA, July 2015, ICES-2015-287.

[44] Owens, A. and de Weck, O., “Systems Analysis of In-Space Manufacturing Applications for the International Space Station and the Evolvable Mars Campaign,” *AIAA SPACE 2016*, American Institute of Aeronautics and Astronautics, Long Beach, CA, Sept. 2016, AIAA-2016-5394.

[45] Sherbrooke, C. C., “Metric: A Multi-Echelon Technique for Recoverable Item Control,” *Operations Research*, Vol. 16, No. 1, Feb. 1968, pp. 122–141.

[46] Kline, R. C. and Sherbrooke, C. C., “Estimating Spares Requriements for Space Station Freedom Using the M-SPARE Model,” Tech. Rep. NS101R2, Logistics Management Institute, Bethseda, MD, July 1993.

[47] Wertz, J. A., *Reliability and Productivity Modeling for the Optimization of Separated Spacecraft Interferometers*, SM Thesis, Massachusetts Institute of Technology, 2002.

[48] Bachman, T. and Kline, R., “Model for Estimating Spare Parts Requirements for Future Missions,” *Space 2004 Conference and Exhibit*, American Institute of Aeronautics and Astronautics, San Diego, CA, Sept. 2004, AIAA-2004-5978.

[49]Wertz, J. and Miller, D., "Expected productivity-based risk analysis in conceptual design," *Acta Astronautica*, Vol. 59, No. 1-5, July 2006, pp. 420–429.

[50]Kline, R. C. and Bachman, T. C., "Estimating Spare Parts Requirements with Commonality and Redundancy," *Journal of Spacecraft and Rockets*, Vol. 44, No. 4, July 2007, pp. 977–984.

[51]Agte, J. S. J. S., *Multistate analysis and design : case studies in aerospace design and long endurance systems*, Doctoral Thesis, Massachusetts Institute of Technology, 2011.

[52]Jones, H., "Design and Analysis of a Flexible, Reliable Deep Space Life Support System," *42nd International Conference on Environmental Systems*, American Institute of Aeronautics and Astronautics, San Diego, CA, July 2012, AIAA-2012-3418.

[53]Lange, K. E. and Anderson, M. S., "Reliability Impacts in Life Support Architecture and Technology Selection," *42nd International Conference on Environmental Systems*, AIAA-2012-3491, San Diego, CA, July 2012, AIAA-2012-3491.

[54]Stromgren, C., Terry, M., Mattfeld, B., Cirillo, W., Goodliff, K. E., Shyface, H. R., and Maxwell, A. J., "Assessment of Maintainability for Future Human Asteroid and Mars Missions," *AIAA SPACE 2013 Conference & Exposition*, American Institute of Aeronautics and Astronautics, San Diego, CA, Sept. 2013, AIAA-2013-5328.

[55]Owens, A. C., *Quantitative Pprobabilistic Modeling of Environmental Control and Life Support System Resilience for Long-Duration Human Spaceflight*, Thesis, Massachusetts Institute of Technology, 2014.

[56]Owens, A. C. and de Weck, O. L., "Use of Semi-Markov Models for Quantitative ECLSS Reliability Analysis: Spares and Buffer Sizing," *44th International Conference on Environmental Systems*, International Conference on Environmental Systems, Tucson, AZ, July 2014, ICES-2014-116.

[57]Do, S., Owens, A., and de Weck, O., "HabNet An Integrated Habitation and Supportability Architecting and Analysis Environment," *45th International Conference on Environmental Systems*, International Conference on Environmental Systems, Bellevue, WA, July 2015, ICES-2015-289.

[58]Owens, A. and de Weck, O., "Automated Risk and Supportability Model Generation for Repairable Systems," *66th International Astronautical Congress*, International Astronautical Federation, Jerusalem, Oct. 2015, IAC-15-D1.3.10.

[59]Do, S., Owens, A., Ho, K., Schreiner, S., and de Weck, O., "An Independent Assessment of the Technical Feasibility of the Mars One Mission Plan Updated Analysis," *Acta Astronautica*, Vol. 120, March 2016, pp. 192–228.

[60]Vitali, R. and Lutomski, M. G., "Derivation of Failure Rates and Probability of Failures for the International Space Station Probabilistic Risk Assessment Study," *International Conference on Probabilistic Safety Assessment and Management*, Berlin, June 2004.

[61]Reysa, R. P., Lumpkin, J. P., El Sherif, D., Kay, R., and Williams, D. E., "International Space Station (ISS) Carbon Dioxide Removal Assembly (CDRA) Desiccant/Adsorbent Bed (DAB) Orbital Replacement Unit (ORU) Redesign," *37th International Conference on Environmental Systems*, SAE International, Chicago, IL, July 2007, SAE 2007-01-3181.

[62]Sherif, D. E. and Knox, J. C., "International Space Station Carbon Dioxide Removal Assembly (ISS CDRA) Concepts and Advancements," *35th International Conference on Environmental Systems*, Rome, Italy, July 2005, SAE 2005-01-2892.

[63]Carter, L., Tobias, B., and Orozco, N., "Status of ISS Water Management and Recovery," *42nd International Conference on Environmental Systems*, American Institute of Aeronautics and Astronautics, San Diego, CA, July 2012, AIAA-2012-3594.

[64]Carter, L., "Status of the Regenerative ECLS Water Recovery System," *40th International Conference on Environmental Systems*, American Institute of Aeronautics and Astronautics, Barcelona, Spain, July 2010, AIAA-2010-6216.

[65]Wald, S. I., "Advanced Habitation Strategies for Aggressive Mass Reduction," *AIAA SPACE 2015 Conference and Exposition*, American Institute of Aeronautics and Astronautics, Pasadena, CA, Aug. 2015, AIAA-2015-4449.

[66]Aggarwal, K. and Gupta, J., "On Minimizing the Cost of Reliable Systems," *IEEE Transactions on Reliability*, Vol. R-24, No. 3, Aug. 1975, pp. 205–205.

[67]Dezfuli, H., Kelly, D., Smith, C., Vedros, K., and Galyean, W., "Bayesian Inference for NASA Probabilistic Risk and Reliability Analysis," Technical Report NASA/SP-2009-569, National Aeronautics and Space Administration, Washington, DC, June 2009.

[68]Siddiqi, A. and De Weck, O. L., "Spare Parts Requirements for Space Missions with Reconfigurability and Commonality," *Journal of Spacecraft and Rockets*, Vol. 44, No. 1, Jan. 2007, pp. 147–155.

[69]Jones, H., "Common Cause Failures and Ultra Reliability," *42nd International Conference on Environmental Systems*, American Institute of Aeronautics and Astronautics, San Diego, CA, July 2012, AIAA-2012-3602.

[70]Taminger, K. M., Hafley, R. A., and Dicus, D. L., "Solid Freeform Fabrication: An Enabling Technology for Future Space Missions," April 2002.

[71]Bodiford, M., Ray, J., Gilley, S., Kennedy, J., and Howard, R., "Are We There Yet?....Developing In-situ Fabrication & Repair Technologies to Explore and Live on the Moon and Mars," American Institute of Aeronautics and Astronautics, Jan. 2005, AIAA-2005-2624.

[72]National Research Council, *3D Printing in Space*, July 2014, DOI: 10.17226/18871.

[73]Prater, T., Bean, Q., Beshears, R., Rolin, T., Werkheiser, N., Ordonez, R., Ryan, R., and Ledbetter III, F., "Summary Report on Phase I Results from the 3D Printing in Zero-G Technology Demonstration Mission, Volume I," Technical Report NASA/TP-2016-219101, National Aeronautics and Space Administration, Huntsville, AL, July 2016.

[74]Johnston, M. M., Werkheiser, M. J., Snyder, M. P., and Edmunson, J., "3D Printing In Zero-G ISS Technology Demonstration," *AIAA SPACE 2014*, American Institute of Aeronautics and Astronautics, San Diego, CA, Aug. 2014, AIAA-2014-4470.

[75]Cooper, K., McLemore, C., and Anderson, T., "Cases for Additive Manufacturing on the International Space Station," *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, American Institute of Aeronautics and Astronautics, Nashville, TN, Jan. 2012, AIAA-2012-0517.

[76]Grenouilleau, J. C., Housseini, O., and Prs, F., "In-Situ Rapid Spares Manufacturing and Its Application to Human Space Missions," American Society of Civil Engineers, Feb. 2000, pp. 42–48.

[77]Bagdigian, R. M., Dake, J., Gentry, G., and Gault, M., "International Space Station Environmental Control and Life Support System Mass and Crewtime Utilization In Comparison to a Long Duration Human Space Exploration Mission," *45th*

International Conference on Environmental Systems, International Conference on Environmental Systems, Bellevue, WA, July 2015, ICES-2015-094.

[78]Shishko, R., Fradet, R., Do, S., Saydam, S., Tapia-Cortez, C., Dempster, A. G., and Coulton, J., "Mars Colony in situ resource utilization: An integrated architecture and economics model," *Acta Astronautica*, Vol. 138, Sept. 2017, pp. 53–67.

[79]Sanders, G., "ISRU - An overview of NASA's current development activities and long-term goals," *38th Aerospace Sciences Meeting & Exhibit*, American Institute of Aeronautics and Astronautics, Reno, NV, Jan. 2000, AIAA-2000-1062.

[80]Sanders, G. B. and Larson, W. E., "Progress Made in Lunar In Situ Resource Utilization under NASAs Exploration Technology and Development Program," *Journal of Aerospace Engineering*, Vol. 26, No. 1, Jan. 2013, pp. 5–17.

[81]Flynn, M. and Rosenberg, S. D., "In Situ Production of High Density Polyethylene and Other Useful Materials on Mars," *35th International Conference on Environmental Systems*, SAE International, Rome, Italy, July 2005, SAE 2005-01-2776.

[82]Edmunson, J. and McLemore, C. A., "In Situ Manufacturing is a Necessary Part of Any Planetary Architecture," *Concepts and Approaches for Mars Exploration*, Houston, TX, June 2012, M12-1867.

[83]McLemore, C. A., Fikes, J. C., Darby, C. A., Good, J. E., and Gilley, S. D., "Fabrication Capabilities Utilizing in Situ Materials," *AIAA SPACE 2008 Conference & Exposition*, American Institute of Aeronautics and Astronautics, San Diego, CA, Sept. 2008, AIAA-2008-7854.

[84]Ebeling, C. E., *An Introduction to Reliability and Maintainability Engineering*, Waveland Press, Long Grove, IL, 2nd ed., 2010.