POLITECNICO DI TORINO

Department of Mechanical and Aerospace Engineering

ISAE-SUPAERO

Space Advanced Concept Laboratory

MSc. in Aerospace Engineering

Master Degree Thesis

Integrating Human Factors into MBSE towards Lunar Habitat Human-Centered Design

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"Success is not final, failure is not fatal: it is the courage to continue that counts."

Winston S. Churchill

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A Torino, che mi ha cullata tra le sue strade e i suoi sogni, vedendomi crescere passo dopo passo.

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Abstract

Following the Artemis program, a global initiative to revitalize lunar exploration is underway, with a firm commitment to establishing a sustained human presence on the Moon. Recognizing the strategic importance of the lunar South Pole, the International Space Exploration Coordination Group (ISECG) has emphasized the necessity of a long-term surface habitat in the Global Exploration Roadmap by the end of the 2030s. This endeavor represents a significant milestone in human spaceflight, requiring the collaboration of multiple international partners and the integration of diverse engineering disciplines. A lunar habitat will be the most complex extraterrestrial settlement ever designed, necessitating a high degree of autonomy, reliability, and adaptability. To ensure crew safety, health, and operational efficiency, the habitat must accommodate a range of intricate system, human, and environmental interactions. Developed in collaboration with ISAE-SUPAERO (Toulouse, FR), this research delves into the crucial role of integrating Human Factors Engineering (HFE) into Systems Engineering (SE) to facilitate early validation of system architecture and behavior in lunar habitats with a Human-Centered Design (HCD) approach. HFE, characterized by iterative, non-functional, and qualitative methodologies, often faces challenges when juxtaposed with the top-down, function-oriented approach of systems engineering. This study proposes a novel framework that harmonizes these disciplines within a unified, model-driven approach, thereby enhancing the accuracy and comprehensiveness of system characterization throughout mission operations. A key limitation in conventional system modeling languages is the depiction of astronauts as external entities rather than integral components of the system. This paradigm is challenged by advocating for a holistic representation of human-system interactions through Model-Based Systems Engineering (MBSE) models. The methodology involves analyzing the sample system to map task sequences, resource utilization, and data flows, followed by the development of interconnected system- and human-centered diagrams that evaluate both functional and physical attributes. These models are then interfaced and merged to generate an integrated habitat model that includes the crew as an active subsystem, offering new analytical perspectives for systems engineers and human factors specialists during early-stage design processes. The proposed framework not only refines the representation of human-related factors but also enhances interdisciplinary communication among engineers, designers, and mission stakeholders. By embedding astronauts as intrinsic system elements, their influence on mission performance, safety, and reliability is systematically evaluated. Here, the critical role of integrating HFE within SE through MBSE is underscored to optimize lunar habitat design, mitigate mission risks, and ensure the long-term sustainability of human spaceflight beyond Earth's orbit.

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Chapter 1

Introduction

The Artemis program, spearheading the resurgence of lunar exploration, is driven by the aspiration to establish a sustainable human presence on the Moon. The Moon represents not only a valuable scientific frontier but also a launchpad for future missions to Mars and beyond [47] [22]. Exploring and inhabiting the Moon will provide unprecedented opportunities to study its geology, harness its resources, and conduct experiments in a unique environment, ultimately expanding our understanding of the solar system and enhancing our capabilities for deep space exploration [18].

Central to the Artemis program is the strategic significance of the lunar South Pole. This region has been identified by the **International Space Exploration Coordination Group** (ISECG) as pivotal for long-term exploration goals (LTE). The South Pole is of particular interest due to the presence of permanently shadowed craters that harbor water ice. This water ice is a critical resource that can be converted into oxygen and hydrogen, supporting life support systems, fuel production, and other in-situ resource utilization (ISRU) activities essential for prolonged missions. Moreover, the South Pole's unique environment offers continuous sunlight for extended periods, which is advantageous for solar power generation. This makes the location ideal for establishing a robust surface habitat that can serve as a lifeline for astronauts and a cornerstone for extended lunar missions. A surface habitat at the South Pole would provide a stable base for scientific research, resource extraction, and technology development, enabling sustainable human exploration and potentially leading to the development of a lunar economy [18].

However, as mission duration and distance from Earth increase, the risk that crew capability and the safety net of ground support will degrade increases. This can lead to a decreased ability to perform tasks necessary for mission success and, in the worst cases, negatively impact both the health and safety of the crew during the mission and their post-mission long-term health (LTH). It is currently unclear how well crew capability can be maintained in a Mars mission, but it is expected to degrade beyond our historical experience base in any Mars mission scenario. The Moon serves as an invaluable proving ground for the Mars program. The Artemis missions allow us to test different capabilities such as life support systems, habitat structures, and ISRU techniques in a real extraterrestrial environment, while still being close enough to Earth to provide a safety net. This proximity offers a crucial advantage: the ability to quickly return astronauts to Earth in case of emergencies, it has been estimated that the duration of evacuation and return to Earth in an emergency would be between 3 and 11 days from the Moon, something not possible during Mars missions [47]. Furthermore, the experience gained from dealing with the Moon's lower gravity, radiation exposure, and resource utilization directly informs our preparations for the more extreme conditions on Mars.

The lessons learned from establishing a sustainable presence on the Moon will directly impact the success of the Mars program [47]. Additionally, the psychological and physiological data collected from long-duration lunar missions will help us understand and mitigate the effects of prolonged space travel on human health, providing a foundation for the design of Mars missions that prioritize astronaut well-being. Because mission success is highly dependent on the proper design of the habitat within which astronauts operate, the main goal of this research is to ensure a comfortable and habitable environment by ensuring that all user needs are met by placing the user at the center of the focus and modeling the subsystems based on them in terms of requirements, operational, functional and physical analysis.

This thesis aims to address the challenge of designing sustainable habitats for long-duration lunar missions, focusing specifically on the lunar South Pole. The central problem explored is how to create a habitat that meets all the necessary human factors requirements, ensuring the well-being and effectiveness of astronauts. This problem is highly relevant because it directly impacts the success of future space missions, including those to Mars, where the challenges will be even greater [18]. By addressing the specific needs of astronauts, this research contributes to the development of systems that will support human life in space for extended periods. The main contribution lies in designing a habitat that prioritizes astronaut needs and proposed a possible methodology for integrating these factors into the habitat's design, ensuring it meets the physiological and psychological needs of the crew.

The work begins by introducing the broader context of lunar exploration, emphasizing the strategic importance of the Artemis program and the role of the lunar South Pole in advancing sustainable space exploration [42]. It discusses the challenges posed by long-duration missions and the necessity of designing habitats that prioritize astronaut well-being, serving as a foundation for future interplanetary missions for the Moon To Mars program [47]. Following this introduction, a review of existing literature provides a comprehensive analysis of past and current research related to space habitat design. This background study helps to contextualize the problem, identify knowledge gaps, and highlight the importance of an astronaut-centered approach to habitat design.

To address the identified challenges, a structured methodology is employed: it starts by considering the profound impact of the space environment on human spaceflight, recognizing that the habitat is not an isolated system but interacts with its surroundings. Astronauts are exposed to several hazards that influence human performance, physical health, and psychological well-being, necessitating the development of countermeasures to mitigate their effects. After this analysis, the core findings are then presented and analyzed, detailing how the proposed habitat design meets the requirements for long-term lunar habitation, and demonstrating how insights gained from lunar missions will contribute to the design of future Mars habitats.

Finally, the thesis concludes by summarizing the key contributions of this research and outlining potential directions for future work. The study not only provides a framework for optimizing lunar habitats but also serves as a stepping stone for the broader goal of enabling sustainable human presence beyond Earth [22].

1.1 Background

1.1.1 The Space race

Space became one of the main topics of the competition between the United States and the Soviet Union during the Cold War, as each side sought to prove the superiority of its technology and its political and economic power. One of the symbols of the colonization of space was the Moon, the unexplored satellite of our planet Earth.

The Soviet Union was the first to develop a program to achieve the objective of reaching the lunar surface with the Luna Program starting in 1958. On the other side of the Pacific Ocean, in the same year, the USA was creating **NASA** (National Aeronautics and Space Administration), a federal agency dedicated to space exploration, which was developing Project Mercury in order to bring humans to space. However, after the Russian cosmonaut Yuri Gagarin became the first man to journey into outer space in 1961, the USA decided to replace their space program with the more ambitious **Apollo Program**: the new target was the first human being walking on the Moon [37].

After a series of unsuccessful attempts, the first mission able to touch the lunar surface was the Soviet Luna 9 in 1966. In the same year, the American Surveyor 1 landed on the Moon in order to study the moon soil for future Apollo missions. December 1968 saw the launch of Apollo 8, the first manned space mission to orbit the Moon. The next year on July 16 Apollo 11 landed with its crew in the Sea of Tranquility, decreeing the achievement of the most important goal that the space race had set itself. By landing humans on the Moon, the United States accomplished what has been called the greatest technological achievement in human history. Due to their important economic cost, the interest in lunar missions waned after the early 1970s and Apollo 17 in 1972 was the final mission of the Apollo program: the most recent time humans have set foot on the Moon or traveled beyond low Earth orbit [54].

1.1.2 State of the art

The past decade has seen a revival of interest in space travel and the technological innovation driving it. Although the last landing took place in 1972, the Moon remains one of the main key points of human space exploration. There are several reasons why numerous space programs from all over the world were born nowadays to achieve the goal of returning to the lunar surface. With future lunar missions, NASA plans to explore the lunar surface in order to allow the colonization of the satellite and the creation of an outpost for the exploration of deep space. Studying lunar soil and ice in lunar craters will allow scientists to understand the satellite's origin and analyze the possibility of using resources from the Moon in future missions.

Creating an outpost in space will also be useful to support astronauts during their mission, for instance in case an emergency occurs and leads to the abortion of the expedition. Moreover, the Moon will provide a proving ground to test technologies and resources that will take humans to Mars and other deep-space destinations [47]. Considering the desire to mitigate space debris and permit more sustainable space travel, re-usability, and in-space manufacturing are two trends that space exploration intends to follow. This could reduce the cost of space missions and have a significantly lower environmental impact.

1.1.3 Apollo 11 Lunar Module

To return to the lunar surface, hundreds of lunar lander concepts have been developed nowadays and all of these are based on the Apollo program's legacy and the iconic Apollo Lunar Module (LM) [41].
The Apollo 11 LM was the first of the six Apollo LMs that landed on the lunar surface. Precisely, two other LMs were designed earlier to be tested in both the Earth's and Moon's orbit. Moreover, future missions were planned but were canceled due to budget cuts. Unfortunately, during mission Apollo 13 an accident hindered the astronauts making it impossible to land on the Moon [37].

The Apollo 11 LM was a two-stage module able to carry two astronauts. The descent stage was octagonal-shaped with four landing legs on its sides, one of which with a built-in stepladder. The legs had a contact-sensing probe to inform the crew that they were about to touch the ground. The module was composed of 5 compartments containing the descent engine and both the oxidizer and the fuel tanks. The outer area compartments called Quadrants, contained equipment such as a water tank, scientific instruments, a helium tank, and a camera to record the first walk on the Moon [37].
The ascent stage was irregularly shaped and pressurized in order to host the two astronauts. Inside the Crew compartment, the astronauts could take off their suits and see the lunar surface through the windows. A Reaction Control System (RCS) with 16 thrusters was installed to maneuver the LM once it was back in orbit. At the end of the mission, the descent stage was used as a platform for the launch of the ascent stage and left on the Moon's surface.

1.1.4 Artemis program

One of the most ambitious space programs in this regard is NASA's Artemis program, which aims to establish a sustainable human presence on the Moon as a

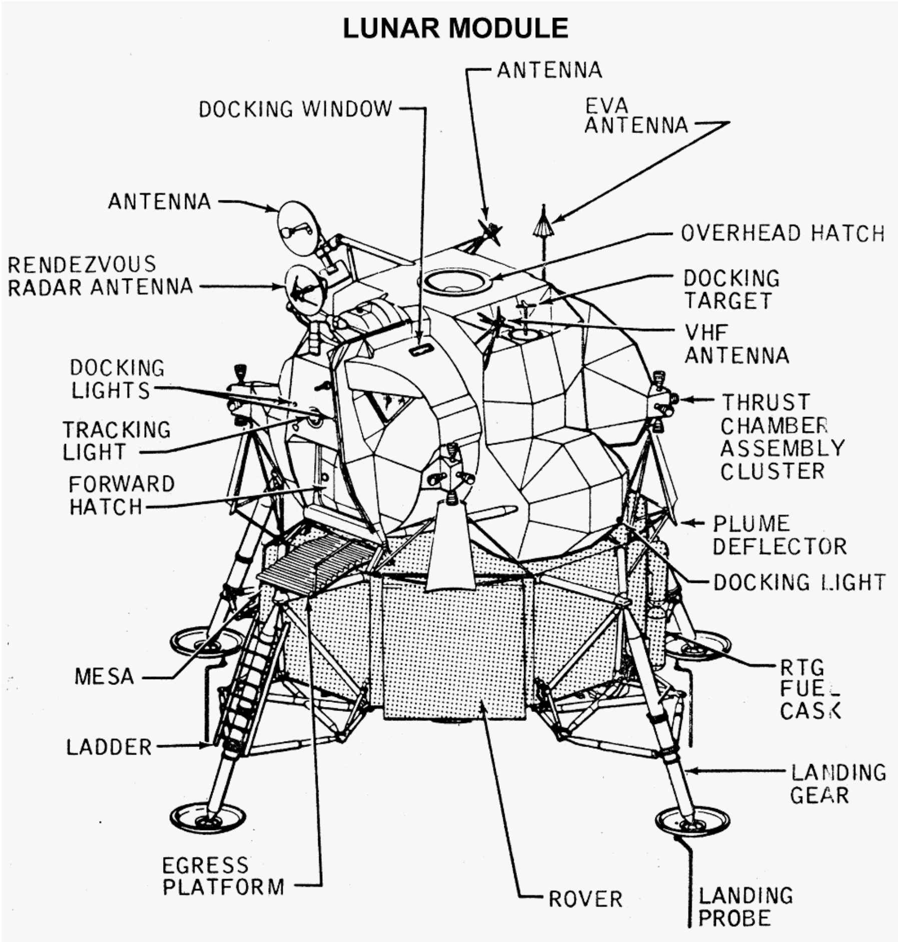


Figure 1.1. Apollo 11 Lunar Module details *[Credit Image: NASA]* [36]

stepping stone for future missions to Mars and beyond [47]. Artemis I, the first uncrewed test mission, successfully launched on November 16, 2022, paving the way for Artemis II, a crewed lunar flyby planned for 2025, and Artemis III, which will land astronauts near the lunar South Pole. Key components of the program include the Space Launch System (SLS), the Orion spacecraft, the Lunar Gateway space station, and commercial Human Landing Systems (HLS) [15].

The **Space Launch System** (SLS) is NASA's super heavy-lift expendable launch vehicle, designed to enable deep space exploration. As the most powerful rocket ever built, it serves as the successor to the retired Saturn V, which carried Apollo missions to the Moon. Standing approximately 98 meters tall, the SLS consists of a Core Stage, an Upper Stage, and twin five-segment solid rocket boosters. The Core Stage houses liquid hydrogen and liquid oxygen tanks for propulsion, avionics, and the Main Propulsion System (MPS). During launch, the solid rocket boosters and Core Stage propel the Upper Stage and payload into space. About eight minutes after liftoff, the Core Stage separates, and the Interim Cryogenic Propulsion Stage (ICPS), part of the Upper Stage, provides the final boost to send the Orion spacecraft toward the Moon. NASA plans to launch SLS missions roughly once per year, supporting Artemis goals through at least the early 2030s.

Orion is a partially reusable multi-purpose crewed spacecraft. It consists of two modules: the Crew Module (CM), a reusable transportation capsule that provides a habitat for the crew, and the European Service Module (ESM), which propels and powers the spacecraft and contains oxygen and water for the astronauts. It is capable of supporting a crew of six people and it can support missions from 21 days up to six months. It is equipped with solar panels, an automated docking system, a spacecraft adapter, and an emergency Launch Abort System (LAS). A single engine provides the primary propulsion and six pods of custom reaction control system engines form the secondary propulsion. The first spacecraft delivered is part of Artemis III and it will carry the next human generations on the Moon Surface.

One of the most important parts of this program is the **Lunar Gateway**. The Lunar Gateway, or simply Gateway, is a planned small space station in lunar orbit intended to serve as a solar-powered communication hub, science laboratory, short-term habitation module for government-agency astronauts, as well as a holding area for rovers and other robots. It is a multinational collaborative project involving four of the International Space Station partner agencies: **NASA**, **European Space Agency** (ESA), **Japan Aerospace Exploration Agency** (JAXA), and **Canadian Space Agency** (CSA). It would be both the first space station beyond low Earth orbit and the first space station to orbit the Moon [54].

The **Gateway** is planned to be deployed in a highly elliptical seven-day orbit around the Moon. It is composed of two main modules: the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO), which includes docking ports for visiting spacecraft. After Artemis III, it will include other two modules: the European System Providing Refueling, Infrastructure, and Telecommunications (ESPRIT) service module, which will provide additional xenon and hydrazine capacity, additional communications equipment, and an airlock; the International Habitation Module (I-HAB), an additional habitation module. So for future missions in deep space, Gateway will be essential as a logistic and refueling support [22].

Finally, the **Human Landing System (HLS)** is a lunar lander developed by SpaceX under NASA's Artemis program. Based on SpaceX's Starship architecture, the HLS is designed to transport astronauts from lunar orbit to the Moon's surface and back, enabling extended surface exploration [15]. It will rendezvous with

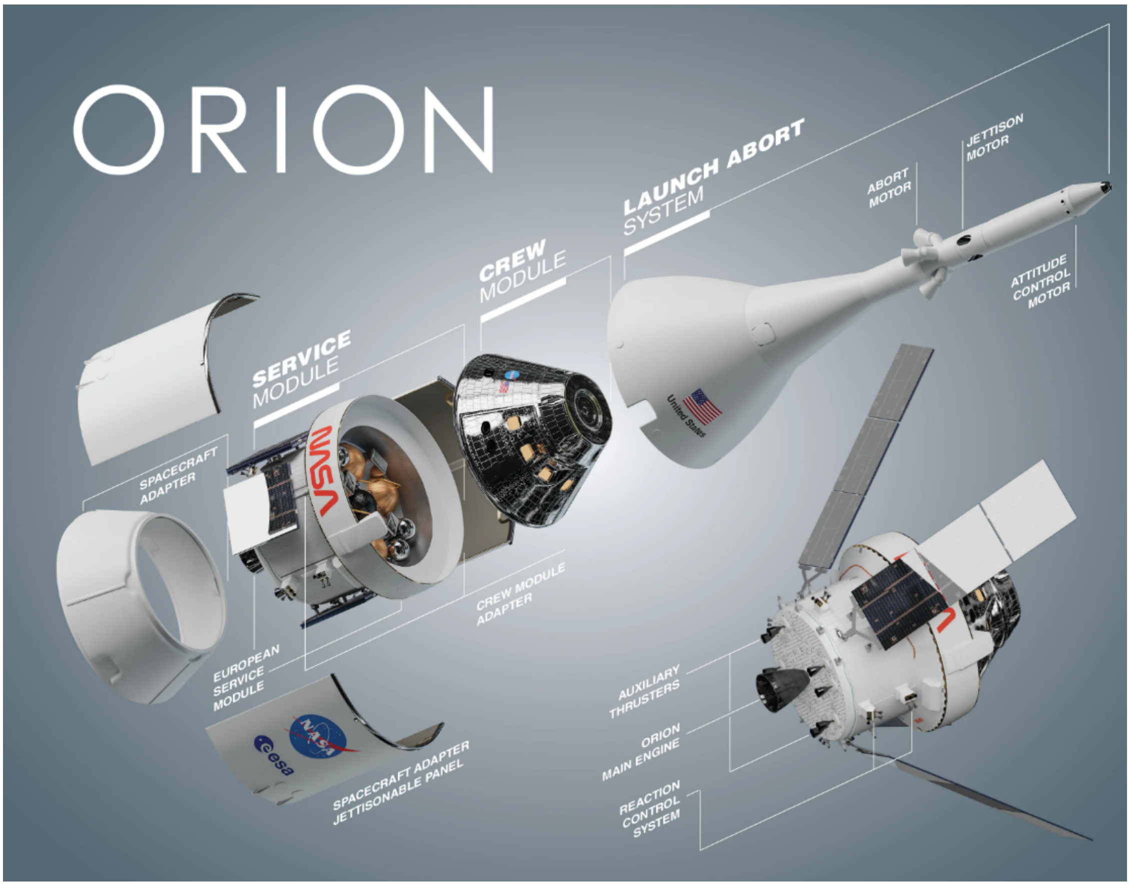


Figure 1.2. The Orion spacecraft *[Credit Image: NASA]* [34]

a crewed Orion spacecraft in orbit, where astronauts will transfer to the HLS for descent to the lunar surface, spending several days conducting scientific research and exploration before returning to Orion. Alternatively, the HLS can ferry astronauts between the Lunar Gateway space station and the lunar surface, supporting longer-duration missions.

Unlike traditional crewed spacecraft, the HLS is designed exclusively for lunar operations and will never re-enter an atmosphere, eliminating the need for a heat shield [15]. Instead, it relies on in-orbit refueling, with multiple SpaceX Tanker Starships transferring cryogenic propellant to the lander before departure. The propulsion system consists of six Raptor engines at the base, which provide primary thrust during descent and ascent, while smaller thrusters positioned along the mid-body assist in precision landing and mitigate plume impingement issues caused by the interaction of rocket exhaust with the lunar regolith. The primary propulsion system utilizes liquid oxygen (LOX) and liquid methane (LCH_4), while

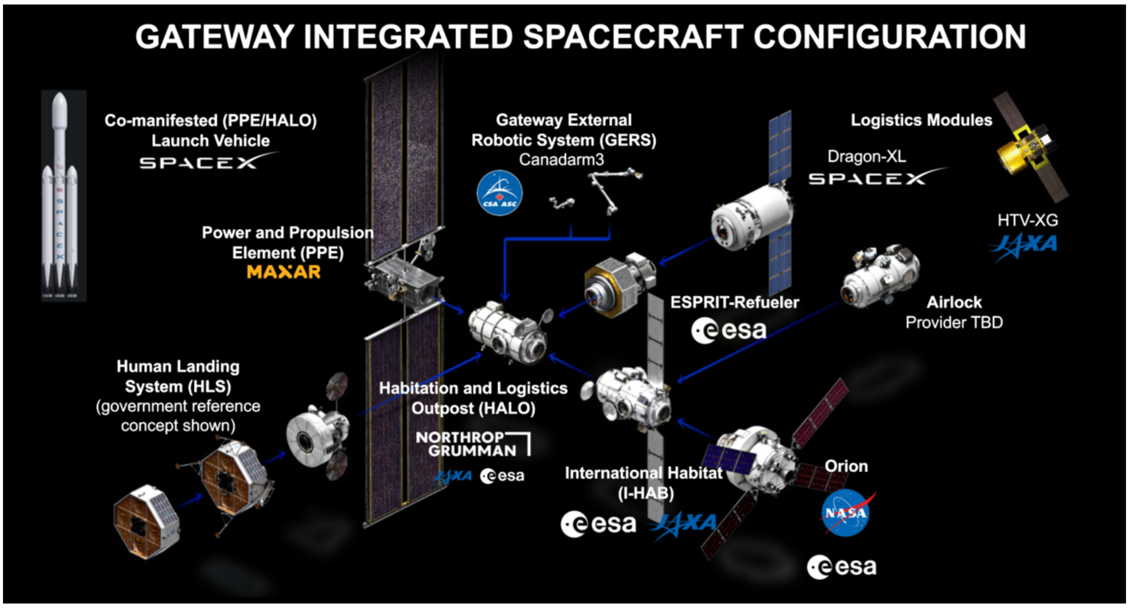


Figure 1.3. A full view of Gateway that includes elements from international partners *[Credit Image: NASA]* [35]

the attitude control thrusters operate using gaseous oxygen and methane. A ring of solar panels provides electrical power, ensuring sustained functionality during surface operations. The HLS marks a significant evolution in lunar lander technology, featuring a fully reusable design that aligns with NASA's long-term vision of sustainable lunar exploration and eventual Mars missions [47].

Chapter 2

Literature review

The purpose of this chapter is to illustrate the principle of System Engineering, to define what Model-Based System Engineering is, its benefits and limits, and to present a state-of-the-art review of the ingredients needed to formally apply it, selecting some of them to conduct the case study of Chapter 3.

2.1 System Engineering

Systems engineering is a structured, interdisciplinary approach to designing, developing, managing, and operating complex systems throughout their life cycle. [33] A system comprises all hardware, software, processes, personnel, and facilities necessary to deliver a functional capability that meets mission requirements. The value of a system emerges from the interactions between its components rather than from individual parts alone. Systems engineering provides a big-picture perspective, ensuring that technical decisions balance stakeholder needs, performance requirements, and constraints such as cost and schedule.
Numerous definitions of systems engineering (SE) have emerged, particularly from space agencies. Some notable ones include:

- **International Council on Systems Engineering** (INCOSE): "*Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems.*"

- **NASA Systems Engineering Handbook**: "*Systems engineering is a methodical, multi-disciplinary approach for the design, realization, technical management, operations, and retirement of a system.*"

- **ESA ECSS-E-ST-10C Rev.1**: "*Systems engineering is an interdisciplinary approach governing the total technical effort to transform requirements into a system solution.*"

In essence, systems engineering ensures that customer requirements are met throughout the entire product life cycle. To achieve this, systems engineers must possess a comprehensive understanding of all relevant technical disciplines, enabling them to define requirements, assess design trade-offs, evaluate technical risks, and address various challenges. Additionally, they play a crucial role in project management, overseeing temporary initiatives aimed at developing a unique product or service while also considering programmatic, cost, and scheduling aspects. This discipline integrates diverse fields, ensuring a coherent design that is not dominated by a single specialty. Systems engineers focus on trade-offs, optimizing the overall design without favoring one subsystem at the expense of another. They oversee requirements definition, architecture development, risk management, interface design, and verification and validation processes. They play a crucial role in developing the **Concept of Operations** (ConOps), defining system boundaries, and assessing design trade-offs while managing technical risks: it is not just about getting the design right; it is about ensuring the right design meets operational goals and stakeholder expectations.

2.1.1 Project Life Cycle

One of the fundamental concepts used for managing major systems is the program/project life cycle. This framework categorizes all necessary actions required to accomplish a program or project into distinct phases, each separated by **Key Decision Points** (KDPs). [33] These KDPs serve as critical junctures where the decision authority evaluates the readiness of a program or project to advance to the next phase. At these phase boundaries, decisions are made regarding whether a project is sufficiently mature to proceed or if further refinement is required. If a project does not meet the necessary criteria at a KDP, it may be given the opportunity to address deficiencies and undergo reassessment at a later stage, or it may be discontinued.

All systems originate from the recognition of a need or the identification of an opportunity, proceeding through various stages of development until project completion. While the most significant impact of analysis and optimization in systems engineering is realized in the early stages, decisions made throughout the project life cycle continue to influence cost, reliability, and performance. The decomposition of the life cycle into well-defined phases provides a structured approach, offering managers incremental visibility into project progress at strategically relevant moments, aligning with both technical and budgetary constraints.

Figure 2.1 illustrates the various stages of a space mission's life cycle, highlighting the terminology used by NASA, which provides a comprehensive breakdown of these phases, detailing key inputs, outputs, and objectives. Each phase concludes

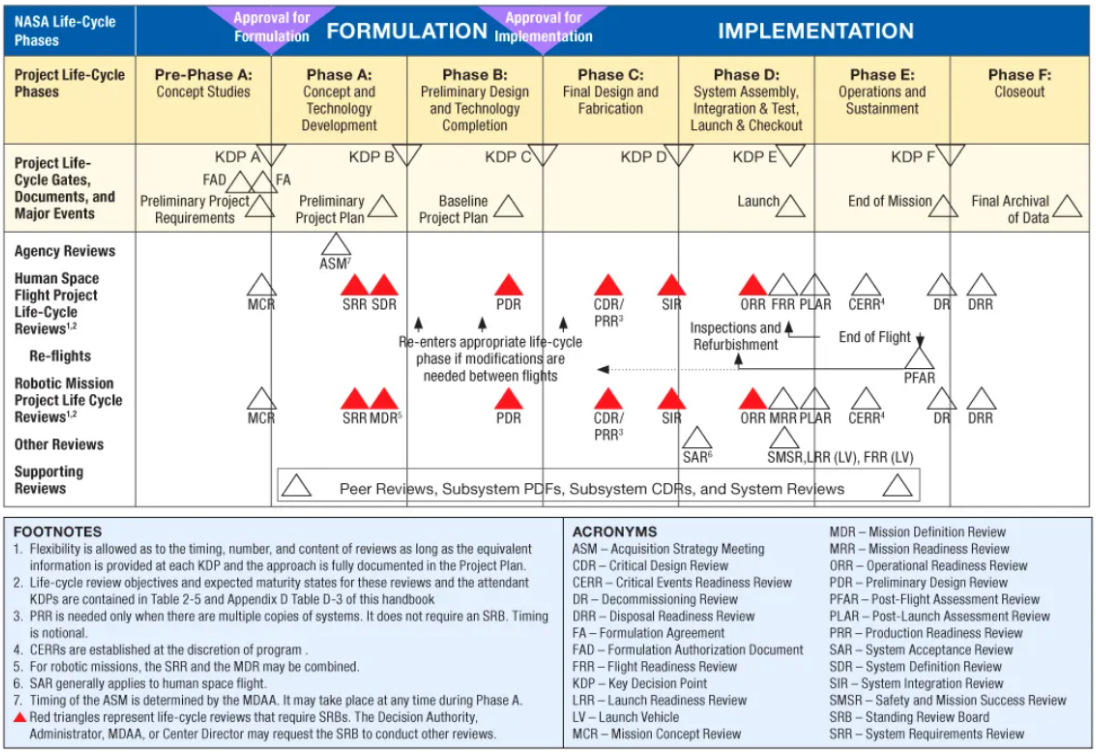


Figure 2.1. NASA Space Flight Project Life Cycle from NPR 7120 5E [33]

with a critical Milestone Review, where a panel of experts and stakeholders assess progress to ensure compliance with mission objectives and requirements.

In particular, Pre-Phase A focuses on generating a diverse range of mission concepts that align with technical, budgetary, and scheduling constraints. During this stage, a study team evaluates potential mission ideas, identifying viable options that contribute to overarching program objectives. This phase may involve assessing high-risk technologies with a low **Technology Readiness Level** (TRL) and engaging with stakeholders to refine mission concepts [52]. If feasible designs are identified, they can proceed to Phase A, which aims to refine a selected mission concept, develop system architecture, and ensure alignment with program goals and resource availability. The focus shifts to in-depth mission analysis, optimization of design alternatives, and formalizing system requirements. Teams work on defining functional and performance specifications, conducting trade studies, and addressing technical risks. A structured approach is used to allocate system functions across hardware, software, and human operations. Reviews such as the **System Requirements Review** (SRR) and **Mission Definition Review** (MDR) are conducted to ensure progress aligns with project goals before advancing to Phase B, which is dedicated to finalizing preliminary designs [30]. The goal is to establish a well-defined project baseline that includes detailed system and subsystem specifications, cost estimates, and scheduling commitments. This phase ensures that the mission is technically and financially viable before advancing to full-scale development.

Teams validate design decisions against initial mission goals, conduct performance assessments, and integrate considerations for safety, and operational sustainability. Configuration management practices are implemented to control design changes, ensuring consistency across subsystems. The phase concludes with a **Preliminary Design Review** (PDR), solidifying the transition to detailed design and implementation.

As modern products become increasingly complex, the intricate physical and functional interdependencies between components grow more significant. This complexity heightens the likelihood of errors, making risk management a critical aspect of any project. One of the primary objectives of systems engineers is to minimize the probability of late-stage design changes, as such modifications can have substantial cost implications and disrupt project timelines.

As illustrated in Figure 2.2, the life cycle cost distribution highlights how expenses escalate as the project progresses. The yellow rectangles represent actual incurred costs, while the committed cost curve depicts the anticipated expenditures. The blue arrow emphasizes that identifying and addressing errors early in the life cycle is significantly more cost-effective [33].

To mitigate the risks associated with late design revisions, it is essential to assess the suitability of a proposed solution in the early design phases, ensuring that it aligns with project needs and constraints. Achieving this requires efficient communication and seamless information exchange among engineers and stakeholders. Moreover, failing to properly address Human Factors at the early stages of a project introduces significant risks, including reduced system usability, operational inefficiencies, and increased likelihood of costly late-stage modifications. Inadequate considerations may lead to interfaces that are difficult to use, suboptimal automation integration, and crew workload imbalances, all of which can degrade system performance and mission success. As projects advance, rectifying these deficiencies becomes increasingly complex and expensive, underscoring the importance of early risk identification and mitigation.

This work primarily focuses on Phases Pre-Phase A, A, and B, collectively known as the Preliminary Design (PD) Phase. As we have seen, these early stages are instrumental in defining the mission's feasibility, objectives, and technical requirements. Traditionally, human factors have been considered in later stages, particularly during the development of physical mockups. However, this research aims

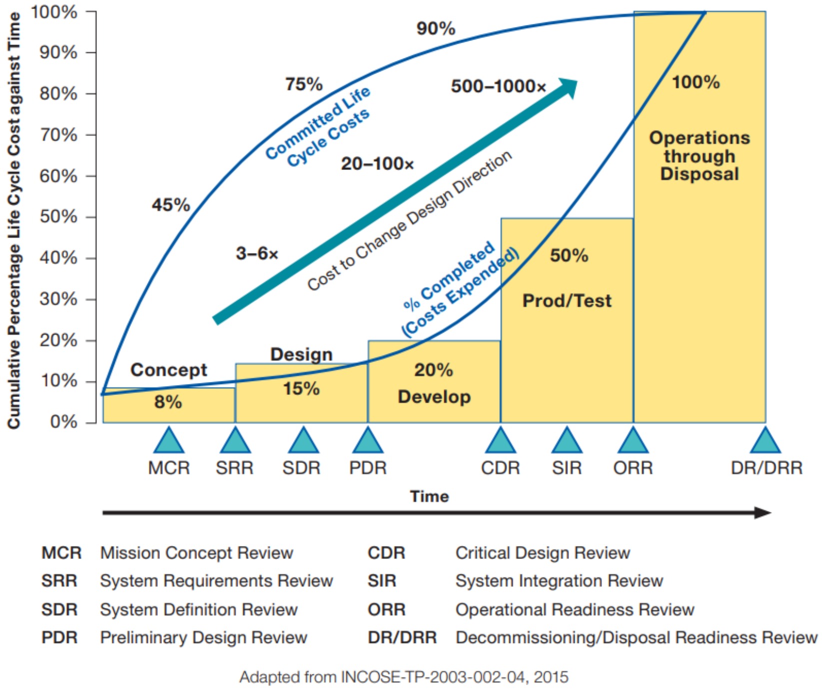


Figure 2.2. Life cycle cost distribution showing the increasing cost of errors as the project progresses. [33]

to enhance this process by integrating human factors into the early design phases, ensuring that astronaut needs related to ergonomics, habitability, safety, and operational efficiency are systematically incorporated from the outset. By adopting this proactive approach, potential risks can be mitigated early, and system architecture can be refined to optimize technical performance, time, costs, and crew well-being throughout the mission life cycle.

2.1.2 The Role of Models in System Representation

What is a model, and why do we use them? According to the INCOSE Systems Engineering Handbook [20], a model is a simplified version of a system created to represent it at a specific point in time or space, with the goal of facilitating a better understanding of the actual system. [9] As a system abstraction, it helps reveal important aspects of the system, such as its functions, structure, properties, behavior, performance, or cost. Modeling complex systems as integrated, value-generating entities has become increasingly recognized as a fundamental aspect of systems engineering. Applying modeling and simulation techniques during the early phases of system design for intricate systems and architectures can:

- Capture system functions and requirements,
- Evaluate mission performance,
- Estimate associated costs,
- Analyze trade-offs,
- Offer valuable insights for enhancing performance, minimizing risks, and managing costs.

The purpose of modeling is to make concepts more tangible and structured, improving quality, productivity, documentation, and innovation while also lowering the cost and risks associated with system development [49]. Modeling occurs at various levels - component, subsystem, system, and systems-of-systems - and spans the entire life cycle of a system. Different types of models are required to represent systems for analysis, specification, design, and verification purposes. This knowledge area offers an overview of the models used to represent diverse aspects of systems. One essential principle in modeling is to establish the model's purpose clearly. Throughout the life cycle of a system, models can serve a variety of roles, such as [9]:

- **Describing an Existing System:** Many systems lack proper documentation, and modeling them can provide an effective method to capture the current system design. This information can support system maintenance or evaluation for improvements.
- **Development and Assessment of Mission and System Concepts:** Early in the system's life cycle, models can be used to formulate and assess alternative system and mission concepts. This includes clearly defining the mission and its value to stakeholders, as well as examining how factors like weight, speed, accuracy, reliability, and cost impact system performance.
- **Synthesis of System Design and Requirement Allocation:** Models are essential for designing system solutions and breaking down mission and system requirements into specifications for system components. Various models are required to address different design aspects, including functional, interface, performance, and physical requirements, along with non-functional needs like reliability and safety.
- **Assistance with System Integration and Verification:** Models are used during system integration to ensure that hardware and software components meet the required specifications. This often includes combining lower-level models with system-level models to verify compliance. Additionally, hardware-in-the-loop and software-in-the-loop testing may replace design models with actual components to incrementally verify system requirements.

2.2 Model-Based Systems Engineering

For over two decades, Model-Based Systems Engineering (MBSE) has been a topic of significant discussion, particularly as the limitations of traditional document-based Systems Engineering (SE) became apparent. The inefficiencies of the document-based approach led the engineering community to seek a more structured and streamlined method as early as the late 1990s. However, MBSE gained widespread recognition only in 2007, following the release of the *Systems Engineering Vision 2020* by the International Council on Systems Engineering (INCOSE) [20]. This document formally defined MBSE as

> *"the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."*

The transition from document-based to model-based approaches was driven by the need for more efficient collaboration, improved traceability of design decisions, and better management of complex systems. One of the fundamental advantages of MBSE is the establishment of a structured *"single source of truth"* for engineering teams, reducing inconsistencies and misinterpretations that often arise in paper-based methodologies. Through the use of digital models, MBSE enables automated analysis, consistency checks, and real-time updates, ensuring that all stakeholders, whether engineers, project managers, or decision-makers, work with the same up-to-date information.

Furthermore, MBSE plays a pivotal role in managing the growing complexity of modern engineering systems [17]. As projects become more intricate and interdisciplinary, traditional methods struggle to keep pace with the increasing volume of data and interdependencies among system components [58]. MBSE tools provide structured frameworks for visualizing, simulating, and verifying system behavior before physical implementation, ultimately reducing costly design errors and rework.

As discussed in Section 2.1, systems engineering is inherently an iterative process that involves continuous refinement between stakeholders and engineers until design specifications reach maturity. Figure 2.3 illustrates this iterative loop, known as the SE process. When this process is managed through a traditional document-based approach, several critical challenges emerge:

- **Inconsistencies and Data Redundancy**: A major drawback of document-based systems engineering is the inefficiency in handling information. Most of the information is presented in textual form, requiring extensive time for documentation, review, and retrieval. As projects grow in complexity, multiple

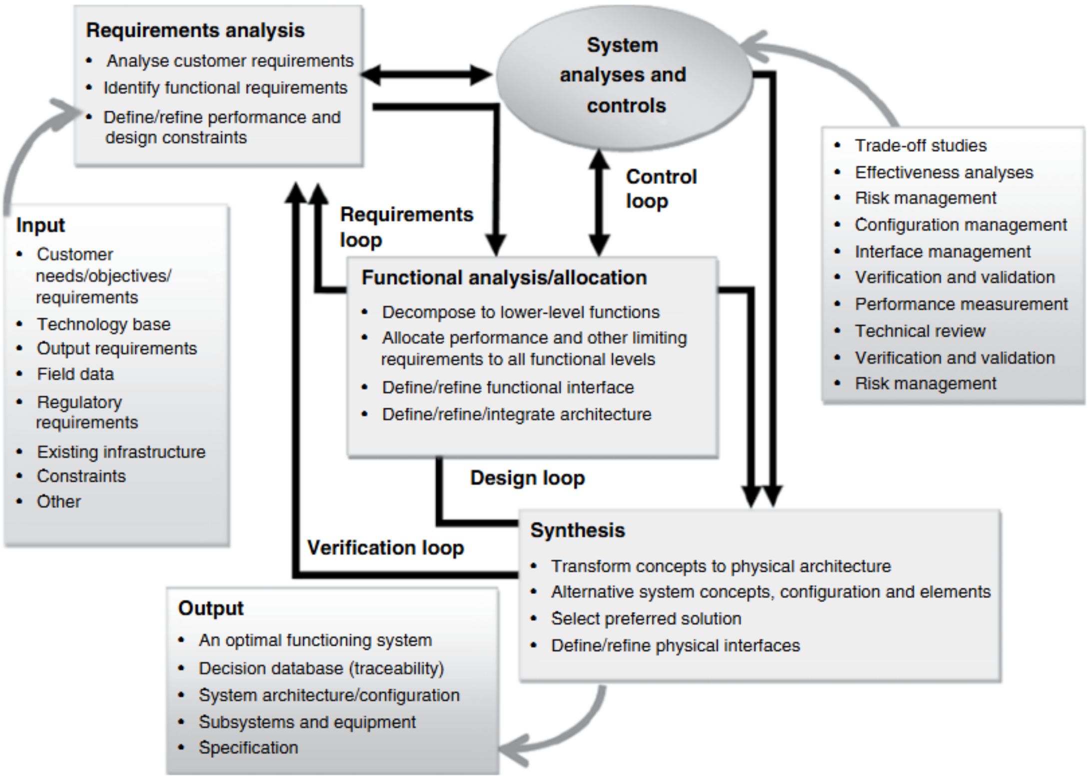


Figure 2.3. The iterative SE process with I/O [58]

contributors are involved in document creation, often leading to duplicated content scattered across different files. This fragmentation results in loosely coupled information, increasing the likelihood of inconsistencies and misinterpretations.

Moreover, the dependency on written descriptions, shaped by individual writing styles, further complicates the process. Variations in wording can lead to ambiguous interpretations, requiring additional clarification efforts and reducing overall team efficiency. Stakeholder reviews also become cumbersome, relying on extensive document exchanges, which pose challenges in ensuring real-time information traceability and consistency across project iterations.

- **Limited Traceability**: One of the primary causes of project failures stems from unclear or ambiguous requirements. In a document-centric approach, requirements are often presented as standalone textual statements without a clear linkage to specific design attributes, system functionalities, or performance parameters. This lack of structured traceability increases the risk of misinterpretation, potentially leading to misaligned expectations between engineering teams and stakeholders [10].

Without an integrated framework to connect requirements to system design elements, ensuring consistency becomes a manual and error-prone process. Ambiguities in textual requirements may result in conflicting interpretations, further complicating decision-making and increasing the likelihood of costly design revisions in later stages.

- **Difficulty in Managing Complexity**: Another significant challenge in document-based engineering workflows is the effort required to process design changes. Even during early development phases, any modification to the system architecture or requirements necessitates a thorough review of multiple documents to ensure end-to-end consistency. Since there is no centralized repository for design dependencies, engineers must manually verify the impact of changes across various subsystems and components.

  This fragmented approach leads to delays, as teams spend considerable time cross-referencing different documents, updating information, and validating consistency. The absence of automated tools for impact assessment further prolongs the design iteration cycle, making it difficult to adapt efficiently to evolving project requirements.

The challenges outlined, combined with the current push for digitalization aimed at enhancing system development and optimizing the entire product life cycle, have led to the increasing adoption of MBSE. One of the key advantages of MBSE is that it incorporates both textual and visual information within a structured model, which has been defined in section 2.1.2. By placing models at the core of the engineering process, MBSE ensures specification completeness, consistency, traceability of requirements and design decisions, reusability of design solutions, and a shared understanding of the system across teams, ultimately benefiting future projects.

In reality, systems engineering has always relied on models. What distinguishes MBSE is the shift from models residing in the minds of experienced engineers, who then communicate their knowledge to align teams, to a centralized digital representation that is accessible to all project members. By establishing the model as a single, authoritative source of truth across different organizational domains and stakeholders, MBSE eliminates ambiguities, making information clearer and more intuitive. This improvement enhances communication among design teams throughout the entire life cycle, ultimately leading to better product quality. A comparative analysis of system life cycle costs between traditional systems engineering and MBSE highlights that while MBSE requires an initial investment in infrastructure and training, these efforts lead to significant long-term improvements in efficiency and accuracy. However, the transition to MBSE is still hindered by cultural barriers, as organizations continue to face challenges in fully embracing its potential to improve current systems engineering methodologies.

2.2.1 MBSE Elements

MBSE goes beyond simply creating diagrams to illustrate results; it serves as a tool to enhance systems engineering activities through modeling. As such, it demands a well-defined methodology, which includes a set of interrelated processes, methods, and tools [21], explained as follows:

- **Process:** A process is a structured sequence of tasks designed to achieve a specific goal. It defines "what" needs to be done but doesn't specify the exact approach for each task. The process structure allows for multiple levels of aggregation, enabling analysis and definitions at varying levels of detail to support diverse decision-making requirements [21].

- **Method:** A method refers to the techniques employed to perform a task. It defines the "how" of each task. At each process level, tasks are carried out using specific methods. Each method itself is a process, consisting of a series of tasks to be completed. The "how" at one level becomes the "what" at the next lower level [21].

- **Tool:** A tool is an instrument that aids in completing tasks when applied to a particular method, provided it is used correctly by someone with the appropriate expertise and training. The majority of tools supporting systems engineering are computer or software-based and are referred to as Computer-Aided Engineering (CAE) tools [21].

These elements form the core components of any MBSE approach, all influenced by the *Environment*, which includes external factors, conditions, or elements that impact the actions of an object, individual, or group.

The primary objective of an MBSE approach is to integrate all these aspects using shared terminology, ensuring clear communication of what the model aims to represent. To achieve this, a modeling language must be adopted, with each language having its own unique syntax and semantics. Syntax pertains to the structure of the language, which can be either abstract or concrete. Abstract syntax relates to the constructs and rules for building the model, while concrete syntax consists of the symbols used to represent these constructs. Semantics provide the meaning behind the constructs, defining the significance attached to the language components [21].

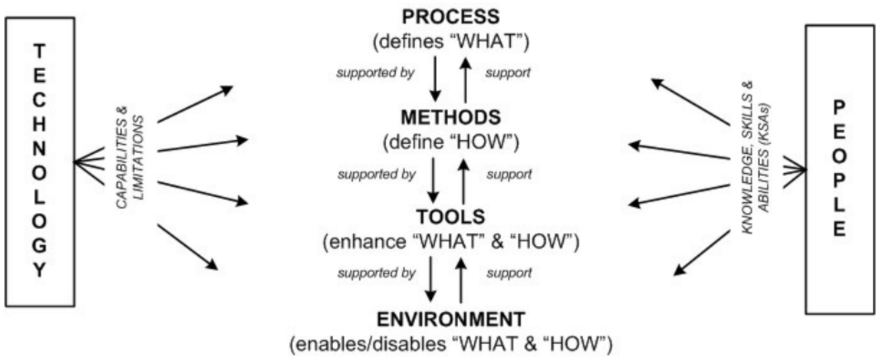


Figure 2.4. The PMTE elements and interactions with technology and people [21]

2.2.2 State-of-the-art

Currently, one of the most widely used languages in MBSE is the OMG Systems Modeling Language (SysML), which was initially developed to bridge the gap between systems engineers and software engineers [21]. SysML is based on the Unified Modeling Language (UML), which introduces new concepts while removing some others. As a language rather than a methodology, SysML aids communication among users familiar with its notation, without enforcing a specific methodology for MBSE [56].

SysML provides nine types of diagrams to model a system, as shown in Figure 2.5. Four of these diagrams focus on system *behavior*:

- **Activity Diagram:** This diagram is used to model the behavior of a system by showing the sequence of actions that transform inputs into outputs.
- **Sequence Diagram:** This diagram models message-based interactions, such as the flow of control and interactions between parts, with consideration of time elements.
- **State Machine Diagram:** This diagram represents the life-cycle of a block, detailing its responses to events over time.
- **Use Case Diagram:** This diagram is used to depict the fundamental functions of the system and the actors that initiate these functions.

In addition to the behavior diagrams, SysML includes four diagrams dedicated to representing the *structure* of a system:

- **Block Definition Diagram:** This diagram illustrates the system hierarchy and the relationships between blocks, helping to define the overall system architecture.

- **Internal Block Diagram:** It specifies the internal configuration of a single block, illustrating how the components within it are connected.
- **Parametric Diagram:** Used for engineering analysis, this diagram expresses constraints or equations that link property values and define system relationships.
- **Package Diagram:** This diagram organizes the model into distinct packages, offering a way to structure and manage the system.

Lastly, the *Requirement Diagram* is essential for defining text-based requirement trees and mapping out their connections to other system elements. Each of these nine diagrams provides a unique perspective, making it crucial for systems engineers to ensure connectivity and consistency between the different views.

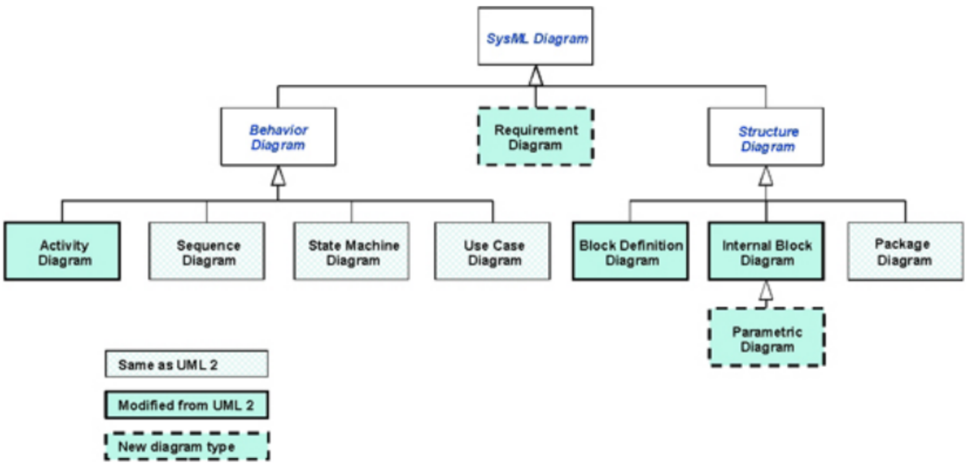


Figure 2.5. SysML Diagram Types [56]

However, SysML, as a modeling language, requires appropriate tools and methodologies for its effective adoption and use [51]. Several tools are available for working with SysML, including IBM Rhapsody, No Magic's Cameo Systems Modeler, and Enterprise Architect, among others. These tools provide the necessary environment for creating, analyzing, and managing models in SysML. Moreover, to fully harness SysML, it is crucial to have a structured methodology in place. A methodology provides the framework for applying the language to real-world engineering challenges, ensuring consistency and coherence across system models. Some of the most widely adopted MBSE methodologies that utilize SysML include the INCOSE Object-Oriented Systems Engineering Method (OOSEM) [20], IBM Telelogic Harmony-SE, and the IBM Rational Unified Process (RUP).

The INCOSE Object-Oriented Systems Engineering Method (OOSEM) emphasizes an object-oriented approach to systems engineering, focusing on modeling and analysis with SysML to manage system complexity. IBM Telelogic Harmony-SE is tailored for system design and development, promoting the use of SysML to structure and refine complex systems from early conceptual design through implementation. The IBM Rational Unified Process (RUP) is an iterative software development methodology that integrates SysML for systems engineering, ensuring that all aspects of a system's design and architecture are addressed throughout its life cycle.

One limitation of the aforementioned languages and methodologies is their object-oriented nature, which can be challenging for engineers without a software background. These engineers often require specialized training and support from highly skilled personnel to effectively use the methodologies. Specifically, SysML, when applied with the OOSEM methodology, has been found to have certain shortcomings. For instance, in the work presented in [1], the author discusses SysML's inability to offer constructs that facilitate the seamless integration of both structural and behavioral aspects of a system. This lack of integration makes it difficult for engineers to model a system holistically. Furthermore, functions within SysML are modeled using either activities or blocks, which can be semantically ambiguous and inefficient for representing complex system behaviors.

In response to these challenges, a new MBSE approach called ARCADIA (ARChitecture Analysis & Design Integrated Approach) has been developed by Thales. ARCADIA is both a methodology and a Domain-Specific Modeling Language (DSML) that is inspired by UML/SysML and adheres to NATO Architectural Framework (NAF) standards. One of the key strengths of ARCADIA is the open-source tool Capella, which is specifically designed to support this methodology and language, providing a tailored environment for systems engineers [6]. Unlike SysML, which requires systems engineers to be familiar with complex modeling techniques, ARCADIA and Capella focus primarily on the methodology itself. This makes it easier for engineers without deep modeling expertise to adopt and use the tool effectively.

Moreover, ARCADIA and Capella offer enhanced support for functional analysis and functional flows, with multiple diagram types that assist in the design process [6]. This is particularly valuable in the context of space mission design, where understanding both the system and subsystems from a functional perspective is essential for defining requirements. In Capella, functions are clearly distinguished from components through dedicated model elements, ensuring that the conceptual difference between structural elements and functions is maintained. In contrast, SysML often uses the same block constructs for both functions and components, which can lead to confusion and a lack of clarity in system modeling.

As shown, Capella offers several key benefits that make it a strong choice for system engineers. To summarize:

- It integrates the three core elements of MBSE - tool, language, and methodology - into a cohesive solution.
- Developed by a leading space company, it has been successfully applied in various industrial contexts.
- Capella is open-source, with customizable add-ons available, and its intuitive interface makes it accessible to users with varying levels of expertise.
- Finally, the official website provides extensive resources to help users quickly learn the methodology and tool.

Due to these advantages, ARCADIA and Capella have been selected as the MBSE solution for this work. A deeper look into their key principles is presented in the next section.

2.2.3 ARCADIA methodology

ARCADIA is a systematic engineering methodology designed for defining and validating the architecture of complex systems. It fosters collaboration among all key stakeholders throughout the system's lifecycle, from the initial engineering and design phase through to Integration, Verification, and Validation (IVV). This approach facilitates iterative development early in the design phase, helping the architecture evolve to meet all identified requirements.

All engineering data, from requirements to solutions, are organized within a central engineering model (or set of models) shared by all involved parties. These models serve as the entry point for each stakeholder, while additional models, such as those for safety, performance, or 3D representation, support specific specialties. The link between these models is essential for maintaining coherence throughout the project. The modeling approach also supports the IVV activities by defining test strategies based on functional capabilities and their relationships to component architecture. Test campaigns and their impacts on system components are planned using the functional chains and use case scenarios defined in the models.

A key difference between Arcadia and SysML is that Arcadia uses a function-driven modeling approach rather than a requirements-driven one. This allows Arcadia to focus on modeling functions and their interfaces while linking functional requirements directly to those functions. Arcadia defines multiple perspectives or

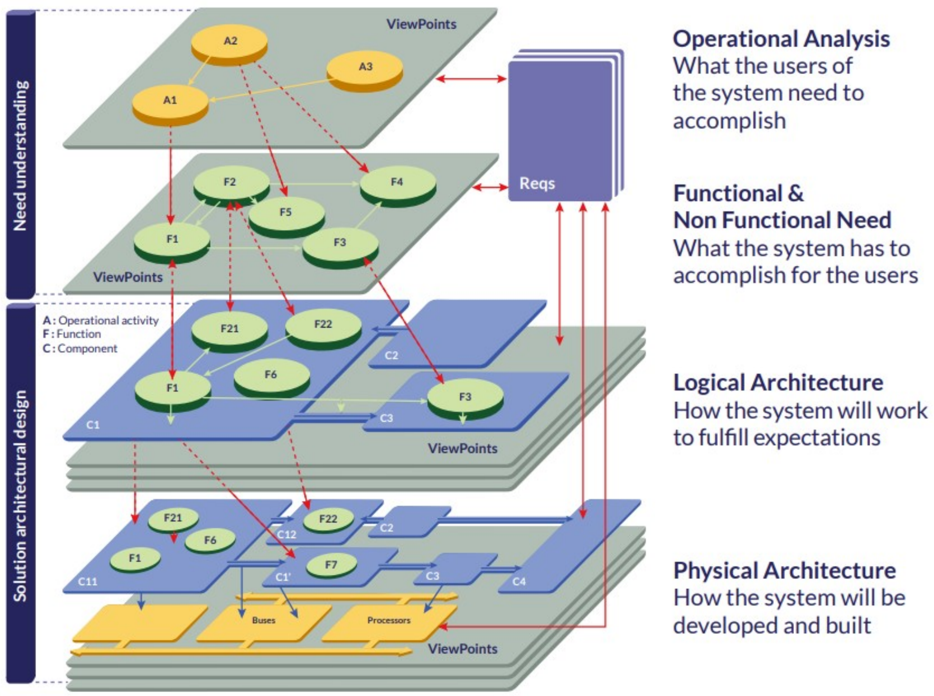


Figure 2.6. ARCADIA method layers [Credits: Capella-mbse]

layers that structure the implementation of an architecture, as detailed in the Fig. 2.6.

The Arcadia method shows how to implement the framework. A framework is made up of one ontology and one or more viewpoints. By definition, an ontology captures concepts descriptions, and relationships between the different ontology elements. These relationships are key to ensuring traceability and consistency. A more detailed description of the four layers has been given in the following section.

Operational Analysis

The Operational Analysis (OA) phase is dedicated to understanding and formalizing stakeholder needs and expectations, ultimately translating them into a structured set of stakeholder requirements. Before this process begins, high-level business or mission objectives are defined by management, ensuring alignment with the organization's strategic vision, operational framework, and long-term goals. These needs are then refined into stakeholder requirements, which are incorporated into the system model within a modeling environment.

Once stakeholder needs are established, the primary business or mission objectives are translated into model elements that define the system's expected functionality at an abstract level. This is typically represented using *use cases* or, in some cases, *capabilities*. Additionally, interactions between the system and external entities or actors are mapped to their respective capabilities, clarifying who benefits from the system's functionality.

At this stage, the operational context is defined, detailing how the system interacts with external components and actors during its operation. According to SE principles, every system is designed to deliver a fundamental function that provides value to its users. This core function is further broken down into specific internal functions necessary for the system to achieve its intended purpose. The overall system functionality is determined by both external and internal operations. Use cases or capabilities describe how the system meets user needs or supports specific operational goals. Identifying high-level system functionality is a crucial outcome of this phase [1].

System Analysis

The stakeholder requirements serve as the foundation for defining both functional and non-functional system requirements. Functional requirements specify the internal operations that the system must perform to fulfill its intended purpose. To represent these operations independently of specific technologies, a functional architecture is developed. This architecture provides a high-level description of the system's functionality, emphasizing interactions between different system elements without specifying the physical components involved [1].

During this phase, it is essential to verify that all functional requirements are accurately captured within the system's capabilities. If necessary, existing requirements can be refined, or new ones introduced. This process, often referred to as system functional analysis, plays a crucial role in defining the system's operational framework. However, while functional analysis at the system level is an important step, it should not be strictly limited to this level, as the approach can be applied across different layers of system development.

Logical Architecture

Following the requirements analysis phase, the next step is defining the system's functional architecture. At this stage, the modeling process transitions from understanding the problem to formulating a solution. The logical architecture represents an abstract system structure that organizes technical concepts and principles to ensure the system's intended functionality. This level of abstraction allows for the identification of logical components that fulfill system functions without being tied to specific technical implementations.

A crucial aspect of this phase is functional decomposition, which breaks down high-level system functions into sub-functions assigned to logical components or subsystems. This hierarchical decomposition ensures that each function is mapped to an appropriate element within the system. The resulting logical elements collectively define the system's logical architecture, which serves as a structured framework for implementing the functional architecture.

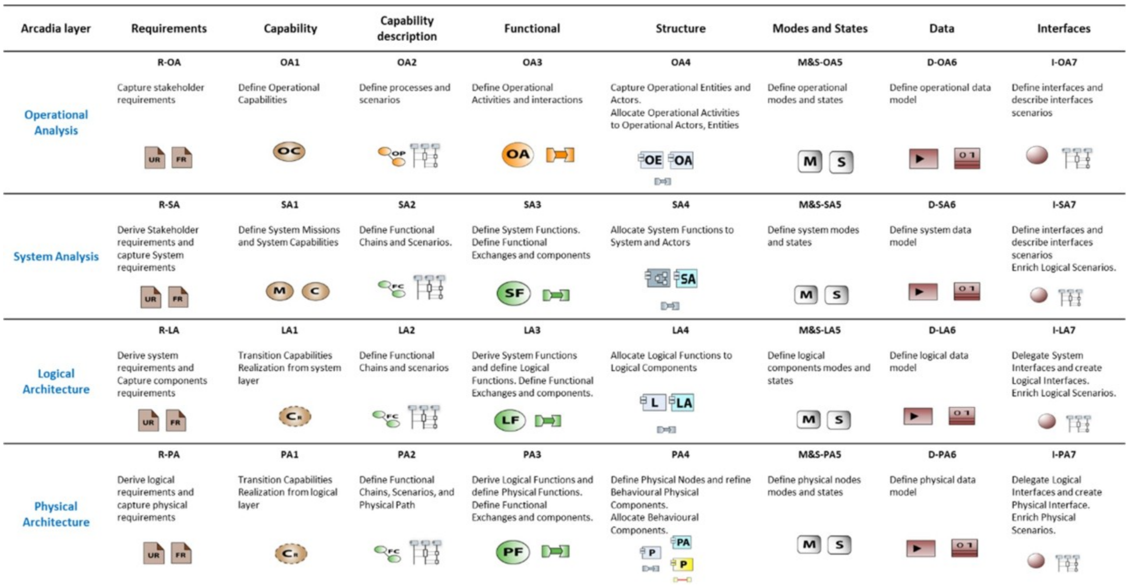
As the logical architecture is refined, additional logical functions may emerge, necessitating the introduction of new logical elements. This iterative process contributes to a more detailed representation of the system's operational structure. Additionally, defining logical components and their interfaces is essential, as it establishes the foundation for system integration and interaction. All component and interface requirements must be systematically documented to ensure consistency and traceability throughout the design process [1].

Physical Architecture

The physical architecture phase focuses on structuring the system's physical components to provide a concrete design solution that aligns with the logical architecture and system requirements. This architecture consists of physical elements, including system components and interfaces, which define how the system will be implemented using appropriate technologies [1].

At this stage, logical components are mapped to actual physical components responsible for executing the system's internal functions. While a logical function may correspond to a single logical component, its physical realization can involve multiple interacting physical components. Based on this structure, component requirements are further refined and documented to ensure a well-defined implementation framework. During the architecture development process, multiple physical architecture alternatives may be generated and evaluated using various methodologies to determine the most effective solution that meets system requirements. The flexibility of this process allows for adaptation across different industries and application domains, highlighting the need for a system engineering methodology that is adaptable to project-specific requirements.

In the Fig. 2.7 a detailed matrix of the Arcadia actrivities matrix has been given, to better understand all the functionalities.



Arcadia layer	Requirements	Capability	Capability description	Functional	Structure	Modes and States	Data	Interfaces
Operational Analysis	R-OA Capture stakeholder requirements	OA1 Define Operational Capabilities	OA2 Define processes and scenarios	OA3 Define Operational Activities and interactions	OA4 Capture Operational Entities and Actors. Allocate Operational Activities to Operational Actors, Entities	M&S-OA5 Define operational modes and states	D-OA6 Define operational data model	I-OA7 Define interfaces and describe interfaces scenarios
System Analysis	R-SA Derive Stakeholder requirements and capture System requirements	SA1 Define System Missions and System Capabilities	SA2 Define Functional Chains and Scenarios.	SA3 Define System Functions. Define Functional Exchanges and components	SA4 Allocate System Functions to System and Actors	M&S-SA5 Define system modes and states	D-SA6 Define system data model	I-SA7 Define interfaces and describe interfaces scenarios Enrich Logical Scenarios.
Logical Architecture	R-LA Derive system requirements and Capture components requirements	LA1 Transition Capabilities Realization from system layer	LA2 Define Functional Chains and scenarios	LA3 Derive System Functions and define Logical Functions. Define Functional Exchanges and components.	LA4 Allocate Logical Functions to Logical Components	M&S-LA5 Define logical components modes and states	D-LA6 Define logical data model	I-LA7 Delegate System Interfaces and create Logical Interfaces. Enrich Logical Scenarios.
Physical Architecture	R-PA Derive logical requirements and capture physical requirements	PA1 Transition Capabilities Realization from logical layer	PA2 Define Functional Chains, Scenarios, and Physical Path	PA3 Derive Logical Functions and define Physical Functions. Define Functional Exchanges and components.	PA4 Define Physical Nodes and refine Behavioural Physical Components. Allocate Behavioural Components.	M&S-PA5 Define physical nodes modes and states	D-PA6 Define physical data model	I-PA7 Delegate Logical Interfaces and create Physical Interface. Enrich Physical Scenarios.

Figure 2.7. MBSE with ARCADIA activities matrix. Credits: Helder Castro

2.2.4 Capella Tool

Capella is an Eclipse-based application designed to implement the ARCADIA methodology, offering structured guidance through an intuitive interface [6]. The tool provides access to a comprehensive set of diagrams and model elements, facilitating system architecture development. Given the importance of graphical representations in communication, Capella employs a standardized color scheme: function-related elements are displayed in green, while component-related elements appear in blue, with the exception of Node Components, which are yellow. Users also have the option to customize these visual settings as needed.

One of Capella's most valuable features is its ability to automatically generate diagrams based on model elements defined in other diagrams. This ensures consistency, traceability, and coherence across the model, as elements are uniquely defined and can be represented in multiple views depending on the context. Additionally, built-in filters allow users to streamline visualizations by focusing on specific subsets of elements. Capella's functionality can be further enhanced through a variety of add-ons, enabling customization to meet specific project requirements.

These capabilities make Capella an effective tool for team collaboration and a reliable single source of truth, helping to minimize late-stage modifications by enabling early error detection and proactive problem-solving. For this study, version 7.0 of Capella has been utilized.

2.3 Human Factors Engineering

When developing complex systems, human involvement is often simplified or considered in later stages. However, incorporating human needs into design can enhance productivity, quality, and technology implementation while also improving operational efficiency and ensuring worker well-being and optimal working conditions [31]. The role of human factors is becoming increasingly relevant in areas such as human-centered work design and human-machine interaction. These factors, which define the nature of human-system interactions, can be categorized into physical aspects (e.g., height), cognitive aspects (e.g., skill levels), and psychological aspects (e.g., motivation), all of which influence system outcomes [23]. Additionally, they contribute to designing human-centered production systems.

One discipline dedicated to this topic is **Human Factors Engineering** (HFE), with a particular focus on **Human Systems Integration** (HSI). In particular, HFE refers to the application of psychological and physiological principles in the design and development of products, systems, and processes [57]. The primary objectives of HFE are to minimize human error, improve productivity and system efficiency, and enhance safety, health, and overall user comfort, particularly in relation to human-system interactions. This multidisciplinary field integrates knowledge from various domains, including psychology, sociology, engineering, biomechanics, industrial design, physiology, anthropometry, interaction design, visual design, user experience, and user interface design. By drawing on methodologies from these diverse disciplines, human factors research aims to analyze human behavior and generate data that contribute to achieving these objectives [50].

HSI is an approach that incorporates human capabilities and limitations into the systems engineering life cycle. A fundamental element of HSI is recognizing the **human as a system**, which should be considered and integrated throughout all phases of the lifecycle. The scope of HSI is extensive and encompasses a variety of technical domains, including personnel, training, safety, environmental factors, toxicology, medicine, human factors, and more [32]. One crucial aspect of the HSI process, which draws from human factors engineering, is human-centered design. This methodology is employed to ensure that designs account for human capabilities and limitations. The following sections delve deeper into the concept of HCD, offering detailed guidance on how to incorporate this approach into systems design.

Human-Centered Design (HCD) is rooted in human factors, ensuring that systems are developed according to individual needs and abilities. This integrated approach bridges technical development with human requirements. For instance, astronauts play key roles in operating, monitoring, and maintaining spacecraft systems. Given the increasing complexity of these systems, it is crucial to account for these roles early in the planning process. Both HSI and human factors provide valuable insights for designing and refining human-system interfaces [16].

Development costs throughout an engineering lifecycle are effectively managed by iteratively refining designs through structured analyses and evaluations. These processes involve the user or customer and are aligned with relevant requirements. By taking these iterative steps, the likelihood of late-stage design changes or rework during production, which can be costly, is minimized.

Mission success is enhanced when human interfaces are carefully designed to ensure operational clarity, consistency, and reduce the potential for human error, performance failure, injury, or illness. While not explicitly designed as part of the system, the human user can be considered a functional subsystem of the larger system. Consequently, mission and system designs must account for the human component while also considering the constraints posed by the natural environment. User satisfaction is improved when users are engaged in the HCD process, allowing them to understand and contribute to design decisions. This involvement is particularly crucial when the human user is responsible for critical control functions or when user interaction plays a significant role in achieving mission objectives [53].

One of the key principles of HCD is the proper allocation of functions, which involves determining which tasks should be handled by the users and which should be managed by the system. These decisions shape the level of automation for specific tasks and functions, influencing how much responsibility is assigned to human performance versus the technology. When making these design decisions, designers must carefully consider the relative strengths and limitations of both human capabilities and technological systems. The decision-making process should take into account various factors such as reliability, speed, accuracy, strength, response flexibility, financial cost, and the importance of completing tasks successfully and on time, while also ensuring user well-being.

Rather than solely focusing on identifying which functions technology can perform and then assigning the remaining tasks to users, the allocation should aim to create a meaningful and well-organized set of human responsibilities. It is essential to involve representative users in these decisions to ensure that the design meets practical needs and expectations.

In this thesis, the *Human Integration Design Processes* (HIDP) document [39], along with related NASA standards and procedural requirements, has been extensively referenced to provide a structured approach to human-systems integration in spaceflight. These documents serve as fundamental resources for ensuring that crewed spacecraft meet rigorous safety, usability, and habitability standards. In more detail, the *HIDP* document is a key reference for human-centered design in space systems, detailing methodologies, best practices, and processes that NASA has developed to comply with human-rating and human-systems requirements [19]. It is built upon the principles of HCD, emphasizing the integration of human capabilities and limitations into spacecraft design to enhance crew safety, performance, and overall mission success.

A major framework supporting these efforts is *NASA-STD-3001*, the *Spaceflight Human-System Standard*, a two-volume set of agency-level standards established to mitigate health and performance risks for astronauts:

- **Volume 1: Crew Health** - Defines standards for astronaut medical diagnosis, spaceflight permissible exposure limits, medical care levels, diagnostics, treatment protocols, and countermeasures essential for maintaining astronaut well-being throughout a mission [45].
- **Volume 2: Human Factors, Habitability, and Environmental Health** - Focuses on human cognitive and physical limitations, establishing guidelines for the design of spacecraft (including orbiters, habitats, and spacesuits), environmental conditions, onboard facilities, payloads, hardware, and software interfaces to optimize astronaut efficiency and comfort [46].

Additionally, NASA's *Procedural Requirements (NPR) 8705.2B*, titled *Human-Rating Requirements for Space Systems*, outlines the agency's processes, procedures, and requirements for achieving **human-rating certification** of spacecraft. This ensures that all critical systems are designed with astronaut safety and operational effectiveness as primary considerations, allowing for reliable interaction with onboard technology [40].

2.3.1 Human-Centered Design Activities

This section outlines the HCD activities specifically adapted for the design of a lunar habitat, and the scope of this study. Within these activities, the term "user" may be replaced by "crew" or "crewmember", reflecting the context of habitat design where the primary users are astronauts. The HCD process is composed of three main activities, which are performed iteratively in a feedback loop, as depicted in Fig. 2.8. These activities are not isolated steps but are continuously revisited and refined throughout the entire systems engineering life cycle, ensuring that human factors are consistently addressed at each phase of the habitat development [13].

In particular, "Understanding the User and the Operating Environment" has been investigated more in dept. A critical aspect of HCD is ensuring that the system is tailored to meet the needs of its users while accounting for the limitations and challenges imposed by the operational environment. This step involves gaining

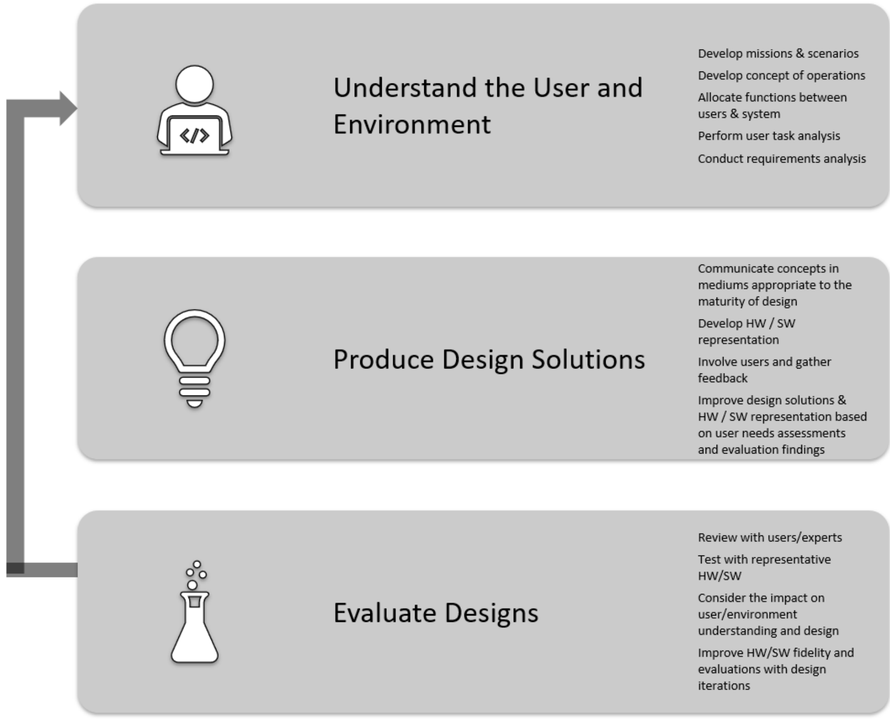


Figure 2.8. HCD Activities loop [11]

an in-depth understanding of the user, considering their capabilities, physical and cognitive limitations, and the tasks they will perform, as well as comprehending the environmental constraints that may influence system performance. For instance, when designing spacecraft systems for astronauts, considerations such as microgravity, confined living conditions, and isolation must be carefully accounted for. Moreover, the design must align with the specific tasks the crew will undertake, such as conducting maintenance, sleeping, or performing daily routines. To achieve this understanding, several key activities have been carried out:

- **Development of Missions and Scenarios:** This process involves identifying the specific mission objectives and outlining possible scenarios in which the system will be used. Reference missions are defined early in the habitat development phases and serve as the foundation for understanding how the crew will interact with the system in various situations, including normal operations and emergency scenarios.

- **Concept of Operations (ConOps):** The ConOps outlines the intended use of the system, detailing how the system will support the mission objectives and how the user will interact with it. This concept helps bridge the gap between design and operational reality, ensuring the system supports human needs throughout the mission.

- **Allocation of Functions Between User and System:** It is essential to determine which tasks will be performed by the user and which will be automated by the system. This allocation is based on a thorough analysis of the user's capabilities and the system's capabilities, ensuring that the system is designed to complement the astronaut's strengths and mitigate their weaknesses.

- **User Task Analysis:** A detailed analysis of the tasks the user will need to perform is necessary to ensure the system can support the effective execution of these tasks. This step involves evaluating how each task is performed and identifying potential challenges or inefficiencies that might arise during the mission.

- **Requirements Analysis:** The requirements analysis focuses on gathering and specifying the system's functional, performance, and usability requirements. These requirements are derived from the tasks, missions, and scenarios that have been developed, ensuring that the system will meet the necessary criteria for successful operation.

Concerning the development of Missions and Scenarios, as outlined in NASA Procedural Requirement (NPR) 8705.2B, human-rating certifications for space systems are grounded in reference missions, which establish the scope and objectives of the mission and the design specifications for the space system. These missions are typically defined during the early stages of spacecraft development, with a focus on creating a clear set of operational and contingency scenarios. The scenarios include **nominal** conditions (routine operations), **off-nominal** conditions (unexpected or abnormal events), and **emergency** situations (critical incidents that require immediate attention). These scenarios play a significant role in shaping the system's design, ensuring that it is adaptable to various conditions and that it can support the crew effectively, even in unexpected or hazardous situations. The process of defining missions and scenarios is crucial for building systems that are not only functional but also resilient, ensuring that human performance is optimized and safety is maintained throughout the mission life cycle.

2.3.2 HCD Impact

This section gives an example of how the physical challenges and changes encountered by the human body due to exposure to the space environment can affect the design of specific components of the spacecraft, to better understand the importance of these principles. In particular, the problem of deconditioning has been taken under analysis.

Deconditioning refers to the diminished physical capabilities of astronauts after experiencing space flight [39]. This condition results in observable impairments in sensorimotor skills, cardiovascular function, the ability to tolerate standing up (orthostatic tolerance), as well as a decrease in muscle and bone strength. When designing spacecraft and space systems, it is crucial to account for the impact of deconditioning and the reduced capabilities of affected crew members. Additionally, countermeasures should be integrated into the operational strategy, both during space flight and after landing, to reduce or manage the effects of deconditioning and maintain astronaut health and performance. While responses to space travel may differ between individuals, all physiological systems are influenced to varying extents by the space environment.

Deconditioning can affect a variety of tasks performed by astronauts. This section will address some of these tasks, with particular emphasis on the design considerations for post-landing unassisted (emergency) egress [39]. Emergency egress includes a range of actions, such as rapid motor control tasks (including fine motor tasks like manipulating objects and gross motor tasks like opening hatches), visual tasks, walking, and maintaining spatial orientation and postural stability, all of which are essential for safe evacuation.

Crews experience deconditioning due to two main factors: gravity unloading and gravity transitions. When exposed to space flight, astronauts undergo changes in both anatomy and physiology. Upon entering the microgravity environment, crewmembers face sensorimotor issues and space motion sickness (SMS) due to a conflict between vestibular and visual signals. The vestibular system, which typically helps humans orient themselves by detecting gravity, becomes confused once gravitational forces are absent. While the sensorimotor system adapts to these new cues, the mismatch causes dysfunction and motion sickness until full adaptation occurs, which usually takes a few days. Furthermore, the lack of gravity causes bodily fluids to shift upward and removes the usual load-bearing forces, leading to progressive changes in the cardiovascular and musculoskeletal systems.

This gravitational unloading leads to issues such as bone demineralization, muscle weakness, and decreased aerobic capacity, even though countermeasures are used. However, these measures do not fully prevent the effects. After landing, astronauts face additional sensorimotor disturbances, including gait dysfunction, reduced visual clarity, balance issues, and motion sickness. They may also experience impaired strength and cardiovascular performance, along with orthostatic intolerance-symptoms like dizziness, rapid heart rate, blood pressure fluctuations, and fainting when standing. Due to these physical challenges, particular attention must be given to deconditioned crewmembers during vehicle egress. If countermeasures do not entirely mitigate these effects, astronauts may suffer from muscle atrophy, poor tolerance to standing, decreased cardiovascular performance, sensorimotor dysfunction (such as gait instability and impaired visual acuity), reduced bone density, and changes in bone structure. The following sections will explore how deconditioning effects should be considered in spacecraft design, with a focus on sensorimotor, musculoskeletal, and cardiovascular systems.

NASA/TP-2014-218556

TABLE 4.15.7-1 OVERVIEW OF CREWMEMBER DECONDITIONING

	In-flight			Descent & Landing		
	Symptoms	Effects	Design Impacts	Symptoms	Effects	Design Impacts
Sensorimotor	SMS (early in flight) Nausea or vomiting, malaise, headache	Restricted movements, reduced activity	Minimize activity; provide easy access to sickness bags and medical kit; provide mobility aids	SMS Nausea or vomiting, malaise, headache	Decreased dynamic visual acuity, nausea or vomiting, gait and/or eye-hand coordination disturbances, ataxia, reduced performance	Openings and walkways that accommodate unsteady, deconditioned crewmembers; assisted egress; provide hand-holds, minimize activity and whole-body and head movements; increased task time
Muscle	Reduced strength	N/A	Exercise hardware	Fatigue, exhaustion	Decreased muscle mass, strength, and endurance; reduced performance	Openings and walkways that accommodate unsteady, deconditioned crewmembers; provide hand-holds and ladders for stability; minimize lifting; minimize force required of mechanisms; assisted egress
Bone	N/A	N/A	Exercise hardware	None	Decreased bone density, altered bone architecture, increased fracture risk	Remove obstructions to egress; provide hand-holds and ladders for stability; provide assisted egress
Orthostatic Hypotension	N/A	N/A	Compression garments and exercise hardware	Presyncope or syncope, swelling of the lower extremities	Incapacitated crewmember	Provide compression garments for egress; provide fluids and salt for fluid-loading reentry protocol; provide cooling; provide recumbent seating; provide assisted egress
Aerobic Capacity	Reduced endurance, fatigue	N/A	Exercise hardware	Fatigue, exhaustion	Decreased endurance, reduced performance	Openings and walkways that accommodate unsteady, deconditioned crewmember; provide hand-holds and ladders for stability; minimize force required of mechanisms; assisted egress

Figure 2.9. Overview of the symptoms, effects, and design considerations for crewmember deconditioning during spaceflight, focusing on both in-flight and descent/landing phases. [39]

Fig. 2.9 provides a comprehensive overview of crewmember deconditioning, a significant concern in human spaceflight. The table is structured to compare and contrast the symptoms, effects, and design impacts of deconditioning during two distinct phases of a mission: in-flight and descent/landing.

Sensorimotor

In-flight, sensorimotor deconditioning is primarily characterized by Space Motion Sickness (SMS), especially during the early stages of a mission. Symptoms include nausea, vomiting, malaise, and headache. The effects of SMS result in restricted movements and reduced activity levels, which can hinder task performance and overall mission effectiveness. To address this, design considerations focus on minimizing activity, providing easy access to sickness bags and the medical kit, and ensuring mobility aids are available.

During descent and landing, the sensorimotor challenges persist, manifesting in decreased dynamic visual acuity, nausea or vomiting, and gait and/or eye-hand coordination disturbances. Ataxia, a lack of muscle control or coordination of voluntary movements, is also a significant concern. These symptoms lead to decreased visual acuity, nausea, or vomiting, gait and/or eye-hand coordination disturbances, ataxia, and reduced performance. Design impacts focus on creating openings and walkways that accommodate unsteady, deconditioned crewmembers, providing hand-holds for stability, minimizing activity and whole-body and head movements, and accounting for increased task time.

Muscle

Muscle deconditioning is observed in-flight as a reduction in strength. Exercise hardware is the primary design consideration to combat this effect. In the descent and landing phase, fatigue and exhaustion are the prominent symptoms, resulting in decreased muscle mass, strength, and endurance, ultimately leading to reduced performance. Design strategies for this phase are similar to those for sensorimotor effects, emphasizing openings and walkways that accommodate unsteady, deconditioned crewmembers, hand-holds and ladders for stability, minimizing lifting, and minimizing the force required to operate mechanisms. Assisted egress is also a key consideration [39].

Bone

Bone deconditioning does not present with immediate symptoms in-flight. However, exercise hardware is crucial to mitigate long-term effects. During descent and landing, the absence of symptoms belies the underlying risk of decreased bone density, altered bone architecture, and increased fracture risk. Design considerations focus on removing obstructions to egress, providing handholds and ladders for stability, and facilitating assisted egress to prevent injuries [39].

Orthostatic Hypotension

Orthostatic hypotension, a condition where blood pressure drops upon standing, is not a primary concern in-flight. However, compression garments and exercise hardware are used as preventive measures. In contrast, descent and landing can induce presyncope or syncope (fainting), accompanied by swelling of the lower extremities. This can lead to an incapacitated crew member. Design impacts include providing compression garments for egress, fluids and salt for fluid-loading reentry protocols, cooling mechanisms, recumbent seating, and assisted egress [39].

Aerobic Capacity

Reduced endurance and fatigue are observed in-flight, and addressed through exercise hardware. These symptoms persist during descent and landing, resulting in decreased endurance and reduced performance. Design considerations are similar to those for muscle deconditioning, focusing on openings and walkways that accommodate unsteady, deconditioned crewmembers, hand-holds, and ladders for stability, minimizing the force required for mechanisms, and ensuring assisted egress.

In summary, Table 2.9 highlights the progressive nature of crewmember deconditioning, emphasizing the distinct challenges presented during in-flight and descent/landing phases. The design impacts outlined in the table underscore the importance of incorporating human factors considerations into spacecraft design to ensure crew safety and mission success [39].

2.3.3 Human-System Integration Domain

Human-Systems Integration (HSI) encompasses various essential human-related elements, commonly referred to as HSI domains [43]. The effectiveness of HSI relies on the seamless integration and collaboration of these domains throughout the system development process. Fig. 2.10 presents and defines these key domains, which can either represent distinct disciplines (such as Human Factors Engineering) or encompass multiple interrelated discipline activities (such as Maintainability, Supportability, and Safety). Regardless of their classification, the success of HSI hinges on a holistic and interdisciplinary approach that ensures all relevant domains work together cohesively.

It is important to highlight that these domains have been defined specifically for HSI implementation within NASA projects, they are intended to function as interconnected components. Each domain has the potential to influence and interact with the others, making a systems-level approach essential. HSI fosters the integration of these domains to capitalize on their interdependencies and achieve a well-optimized system. To maximize overall system performance, considering the interaction of humans, hardware, software, and the operational environment, it is essential to engage the relevant HSI domains at every stage of the system life cycle. Effective implementation of HSI principles necessitates continuous communication, coordination, and collaboration among the various domains. This ensures that human-centered expertise is consistently integrated into the design, development, and operational phases.

Figure 2.10. Human-System Integration Domains [11]

In this study, two primary areas have been investigated: HFE, which has been discussed in the previous section, and the other focusing on habitability. While HFE addresses the interaction between humans and systems to optimize performance and safety, habitability considerations ensure that the living and working environments support crew well-being, mission effectiveness, and long-term sustainability. This section explores the critical aspects of habitability and environmental design, emphasizing their role in mission success.

The habitability and environment domain plays a crucial role in ensuring seamless integration between human operators, the crew in this sense, and the system. This is achieved through deliberate design choices and continuous assessment of both the internal and external environments in which astronauts live and work. Maintaining suitable habitability conditions is essential for sustaining safety, optimizing human and mission performance, and preserving crew health [25]. Given the direct impact of habitability factors on astronauts' well-being, their proper implementation is vital for operational success [24].

Habitability considerations extend across various work environments, including ground-based testing and operational facilities, mission control centers, in-flight spacecraft, planetary habitats, and surface exploration vehicles. Key factors contributing to a habitable environment include appropriate lighting, spatial distribution, air quality, temperature and noise control, sanitation systems, and architectural layout. Additionally, factors such as ingress/egress pathways, movement corridors, and environmental health measures must be carefully planned to facilitate efficient operations and minimize risks.

A well-designed living and working environment should not only provide physical safety and comfort but also foster morale and psychological well-being, ensuring sustained crew effectiveness over long-duration missions. Poorly optimized habitability conditions can lead to fatigue, stress, and decreased cognitive performance, ultimately compromising mission objectives [24]. For example, inadequate ventilation or poorly controlled noise levels in confined spacecraft environments may negatively impact crew concentration and communication, reducing overall operational efficiency. Although system design must account for multiple technical and operational constraints, habitability factors should not be sacrificed in favor of other system elements without careful consideration. Overlooking these aspects or systematically trading them off for competing priorities can result in long-term performance degradation and increased risk to astronauts' safety and mission reliability. A balanced approach that incorporates human-centered design principles while maintaining technical feasibility is crucial for achieving sustainable and effective mission operations [12].

HSI in Life Cycle

A fundamental objective of HSI is to optimize project costs while enhancing overall system safety, efficiency, and performance. Effective HSI implementation ensures that human-related considerations are incorporated throughout the design process, preventing costly redesigns and operational inefficiencies. One of the key financial challenges in system development is that design decisions made early in a project have long-term cost implications. As a project progresses through its life cycle, making modifications becomes increasingly expensive. Decisions made in the early stages lock in a significant portion of future costs, which makes iterative evaluations of alternative design concepts essential to identify cost-effective solutions. If personnel costs and operational constraints are not properly evaluated at the outset, they may escalate unexpectedly during later phases.

Although structured cost estimation models exist, there is a lack of extensive case studies that quantify the true impact of HSI on **Life Cycle Cost** (LCC) or the **return on investment** (ROI) of effective HSI implementation [11]. Since it is rare to have a direct comparison between projects with and without HSI considerations, the long-term cost benefits of HSI can be difficult to measure definitively. However, incorporating human-centered alternatives into SE trade studies provides an opportunity to analyze their financial implications and optimize LCC.

As illustrated before in established systems engineering frameworks, a project's life-cycle cost is largely determined during its initial development phases (Fig. 2.2). While this principle applies to all system design elements, it is particularly crucial for HSI, as technological advancements often take precedence over human-system interactions. For HSI to be fully effective, its value must be consistently demonstrated, particularly in the early stages of a project. The HSI Lead may need to justify the importance of tracking human-related costs and integrating them into decision-making processes. By embedding HSI into systems engineering methodologies and cost estimation frameworks, organizations can make informed decisions that enhance both financial efficiency and mission effectiveness.

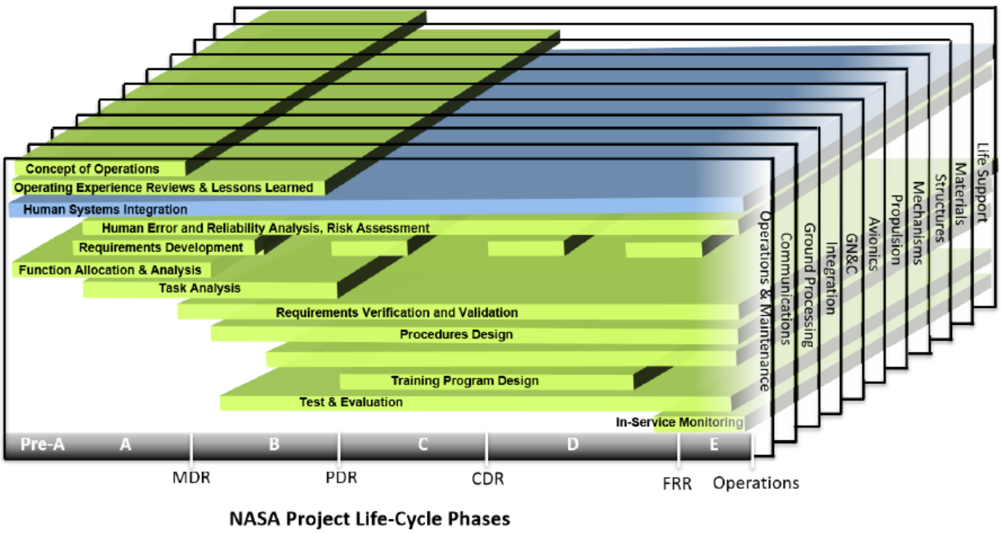


Figure 2.11. HSI activities integrate across all Project Subsystems and Life Cycle Phases [11]

NASA's HSI Plan establishes the framework for integrating human-centered principles throughout the project life cycle. Some key components have been highlighted:

- **Implementation Strategy:** Defines the approach for incorporating HSI principles and processes across all project phases, ensuring integration within technical efforts either through direct leadership or collaboration with other teams.

- **HSI Objectives and Deliverables:** Outlines goals, planned activities, and expected outputs for each phase of the project life cycle.
- **Human-Centered Requirements:** Establishes requirements based on the Concept of Operations (ConOps) and functional analyses conducted during early project development stages.
- **Risk Management Strategy:** Defines the approach for identifying, mitigating, and resolving potential HSI-related risks.
- **Alignment with Systems Engineering:** Ensures consistency with the SE Management Plan and outlines how HSI considerations are incorporated into systems engineering processes and analyses.
- **Compliance with Health and Safety Policies:** Aligns HSI practices with relevant Health and Medical policies, as well as Safety and Mission Assurance guidelines.
- **HSI Maintenance and Updates:** Establishes a process for continuously updating and refining the HSI as the project evolves.

By structuring the HSIP in this manner, the integration of human factors is ensured from the earliest stages of development through the entire project life cycle, enhancing both system performance and human effectiveness.

Chapter 3

Human-System Integration model

This section presents a risk assessment based on evidence collected from **NASA review documents**. The objective is to provide a comprehensive understanding of potential hazards and challenges related to space exploration missions, with a particular emphasis on human factors and performance. The information presented is derived from multiple sources, including:

- **Research reports:** Studies funded by NASA's Human Research Program (HRP), previously published data, research from international partners, and studies from related fields.
- **Crew experiences:** Feedback from International Space Station (ISS) crew members and reports from Space Shuttle missions.
- **Incident analyses:** Data gathered from investigations, focus groups, case studies, and accident investigation reports.
- **Observations:** Non-experimental observations, comparative studies, correlations, and case study analyses.
- **Expert evaluation:** Reports from expert committees and assessments by authoritative figures based on clinical experience, fundamental research, or theoretical principles.
- **Databases:** Records from ISS Flight Crew Integration (FCI) databases containing crew comments.

Through a thorough analysis of this evidence, this section aims to identify the root causes of risks, assess their likelihood and potential impact, and develop effective mitigation strategies to ensure the safety, health, and performance of astronauts during future space exploration missions.

3.1 Risk assessment

Risk is formally defined as the likelihood and severity of an adverse event, including potential losses, disasters, or undesired outcomes. **Risk management** involves identifying, assessing, and prioritizing risks, followed by the strategic and cost-effective allocation of resources to mitigate, control, and monitor both the probability and impact of these events. [3]

Human System Risks represent a specific subset of risks that it is mandatory to address when tackling the complexities of human spaceflight. While institutional and programmatic safety risks are typically associated with specific projects or activities, Human System Risks play a broader role in shaping technical standards to safeguard astronauts, regardless of the mission or program. To align with NASA's standard risk management framework, the terms **Likelihood** and **Consequence** are used. [3]

A **Human System Risk** is defined as a known potential threat to astronaut health or performance that has a measurable likelihood and consequence, supported by available evidence for a specific **Design Reference Mission (DRM)** category [55]. Given the relatively small number of humans who have traveled to space, there are still significant gaps in knowledge and considerable uncertainty about how spaceflight affects human health. These physiological and cognitive changes may impact astronauts' ability to perform critical tasks during a mission and could also influence their medical eligibility for future spaceflight assignments.

DRM Categories	Mission Type and Duration	Gravity Environment	Radiation Environment	Vehicle/Habitat Design	Distance from Earth		EVA
					Evacuation	Communication	Frequency
Low Earth Orbit	Short (<30 days)	Microgravity	LEO-Van Allen (<5-15 mGy)	Mid-sized volume, resupply	1 day or less	Real time	1-4 EVAs
	Long (30 days-1 year)	Microgravity	LEO-Van Allen (5-150 mGy)	Mid-large optimized volume, resupply	1 day or less	Real time	1-10 EVAs
Lunar Orbital	Short (<30 days)	Microgravity	Deep Space-Van Allen (15-20 mGy)	Small volume, self contained, resupply	3 – 11 days	Real time	Contingency EVA only or very few EVA
	Long (30 days-1 year)	Microgravity	Deep Space (175-220 mGy)	Mid-sized volume, self contained, limited resupply	3 – 11 days	Real time	Contingency EVA only or very few EVA
Lunar Orbital + Surface	Short (<30 days)	Microgravity & 1/6g	Deep Space-Van Allen (15-20 mGy)	Small volume, resupply	3 – 11 days	Real time	5 EVAs, some back to back
	Long (30 days-1 year)	Microgravity & 1/6g	Deep Space (100-120 mGy)	Mid-large sized optimized volume, limited resupply	3 – 11 days	Real time	3-4 EVA per week, 20-24 EVA hrs. per week
Mars	Preparatory (<1year)	Microgravity	Deep Space (175-220 mGy)	Midsized optimal volume, limited resupply, closed loop environment	Days – weeks	Controlled - Delayed	Contingency EVA only or very few EVA
	Mars Planetary* (730-1224 days)	Microgravity & 3/8g	Deep Space – Planetary (300-450 mGy)	Midsized optimal volume, no resupply, closed loop environment	Mission duration	No real time	2 crew x 8-hour EVA x 20 EVA days

*Based on memo - HEO-DM-1002 HEO Systems Engineering and Integration (SE&I) Decision Memo on Mars Mission Duration Guidance for Human Risk Assessment and Research Planning Purposes

Figure 3.1. Official NASA Design Reference Mission (DRM) Categories [3]

Unlike other risk categories, Human System Risks also account for the long-term health consequences of space travel, extending beyond the duration of a single program. Our understanding of both the short-term and long-term effects of space exposure on human health and performance continues to evolve. **Health** refers to the absence of medical conditions that could impair performance or jeopardize mission success, while **Performance** relates to an astronaut's ability to complete assigned tasks effectively. Any medical conditions or health impairments can contribute to a decline in performance, affecting mission execution. By integrating knowledge gained from past spaceflight experiences with advancements in terrestrial medicine and human performance research, the aim is to reduce risks for current and future space exploration missions. This process ensures that lessons learned from human spaceflight are continuously applied to enhance astronaut safety and mission success, both in present-day operations and in future deep-space missions.

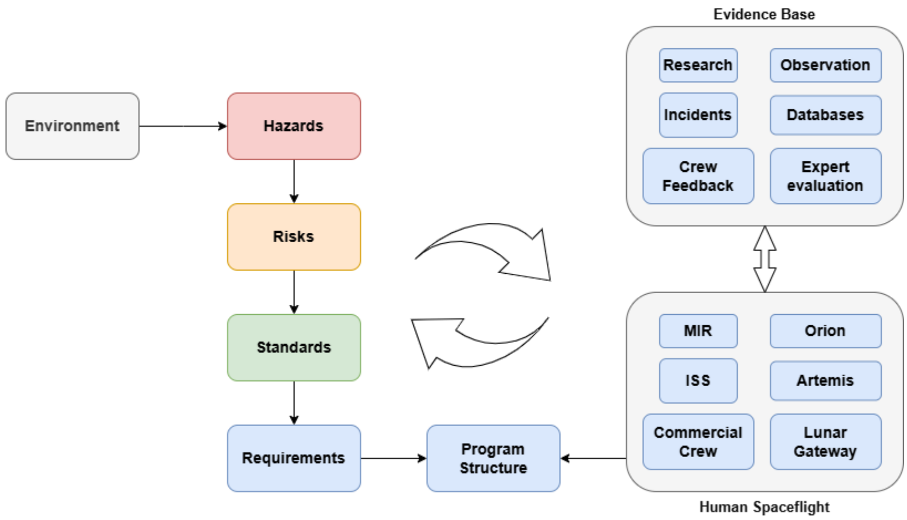


Figure 3.2. Adaptation of the evolution of Human System Risks in Human Spaceflight [3]

The Figure 3.2 outlined the process of risk assessment and management at a high level, with key elements highlighted. Astronauts are inevitably exposed to the inherent conditions of the space environment during missions. These conditions present hazards- fundamental and unalterable aspects of spaceflight that pose risks to human health and performance. Researchers have identified five primary hazards associated with space travel:

- **Altered Gravity**: Being in a reduced-gravity environment initiates physiological adaptations in the human body. Since the body has evolved to function under Earth's 1g conditions, these adaptations can lead to challenges that may affect health and performance.

- **Radiation Exposure**: Space radiation can damage biological cells, with effects dependent on both the duration and intensity of exposure. Over time, this damage may contribute to health complications and impair crew performance.

- **Isolation and Confinement**: Extended periods of isolation and confinement increase the likelihood of psychological, emotional, and physiological stressors, potentially affecting both individual well-being and team dynamics.

- **Hostile and Enclosed Environment**: Space habitats and vehicles provide controlled life-support systems but also introduce risks related to atmospheric composition, water quality, microbial contamination, and acceleration forces, all of which could impact crew safety.

- **Distance from Earth**: As missions venture farther from Earth, challenges arise due to delays in communication, limited opportunities for resupply, extended evacuation times, and constraints on available space and mass for countermeasures.

From these fundamental hazards, specific **Human System Risks** are identified [3], outlining the probability and potential impact of challenges that the human body may encounter in spaceflight. These risks emphasize the physiological and psychological capabilities and needs of astronauts, which must be systematically assessed, mitigated where possible, or accepted when necessary.

One key strategy for risk mitigation involves drawing upon prior human spaceflight data and experiences to develop new standards or refine existing ones, incorporating lessons learned over time [8]. These standards are overseen and applied as mandatory requirements where appropriate when initiating new space programs. Once a spaceflight program is active, monitoring the human system's response to both the space environment and spacecraft systems becomes crucial. This process involves continuously updating the body of evidence by collecting data on crew health and performance from various sources, such as medical evaluations or research studies [55]. Given that human spaceflight remains a relatively recent field, ongoing research and surveillance are essential for refining our understanding of **Risk Posture**.

By analyzing available evidence [55], it is possible to determine the likelihood, consequences, and overall risk disposition associated with a given Human System Risk. This enables informed decision-making regarding acceptable risks and necessary countermeasures. Such an approach ensures that lessons learned from current missions are effectively applied to future space exploration programs, enhancing astronaut safety and mission success.

Risk Posture can be classified into three primary categories, which influence either the crew or the Agency. These categories are depicted in the LxC matrix to demonstrate the corresponding Risk Posture for each Design Reference Mission (DRM) category, as applicable. [3]

- **In-Mission Risk (Ops)**: This category defines the Risk Posture for crews during the mission, starting from a successful launch and continuing through to the safe egress from the landing vehicle. The *Crew Health* impact subcategory highlights health-related issues, while the *Mission Objectives* impact subcategory addresses potential performance decrements that could result in the failure to achieve mission objectives.

- **Flight Re-certification**: This category applies when the manifestation of a risk negatively impacts the astronaut's physical or mental health following a mission, leading to a delay in their flight certification or re-certification status. This risk applies throughout an astronaut's career.

- **Long Term Health (LTH)**: The LTH category refers to the enduring effects of spaceflight on an astronaut's physical and mental health, as well as their performance after completing spaceflight, including post-career impacts. The LTH category is subdivided into two subcategories: the *Health Outcomes* impact, which includes medical conditions resulting from prolonged exposure to the spaceflight environment, and the *Quality of Life* impact, which addresses limitations in an astronaut's ability to perform everyday activities due to the effects of spaceflight exposure during their career.

For each DRM, a **risk scenario** refers to a sequence of credible events that describe the progression of a system or process from its current state to an undesirable outcome. This progression is captured within the **Risk Statement**. Each risk scenario can be classified into up to five distinct categories of consequence, with associated likelihood categories. The likelihood categories are assigned on a 1-5 scale, corresponding to specific ranges of event probabilities, taking into account the level of uncertainty related to the available risk evidence base for any particular DRM risk scenario [55].

The LxC matrix used for Human System Risk (HSR) assessment is depicted in Figure 4, where it shows definitions for both likelihood and consequence across their respective scales and risk impact categories. The numbers in the matrix cells represent priority weights derived from the ISS scorecard, which maps combinations of likelihood and consequence categories for a given DRM and Risk Impact

Category to **LxC Scores**.

At a broader level, the highest LxC Score for each risk is assigned to one of three risk categories: green, yellow, or red. This categorization allows for clear communication of critical information regarding the risk scenario to management and program officials. For example, in a given DRM, risks classified as red include at least one risk scenario with a severe consequence/likelihood combination. These risks are prioritized for mitigation over yellow risks, which have a worst-case consequence/likelihood combination, and these, in turn, are prioritized over green risks. Although the LxC matrix is informed by the best available evidence, it is not designed as a statistically precise tool for risk evaluation. Instead, it serves to provide clear and efficient communication to stakeholders regarding the Risk Posture.

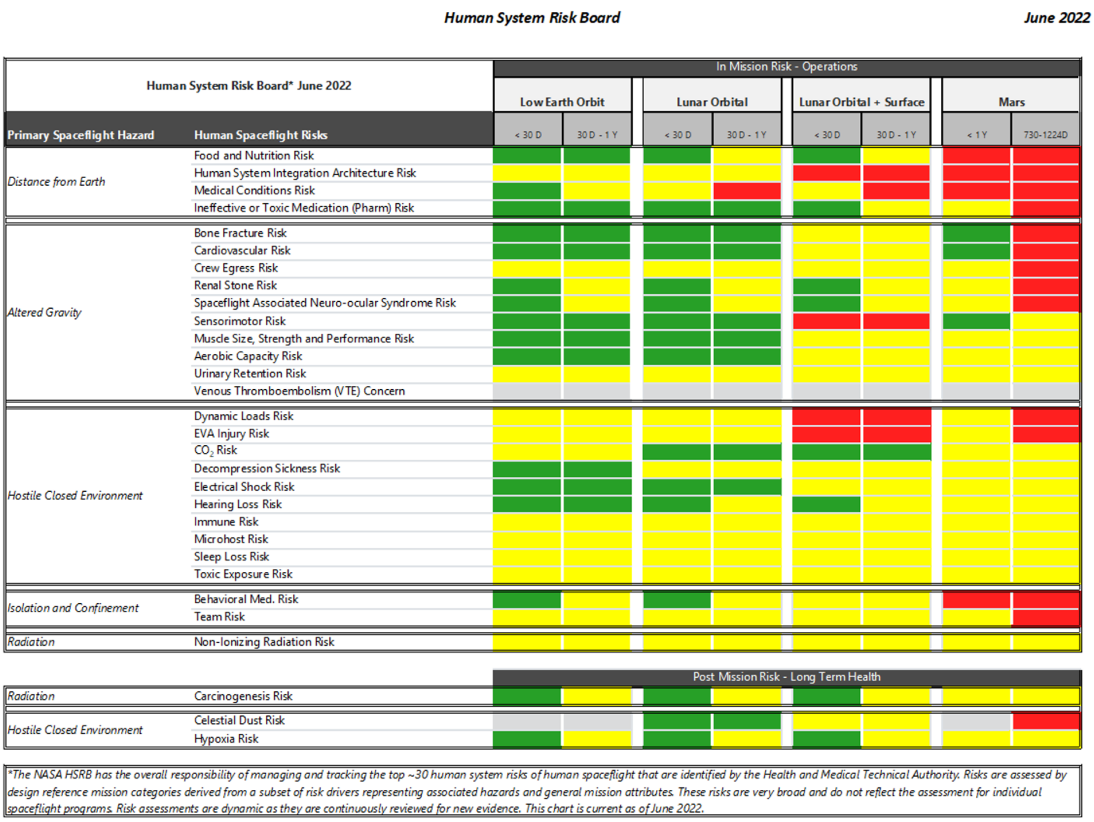


Figure 3.3. Human System Risk Board merged from [3]

All risks exist concurrently during a mission, even though they are often categorized separately for research purposes. When possible, risks that have the potential to impact multiple other risks through their nature or countermeasures should be prioritized over those with fewer interconnections. For instance, the vehicle design is part of the **Human System Integration Architecture** (HSIA) risk, which is the main interest of this research. This risk is addressed, in part, by involving experts in human systems integration throughout the vehicle design process, ensuring that human system countermeasures for other risks are also incorporated. As a result, the HSIA risk is connected to the effective mitigation of all other risks.

To better understand these interdependencies, **Directed Acyclic Graphs** (DAGs) have been developed. These graphs are used to identify the relationships between risks and illustrate the causal flow, from spaceflight hazards to mission-level outcomes, for each risk.

3.1.1 Directed Acyclic Graphs (DAGs) in Risk Assessment

Directed Acyclic Graphs (DAGs) serve as network diagrams characterized by unidirectional connections (directed) and the absence of cyclical feedback loops (acyclic). These properties make DAGs particularly effective for illustrating causal relationships. Within NASA reports [5], DAGs are employed to depict the sequence of events linking spaceflight exposures to adverse mission-level consequences. This visualization serves two primary functions while also laying the groundwork for the continued refinement of causal models for analytical purposes [44].

This tool is a structured knowledge representations that outline the origin and propagation of risks. These risk pathways emerge from the five fundamental spaceflight hazards and, through interconnected causal chains, result in Mission-Level Outcomes. These outcomes encompass health and performance impacts that hold significance both for the agency as an organization and for individual astronauts assigned to missions.

Four of the five spaceflight hazards continuously contribute to physiological and cognitive degradation, affecting astronaut well-being and functionality from the moment of launch. The fifth hazard, distance from Earth, imposes constraints on in-mission support systems and resource availability. As mission distance increases, astronauts encounter greater limitations in terms of mass, volume, power, and data bandwidth allocated to vehicle systems and habitats. Simultaneously, the need for support capabilities escalates due to prolonged exposure to spaceflight conditions, further amplifying the challenges associated with deep-space exploration [44].

Traditionally, risk prioritization has been conducted using Likelihood and Consequence (LxC) scores, which categorize risks using a stoplight system (Red, Yellow, Green) on an individual basis. However, this method does not account for the intricate interdependencies between risks or the compounded effects that arise from their interactions during missions. For instance, a seemingly minor medical condition may pose little immediate threat when assessed in isolation. However, due to the interconnected nature of physiological and psychological stressors, such a condition could escalate over time or amplify the severity of other risks, ultimately increasing mission-wide vulnerability [44].

Recognizing this challenge through the analytical framework provided by DAGs, critical nodes within the causal network can be systematically identified. In this context, a node's "importance" is characterized by several factors, such as its role as a convergence point for multiple causes, its broad influence over various effects, its function as a bridge between disparate risks, or its positioning at a crucial juncture within the system [5]. The practical significance of scoring highly on these measures is that such nodes exert widespread influence over the probability of one or more risks materializing.

A graph is a data structure composed of a set of **vertices** (nodes) and **edges** (links), denoted as $G = \langle V, E \rangle$. Each edge establishes a connection between two nodes, defining them as adjacent [5]. The nature of these edges can be either directed or undirected, leading to two primary graph types: directed graphs, where edges have a specific direction, and undirected graphs, where connections are bidirectional.

For instance, in an undirected graph, if an edge exists between nodes A and B (denoted as $A - B$), both nodes are considered mutually adjacent. However, in a directed graph, an edge from A to B (denoted as $A \rightarrow B$) implies that A is adjacent to B, but the relationship is not reciprocated unless an additional edge ($B \rightarrow A$) exists. A directed graph may contain cycles, meaning a path exists that loops back to the starting node. However, if a directed graph is structured such that no cycles exist, it is classified as a Directed Acyclic Graph (DAG). Figure 3.4 provides an example of a DAG illustrating how various factors contribute to human spaceflight risks [44].

In the context of human spaceflight, DAGs provide a structured representation of how hazards propagate through multiple causal pathways to impact mission success. At the foundation of this framework, the "*Hazards*" node represents fundamental spaceflight stressors such as microgravity, radiation, and isolation. These hazards lead to "*Health and Performance Risks*," which encompass physiological and psychological challenges faced by astronauts. The effects of these risks extend to "*Individual Readiness*," reflecting an astronaut's ability to perform mission tasks effectively.

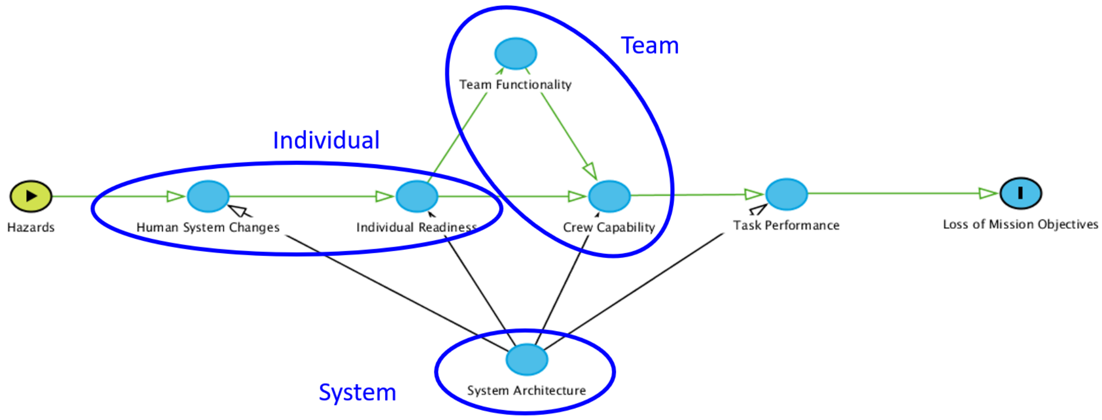


Figure 3.4. Example of a Directed Acyclic Graph. This simplified diagram demonstrates how an individual, the team, and the overall system influence the probability of successfully completing a mission task. [5] [44]

However, the impact of individual performance does not operate in isolation; it contributes to "*Team Functionality*" and "*Crew Capability*." If one crew member experiences a performance decline, other team members may compensate. The success of specific mission tasks depends on both human factors and systemic factors, including the "*Human System Integration Architecture* (HSIA)." The HSIA encapsulates design constraints and resource availability, such as spare parts and repair protocols, which influence overall mission execution. Even a well-prepared crew may struggle if critical system redundancies are lacking.

By capturing these relationships in a graphical format, DAGs enable the mathematical analysis of causal structures. If empirical evidence supports the assignment of quantitative values to nodes and edges, these graphs can be further refined to assess the strength of different causal relationships. Importantly, every connection in a DAG represents a testable hypothesis: should new data contradict an assumed causal link, the DAG can be updated to reflect a revised understanding of risk propagation. These configuration-managed models provide a systematic approach to understanding the interplay of risks in human spaceflight, forming a foundation for future refinement and decision-making in mission planning.

As we move forward in applying these rules, the reader can learn more by referring to NASA/TM 20220006812 - Directed Acyclic Graph Guidance Documentation [5]. This document provides fundamental guidance on creating and standardizing DAGs for cross-risk analysis. It also includes the initial configuration-managed DAGs developed through the application of these principles. To summarize, **nodes** are depicted as circles, while **edges** are illustrated as arrows that indicate causal relationships. Each arrow originates from a causal factor and extends toward its corresponding effect.

Nodes can be categorized based on their connectivity:

- **Exogenous nodes**: Nodes with one or more outgoing arrows but no incoming arrows. These nodes represent variables that are not influenced by any other nodes within the network.
- **Endogenous nodes**: Nodes with one or more incoming arrows. These nodes have causes within the network, meaning their states are influenced by other factors.

Contributing factors include any hazard, operational design element, or human system variable that affects the outcomes of concern in human spaceflight. These factors can be viewed as system variables whose states influence mission success or failure. Importantly, they can be modified through the implementation of **risk mitigations**, which are also referred to as **countermeasures**.

By definition, any node that precedes the **Mission Level Outcomes** within a DAG can be classified as a contributing factor. To align with established terminology, we adopt the following conventions for naming:

- **External factors**: Exogenous nodes, representing variables that originate outside the system and are not influenced by other network elements.
- **Integral factors**: Endogenous nodes, which serve as intermediaries in the causal chain between spaceflight hazards and mission-level outcomes.

Integral factors play a critical role in completing the causal pathways between spaceflight hazards and mission success or failure. These nodes serve as intermediate variables linking a specific exposure (e.g., radiation, microgravity, isolation) to a final outcome of interest. In particular, the two primary categories of nodes are:

- **Exposures**: The set of spaceflight hazards that initiate risk pathways.
- **Mission Level Outcomes**: The final consequences of risk propagation, representing the ultimate effects on crew health, performance, and mission success.

The terms *exposure* and *outcome* are relative within the structure of a DAG. Any node that lies upstream of another node can be considered an exposure, while any node downstream can be classified as an outcome. When referring specifically to the initial and final nodes within a given risk DAG, the terms **Hazard** (starting point) and **Mission Level Outcomes** (ending point) to provide clear contextual differentiation [5].

The aim now is to apply these rules to create a narrative that explains the **Human System Integration Architecture (HSIA) Risk**. Using the same principles of expanding and detailing causal pathways, it will illustrate how the HSIA risk interrelates with other human system risks and how it affects mission outcomes. By employing Detailed DAGs, we can construct a clearer, more comprehensive narrative to convey the complex dependencies and causal mechanisms that underpin the HSIA risk, ensuring it is understood in the context of the broader system of human spaceflight risks. The DAG was created using **DAGitty 3.0**, a publicly available browser-based tool for constructing, editing, and analyzing causal diagrams [4].

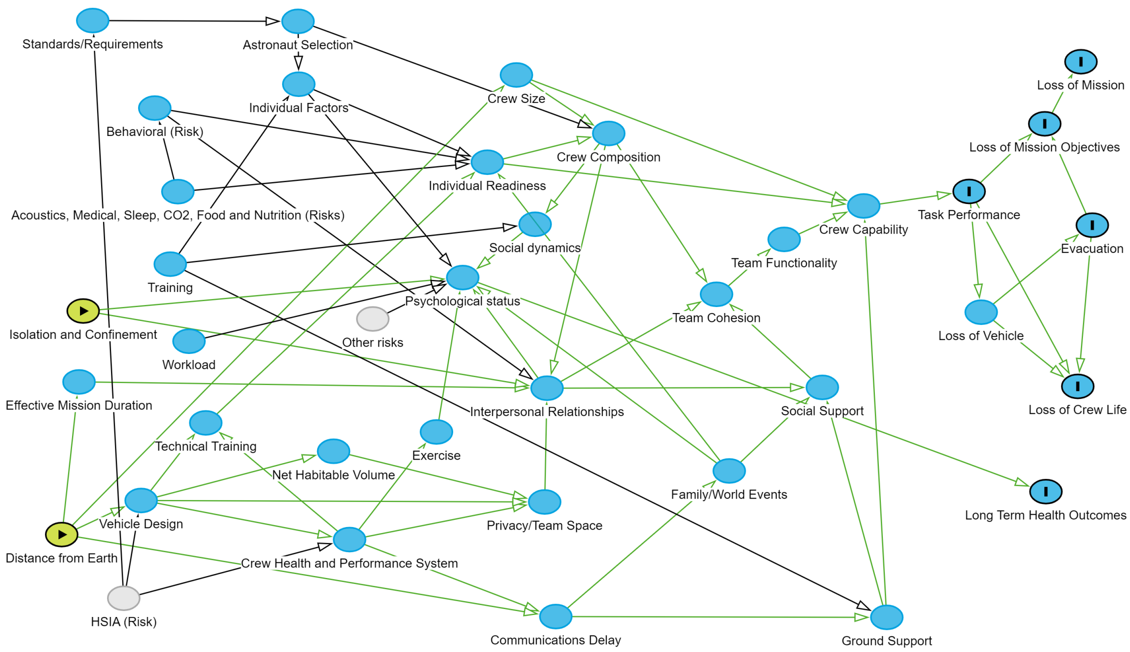


Figure 3.5. Risk of Performance and Behavioral Health Decrement due to inadequate Habitability

Fig. 3.5 presents the narrative of the risk of performance and behavioral health decrement due to inadequate habitability in spaceflight, arising from multiple interrelated factors that stem from **vehicle design** and **environmental constraints**. A poorly designed spacecraft can introduce significant stressors that negatively impact the physical and psychological well-being of the crew, leading to potential mission failure.

Key environmental factors such as **acoustics, CO_2 levels, sleep conditions,**

medical support, and food and nutrition availability are critical determinants of astronaut well-being. Inadequate control over these variables can disrupt circadian rhythms, impair cognitive function, and contribute to chronic fatigue. Furthermore, the **hostile closed environment** of space exacerbates feelings of isolation and confinement, which can deteriorate the **psychological status** of crew members, increasing their **stress levels** and vulnerability to behavioral health issues.

The constraints on **net habitable volume** and the availability of **privacy/team space** significantly influence **interpersonal relationships** and **social support** among crew members. Limited personal space can lead to interpersonal tension, reducing **team cohesion** and negatively affecting **team functionality**. The psychological strain of prolonged space missions is further intensified by **communication delays with Earth**, which limit real-time interaction with family and ground support.

The cumulative effect of these stressors leads to a **decline in individual readiness**, which in turn affects **crew capability** and **task performance**. Factors such as **inadequate training, insufficient exercise opportunities, and an overwhelming workload** can compromise both physical and cognitive functioning. Moreover, external stressors like **family and world events**- amplified by delayed communications - can further degrade an astronaut's mental state.

The **effective mission duration** and **distance from Earth** serve as aggravating factors, extending the exposure of crew members to these adverse conditions. If left unmitigated, these risks can result in **loss of mission objectives**, **loss of mission**, or, in extreme cases, **loss of crew life**. Additionally, long-duration spaceflight can lead to **long-term health outcomes** that persist post-mission, necessitating continued medical surveillance.

While factors as **standards/requirements and astronaut selection** provide a foundational framework for mitigating risks, they are not direct inputs into this particular risk pathway. Instead, **proactive countermeasures** - including **optimized vehicle design, psychological support systems, and adaptive training protocols** - must be implemented to ensure that astronauts can maintain optimal performance and well-being throughout the mission. Understanding and addressing this risk requires a **systems-based approach** that integrates **human factors engineering, environmental monitoring, and psychosocial support strategies** to create a sustainable, habitable environment for long-duration space exploration.

As we can see, the "Risk of Performance and Behavioral Health Decrement due

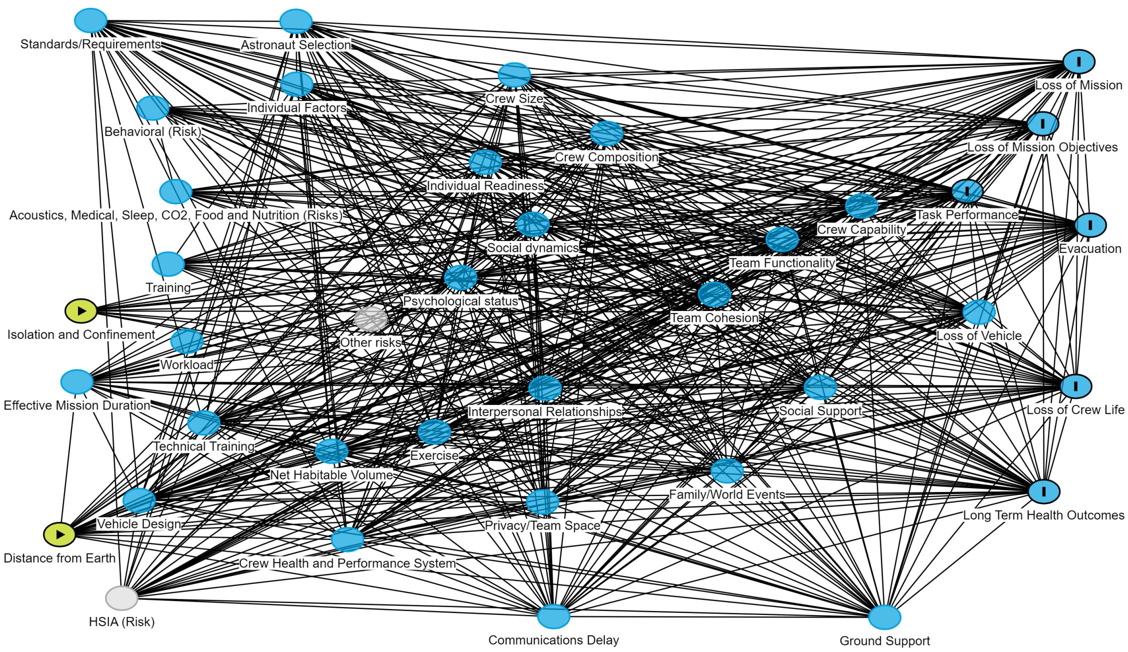


Figure 3.6. Correlation with covariant in the model

to Inadequate Habitability" involves a network of factors influencing crew health and performance. It's important to summarize in a more simple way all the correlations (Fig.) and to create an ontology. Furthermore, it's important to note that **Standards/Requirements** and **Astronaut Selection** are not direct inputs in this DAG but rather prerequisites that lay the foundation for managing the risk.

The **Vehicle Design** is the primary factor impacting several critical aspects:

- **Acoustics, Medical, Sleep, CO_2, Food and Nutrition (Risks)**: Suboptimal conditions in these areas can lead to both physiological and psychological stress, impairing overall crew well-being.
- **Net Habitable Volume**: Limited space can result in psychological strain, affecting privacy and overall comfort.
- **Privacy/Team Space**: Lack of privacy can negatively affect individual well-being and interpersonal relationships, undermining crew dynamics.

Isolation and Confinement during spaceflight can further exacerbate the situation, leading to:

- **Psychological Status**: Changes in mood, cognition, or behavior that can affect performance and mental health.

- **Interpersonal Relationships**: Strain between crew members due to close proximity and limited social interaction, leading to potential conflicts and psychological discomfort.

In addition, **Other Risks** can arise from various sources, including:

- **Workload**: Excessive workload can lead to fatigue, decision-making errors, and reduced cognitive function.
- **Training**: Inadequate training may reduce preparedness and increase stress levels, diminishing crew readiness for unexpected situations.
- **Exercise**: Insufficient physical activity can lead to various health problems, such as muscle atrophy and cardiovascular issues.
- **Family/World Events**: Worrying about events on Earth, as family issues or global crises, can distract crew members and hinder focus.
- **Communications Delay**: Difficulty in communicating with ground support can increase stress, making it harder to receive real-time assistance in critical moments.

Individual Factors, such as **Behavioral Risks** and **Crew Composition**, also play a significant role in overall mission success. These factors can contribute to:

- **Individual Readiness**: A reduced ability to perform tasks effectively, which can lead to mission delays or errors.
- **Team Cohesion**: Weakened bonds among crew members, which can affect cooperation and task efficiency.
- **Social Dynamics**: Negative interactions within the crew, which can further strain psychological well-being.
- **Social Support**: A lack of support from fellow crew members, increasing the potential for individual distress.

Ultimately, these factors can result in a decline in overall mission success, leading to:

- **Crew Capability**: A reduced ability to complete mission objectives and deliver expected outcomes.
- **Task Performance**: Increased errors, reduced efficiency, and compromised quality of work.

- **Team Functionality**: Impaired teamwork, coordination, and the ability to adapt to challenges.

In severe cases, these issues can lead to:

- **Loss of Mission Objectives**: Failure to achieve key goals and milestones of the mission.
- **Loss of Mission**: Premature termination of the mission due to insurmountable obstacles.
- **Loss of Vehicle**: Damage to or complete loss of the spacecraft, potentially jeopardizing the entire crew.
- **Loss of Crew Life**: The tragic death of crew members, the worst possible outcome in any space mission.

Furthermore, **Long-Term Health Outcomes** can be affected by prolonged exposure to these stressors, including physical and psychological health issues that persist after the mission. The **Crew Health and Performance System**, **HSIA**, and **Ground Support** are crucial for mitigating these risks. They provide essential services as:

- **Evacuation**: Emergency return to Earth if necessary to ensure crew safety.
- **Support**: Ongoing medical and psychological assistance to maintain crew well-being throughout the mission.

Finally, **Effective Mission Duration** and **Distance from Earth** can exacerbate these risks, as longer missions and greater distances increase the time exposed to these stressors. In summary, the DAG provides a comprehensive framework for understanding the complex interplay of factors affecting astronaut health and performance. It underscores the need for a holistic, human-centered approach to space mission planning, with a focus on not just immediate mission success but also the long-term well-being of the crew.

3.1.2 Risk of Inadequate Human-System Integration

The effective management of Human Systems Integration Architecture (HSIA) risks is fundamentally predicated on a human-centered approach, particularly as mission complexity increases. As illustrated in Table 3.7, the risk disposition varies significantly across different Design Reference Missions (DRMs), underscoring the necessity for adaptive and human-focused strategies.

DRM Categories	Mission Type and Duration	LxC Ops	Risk Disposition	LxC LTH	Risk Disp
Low Earth Orbit (LEO)	Short (<30 days)	5x2	Accepted	N/A	N/A
	Long (30 d-1 yr)	5x2	Accepted	N/A	N/A
Lunar Orbital	Short (<30 days)	5x2	Requires Mitigation/Standard Refinement	N/A	N/A
	Long (30 d-1 yr)	5x2	Requires Mitigation/Standard Refinement	N/A	N/A
Lunar Orbital + Surface	Short (<30 days)	5x3	Requires Mitigation	N/A	N/A
	Long (30 d-1 yr)	5x3	Requires Mitigation	N/A	N/A
Mars*	Preparatory (<1 year)	5x4	Requires Mitigation	N/A	N/A
	Planetary (730-1224 days)	5x5	Requires Mitigation	N/A	N/A

Figure 3.7. HSIA LxC Risk Disposition (updated 01/2021) [2]

The central tenet of HSIA is to empower crew members with the autonomy to respond effectively to unexpected and off-nominal events, thereby enhancing safety, efficiency, and mission success. This necessitates that human-system designs are meticulously crafted, placing human capabilities and limitations at the forefront, especially during Long Duration Exploration Missions (LDEMs). Given the inherent challenges of LDEMs, including inevitable safety and mission-critical anomalies and communication delays with Earth, the crew's ability to independently resolve issues is paramount [2].

To support this autonomy, reliable onboard capabilities are crucial, not only for anomaly resolution but also for fostering situation awareness (SA) and mitigating workload. Spaceflight missions subject crew members to a diverse range of environmental conditions, demanding versatile task performance. To comprehensively address the associated risks, a mapping of the five primary human spaceflight risks to HSIA contributing factors and Countermeasures (CM) strategies has been presented via a directed acyclic graph (DAG) in Fig. 3.8.

This HSIA DAG representation visually articulates the causal pathways from hazards (orange boxes), such as distance from Earth and hostile closed environments, to contributing factors (blue boxes), like autonomous operations and anomalous events, and ultimately to potential consequences (red boxes), such as loss of crew or vehicle. The DAG employs arrows and dashed lines to depict causal relationships, emphasizing the impact of factors like communication delays and distance from Earth. The anticipated CM strategies, crucial for risk mitigation, are highlighted in green boxes within the DAG, focusing on areas like communication tools, procedure design, and crew training.

In the context of specific DRMs, LEO missions benefit from existing CM protocols, while lunar orbital missions necessitate Standard Refinement and potential further mitigation. Extended lunar orbital, lunar surface, and Mars missions require more extensive mitigation strategies due to increased uncertainties and prolonged durations.

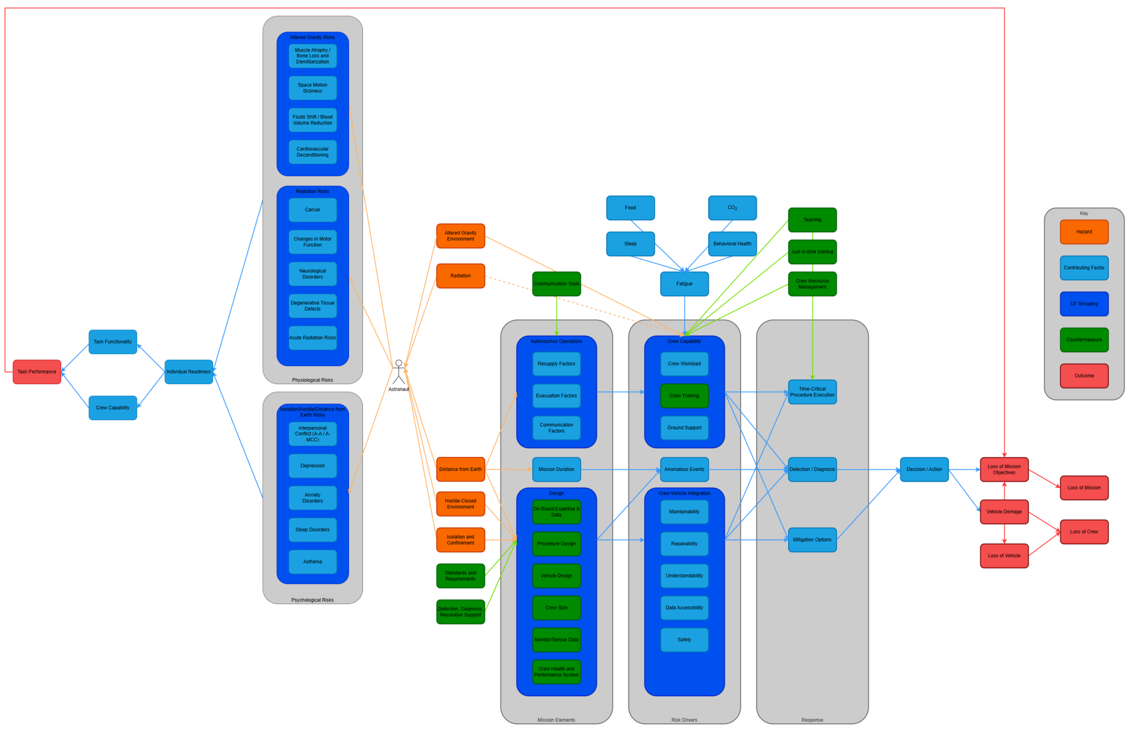


Figure 3.8. Adaptation from NASA's HSIA Directed Acyclic Graph with Expected Countermeasures, (as of January 2021), with the integration of the astronaut as an integral part of the system and relative physiological and psychological problems due to the exposure to the five hazards [4]

The hazards encountered during space missions, particularly deep space exploration, can have a profound and wide-ranging impact on astronauts' performance abilities. These impacts can be categorized into psychological and physiological effects, which together can severely affect crew performance and well-being. In particular, for what concerns the psychological effects, it has been highlighted:

- **Stress and Anxiety:** Chronic stressors, including isolation, confinement, and communication delays, can lead to elevated anxiety levels. The inability to maintain a healthy work-life balance in the extreme environment of space can exacerbate these psychological states.

- **Depression:** Prolonged isolation, distance from Earth, and lack of social interaction can contribute to depressive symptoms, impacting crew members' mental health and overall mission engagement.

- **Sleep Disturbances:** The absence of natural circadian rhythms, changes in environmental conditions (e.g., light exposure), and the demands of mission schedules can lead to irregular sleep patterns, resulting in sleep deprivation and impaired cognitive functions.

- **Cognitive Impairment:** Extended exposure to space's microgravity environment, combined with high-stress levels and sleep disturbances, can impair attention, memory, decision-making, and problem-solving abilities, all crucial for mission success.

- **Interpersonal Conflicts:** The confined living spaces and the constant proximity to fellow crew members can strain interpersonal relationships. The lack of privacy and increased tension due to limited social support can lead to interpersonal conflicts that undermine crew cohesion and performance. Thus, it's also important to highlight the international environment in which they live that sometimes can lead to particular problems related to the different cultural habits and ways of working.

On the other hand, for what concerns the physiological effects, the most known ones have been taken into account:

- **Muscle Atrophy:** In microgravity environments, muscles are not required to support the body against gravity, leading to muscle weakening and atrophy. Prolonged missions can exacerbate this effect, making physical tasks more difficult and potentially jeopardizing mission success.

- **Bone Loss:** The absence of gravitational forces can lead to significant bone density reduction, a condition known as spaceflight osteoporosis, increasing the risk of fractures and long-term skeletal health issues.

- **Cardiovascular Deconditioning:** Reduced gravitational load in space leads to changes in cardiovascular function, including a decrease in cardiac output, which can result in decreased exercise tolerance and increased susceptibility to post-flight orthostatic hypotension.

- **Immune Dysfunction:** Space radiation, stress, and confinement can compromise the immune system, leaving astronauts more vulnerable to infections and reducing their ability to respond to illness.

- **Radiation Exposure:** Increased exposure to cosmic radiation and solar particles poses long-term health risks, including cancer, cardiovascular disease, and potential genetic damage; this, in particular, is time-dependent, so the longer the exposure, the worse the damage on the human body.

- **Sensory Disturbances:** Altered visual and vestibular inputs due to microgravity can cause disorientation, balance issues, and motion sickness, which can interfere with astronauts' ability to perform tasks and maintain overall well-being.

If these psycho-physiological risks are not effectively mitigated, they can lead to a cascade of adverse consequences, severely affecting the mission and the crew's health.

- **Reduced Crew Capability:** Impaired psychological and physiological abilities can lead to a diminished capacity to perform mission-critical tasks, making it difficult to meet mission objectives and manage emergencies.

- **Compromised Task Performance:** As cognitive and physical abilities decline, the likelihood of errors, accidents, and inefficiency increases, which may compromise mission outcomes and crew safety.

- **Loss of Mission Objectives:** When crew members cannot perform at optimal levels, mission goals may not be achievable, resulting in partial or complete failure to fulfill mission objectives.

- **Loss of Mission:** In extreme cases, unresolved psycho-physiological impairments may force the mission to be aborted. Critical failures in crew health or performance could jeopardize the entire mission's safety and success.

- **Loss of Crew Life:** In the most severe scenarios, if psycho-physiological risks are left unaddressed, the safety of the crew may be compromised to the point of fatal outcomes. Health deterioration from psychological stress, physical ailments, or medical emergencies can lead to the loss of crew members, with irreversible consequences.

To minimize these risks, a **human-centered design approach** has been identified as a fundamental strategy for enhancing crew health, performance, and resilience in space missions. Human-centered design prioritizes astronaut needs, capabilities, and limitations in system development, ensuring that operational environments and support systems are optimized for crew well-being. This approach integrates advanced technological, operational, and medical solutions to create a sustainable and adaptive spaceflight environment.

3.1.3 Habitat Design Factors

The design of space habitats and vehicles must account for a range of environmental factors that influence human performance and safety. Microgravity, acceleration, vibration, and other spaceflight conditions impose unique constraints on human-system interactions. Therefore, it is essential to integrate human capabilities and limitations into the design of spacecraft interfaces, habitats, and operational systems, particularly for LDEMs. Failure to incorporate these considerations may result in suboptimal vehicle habitat configurations that are misaligned with human physiological and cognitive constraints. Such discrepancies can lead to inefficiencies, increased workload, and potential safety hazards.

In particular, design inadequacies can lead to both short-term and long-term performance issues:

- **Short-term effects** include physical overexertion, impaired readability of displays due to spacecraft vibrations or insufficient lighting, thermal discomfort caused by inefficient hardware placement, and difficulties in donning space suits due to constrained habitable volume. Additional issues include impaired communication between crew members due to excessive ambient noise and unnecessary physical translations between workstations, leading to inefficiencies in task execution [38].

- **Long-term effects** may encompass cumulative trauma disorders due to repetitive motion and awkward postures, musculoskeletal stress from suboptimal workspace clearances, and permanent hearing impairment due to sustained exposure to high noise levels. Moreover, prolonged interaction with ergonomically deficient equipment may result in chronic injuries and reduced operational efficiency, posing risks to both crew well-being and mission success [38].

To mitigate these risks, the design of space habitats should incorporate the following key HSIA factors [27]:

1. **Anthropometric and biomechanical constraints:** Accommodating a diverse range of body sizes and movement capabilities to ensure ergonomic efficiency.

2. **Visual environment considerations:** Optimizing lighting conditions and display readability under varying gravitational conditions.

3. **Vibration and g-force impact:** Designing support structures and restraints to minimize adverse physiological effects.

4. **Acoustic environment:** Implementing noise reduction strategies to prevent communication difficulties and long-term auditory damage.

5. **Seating, restraints, and personal equipment:** Developing adjustable and secure interfaces to enhance stability and comfort.

6. **Window design and placement:** Providing external visibility while balancing structural integrity and radiation protection.

7. **Habitat volume and layout:** Ensuring adequate net habitable volume (NHV) to facilitate efficient task execution and mitigate spatial confinement effects.

Comprehensive testing and validation are imperative to ensure the compatibility of human and vehicle habitat interactions. These are the methodologies recommended to follow, and in particular, in this study the first two have been employed:

- **Population Analysis:** Studying diverse anthropometric data to inform design decisions.

- **Digital Modeling and Simulation:** Utilizing computational tools to predict human-system interaction outcomes.

- **Human-in-the-Loop (HITL) Evaluations:** Conducting tests with astronauts experienced in spaceflight to identify potential incompatibilities.

- **Physical Mockups and Simulators:** Creating high-fidelity representations of habitat layouts to assess functionality under microgravity and reduced-gravity conditions.

To develop an operational environment that effectively accommodates the physical and cognitive capabilities of the crew, it is essential to systematically document and analyze these attributes across all mission phases. In particular, defining the minimum Net Habitable Volume (NHV) necessary to carry out mission-critical tasks is paramount to mitigating risks associated with inefficiencies and potential injuries.

A crucial aspect of this process involves the use of high-fidelity mockups and simulators that accurately replicate the spatial configuration and constraints of the habitat in microgravity and partial gravity conditions. These tools facilitate early-stage design assessments and continue to serve in design validation and crew training throughout the mission lifecycle. But to avoid a waste of costs here it has been identified that employing high-resolution computational models is indispensable, particularly during the development phase when multiple subsystems are being designed concurrently. This approach helps address challenges associated with verifying requirements when physical prototypes are not readily available for empirical testing.

Incorporating a comprehensive understanding of human capabilities, limitations, and functions (particularly in states of illness, injury, or deconditioning) into the systems engineering process is crucial for ensuring optimal performance. This involves developing methods to evaluate human performance and translate these insights into technical requirements that guide system development. To ensure that existing requirements are properly identified and leveraged, the NASA STRD-3001-Vol-2 standard [46] has been utilized to detect which requirements are already in place. This resource provides a structured framework for evaluating human performance-related requirements, ensuring that previously established guidelines and standards are incorporated into the design process. By cross-referencing existing requirements, this approach helps avoid redundancy and ensures that all relevant human performance considerations are accounted for in system development. Therefore, to each of them a link between how physical restriction affects the design of the components, as has been done in the example of the deconditioning problem (Fig. 2.9).

Anthropometry and Biomechanical Limitations

The physical characteristics of astronauts, including body dimensions, strength, dexterity, and mobility, must be carefully considered in spacecraft design to ensure safety and operational efficiency. Inadequate consideration of these factors can lead to hazardous conditions that may increase the risk of injuries, fatigue, and impaired performance. While directly linking anthropometric and biomechanical constraints to flight accidents is challenging, studies indicate that poor workspace design, such as insufficient clearance around operators or inadequate accommodation of physical exertion capabilities, can lead to injuries ranging from repetitive strain disorders to more severe conditions. To prevent such risks, it is essential that spacecraft environments are designed to support a wide range of physical attributes while minimizing physical strain and discomfort [27].

The following table (Fig. 3.10) outlines various requirements related to human systems integration (HSI) in spacecraft design and operations. Each row in the table lists a specific requirement, along with its corresponding number from the NASA-STD-3001 [45] [46] document and a brief description of the requirement. For example, the first row states that "*The system shall provide crew interfaces that result in a Borg-CR10 rating of perceived exertion (RPE) of 4 (somewhat strong) or 1 less.*" This means that the spacecraft's systems and controls should be designed in a way that minimizes the physical workload on crew members, ensuring they do

Risk of inadequate HSIA and Vehicle Habitat Design - Spaceflight Evidence			
Design Factor	Subcase	Problem	Design Impact
Anthropometry and Biomechanical Limitations	Repetitive Stress Injuries	In-flight musculoskeletal injuries. Causing injuries were related to habitat design: these included impacting structures, stowing equipment, translating through the spacecraft, repairing equipment, and abnormal positioning.	Internal layout configuration
	Impacts of Microgravity on Anthropometry, Posture, and Strength	Spinal Elongation	Seats
		Neutral Body Posture	Suits
		Hardware and Task Considerations: constraints related to accessibility or obstructions. This can increase task duration, impede performance, and induce injury.	Internal volume, Hardware position

Figure 3.9. Impact on the Design of Anthropometry and Biomechanical Limitations

not experience excessive fatigue or exertion during their tasks.

Visual Environment Considerations

The ability of astronauts to perform tasks effectively can be significantly affected by environmental conditions such as darkness, dust, smoke, or other visibility-reducing factors, both inside and outside the spacecraft. Reduced visibility can increase the likelihood of errors, compromise task performance, and contribute to unsafe conditions. Since visual perception is the primary means through which astronauts gather information about their surroundings, an optimized lighting system is essential for maintaining situational awareness (Fig. 3.11) [4].

In addition to task performance, lighting conditions play a key role in regulating circadian rhythms, which directly affect astronaut health and cognitive function. Properly designed spacecraft lighting should include adjustable brightness levels and color temperature variations to align with natural sleep-wake cycles, promoting alertness and well-being. However, designing a lighting system that meets both physiological and operational requirements presents challenges, especially when balancing power consumption, spatial constraints, and mission objectives (Fig. 3.12). Therefore, future spacecraft should incorporate dynamic lighting solutions that optimize human performance while minimizing resource demands [27].

Vibration and G-Force Exposure

High-intensity vibration and gravitational forces during critical flight phases, e.g. launch, emergency aborts, and reentry, can negatively impact astronaut performance and well-being. Excessive vibration can degrade visual acuity, disrupt manual control tasks, and impair communication due to reduced speech intelligibility. If prolonged or severe, vibratory forces may also impose mechanical stress on internal organs and the musculoskeletal system, increasing the risk of physiological injuries.

	NASA-STD-3001, Volume 2		
	Title	Number	Requirement Text
Repetitive Stress Injuries	Physical Workload	[V210200]	The system shall provide crew interfaces that result in a Borg-CR10 rating of perceived exertion (RPE) of 4 (somewhat strong) or less.
	Acceleration Injury Prevention	[V26069]	The system shall mitigate the risk of injury to crewmembers caused by accelerations during dynamic mission phases per Table 6.5-9—Acceptable Injury Risk Due to Dynamic Loads.
	Injury Risk Criterion	[V26070]	The system shall limit crew exposure to transient translational acceleration (≤0.5 seconds) by limiting the injury risk criterion (β/beta) to no greater than 1.0 (Low) for seated or standing crew as defined by Dynamic Response (DR) limits in NASA/TM-20205008198 Table 2 "Updated Dynamic Response Limits for Standing", while crew are restrained as required in NASA/TM-2013-217380REV1 for seated crew, or NASA/TM – 20205008198 for standing crew.
	Dynamic Mission Phases Monitoring and Analysis	[V26111]	The system shall collect vehicle and crewmember acceleration parameters, specific kinematic responses, and associated metadata, during all dynamic mission phases and suited operations (defined as ascent, abort, entry, descent, landing, postlanding, and EVA operations) to correlate with any injuries incurred by crewmembers.
	Dynamic Mission Phases Monitoring and Analysis	[V26111]	The system shall collect vehicle and crewmember acceleration parameters, specific kinematic responses, and associated metadata, during all dynamic mission phases and suited operations (defined as ascent, abort, entry, descent, landing, postlanding, and EVA operations) to correlate with any injuries incurred by crewmembers.
	Physiological Countermeasures Capability	[V27038]	The system shall provide countermeasures to meet crew bone, muscle, sensorimotor, thermoregulation, and aerobic/cardiovascular requirements defined in NASA-STD-3001, Volume 1.
	Medical Equipment Usability	[V27045]	Medical equipment shall be usable by non-physician crewmembers in the event that a physician crewmember is not present or is the one who requires medical treatment.
	Stowage Restraints	[V27054]	The system shall provide the capability to restrain hardware, supplies, and crew personal items that are removed or deployed for use as defined by crew task analysis.
	Trash Accommodation	[V27064]	The system shall provide a trash management system to contain, mitigate odors, prevent release, and dispose of all expected trash.
	Intravehicular Translation Paths	[V28013]	The system shall provide intravehicular activity (IVA) translation paths that allow for safe and unencumbered movement of suited and unsuited crew and equipment.
	Protection from Functionally Sharp Items	[V29010]	Functionally sharp items shall be prevented from causing injury to the crew or damage to equipment when not in use.
	Pinch Points	[V29013]	Pinch points shall be covered or otherwise prevented from causing injury to the crew.
	Sharp Edge and Burr Injury Prevention	[V212028]	The system shall protect ground support personnel from injury resulting from sharp edges and burrs.
	Pinch Point Prevention	[V212029]	The system shall be designed to protect ground personnel from injury due to pinch points.
Spinal Elongation	Anthropometry, Biomechanics, Range of Motion, and Strength	[V212004]	Each program shall identify an anthropometry, biomechanics, range of motion, and strength data set for the ground support population to be accommodated in support of all requirements in this section of this NASA Technical Standard.
Hardware and Task Accessibility	Restraints and Platforms	[V212024]	The system shall accommodate restraint and platform placement that ensures the reach and work envelope of the suited or unsuited ground support personnel for the required tasks.
	Crew Interface Commonality	[V29001]	Hardware and equipment performing similar functions shall have commonality of crew interfaces.
	Differentiation	[V29002]	Hardware and equipment that have the same or similar form but different functions shall be readily identifiable, distinguishable, and not be physically interchangeable.
	Routine Operation	[V29003]	Worksites shall be designed to provide rapid access to needed tools and equipment for routine/nominal operations.
	Training Minimization	[V29004]	Hardware and equipment with which crew interact shall minimize the time required for training.

Figure 3.10. Anthropometry and Biomechanical Requirements from NASA STRD-3001-Vol-2 [46]

Additionally, uncontrolled body movement due to excessive vibration may lead to unintended impacts with onboard structures or fellow crew members [7].

During dynamic flight phases, astronauts are subjected to varying levels of vibration and G-loading, the intensity of which depends on the spacecraft's propulsion system and structural design. In capsule-type crew vehicles, astronauts typically adopt a semi-supine posture during launch and reentry, experiencing increased gravitational forces along the chest-to-spine axis. These forces, combined with propulsion system oscillations and aerodynamic interactions, create complex vibratory environments that can challenge crew operations [4].

Risk of inadequate HSIA and Vehicle Habitat Design - Spaceflight Evidence			
Design Factor	Subcase	Problem	Design Impact
Visual Environment	Light Levels for Task Performance	Lighting levels may affect the ability to access equipment and information	Alternative lighting, technologies, cameras, or resources
	Glare and Uniformity	Overly bright or dark areas may become a distraction or reduce visual contrast when	Uniformity, glare, and lighting gradients
	Color Accuracy	Crewmembers reported issues with a task involving comparing the color of a liquid to a	Color light
	Blue Light Radiation	Exposure of predominantly blue light suppresses melatonin production that can affect sleep	Install new solid-state lighting
	Flicker	The light source met human factors flicker limitations but ISS camera systems failed to operate properly within the lighting environment provided.	Flicker index or flicker limit levels requirements
	System Layout Design	Inclusion of visibility and lighting considerations during development of concept of operations and system design, and during task analysis is likely to preclude costly engineering changes later in the program.	Design and placement of lights and lighting schemes within modules must be carefully considered
	Design Consistency	Poor consistency across systems, including inconsistency between flight and ground training hardware and software, can lead to errors and increase time to perform tasks.	Consistency of displays and controls
	Readable Labels	The effects of microgravity (e.g., viewing angles), and how packaging may affect the label readability.	Use of colors in labels, especially for safety-critical tasks
	Controllable Environmental Factors	Crewmembers must call down to MCC and request a temperature adjustment, but all crew quarters are adjusted to the same temperature, this results in situations where some crewmembers are uncomfortable	Individual crewmembers should have control over environmental factors with each crewmember controlling their own individual crew quarter

Figure 3.11. Design Impact of the Visual Environment

To mitigate these effects, engineering efforts have focused on minimizing propulsion-induced oscillations and structural vibrations. Advances in vibration-damping technologies and adaptive control systems aim to reduce adverse effects on human performance. Additionally, ongoing research explores how specific vibratory frequencies and directional forces influence astronaut health and operational capability, with the goal of developing improved countermeasures and spacecraft designs that enhance crew safety and efficiency [27].

Visual Environment

The ability of astronauts to perform tasks effectively can be significantly influenced by environmental factors such as weather conditions, haze, darkness, dust, and smoke. When these elements reduce visibility to the extent that operational tasks become challenging, safety risks may arise. Impaired visual conditions can contribute to an increased probability of errors, injuries, or a decline in task efficiency [4].

Illumination plays a fundamental role in spacecraft operations, as visual perception is the primary means by which crew members acquire information about their

Light Levels for Task Performance	Illumination Levels	[V28051]	For interior architectures and exterior operations that do not include the presence of orbital sunlight, the system shall provide illumination levels to support the range of expected crew tasks, at minimum, per Table 8.7-1—Surface Illuminance Levels, that accommodate both human observers and remote camera systems.
	Task-Specific Exterior Lighting for Operational Areas Partially or Fully Lit by Sunlight	[V28104]	For operational areas that include shadowed areas and areas illuminated by the Sun and celestial bodies, the system shall provide passive and/or active solutions that reduce the contrast within shadowed areas of worksites/tasks to within 2 orders of magnitude of the predicted maximum surface luminance of objects, that accommodate both human observers and remote camera systems.
	Navigation and Wayfinding (Exterior)	[V28105]	The system shall provide luminous powered and passive indicators that assist with proximity, navigation, and object recognition for validation of targets critical to the surface operation.
	Emergency Lighting	[V28053]	The system shall provide emergency lighting (interior and exterior) to maintain visibility in the event of a general power failure.
Glare and Uniformity	Environmental Lighting Attenuation	[V28103]	The integrated system architecture shall provide countermeasures to attenuate environmental lighting and complement existing active lighting architecture.
	Glare Prevention	[V28058]	The integrated system architecture including surrounding surfaces, support equipment, visualization tools, and supporting lighting systems shall work in conjunction to minimize visibility and eye-safety impacts from direct and indirect glare.
Color Accuracy	White Lighting Chromaticity	[V28059]	Interior and exterior lighting intended for operational environments requiring human/camera color vision shall have a chromaticity that falls within the chromaticity gamut for white light for the Correlated Color Temperature (CCT) range of 2700 K to 6500 K as defined by ANSI C78-377, Electric Lamps—Specifications for the Chromaticity of Solid-State Lighting Products.
	White Lighting Color Accuracy	[V28060]	Interior and exterior lighting intended for human operational environments requiring photopic vision accuracy shall have a score of 90 ± 10 on a color fidelity metric that is appropriate for the utilized lighting technology, as designated by the Color Fidelity Metric (Rf) defined by IES TM-30, Method for Evaluating Light Sources Color Rendition methodology.
Blue Light Radiation	Physiological Effects of Light (Circadian Entrainment)	[V28055]	The system shall provide the levels of light to support the physiological effects of light in accordance with Table 8.7-2—Physiological Lighting Specifications.
Flicker	??	[V210048]	
System Layout Design	Volume Allocation	[V28001]	The system shall provide the defined habitable volume and layout to physically accommodate crew operations and living.
Controllable Environmental Factors	Lighting Controls	[V28056]	Lighting systems shall have on-off controls.
	Lighting Adjustability	[V28057]	Interior and exterior lights shall be adjustable (dimmable).
	Extraterrestrial Surface Transport Vehicle (ESTV) Dashboard and Control Lighting	[V28106]	The system shall provide active lighting and attenuation of solar light for manual controls (e.g., unpressurized surface transport vehicle joystick controls, switches and dashboard) and display screens to be visible in all potential natural light levels, including complete darkness.

Figure 3.12. Visual requirements from NASA STRD-3001-Vol-2

surroundings. Additionally, lighting serves as the most influential external factor in regulating circadian rhythms. To support astronaut health and performance, future spacecraft lighting systems should be designed with adjustable intensity and color temperature, adapting to different phases of the mission to reinforce proper sleep-wake cycles. However, integrating an effective lighting system within the constraints of available space and power presents engineering challenges, requiring careful trade-offs to balance mission objectives with resource limitations [27].

Effects of Vibration and G-Forces

Exposure to vibration and gravitational forces during spaceflight can pose challenges to crew performance and safety. When vibration reaches levels that impair visual perception, manual dexterity, or speech communication, it can significantly hinder the ability to carry out operational tasks. In extreme cases, prolonged exposure to intense vibration may lead to physiological strain, including mechanical stress on internal organs and the musculoskeletal system (Fig. 3.13). Additionally, uncontrolled movement caused by vibration can result in accidental collisions with spacecraft structures or other crew members.

Astronauts are subjected to substantial vibration and G-loading during launch, emergency abort scenarios, and reentry. These dynamic flight phases require precise interactions with spacecraft systems, necessitating rapid responses despite the presence of these physical stressors. The degree to which performance is affected depends not only on the magnitude of vibration and G-loading but also on the ergonomic design of the spacecraft, including crew interfaces and operational procedures [4].

In capsule-type crew vehicles, astronauts typically adopt a semi-supine posture during launch and reentry, experiencing elevated gravitational forces primarily along the chest-to-spine axis. During these critical phases, significant vibration can arise from propulsion systems, aerodynamic interactions between the vehicle and the surrounding atmosphere, and structural resonances within the spacecraft itself. Engineering efforts have focused on mitigating these effects by minimizing propulsion-induced oscillations, such as pogo oscillations in liquid-fueled rocket engines and thrust oscillations in solid rocket motors. Furthermore, research continues to investigate the impact of specific vibration frequencies and directional forces on crew health and task performance to inform the development of countermeasures that enhance spacecraft habitability and operational efficiency [27].

Impact of Noise Interference

Noise interference in a spacecraft environment can have significant implications for crew performance, health, and overall mission success. High noise levels can degrade the effectiveness of communication during tasks that require coordination, potentially leading to operational errors. Additionally, excessive noise can impair cognitive functions, reducing concentration, decision-making efficiency, and reaction time.

Prolonged exposure to loud environments has been linked to long-term auditory health risks, including hearing loss and temporary threshold shifts, where sensitivity to certain frequencies is reduced after exposure to intense noise levels. Research has indicated that noise exposure can also contribute to non-auditory effects, such as increased stress, cardiovascular strain, and disruptions to sleep cycles [4]. In space missions, where uninterrupted rest is critical for cognitive and physiological recovery, noise-related sleep disturbances can exacerbate fatigue, impairing alertness and task performance.

NASA and other space agencies have implemented noise control measures, including acoustic insulation, noise-dampening materials, and active noise-canceling

Vibration and G-Forces	Vibration during Preflight	[V26089]	The system shall limit vibration to the crew such that the frequency-weighted acceleration between 0.1 to 0.5 Hz in each of the X, Y, and Z axes is less than 0.05 g (0.5 m/s2) root mean square (RMS) for each 10-minute interval during prelaunch (when calculated in accordance with ISO 2631-1:1997(E), Mechanical Vibration and Shock - Evaluation of Human Exposure to Whole-Body Vibration - Part 1: General Requirements, Annex D, Equation D-1).
	Vibration Exposures during Dynamic Phases of Flight	[V26090]	The system shall limit vibration during dynamic phases of flight at interfaces that transmit vibration to the crew such that the vectorial sum of the X, Y, and Z accelerations between 0.5 and 80 Hz, calculated in 1-s intervals and weighted in accordance with ISO 2631-1:1997(E), is less than or equal to the levels for the accumulated durations in Table 6.7-1—Frequency-Weighted Vibration Limits by Exposure Time during Dynamic Phases of Flight, and Figure 6.7-1—Frequency-Weighted Vibration Limits by Exposure Time during Dynamic Phases of Flight.
	Long-Duration Vibration Dosage Limits for Health during Non-Sleep Phases of Mission	[V26091]	The system shall limit vibration at interfaces that transmit vibration to the crew such that the accumulated dosage of the vectorial sum of the X, Y, and Z frequency-weighted accelerations, as computed according to ISO 2631-1:1997(E), does not exceed the minimum health guidance caution zone level defined in Figure 6.7-2—Long-Duration Vibration Dosage Limits for Health during Non-Sleep Phases of Mission.
	Vibration Exposure Limits during Sleep	[V26092]	The system shall limit vibration to the crew such that the acceleration between 1.0 and 80 Hz in each of the X, Y, and Z axes, weighted in accordance with ISO 20283-5, Mechanical Vibration—Measurement of Vibration on Ships; Part 5 - Guidelines for the Measurement, Evaluation and Reporting of Vibration with Regard to Habitability on Passenger and Merchant Ships, Annex A, is less than 0.01 g (0.1 m/s2) RMS for each two-minute interval during the crew sleep period.
	Vibration Limits for Performance	[V26093]	The system shall ensure the appropriate level of crew task performance (e.g., motor control accuracy and precision, vision/readability, speech clarity, attentional focus) during vibration by evaluating task performance under all expected (nominal and off-nominal) vibration levels.
	Hand Vibration	[V26094]	The system, including tools, equipment, and processes, shall limit vibration to the crewmembers' hands such that the accelerations, as computed according to ANSI/ASA S2.70-2006, Guide for the Measurement and Evaluation of Human Exposure to Vibration Transmitted to the Hand, do not exceed the Daily Exposure Action Value defined by ANSI/ASA S2.70-2006, Annex A, Figure A.1.
	Extraterrestrial Surface Transport Vehicle Vibration Limits for Health and Performance	[V26160]	The extraterrestrial surface transport vehicle (ESTV) system shall limit crewmember exposure to vibration such that the vectorial sum of the X, Y, and Z accelerations between 0.5 and 80 Hz, calculated in 1-s intervals and weighted in accordance with ISO 2631-1:1997(E), is less than or equal to the levels given in Figure 6.7-3—Extraterrestrial Surface Transport Vehicle Vibration Limits (Seated or Standing Vehicle Occupants) and Table 6.7-2—Extraterrestrial Surface Transport Vehicle Vibration Limits (Seated or Standing Vehicle Occupants), which specify the allowable accumulated duration (per 24-hour day) of vibration for both standing or seated crewmembers in all restraint conditions.

Figure 3.13. Vibration requirements

technology. Acceptable noise levels in spacecraft environments are typically regulated, with guidelines such as those from NASA's Technical Standard **NASA-STD-3001** [46] specifying thresholds to protect crew health and mission effectiveness.

Seating, Restraints, and Personal Equipment

The ergonomics of seating, restraints, and personal equipment in spacecraft environments play a crucial role in maintaining astronaut comfort, performance, and safety. Poorly designed seating can lead to discomfort and musculoskeletal strain, particularly during prolonged mission phases where crew members remain in a recumbent or restrained position for extended durations. Improperly designed restraints may cause additional stress, reducing mobility and increasing the likelihood of fatigue-related errors.

Noise Interference	Launch, Entry, and Abort Noise Exposure Limits	[V26073]	During launch, entry, and abort operations, the noise exposure level (not including impulse noise) at the crewmember's ear, calculated over any 24-hour period, shall be limited such that the noise dose (D) is ≤100:
	Ceiling Limit for Launch and Entry	[V26074]	During launch and entry operations, the system shall limit the combined A-weighted sound levels (not including impulse noise) at the crewmembers' ears to a maximum of 105 dBA.
	Ceiling Limit for Launch Abort	[V26075]	During launch abort operations, the system shall limit the combined A-weighted sound levels (not including impulse noise) at the crewmembers' ears to a maximum of 115 dBA.
	Launch, Entry, and Abort Impulse Noise Limits	[V26076]	During launch, entry, and abort operations, impulse noise measured at the crewmember's ear location shall be limited to less than 140 dB peak SPL.
	Hazardous Noise Limits for All Phases Except Launch, Entry, and Abort	[V26077]	For off-nominal operations, broadcast communications, pressurization valve noise, and maintenance activities, the A-weighted sound level (excluding impulse noise and alarm signals) shall be less than 85 dBA (using fast exponential-time-averaging), regardless of the measured time interval; except in the case of pressurization valve noise, the noise attenuation effectiveness of hearing protection or communications headsets may not be used to satisfy this requirement.
	24-Hour Noise Exposure Limits	[V26115]	The noise exposure level (not including impulse noise) at the crewmember's head, calculated over any 24-hour period, except during launch, entry, and abort operations, shall be limited such that the noise dose (D) is ≤100:
	Continuous Noise Limits	[V26078]	In spacecraft work areas, where good voice communications and habitability are required, SPLs of continuous noise (not including impulse or intermittent noise sources) shall be limited to the values given by the Noise Criterion (NC)-50 curve in Figure 6.6-1—NC Curves, and Table 6.6-3—Octave Band SPL Limits for Continuous Noise, dB re 20 μPa; hearing protection cannot be used to satisfy this requirement.
	Crew Sleep Continuous Noise Limits	[V26079]	For missions greater than 30 days, SPLs of continuous noise shall be limited to the values given by the NC-40 curve (see Figure 6.6-1—NC Curves, and Table 6.6-3—Octave Band SPL Limits for Continuous Noise, dB re 20 μPa) in crew quarters and sleep areas. Hearing protection cannot be used to satisfy this requirement.
	Intermittent Noise Limits	[V26080]	For hardware items that operate for eight hours or less (i.e., intermittent noise), the maximum noise emissions (not including impulse noise), measured 0.6 m from the loudest hardware surface, shall be determined according to Table 6.6-4—Intermittent Noise A-Weighted SPL and Corresponding Operational Duration Limits for Any 24-hour Period (measured at 0.6 m distance from the source or closest distance to crew head, whichever is less). Hearing protection cannot be used to satisfy this requirement.
	Alarm Maximum Sound Level Limit	[V26081]	The maximum alarm signal A-weighted sound level shall be less than 95 dBA at the operating position of the intended receiver.
	Annoyance Noise Limits for Crew Sleep	[V26082]	With the exception of communications and alarms, the system shall limit impulse and intermittent noise levels at the crewmember's head location to 10 dB above background noise levels during crew sleep periods. Hearing protection cannot be used to satisfy this requirement.
	Impulse Noise Limit	[V26083]	The system shall limit impulse noise measured at the crewmember's head location to less than 140 dB peak SPL during all mission phases except launch, entry, and abort. Hearing protection cannot be used to satisfy this requirement.
	Narrow-Band Noise Limits	[V26084]	The maximum SPL of narrow-band noise components and tones shall be limited to at least 10 dB less than the broadband SPL of the octave band that contains the component or tone.
	Infrasonic Sound Pressure Limits	[V26085]	Infrasonic SPLs, including frequencies from 1 to 20 Hz but not including impulse noise, shall be limited to less than 150 dB at the crewmember's head location. Hearing protection cannot be used to satisfy this requirement.
	Noise Limit for Personal Audio Devices	[V26106]	The system shall limit the maximum A-weighted sound level at the crewmember's ear created by a personal audio device to 115 dBA or less when converted to a diffuse field.
	Acoustic Monitoring	[V26087]	Broadband and frequency-dependent SPLs shall be monitored and quantified as needed for crew health and safety.
	Individual Noise Exposure Monitoring	[V26088]	Noise exposure levels shall be monitored and quantified for each crewmember as needed for crew health and safety.

Figure 3.14. Noise Requirements

Microgravity presents unique challenges for restraint systems, as traditional seating configurations and safety harnesses used in terrestrial vehicles may not function as intended in space. If restraints are cumbersome or inefficiently designed, crew members may experience difficulty in securing themselves for high-G phases of flight, sleep periods, or delicate extravehicular activities (EVAs). Studies have shown that prolonged use of inadequate restraint systems can lead to repetitive strain injuries (RSIs), negatively affecting astronaut performance and increasing mission risk [27].

Personal equipment, such as portable breathing apparatuses, sleep stations, and mobility aids, must be designed with a comprehensive systems engineering approach to ensure seamless integration with other spacecraft components. Poor compatibility between equipment and vehicle architecture can result in inefficiencies, reducing the effectiveness of life-support systems and other mission-critical operations. Future design efforts should incorporate anthropometric data, biomechanics research, and astronaut feedback to refine hardware configurations for improved comfort and usability [48].

Risk of inadequate HSIA and Vehicle Habitat Design - Spaceflight Evidence			
Design Factor	Subcase	Problem	Design Impact
Vibration and G-Forces	N/A	Health consequences of vibration at the crew-seat interface	Seat design
Noise Interference	N/A	The continuous nature of noise exposure from constant sources such as air handling equipment results in a relatively higher noise dosage for crews. There is a detrimental effect on face-to-face speech communication, speech intelligibility for radio communications and caution-warning signals, habitability, safety, productivity, and sleep. This increases the risk to crew safety because the crew may not be able to hear cautions and warnings. Potential impacts of noise on LDEM crews include increased perceived workload; decreased efficiency of teamwork where voice communications are necessary; increased stress levels; reduced intelligibility; negative impacts on interpersonal voice communication; effects on sleep quality; effects on learning and retention; and subjective impression of degraded habitat quality.	Combination of noise mitigation techniques for individual components, active noise cancellation, sound masking, variable acoustics, design for acoustic isolation and privacy, and the use of hearing protection devices.
Restraints	N/A	Some crewmembers require restraints while taking photos in the Cupola because both hands are needed to take a picture. During acclimation period, crewmembers rely more heavily on handrails placed along translation paths.	Restraints that offer greater stability may be required to optimize tasks such as teleoperation and science glovebox operations.
Visibility/ Window Design & Placement	N/A	Restrictions on the use of existing onboard windows create some frustration among ISS crewmembers	Windows provide additional onboard lighting, allow the crew to observe Earth and to perform scientific observation and measurements, robotics, rendezvous and docking operations support, and they provide a means of rest, relaxation and improved crew morale. Windows on space vehicles and habitats must allow for successful viewing and imaging.

Figure 3.15. Noise interference/Restrains/Windows design impact

Visibility and Window Placement

Proper visibility within a spacecraft is essential for both operational efficiency and crew situational awareness. Various factors, including window placement, glare, reflections, and inadequate lighting, can create visual obstructions that hinder performance and increase the risk of errors. Poorly positioned windows may restrict necessary views of external spacecraft components, docking mechanisms, or planetary surfaces, while excessive glare can strain the eyes and reduce visibility.

Task analyses and concept of operations (ConOps) studies help identify critical visibility requirements for different mission scenarios, enabling engineers to design environments that enhance visual clarity and minimize obstructions. High-fidelity simulations incorporating real-world lighting conditions and reflections can be utilized to refine designs before implementation. Future spacecraft designs should also consider adaptive lighting technologies, including tunable LEDs that adjust brightness and color temperature to accommodate different operational phases. Advanced coatings and polarization techniques may be applied to windows and display interfaces to reduce glare while maintaining transparency [27].

Vehicle and Habitat Volume/Layout

The architectural design and spatial configuration of space habitats and vehicles are critical factors that influence crew performance, safety, and overall mission success. Inadequate volume allocation can restrict crew movement, create ergonomic inefficiencies, and contribute to psychological stress. Beaubien and Baker !!!!! identified constrained living and working space as a significant stressor that can negatively impact crew well-being and operational effectiveness. A well-designed habitat should optimize space utilization while accommodating both individual and team-based activities.

Habitat and vehicle layouts must be designed to support mission-specific tasks while ensuring accessibility, mobility, and adaptability to various operational requirements. Factors influencing habitat configuration include the nature of tasks performed, whether workstations are shared or isolated, and individual anthropometric differences among crew members. Poorly designed workspaces may increase cognitive and physical workload, leading to inefficiencies in task execution and a heightened risk of human error [27].

Appropriate spatial planning is essential to ensure that living and working environments are compatible with human physiological and psychological needs. Inadequate net habitable volume (NHV) and suboptimal functional arrangements can reduce productivity and diminish habitability, which becomes increasingly critical for LDEMs. Given the extended nature of such missions, special attention must be given to habitat layout to prevent task interference, mitigate stress, and foster an environment conducive to long-term well-being.

Risk of inadequate HSIA and Vehicle Habitat Design - Spaceflight Evidence			
Design Factor	Subcase	Problem	Design Impact
Vehicle/Habitat Volume/ Layout	Task Volumes	The volume of the sleep quarters was deemed too small for changing clothes and to accommodate comfortable sleep positioning for larger crewmembers	Habitable Volume
	Co-location of Tasks, Zoning, and Topology	Placing sleeping quarters adjacent to the waste and hygiene facilities is not optimal because noise made by the equipment can disrupt sleep. Locating dining facilities near exercise equipment and waste collection facilities compromises meal schedules. In addition, locating dining facilities near laboratory work jeopardizes habitability, and compromises the integrity of science activities if foreign debris (such as food products) contaminates the laboratory area.	Dedicated private space for personal hygiene, reconfigurable internal layout
	Accessibility, Stowage, and Clutter	Reliance on cabled hardware, and a lack of appropriate cable management, increases difficulty when performing hardware maintenance tasks, prevents hardware relocation, obstructs crew movement and translation, reduces crew efficiency, and in some cases may cause hazards. Contaminants such as fungi and bacteria could lead to unhealthy conditions, and dirty surfaces can affect the comfort and well-being of the crew. All designated stowage areas on the ISS are now full, and items are being stowed in areas intended for habitability and work-related functions, items have blocked emergency fire ports, illustrating the risk that excessive stowage can pose on the crew's safety and efficiency. the trash may be stowed for long periods of time and crewmembers have reported smelling bad odors after a few months	More hardware that uses wireless technology. Interior surfaces should be constructed of easily cleanable material; stowage systems be designed to accommodate the specific task constraints and the location in the habitat where the tasks take place. Require a trash system that minimizes impacts on the habitable volume
	Habitat Configuration for EVA Operations	Hazards included sharp edges, fragile materials, fluid contamination, touch temperature issues, and entanglement hazards from fans.	Habitat Configuration
	Habitat Integration	When a task or operation requires multiple components that are not integrated, crewmembers become frustrated and dissatisfied	Integrate systems within habitats and vehicles
	Behavioral Impacts on NHV	The prominence of habitability does not seem to diminish over time, and in fact if left unresolved, may present a stressor that accumulates with time.	Habitability
	Layout Re-configurability	Ability to manually re-configure the layout of a space may help astronaut to perform certain tasks	Re-configurable Habitable volume

Figure 3.16. Impact on the design of Vehicle and Habitat Volume/Layout

3.1.4 Lessons Learned from Spaceflight

Spaceflight experience accumulated over the past five decades, along with findings from ground-based research, provides valuable insights into the challenges associated with habitat and vehicle design. Evidence gathered from crew reports, observational studies, and comparative analyses [55] highlights the importance of optimizing spatial configurations to align with human operational needs.

In particular, the ISS represents a collaborative effort among governments, industries, and academic institutions to establish and maintain a continuously inhabited research facility in LEO. Designed as a long-term human outpost, the ISS builds upon experience gained from earlier missions, like Skylab and Mir, and has facilitated continuous human presence in space since November 2, 2000. The extensive time spent aboard the ISS has provided critical insights into the challenges of habitability and human factors in microgravity.

Ensuring habitability in space involves designing environments that support both physical and psychological well-being. A spacecraft must offer sufficient living space, safeguard against hazards, and provide systems that maintain crew health and performance. The field of human factors engineering plays a fundamental role in optimizing these environments by designing systems that accommodate human needs, enhance safety, and improve efficiency. Effective application of human factors principles helps to minimize operational errors, maximize productivity, and promote crew comfort in space.

	Total number of Mir specific issue comments	% of Mir comments that were negative	Total number of ISS	% of ISS comments that were negative
Excessive On-orbit Stowage	122	68.0%	174	46.0%
Architecture & Environment	337	47.2%	232	55.6%
Communication	61	60.7%	91	61.5%
Procedures	5	60.0%	115	58.3%
Lack of Human-Centered Design	105	40.0%	399	60.4%

Figure 3.17. Total habitability issue comments and the percentage of those that are negative, with a particular highlight on the high % of ISS negative comments due to Lack of HCD (Sept. 2004) [7].

The success of any design can be evaluated based on two primary criteria: (1) its ability to function as intended and (2) its usability by the end-users. **Human-centered design** (HCD) seeks to achieve both of these objectives by prioritizing user needs throughout the design process. In the context of spaceflight, HCD encompasses factors such as accessibility, maintainability, and intuitive labeling, which have frequently been cited as concerns by astronauts. However, beyond these elements, a truly human-centered approach must account for a broad spectrum of human capabilities and limitations, ensuring that spacecraft systems effectively support mission goals and operational tasks.

A study conducted by Baggerman S. et all [7] in 2004 underscored significant usability concerns in space systems, revealing that inadequate human-centered design was already a well-documented issue at the time. Onboard the Russian space station Mir, astronauts reported moderate levels of dissatisfaction with system usability, with design-related feedback accounting for 11.2% of all crew comments, 40.0% of which were negative. Despite lessons learned from Mir, similar issues have persisted aboard the ISS. By 2004, astronaut feedback indicated that design-related concerns comprised 26.3% of all ISS comments, with an alarming 60.4% categorized as negative (see Table 3.17). Even at that early stage of ISS operations, inadequate design had already emerged as a leading habitability challenge, ranking as a major concern in seven out of eight expeditions. Although this data dates back to 2004, it remains highly relevant today, as recent astronaut feedback continues to highlight the persistence of design deficiencies. Despite two decades of advancements in space system engineering, challenges related to human-system integration, usability, and habitability remain prevalent.

Lessons learned from space missions reveal that suboptimal habitat design can impede performance, create inefficiencies, and contribute to psychological stress. The Functional Cargo Integration ISS crew comments database [4] [28] has documented feedback from astronauts regarding the usability and comfort of spacecraft interiors. Although this database is not publicly accessible due to the sensitivity of raw crew data, it serves as a key reference for refining future habitat designs.

It is important to note that most spaceflight data available to date originate from missions lasting six months or less, limiting the applicability of findings to extended-duration missions. Future research must expand upon these insights by incorporating data from longer-duration missions, such as those planned under the Artemis and Moon To Mars programs. This campaign aims to generate a more comprehensive understanding of habitat design considerations for missions involving partial gravity environments, prolonged isolation, and increased reliance on autonomous systems.

Designing spacecraft and planetary habitats for long-term missions necessitates a human-centered approach, integrating engineering constraints with physiological, psychological, and operational requirements. Future space architecture must prioritize adaptability, modularity, and efficient space utilization while minimizing potential stressors [25]. Lessons learned from prior missions underscore the necessity of designing environments that balance habitability with mission functionality.

As space exploration progresses beyond low Earth orbit (LEO) to destinations on the Moon and Mars, mission durations will significantly increase, and crews will operate with reduced direct support from Earth. These deep-space missions will necessitate innovative technological solutions, adaptive operational strategies, and robust integration of automation to ensure mission success and crew safety. Given the constraints of LDEMs, crews will need to function with a higher degree of independence, adapting to limited real-time communication with ground control and developing alternative methods for troubleshooting and decision-making.

One of the primary challenges in these missions is maintaining spacecraft operability and ensuring that all necessary tasks can be completed with a small crew. Since deep-space environments introduce communication delays and the possibility of unexpected system failures, spacecraft must be designed with self-sufficiency in mind. Knowledge resources, such as onboard databases and artificial intelligence-driven support systems, will be essential to assist crew decision-making. However, critical tasks must be executable without requiring immediate external input beyond what a limited crew can access. Therefore, automation should be strategically implemented to handle repetitive and time-intensive processes, allowing astronauts to focus on complex, high-level problem-solving.

A critical aspect of automation design is preventing over-reliance, where crew members become detached from system monitoring and intervention. Poorly designed automation can lead to a false sense of security, reducing situational awareness and increasing the likelihood of errors. To mitigate these risks, human-centered design principles must be applied, ensuring that automated systems remain intuitive, transparent, and easy to override when necessary. Crew training programs should incorporate scenarios where astronauts manually perform key tasks, reinforcing their ability to respond effectively to system malfunctions.

To support crew well-being and operational effectiveness, it is crucial to establish well-defined performance thresholds, such as performance operating limits (POLs) and permissible exposure limits (PELs). The Human Factors and Behavioral Performance Element is key in defining these parameters, ensuring that work conditions are optimized to sustain astronaut health and efficiency throughout the mission.

3.2 Gaps in HSI for Space Exploration

In the context of HSI for long-duration space missions, several critical gaps have been identified [4] that must be addressed to ensure crew safety, health, and performance. These gaps highlight areas where further research and technological advancements are necessary to optimize the interaction between astronauts and onboard systems. The following eight key gaps have been recognized:

1. **Defining Crew Health and Performance Metrics:** Establishing standardized measures and assessment techniques to evaluate crew well-being and operational effectiveness during extended missions.

2. **Identifying Risk Factors in Future Spacecraft and Habitats:** Understanding how different environmental and operational conditions in space habitats and vehicles affect astronaut health and performance, particularly in exploration scenarios beyond low Earth orbit.

3. **Developing Onboard Health Monitoring Systems:** Designing and implementing onboard diagnostic tools capable of continuously tracking physiological and cognitive indicators, as well as defining thresholds for countermeasure (CM) activation.

4. **Optimizing Human-Systems Integration in Spacecraft and Habitat Design:** Ensuring that the architecture of space habitats and the layout of control interfaces are developed with human factors in mind to minimize performance degradation and enhance usability.

5. **Adapting Mission Procedures for Dynamic Environments:** Creating flexible, adaptive mission protocols that accommodate the evolving challenges and constraints of deep-space exploration.

6. **Enhancing Training Programs for Space Crews:** Refining both preflight and in-mission training approaches to reduce cognitive load, improve efficiency, and maintain high levels of individual and team performance over extended periods.

7. **Advancing Human-Automation-Robotics Integration:** Developing intelligent automation and robotic assistance systems that complement human capabilities, enabling enhanced monitoring, decision-making, and task execution in exploration missions.

8. **Addressing Cross-Disciplinary Risks in HSIA and Countermeasure Implementation:** Establishing a comprehensive framework for integrating various risk factors related to human-systems interaction, while ensuring that countermeasures are effectively applied to mitigate potential hazards.

To effectively bridge these gaps, continuous data collection on workload management, system usability, task design, and astronaut performance is required during operational missions. Analyzing this data will allow for a deeper understanding of the risks associated with HSI and will inform the development of mitigation strategies.

3.3 Habitat Architecture Description

This section presents the MBSE approach developed using the ARCADIA method and the Capella tool for Phase-A of the lunar habitat. A summary of the mission is provided at first, followed by the implementation of systems engineering practices in an MBSE environment. The way requirements are managed is presented and the four ARCADIA levels are explored.

3.3.1 Background and Mission Constrain

The successful launch and landing of the uncrewed **Orion** capsule under the **Artemis I** mission marked a significant milestone in humanity's return to the Moon. This mission demonstrated the capabilities of the **Space Launch System** (SLS) and Orion spacecraft, paving the way for future crewed missions. The return of astronauts to the lunar surface is planned for the **Artemis III** mission, currently scheduled for 2028, which will mark the first human presence on the Moon since Apollo 17 in 1972 [29].

The upcoming lunar missions are strategically focused on the Moon's south pole, a region of significant scientific and exploratory interest. NASA has identified 13 potential landing sites for the Artemis III mission (Fig. 3.18), each covering an area of approximately 15 by 15 kilometers. These locations have been carefully selected based on their scientific value, accessibility, and operational feasibility.

Unlike the short-duration Apollo missions, Artemis aims to establish a long-term human presence on the Moon's south pole, where permanently shadowed regions hold the potential for water ice deposits, a key resource for future life support systems and in-situ resource utilization (ISRU). With the *Artemis Accords* in place, a growing coalition of 21 nations is collaborating on this effort, supporting advancements in lunar exploration, infrastructure, and sustainability.

The initial Artemis missions will prioritize scientific research, surface exploration, and the identification of key resources essential for long-term sustainability. Among the most critical areas of interest are the **Peaks of Eternal Light** (PEL), high-altitude regions that receive nearly continuous sunlight, providing a stable power source, and the **Permanently Shadowed Regions** (PSR), which have been confirmed to contain water ice deposits. These water ice reserves are particularly valuable, as they could be processed into life-supporting resources such as oxygen and drinking water, as well as converted into hydrogen and oxygen for rocket fuel production.

One of the fundamental aspects of sustaining human presence on the Moon is

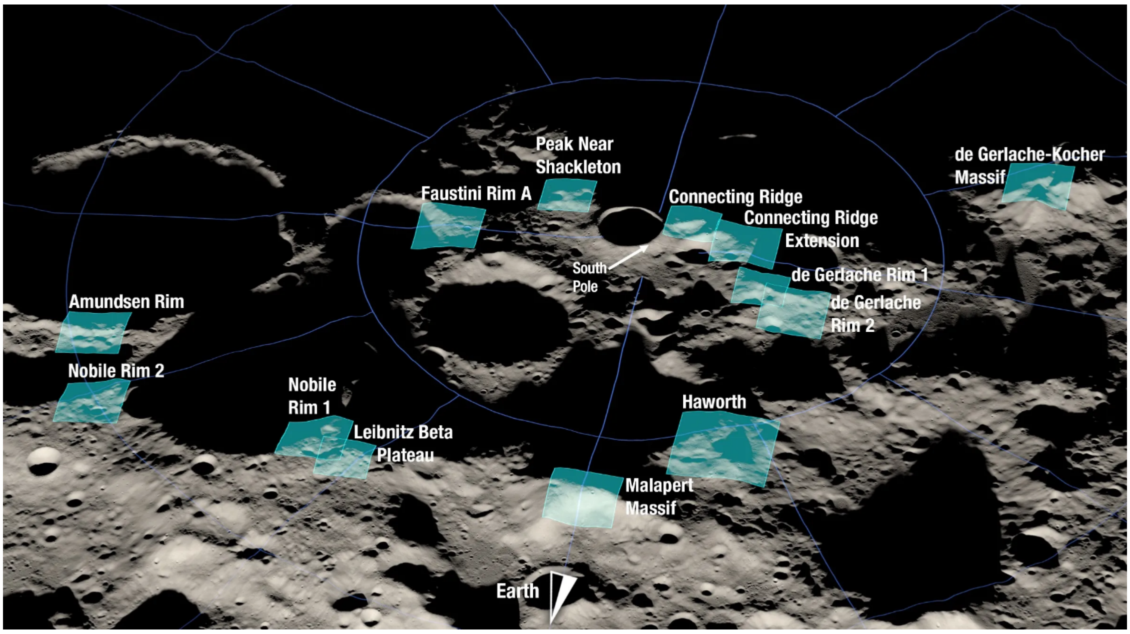


Figure 3.18. 13 candidate landing regions for Artemis III.[Credit Image: NASA]

the development of a lunar habitat infrastructure that enables self-sufficiency and reduces dependence on Earth-based supply chains that can support astronauts during extended surface missions. The lunar habitat must be capable of withstanding extreme temperature variations, high radiation exposure, and the challenges posed by lunar regolith. This chapter details the methodology, design, and development process of the lunar habitat, starting with Mission Requirements and Constraints by identifying the primary challenges and objectives shaping habitat design.

To deepen our knowledge of the lunar environment and advance theoretical models, numerous nations have integrated lunar exploration into their strategic space initiatives. These efforts not only facilitate scientific progress but also demonstrate national capabilities in space exploration. Several major spacefaring countries have formulated ambitious lunar missions, with an overview of the Artemis program depicted in Figure 3.19.

Several national exploration strategies emphasize the significance of studying the low lunar orbit and the near-Moon space environment as fundamental mission objectives. Ultimately, the long-term ambition is the establishment of a sustainable lunar base, marking a significant milestone in humanity's deep space exploration journey. A permanent habitat on the Moon would serve as a testing ground for off-Earth living, enabling the development of new systems and technologies. Such a base would act as a stepping stone for further missions to Mars and beyond,

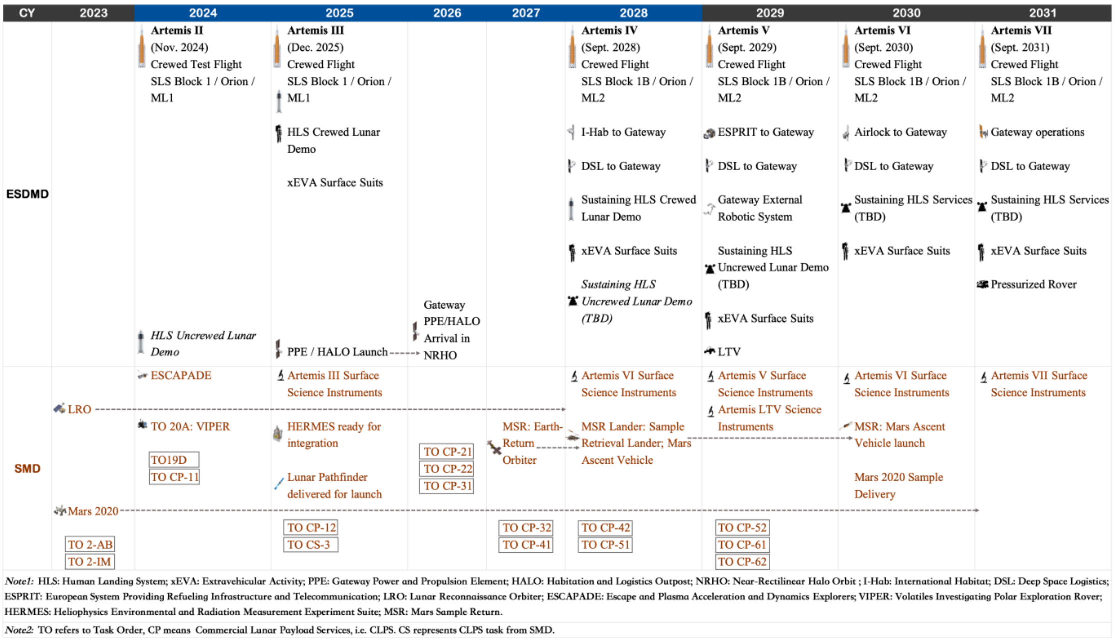


Figure 3.19. An overview of Artemis mission (Moon to Mars Planning Manifest) [59]

advancing our ability to thrive in extraterrestrial environments.

3.3.2 Requirements

Modern systems engineering practices, particularly in the space sector, heavily rely on requirements as a primary means of communication between engineers. These requirements serve as a crucial tool for ensuring that system designs are correctly implemented while also providing a structured description of the system's architecture. A requirement can be described as a formal statement that defines the functional and performance characteristics of a system or imposes specific constraints [26]. Space systems, due to their inherent complexity, are typically governed by hundreds of requirements. As a result, an efficient method for organizing and verifying these requirements is essential.

The most widely adopted approach in requirement-based engineering involves the use of textual requirements, which are mapped to system functionalities [14]. However, managing traceability through a document-based methodology presents significant challenges. Navigating multiple documents increases the risk of misinterpretation, particularly as the number of requirements grows alongside system complexity. In fact, unclear or ambiguous requirement definitions are recognized as a major source of project risk.

To address these challenges, an alternative concept known as model-based requirements has been proposed, as outlined in previous research. These requirements correspond to specific model elements, such as Functions, Functional Exchanges, Components, and Component Exchanges, which are fundamental within MBSE methodologies. Unlike traditional textual requirements, model-based requirements follow a structured syntax and precise semantics, allowing for improved clarity and traceability. Nevertheless, despite the advantages of model-based requirements, textual requirements remain essential in certain aspects of system development. They are often better suited for capturing specific details in a more intuitive and comprehensive manner. Therefore, the approach discussed in this work integrates both textual and model-based requirements, establishing links between them to enhance traceability and completeness. This combined approach aims to leverage the strengths of both methodologies, ensuring a more robust and effective requirement management process in space systems engineering.

These mission requirements are designed to ensure that the lunar habitat is capable of supporting long-term human missions on the Moon while meeting safety, performance, and operational objectives. They are aligned with NASA and ECSS standards and cover all aspects of mission planning, environmental control, crew health, science, energy, communication, and system reliability.

ID	**Requirement Description**	**Reference Standard**
MR-1	The mission must support continuous human presence on the lunar surface for a minimum of 12 months, with the potential for extension based on operational success and available resources.	NASA-STD-3001, ECSS-E-ST-32-02C
MR-2	The mission success criteria include sustained human habitation, continuous communication with Earth, completion of scientific objectives, and effective operation of all systems.	NASA-STD-3001, ECSS-E-ST-32-01C
MR-3	The habitat must be capable of handling emergency situations, such as fire, pressure loss, and CO_2 buildup, ensuring crew safety and evacuation capability.	NASA-STD-3001, ECSS-E-ST-32-16C

ID	Requirement Description	Reference Standard
MR-4	The mission schedule must consider lunar day-night cycles, optimizing energy use and storage.	NASA-STD-3001, ECSS-E-ST-32-10C
MR-5	Life support systems must ensure continuous oxygen generation, CO_2 removal, and water recovery, with redundancy in case of failures.	NASA-STD-3001, ECSS-E-ST-32-13C
MR-6	The habitat must support crew health through monitoring systems for physical health, psychological well-being, and medical care, including telemedicine capabilities.	NASA-STD-3001, ECSS-E-ST-32-14C
MR-7	Continuous environmental monitoring of air quality, temperature, humidity, and radiation levels must be conducted.	NASA-STD-3001, ECSS-E-ST-32-17C
MR-8	The habitat location must be selected based on safety, geological stability, and resource accessibility (e.g., water ice deposits).	NASA-STD-5001, ECSS-E-ST-32-02C
MR-9	The habitat must withstand lunar surface conditions, including micrometeorite impacts, thermal extremes, and dust.	NASA-STD-3001, ECSS-E-ST-32-02C
MR-10	The habitat must support extravehicular activities (EVA) through airlocks, suit storage, and lunar surface mobility solutions.	NASA-STD-3001, ECSS-E-ST-32-02C
MR-11	The habitat must include a power generation system, such as solar panels, providing sufficient energy for all operations.	NASA-STD-3001, ECSS-E-ST-32-10C
MR-12	Energy storage systems must support continuous operations during the lunar night.	NASA-STD-3001, ECSS-E-ST-32-10C
MR-13	The mission must support scientific research in lunar geology, resource utilization, and biological experiments.	NASA-STD-3001
MR-14	The habitat must provide data collection and real-time transmission of scientific and operational data to Earth.	NASA-STD-3001, ECSS-E-ST-50-13C

ID	Requirement Description	Reference Standard
MR-15	The crew must undergo extensive training in habitat operations, emergency procedures, and EVA techniques before the mission.	NASA-STD-3001, ECSS-E-ST-50-10C
MR-16	A mission operations center on Earth must provide real-time monitoring, decision support, and emergency intervention capabilities.	NASA-STD-3001, ECSS-E-ST-50-09C
MR-17	Continuous voice and data communication with Earth must be maintained, ensuring redundancy in case of failures.	NASA-STD-3001, ECSS-E-ST-50-13C
MR-18	The habitat must support communication with lunar surface assets such as rovers and landers.	NASA-STD-3001, ECSS-E-ST-50-13C
MR-19	The habitat must incorporate in-situ resource utilization (ISRU) capabilities for lunar regolith processing, water extraction, and oxygen production.	NASA-STD-3001, ECSS-E-ST-32-10C
MR-20	Efficient waste management and recycling systems must be integrated to minimize reliance on Earth resupply missions.	NASA-STD-3001, ECSS-E-ST-32-12C
MR-21	Critical systems (life support, power, communication) must have redundancy to ensure continuous operation in case of failure.	NASA-STD-3001, ECSS-E-ST-32-01C

Ensuring the safety, efficiency, and functionality of such a system requires a structured approach to defining its **Operational Requirements** (ORs). These requirements define how the habitat must function in real-world conditions to meet mission objectives. They account for critical aspects such as crew life support, environmental control, communication, power management, and emergency preparedness, ensuring that astronauts can live and work safely in the harsh lunar environment. Compliance with NASA and ECSS standards guarantees that the habitat is built following internationally recognized practices, enhancing mission safety, reliability, and interoperability with other space systems.

ID	Requirement Description	Reference Standard
OR-1	The lunar habitat must provide a livable environment for the crew, including controlled temperature, pressure, humidity, and radiation protection.	NASA-STD-3001, ECSS-E-ST-32-02C
OR-2	The habitat must accommodate at least four crew members with dedicated sleeping, working, and recreational areas.	NASA-STD-3001, ECSS-E-ST-32-10C
OR-3	The life support system must ensure a continuous supply of oxygen, CO_2 removal, and water recycling.	NASA-STD-3001, ECSS-E-ST-32-13C
OR-4	The habitat must be equipped with an emergency response system, including fire suppression, leak detection, and crew evacuation protocols.	NASA-STD-3001, ECSS-E-ST-32-16C
OR-5	The habitat must support food storage, preparation, and waste management for long-duration missions.	NASA-STD-3001, ECSS-E-ST-32-12C
OR-6	The habitat structure must withstand lunar environmental conditions, including temperature extremes, dust accumulation, and micrometeorite impacts.	NASA-STD-3001, ECSS-E-ST-32-02C
OR-7	The habitat must provide at least two airlocks for extravehicular activities (EVA) and docking with lunar surface vehicles.	NASA-STD-3001, ECSS-E-ST-32-02C
OR-8	Power generation systems, such as solar arrays and energy storage units, must provide uninterrupted energy supply.	NASA-STD-3001, ECSS-E-ST-32-10C
OR-9	The habitat must include redundancy for all critical systems to ensure operational reliability and crew safety.	NASA-STD-3001, ECSS-E-ST-32-01C
OR-10	The habitat must support scientific research, including lunar geology, ISRU (In-Situ Resource Utilization), and human factors studies.	NASA-STD-3001, ECSS-E-ST-32-10C

ID	Requirement Description	Reference Standard
OR-11	The habitat must enable real-time monitoring and communication with Earth through a high-bandwidth, low-latency system.	NASA-STD-3001, ECSS-E-ST-50-13C
OR-12	The habitat must integrate radiation shielding strategies, such as regolith-based protective structures or water shielding.	NASA-STD-3001, ECSS-E-ST-32-17C
OR-13	The habitat must be modular and scalable to allow future expansion or integration with other lunar infrastructure.	NASA-STD-3001, ECSS-E-ST-32-02C
OR-14	The habitat must include a health and medical support area with telemedicine capabilities and emergency treatment options.	NASA-STD-3001, ECSS-E-ST-32-14C
OR-15	Waste management systems must minimize environmental impact and support resource recycling, including air, water, and solid waste processing.	NASA-STD-3001, ECSS-E-ST-32-12C
OR-16	The habitat must allow for long-term autonomous operation with minimal Earth-based intervention.	NASA-STD-3001, ECSS-E-ST-32-01C
OR-17	The habitat must be designed with maintainability in mind, ensuring that the crew can easily perform repairs and upgrades.	NASA-STD-3001, ECSS-E-ST-32-01C
OR-18	Human factors engineering must be incorporated to optimize crew efficiency, comfort, and psychological well-being.	NASA-STD-3001, ECSS-E-ST-32-14C
OR-19	The habitat must support robotic assistance and automation for logistics, maintenance, and resource utilization.	NASA-STD-3001, ECSS-E-ST-32-10C
OR-20	Redundant communication systems must ensure connectivity with lunar orbiting assets and surface vehicles.	NASA-STD-3001, ECSS-E-ST-50-13C
OR-21	The habitat must include provisions for exercise and fitness to maintain crew health in reduced gravity conditions.	NASA-STD-3001, ECSS-E-ST-32-14C

The **Functional Requirements** (FRs) define the essential capabilities and performance characteristics that the lunar habitat must fulfill to ensure successful mission operations and crew safety. These requirements establish the technical foundation for system design, ensuring that all subsystems work together seamlessly to provide a habitable environment on the lunar surface.

Functional Requirements are critical in mission planning as they guide the development of life support systems, power generation, thermal control, communication, radiation protection, and other fundamental aspects necessary for sustaining human life in the extreme conditions of space. They also ensure compliance with NASA-STD-3001 and ECSS regulations to maintain interoperability, reliability, and safety. The following table outlines the key functional requirements that the lunar habitat must meet, along with the relevant industry standards that guide their implementation.

ID	**Requirement Description**	**Reference Standard**
FR-01	The habitat shall provide a controlled atmospheric environment suitable for human habitation, including oxygen, carbon dioxide removal, temperature, and humidity regulation.	NASA-STD-3001, ECSS-E-ST-32-10C
FR-02	The habitat shall include a life support system capable of maintaining atmospheric conditions for a minimum of four crew members for 30 days without resupply.	NASA-STD-3001
FR-03	The habitat shall provide an integrated power management system capable of generating, storing, and distributing electrical power from multiple energy sources (solar, nuclear, etc.).	ECSS-E-ST-20C
FR-04	The habitat shall be equipped with thermal control systems to maintain internal temperatures between 18°C and 26°C under lunar conditions.	ECSS-E-ST-31C
FR-05	The habitat shall include communication systems for continuous voice, video, and data transmission with Earth and lunar assets.	ECSS-E-ST-50C

FR-06	The habitat shall be capable of supporting extravehicular activity (EVA) operations by providing an airlock system for safe ingress and egress.	NASA-STD-3001, ECSS-E-ST-33C
FR-07	The habitat shall provide radiation shielding to limit crew exposure to less than 50 mSv per year in compliance with space radiation safety guidelines.	NASA-STD-3001
FR-08	The habitat shall include food storage, preparation, and waste management systems to support a self-sustaining environment.	NASA-STD-3001
FR-09	The habitat shall support mobility and docking with lunar surface vehicles and modular extensions.	ECSS-E-ST-50C
FR-10	The habitat shall be designed to allow remote monitoring, diagnostics, and maintenance to extend mission longevity.	ECSS-E-ST-40C

Finally, as we have seen, the success of a lunar habitat depends not only on its technical capabilities but also on its ability to support the physiological, psychological, and operational needs of the crew. HSI Requirements ensure that the habitat is designed with the astronaut experience in mind, promoting efficiency, safety, comfort, and long-term well-being. These requirements address critical factors such as habitability, ergonomics, human-machine interaction, environmental conditions, and medical support to optimize astronaut performance and mission sustainability. Adherence to established standards, including NASA-STD-3001, ECSS-E-ST-10-04C, and ISO 9241-210, ensures that the habitat aligns with industry practices for HCD.

ID	**Requirement Description**	**Reference Standard**
HSI-01	The habitat shall be designed to support human physiological and psychological needs for long-duration missions, including space for sleep, work, and recreation.	NASA-STD-3001, ECSS-E-HB-32-25A

HSI-02	The habitat shall provide an ergonomic workstation layout that reduces fatigue and cognitive overload for crew members during operations.	NASA-STD-3001, ISO 9241-210
HSI-03	The habitat shall include human-machine interfaces (HMI) designed for intuitive interaction, including emergency response and system controls.	ECSS-E-10-11A, NASA-STD-3001
HSI-04	The life support system shall maintain atmospheric conditions, including oxygen levels, CO_2 removal, temperature, and humidity, within safe human limits.	NASA-STD-3001, ECSS-E-ST-32-02C
HSI-05	The habitat shall provide radiation shielding to maintain exposure within permissible astronaut health limits for the duration of the mission.	NASA-HDBK-6022, ECSS-E-ST-10-04C
HSI-06	The interior lighting system shall support circadian rhythms and mitigate sleep disruption in crew members.	NASA-STD-3001
HSI-07	The habitat shall include provisions for mental health and social well-being, including private space, communication with Earth, and leisure activities.	NASA-STD-3001, ECSS-E-HB-11A
HSI-08	The food storage and preparation areas shall support nutritional balance and meal variety, considering storage constraints and mission duration.	NASA-STD-3001, ECSS-E-ST-70-41C
HSI-09	The habitat shall include onboard medical capabilities to address minor injuries, illnesses, and emergency medical conditions.	NASA-STD-3001, ECSS-E-HB-32-25A
HSI-10	The habitat design shall ensure crew accessibility and mobility in microgravity and partial gravity conditions.	NASA-STD-3001, ISO 9241-210

3.3.3 Concept of Operations

This Concept of Operations (ConOps) outlines the mission architecture and operational phases for deploying and utilizing a permanent lunar habitat in alignment with NASA and ESA standards. The lunar habitat will serve as a living and working environment for astronauts conducting surface operations, providing life support, radiation protection, mobility solutions, and scientific research capabilities. It will also act as a testbed for future missions to Mars and beyond.

The launch of the Artemis 1 mission to the Lunar orbit and back marks the start of missions that will lead into crewed missions to the Lunar orbit and back under Artemis 2 and the Lunar surface mission starting the Artemis 3 mission. NASA's Space Launch System (SLS) will be used to launch crew onboard the Orion Capsule with the European Service Module (ESM) that will bring the crew to the Lunar orbit and back. The Orion capsule has the capability to dock to the Lunar Gateway in the Near Rectilinear Orbit (NRHO). The Lunar Gateway has the capability to host four astronauts for a duration of 30 to 90 days. It will act as a space station around the Moon to host astronauts and scientific experiments on board. Currently, the Human Landing System (HLS) that will bring the crew to and from the Lunar surface for the Crew Segment has not been decided, so the two most probable scenarios have been listed as options.

1. **Option 1:** A Lander consisting of a descent and ascent stage to transport crew to the Lunar Surface and back. This option requires the Lander to be launched using single or multiple launches of NASA's SLS Block Cargo to the Gateway. In the case of multiple launches, the Lander is assembled robotically on the Gateway. The crew is launched onboard Orion by NASA's SLS Block Crew launcher to the Gateway. The gateway acts as a rendezvous point for the crew and the Lunar Lander. The Orion is docked to the gateway, and the crew is transferred to the already assembled Lunar Lander docked to the Gateway. Then, it is transported to the Lunar surface by the Lander, and after the completion of the surface mission, the crew is transported back to the Gateway by the Lander's ascent module.

2. **Option 2:** SpaceX is developing its variant of Starship called Starship HLS under a NASA contract for the Artemis Missions. It is launched on the Super Heavy booster into Earth's Orbit, where it is refueled by the multiple Starship tankers before being boosted in LTO. The crew is launched onboard Orion by NASA's SLS Block Crew launcher to Earth's orbit and boosted to the Lunar orbit by the ESM. In the Lunar Orbit, it rendezvouses with the Starship HLS. The crew is transferred to the HLS and then transferred to the Lunar surface and back to the Lunar orbit.

Mission Overview

The mission will follow a phased approach, leveraging Artemis program assets, including the Orion spacecraft, the Lunar Gateway, and Human Landing Systems (HLS), to ensure a safe and reliable transport of crew and cargo to the Moon.

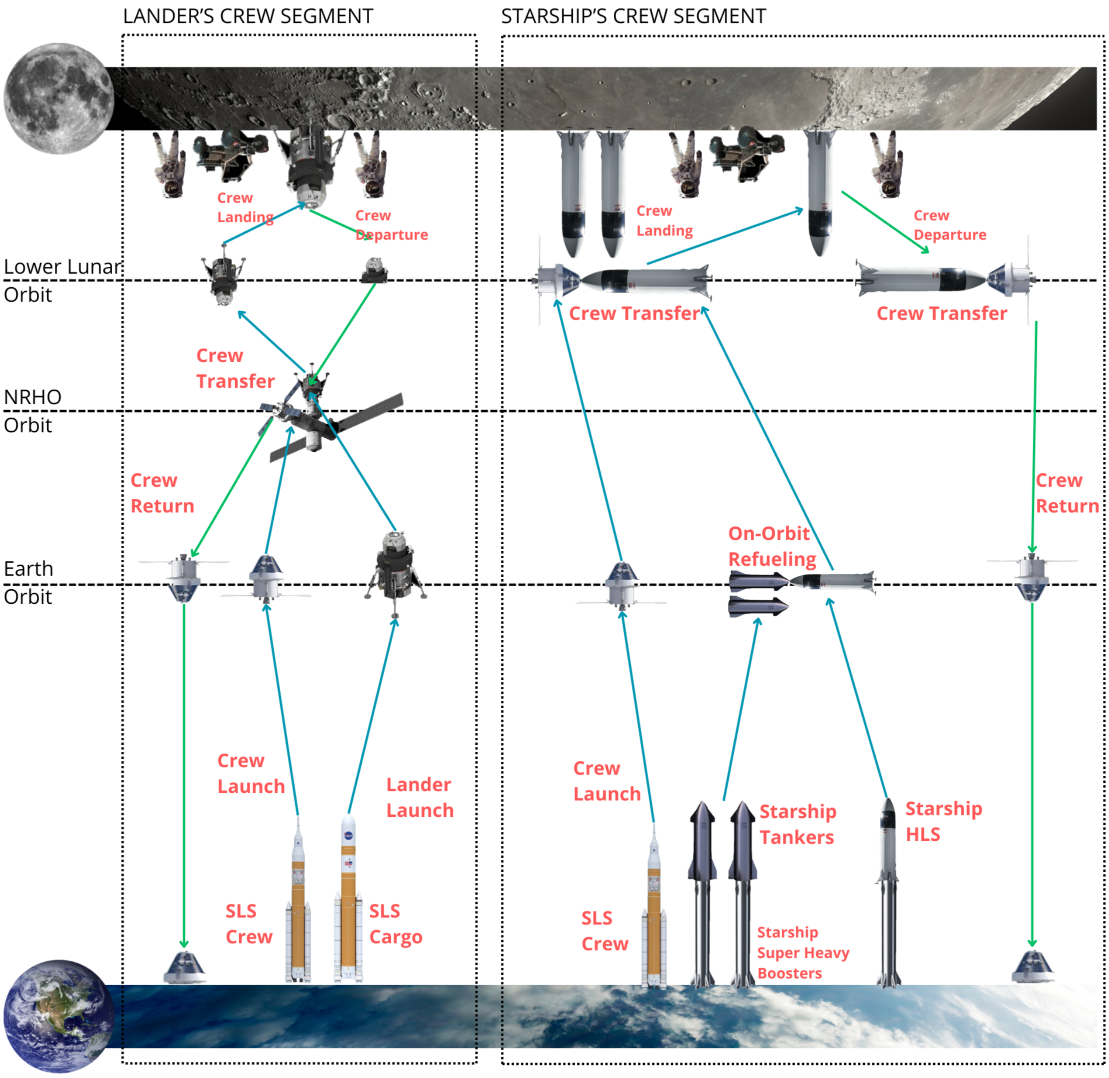


Figure 3.20. ConOps options

- **Launch Vehicles:** NASA's Space Launch System (SLS) and commercial heavy-lift rockets.
- **Crew Transport:** Orion spacecraft, in combination with HLS or other commercial lunar landers.
- **Surface Operations:** Lunar habitat with radiation shielding, closed-loop life support, power systems, and ISRU technologies.
- **Mission Duration:** Initial stays of 30-90 days, with a gradual increase to

continuous occupation.

3. Deployment and Transportation Architecture

The transportation architecture will rely on two primary phases: Habitat Deployment and Crew Transport.

Habitat Deployment

The habitat will be delivered to the lunar surface using one or multiple heavy-lift rockets. The structure will be pre-integrated and tested on Earth before launch to minimize on-site assembly requirements. Two main deployment scenarios are considered:

- **Option 1: Single-Launch Habitat Deployment**
  - A fully integrated habitat is launched using a heavy-lift vehicle.
  - It autonomously lands at the designated lunar base site.
  - Robotic systems deploy external infrastructure (solar arrays, communication antennas, thermal protection).
- **Option 2: Modular Habitat Assembly**
  - Multiple habitat modules are launched separately and assembled on the surface.
  - Robotic or crew-assisted assembly ensures seamless integration.
  - This approach allows for scalability and upgrades over time.

Crew Transportation and Operations

Astronauts will be transported to and from the Moon using the following mission sequence:

1. **Launch to Lunar Orbit:** Crew launches aboard Orion (via SLS) and docks with the Lunar Gateway in Near-Rectilinear Halo Orbit (NRHO).
2. **Transfer to Lunar Surface:** Astronauts board the Human Landing System (HLS) or an alternative lander.
3. **Habitat Ingress and Operations:** Upon arrival, the crew activates the habitat, conducts system checks, and begins surface operations.
4. **Mission Activities:** Crew members perform scientific experiments, ISRU demonstrations, habitat maintenance, and extravehicular activities (EVAs).
5. **Return to Gateway:** After mission completion, the lander ascends back to Lunar Gateway, where astronauts transfer to Orion for Earth return.

Lunar Habitat Design Considerations

To support long-duration missions, the habitat will integrate advanced technologies in the following key areas:

- **Environmental Control and Life Support Systems (ECLSS):**
  - Closed-loop oxygen, water, and waste recycling.
  - Radiation shielding using regolith-based protective structures.
  - Temperature and pressure regulation to maintain a habitable environment.
- **Power Generation and Storage:**
  - Solar power arrays optimized for lunar conditions.
  - Battery and fuel cell backups for energy storage.
- **Communications and Navigation:**
  - Lunar Relay Satellites for continuous connectivity with Earth and Gateway.
  - Navigation beacons for surface mobility.
- **Surface Mobility and Operations:**
  - Lunar rovers for exploration and logistics.
  - Autonomous robotic systems for maintenance and cargo handling.

3.3.4 Operational analysis

The development of a lunar habitat requires a structured approach that begins with defining high-level objectives. These objectives are then translated into key drivers and constraints that guide the selection of design alternatives while also identifying the relevant stakeholders and their responsibilities. Given the complexity of such an endeavor, a systematic methodology is essential to ensure coherence across different design phases.

The ARCADIA methodology provides an effective framework for this process. Through its **Operational Analysis**, ARCADIA focuses on understanding the goals and needs of the entities involved before introducing specific system concepts. This early-stage analysis ensures that the design aligns with mission objectives and stakeholder expectations without being prematurely constrained by technical details. Unlike rigid methodologies that enforce a strict sequence of design steps, ARCADIA allows for flexibility. Systems engineers can determine which methodological activities to prioritize and in what order to execute them, adapting to the unique challenges of a lunar habitat design. Given the complexity of a lunar habitat, where multiple disciplines must interact seamlessly, modeling the Operational Analysis is crucial. Just as ARCADIA has been successfully applied in complex space missions, such as CubeSat designs, its implementation in lunar habitat development can facilitate interdisciplinary collaboration, improve information flow, and enhance decision-making throughout the mission life cycle.

The first step in the design process involves defining a set of high-level services, referred to as *Capabilities*, which at this stage remain independent of the specific system to be implemented and are further refined in successive design iterations. The diagram used to represent this conceptualization is known as the *Operational Capabilities Blank*, which highlights the key Entities involved and their respective Capabilities, represented graphically by gray rectangles and bronze medallions, respectively. It is important to note that each graphical element corresponds to a model element, which may have multiple representations within the system model. All connections within this diagram originate from an Operational Capability and are directed toward an *Entity* or an *Actor*, illustrating a relationship without implying any temporal sequence. The presence of shared Capabilities between different Entities indicates expected collaboration among them. In the context of a lunar habitat, for instance, mission control, habitat infrastructure, and astronaut operations may share certain Capabilities, emphasizing the necessity of coordinated efforts throughout the mission life cycle.

An *Entity* is not strictly limited to a company or institution but can also represent an abstract concept that interacts with the system under development. In the context of a lunar habitat, the lunar environment itself is modeled as an Entity due to its critical role in imposing constraints on the future system, such as radiation exposure, reduced gravity, and limited resource availability. Meanwhile, an Operational Actor, such as a Mission Control Operator, is represented distinctly, as indicated by its designated icon.

For this diagram, a key modeling decision is to include only those stakeholders that actively interact with the system being designed, omitting entities like suppliers, sponsors, and testing organizations. These elements, while relevant in later phases, remain undefined in the initial mission stages, and their inclusion at this point would not provide additional value. However, primary contributors, as for example the Habitat Infrastructure Provider, play a central role in shaping the mission, ensuring that critical operational and structural needs are addressed early in the design process.

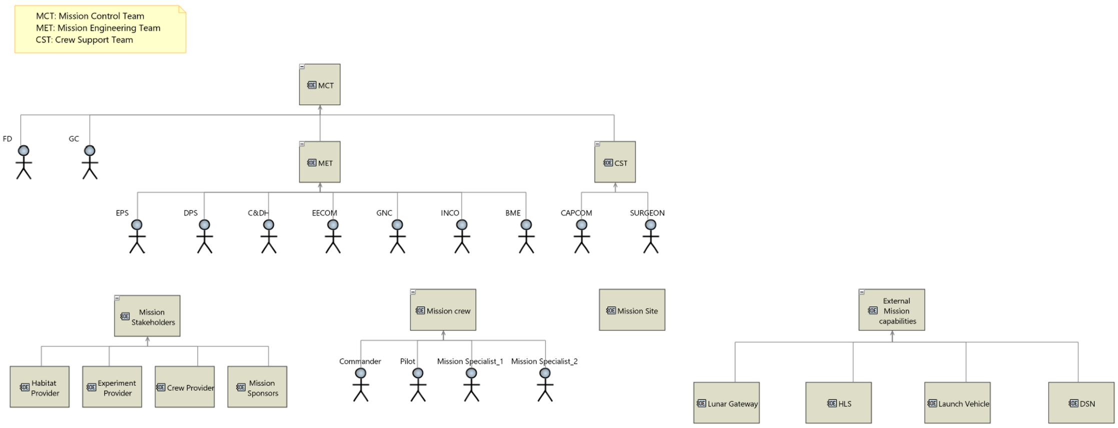


Figure 3.21. Operational Entities

Figure 3.21 illustrates an Operational Analysis scenario modeled in Capella, focusing on the interactions and relationships between key entities involved in a space mission. This analysis provides a high-level view of the operational architecture, highlighting the roles and responsibilities of different teams and stakeholders. The diagram centers around the **Mission Control Team (MCT)**, positioned at the top to emphasize its central role in mission coordination and oversight. The MCT is linked to both the **Mission Engineering Team (MET)** and the **Crew Support Team (CST)**, reflecting its supervisory and coordinating functions. The MET, responsible for the engineering aspects of the mission, reports to and operates under the direction of the MCT. Similarly, the CST, dedicated to supporting the mission crew, also reports to the MCT, highlighting the importance of crew well-being and performance. The MCT is further detailed into specific roles, including the **Flight Director (FD)**, responsible for flight planning; the **Ground Controller (GC)**, overseeing ground systems; and specialists for subsystems such as **Electrical Power Systems (EPS)**, **Data Processing Systems (DPS)**, **Command and Data Handling (C&D)**, **Electrical, Environmental, and Consumables Management (EECOM)**, **Guidance, Navigation, and Control (GN&C)**, **Instrumentation and Communications (INCO)**, and **Integrated Mission Engineering (IME)**. The **CAPCOM (Capsule Communicator)** serves as the primary communication link with the crew, while the **SURGEON** is responsible for crew health and medical aspects.

The diagram also depicts the broader mission context, including **Mission Stakeholders**, such as the **Habitat Provider**, **Experiment Provider**, **Crew Provider**, and **Mission Sponsors**, all with vested interests in the mission's success. The **Mission Crew** is represented by roles like **Commander**, **Pilot**, and **Mission**

Specialists, highlighting their active involvement. The **Mission Site** is represented by potential locations or infrastructure, such as the **Lunar Gateway**, **Human Landing System (HLS)**, **Launch Vehicle**, and **Deep Space Network (DSN)**. Finally, **External Mission Capabilities** represents resources and support available from external sources. As we can see, the Capella Operational Analysis diagram provides a comprehensive representation of a space mission's operational ecosystem, emphasizing the critical roles, interactions, and dependencies between human teams, technological systems, and external entities. It serves as a valuable tool for understanding the operational architecture, planning mission execution, and identifying potential areas for optimization.

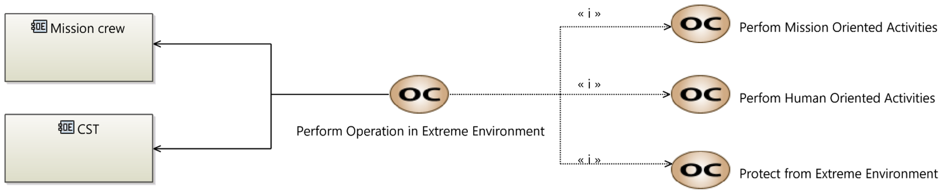


Figure 3.22. Operational Capabilities

The diagram of Operational Capabilities in Fig. 3.22 highlights the crucial interaction between the **Mission Crew**, representing the astronauts or personnel directly involved in the mission, and the **Crew Support Team (CST)**, representing the ground-based or remote team providing support. Both entities directly interact with the central operational capability, emphasizing their shared responsibility in mission success. The core operational capability is represented by **OC: Perform Operation in Extreme Environment**. This central element underscores the challenging and hazardous nature of the mission environment and the need for specialized operational capabilities. The central operational capability is further decomposed into three key sub-capabilities, each representing a distinct aspect of mission operations:

- **OC: Perform Mission Oriented Activities:** This sub-capability encompasses the operational activities directly related to achieving the mission's primary objectives.

- **OC: Perform Human Oriented Activities:** This sub-capability focuses on activities related to the well-being and performance of the crew, including health maintenance and psychological support.

- **OC: Protect from Extreme Environment:** This sub-capability encompasses activities related to safeguarding the crew and equipment from the hazards inherent in the extreme environment.

The relationships between these elements are represented by lines and stereotypes. Solid lines indicate a direct relationship or interaction between the Mission Crew, CST, and the central operational capability. Dashed lines with stereotypes «i» and «a» represent decomposition or refinement relationships. The stereotype «i» likely indicates an inclusion or instantiation relationship, suggesting that the sub-capabilities are part of or instances of the central capability. The stereotype «a» indicates an abstraction or refinement relationship, showing that the central capability is a more general concept refined into the more specific sub-capabilities. To sum up, it illustrates the decomposition of the overall operational capability into mission-oriented, human-oriented, and protection-oriented sub-capabilities, highlighting the multifaceted nature of operations in challenging conditions.

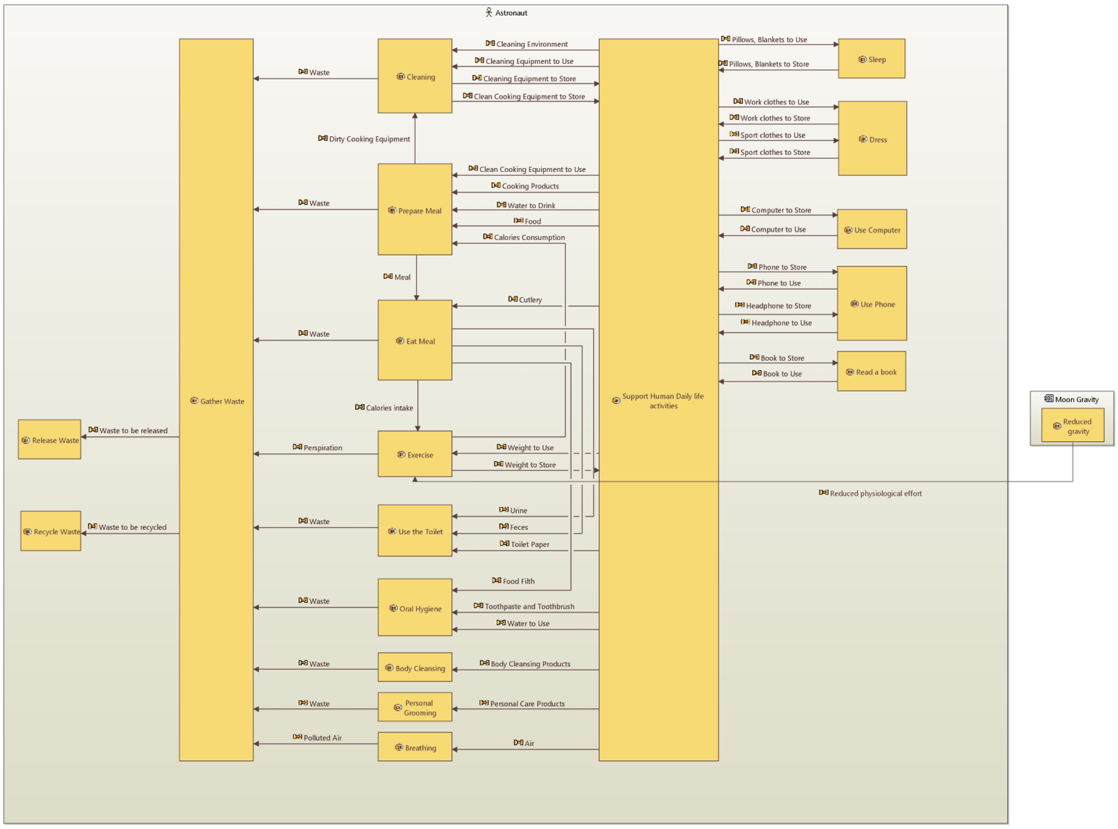


Figure 3.23. [OAB] Human-centered Operational Architecture

The final and most comprehensive diagram in the Operational Analysis is the Operational Architecture Blank (OAB), which serves to illustrate the entirety of operational activities defined within the Scenario Diagrams, their allocation to relevant entities, and the interactions between them. In the context of a lunar habitat, this diagram is crucial in visualizing the complex interplay of activities necessary to sustain astronaut operations and ensure mission success.

As seen in the provided diagram, the astronaut assumes a central role in executing various mission tasks, spanning scientific experiments, maintenance, stowage operations, and environmental sampling. The operational process, highlighted as a structured sequence of activities, ensures that mission objectives are met within the defined constraints. The logical flow of activities, including sample collection, waste management, and interaction with telemedicine for health assessments, reflects the structured approach required for sustained lunar operations. A key feature of the OAB is the ability to trace high-level mission constraints and objectives back to operational activities. This enables early identification of requirements, ensuring consistency and traceability within the model-based approach. For instance, requirements related to waste recycling and return-to-Earth logistics are explicitly linked to corresponding operational tasks, facilitating structured system development.

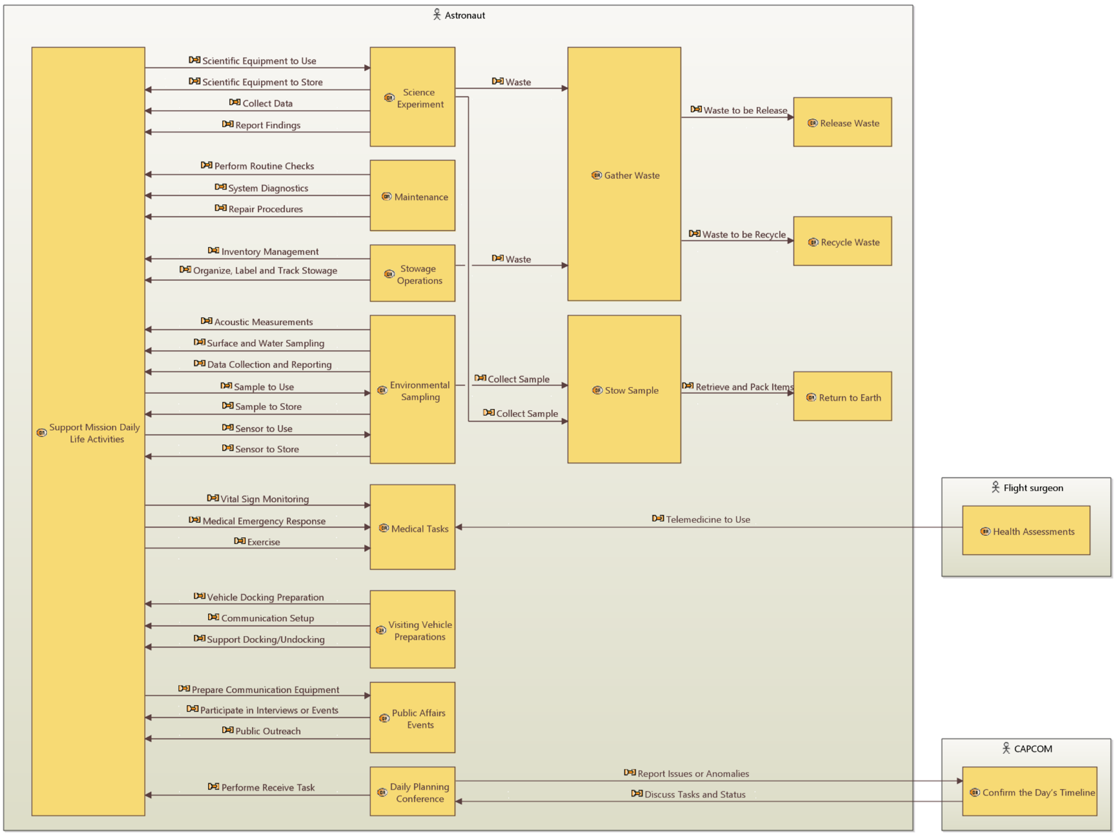


Figure 3.24. [OAB] Mission-centered Operational Architecture

Comparing this diagram (Fig. 3.24) with the previous one (Fig. 3.23), which focused on daily life support activities, a notable shift in emphasis is observed. While the earlier diagram concentrated on fundamental life-support functions such as cleaning, eating, exercising, and breathing, the current diagram incorporates mission-critical tasks such as scientific operations, medical assessments, and public outreach. This evolution in scope underscores the increasing complexity of lunar habitat operations, where sustaining life is just one aspect of the broader mission framework. Despite being a high-level representation, the OAB provides a global perspective on the interactions between major system entities, abstracting technical solutions to focus on operational requirements. This diagram ultimately serves as the primary output of the Operational Analysis phase and as the foundational input for the subsequent System Analysis phase, ensuring a seamless transition between conceptualization and implementation in lunar habitat design.

3.3.5 System Analysis

Following the transition from Operational Analysis, the System Analysis phase represents a crucial step in refining the system architecture and ensuring alignment with mission requirements. This phase further elaborates on the functional and behavioral aspects of the system, establishing a structured framework that integrates both stakeholder expectations and technical feasibility. The first step in System Analysis is to consolidate the functions identified in Operational Analysis and determine which will be performed by the system itself and which will remain the responsibility of external actors. The System Functions, derived from the previously identified Activities, are refined and expanded where necessary to cover all operational needs. These functions are then linked to specific System Capabilities, which represent high-level competencies the system must exhibit to fulfill mission objectives.

In the Mission Capabilities Blank diagram, the system's core capabilities are structured hierarchically, ensuring a clear relationship between mission goals, functions, and system actors. The Capability Exploitation relations further refine these interactions by defining how different elements contribute to achieving mission success. Once System Functions are defined, the next step is to transition toward a more detailed architectural breakdown. At this stage, the system is decomposed into its primary subsystems and components, each responsible for executing specific functions. This process facilitates the allocation of responsibilities within the system and provides a foundation for subsequent development phases. Key aspects addressed in this stage include:

- **Function Allocation:** Determining which system elements (hardware, software, human operators) are responsible for specific functions.

- **Data Flow and Interactions:** Establishing communication pathways between different system components.
- **Operational Scenarios:** Defining key use cases that illustrate how the system operates under different conditions.

Throughout the System Analysis, traceability with the initial mission requirements remains a priority. Each function and capability must be mapped back to stakeholder expectations to ensure consistency with the overall mission goals. This is particularly relevant when considering design constraints such as power consumption, data handling, and environmental conditions. By methodically refining the system's behavior and structure, System Analysis provides a robust foundation for the subsequent Logical and Physical Architecture phases. These steps will further detail subsystem interactions, performance characteristics, and system constraints, ultimately leading to a comprehensive and validated system design.

Given the high number of interconnected systems, the complexity of the lander architecture, and the multidisciplinary nature of the subject, fully implementing the System Analysis phase requires an extensive and detailed approach. The interactions between various subsystems, including propulsion, power, thermal management, communication, and scientific payloads, introduce significant challenges in defining a coherent and optimized system architecture. For this reason, while this work establishes a foundational approach to System Analysis, a comprehensive implementation and validation of the model will be pursued as part of future research. Further efforts will focus on refining the allocation of functions across subsystems, conducting performance trade-offs, and integrating cross-disciplinary expertise to ensure a robust and mission-compliant system design.

Chapter 4

Conclusion

This study investigates the application of HCD in space habitat development, emphasizing a user-centered approach. By conducting an extensive literature review, developing a theoretical framework, and analyzing a case study, several important insights have emerged. In particular:

- A HCD approach is essential for space habitats, ensuring that astronauts and other stakeholders are actively involved in the design phase.
- Implementing HSI principles enables space habitats to address astronauts' diverse needs while prioritizing functionality, efficiency, and sustainability.
- The case study of a Lunar habitat demonstrates the practical application of HF, showcasing the advantages of iterative prototyping, incorporating user feedback, and fostering interdisciplinary collaboration.

The insights gained from this research emphasize the critical role of a user-centered approach in space habitat development. The findings also highlight the importance of interdisciplinary collaboration, as expertise from various fields (engineering, psychology, architecture, and human factors) contributes to more holistic and effective habitat designs. However, several challenges and limitations must be addressed to refine the approach and optimize space habitats for future missions.

As space missions become increasingly ambitious, further research is essential to optimize space habitat design for long-duration missions. One critical area for exploration is the long-term impact of habitat design on astronaut performance, mental health, and overall well-being. Future studies should consider factors such as social interaction dynamics, privacy considerations, and psychological support systems to ensure that habitats not only sustain life but also promote a positive and productive living environment in space.

Additionally, emerging technologies hold great potential for revolutionizing space habitat design. The integration of artificial intelligence (AI) and virtual reality (VR) could enable habitats to be more adaptive, responsive, and intelligent. AI-driven systems could personalize environmental settings based on individual astronaut preferences, optimize resource management, and enhance safety protocols. Meanwhile, VR applications could aid in psychological well-being, allowing astronauts to simulate Earth-like environments, participate in virtual social interactions, and train for complex tasks in immersive settings. Moreover, a multidisciplinary approach is crucial in advancing the field. Insights from psychology, sociology, and architecture can offer a deeper understanding of human behavior in isolated and extreme environments, informing more holistic and human-centric design solutions. By fostering collaboration between engineers, HFE, and designers, future research can develop innovative strategies that improve astronaut adaptability and comfort during long-term space missions.

In conclusion, this study has provided some insights into the integration of HCD in space habitat development, highlighting both its benefits and the challenges that must be addressed. Furthermore, documenting and sharing lessons learned from past projects will be crucial in overcoming future challenges. The application of accumulated knowledge will not only inform the design of upcoming missions but also help establish best practices for the sustainable habitation of extraterrestrial environments. As humanity moves closer to long-term space exploration and potential colonization efforts, embracing innovation and a user-driven approach will be fundamental in shaping the future of space habitats.

List of Acronyms

Acronym	**Full Name**
ARCADIA	Architecture Analysis and Design Integrated Approach
CAE	Computer-Aided Engineering
CM	CounterMisure
ConOps	Concept of Operations
CST	Commercial Space Transportation
DAGs	Directed Acyclic Graphs
DRM	Design Reference Mission
ESA	European Space Agency
ESM	European Service Module
ESPRIT	European System Providing Refueling, Infrastructure, and Telecommunications
EVA	Extravehicular Activity
HALO	Habitation and Logistics Outpost
HCD	Human-Centered Design
HFE	Human Factors Engineering
HLS	Human Landing System
HSI	Human Systems Integration
HSIA	Human Systems Integration Approach
I-HAB	International Habitation Module
INCOSE	International Council on Systems Engineering
ISECG	International Space Exploration Coordination Group
JAXA	Japan Aerospace Exploration Agency
KDPs	Key Decision Points
LM	Lunar Module
LXC	Likelihood x Consequences
MBSE	Model-Based Systems Engineering
MDR	Mission Definition Review
NASA	National Aeronautics and Space Administration
OOSEM	Object-Oriented Systems Engineering Method
ORs	Operational Requirements
PDR	Preliminary Design Review
SE	Systems Engineering
SLS	Space Launch System
SRR	System Requirements Review
SysML	Systems Modeling Language
TRL	Technology Readiness Level

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