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Quantifying the Impact of Systems Interdependencies in Space Systems Architectures

Cesare Guariniello[a]*, Melanie Grande[a], Christopher Brand[a], Liam Durbin[a], Michael Dai[a], Ashwati Das-Stuart[b], Reginald Alexander[c], Kathleen Howell[a], Daniel DeLaurentis[a]

[a] *School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Ave, West Lafayette, IN 47907*
[b] *NASA Jet Propulsion Laboratory, 4800 Oak Grove Dr, Pasadena, CA 91109*
[c] *NASA Marshall Space Flight Center, Martin Rd SW, Huntsville, AL 35808*
* Corresponding Author

Abstract

Due to the high number of systems in a space mission architecture and to their complex interactions, identifying risk and critical operational dependencies is not obvious. Traditional systems engineering methodology and risk assessment does not capture the impact of interactions between systems nor the cascading effects of disruptions. Based on these considerations, the Systems Operational Dependency Analysis methodology was developed for use by systems analysts and decision makers. This methodology utilizes a parametric model of interdependencies between systems to quantify the direct and indirect impact of system disruptions on other systems, as well as identify root causes. The results are effective at providing decision support for prioritizing technology investment based on risk reduction associated with potential system disruptions. Expanding on research presented at IAC 2018 and based on a collaboration with NASA Marshall Space Flight Center, this paper applies the Systems Operational Dependency Analysis methodology to NASA Lunar Gateway in collaboration with NASA's lunar exploration plans. The paper presents a hierarchical representation of the interdependencies between a Gateway habitat's systems and subsystems, demonstrates quantification of the impact of disruption, and assesses the criticality of the constituent systems and subsystems.
Keywords: System-of-Systems, Dependencies, Gateway, Lunar

Acronyms

AWB	Analytic Work Bench
C&DH	Command and Data Handling
COD	Criticality of Dependency
DIM	Disruption Impact Matrix
DoD	Department of Defense
ECLSS	Environmental Control and Life Support System
IOD	Impact of Dependency
MMOD	Micro Meteoroid and Orbital Debris
PPE	Power and Propulsion Element
RPO	Robust Portfolio Optimization
SERC	Systems Engineering Research Center
SE	Self-Effectiveness
SME	Subject Matter Expert(s)
SOD	Strength of Dependency
SoS	System-of-Systems
SODA	Systems Operational Dependency Analysis

1. Introduction

The most common and well-established methodologies for the design and architecture of space missions and systems [1, 2] are not always capable of dealing with the many variables and considerations involved with space systems. Interactions between systems can cause unexpected cascading impact when failures occur, as well as propagation of delays. Optimization of every system, while at the same time considering possible budget limitations, goals of all individual stakeholders and the potential changes in some of the mission goals and policies, may be an unattainable goal. In previous research [3] we highlighted the importance of a systemic view, meant to be integrated with the conventional approach to space mission architecture design, and capable of providing objective analysis of a large amount of technologies and architectures.

Furthermore, space missions are characterized by possible independence of constituent systems, emergent behavior due to the interactions, and a dynamic nature. These are some of the traits that characterize a System-of-Systems [4]. Various authors agree that space missions and systems are well suited to be treated as SoS [5, 6]. Based on these considerations and on experience gathered in the study of complex systems in Defense and Air Transportation, we advocated the use of SoS methodology for high-level analysis of space systems and for decision support [7]. We also proposed and demonstrated the use of a SoS Analytic Work Bench (AWB), which is a set of tools and methodologies addressing different aspects of a SoS problem [3, 8].

Previous work included a continuing effort to develop the AWB, with the support and collaboration of Subject Matter Experts (SME) at NASA, and to tailor it to space architecture analysis. The methodology proved effective to the study or Mars architectures and was later applied to the analysis of lunar exploration architectures, with evaluation in terms of cost, performance, cascading failures and criticalities, schedule and delays. The ongoing research effort identified multiple areas of interest for further assessment improvement of the methodology. This paper describes three of the features added to the application of AWB methodology to the analysis of space systems:

- Use of functional decomposition for identification of systems and subsystems (and their dependencies) for analysis with Systems Operational Dependency Analysis (SODA).
- Analysis of systems and subsystems at a lower level of abstraction (past applications focused on whole architectures, the case study presented in this paper addresses the dependencies of systems and subsystems of the habitat in NASA Lunar Gateway). This approach yields multiple results of interest for what concerns the cascading impact of disruptions.
- Identification of the most critical subsystems is also used to guide technology insertion and enhancement, to project the impact of each subsystems on a mission architecture.
- Implementation of the Disruption Impact Matrix (DIM), a graphic user interface for quick visualization of large amount of information concerning cascading impact of systems and subsystems disruptions.

2. Overview of the System-of-Systems Analytic Work Bench

The SoS AWB has been developed within research projects of the Systems Engineering Research Center (SERC) to meet the needs of the US Department of Defense (DoD) for new methodologies to be used for analysis and synthesis of SoS architectures [8, 9]. The AWB provides a set of tools to analyze various aspects of complex SoS Architectures, such as robustness, performance, schedule, and cost. The toolset is meant to support decision-making by facilitating analysis of the trade space and providing quantitative and visual results of the analysis of SoS behavior.

While tools in the AWB have been used in a variety of research sectors, including Cybersecurity [10] and Global Navigation Satellites Systems [11], collaboration with SME from NASA provided a testbed for analysis of space mission which resulted in substantial improvement of the usefulness and usability of the AWB. While multiple methods from the AWB have been continuously used in this research effort, this paper focuses on the use of SODA for the analysis of the habitation portion of NASA Lunar Gateway.

2.1. Systems Operational Dependency Analysis (SODA)

SODA methodology, developed in part based on Functional Dependency Network Analysis [12, 13], addresses the operational domain of a SoS, by providing analysis of the impact of dependencies between constituent systems on the propagation of the effect of disruptions.

In SODA, a parametric model of system behavior is combined with a network representation for the system architecture. Figure 1 shows an example of this representation for the high-level systems of a Lunar Gateway habitation module, where the nodes are systems within the architecture, and the edges are operational dependencies between the systems.
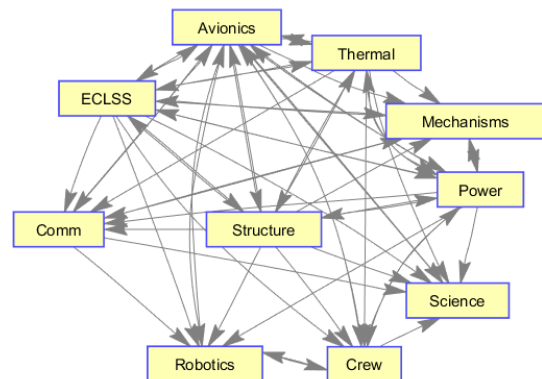

Figure 1. High-level dependency network for a habitation module.

In SODA, a small set of parameters were used to simplify the dependencies between each system. These parameters were chosen to represent aspects of the dependency of the operability of a system on the operability of another systems [14]. The Strength of Dependency (SOD) represent a linearized operational dependency between systems in the case of small disruptions. The Criticality of Dependency (COD) represents the loss of operability due to major disruptions. The Impact of Dependency (IOD) models the boundary between the small disruption regime and the major disruption regime. Figure 2 Based on the parameters of the model, SODA can quantify the cascading effect of disruptions in the architecture and constitutes a quantitative method of risk analysis which can be used to expand the traditional risk matrix.

The algorithm can also model partial failures, both deterministic and stochastic, and multiple paths of propagation within the model. SODA thus provides early-stage feedback for the architecture's design, reducing the amount of simulation and other verification methods required to ensure mission feasibility and to identify criticalities and areas of potential emergent behavior.

3. Application of SODA in support of strategic decisions in space mission design

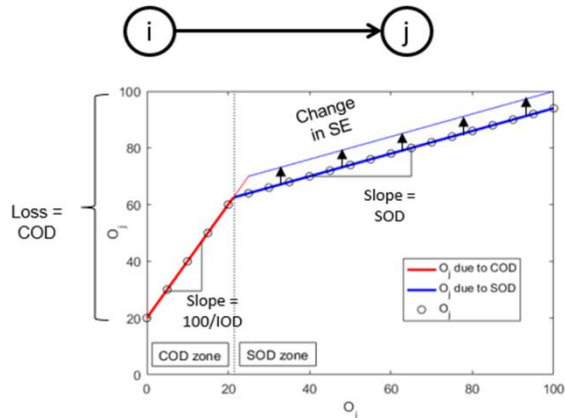*Figure 2. SODA piecewise linear model of dependency of the operability of systems j on the operability of system i.*

The continuing collaboration with SME from NASA Marshall Space Flight Center focused on determining how to tailor SODA can be tailored to specific applications while maintaining the flexibility and domain-agnosticism of the tool, so that changes in mission aspects would not hinder the usefulness of the method. In particular, the research effort that produced the results presented in this paper focused on application to the study of the Lunar Gateway habitation module, including major on-board systems (for example, Environmental Control and Life Support System, ECLLS), and their constituent subsystems (for example, the Water Management Subsystem).

We ran a variety of tests where different level of disruptions of individual elements or sets of elements were fed into the SODA tool to evaluate the impact of these disruptions on all the other elements. The resulting operability due to the combined cascading effect of the disruptions was analyzed to gather useful insight into the behavior of the systems and subsystems of the habitation module in the operational domain.

Some of the simplest scenarios we used to verify that the computational tool provided the expected results. Other scenarios provided information on criticalities of the architecture and constitute the first step in a process of root cause analysis.

4. Case Study: Gateway Habitat Module

Through our partnership with NASA, this research considered a large-scale space architecture with in-depth analysis of a selected number of systems. The Lunar Gateway was selected for this case study since it is an ideal example of a complex collection of systems to be used in a large architecture. The Lunar Gateway is envisioned by NASA as a spaceport in lunar orbit which will enable human exploration of the Moon and beyond [15]. In particular, a notional habitat element has been identified as the focus for the SODA application. The goals of this research were to review NASA's plans for the Lunar Gateway, to develop a framework by which to study the systems design and alternatives, and to assess critical technology development needs for human space exploration.

4.1. Functional Decomposition of the Gateway

The first step in the SODA process involved decomposition of the Gateway into relevant elements and systems, based on a functional decomposition. This process was performed using publicly available information for the current Gateway architecture. At the time of execution of this study, NASA's plans for the Lunar Gateway included delivery to lunar orbit of multiple elements, including a Power and Propulsion Element, habitats, a robotic arm, an airlock, and logistics and utilization modules, as shown in Figure 3. Each of these elements was further decomposed into systems based on the functional responsibility expected from each, in a process based on discussion with NASA SMEs. Further, the systems constituting the habitation module were decomposed into subsystems, based on a standardized statement of
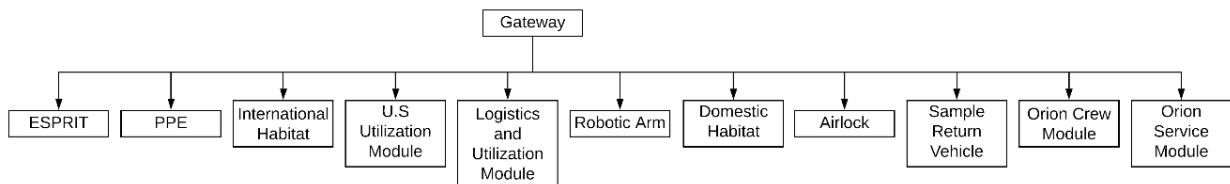

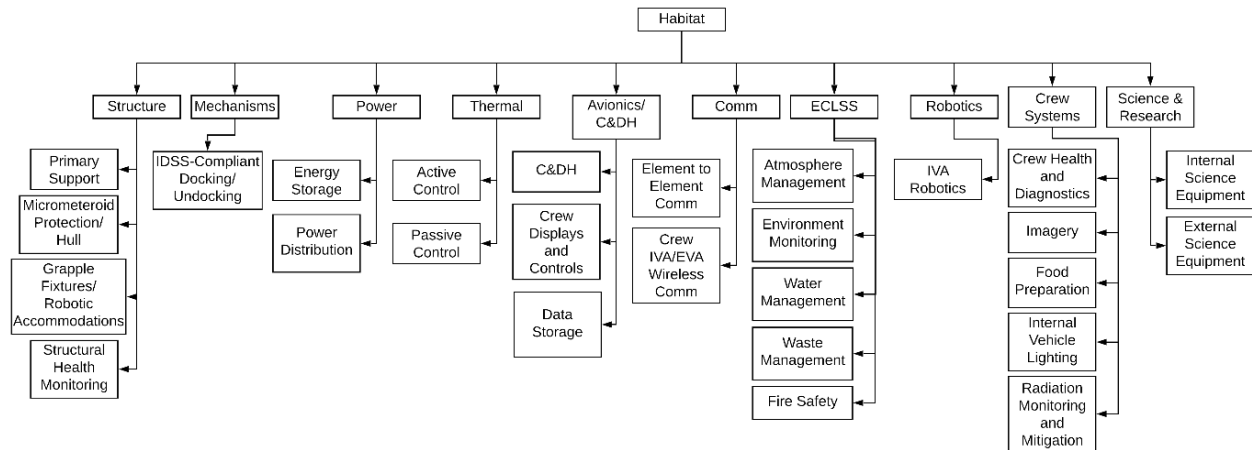*Figure 3. Elements envisioned for NASA Lunar Gateway.*

Figure 4. Habitat systems and subsystems decomposition.

functionality, and assessed for dependencies—again based on discussion with SMEs and a detailed literature review of previous flight systems. This work identified 10 systems in the habitation module and 27 constituent subsystems. The system- and subsystem-level breakdown, is shown in Figure 4. This deeper breakdown into subsystems allows for more detailed and nuanced results than would be possible by staying at the system level. On the other hand, systems can be grouped up to provide analysis of entire space mission and space architectures. Each system and subsystem is accompanied by description and documentation.

4.2. Habitat Dependency and SODA Parameters

Next, a Dependency Matrix was created for a notional habitat element, which displays both the existence of dependencies between subsystems and the SODA dependency parameters. An understanding of the functional responsibilities of each subsystem—found in the previous step—was critical to the identification of operational dependencies, appropriate ratings, and key failure modes. Considerations about the specifics of the Gateway were also kept into account to determine the potential direct interaction between systems, which is used in SODA to evaluate the cascading effect of disruptions. For ease of use in this demonstrative application, the three SODA parameters describing each dependency—SOD, COD, and IOD—were given representative values corresponding to "Low" (L), "Medium" (M), or "High" (H). For SOD, which ranges from 0 to 1, the three levels were respectively 0.1, 0.4, and 0.9. For COD, which ranges from 0 to 100, the three levels were respectively 20, 50, and 100 (values of 10, 40, and 90 could result in trivial cases). For IOD, which ranges from 0 to 100, the three levels were respectively 10, 40, and 90. With this "LMH" method, the dependency parameters could be assigned to each

subsystem in a more intuitive manner for the team, based on expertise and literature review. Since this is a non-traditional analysis methodology, selection of exact parameter values requires an understanding of the sensitivities in the methodology. However, the selection of low, medium, and high levels is enough to provide understanding of the dynamics of the SoS.

A selection of the results of the assignment (L, M, or H in the order: SOD, COD, then IOD) is shown in the Dependency Matrix in Figure 5. Each column is a subsystem that may be impacted based on its dependency on a subsystem in each row. A preliminary review of this matrix clearly shows that some subsystems have impact on many other subsystems (for example, the blue-highlighted rows), while others do not appear critical to the habitat's operation based on few dependencies (pink-highlighted rows). For example, many subsystems depend on power distribution, often with "high" criticality of dependency, since many subsystems need electrical power to work at all. These dependencies have a range of values for impact and strength of dependency, though. In this case, low or medium SOD, for example, reflects that a disrupted power distribution subsystem does not immediately impact critical functions—in other words, as power flow is reduced, the subsystem may flexible enough to be capable of prioritizing functions or operating in a low-power mode before losing significant functionality. However, the matrix shows only direct impact, while SODA uses this information to build a model to evaluate the impact of single or multiple disruptions on all of the elements, accounting for the whole network of dependencies, and therefore being able to identify potential emergent behavior and root causes of indirect impact of disruptions.

It should be noted that the set-up for running the SODA tool—the two steps described above—has in this work be performed by hand with extensive

Impacted Subsystems →

System	Subsystem	Structures				Mechanism	Power		Thermal		Avionics/C&DH			Communications		ECLSS					Robotics	Crew Systems					Science and Research	
System	**Subsystem**	Primary Support Structure	MMOD Protection/Hull	Fixtures/Robotic Accommodations	Structural Health Monitoring	IDSS-Compliant Docking/Undocking Subsystem	Energy Storage	Power Distribution	Passive Thermal Control	Active Thermal Control	Command & Data Handling and Data Processing	Crew Displays and Controls	Data Storage	Element to Element Communication	Crew IVA/EVA Wireless Comms	Atmosphere Management	Environmental Monitoring	Water Management	Waste Management	Fire Safety	IVA Robotics	Crew Health and Diagnostics	Imagery Subsystem	Food Preparation Subsystem	Internal Vehicle Lighting	Radiation Monitoring and Mitigation	Internal Science and Research	External Science and Research Accommodations
Structures	Micrometeoroid Protection/Hull		■	LHL				MHM	HHH	MHM	LHL	LHL	LHL			LHL		LLM	LHL	LHL		LHL			LHL		LHL	
Mechanisms	IDSS-Compliant Docking/Undocking					■	LMH	HHH						LML		LLM				LHL								
Power	Power Distribution			MHM	LHL	MMM		■	HHL	MHM	HHH	LMH	LHL	MHM		MHM	HHL	MHM	LML	HHL	MHM	MMM	LHL	LML	LHL	MHM	LML	MHM
Thermal	Active Thermal Control			LHL			LML	MHM		■						LML		MHM	LML									
Avionics/ C&DH	Command & Data Handling			MHH				LML		MHM	■	LML	LLM	LML		MHM		MHM	LML	MMM	LHL		LHL		LHL	MHM	MHM	MHM
Communications	Element to Element Communication					LMH							LLM	■							HHL							
ECLSS	Environmental Monitoring												LLM			MHM	■	MHM	MHM	LLM								
ECLSS	Fire Safety	HHH	MHM	MHM	HHH	HHH	MHM	MHM	MHM	MHM	LLM		LLM	LLM		MHM	MHM	MHM	MHM	■	MHM	MHM	MHM	MHM	MHM	MHM	MHM	MHM
Crew Systems	Crew Health and Diagnostics												LLM									■						
Crew Systems	Food Preparation Subsystem																							■				
Science and Research	Internal Science and Research												LLM														■	

Figure 5. Selected rows of the dependency matrix for the Gateway habitat subsystems.

literature review and essential discussions with SMEs. However, future advancements in machine learning have the potential to support the human-in-the-loop. Organizations may benefit from machine learning or artificial intelligence to perform literature review and even parameter assessment for quicker model-building in the future.

4.3. Results from SODA Analysis

We used both the stochastic and the deterministic versions of SODA to analyze the effect of dependencies between the Gateway subsystems as defined by the L/M/H values for SOD, COD, and IOD. In the stochastic analysis, we determine the expected operability of all subsystems in a nominal case (Figure 6). This considers a probability distribution on each subsystem's self-effectiveness (SE), which is a quantification of its internal status, independent from the impact from other subsystems. The dependencies are then taken in consideration according to the SODA model, resulting in a distribution of the operability of each subsystem, i.e. its overall status. As expected, in the nominal case the operability of the subsystems is very high, especially those related to crew and environmental control. The operability of some of the subsystems, especially those exposed to space environment, exhibit lower expected value and a larger variability in operability, due to the higher probability to be potentially subject to minor disruptions.

In the deterministic analysis, we disrupted individual or multiple subsystem, that is we simulated the SoS behavior at different levels of SE of the disrupted system (ranging from fully functional to fully inoperative) and measured the resulting impact on the operability of other systems or subsystems. This provides direct insight into the criticality of each subsystem to the operability of the Habitat module. These results are presented in disruption impact range
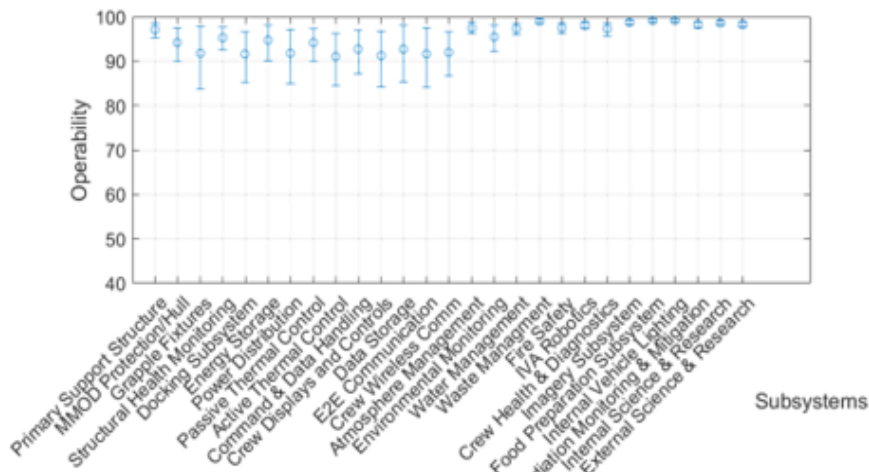

Figure 6. Results of stochastic SODA analysis of the Gateway habitat subsystems.

plots such as the example shown in Figure 7. The systems or subsystems will be referred to as nodes when describing these plots. The vertical axis shows the SE of the disrupted node(s), with lower SE indicating more disruption. Each disrupted node or set of nodes is listed along the horizontal axis. The colored bars corresponding to each disrupted node show the resulting operability of the impacted node(s) for each SE of the disrupted node(s). For quick visual understanding, the user can select three ranges of resulting operability, corresponding to nominal operability (green), sub-nominal operability (yellow), and critical status (red). For example, Figure 6 shows the impact of disrupting power subsystems on the operability of thermal control system. Disrupting the power distribution subsystem to an SE of 50 will result in a sub-nominal operability of the thermal system, while disrupting energy storage by the same amount will leave the thermal system in the range of nominal operability. This suggests that power distribution is more critical than energy storage to the thermal system. We used these plots to investigate impacts of single disruptions and combined disruptions with both direct and indirect dependencies of the impacted node on the disrupted node. While the plots provide a preliminary understanding of the behavior of the SoS in terms of ranges of operability, the SODA tool can be used to simulate specific levels of disruption, deterministic or stochastic, and compute the value of the resulting operability based on the parametric model.
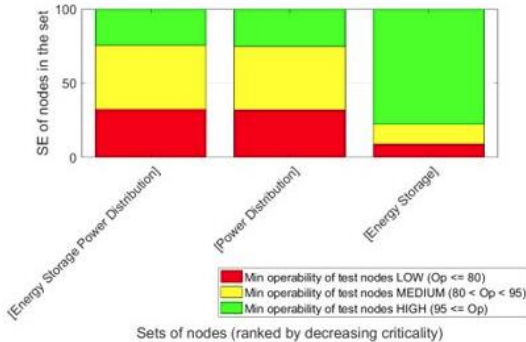

Figure 7. Impact of disrupting power subsystems on the operability of the thermal control system.

4.3.1 Single Subsystem Disruptions

The most straightforward deterministic analysis consists of disruption of individual subsystems, in order to observe the operability of a single impacted subsystem. Figure 8 shows the impact of disrupting each subsystem individually on the Atmosphere Management subsystem in ECLSS.

Fire Safety has the most critical impact on the operability of Atmosphere Management while disruptions in other subsystems like Water Management or IVA Robotics have little or no effect. Figure 9 shows the results of disrupting each of the ECLSS subsystems and observing the impact on the Avionics subsystems. Fire Safety is again the most critical subsystem, while disrupting any other subsystem in ECLSS has little impact on the operability of Avionics (for example, disruptions in the atmosphere management subsystem do not strongly impact avionics). We found Fire Safety to be a critical subsystem for the operability of most systems in the Gateway Habitat as an unchecked fire could damage many subsystems and cause a cascading effect on the overall operability of the Habitat module.
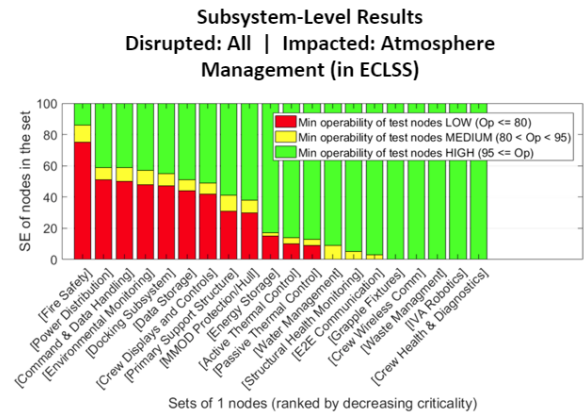

Figure 8. Impact of disrupting each individual subsystem in the lunar Gateway habitat on the operability of the atmosphere management subsystem.
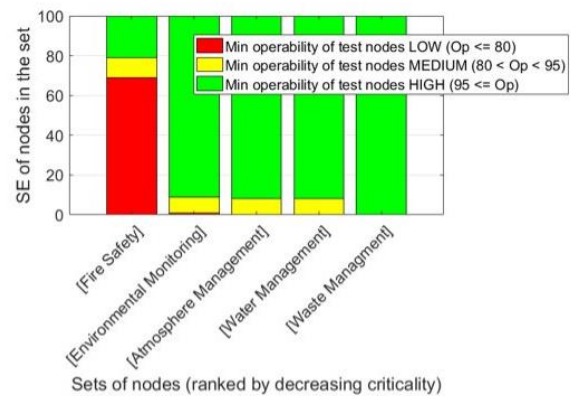

Figure 9. Impact of disrupting each ECLSS subsystems on the operability of avionics, which highlights the criticality of the fire safety subsystem.

If the user is interested in further details about the cause of observed results, analysis of the paths connecting the subsystems provides root cause analysis. For example, Figure 10 shows all the dependencies between subsystems in the habitation module of the lunar Gateway. Dependencies belonging to paths that connect Fire Safety and Atmosphere Management to subsystems in the Avionics system (blue boxes) are highlighted in colors. Dependencies with low COD and SOD appear in green, dependencies with medium strength and criticality are yellow, while strong dependencies are red. While there are no major direct dependencies between the subsystems under consideration, the path connecting Fire Safety, Power Distribution, and Crew Displays and Controls has all strong dependencies, which causes the observed criticality of the Fire Safety subsystem on the operability of Avionics, due to the cascading impact of disruptions. Instead, all the paths between the Atmosphere Management subsystem and Avionics subsystem present at least one weak dependency, resulting in a nominal range of operability of Avionics following disruptions of the Atmosphere Management subsystems.

Figure 10 also highlights the complexity of the interactions in a SoS, even for just one module in the whole architecture, and therefore it underlines the importance of providing results with different level of detail, varying from specific disruption impact range plots for preliminary analysis to detailed root cause analysis.

The ranked criticalities of disruptions shown in the impact range plots can be combined with stochastic results for the "likelihood" of each disruption occurring, to obtain more nuanced results than what is usually available from the traditional risk-severity matrix.

4.3.2 Combined Disruptions

Disruptions of multiple subsystems at once can be used to study more complex disruption scenarios. Figure 11 shows the impact that disrupting multiple subsystems in Structures has on Crew Systems and Thermal. Note that some of the labels along the horizontal axis contain more than one subsystem, so the bar indicates the impact of the combined disruption of those subsystems. Disrupting multiple subsystems generally has a more significant impact, as would be expected. However, sometimes disrupting an additional subsystem has no appreciable change on the impacted node's operability if the impacted node has weak dependence on the added disrupted node. A trivial case of this can be seen in the lack of effect that combining a disruption in any structural subsystem
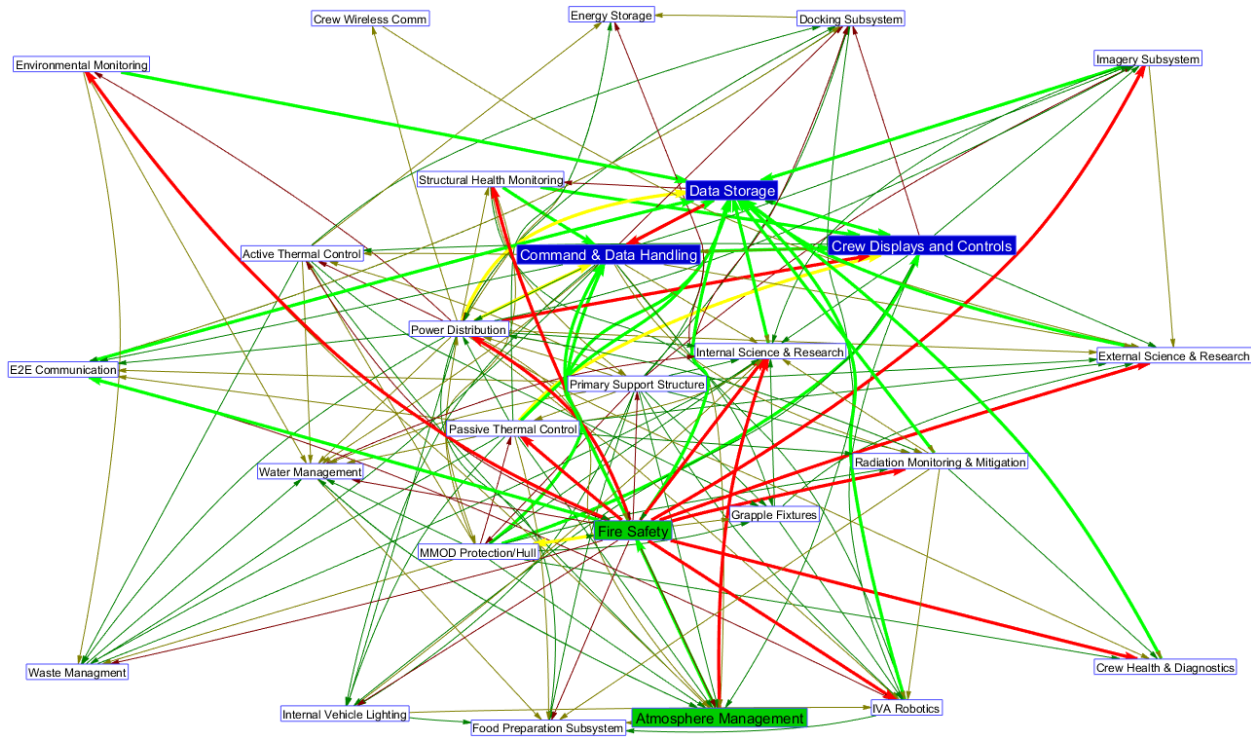

Figure 10. Network of operational dependencies of the subsystems in the lunar Gateway habitation module. All the paths connecting Fire Safety subsystem and Atmosphere Management subsystems to the avionics subsystems are colored according to their strength and criticality (green indicating a weak dependency, yellow a medium one, and red a major dependency). Analysis of paths provides root cause analysis of observed behavior.

with a disruption in Grapple Fixtures has on the operability of Crew Systems or Thermal. A more interesting example is shown in Figure 7. Here Thermal has a weak dependence on Energy Storage but combining a disruption in Energy Storage with a disruption in Power Distribution appears to have no more impact than disrupting the Power Distribution alone. This suggests that some or all of the impact of disrupting one node is already accounted for in the impact of the disruption of the other system.

Figure 11 also shows the different effects of disruptions in a given system. Both plots in the figure show high impacts of combining disruptions of the primary support structure, hull, and structural health monitoring. The Thermal system is more strongly impacted by damage to the primary support structure and hull than Crew Systems since much of the thermal control components (e.g. radiators, insulation) are attached directly to the outside structure. Neither Thermal nor Crew Systems are impacted much by disruptions in structural health monitoring or grapple fixtures.

4.3.3 Hierarchical Model

The SODA model built on the system decomposition of the Habitat module considers interfaces to other levels on the system hierarchy. For example, one assumption used in this analysis was that power is generated outside the Habitat module in a Power and Propulsion Element (PPE). Therefore,
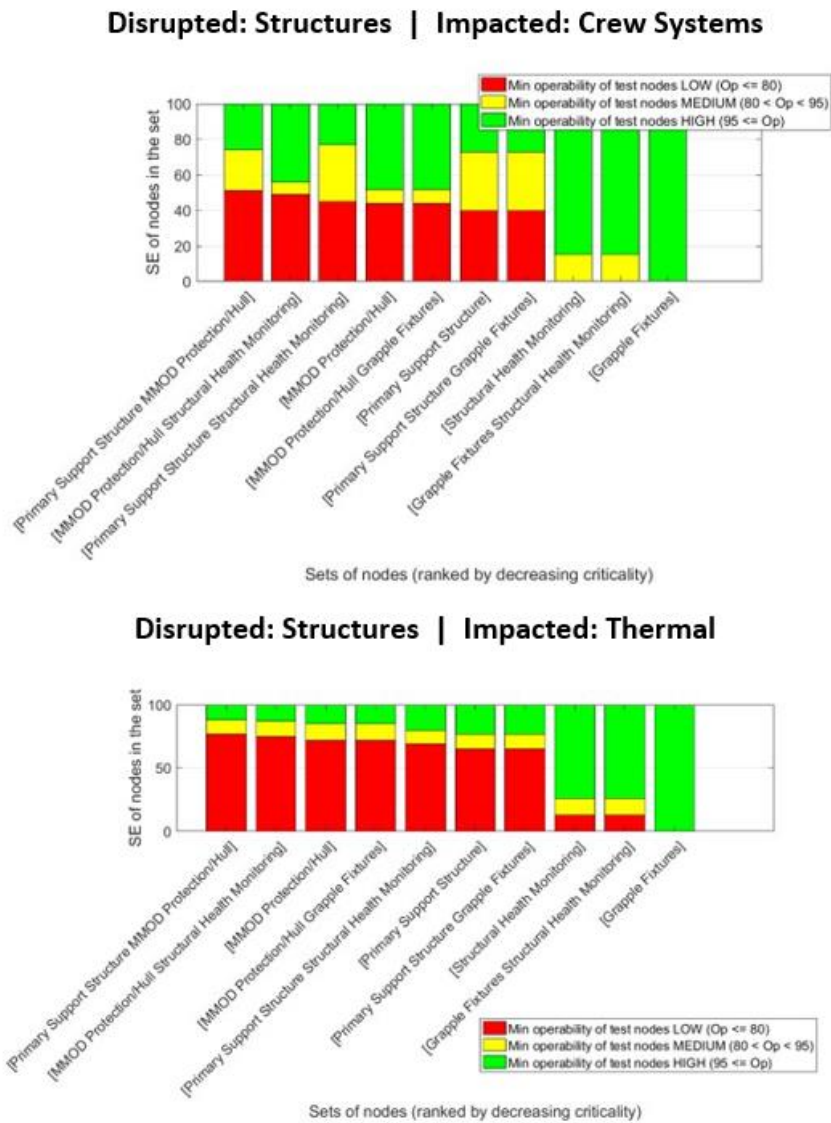

*Figure 11. Combined disruptions of structural subsystems and their varying impacts
on crew systems and thermal systems.*

power must be transferred to the Habitat through its docking port connection to the PPE. The model captures this relation by assigning to Power Distribution a dependency on the Docking subsystem, with the results shown in Figure 12.
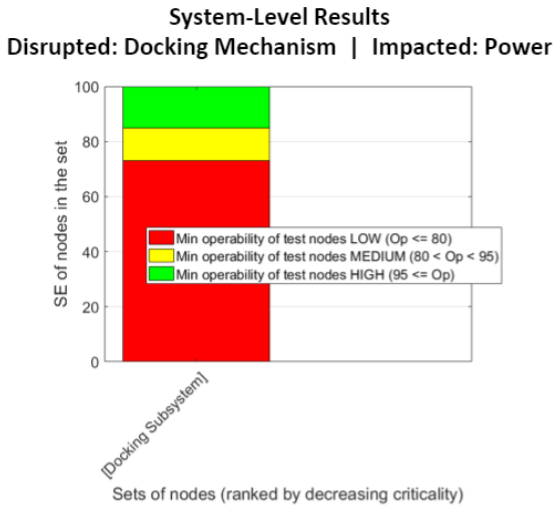

Figure 12. The hierarchical model allows for dependency on outside systems through interfaces, such as the dependency of the power system on the docking mechanism.

The consideration of hierarchy in this analysis allows for the easy combination of results for multiple elements in an architecture through their interfaces.

4.4 Disruption Impact Matrix

The disruption impact range plots, though simplified with respect to the full visual network of dependencies, provide much useful information but they can become overwhelming when considering all the possible permutations for complex analyses. We developed the Disruption Impact Matrix (DIM) to provide a compact view of all impacts from disrupting a system or subsystem at a specified level. For the habitat case study, a DIM was created at both the system and subsystem levels. The system-level DIM is shown in Figure 13. Each row corresponds to a disrupted system and each column corresponds to an impacted system. The color of each cell represents the range of operability of the system in that column given a disruption in the system in that row. The number (1-27) in the cell indicates the individual subsystem that has the most impact. For example, the cell (ECLSS, AVN) in the matrix represents the results shown in Figure 9. The cell is colored red to indicate the high criticality of ECLSS subsystems to Avionics and the 19 in the cell indicates that Fire Safety is the most impactful disruption. The amount of disruption can be adjusted with a slider and the matrix is updated in real time.

The DIM allows users to quickly get an idea of the most critical dependencies so that more focused analysis can be conducted. Clicking on a cell in the matrix will open the corresponding disruption impact range plot for closer inspection of the dependencies. The subsystem-level DIM (Figure 14) provides more granularity and insight into the specific subsystem-to-subsystem dependencies. At first glance, Figure 14 shows that Fire Safety is highly critical at a disruption level of 55. Primary Support Structure, Micro Meteoroid and Orbital Debris (MMOD) Protection, Power Distribution, and Avionics are also critical. Similarly, those are the subsystems for which technological enhancement or insertion will have the highest impact on the whole mission. The slider in the subsystem DIM can be adjusted to observe how the criticalities of dependencies change at different amounts of disruption.
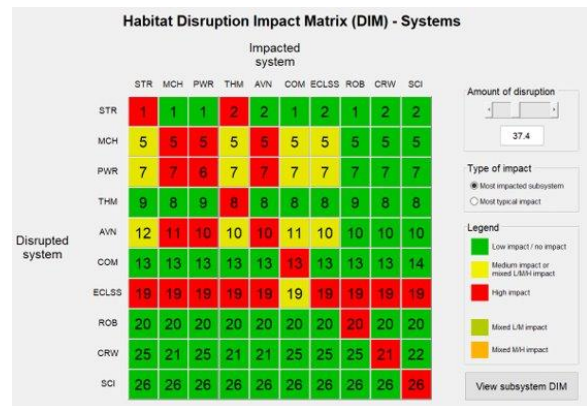

Figure 13. Results for habitat's system-level Disruption Impact Matrix (DIM) at a level of disruption of 37.4.

5. Conclusions

This work illustrated an application of the AWB methodology to a more detailed and lower-level case study, that is the habitation module of NASA lunar Gateway. The main tool used for this application, SODA, has been improved based on feedback provided by SME. Methodological advances and results include:

- Construction of the dependency networks based on functional and systems decomposition, built upon publicly available information and data and insights provided by experts.
- Simplification of the modeling phase by using standard levels to quantify the parameters of the model.

 This is to address the need to facilitate the use of the methodology and to provide better
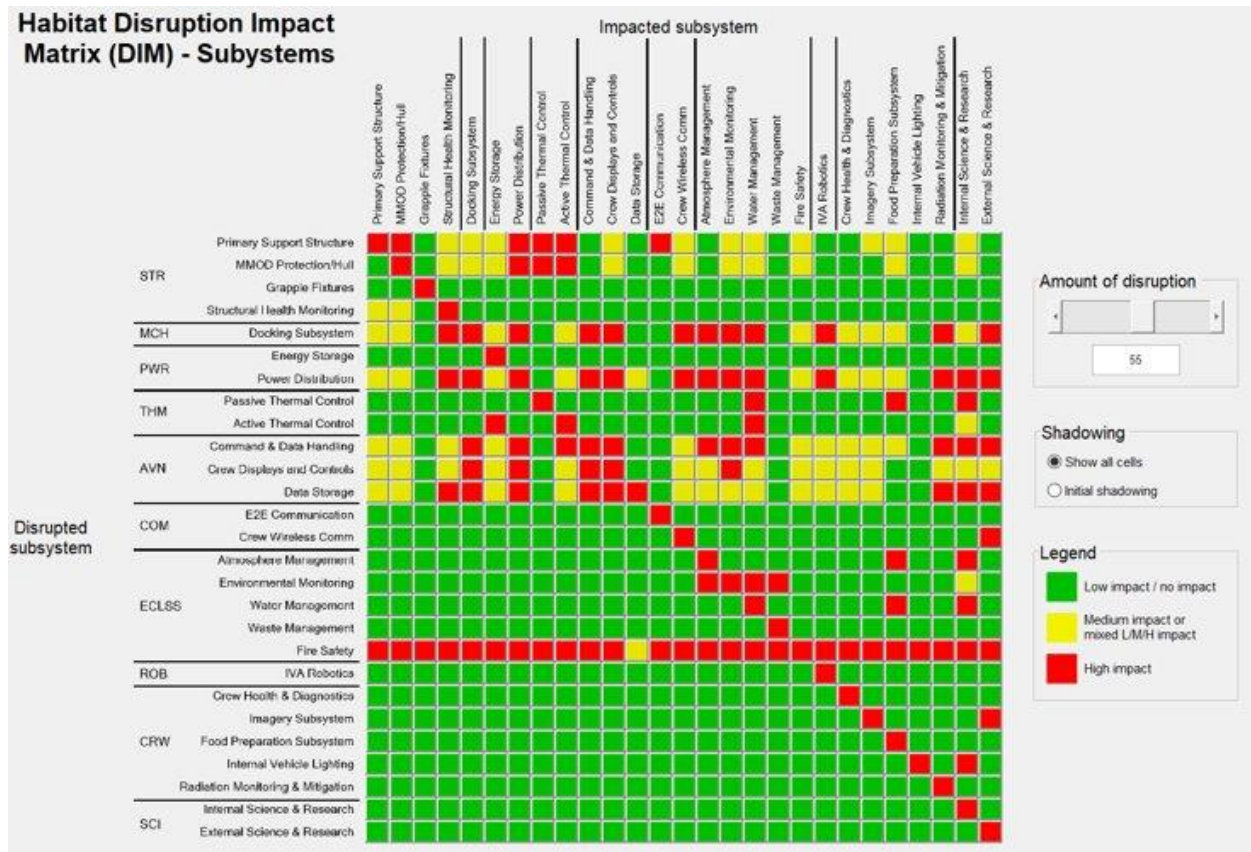
Figure 14. Results for the habitat's Disruption Impact Matrix (DIM) at a level of disruption of 55/100.

visualization and interpretation of result. The standard levels can be refined as needed.

- Case study demonstrated how results can be provided at different level of detail: colored bars are used to clearly show the cascading impact that different level of disruptions in elements of the habitat module have on other elements, while root cause analysis offers deeper and more complex details on the reasons of the observed behavior.

  While these graphic products are associated with the effect of disruptions, stochastic analysis is used to keep into account the likelihood of disruption events.

- Results of SODA analysis identify and quantify the impact of direct and indirect dependencies, thus highlighting the most critical systems. High impact suggests technologies that might requirement enhancement or insertion.

- Implementation of the Disruption Impact Matrix, a comprehensive graphic product which shows at a glance a summary of the large amount of information provided by SODA. In particular, the matrix depicts the various criticalities that can occur in the whole network of systems and subsystems.

- In the case of the lunar Gateway habitation module, SODA analysis suggests that the Fire Safety subsystem is the most critical, together with the primary support structure, MMOD, power distribution and avionics subsystems.

Since the proposed methodology is constantly evolving and being improved based on user needs, we identified promising future directions of research. Since the modeling phase can be time-consuming and involve a large number of sources, we advocate the use of Artificial Intelligence, in particular of search algorithms and Machine Learning, to support the humans-in-the-loop during the modeling phase.

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