Master Thesis

DESIGN OF AN ANALOG FOR HUMAN SPACE EXPLORATION USING A MBSE APPROACH

POLYTECHNIC OF TURIN

DIMEAS - DEPARTMENT OF MECHANICAL ENGINEERING AND AEROSPACE

MASTER IN AEROSPACE ENGINEERING

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ABSTRACT

The objective of this document is to explore the design of a simulative analog of a space habitat, intended as a platform for testing and validating various technologies to advance knowledge in human space exploration. The design process follows the ARCADIA, Architecture Analysis and Design Integrated model-based Approach, which, in recent years, has proven to provide a clear, precise, and fast way to manage and modify projects.

This model-based approach is implemented using the modeling software Capella™. Following a comprehensive analysis of the working context, the project begins with a theoretical phase, during which objectives, functions, and corresponding components are defined. It then proceeds with the development of several models in Capella™, focusing on the initial stages of the design methodology: Operational Analysis and System Analysis, as well as a portion of the third stage, Logical Analysis. Given the complexity and scope of the project, these stages serve as a foundational framework for future developments, which will include the completion of the Logical Analysis, the implementation of the Physical Architecture, and further refinements and improvements of the existing models.

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ACRONYMS

ACS	Atmosphere Control and Supply
AI	Artificial Intelligence
ARCADIA	Architecture Analysis and Design Integrated model-based Approach
ARS	Atmosphere Revitalization and Sampling
ATHLETE	All Terrain Hex Limed Extra Terrestrial Explorer
BAS	British Antarctic Survey
BLSS	Bio-regenerative life support systems
CHAPEA	Crew Health and Performance Exploration Analog
CheCS	Crew Health Care System
DLR	German Aerospace Center
DRATS	Desert Research and Technology Studies
DSH	Deep Space Habitat
ECLSS	Environmental Control Life Support System
ESA	European Space Agency
EVA	Extravehicular activity
FDS	Fire Detection and Suppression
FLaSH	Facility for Life-Support and Sustainability in Habitats
FMARS	Flashline Mars Arctic Research Station
FSP	Food Storage and Preparation
HDU	Habitat Demonstration Unit
HERA	Human Exploration Research Analog
HI-SEAS	Hawaii Space Exploration Analog and Simulation
IBC	International Building Codes
IBMP	Institute of Biomedical Problems, Moscow Academy of Sciences
ISPR	International Standard Payload Rack
ISRU	In-Situ Resource Utilization
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JSC	NASA's Johnson Space Center
LA	Logical Analysis
MBSE	Model-Based Systems Analysis
MDRS	Mars Desert Research Station
MELISSA	Micro-Ecological Life-Support System Alternative
NASA	National Aeronautics and Space Administration
NEEMO	NASA Extreme Environment Mission Operations
OA	Operational Analysis
PA	Physical Analysis
PTSD	Post-Traumatic Stress Disorder
SA	System Analysis
SE	Systems Engineering
SHEE	Self-deployable Habitat for Extreme Environments
SysML	Systems Modeling Language
THC	Temperature and Humidity Control
UML	Unified Modeling Language
WM	Waste Management
WRM	Water Recovery and Management

1 Introduction

Designing and developing a space habitat for analog simulation is an extraordinarily complex undertaking, requiring the seamless integration of multiple interconnected subsystems and disciplines. The success of such a project depends on the ability of diverse teams to collaborate effectively, ensuring the system operates cohesively to fulfill its primary objectives. In this context, analog missions play a crucial role in evaluating habitat designs, technologies, and operational procedures in Earth-based environments before their deployment in actual space missions, as emphasized by NASA [1].

The primary objective of this project is to design an habitat where technologies and operational strategies for human space exploration can be tested, mitigating risks and optimizing solutions before their application in real missions. To address this complexity, the study follows a structured approach, covering the essential topics necessary to understand and develop an analog habitat. To achieve these objectives, it is crucial to fully understand several key aspects, which are presented in the section 2.

Firstly, subsection 2.1 begins by analyzing the extreme conditions present on Mars and the Moon. To perform effective tests, it is crucial to simulate these conditions as accurately as possible. However, given the inherent limitations in replicating the exact planetary environments of these celestial bodies, it is necessary to focus on the primary environmental challenges they pose during analog simulations [2]. Taking these factors into account is essential for designing habitats that can reliably operate under such harsh conditions, laying a solid foundation for future planetary missions.

Secondly, subsection 2.2 explores the idea of analog simulations in order to gain a comprehensive understanding of their purposes and applications. It reviews past, present, and future analog missions, revealing insights into where competitors are directing their efforts, identifying the key drivers behind upcoming projects, and examining the historical uses of analogs. This assessment underscores both the limitations and potential of existing habitats. Notably, the International Space Station, ISS, remains the most closely aligned model to a space habitat that can sustain human life for extended periods, offering valuable expertise in system integration, sustainability, and operations within the space environment.

In subsection 2.3, the discussion focuses on one of the most critical technological components of an analog habitat: the Environmental Control and Life Support System, ECLSS. This system is indispensable for future human space exploration missions, which NASA predicts will entail increasing demands regarding duration and scale [3]. The ECLSS necessitates the implementation of innovative, regenerative, and closed-loop technologies. It plays a fundamental role in maintaining the viability of an isolated environment such as a space habitat, by addressing essential requirements, including air quality, water recovery, waste management and thermal regulation. The design of the ECLSS aims to ensure the system's autonomy from external resources, thereby fostering a self-sufficient habitat capable of sustaining life throughout the entirety of the mission. However, the accomplishment of this critical objective remains, at present, a significant challenge.

In addition to ECLSS, the second part of the project, section 3, targets the enhancement of other mission-critical technologies. These include the implementation of artificial intelligence for system control, the development of innovative and user-friendly interfaces and the design of modular systems that facilitate easy modification and improvement with crew support facilities integrated. A fundamental requirement is the existence and effective utilization of a mobility system that allows efficient reuse of the simulation habitat. Furthermore, this initiative is supported by a self-sufficient framework for energy production, command management, data handling, and communication systems. The rigorous testing and refinement of these technologies within analog scenarios yield invaluable insights into the challenges and solutions pertinent to sustaining human life during prolonged space missions.

Finally, subsection 2.4 focuses on systems engineering, SE, with a particular emphasis on the methodology used in this study: Model-Based Systems Engineering, MBSE, in subsubsection 2.4.1. MBSE replaces the traditional document-centric approach with a model-driven methodology, providing a structured and integrated framework for the development of complex systems. By consolidating design, analysis and validation into a unified and dynamic model, it enhances consistency, improves traceability and enables real-time updates as requirements evolve [4]. In this study, MBSE is applied to the design of an analog space habitat, facilitating interdisciplinary collaboration, improving system reliability and accelerating the validation of critical technologies for human space exploration. Its ability to provide a centralized and interactive modeling environment makes it a more adaptable and efficient alternative to document-based approaches, ensuring a scalable and robust system architecture [5].

In this context, the Architecture Analysis and Design Integrated model-based Approach, ARCADIA, has been selected, as it offers a comprehensive systems engineering methodology that enables the effective modeling of complex systems [6]. Capella™, the supporting software that facilitates the ARCADIA methodology, helps to visualize and simulate system behavior, ensuring that all components of the habitat interact harmoniously. The combination of ARCADIA and Capella™will allow for the assessment of the feasibility of the design, ensuring that all functional requirements are met and that the system can evolve as new information becomes available [6].

Through this structured approach, the study aims to provide a comprehensive framework for designing and evaluating an analog space habitat, laying the groundwork for future planetary exploration. In the section 2, each of these key areas will be explored in depth, leading to the application of MBSE in the actual design process from section 3 onward, until the conclusion of the report in section 8.

2 Context Analysis

In this section, the objective is to establish a clear and comprehensive framework for understanding the context of this study, as anticipated in the introduction. The following key topics will be examined:

- Planetary Conditions
- Analog Simulations
- Environmental Control and Life Support System ECLSS
- Systems Engineering SE

By analyzing these aspects in detail, this section aims to provide a solid foundation for the subsequent design phase of the study, ensuring a thorough understanding of the relevant challenges and requirements before proceeding with the development process in the following sections.

2.1 Planetary Conditions

When talking about exploring planets and analog simulations, it's important to know what an analog is. Analogs are controlled experiments that take place in settings that mimic very tough conditions. They serve as testbeds for technologies, humans and materials. By simulating important challenges from extreme explorations, analogs help improve systems and methods before they are used in real missions [1]. In this particular case, the focus is on simulating conditions on an unknown planet. The aim is to do research that can help humans improve their capabilities for future space trips.

Planets have many natural conditions that are very unsafe for humans. These include things like gravity, the air conditions, limited resources, possible exposure to unknown substances, and how far the planet is from Earth [2]. The main characteristics and some of their corresponding consequences are summarized in the following Table 2.1, providing a general overview of the challenges associated with planetary exploration.

Table 2.1: Summary of environmental characteristics of unknown planets and their consequences [2].

Characteristics	**Consequences**
Distance from the Earth	Communication delay, extended mission durations
Gravity fields	Structural loads, muscle atrophy, bone density loss
Atmosphere	Pressure, temperature, density, level of irradiation
Confinement	Isolation, logistical challenges, stress
Hostile Environments	Potential toxicity, unknown contaminants and elements

Instead, specifically, the primary characteristics of the Moon and Mars are fundamental to understanding the challenges associated with designing a functional analog habitat. These two celestial bodies, while different from each other, share conditions that are significantly more hostile than those on the Earth. Key factors such as gravity, atmosphere, temperature ranges, and radiation levels directly influence the design of technologies and systems necessary for survival. To provide a clear overview, Table 2.2 summarizes the most relevant environmental parameters of the Moon and Mars in a comparative manner.

Table 2.2: Moon and Mars environmental characteristics [7],[8].

Characteristics	Moon	Mars
Radius [km]	1740	3396
Distance Earth [km]	384400	225000000
Communications delay [s]	1.25	780 (on average)
G-force [m^2/s]	1.62	3.73
Surface pressure [bar]	$3x10^{-15}$	$6.36x10^{-3}$
Temperature range [K]	95÷390	120÷293
Level of irradiation [mSv]	110÷380	240÷300
Solar irradiance [W/m^2]	1361	586

The Moon is characterized by an extremely thin atmosphere, which provides no significant protection from solar radiation or meteoroid impacts. Furthermore, the Moon's magnetic field is almost negligible, offering minimal shielding against cosmic rays and other forms of harmful radiation [7].

Mars has a thin atmosphere made of carbon dioxide, nitrogen and argon gases. It only offers some protection from falling meteorites and radiation. Unlike Earth, Mars does not have a strong magnetic field to protect it [8].

Designing a functional habitat for such environments, presents numerous challenges due to the extreme conditions highlighted above. Among these, two factors stand out as particularly problematic: irradiation and the absence of a viable atmosphere [7],[8].

Radiation on the Moon and Mars is much higher than on Earth, which can be very harmful to people's health and can damage technology. To keep everyone safe, special coverings and safety plans that use new materials and designs are essential. You can find more information on this issue in Appendix A.

The absence of a suitable atmosphere makes these problems worse because it restricts the possibilities for using resources on-site. Unlike Earth, where abundant oxygen, water and other essential elements can be freely extracted, the Moon and Mars need special systems that keep recycling resources to support life. This rule makes habitat design more complicated and shows how important it is to develop new technologies that can use resources efficiently and waste less. Building a self-sustaining environment that can handle these difficulties is a great achievement in engineering and creativity. The use of advanced technologies for recycling air and water, controlling temperature, and producing energy is necessary, all designed for the unique conditions on the Moon and Mars [2], [3].

2.2 Analog

An analog refers to a simulation or environment designed to replicate extreme conditions. These environments are used to study how humans, technologies and materials behave under such circumstances. By mimicking these conditions, analogs allow for preparation and experimentation without the need to face the immediate risks and high costs associated with actual missions to such locations [1].

One prominent example is the use of Antarctica as an analog environment. The remote and hostile environment of Antarctica makes it a good setting for space analog [9]. Another example involves space analogs that simulate conditions such as isolation, microgravity and confined living spaces. These simulations are critical for astronaut training and for studying psychological and physiological responses to extreme and isolated conditions [1].

By replicating these challenging environments, analog missions allow researchers to evaluate new technologies, refine operational procedures, and gain insights into human factors, thereby enhancing the safety and efficacy of actual space missions.

These analogs are also used for a variety of purposes beyond simply preparing for space missions or expeditions to Antarctica. These unique environments offer opportunities to test technologies, study human behavior or develop devices that can be applied in other contexts as well. Some applications are exposed as follows:

- Medical and Psychological Research

  Extreme environments offer an ideal setting for studying the effects of isolation, sensory deprivation, and stress management. These conditions provide valuable insights into psychological and medical challenges that may arise during extended space missions. Key examples of research include the study of Post-Traumatic Stress Disorder PTSD treatments, where simulations help researchers understand how individuals respond to extreme stress, isolation, and claustrophobia. This research informs the development of better psychological treatments and stress management techniques. Additionally, conditions such as limited natural light and sensory input in these analog environments allow for the investigation of sleep disorders and mental health challenges, such as insomnia and depression, that are associated with prolonged isolation [10].

- Testing New Technologies

  Analog environments play a vital role as essential testing platforms for the advancement and enhancement of cutting-edge technologies. These environments allow researchers and engineers to evaluate the performance of different innovations prior to their implementation in practical applications [1].

  A primary focus of testing encompasses technologies designed for hostile environments, including radiation-resistant suits and sophisticated heating, cooling, and water and air recycling systems. These advancements are essential for industries that function under extreme conditions, such as mining, deep-sea exploration, and offshore activities [3].

  Additionally, a significant emphasis is placed on renewable energy solutions, where the performance and dependability of solar panels, wind turbines and other sustainable energy technologies are evaluated in remote or challenging environments. In parallel, sustainable architecture is investigated through the creation of shelters that can withstand severe climates while optimizing resource use [2].

  Furthermore, analogs serve as an optimal environment for agriculture in extreme conditions, where enclosed greenhouses and hydroponic systems are tested to facilitate food production in regions with poor soil quality or extreme weather. Finally, the assessment of emerging communication technologies, including mesh networks and satellite systems, guarantees reliable connectivity in remote and rural areas, thereby enhancing communication resilience in isolated environments [11].

- Climate Change Research

  Analogs are useful for learning about climate change and being ready for natural disasters. They offer safe ways to study environmental problems and ways to solve them. Scientists study these settings to see how global warming affects the air, weather and how nature can adapt. They also act as places to try out new ways to protect the environment, helping to reduce harm to delicate ecosystems. In disaster response, models help train rescue teams so they can work well in tough situations. They are also important for checking strong buildings, like those that can withstand earthquakes, materials that don't catch fire, and emergency plans, which help communities be better prepared for natural disasters [12], [11].

- Military Applications

  Many similar methods are used to train soldiers and test equipment in tough situations. These simulations help improve survival plans, procedures, and technology needed for carrying out missions in difficult or dangerous places. By putting staff in situations like those they will face in real operations, analogs help them be more prepared, flexible, and successful in military missions [13].

- Extreme Tourism and Experiential Simulations

  Analog experiences are being used more and more for education and hands-on learning. They give people a chance to actively participate in space exploration and scientific research. Simulated space tourism experiences help people learn about the physical and mental difficulties of traveling to space. Furthermore, analog settings support public scientific training programs, fostering awareness of exploration, sustainability and technological advancements. These initiatives, as HERA [14] and HI-SEAS [15] programs, not only inspire future generations but also contribute to broaden scientific literacy and interest in space and environmental sciences.

In summary, analog environments offer a safe and controlled setting for testing innovations and studying phenomena that have a broad societal and technological impact. From medical research to disaster preparedness, climate studies and the development of new technologies, analogs provide invaluable insights and solutions that extend far beyond their initial purpose of mission preparation.

2.2.1 Analog Simulation Programs

To gain a clearer insight into the concept of analog environments, it is beneficial to investigate specific examples that demonstrate the functionality of these simulations and their impact on research. This section showcases a variety of significant cases, offering an in-depth examination of some of the most representative projects and missions. By analyzing these examples, it becomes evident how analogs are intentionally crafted to replicate the difficulties of extreme situations, facilitating the thorough exploration of human behavior, technological capabilities and resource management.

Grasping the context and aims of these analogs is essential for creating projects of this kind with the utmost accuracy and precision. Each instance not only emphasizes the scientific objectives and methods utilized but also highlights the practical consequences for upcoming missions to extreme or extraterrestrial settings.

There are numerous notable projects and missions that have been designed to simulate the conditions of Antarctica and space. Below are presented some of the most significant projects, shown by a figure of the specific mission and a brief description, to present some real examples and to learn more about this topic.

1. Mars Desert Research Station MDRS – Utah, USA

Figure 2.1: Mars Desert Research Station [12].

Located in the Utah desert, the Mars Desert Research Station replicates conditions analogous to a Martian base. Crews reside at the station for weeks or months, conducting activities such as scientific experiments and extravehicular activities EVA within a confined environment and a desert landscape. This analog enables the study of psychological resilience in isolation, resource management, and adaptation to Mars-like hostile environments [12].

2. NASA Extreme Environment Mission Operations NEEMO – Florida, USA

Figure 2.2: NASA Extreme Environment Mission Operations [16].

NEEMO is a NASA initiative that utilizes the Aquarius Reef Base, an underwater habitat off the coast of Florida, to simulate space missions. Participants live underwater for extended periods, mimicking the constraints of microgravity and confined spaces. The mission provides valuable insights into how the human body and team dynamics adapt to isolation, stress, and teamwork under extreme conditions [16].

3. Hawaii Space Exploration Analog and Simulation HI-SEAS – Hawaii, USA

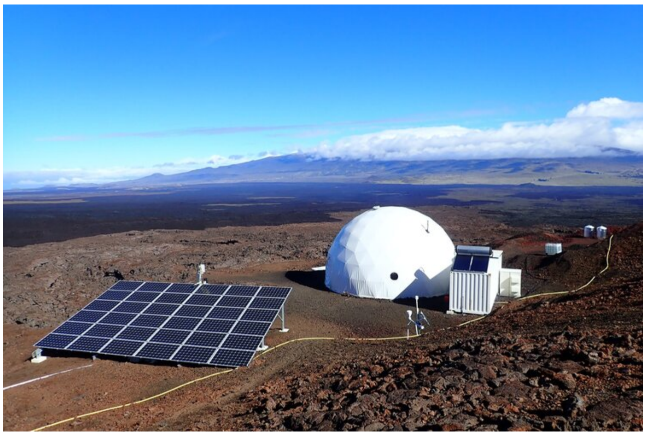


Figure 2.3: Hawaii Space Exploration Analog and Simulation [15].

HI-SEAS is a Mars analog located on the volcanic slopes of Mauna Loa, chosen for its resemblance to the Martian surface. Simulations, lasting from several months to a year, focus on group dynamics, psychological adaptation, and the evaluation of technologies required for long-duration missions to Mars [15].

4. Concordia Research Station – Antarctica

Figure 2.4: Concordia Research Station [17].

Antarctica is widely regarded as a natural analog for space exploration. Concordia Research Station, situated at an elevation of 3,200 meters on a polar plateau, is jointly operated by France and Italy. The extreme isolation, prolonged periods of darkness, and severe cold make it ideal for studying the psychological and physiological challenges astronauts may face during missions to Mars. Additionally, Concordia facilitates the testing of life support systems, medical research, and studies on human endurance in extreme conditions [17].

5. McMurdo Station – Antarctica

Figure 2.5: McMurdo Station [18].

As the largest research station in Antarctica, McMurdo serves as a base for scientific studies related to human behavior, technology, and environmental conditions in extreme settings. Researchers investigate the effects of prolonged isolation, extreme cold, and limited light exposure, while the station also functions as a launch point for smaller missions to more remote areas of the continent [18].

6. British Antarctic Survey BAS

Figure 2.6: British Antarctic Survey [19].

The British Antarctic Survey operates several research stations, including the Halley Research Station, which is crucial for climate research and preparation for space missions. Its modular infrastructure is specifically designed to withstand extreme Antarctic conditions, offering insights into the development of habitats for extraterrestrial environments such as the Moon or Mars [19].

7. Crew Health and Performance Exploration Analog CHAPEA – Johnson Space Center, Houston, Texas, USA

Figure 2.7: Crew Health and Performance Exploration Analog [20].

CHAPEA is a NASA program that conducts a series of simulated Mars missions, focusing on human health and performance in conditions mimicking those of a Martian habitat [20].

8. Human Exploration Research Analog HERA – Johnson Space Center, Houston, Texas, USA

Figure 2.8: Human Exploration Research Analog [14].

HERA is another NASA initiative involving a habitat designed for mission simulations. It facilitates studies on human behavior, resource utilization, and team dynamics during extended missions in confined spaces [14].

9. Desert Research and Technology Studies DRATS

Figure 2.9: Desert Research and Technology Studies [21].

DRATS conducts annual field tests to evaluate and demonstrate technologies and systems that may be employed during future human exploration of the Moon, Mars, or other planetary bodies [21].

10. PILOT Mission – Russia

Figure 2.10: Mars 500 [22].

The PILOT program, based in Moscow, involves simulations of interplanetary space missions within a controlled, enclosed environment. Notably, the MARS-500 mission, a component of this program, lasted up to 520 days, replicating the duration and conditions of a round trip to Mars [22].

Some of these projects, along with others, are examined in greater detail, divided into three categories underlining similar characteristics selected on a personal basis.

- Long duration mission simulations analogs
- Scientific and technological analogs
- Future analogs

These categories do not imply any certified classification but aim to facilitate an understanding of the context by identifying, for each category, how analogs have been designed and utilized to achieve their objectives. It should be noted that inclusion in one category does not preclude relevance to another.

2.2.1.1 Long duration mission simulations analogs

MARS 500 – 2007 to 2011

The MARS-500 mission, conducted between 2007 and 2011, was a psychosocial isolation experiment designed to simulate a future crewed mission to Mars. This international collaboration, led by Russia in partnership with the European Space Agency, ESA, and China, took place at the Institute of Biomedical Problems, IBMP, of the Russian Academy of Sciences in Moscow. The experiment sought to investigate the physiological and psychological challenges of prolonged isolation and confinement in a simulated Martian environment [23].

The objective of the MARS-500 experiment was to recreate the circumstances of an interplanetary expedition, encompassing the voyage to Mars, a landing on the Martian terrain and the journey back. In order to accomplish this goal, the imitation facility at IBMP was structured to mirror the key elements of a Mars mission, comprising a spacecraft, a landing module, and a simulated Martian surface. Throughout a span of four years, three distinct crews of skilled volunteers, possessing expertise in fields such as engineering, medicine, biology, and space exploration, participated in the experiment [23].

The volunteers offered significant contributions regarding the impact of extended isolation in enclosed environments. They encountered various difficulties such as communication delays ranging from 13 to 25 minutes, scarcity of food supplies, a sealed environment and limited medical assistance within the spacecraft [23].

The study comprised three distinct phases, with the last phase spanning 520 days to replicate a full Mars mission, incorporating a simulated Mars landing and surface exploration. While the crew's physical and psychological well-being was generally well-preserved, certain individuals faced notable disturbances in their circadian rhythms and sleep schedules [23].

Facility Description

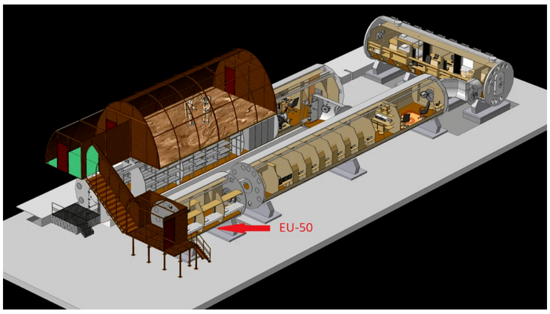


Figure 2.11: Mars 500 Station [24].

The MARS-500 isolation facility, shown in Figure 2.11, consisted of five interconnected modules with a total volume of 550 m^3 and an internal floor area of 243 m^2. These modules replicated the various components of a Mars mission and were equipped with the necessary systems to sustain the crew and conduct experiments [23]. They are briefly explained in the paragraphs below.

The habitat module is the main living area. It has six private rooms for crew members, a kitchen and dining area, a living room, a main control room, and a bathroom.

The medical area has two stretchers, a bathroom, and tools for basic health checks, remote medical consultations, and tests. It is made to separate and care for crew members if they get sick.

The Mars landing module is a model of a spacecraft that lands on Mars. It has three bunk beds, two work areas, a bathroom, and systems to control everything, collect data, and support life.

The storage area has a cold section for keeping food, a test greenhouse, and places like a bathroom, sauna, and gym.

Finally, the Martian surface module looks like the surface of Mars and is linked to the landing module, helping with exploring the surface.

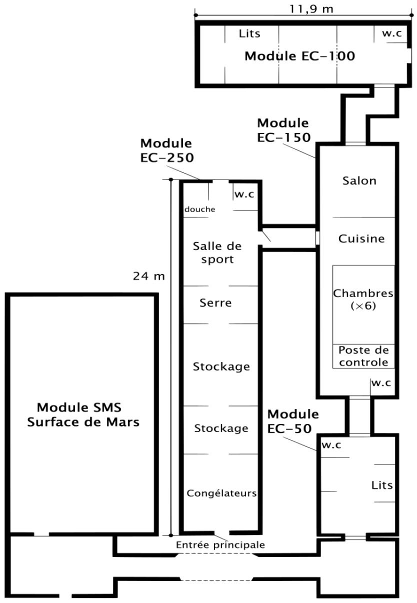


Figure 2.12: Mars 500 Facility [23].

All modules, displayed as shown in Figure 2.12, were maintained at normal Earth barometric pressure and included systems for air and water supply, recycling, ventilation, fire safety and emergency response.

Researches Conducted

The MARS-500 experiment had various research activities to understand the challenges of traveling between planets. Some state-run studies included heart tests like electrocardiograms and blood pressure checks, along with experiments where people were put in water to study disorders related to low movement. Also, psychological studies looked at stress, thinking ability, and sleep patterns during the mission, giving valuable insights into the mental and emotional challenges of being in space for a long time.

Also, scientists looked at how radiation like what is on Mars affects living things by using animals in their experiments. This research helps to understand the potential health issues astronauts may encounter in the future. Environmental and safety studies examined critical aspects such as air quality, water recycling efficiency, and the effects of low-oxygen environments on crew performance.

These studies, carried out under high-pressure conditions to lower fire risks using a mix of oxygen, nitrogen, and argon gases, ensured that life support systems can function properly in isolated and closed-off areas.

Conclusion

The MARS-500 mission has effectively demonstrated the viability of maintaining a crew in a confined and isolated environment for prolonged periods. Throughout the mission, the crew exhibited cohesive teamwork, without significant interpersonal conflicts [23].

As the mission progressed, a gradual decrease in activity levels was noted, particularly during the return phase. During this phase, the crew spent an additional 700 hours in bed compared to the initial journey. Some participants encountered difficulties with sleep patterns and psychological well-being. Notably, one individual experienced chronic sleep deprivation, resulting in reduced concentration and cognitive performance. To address these challenges, the utilization of blue light therapy was implemented to regulate circadian rhythms and replicate natural daylight conditions within the isolated environment [23].

Despite the obstacles faced, the MARS-500 experiment yielded valuable insights into the physiological and operational dimensions of extended space missions. The outcomes of this experiment continue to offer significant contributions to the understanding and enhancement of long-duration space exploration endeavors.

HI-SEAS – 2013 to today

The Hawaii Space Exploration Analog and Simulation, HI-SEAS, is a research facility created to replicate extended human space missions, particularly those destined for Mars. Operated by the International MoonBase Alliance, HI-SEAS is situated at an altitude of 2,500 meters on the Mauna Loa volcano in Hawaii. This location offers Mars-like conditions, including isolation, minimal vegetation and volcanic terrain. Established in 2013, HI-SEAS has hosted a series of missions supported by NASA and independent organizations. These missions aim to investigate the obstacles associated with prolonged space living, with a specific focus on the well-being of the crew, their behavior and team dynamics [15]. These missions are briefly presented:

- HI-SEAS I-IV (2013–2016)

  The initial four missions, varying in duration from four months to a complete year, were centered on culinary research, social isolation, and interpersonal relationships. The extended missions specifically examined the utilization of 3D printing technology, the reliability of equipment, and the resilience of the crew.

- HI-SEAS V-VI (2017–2018)

  These missions, lasting up to eight months, emphasized team dynamics and technical challenges. The final NASA-associated mission was halted after four days due to a medical emergency.

Subsequent missions, such as EMMIHS (2019–2020), Selene (2020–2021), and Valoria, expanded research into geological studies, robotics, and alternative uses of biological materials like human hair as fertilizer [25].

Facility Description

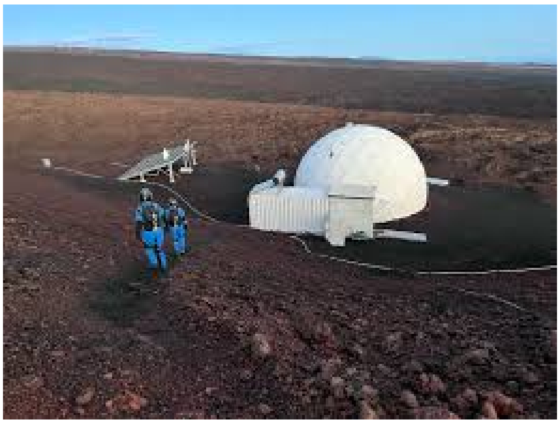


Figure 2.13: HI-SEAS [26].

The HI-SEAS habitat, shown in Figure 2.13, is a geodesic dome with a two-story open layout and a diameter of approximately 11 meters, providing a total area of 80 m^2 to accommodate up to six crew members. The ground floor includes communal areas such as a kitchen, dining room, shared workspace, laboratory, exercise area, and a small bathroom with a shower. This floor offers 30.3 m^2 of space, with 26.8 m^2 of usable area. The upper floor, spanning 39.4 m^2, houses six private sleeping quarters and an additional small bathroom equipped only with a toilet. The two floors are designed as shown in Figure 2.14. An attached shipping container is used for storage and to house the habitat's critical water and energy systems.

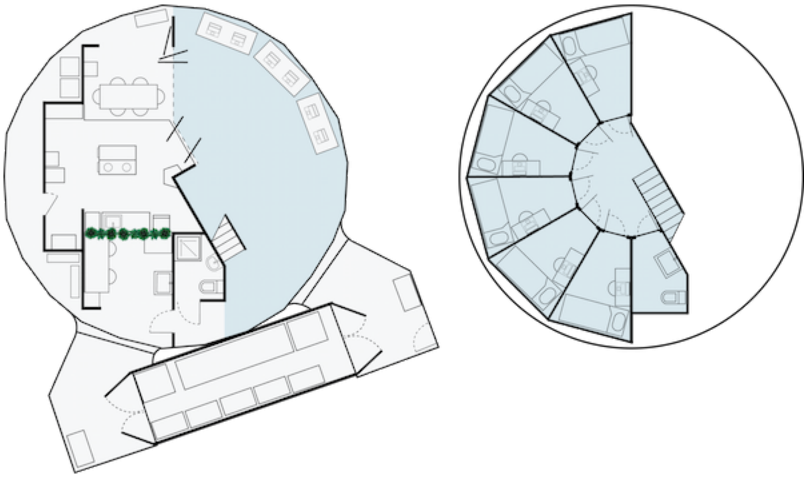


Figure 2.14: HI-SEAS Planimetry - Ground and first floor [27].

Researches Conducted

The HI-SEAS research project investigates the necessary conditions for ensuring the well-being of crew members during prolonged missions to Mars. This study encompasses various critical areas such as life support systems, crew interactions and the design of habitats.

In the initial phases of the missions, the focus was on assessing dehydrated food options to improve the diversity and nutritional quality of astronauts diets. Subsequent experiments involved the cultivation of crops, as shown in Figure 2.15, such as lettuce, radishes, peas, and tomatoes in controlled environments, with the goal of establishing sustainable food production methods for extraterrestrial habitats. Different lighting systems were tested to determine the most effective ways to promote plant growth while maximizing energy efficiency [28].

(a) The ORBITEC BPSe - Biomass Production System for education.

(b) Lamp set-up grow plants.

Figure 2.15: HI-SEAS Plant Set Up [28].

Additionally, the impact of plant growth on the habitat's atmosphere was monitored using a spectroscopy and waste management procedures were also rigorously examined. For examples, researches included the utilization of the steam reforming reactor at the Kennedy Space Center to convert waste materials into useful gases like methane and hydrogen [28].

Instead, research on crew dynamics delved into aspects such as stress levels, morale, problem-solving abilities, and communication within the group [29].

In addition, the research on habitat design focused on developing adaptable and versatile spaces influenced by intricate settings like Asian gardens. Despite this, issues like insufficient sound insulation and restricted privacy were identified. To address these challenges, suggestions were made for enhancements like soundproofing techniques, the use of warmer materials, and the implementation of advanced lighting systems. Additionally, concerns regarding dust control and exposure to radiation were highlighted as crucial research areas. Proposed solutions involved the construction of underground shelters to protect residents from cosmic radiation [29].

Conclusion

The research conducted in the HI-SEAS project has significantly contributed to understand the difficulties linked to extended space missions. For future missions to Mars and other destinations, advancements in habitat design, waste management, and life support systems are essential. Recommendations put forward emphasize the importance of integrating 3D printing technologies to reduce reliance on spare parts, leveraging virtual and augmented reality to mitigate feelings of isolation, and focusing on human-centered design principles to establish habitable and flexible living spaces for astronauts.

CHAPEA - 2023 to today

The Crew Health and Performance Exploration Analog, CHAPEA, is a NASA initiative to simulate the challenges of long duration human missions to Mars. The program includes three missions, with the first starting on June 25, 2023, and ending on July 6, 2024. The missions are conducted in a dedicated habitat located within a hangar at NASA's Johnson Space Center, JSC, in Houston, Texas [20].

The CHAPEA missions are designed to study the challenges of long term Mars exploration, with a focus on resource management, operational performance, and crew well-being. Details of each mission are as follows:

- CHAPEA 1 (2023–2024)

  The first mission, lasting 378 days, included four participants selected through a rigorous process. Candidates were required to meet specific qualifications, such as U.S. citizenship, STEM or piloting experience, and the completion of a long-duration astronaut physical exam.

- CHAPEA 2 (2025)

  Scheduled to begin in Spring 2025, with applications accepted between February and April 2024.

- CHAPEA 3 (2026)

  Planned to commence in 2026, with further details pending.

Facility Description

Figure 2.16: CHAPEA Analog [20].

The missions of CHAPEA are carried out in Mars Dune Alpha, a 158 m^2 3D-printed habitat created to replicate potential structures that could be constructed on Mars using local resources. Developed by

ICON Technology Inc. utilizing the Vulcan 3D printing system, as shown in Figure 2.16, the habitat is made of a special concrete known as Lavacrete, colored to resemble the reddish tint of Martian soil [20], [30].

It is divided into separate sections, Figure 2.17, to support to different mission tasks. Within the habitat, there are crew quarters that offer individual living spaces for four crew members, ensuring their personal comfort and relaxation. A designated workspace supports scientific research and operational tasks, while areas for exercise and recreation promote physical health and mental well-being. Sections for crop growth allow for the cultivation of vegetables such as peppers and tomatoes, contributing to self-sufficiency and nutritional studies for future Mars expeditions [30].

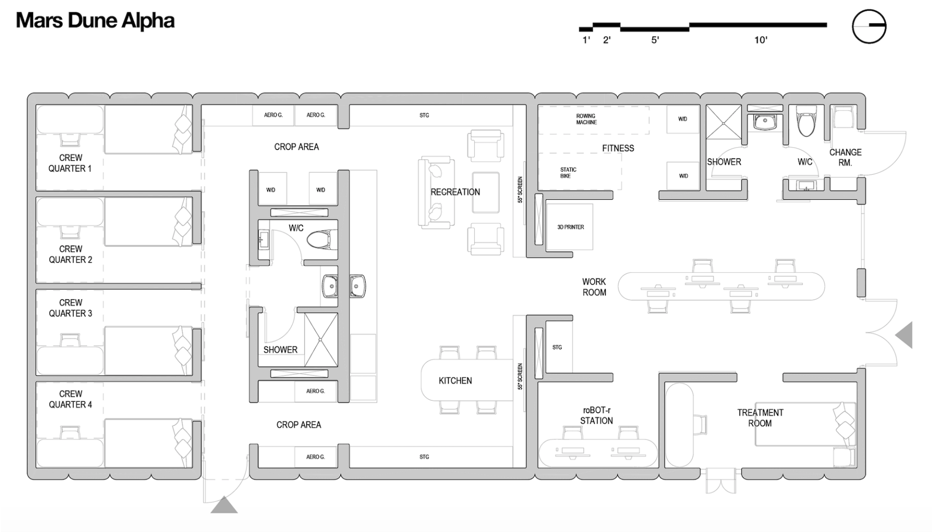


Figure 2.17: CHAPEA Planimetry [30].

The exterior environment, Figure 2.18, replicates the Martian surface, complete with red soil and cliffs. Crew members can access the outside through an airlock. Following the procedures, the habitat allows for the examination of spacewalk protocols and airlock efficiency [30].

Figure 2.18: CHAPEA External Environment [20].

Guided by NASA, the design and construction of the habitat incorporate various innovations to maximize functionality and ensure the safety of the crew.

The structure is designed in a way that transitions from private to public spaces, improving operational efficiency and personal comfort. An underfloor air distribution system maintains the habitat temperature stable. Lighting systems are adjustable and controlled by the mission control center to replicate real mission conditions [30].

Instead, as far as safety is concerned, walls have varying thicknesses depending on whether they are load bearing or no load bearing structures. Safety measures against fire include smoke detectors, CO_2 monitors, and sprinkler systems. Surveillance cameras are installed to monitor activities within the habitat, excluding private areas to uphold privacy while ensuring security [30].

Mars Dune Alpha complies with a combination of building codes, including those from the city of Houston, NASA standards and the International Building Codes, IBC, all play a role in regulating additive manufacturing. Nevertheless, the differences in these regulatory frameworks emphasize the necessity for more thorough guidelines for 3D printed analog habitats [30].

Researches Conducted

The CHAPEA program is dedicated to replicating the challenges of a real Mars mission, with a focus on comprehending the physical, mental and operational obstacles presented by prolonged isolation and confinement. The mission is structured to include various essential components aimed at creating an authentic simulation of Martian conditions.

One significant aspect of the mission involves a 22 minute communication delay, mirroring the real time limitations of communication between Earth and Mars. Additionally, constraints on resources are imposed to simulate what astronauts would encounter on Mars. The simulation also includes equipment malfunctions to assess the crew's problem solving abilities and resilience, along with external habitat environments for simulated Mars excursions [20].

Crew members participate in a range of mission related tasks such as operating robots, maintaining the habitat, following exercise routines and cultivating crops. The mission deliberately introduces stressors like isolation, confinement and limited resources to examine their impact on the crew [20].

Conclusion

The importance of 3D printing technologies in building habitats on Mars is highlighted by the CHAPEA project. The Vulcan construction system demonstrates how utilizing materials found on Mars such as regolith, can lead to the creation of structures that are well-suited for the Martian environment.

One of the main challenges is to ensure that different materials can work together seamlessly, which is essential to integrate various structural elements. It is crucial to address issues related to sealing and structural support to account for the temperature changes on Mars, which can cause thermal expansion and contraction of 3D materials. To improve the strength and durability of printed structures, reinforcements such as fibers or composites are indispensable. Moreover, it is vital to design adaptive joints capable of handling varying loads and environmental conditions to ensure structural flexibility [30].

Advancements in additive manufacturing can help future missions reduce dependence on resources from Earth. This progress allows for the development of self-sustaining facilities on Mars to support long term human presence.

2.2.1.2 Scientific and technological analogs

MDRS – Early 2000s to today

The Mars Desert Research Station, MDRS, is the largest and longest running Mars surface research facility, operated by the Mars Society [12]. Established in the early 2000s near Hanksville, Utah, MDRS is a key component of the Mars Analog Research Station Project [12]. This project aims to develop essential knowledge for human exploration of Mars. The facility provides a platform for testing field tactics, habitat designs, tools and crew protocols under Mars-like conditions.

Facility Description

Figure 2.19: MDRS [12].

MDRS, shown in Figure 2.19, is located in the San Rafael Swell region of southern Utah, chosen for its geological and environmental similarity to Mars. It is the second Mars analog station established by the Mars Society, following the Flashline Mars Arctic Research Station FMARS on Devon Island, Canada. Both FMARS and MDRS were initially based on an 8 m in diameter, two levels habitat design. Over time, MDRS was expanded to include additional modules, making it more robust and versatile than FMARS due to its frequent use.

The main habitat consists of two levels, each designed to support different mission activities and organised as shown in Figure 2.20.

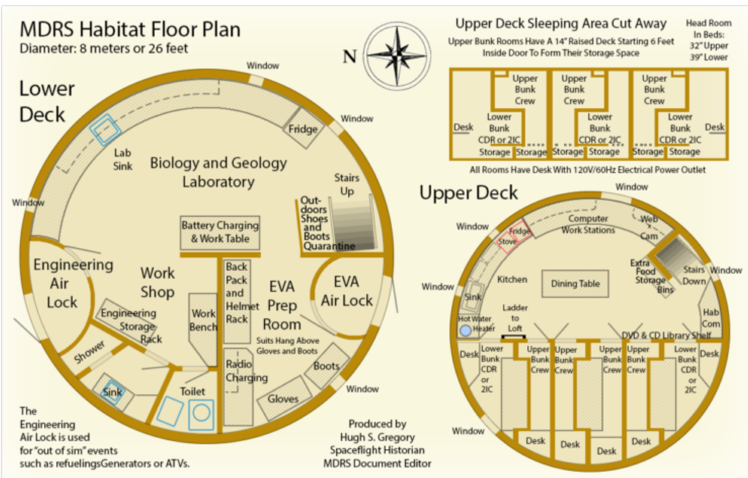


Figure 2.20: MDRS Main Habitat [31].

The lower level houses essential operational areas, including airlocks for external access, a laboratory for scientific research and an EVA preparation area where crew members suit up for simulated spacewalks. The upper level is dedicated to living and communal spaces, featuring private crew quarters, a shared common area for leisure and social interaction and a kitchen for meal preparation. This layout optimizes functionality by separating technical operations from daily living activities, ensuring an efficient and organized habitat environment.

The campus of the MDRS has grown over time to incorporate various specialized facilities that aid in research and simulation activities.

Among these facilities, the GreenHab functions as a greenhouse where crops such as herbs and vegetables are grown, offering valuable insights into sustainable food production in environments similar to space.

The observatories contain telescopes that are operated remotely for educational and scientific purposes, facilitating studies in astronomy.

The Science Dome is specifically designed for biological and geological research, allowing for experiments in planetary sciences.

Moreover, the Repair and Assembly module serves as a workshop for conducting repairs and maintenance to ensure the station's infrastructure remains functional during missions.

To enhance ease of movement and safety in simulated Martian conditions, most modules are interconnected by tunnels, as shown in Figure 2.21.

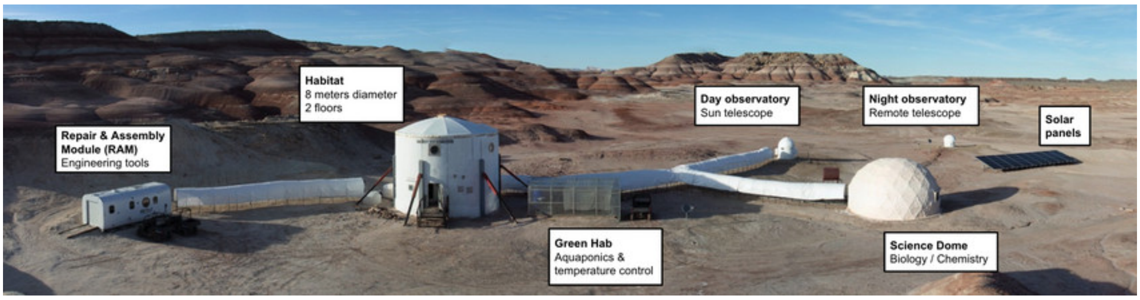


Figure 2.21: MDRS Campus [32].

Researches Conducted

The Mars Desert Research Station MDRS aims to replicate the conditions of life on Mars. Crew members must wear analog space suits during outdoor tasks, mimicking the challenges faced during actual space missions and enabling researchers to investigate the impact of EVA suits on various mission factors. Explorations are carried out either on foot or by utilizing special vehicles to access specific research sites [12].

A typical MDRS crew is made up of six members who take part in two week shifts in the winter months of the northern hemisphere to escape the extreme heat of the desert. The team comprises scientists, engineers, and sometimes journalists. These individuals are volunteers who fund their own travel and do not receive any payment for their contribution [12].

MDRS supports various research endeavors. Studies on human factors delve into how cognitive human function work in confined spaces. In terms of biological research, the focus is on extremophiles, which are organisms that have adapted to extreme conditions. Researchers, also, analyze bacteria and algae found in the desert.For example, research on methanogens has revealed the presence of methane producing microbes in desert soil. Additionally, investigations on endoliths, bacteria residing inside rocks, explore their capability to harness light for photosynthesis through rock surfaces. These discoveries have practical implications in industries like food production, medicine and pharmacology [12].

Emphasizing resource efficiency in a closed-loop system is another study for MDRS. The station relies on rechargeable batteries and generators for power, with water carefully rationed and supplied manually. Sustainability practices such as greywater recycling are tested and internet connectivity allows for remote monitoring of missions [12].

These initiatives help in comprehending the logistical and technical obstacles involved in sustaining a habitat for extended periods in harsh conditions.

Conclusion

Since its establishment, the Mars Desert Research Station has played a crucial role in enhancing knowledge related to human and scientific aspects of Mars exploration. Up to 2017, 175 teams had finished their missions, offering essential information and perspectives that are still shaping the planning of upcoming expeditions to Mars [33].

HDU - 2010 to 2013

Between 2010 and 2013, the Habitat Demonstration Unit, HDU, functioned as a prototype aimed at replicating a livable setting for extended missions on Mars. During this period, the HDU was utilized to assess essential systems and operational ideas, enabling NASA to enhance plans for upcoming deep space missions. The HDU is shown in Figure 2.22.

Figure 2.22: HDU [34].

Facility Description

The shell of the HDU was built with a segmented design consisting of eight composite fiberglass sections, as shown in Figure 2.23. Steel ribs were added for structural support. This innovative construction method enabled quick assembly and integration at NASA's Johnson Space Center, JSC, in 2010. Inside the habitat, there were four quadrants, each designated for different purposes like maintenance, medical operations, suit maintenance and geology activities. To make the most of the available space, essential systems like avionics and environmental controls were installed below the floor [34].

Figure 2.23: HDU Planimetry Prototype 2010 [34].

The primary focus of the structural design was on enhancing strength and reducing weight through the incorporation of composite honeycomb panels. Electronic components, as already said, were stored below the floor in two protective racks that were specifically engineered to withstand dust, enabling smooth operation of power distribution and data transmission to support critical habitat functions. The power and thermal management systems made use of off-the-shelf components, drawing energy from generators and solar panels. Remote control was implemented for power distribution to optimize energy efficiency, while temperature control was achieved through a forced air conditioning system that circulated air beneath the floor to establish a consistent internal climate [34].

As far as communications are concerned, the HDU utilized a wired and wireless communication network, in collaboration with wireless sensors to offer real-time environmental monitoring of the habitat [34].

In the design of the HDU, human factors and usability played a critical role. HDU incorporated life support simulations, including fire, air, water and hygiene management. In particular, the Hygiene Module offered the basic facilities such as a small wet bath and a camper style toilet. Moreover, there were areas such as the galley, medical workstation and sleeping quarters to support the crew members during extended missions [34].

Researches Conducted

Extensive testing was conducted on the HDU to replicate real conditions and confirm its functionality and compatibility with other exploration systems. The testing procedure consisted of three main phases: integrated systems testing, dry run tests and full tests [34].

During the integrated systems testing phase, critical operational parameters such as power distribution, bandwidth capacity, radio frequency usage and essential sequences like activation and emergency shutdown procedures were verified.

The dry run tests focused on loading the habitat, transportation and setup processes to ensure smooth integration with also the utilization of space exploration rovers.

Lastly, the full tests included a two week mission, where multiple rover dockings were conducted to evaluate collaborative science operations in practical mission scenarios.

Additionally, due to its adaptable structure, a thorough assessment of transportation strategies was made possible. In order to reduce the risks linked to on site assembly, the team decided to transport the fully integrated HDU. They designed a special cradle to ease transportation and guarantee alignment with NASA's All Terrain Hex Limed Extra Terrestrial Explorer robot, ATHLETE, rover docking systems, as shown in Figure 2.24 [35]. This improvement enhances the efficiency of deployment for upcoming analog and extraterrestrial missions.

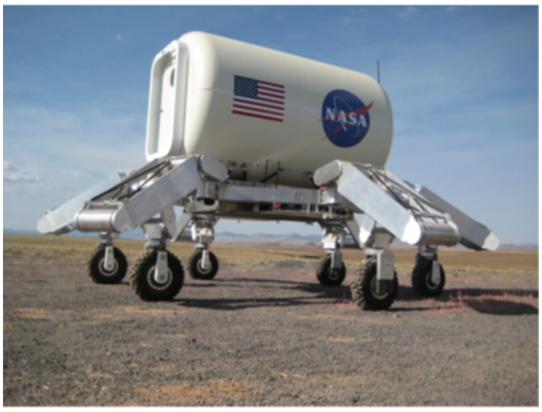


Figure 2.24: ATHLETE robot [35].

During 2011, the HDU underwent a transformation and became known as the Deep Space Habitat, DSH, prototype, as shown in Figure 2.25. This shift in focus involved enhancements in tele-robotics and airlock systems. The airlock was further developed to improve dust control and astronaut assistance [34].

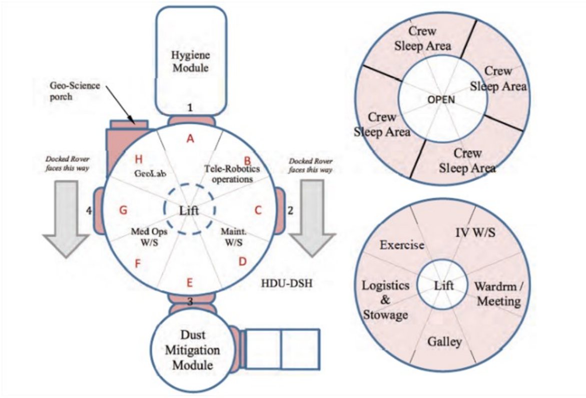


Figure 2.25: HDU Planimetry Prototype 2011 [34].

The following year, tests were conducted to simulate long-duration missions. Specifically, a mission scenario mimicking the return phase of a 400 day asteroid mission was carried out. The emphasis was on improving workstations and incorporating advanced technologies. To replicate varying mission distances, communication delays were intentionally introduced [34].

In addition, experiments were conducted on bioregenerative systems to assess food production capabilities, specifically focusing on cultivating lettuce, basil, and mizuna under LED lighting. The introduction of fresh produce had a positive impact on the psychological and nutritional well-being of the crew [34].

The GeoLab, also, facilitated on-site sample analysis and underwent upgrades to incorporate robotic tools and interfaces for remote operation. Research conducted in this facility underscored the advantages of autonomous systems and robotic support for upcoming missions [34].

These tests were mainly conducted at the Johnson Space Center, JSC, to cut down costs. This approach allowed teams to refine habitat systems and operations within a controlled setting [34].

Conclusion

The Habitat Demonstration Unit was important in advancing research on deep space habitats. It provided important knowledge on integrating systems, human factors and operational strategies. The findings from testing the HDU have greatly impacted future projects like the Human Exploration Research Analog, HERA. By working together across different fields and conducting repeated tests, the HDU missions showed that it is possible to create sustainable and livable environments for upcoming exploration endeavors.

HERA - 2014 to today

The Human Exploration Research Analog HERA program, developed by NASA, is a series of missions designed to simulate the challenges of long-duration interplanetary space travel. Built upon the Habitat Demonstration Unit HDU used in D-RATS missions, HERA, shown in Figure 2.26, investigates human performance and adaptation in isolated and confined environments. The program is organized into campaigns, each consisting of four missions of increasing duration, ranging from 7 to 45 days.

Figure 2.26: HERA Analog [14].

The program has progressed through multiple campaigns:

- Campaign 1 (2014): 7-day missions.
- Campaign 2 (2015): 14-day missions.
- Campaign 3 (2016): 30-day missions.
- Campaign 4 (2017–2018): 45-day missions.
- Campaign 5 (2019): 45-day missions.

Facility Description

The HERA habitat at NASA's Johnson Space Center, JSC, is a two-story, three-module structure with a total volume of 148.6 m^3 and a total area of 58.3 m^2, shared among six crew members. The habitat includes a ground floor, upper floor, airlock module, and hygiene module, providing realistic constraints similar to a spacecraft environment. It is presented in Figure 2.27.

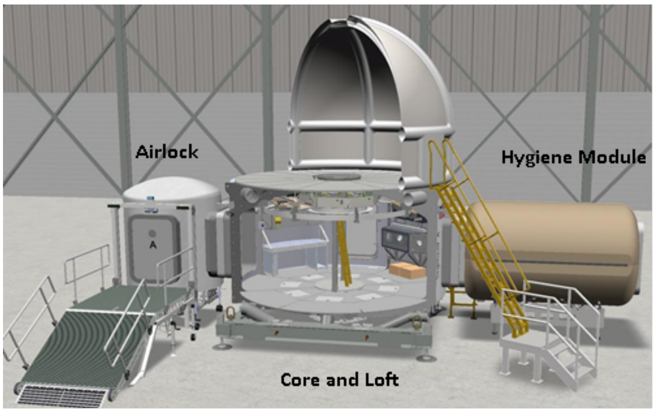


Figure 2.27: HERA Analog [14].

HERA incorporates a range of environmental and operational factors. The habitat includes artificial lighting, sound and vibration features to mimic space travel conditions. Additionally, communication delays and occasional signal disruptions are introduced to enhance the authenticity of the experience. Participants are isolated from external influences. Their diet consists of rehydrated food similar to what astronauts consume on the International Space Station, ISS. To practice extravehicular activities and spacecraft piloting, virtual reality systems and flight simulators are available [14].

Researches Conducted

The HERA program aims to explore and create solutions for the various challenges that astronauts might encounter during long-distance space missions. These challenges encompass physical, psychological, and operational aspects. The program's main focus lies in comprehending the impacts of isolation, confinement, communication delays from being distant from Earth and the effects of artificial day and night cycles on biological astronauts rhythms [14].

Moreover, HERA investigates the consequences of limited resupply options on crew behavior and performance. It also delves into team dynamics, conflict resolution technique, and the level of independence necessary for extended missions. The program's daily routine mirrors the operations on the ISS, starting at 7:00 AM and ending at 11:00 PM. Tasks range from scientific research, maintenance duties, and robotic operations to piloting and physical workouts. In some missions, participants experienced challenging conditions like sleep deprivation, where they worked for up to 19 hours a day and only had five hours of sleep [14].

During these campaigns, participants engaged in a range of experiments. They tested hardware prototypes, created tools using 3D printers, and practiced piloting spacecraft through virtual reality simulations. Additionally, they conducted EVAs on simulated asteroid terrains to gather samples [14].

Conclusion

The HERA, an advancement of the HDU, has provided and will continue to provide advancements for human space exploration. The program has focused on studying key areas of development concerning the design and functioning of habitats and missions for such endeavors.

2.2.1.3 Future analogs

EXOHAB1

The facility known as EXOHAB1, shown in Figure 2.28, is designed for the purpose of creating and evaluating technologies for habitat operating in extreme settings. These habitats are intended for use in space missions as well as during disasters on Earth. EXOHAB1 operates independently from the grid and offers self-reliant systems for energy, communication and water management. These systems are comparable to those found on the ISS and cater to the needs of geological and medical professionals [11].

Figure 2.28: EXOHAB1 Facility [11].

Facility Description

The EXOHAB1 habitat has been created as a modular container structure to facilitate habitability and operational trials. It is designed with various functional zones [36], divided as shown in Figure 2.29.

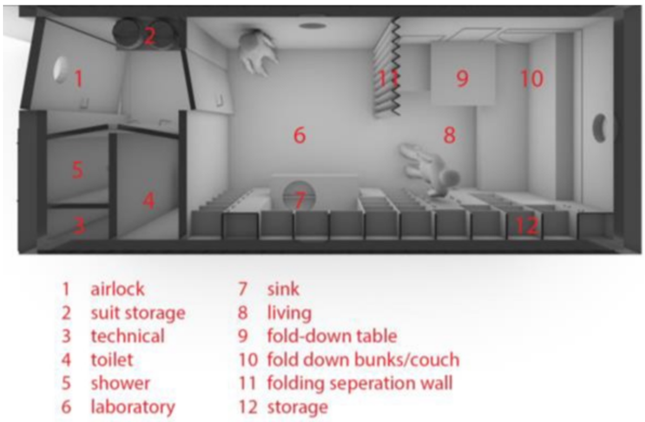


Figure 2.29: EXOHAB1 Planimetry [36].

The laboratory space is a versatile working area that can be adjusted for geological, medical or general research tasks. There is a specialized medical treatment section that is fully equipped to manage emergencies independently. The EVA preparation area consists of an airlock and all necessary gear, including suits and helmets. For daily living, there are living quarters that cater to meal preparation, sleeping arrangements, and personal activities. The sanitary facilities are fully operational to ensure the comfort of the crew members. Moreover, there is a designated storage area that stores crucial equipment and supplies required to meet operational demands [36].

Potential Researches

EXOHAB1 represents a cutting-edge facility created to improve disaster response capabilities by conducting real-time, on-site screening. It also ensures the safety and operational efficiency of experts. This self-sufficient habitat is designed for quick deployment in secure areas right after a disaster, offering disaster management agencies an affordable operational base [36].

The potential uses of EXOHAB1 are wide-ranging. They include supporting space missions such as lunar expeditions, conducting assessments for post-earthquake aid, managing nuclear or radioactive disaster areas, facilitating Antarctic research expeditions and establishing self-sustaining habitats for remote or harsh environments. These various applications underscore the habitat's adaptability in sustaining human activities and presence in demanding circumstances [36].

Conclusion

EXOHAB1 represents a versatile and innovative approach to addressing the challenges of extreme environments. Its adaptability to both space and Earth-based scenarios positions it as a valuable tool for advancing scientific research, improving disaster response, and promoting sustainability. By bridging the gap between space exploration and terrestrial applications, EXOHAB1 contributes to technological and social progress in addressing some of the most pressing challenges of these years.

FLASH INTIATIVE

The Facility for Life-Support and Sustainability in Habitats, FLaSH, is an innovative European project focused on enhancing research into sustainable living systems for human habitats. It utilizes cutting-edge technologies and methods to create closed-loop environments that mimic the essential conditions required for extended human living, whether on Earth or in space.

Facility Description

The FLaSH facility comprises a central dome encircled by interconnected modules, each serving specific habitat functions, as shown in Figure 2.30. This design allows for the seamless exchange of vital resources, offering adaptability for research purposes and future adjustments.

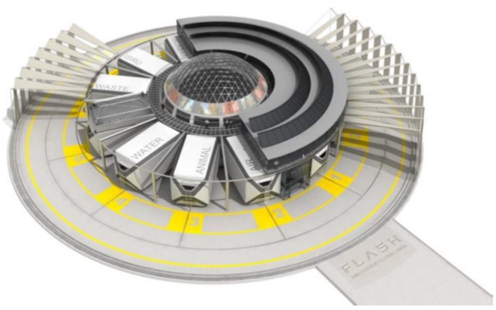


Figure 2.30: FLaSH [11].

FLaSH ensures sustainability and resilience through the integration of life-support and bio-regenerative systems. By hermetically sealing the facility, FLaSH can replicate closed-loop environments, enabling researchers to mimic the challenges faced in isolated habitats [11].

Potential Researches

The modular design of the FLaSH facility allow for a wide range of applications, including resource utilization and studies on psychological and physiological aspects in isolated conditions. This facility is a valuable asset for universities, research institutions and the space industry throughout Europe [11].

FLaSH is dedicated to various research areas related to space exploration and sustainability. It could improve tests for methods of In-Situ Resource Utilization, ISRU, to make use of locally available resources for sustaining human life. Moreover, it could conduct tests on advanced medical systems and robotic technologies for remote operations in isolated environments. The facility also contributes to space exploration and EVA studies by exploring technologies that can support space missions [11].

Conclusion

FLaSH could be a notable progress in the study of sustainable human living systems. Its adaptable design and state-of-the-art life-support technologies render it a versatile solution for tackling the obstacles of extended human life on Earth and beyond. Through promoting cooperation among academic, industrial and research entities, FLaSH could play a part in enhancing Europe's position in space exploration and sustainability-focused research.

LUNA - SHEE

The LUNA project, created by the LUNA consortium on behalf of ESA, has the goal of establishing a facility dedicated to testing and validating technologies, Figure 2.31. It functions as a training ground for astronauts and also provides a platform for conducting mission simulations for the general public.

Figure 2.31: LUNA Testing [11].

Facility Description

Central to the LUNA project is the Self-deployable Habitat for Extreme Environments SHEE habitat module, a planetary habitat designed specifically for Earth-based analogue simulations, shown in Figure 2.32. SHEE is engineered for use in remote and extreme environments lacking infrastructure, with applications ranging from space analogues to disaster response on Earth [11].

Figure 2.32: SHEE Module [37].

The SHEE habitat features a hybrid design that combines rigid, deployable 'petals' and robotic components, expanding to create a secure, modular habitat offering 20–25 m^3 of habitable space. Its transportable nature allows it to be packed into a standard container for easy relocation, with multiple units able to interconnect, providing scalability for different mission sizes and purposes. The interior includes essential facilities such as sleeping quarters, a kitchenette, hygiene areas, and workspaces, with reconfigurable furnishings that adapt to various functions such as habitation, laboratories, or greenhouses [11].

The habitat incorporates systems for controlling temperature, managing water and air, that allows for the sustainable utilization of resources. The ECLSS functions using a power system with three levels, which combines electricity from the grid, batteries and fuel cells [11].

Its expandable components are made up of eight identical petals that utilize radial and telescopic mechanisms to expand efficiently. This configuration reduces heat transfer points, improves the overall strength of the structure, and optimizes the size for transportation. Moreover, the habitat is built using durable composite panels that are resistant to fire [11].

Potential Researches

The SHEE system is created to accommodate two crew members for missions lasting a maximum of two weeks. Its flexibility and ability to scale make it suitable for tailoring to various mission requirements. The habitat can be adjusted for different research purposes such as assessing astronaut adaptability in isolated and harsh environments, verifying life support systems and environmental control technologies, and facilitating EVA [11].

Conclusion

The SHEE holds great promise for space exploration as well as various uses on Earth. In terms of space exploration, it provides a flexible and portable option for evaluating how well humans can adapt and testing life systems. This is especially valuable for missions to the Moon and Mars. Moreover, its modular design and sustainability features make it well-suited for applications on Earth. By incorporating space technologies into its architectural design, the habitat encourages the efficient use of resources and environmental sustainability. This approach could potentially set a standard for future habitats.

EDEN - ISS

The EDEN-ISS project, shown in Figure 2.33, spearheaded by the German Aerospace Center DLR, is a groundbreaking initiative focused on developing advanced plant cultivation technologies for space exploration and other isolated environments. Sustainable food production is a critical component of long-duration missions, where access to traditional food supplies is impossible. By addressing this challenge, EDEN-ISS contributes to the creation of bio-regenerative life support systems BLSS, which integrate plant-based solutions for vital functions such as food production, oxygen generation, carbon dioxide reduction, water recycling, and waste management.

Figure 2.33: EDEN [11].

Facility Description

The EDEN-ISS project revolves around a mobile greenhouse container, shown in Figure 2.34, created to replicate and confirm plant cultivation techniques in harsh conditions. This greenhouse system is modular and comes with advanced life-support systems that allow for controlled cultivation in difficult environments [11].

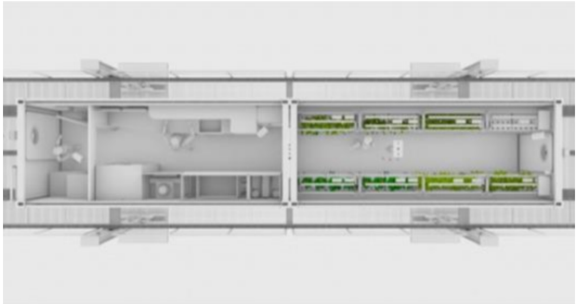


Figure 2.34: EDEN Planimetry [11].

Potential Researches

The potential researches could involve three key phases: testing, integration and operational deployment. The final phase involves deploying the greenhouse, once it is been validated, to the Neumayer III station in Antarctica, where it will undergo real-world testing in an extreme environment [11].

The deployment to Antarctica offers a unique opportunity to test the greenhouse's performance under harsh conditions that mirror the extreme environments of space. Key research objectives for the deployment include demonstrating the ability to cultivate plants in extreme environments, with the Neumayer III station serving as an ideal analogue for extraterrestrial settings. The greenhouse will also aim to sustain year-round food production, supplying fresh produce to the station's crew throughout the year, which showcases the feasibility of self-sufficient food systems. Additionally, the insights gained from this rigorous testing will inform the development of plant cultivation systems for future space missions, such as those planned for the Moon or Mars [11].

Conclusion

The EDEN-ISS project holds significant importance for space exploration and applications on Earth. Concerning space exploration, the project's technologies play a crucial role in preparing for future human missions.

On Earth, the greenhouse's design offer a step for food production in remote areas, regions affected by disaster and harsh climates. This model supports global sustainability efforts. Additionally, the psychological benefits of growing fresh could produce good outcomes on crew morale and mental well-being, addressing the psychological challenges of long-term isolation.

Overall, the EDEN-ISS project could mark a significant progress in developing plant-based life support systems for space missions and extreme environments. By combining cutting-edge technology with extensive testing in Antarctica, this initiative addresses the issues surrounding sustainable food production and has the potential to provide valuable knowledge for upcoming missions.

2.2.1.4 Analog conclusion

This concise and swift analysis marks the conclusion of this section, which presents the analogs and their key specifications.

The variations in structure, function and complexity of these analogs have been demonstrated. Ranging from the minute analogs such as EXOHAB1 to the more elaborate designs like MARS 500 and CHAPEA, the evolution of analogs based on their specific characteristics is evident.

Currently, a comprehensive solution that addresses all the challenges posed by the space environment to humans is yet to be achieved. However, by consolidating the outcomes of these projects and programs, significant progress can be made in enhancing mankind's understanding of space exploration.

The primary focus of the various initiatives examined lies in systems related to life support, human testing within habitats, health monitoring and the development of innovative technologies. Particularly noteworthy are advancements in 3D printing and bio-based technologies, many of which are associated with the artificial cultivation of crops.

Architectural procedures and innovations have, also, been developed to facilitate progress in various areas. While simulations, procedures and training assist experts in reducing risks and optimizing mission operations, that in real missions pose greater complexity and challenges. Despite the current limitations preventing the complete viability of analog structures on the Moon or Mars due to their size, the exploration of modular structures, structural innovations, as 3D printing in CHAPEA or composite materials in HDU, help in testing the impact of environmental factors such as temperature and vibrations. These advances contribute to the protection and successful execution of planetary exploration missions.

There are countless research goals to pursue and the importance of projects and initiatives in this regard remains crucial. Many other projects are currently underway to enhance our understanding of human exploration, on the Earth and beyond it.

Other projects, simulations, prototypes are presented below [11].

- HOPES – France
- EURO M.A.R.S – Europe
- GREEN PYRAMID – Netherlands
- MARS MICROSETTLEMENT – USA
- HEXHAB – USA
- M.A.R.S – Poland
- Moon Inflatable Habitat – USA

The following Table 2.3 presents a summary of the ANALOG programs analyzed thus far.

Table 2.3: ANALOG Summary.

ANALOG	Years	References
MARS 500	2007 - 2011	[12], [33]
HI-SEAS	2013 - today	[15], [28]
CHAPEA	2023 - today	[20], [30]
MDRS	Early 2000s - today	[12], [33]
HDU	2010 - 2013	[34]
HERA	2014 - today	[14]
EXOHAB1	in development	[11], [36]
FLASH INITIATIVE	in development	[11]
LUNA - SHEE	in development	[11], [37]
EDEN - ISS	in development	[11]

In particular, the Environmental Control and Life Support system is a key focus. The subsection 2.3 delves into the details of this intricate system and its specifications.

2.3 Environmental Control and Life Support System ECLSS

The development and understanding of Environmental Control and Life Support Systems, ECLSS, are fundamental for ensuring human survival in space. These systems are critical for sustaining life during current and future space missions, particularly for long-duration exploration mission. Despite significant advancements, achieving fully self-sustaining ECLSS remains a highly complex challenge. Future missions, such as those to Mars or extended stays in lunar space, require innovations to improve system efficiency and enable resource circularity [38].

The origins of life support systems trace back to early crewed missions, such as the Apollo program, where astronauts relied on physicochemical systems for oxygen supply, carbon dioxide removal, and water recovery. For example, oxygen was carried aboard, while carbon dioxide was removed using molecular sieves, and water was recovered from atmospheric moisture and fuel cells [39]. While the Mir space station, 1986–1996, marked a significant advancement in life support technology, introducing the Vozdukh module, which absorbed carbon dioxide and regenerated air [39].

Nowadays, the ISS features advanced environmental control and life support systems, including oxygen generation through water electrolysis, carbon dioxide removal using the Vozdukh system and the Sabatier reactor, which converts CO_2 and hydrogen into methane and water to improve resource recycling [39].

While these systems are known for their reliability and compact design, they do have limitations when it comes to achieving complete resource recycling. One of the main challenges is the demanding operating conditions they face, including high temperatures and pressures necessary for their processes, which can lead to hardware degradation. Moreover, these systems currently depend on regular shipments from Earth for essentials, underscoring the importance of developing more sustainable alternatives.

Future long-duration missions, such as those to Mars, highlight the unsustainability of current systems. NASA estimates, as presented in Figure 2.35, that a single astronaut requires 1,450 kg of food, 2,028 kg of water, and 370 kg of oxygen for a Mars mission, leading to consumable payloads exceeding 10 tons for a four-member crew [40]. Moreover, the Figure 2.35 highlights additional details regarding the requirements for sustaining an average human male, as well as the resulting outputs that an ECLSS must account for [38].

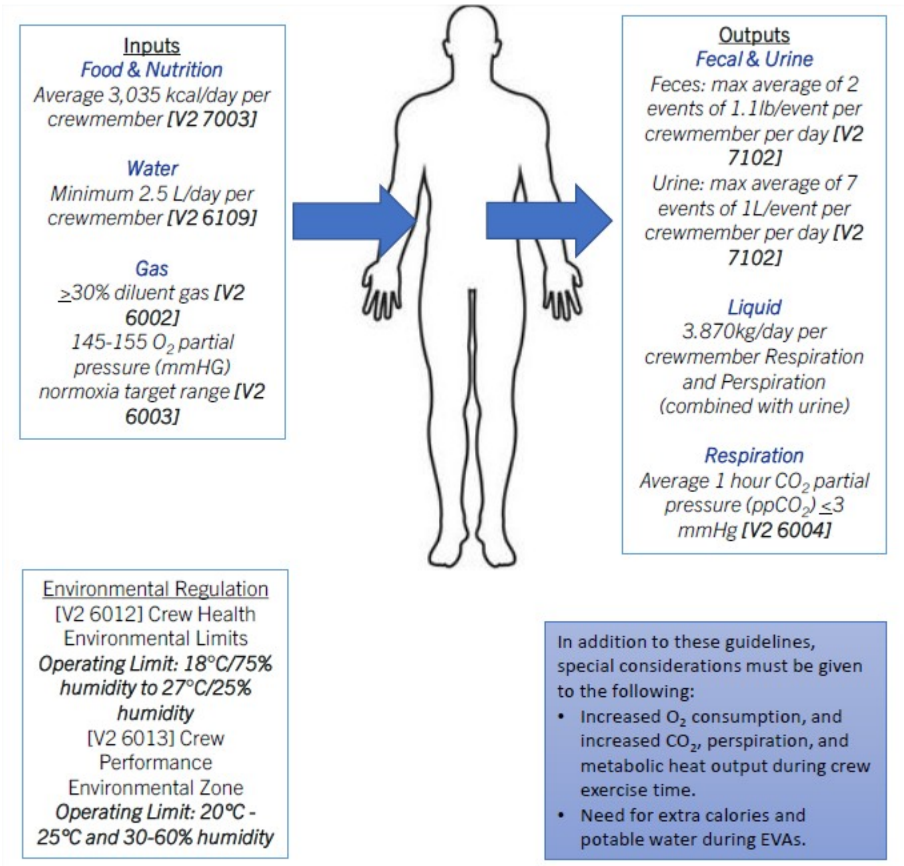


Figure 2.35: Human Body Inputs and Outputs [38].

To address the limitations of physicochemical systems, Bio-regenerative Life Support Systems, BLSS, are being developed. These systems aim to achieve a closed-loop approach, integrating regenerative processes to recycle air, water, and waste, while also enabling food production. For example: NASA's roadmap for Mars missions outlines a journey of 420–620 days [41], requiring self-sufficient systems that minimize resource loss.

Since the early 20th century, researchers have been studying BLSS which aim to mimic Earth's ecosystems in order to support human life. Soviet scientists, such as Vernadski and Tsiolkovsky [42], conducted pioneering studies in this field. Plants, algae and cyanobacteria are essential components of BLSS as they can generate oxygen through photosynthesis, absorb carbon dioxide, assist in wastewater treatment and offer nutritional advantages to crew members [43], [44].

Various space agencies are actively developing advanced biological life support technologies to enhance sustainability in space missions. NASA has successfully cultivated crops on the ISS since 2014, integrating plant growth with environmental controls [45]. JAXA has made significant progress in food self-sufficiency [46], while Russia's BIOS program pioneered algae-based systems for oxygen and nutrition [11], [47]. ESA's MELISSA project focuses on creating a fully regenerative ecosystem using plants and microorganisms [48], and China's Lunar Palace habitat has demonstrated a self-sustaining system that combines crop cultivation with waste recycling. Despite these advancements, fully integrating plant-based systems into life support remains a challenge [49].

The development of BLSS is essential for sustaining human presence beyond low Earth orbit. While current ECLSS effectively support missions in space, they are not sufficient for long-duration exploration, such as missions to Mars. BLSS represents the next step in life support technology, aiming to create self-sustaining ecosystems that minimize reliance on Earth resupply. Continued research and testing are crucial to overcoming technical and operational challenges, ensuring these systems can support future deep-space exploration.

Specifically, these systems encompass specific functions outlined in the subsubsection 2.3.1.

2.3.1 ECLSS

ECLSS is composed of different subsystems. These are summarized in Table 2.4 with their respective functions.

Table 2.4: ECLS Subsystems and Functions [50].

Subsystem	Function
Temperature and Humidity Control THC	thermal control humidity control heat exchange and ventilation
Atmosphere Control and Supply ACS	gas storage and distribution pressure control gas leakage detection emergency oxygen supply
Atmosphere Revitalization and Sampling ARS	oxygen generation carbon dioxide removal trace contaminant control particulate filtration
Water Recovery and Management WRM	water filtration and purification humidity recovery waster water management
Fire Detection and Suppression FDS	smoke detection fire suppression emergency ventilation
Waste Management WM	solid waste storage

(Continued on next page)

(Continued from previous page)

	liquid waste management odor control
Food Storage and Preparation FSP	food preservation food preparation inventory management waste management for food packaging
Crew Health Care System CheCS	medical monitoring and diagnostics medical supplies and emergency equipment preventive care and health maintenance telemedicine capabilities

Additionally, the Figure 2.36 illustrates some of the potential interconnections among the ECLSS subsystems.

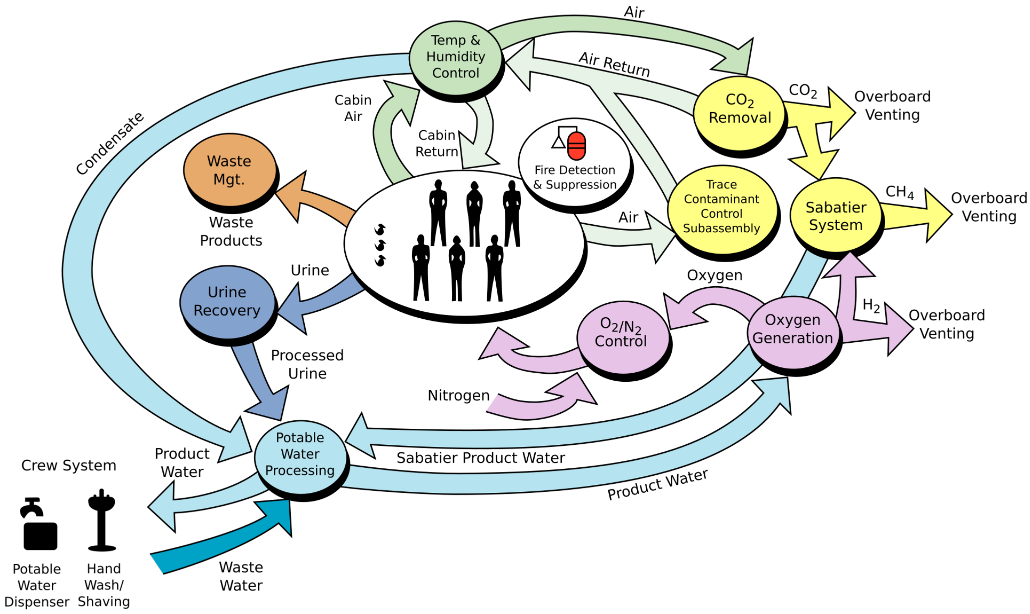


Figure 2.36: ECLSS interconnections [38].

Further details on the specific components and processes currently, and in the past, employed for the various functions and subsystems of the ECLSS, as well as ongoing studies for future advancements, are provided in the Appendix B. This in-depth analysis highlights both the extreme complexity of developing highly advanced and mutually compatible processes, as well as the practical constraints imposed by current technological limitations.

The preceding discussion has given a concise summary of current analog habitats, upcoming initiatives and the multidisciplinary aspects of the ECLSS. The extensive interdisciplinary nature and the intricate interplay of advanced subsystems, all requiring flawless coordination, notably increase the complexity of such habitat design.

Fortunately, the field of Systems Engineering, SE, has traditionally been dedicated to design complex and integrated systems. SE offers a methodical way to handle the complexities of interconnected parts, guaranteeing the smooth and effective operation of all subsystems [51], [52]. Moreover, during the past few years, Model-Based Systems Engineering, MBSE, has transformed the design process, allowing for quicker, more transparent, and highly flexible system development [4], [5].

Further details of these aspects will be provided in subsection 2.4 and subsubsection 2.4.1.

2.4 System Engineering SE

Systems engineering is a methodical, multidisciplinary approach to the design, realization, technical management, operations and decommissioning of a system. A system comprises interconnected elements such as hardware, software, equipment, personnel, processes, and procedures, that collectively work together to meet specific requirements. The value of a system lies not just in the sum of its individual components but in the synergy created through their interconnections [52].

The field of Systems Engineering offers a comprehensive structure for making technical choices, guaranteeing that all functional, physical and operational needs are fulfilled from the inception to the retirement phase of a system. This methodology plays a vital role in effectively handling budget, timeline and efficiency limitations, thereby enhancing the cost-effectiveness of the entire life cycle [52].

Systems Engineering integrates inputs from various fields including structural, electrical, mechanical, power and human factors engineering, promoting a unified viewpoint that enhances the overall performance of the system. It entails recognizing critical design choices, refining system structure and managing risks to ensure seamless collaboration among all system components [52].

In summary, systems engineering is about decision-making, not only ensuring that the design is technically correct but also ensuring that it meets operational goals and stakeholder expectations. It provides a comprehensive perspective by integrating technical, organizational and financial considerations [52].

By adopting a structured methodology, systems engineering enhances efficiency, fosters collaboration and improves risk management, ensuring that complex aerospace and engineering projects achieve optimal performance within the given constraints.

NASA methodology offers an examples about SE. NASA follows a structured method to design and develop complex systems, ensuring that every part of a project is carefully planned, built, and managed. This approach is divided into three main categories: system design, product realization, and technical management processes; defining what is called SE Engine, Figure 2.38 [53].

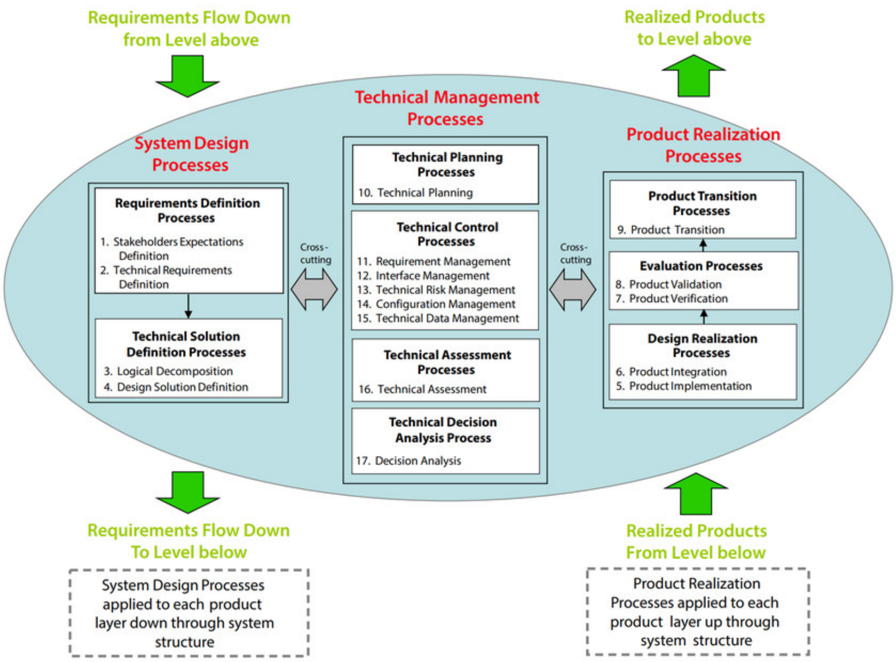


Figure 2.37: System Engineering Engine [4].

In the field of System Design, the initial phase is crucial as it sets the foundation for the project's structure. This stage involves various key steps such as understanding the expectations of stakeholders, defining system requirements, creating models to illustrate system interactions, and establishing a detailed design for engineers to implement [53].

After the design phase is completed, the focus shifts to Product Realization, where the emphasis lies on constructing and testing the components [53].

In parallel, Technical Management focuses on maintaining organization and adherence to timelines within a project. This includes the development and modification of technical plans [53].

Two important principles guide these processes: iteration and recursion. If something doesn't meet expectations, the process is repeated to fix any issues and the same processes are applied at different levels, from small components to the entire system, refining details and ensuring smooth integration [53].

Consistently with the presented framework, this project is aligned with the initial phase of the SE process, specifically the System Design. Only after completing the entire design phase, the process could transition to the second phase, Product Realization.

2.4.1 Model-Based System Engineering MBSE

Model-Based Systems Engineering, MBSE, is a standardized approach in systems engineering that places a digital model at the core of the design of systems and development process [51]. MBSE is defined 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' [54].

In MBSE, models are the main characters of the entire life cycle of a system. They play a crucial role in guiding each stage of development, improving efficiency, clarity and collaboration [5]. The primary objective of using models is to streamline intricate realities by concentrating on essential elements, frequently employing visual helps. Even though models are abstract, they are structured representations that adhere to specific rules [51].

Due to its many benefits, MBSE is used in software and system engineering. Models offer a crucial level of abstraction that helps in handling the intricate nature and connections within contemporary systems. These models decrease ambiguity, improve communication among stakeholders and maintain consistency among different design teams [5].

Another advantage of MBSE is its machine-readable feature, which facilitates automated verification. This feature enables the early detection of inconsistencies and design flaws, thus helping to avoid expensive modifications during later stages of development [5].

Moreover, MBSE provides flexibility and adaptability. When system designs change, models offer a flexible space for modifications. MBSE allows for the examination of various solutions, considering operational, economic and environmental factors. Through precise quantitative simulations, engineers can assess diverse design options and enhance performance and cost-efficiency prior to actual implementation [5].

2.4.1.1 Architecture Analysis and Design Integrated Approach ARCADIA

The Architecture Analysis and Design Integrated Approach, ARCADIA, is a systems and software architecture engineering method that emphasizes model-driven engineering and architecture-centric activities. Developed by Thales in 2007, ARCADIA was designed to manage various engineering disciplines and support the development of complex systems [55].

Traditional system development methods primarily focused on defining requirements, allocating them to system components, and ensuring traceability. However, modern approaches prioritize functional analysis, system design, justification of architectural choices, and verification processes. Systems engineering now encompasses various perspectives, including integration constraints, product line management, safety, and performance. ARCADIA addresses these challenges by introducing a structured methodology that facilitates cross-disciplinary collaboration [55].

ARCADIA is inspired by Unified Modeling Language UML and Systems Modeling Language SysML [52], integrating concepts from these methodologies while offering enhanced modularization and functionality. The framework supports various diagram types for defining system components behavior and information exchange, illustrating operational scenarios and organizing system functions in a structured manner [55].

ARCADIA stands out due to its improved accessibility for engineers who have not an object-oriented approach. This language is specifically designed for use in industrial sectors. It caters to a range of engineering aspects such as system, subsystem, mechanical design, electronics and software by providing a structure that eases collaborative model creation. The models created at various levels are derived, validated, and interconnected to ensure coherence and consistency [55].

The benefits of ARCADIA lie in its ability to be extended and its compatibility with tools based on SysML. In contrast to conventional SysML methods that focus on modeling driven by requirements, ARCADIA gives precedence to modeling driven by functions.

ARCADIA follows a structured, iterative approach to systems engineering, consisting of four key steps, defining multiple perspectives, or layers, that structure the implementation of an architecture [56]:

- Operational Analysis OA

  This perspective analyzes operational users' needs by identifying interacting actors, their goals, activities, constraints, and interactions. It models high-level operational capabilities without defining the system itself.

- System Analysis SA

  This perspective examines the system as a black-box to determine how it can satisfy the operational needs. It constructs an external functional analysis based on operational analysis and textual requirements.

- Logical Analysis LA

  This perspective defines the system solution in response to previous analyses. It identifies and assembles functions necessary to fulfill user requirements, establishing a component-based architecture. Technology decisions are deferred to the physical analysis stage. Logical analysis also serves as a communication tool among project stakeholders.

- Physical Analysis PA

  This perspective finalizes the system architecture, integrating implementation-specific functions and technical choices. It identifies behavioral components and their hosting implementation components, ensuring the necessary material resources for execution.

Capella™, a specialized software, offers the required symbols and charts to adhere to the methodology of ARCADIA [55].

2.4.2 Capella™

Capella™ is a tool that is open-source and specifically created for MBSE. It has been developed to align with the ARCADIA method. The tool allows for the graphical modeling of systems. It is maintained by PolarSys, a subgroup within the Eclipse Foundation. Capella™ offers a structured engineering process along with specialized tools to help system design [55].

It is utilized in the creation of complex systems in various sectors. Capella™ is constructed based on a distinct metamodel that outlines its fundamental language concepts. Users generate model instances and engage with them through different diagrammatic viewpoints. The tool is user-friendly and easy to navigate, providing methodological assistance to ensure a systematic approach to system design [55].

Capella™ provides a structured framework for each of the four layers of the ARCADIA approach, ensuring traceability of elements across different layers. By following this framework, it becomes easier to modify and enhance interdisciplinary comprehension of all model components. This enables a smooth progression from a high-level abstract representation to the ultimate design stage [55].

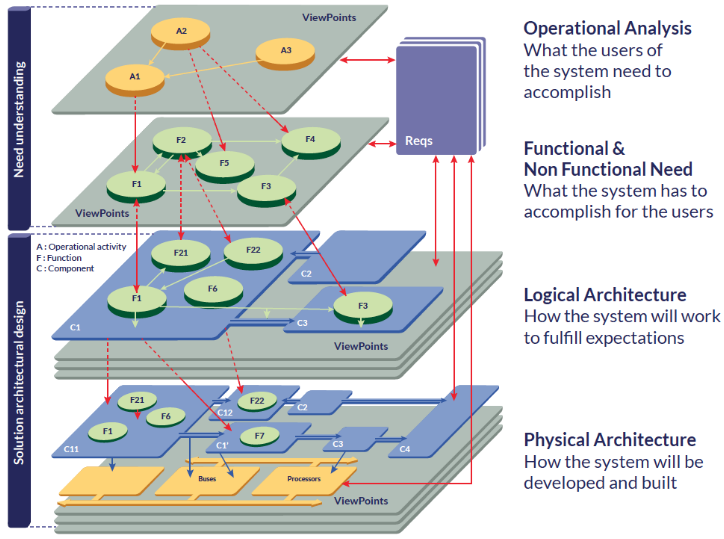
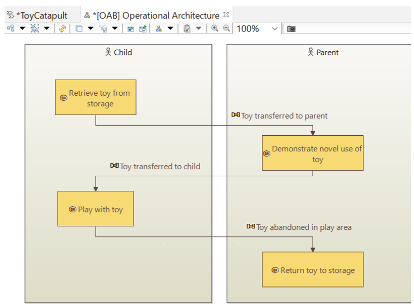
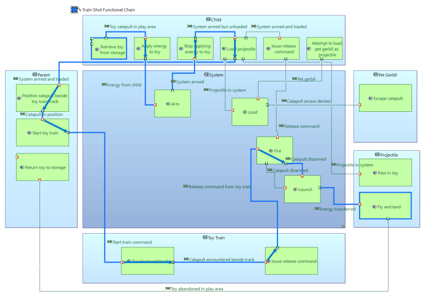


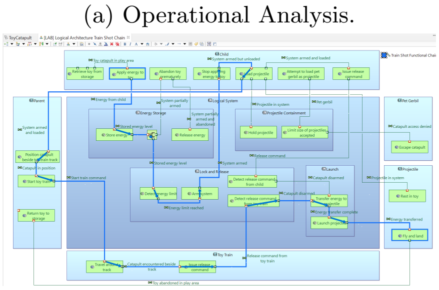
Figure 2.38: Capella™ Approach [55].



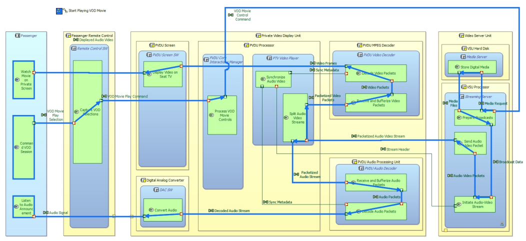
(a) Operational Analysis.



(b) System Analysis.



(c) Logical Analysis.



(d) Physical Analysis.

Figure 2.39: Arcadia layers in Capella [57].

By combining a structured methodology with an intuitive user interface, Capella™ supports the development of robust, verifiable system architectures while promoting collaboration across engineering teams.

Having completed the analysis of the key components, analogs, ECLSS, SE, MBSE, ARCADIA and Capella™, that are crucial to understand the entire context, the project pass to the section 3 preceding the detailed design phase in Capella™, where the development will be presented up to the Logical Analysis, LA.

3 Mission

This section marks the beginning of the actual project execution. Following a thorough and as diverse as possible analysis of analogs, systems engineering, and Model-Based Systems Engineering, MBSE, a solid theoretical foundation can be established for the subsequent development of the model in Capella™.

In particular, this section outlines the initial steps and analyses required in the system design process. Before proceeding with the creation of a model in Capella™, it is essential to establish the fundamental basis for the project's mission, define the stakeholders' objectives, and consequently, determine the key pillars that will support the design phase and subsequent iterative steps: Operational Analysis, System Analysis, Logical Analysis and Physical Analysis. Although system design may be influenced by the subjective approach of the engineering team, it follows a structured methodology composed of well-defined processes and steps.

The process begins with the definition of a Mission Statement and the identification of Primary Objectives. Following a detailed stakeholder analysis, the secondary objectives and the mission requirements are determined. While the secondary objectives emerge from stakeholder expectations, not all of them are necessarily achievable. The feasibility of their implementation will be assessed throughout the design and development phases [56].

Additionally, an initial Functional Analysis is conducted, serving as a foundation upon for the next steps developed in Capella™.

The Functional Analysis aims to explore system behavior in order to define its functional architecture. It builds upon the results of the Operational Analysis and is considered system-centered, as it translates operational needs into requirements, functions, and architecture. According to SE methodology [56], a function represents what the system must perform to fulfill a specific need, typically expressed by a stakeholder, within a defined scenario of the selected mission. This need is formally stated as a requirement.

The Functional Analysis is carried out in three key steps [56]:

1. translating high-level requirements into functions necessary to fulfill them
2. decomposing and allocating these functions into lower levels of the product breakdown structure
3. identifying and defining functional and subsystem interfaces;

which materialize into five models that support their implementation [56].

- Functional Tree
- Functions/Devices Matrix
- Product Tree
- Connection Matrix
- Functional Block Diagram

Although this phase is premature and it has not been carried out in all five forms but only in those deemed most important to lay the foundation for the continuation of the work, it is documented in Appendix C. The objective is to establish a solid foundation for future enhancements and additions, considering that not the entire project will be performed. Furthermore, this documentation aims to convey the initial design logic, facilitating a clearer understanding of the work and ensuring better accessibility for future developments.

3.1 Mission Statement

Human space exploration beyond low Earth orbit is a major objective for international space agencies, with the Moon and Mars as the primary targets. The development of sustainable and reliable Environmental Control and Life Support Systems, ECLSS, is crucial to enabling both short- and long-duration human missions on extraterrestrial surfaces. Addressing key challenges such as habitability, autonomous operations and system reliability, an analog habitat serves as a testbed to advance scientific and technological knowledge in this domain.

Building upon the 'Moon to Mars' strategy [58] and leveraging analog environments for testing [1], this project aims to develop and validate enabling technologies essential for future human exploration missions. The focus is on testing ECLSS integration, AI-assisted control, and innovative human-machine interfaces, while also ensuring modularity and mobility to facilitate analog habitat deployment in different environments and configurations.

A mission statement is a brief, clear, and concise declaration of the project's purpose [56]. Based on the objectives outlined, the following Mission Statement has been defined:

To develop and validate technologies that support future human space exploration, enhance the capabilities of the space sector, and improve existing systems by testing them in conditions analogous to those found on the Moon or Mars.

3.2 Primary Objectives

Primary mission objectives are a slicing of the mission statement:

- To develop and validate technologies for human space exploration
- To enhance space sector capabilities for human space exploration
- To improve existing systems for human space exploration.

3.3 Stakeholders' Analysis

The principal stakeholders of the mission is a consortium formed by space companies and universities, which serve as the main sponsors of the project. This consortium aims to develop technologies useful for future human space exploration and to enhance and expand scientific and technological knowledge applicable to space missions.

Both entities collaborate to test new solutions, while space companies can also become customers by leveraging the mission's results. Operators and astronauts, on the other hand, require effective communication, safe technologies to test, and systems that are easy to use and maintain.

The consortium aim to assess the impact of humans in the loop by measuring key parameters such as metabolic activities and the interaction between humans, the environment, and onboard materials under controlled atmospheric conditions. A key objective is to develop and test new ECLSS technologies and integrate them to improve regenerative systems, ensuring their suitability for future long-duration human space exploration missions.

Another important goal is the development of a digital twin of the system, alongside integrated technologies and subsystems, to investigate AI-assisted integrated control systems, such as home automation, to support both human-led operations and autonomous functionality.

The mission will provide independent capabilities for electric power, command and data handling, and communication. Furthermore, it will focus on innovative strategies to improve human-machine interfaces for both short- and long-duration missions, ensuring usability and efficiency in future exploration scenarios.

Flexibility and adaptability are critical aspects, and the mission aims to demonstrate modularity, allowing for future upgrades and expansions. Lastly, the mission prioritizes mobility, enabling to be transferable from one place to another.

In addition space agencies could also be interested in the project due to its alignment with broader goals in space exploration. For instance, ESA might find value in developing technologies for lunar and Martian exploration, potentially integrating mission components into its programs such as the Gateway or Lunar Village initiatives [59], [60]. Similarly, NASA could collaborate on life support systems and habitat technologies, leveraging the mission outcomes to support Artemis missions [58] and other exploration objectives.

These additional stakeholders broaden the scope of the project, fostering global collaboration and ensuring alignment with international priorities in human space exploration and technological advancement.

Consequently, to provide a clearer representation of the potential stakeholders involved in the project, the Figure 3.1 outlines their levels of interest and influence. This visual representation helps to better understand who the stakeholders are, their role, and how they might be connected to the project. By analyzing their degree of engagement and impact, it becomes easier to identify key players and prioritize efforts to align their objectives with the mission's goals.

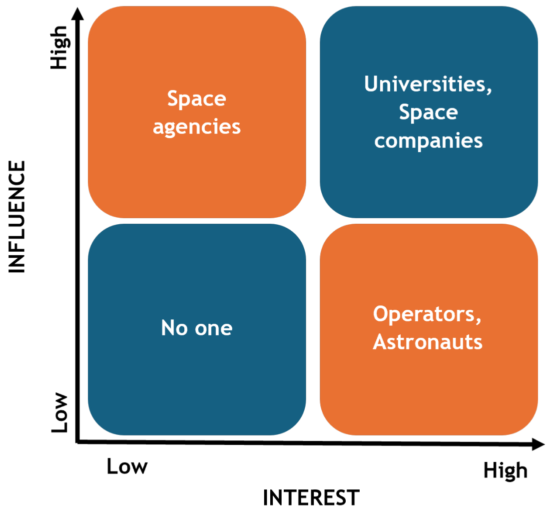


Figure 3.1: Stakeholder Table.

The map divides stakeholders into four areas, while also outlining some potential needs and values for each category.

- Stakeholders with high influence and high interest – Keep engaged

  This area encompasses stakeholders with a high degree of decision-making authority regarding the product. Their participation is crucial during the formulation of the product strategy, the development of the roadmap, and the evaluation of key trade-offs.

Table 3.1: Space company/University Needs and Values.

Need	Value
Test technologies and environments.	Contribution to pioneering human space exploration.
Scalability, flexibility and mobility for future upgrades.	Strengthening collaboration in the Moon-to-Mars strategy.
Obtain high-quality results.	—
Mitigating risks and costs.	—

- Stakeholders with high influence and low interest – Keep satisfied

  This area includes stakeholders who hold considerable authority, making it imperative to ensure their satisfaction. Given their typically limited availability, they require concise and efficient updates, along with reassurances that progress is on track and standards are being met.

Table 3.2: Space Agency Needs and Values.

Need	**Value**
Receive progress updates.	Maintaining institutional and political support for human exploration.
Obtain high-quality results.	Enhancing reputation through successful technology validation.
Demonstrate cost-effectiveness and return on investment.	—-
Install their paylods, as experiments or technologies, in the habitat.	—-

- Stakeholders with low influence and high interest – Keep informed

  Stakeholders in this area have minimal decision-making power or influence on the project. However, they can provide valuable contributions to specific aspects of the project. It is important to maintain open communication with them to address any concerns and avoid potential issues.

Table 3.3: Operator/Astronaut Needs and Values.

Need	**Value**
Clear and effective communication.	Involvement in advancing human spaceflight technology.
Safe and reliable technologies.	Professional development through direct participation in space research.
Training and operational support.	Academic and industry collaborations.

- Stakeholders with low influence and low interest – Monitor

  This area is composed of stakeholders with low interest in the product and little to no influence. For this reason, a minimal level of engagement is sufficient, primarily limited to periodic monitoring and updates on the project's progress. In this case, no stakeholders of this type have been explicitly defined. However, for the sake of completeness, the media, newspapers, and the scientific community could be considered as stakeholders of this category.

Table 3.4: Media/Scientific Community Needs and Values.

Need	**Value**
Receive periodic updates.	Contribution to public awareness of human spaceflight advancements.
Have minimal engagement.	Enhancement of public participation and scientific literacy.
Opportunities for knowledge dissemination.	Strengthening of academic and industrial research networks.

By introducing stakeholders and creating a table that categorizes them based on their roles, hypothetical needs, and values, a comprehensive understanding of the environment in which the project's key players will be involved it is defined. This approach effectively showcases their roles and interactions, both among themselves and with the environment.

As the project progresses, any potential adjustments can be easily made, including within Capella™, to modify the parameters that have been established thus far.

3.4 Secondary Objectives

Secondary objectives derived from the stakeholder analysis are presented:

1. To test the impact of human metabolic activities on environmental parameters and systems
2. To evaluate the interaction between humans and the environment
3. To advance the development and testing of new Environmental Control and Life Support Systems ECLSS
4. To investigate AI assisted control systems
5. To develop and validate innovative human-machine interface solutions
6. To enable modularity and scalability
7. To provide crew support facilities
8. To provide movement
9. To provide independent power generation, command, data handling, and communication

3.5 Mission Requirements

Finally, the initial requirements, analog mission requirements, are defined in Table 3.5. The mission requirements are defined with the following structure: 'NLG-MIS-0000'. In this structure, 'NLG' represents 'Analog', the primary focus of the project, 'MIS' indicates the type of requirements, mission requirements in this step, and '0000' denotes the specific requirement number being referenced.

Table 3.5: Mission Requirements List [61].

ID	Status	Requirement
NLG-MIS-0001	Draft	The mission shall test and validate technologies and capabilities to support human space exploration.
NLG-MIS-0002	Draft	The mission shall improve existing systems for human space exploration.
NLG-MIS-0003	Draft	The mission shall test the impact of human metabolic activities on environmental parameters and systems.
NLG-MIS-0004	Draft	The mission shall evaluate the interaction between humans and the environment, including on-board materials.
NLG-MIS-0005	Draft	The mission shall demonstrate new Environmental Control and Life Support Systems ECLSS.
NLG-MIS-0006	Draft	The mission shall validate AI-assisted control systems.
NLG-MIS-0007	Draft	The mission shall demonstrate innovative human-machine interface solutions.
NLG-MIS-0008	Draft	The mission shall enable modularity and scalability for systems, ensuring flexibility.
NLG-MIS-0009	Draft	The mission shall provide crew support facilities.
NLG-MIS-0010	Draft	The mission shall provide a mobility system, enabling transferability.
NLG-MIS-0011	Draft	The mission shall provide independent power generation, command, data handling, and communication capabilities.

Mission requirements are defined as ’Requirements related to a task, a function, a constraint, or an action induced by the mission scenario’ [61].

With this final step and the functional analysis available in Appendix C, the foundation is completed, allowing the transition to the work in Capella™. The sequence is as follows:

- Operational Analysis OA in section 4
- System Analysis SA in section 5
- Logical Analysis LA in section 6

It is worth noting that the Physical Analysis, section 7, is left for future developments and is not examined in this study.

4 Operational Analysis OA

The Operational Analysis phase, OA, is the first fundamental step in the Capella™ Model-Based Systems Engineering, MBSE, process, following the ARCADIA methodology. It aims to define the objectives and needs that the future system must fulfill. This phase begins with the identification of Operational Entities and Operational Actors, as well as the relationships among them. The primary objective is to capture what the users of the system need to achieve, ensuring that all relevant operational aspects are considered before defining the system itself [62].

The Operational Analysis follows a structured methodology, which includes the following key activities:

- Identification and definition of stakeholders to establish all relevant actors that will interact with the system.
- Definition of Operational Capabilities, outlining the high-level functions required to meet user needs.
- Operational Architecture Analysis, which includes:
  - Identification and capture of Operational Activities for each stakeholder.
  - Definition of interactions between activities and actors.
  - Specification of information exchanged during interactions.
  - Identification and modeling of Operational Processes and Scenarios.
  - Definition of Operational Modes and States, considering different operational conditions.

Stakeholder textual requirements, if provided, serve as input to the Operational Analysis and can be further formalized and analyzed when defining Operational Processes and Scenarios. These scenarios should propose a comprehensive analysis of the system's behavior [62].

ARCADIA method not enforces a strict sequence for defining Operational Analysis activities and artifacts. However, a structured and logical progression can facilitate the modeling process and ensure consistency across different stages [62] .

The following Table 4.1 presents a reasoned step-by-step approach, outlining the key activities, the corresponding diagrams generated at each stage, and their mapping to the Arcadia methodology as previously defined. This structured representation provides a clear reference for systematically conducting Operational Analysis while maintaining flexibility in its application [62].

Table 4.1: Operational Analysis Steps [62].

Step	Diagram	Description
1	OEBD	Capture Operational Entities and Actors
2	OCB	Capture Operational Capabilities
3	OABD	Define Operational Activities
4	OAIB	Define Operational Activities Interactions
5	OAB	Allocate Operational Activities
6	OPD/OAS/OES	Describe Operational Capability with Operational Process and Scenarios
7	M&S	Capture Operational Entities and Actors

From this point onward, the actual design phase of the mission described in section 3 begins within Capella™. As previously mentioned, the presented order will not be executed indiscriminately. Instead, the order is explained in the following sections and applied in a personalized manner, allowing for modifications, improvements and further detailing.

4.1 Operational Entity Breakdown

The analysis within Capella™ begins with the identification of actors and entities that play a role in the mission and interact with the system. From the stakeholder analysis, the following actors and entities are identified Figure 4.1.

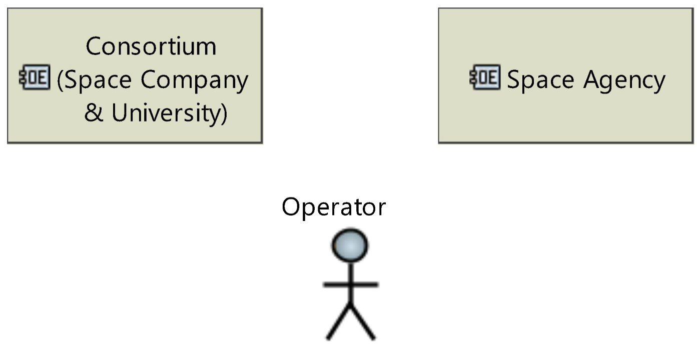


Figure 4.1: [OEBD] Operational Entities.

Specifically, the space company and university lead the entire project, acting as the primary actors in defining objectives, developing the technologies to be tested, conducting the actual space mission simulation, and performing the subsequent technology testing. Finally, they are responsible for analyzing the obtained results, which may lead to a redesign in collaboration with other companies, validating the outcomes through third-party operators, and leveraging the results with partnering agencies.

4.2 Operational Capabilities

After defining the main actors, the operational capabilities of the system are determined. These capabilities outline the necessary functions or tasks that the system needs to have or carry out in order to successfully accomplish the mission objectives. They mirror the actors' expectations in terms of execution and achievement throughout the mission, similar to goals or desired results. Additionally, the relationship between each actor and entity with these capabilities is shown in Figure 4.2.

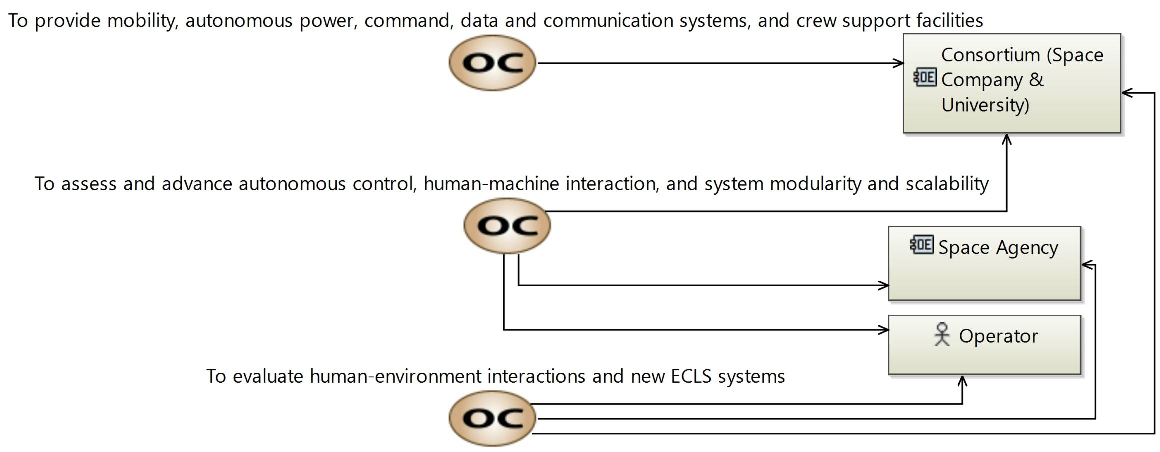


Figure 4.2: [OCB] Operational Capabilities.

As shown in Figure 4.2, only three general capabilities have been identified, encompassing, to a large extent, all the primary and secondary objectives previously defined in section 3. The following capabilities have been identified:

- To provide mobility, autonomous power, command, data and communication systems, and crew support facilities.
- To assess and advance autonomous control, human-machine interaction, and system modularity and scalability.
- To evalutate human-environment interactions and new ECLS systems.

The last two capabilities are linked to all three actors and entities, while the first one is associated only with the 'Consortium' entity.

This marks the beginning of the actual design phase. The way these capabilities are implemented determines the entire course of the project development. For instance, an initial approach considered defining the three primary objectives as capabilities, from which the secondary objectives would subsequently be derived, as shown in Figure 4.3. However, in this perspective, the secondary objectives were incorrectly treated as subordinate to the primary ones, despite their equivalent level of importance.

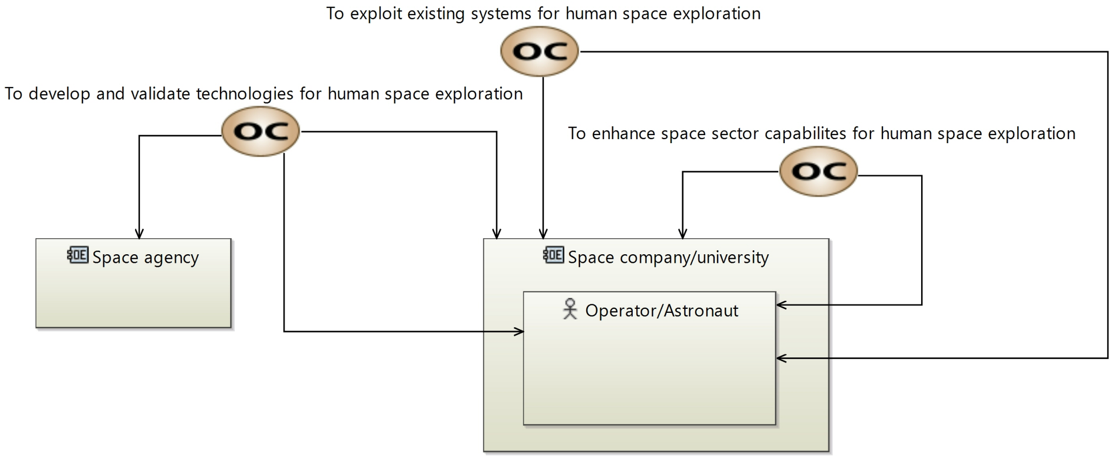


Figure 4.3: [OCB] Operational Capabilities Test.

Another approach considered defining three distinct capabilities for technology testing, categorized into three different groups concept that, as will be seen later, was partially adopted. These categories included: testing technologies related to human-environment interaction, testing life-support technologies, and testing operational support technologies for the mission. Additionally, one capability, similar to the one presented in Figure 4.2, was defined as 'to provide mission support services'.

The current approach has implemented a simplified version of the latter strategy, specifically the final one mentioned.

The initial capability is mainly associated with the third main objective, subsection 3.2, with the goal of utilizing and potentially enhancing existing systems that support the simulation mission. This capability also addresses the last three secondary objectives, subsection 3.4.

In contrast, the last two capabilities are defined concerning all primary objectives, subsection 3.2. Among these two, the second capability focuses on the first three secondary objectives, subsection 3.4, emphasizing the testing of ECLSS and human research. On the other hand, the first capability concentrates on the fourth, fifth, and sixth secondary objectives, subsection 3.4, which pertain to operational support like AI and interfaces. These capabilities integrate the testing capabilities described earlier and comprehensively cover all the objectives outlined in section section 3.

In fact, while the primary objectives are implicit in the defined capabilities, the secondary objectives are explicitly defined in the capabilities. The capabilities are named as the definition of secondary objectives, as evident from the explanation, Figure 4.2.

4.3 Operational Activities and Interactions

After defining the capabilities, the operational activities necessary to describe them are determined in the Figure 4.4 and Figure 4.5.

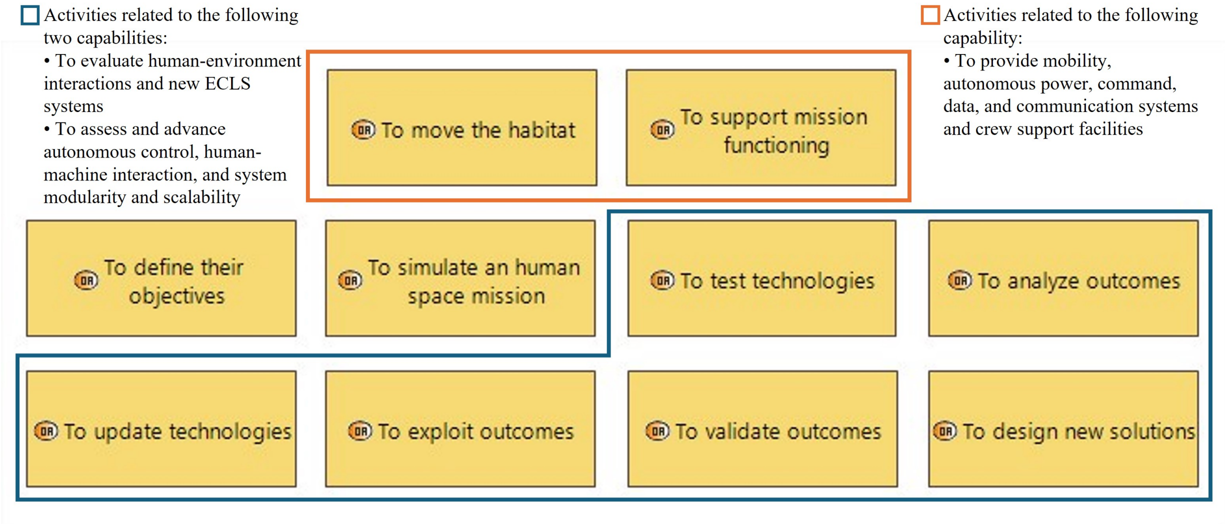


Figure 4.4: [OABD] Root Operational Activity.

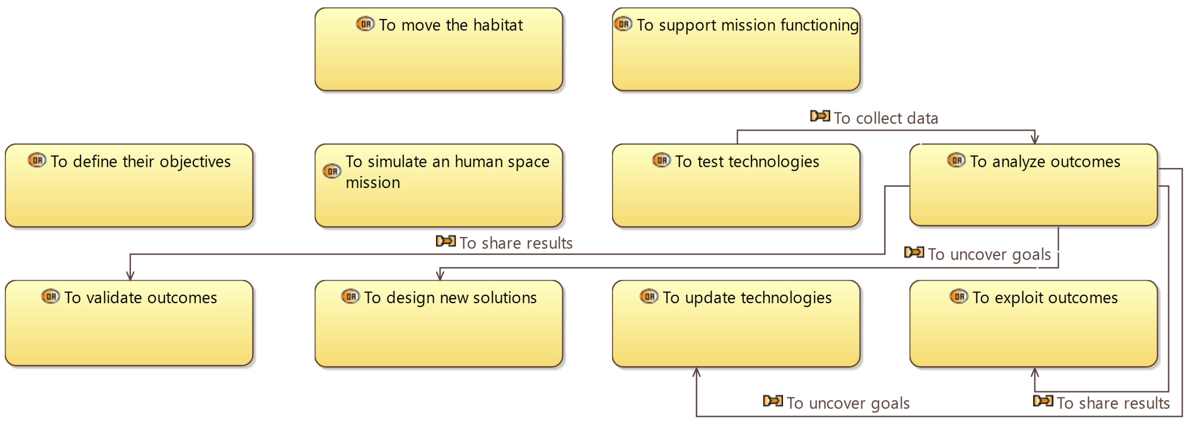


Figure 4.5: [OAIB] Root Operational Activity Interaction.

In the two figures provided, the activities are first presented, along with their groupings, when they share similar operational processes, to enhance the diagram's readability. Subsequently, their interactions are depicted, where applicable or deemed significant to include in the diagram.

In particular, as shown in Figure 4.4, the described activities are those carried out by the identified actors and entities to accomplish the previously defined capabilities, subsection 4.2.

They primarily revolve around technology testing, blue box, starting from the definition of the mission to be simulated, potentially in collaboration with space agencies when applicable, and progressing to the analysis of test results. If the results are positive, they may be utilized in the space industry; otherwise, the technologies will undergo further updates and redesign by the space company and university themselves, potentially in collaboration with others companies, if they fail to meet the initially defined requirements and objectives.

The activities related to the last two capabilities are highlighted by the blue box in Figure 4.4. On the other hand, those highlighted in orange are associated with the first capability, defining the activities necessary to achieve it, namely moving the simulated mission and supporting its autonomous operation.

A previous approach was developed slightly differently, replacing the single 'to test technologies' activity with multiple 'to test' activities, each corresponding to a specific secondary objective, such as testing AI, life support technologies, interfaces, and so on. However, this variation affected only the definition of that single activity, while the overall structure remained the same, as all these activities ultimately converged into the same subsequent step. Initially, defining all the different testing activities at this stage seemed beneficial, but it eventually proved to be redundant, as they all followed the same overall process.

Regarding the interactions between activities in Figure 4.5, only the most relevant ones related to testing have been highlighted. These outline the approach to the activities presented three paragraphs earlier. Instead, mission support activities such as mission transfer between environments, if required, proper maintenance during the simulation or the definition of objectives followed by simulation and actual test execution, have, at this stage, been considered peripheral to the main testing goal, with no specific interactions yet defined.

4.4 Operational Architecture

The operational architecture of the work conducted thus far is subsequently presented. As a synthesis of the previous sections, this part illustrates how each actor and entity performs its related activities and how these activities interconnect. Specifically:

- activities performed by each actor and entity are allocated
- new interactions between actors and entities are identified
- operational processes are defined, representing sequences of activities that accomplish a specific mission function.

At this stage, the previously described concepts become clearer, allowing for the introduction of the involved actors and entities and illustrating how they, along with their respective activities, are interconnected, as shown in Figure 4.6.

The consortium, which is the main creator of the project, oversees a wide range of activities. These activities range from defining, supporting and transporting the simulation mission to conducting essential tasks such as testing technologies, analyzing results and taking responsibility for the consequences of the outcomes, whether they are positive or not. These consequences have already been detailed in subsection 4.3.

In this case, also an operational process, the blue one, have been explicitly reported, referring to 'to test technologies' activities to highlight that sequence of elements in the diagram.

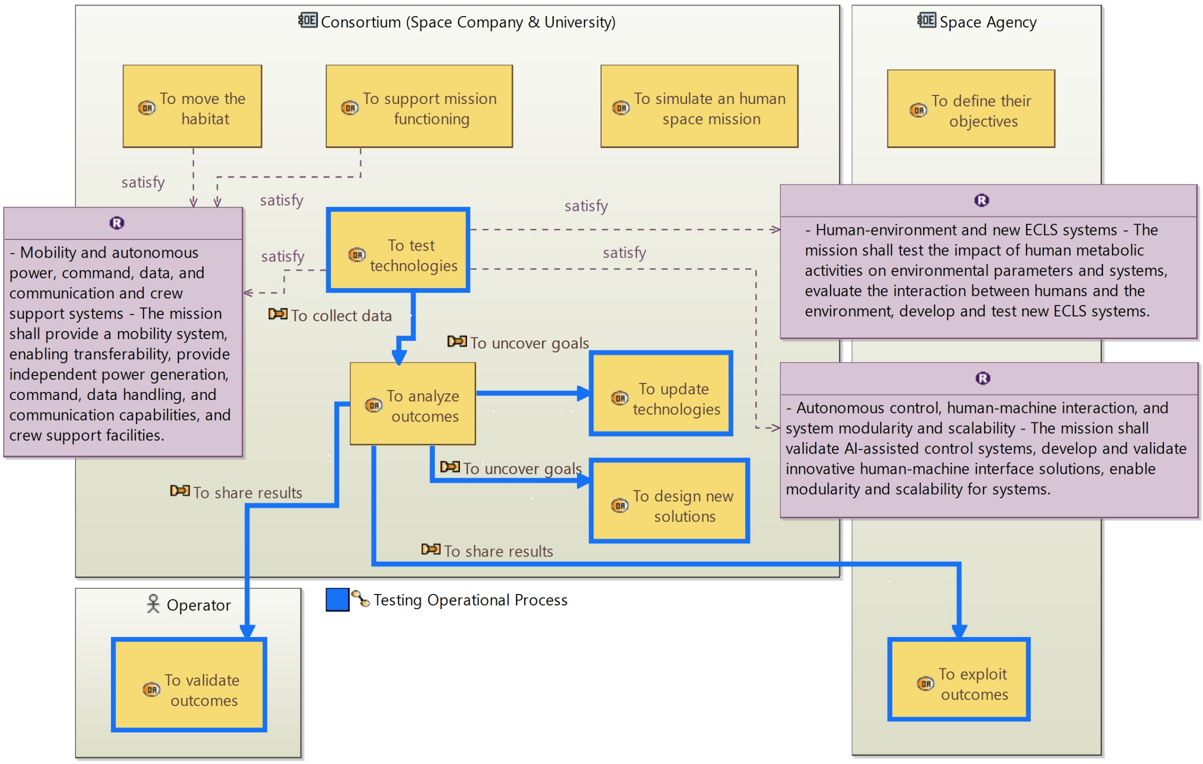


Figure 4.6: [OAB] Operational Structure.

At this point, an effort has been made to keep the capabilities relatively general and high-level, as previously described, to avoid overloading and consequently restricting the design process of the subsequent, more detailed steps.

This approach will remain a constant throughout the development. As a result, questions will continually arise regarding the appropriate level of detail for each phase in relation to the preceding and following ones. This leads to an ongoing iterative process and continuous refinement of ideas, which, when executed correctly, represents the true strength of this design methodology.

In Figure 4.6, three requirements are illustrated, known in Capella™ as 'Stakeholder Requirements', aligning with mission requirements in this project. These requirements are categorized similarly to the capabilities outlined in subsection 4.2 in relation to the objectives specified in subsection 3.2 and subsection 3.4, but focusing on requirements within the domain of subsection 3.5, as shown in Table 4.2. This method guarantees uniformity during the design phase, preserving harmony among capabilities, objectives and requirements.

Table 4.2: Mission Requirements in the OA [61].

ID	Status	Requirement
NLG-MIS-OA-0001	Draft	The mission shall provide a mobility system, enabling transferability, provide independent power generation, command, data handling, and communication capabilities, and crew support facilities.
NLG-MIS-OA-0002	Draft	The mission shall validate AI-assisted control systems, develop and validate innovative human-machine interface solutions, enable modularity and scalability for systems.
NLG-MIS-OA-0003	Draft	The mission shall test the impact of human metabolic activities on environmental parameters and systems, evaluate the interaction between humans and the environment, develop and test new ECLSS systems.

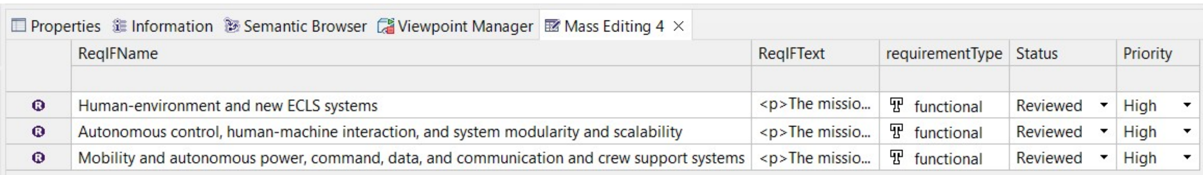
The 'OA', Operational Analysis, part has been added to the requirements structure definition, related to the specific design phase where the requirements are defined.

Capella™ enables the integration of textual requirements defined on paper into the ARCADIA design methodology, specifying their nature, relationships, and classification [63]. These specifications vary in their application depending on project needs [64], [65].

In this specific case, functional requirements have been defined. Functional requirements are crucial in outlining the actions that a product needs to perform to fulfill user needs or mission objectives. During this phase, the emphasis is on identifying the roles and entities participating in the project and outlining their responsibilities in achieving the set goals. Subsequently, these requirements will play a key role in determining the collaborative efforts between the system, actors, and entities to accomplish the mission objectives.

Regarding their relationships, a 'satisfy' relationship is considered. A 'satisfy' relationship is a dependency between a requirement and a model element that fulfills that requirement [64]. This relationship is represented by purple arrows in Figure 4.6, linking requirements to the activities that, according to the design, satisfy them.

Moreover, Capella™ enables the specification of attributes for various requirement types, thereby improving their effectiveness in the project. In reference [63], attributes like 'Status' and 'Priority' have been established to categorize the status and importance level of a requirement. For instance, statuses can be 'Draft' or 'Reviewed', while priorities can be 'High' or 'Low'. The visual representation in Figure 4.7 presents a well-organized and customizable table displaying the defined requirements and their corresponding attributes, guaranteeing clearness and ease of access [64], [65].


Properties | Information | Semantic Browser | Viewpoint Manager | Mass Editing 4

	ReqIFName	ReqIFText	requirementType	Status	Priority
R	Human-environment and new ECLS systems	<p>The missio...	functional	Reviewed	High
R	Autonomous control, human-machine interaction, and system modularity and scalability	<p>The missio...	functional	Reviewed	High
R	Mobility and autonomous power, command, data, and communication and crew support systems	<p>The missio...	functional	Reviewed	High

Figure 4.7: Requirements Capella Table.

4.5 Operational Scenario

Finally, the operational scenario presents the same activities described previously but with an additional detail dimension: time. The sequences of interactions among activities of each actor and entity over time are illustrated in Figure D.1 and Figure 4.9.

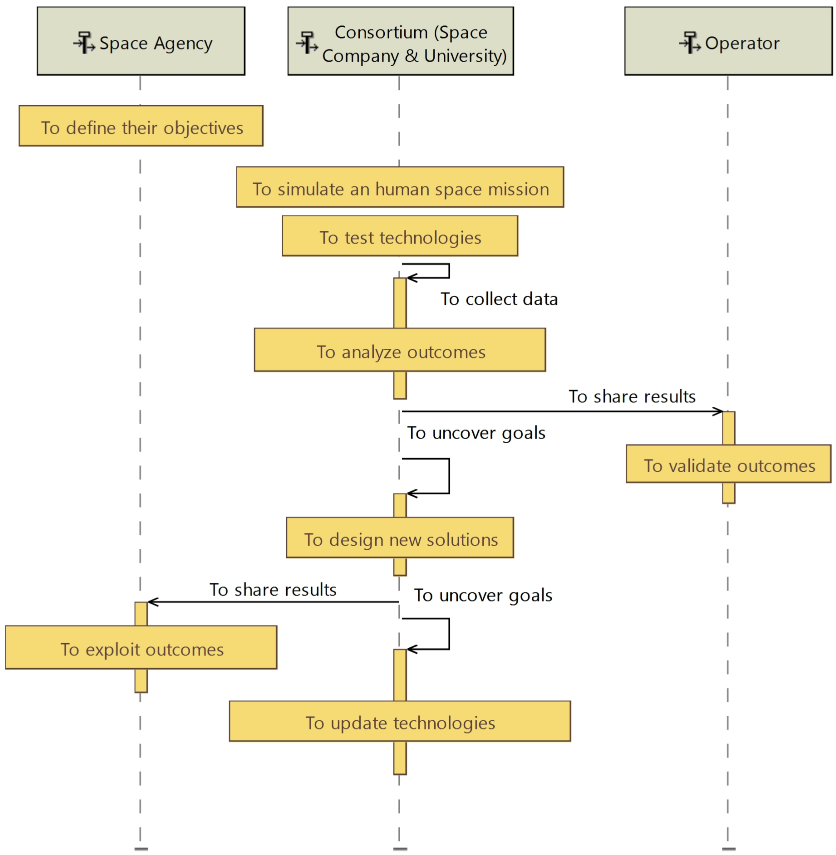


Figure 4.8: [OES] Human Life Technologies Scenario.

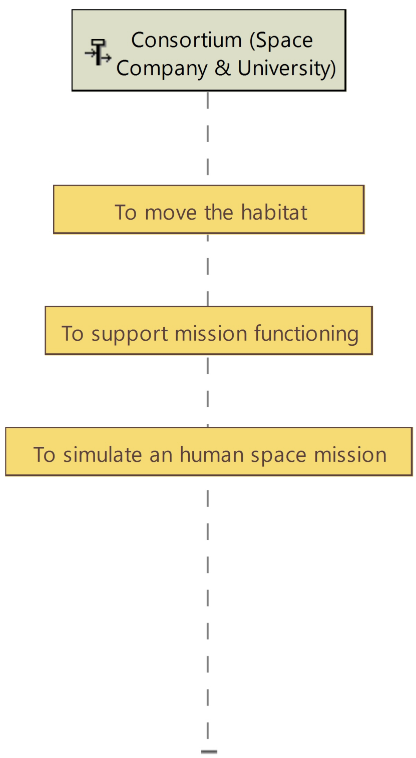


Figure 4.9: [OES] Mission Support Services Scenario.

The scenarios are developed individually for each previously defined capability, resulting in three scenarios, as only three capabilities have been identified. However, only two diagrams are proposed since, at this stage of the design process, the last two capabilities share the same activity structure and scenario, Figure D.1, whereas the first capability is presented in Figure 4.9.

This differentiation is also evident in Figure 4.6, where the requirements have been defined. As previously explained, these follow the same categorization as the capabilities. It is noteworthy that the requirement associated with the first capability also correlates with the operational process linked to 'to test technologies', specifically regarding the 'crew support facilities'. However, this aspect is not explicitly incorporated into the scenario, as in the following steps, 'crew support facilities' will be treated in the same manner as the other technologies to be tested. At this stage, creating three nearly identical scenarios would be redundant. Therefore, an alternative approach could be considered, wherein a single scenario is defined at this stage of the project.

These scenarios offer an alternative perspective on the activities and their interactions, facilitating modifications and verification of their definition when necessary.

4.6 Mission Modes and States

A mission modes and states diagram can be created in OA to outline the different phases and modes of the mission. This diagram serves as a tool for planning and defining the mission, guaranteeing clarity on the current status and the upcoming steps once the mission commences. By following this structured approach, a coherent sequence of events is control during the mission.

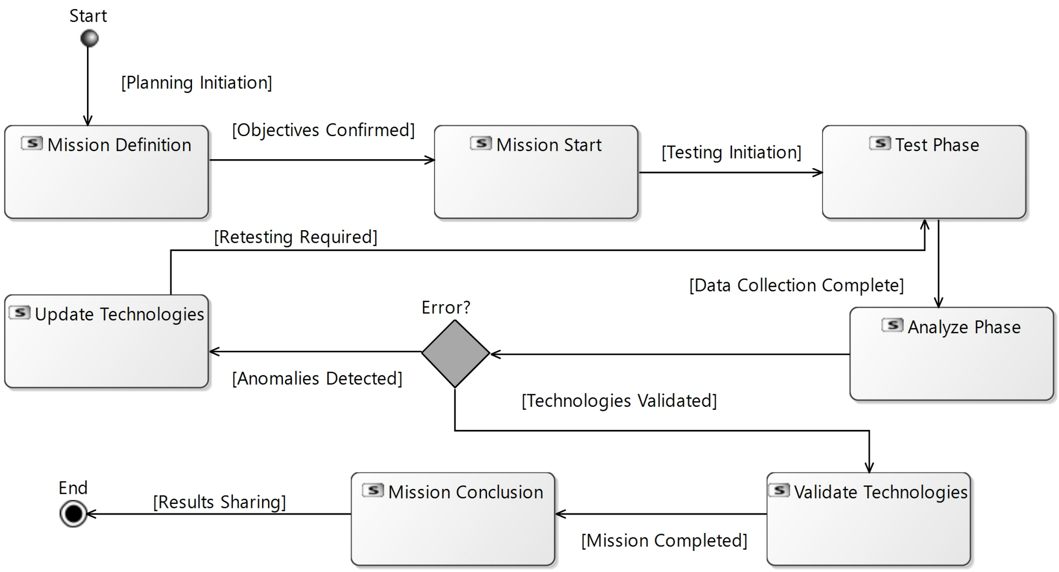


Figure 4.10: [M&S] Modes and States.

The Figure 4.10 helps visualize a hypothetical simulation mission, starting from its definition, establishing objectives and identifying technologies to be tested, as well as executing the necessary transfers, to its actual execution, including maintaining proper mission operations, testing, analyzing and validation, and finally, reaching its conclusion.

To conclude, Operational Analysis has defined key actors, operational capabilities and activities, with their interactions, ensuring that all mission objectives and stakeholder relationships are clearly understood and aligned, without yet detailing the system itself.

Moving on to the system analysis SA phase, the analysis now shifts its focus to the system itself. During this phase, the elements identified earlier are elaborated upon, delving into more specific details.

5 System Analysis SA

The Operational Analysis previously described involves defining and establishing a domain model that remains independent of the future system to be developed. This abstraction allows for a clear focus on the needs and expectations of the various stakeholders, without being constrained by specific system design considerations [66].

The System Analysis phase, instead, represents the stage where the System-of-Interest starts to form. During this phase, the emphasis is on defining the functions that the system needs to carry out and recognizing the external connections it needs to have. In order to establish the anticipated behavior of the system, its functionality is methodically depicted in relation to functions, guaranteeing a well-organized portrayal of how the system meets the requirements of stakeholders [66].

Furthermore, if textual requirements have been identified during the Operational Analysis, they should be refined, formalized, and traced at this level, ensuring a clear link between high-level operational needs and system specific design considerations [66].

The following Table 5.1 presents the expected key activities involved in the System Analysis layer.

Table 5.1: System Analysis Steps [66].

Step	Diagram	Description
1	CSA	Capture Context System Actors
2	MCB	Define Missions and System Capabilities
3	SFBD	Define System Functions Breakdown Structure
4	SDFB	Define Functional Exchanges
5	SAB	Allocate System Functions to System Component and Actors
6	SFCD	Describe System Capabilities with Functional Chains
7	FS	Describe System Capability with Functional Scenarios
8	ES	Describe System Capability with Entity Scenarios

The approach followed in the System Analysis is essentially the same as in the Operational Analysis, but with a higher level of detail, introducing a more granular breakdown of the previously conducted work.

5.1 System Context

Initially, once the work from the Operational Analysis has been transferred to the System Analysis, the system context is defined. The diagram captures the system of interest along with both previously defined and newly introduced actors.

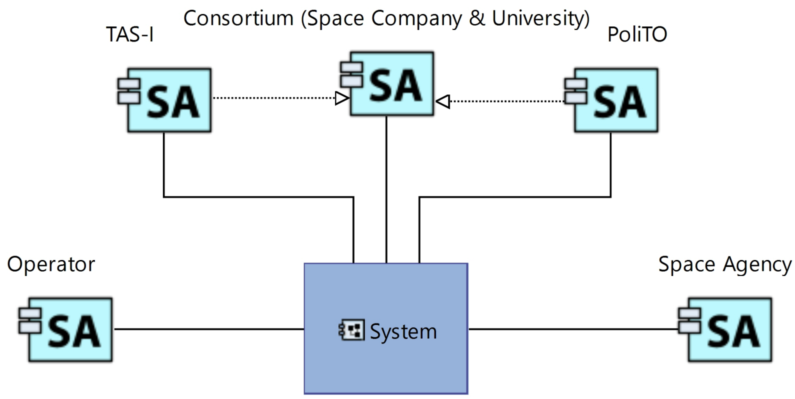


Figure 5.1: [CSA] System Context.

As shown in Figure 5.1, in addition to the system, which is central to this phase of the project, further specifications have been introduced for the entity Consortium, specifically Thales Alenia Space Italia, TAS-I and Politecnico di Torino, PoliTO.

5.2 Mission and Capabilities

Next, the so-called missions and their corresponding capabilities for this phase are represented in Figure 5.2.

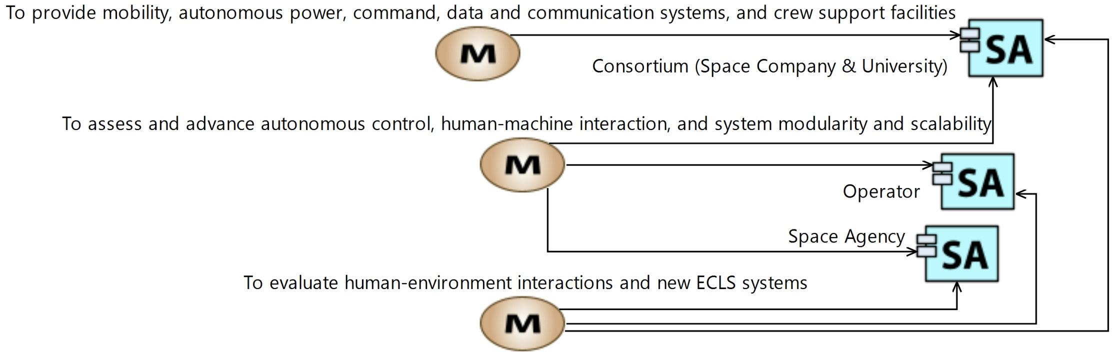


Figure 5.2: [MB] Missions.

The missions are carried over exactly as the capabilities defined in the Operational Analysis, subsection 4.2. At this stage, the previously identified capabilities are now considered as the missions to be accomplished.

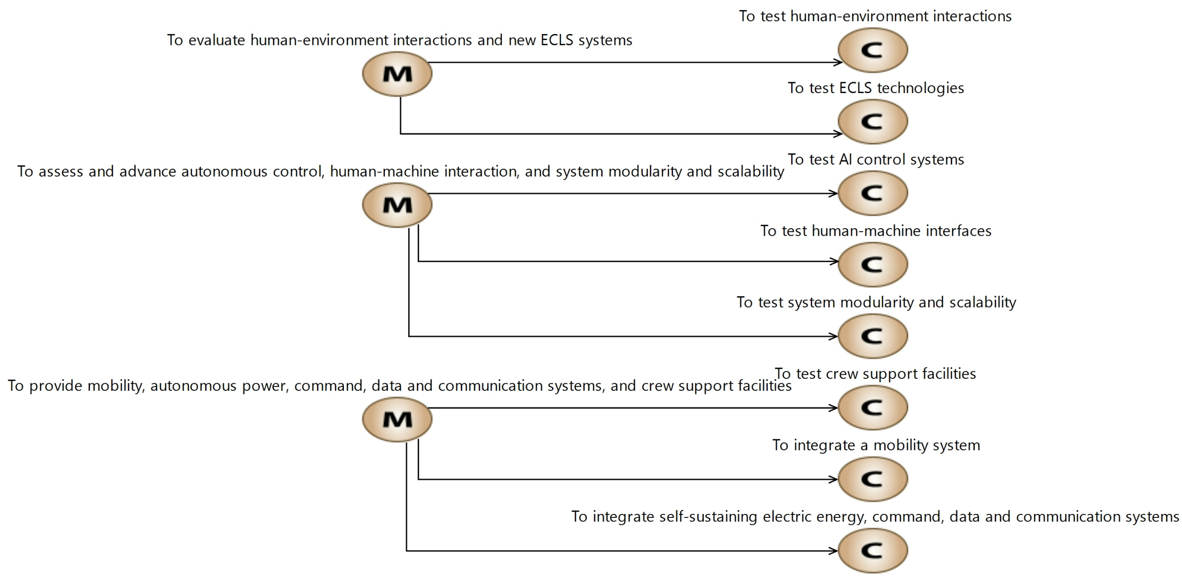


Figure 5.3: [MCB] Capabilities.

The capabilities, as in the Operational Analysis, represent what the entities and actors expect to achieve in order to fulfill the previously defined missions. Various approaches can be adopted at this stage. Based on the Operational Capabilities, subsection 4.2, and the decisions made during that phase, six distinct testing capabilities have been identified to cover both primary and secondary testing objectives, along with two support capabilities addressing the secondary objectives related to the transportation and maintenance of the simulated mission, as shown in Figure 5.3. These are a detailed, lower-level specification of what was previously defined.

At this stage, the process follows the reverse approach of the grouping performed in the OA, subsection 4.2, essentially returning to a definition of capabilities very similar to that of the identified objectives, in subsection 3.2 and subsection 3.4. The grouping in the OA was carried out to ensure consistency with that phase of development, which is high-level and focused on actors and entities. In this phase, however, the focus shifts back to the core of the mission, defining capabilities that precisely represent the objectives to be achieved while concentrating on the actual system and its structure.

5.3 System Functions and Functional Exchanges

Once the capabilities have been defined, as in the operational analysis, the functions that describe them are specified. The diagrams will be similar to those representing the activities and interactions in the OA but will provide a more detailed representation of the newly defined capabilities.

From this point forward, some of the diagrams will be included as PDFs to ensure the readability of each individual element while minimizing quality loss due to their size and level of detail.

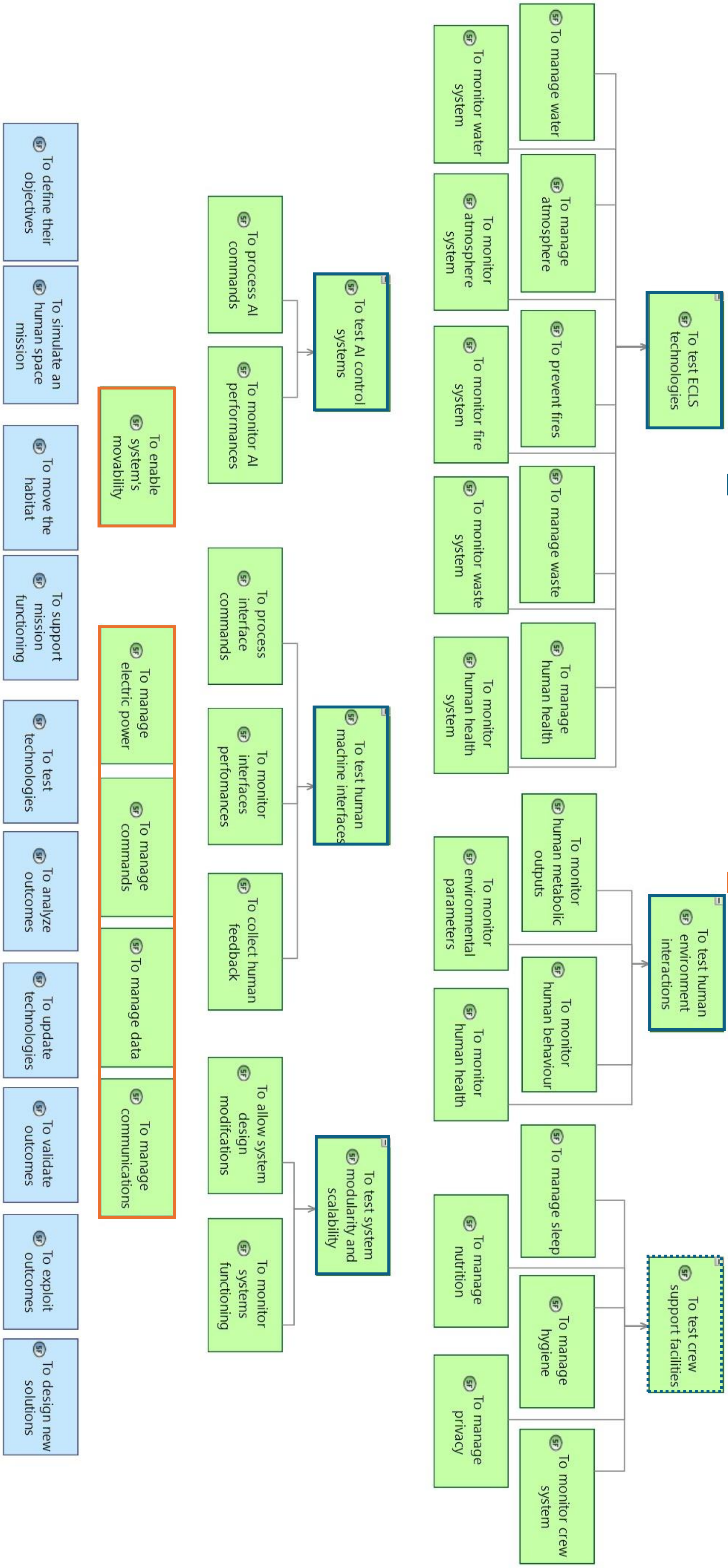
In particular, in '[SFBD] System Functions' PDF, the blue functions, which have already been previously described and are associated with the actors and entities without any changes, are presented. The green functions, which are new and related to the system of interest, the actual habitat, are also depicted.

The green functions specify the activities 'to test technologies', 'to transfer the mission', and 'to support mission functioning'. At the same time, they assist the actors and entities in performing their respective functions, thereby contributing to the achievement of the defined capabilities in subsection 4.2, those signed in blue related to the last two and those in orange to the first one, ultimately leading to the fulfillment of the objectives.

The function marked in dashed blue, 'to test crew support facilities', is highlighted. This function is part of the first defined capability, related to supporting the simulated mission. However, from this phase onward, due to its critical importance in human exploration, since the facilities that support the crew directly impact their operations and, consequently, the success or failure of the mission, it will be considered in the same manner as the other technologies and the corresponding technology testing functions.

Furthermore, in this case, some of the green functions have been grouped based on their similarity, specifically concerning the types of technologies that need to be tested.

[SFBD] System Functions



Functions related to the following two capabilities:

- To evalutate human-environment interactions and new ECLS systems
- To assess and advance autonomous control, human-machine interaction, and system modularity and scalability

Functions related to the following capability:

- To provide mobility, autonomous power, command, data and communication systems, and crew support facilities

The macro-functions and the nature of their sub-functions, when necessary to specify, that define 'to test technologies' are as follows:

- To test ECLS technologies
  - Water
  - Atmosphere
  - Fire
  - Waste
  - Human health
- To test human-environment interactions
  - Human metabolic products
  - Human behavior
  - Human health
  - Environmental parameters
- To test crew support facilities
  - Human sleep
  - Human hygiene
  - Human nutrition
  - Human privacy
- To test AI control systems
- To test human-machine interfaces
- To test system modularity and scalability
- To test crew support facilities

As can be observed, the 'human health' nature, present in the first two macro-functions, while identical in definition, differs in its scope: in the first case, it refers to human health management, whereas in the second, it specifically concerns human health monitoring.

The specific sub-functions of each macro-function have also been presented in the corresponding PDF, representing those identified during the design phase as best suited to fulfilling the secondary objectives related to these technologies under testing.

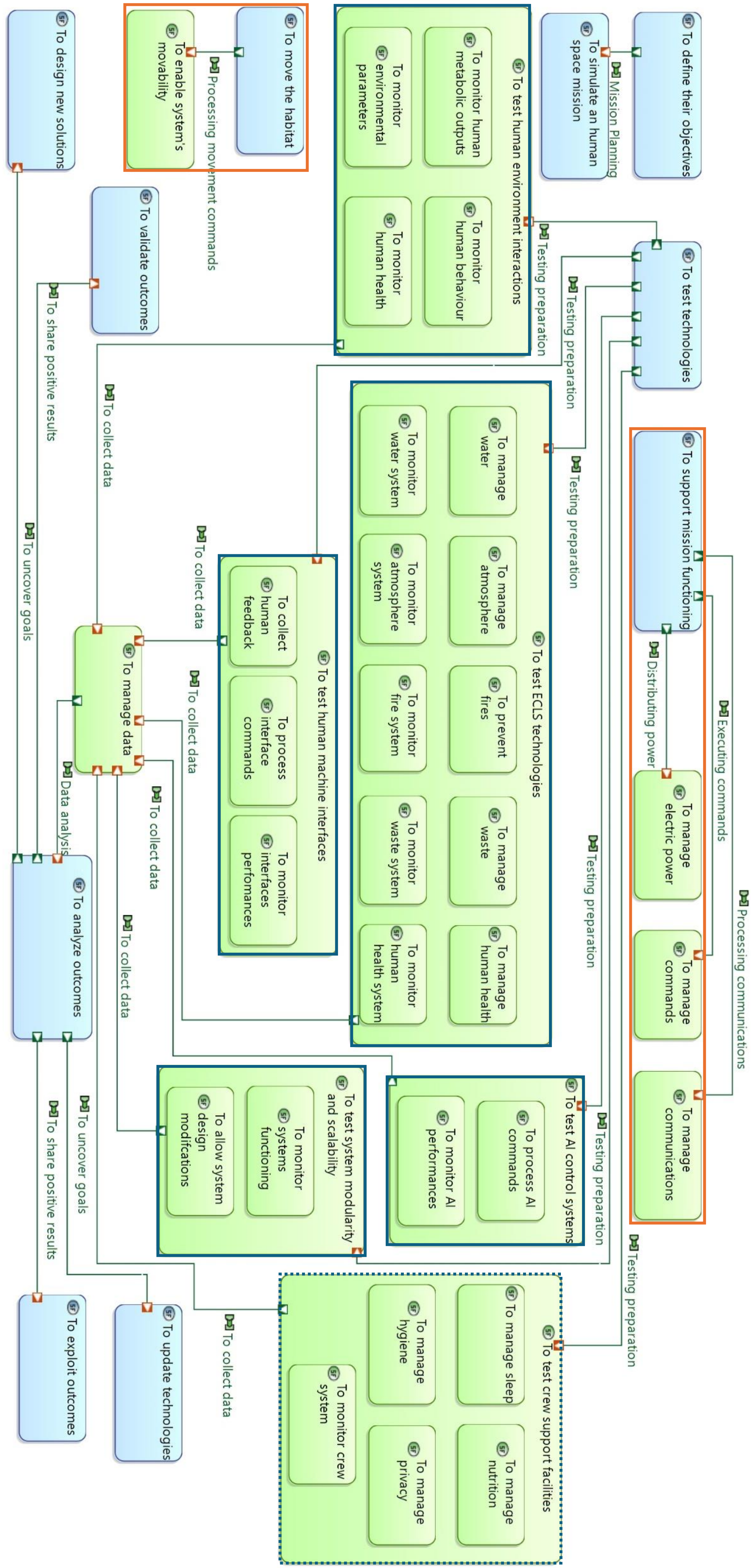
Each macro-function is described by these sub-functions following two main aspects: an operational aspect, which pertains to the effective execution of each technology's tasks, and a monitoring aspect, which ensures that all functions operate correctly, data is collected, and analysis is conducted.

Conversely, the functions that operate in parallel with the previously defined activities 'to transfer the mission' and 'to support mission functioning' are, in orange,:

- To enable system's movability
- To manage electric power
- To manage commands
- To manage data
- To manage communications

For these functions, no sub-functions have been defined, as the outlined functions themselves are deemed appropriate for the level of specification of the SA.

[SDFB] System Function Exchange



Instead, regarding the interactions of the OA, these are now represented as functional exchanges between the previously described functions in '[SDFB] System Function Exchange' PDF.

At a lower level of design, these exchanges will define actual components that collaborate to perform the various functions. Some functional exchanges, similar to those of the OA, are related to the analysis, redesign, and validation of the results. Additionally, some functional exhanges have been added regarding the functions related to the transfer and maintenance of the mission.

For the various types of tests to be performed, a particular functional exchange approach has been chosen. This approach defines an exchange from the 'to test technologies' function of the 'consortium' entity to each of the macro-functions that group the previously described functions. This approach has been adopted because, at this stage of the design, the sub-functions within each group must be carried out simultaneously. Defining functional exchanges among each sub-functions at this stage, as described, would be difficult and potentially lead to errors.

Although this approach results in six nearly identical flows, which was previously avoided in the OA due to their minimal differences, it introduces a certain degree of repetition. However, it has been decided to adopt this approach to avoid creating an overly redundant and restrictive burden for the subsequent stages of the design. The color coding, also in this diagram, follows the same reasoning as previously applied.

5.4 System Architecture

The system architecture, like its counterpart in the OA, provides a more detailed representation of the elements introduced in the previous steps. It illustrates which functions correspond to specific actors, entities or the system of interest, and how these actors are interconnected through their functional exchanges.

In this section, functional chains can also be defined, serving as the counterparts to the operational processes in the OA. These represent sequences of functions that collectively achieve a specific capability.

In particular, in the following '[SAB] System Structure' PDF, the diagram highlights how actors collaborate with each other and with the system, illustrating the transitions between actors and, when necessary, the return to a previous one. In this case, functional chains have been explicitly identified to provide a clear and accessible representation within the diagram. Specifically, five distinct functional chains have been defined:

- Testing Functional Chain - Blue
- Supporting Functional Chain - Red
- Miss Goals Functional Chain - Green
- Meet Goals Functional Chain - Purple
- Moving Functional Chain - Yellow

The first of these presents six nearly identical sequences of functions associated with the 'to test technologies' function. These six sequences involve functions in italics, representing those that encompass the previously described sub-functions, subsection 5.3. These sub-functions have not been explicitly detailed at this stage, as their inclusion would result in an excessive number of elements, making the diagram less readable. Furthermore, since these sub-functions are intended to be executed simultaneously, they involve the same functional exchanges. The chosen representation instead facilitates understanding by clearly indicating that these functions must be performed together, despite belonging to six distinct functional streams.

The second and the last functional chains, on the other hand, represent the functional process related to the first capability, as previously specified. Meanwhile, the 'Miss Goals' and 'Meet Goals' functional chains are associated with the functions, previously considered activities in OA, that the actors will perform depending on the success or failure of the collected data. In the case of success, they will serve to validate and exploit the obtained results; otherwise, they will be used to reassess the design and implement necessary corrections.

Furthermore, as in Figure 4.6, an additional eight types of requirements have been introduced, following a cascading structure from the three previously defined ones, Table 4.2. Like the capabilities and functions, these requirements provide a further level of detail for those defined in OA, as shown in Table 5.2.

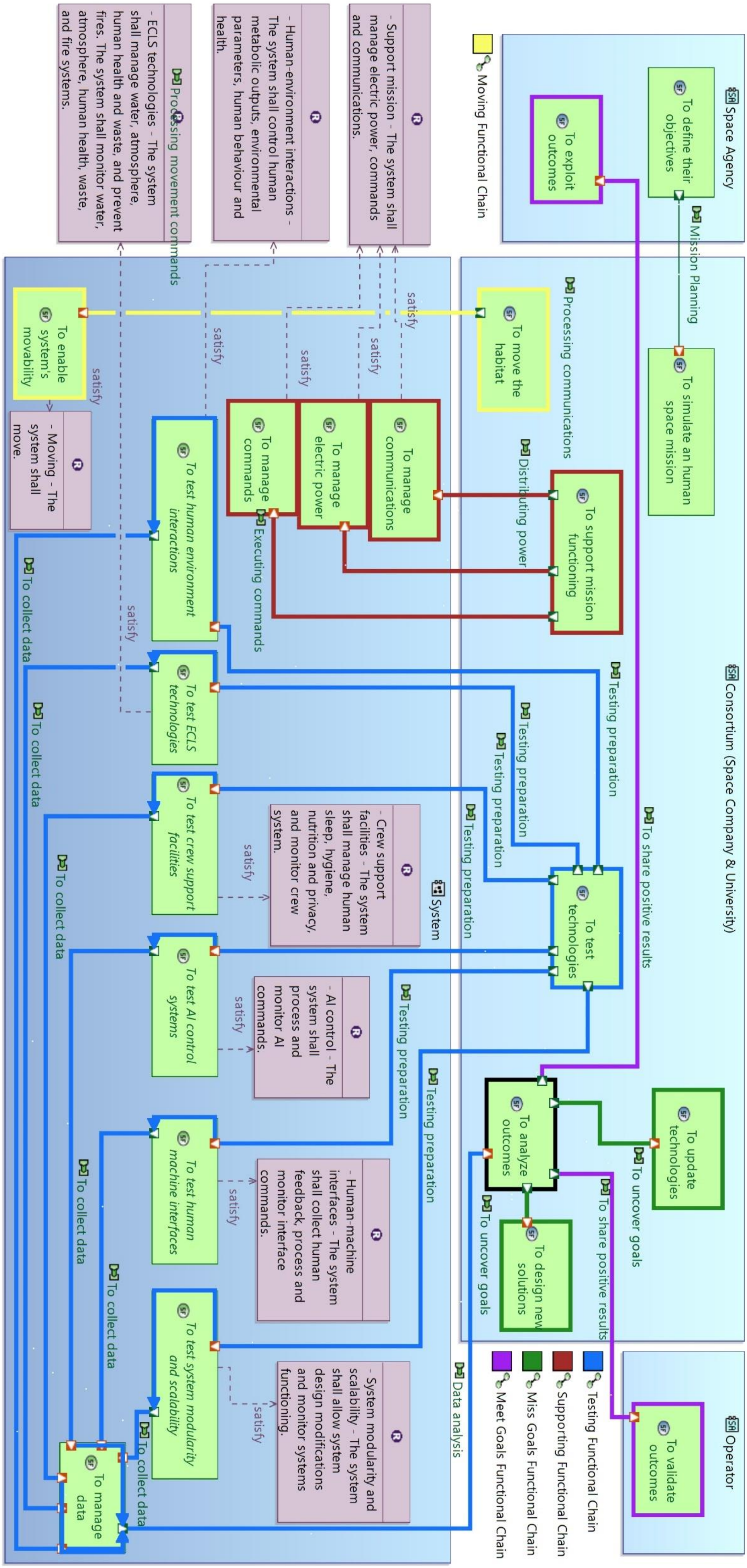
Table 5.2: Mission Requirements in the SA [61].

ID	Status	Requirement
NLG-MIS-SA-0001	Draft	The system shall move.
NLG-MIS-SA-0002	Draft	The system shall manage electric power generation, commands and communications.
NLG-MIS-SA-0003	Draft	The system shall manage human sleep, hygiene, nutrition and privacy, and monitor crew systems.
NLG-MIS-SA-0004	Draft	The system shall process and monitor AI commands.
NLG-MIS-SA-0005	Draft	The system shall collect human feedback, process and monitor interfaces commands.
NLG-MIS-SA-0006	Draft	The system shall allow system design modifications and monitor systems functioning.
NLG-MIS-SA-0007	Draft	The system shall control human metabolic outputs, environmental parameters, human behaviour and health.
NLG-MIS-SA-0008	Draft	The mission shall manage water, atmosphere, human health and waste, and prevent fires. The system shall monitor water, atmosphere, human health, waste and fires systems.

Specifically, six requirements have been established for the different types of technologies to be tested, each encompassing what the system should perform within its sub-functions, which are grouped according to the macro-functions associated with a specific type of technology.

Additionally, two distinct requirements are defined, incorporating the functions related to the movement and support of the simulated mission. As described in OA, the requirements are functional with a 'satisfy' relationship requirements type, as illustrated by purple arrows in the corresponding PDF.

[SAB] System Structure



5.5 System Scenario

Unlike the scenarios defined in the OA, at this stage, also two more different types of scenarios can be identified: Function Scenarios and Entity Scenarios. These scenarios exclusively represent functional exchanges to illustrate how, in the sequence of functions to be performed, the transition occurs from one function or entity to another. Additionally, it remains possible to create complete scenarios, including entities, functions, and exchanges, as in the OA.

Scenarios are defined for each capability, as shown in Figure 5.4 and Figure 5.4, in this phase as well. A decision was made to use general scenarios, as in OA, to best represent the described capabilities.

Since functional exchanges have been defined only among macro-functions, Capella™ presents a different representation of functional exchanges between two functions, one a standard function and the other a macro-function, as highlighted in Figure 5.6. These macro-functions are 'virtual' constructs used for project organization rather than actual sub-functions that fulfill the objectives. The two black dots marking the beginning and end of the macro-function indicate that additional functions are present within that section. However, at this stage of the project, it was decided to present them without specifying their exact execution sequence or structure.

Regarding the testing capabilities, only one scenario, the 'Human Machine Interfaces Scenario', is reported, as the remaining five are almost identical to it. The latter are presented in Appendix D for completeness.

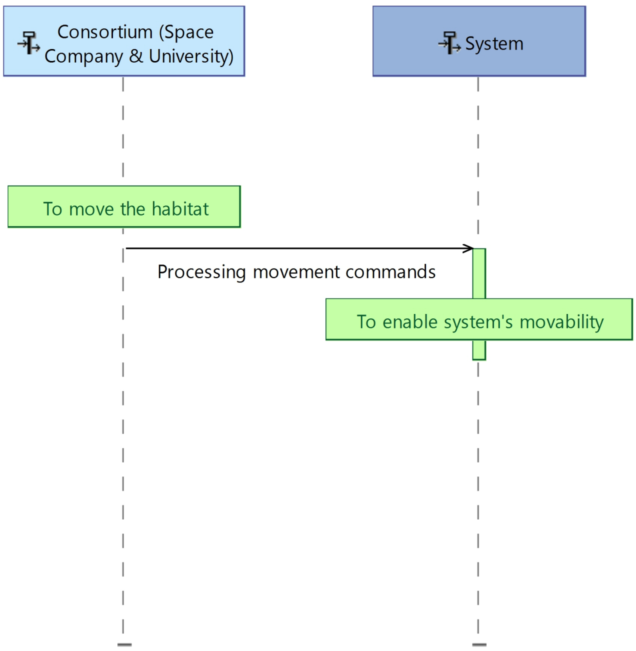


Figure 5.4: [ES] Mobility Systems Scenario.

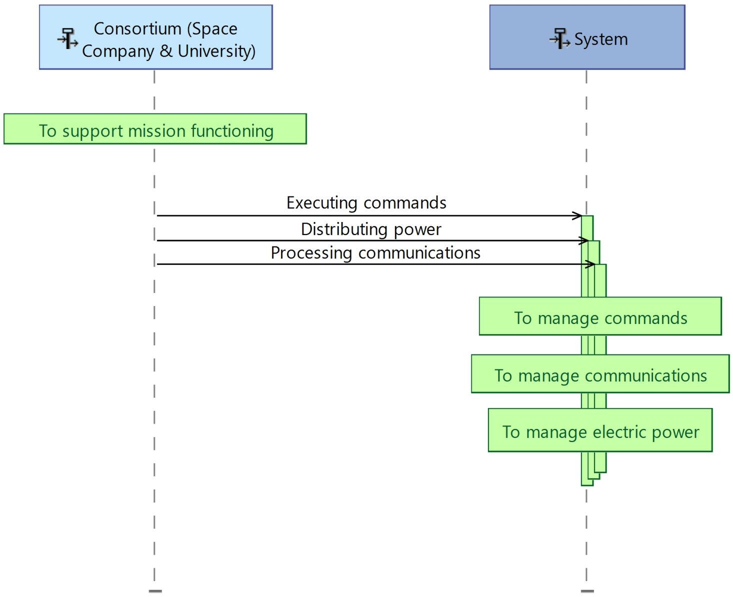


Figure 5.5: [ES] Utility Systems Scenario.

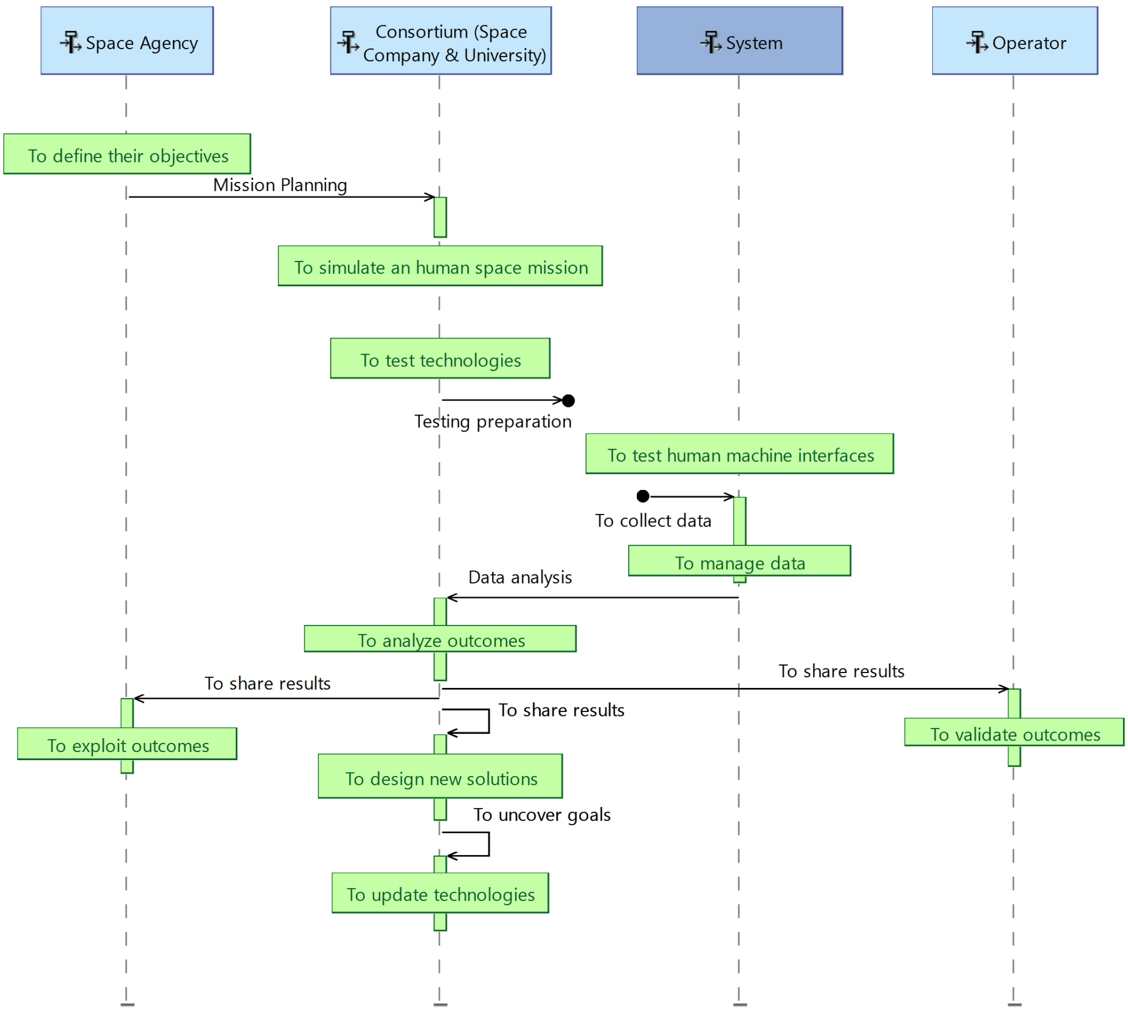


Figure 5.6: [ES] Human Machine Interfaces Scenario.

6 Logical Analysis LA

The System Analysis layer focuses on analyzing the system as a 'black box', defining its expected behavior and identifying key external interactions with actors. In contrast, the Logical Architecture layer begins to 'open the box' by structuring the system's internal components and defining the principles that will guide its implementation. This stage involves making fundamental architectural decisions to ensure that the system effectively meets stakeholder expectations.

Capella™ facilitates this process by automatically creating realization links between Logical Architecture elements, such as functions, functional exchanges, and functional chain, and their corresponding elements at the System Analysis level. The transition between these levels is iterative and incremental, meaning that if a missing system function is identified while working on the Logical level, it must be incorporated into the System level before reapplying the transition [67].

Defining the high-level Logical Architecture involves several key activities. These activities include identifying architectural drivers and organizing the system around components. Additionally, it entails outlining the core behavioral principles of the system and performing trade-off analyses to identify the best architectural solution [67].

As previously mentioned, the methodological steps involved in this process follow a structured yet flexible approach. The following Table 6.1 presents the expected key activities involved in the System Analysis layer [67].

Table 6.1: Logical Analysis Steps [67].

Step	**Diagram**	**Description**
1	CRB	Capabilities Realization at Logical Architecture
2	LFBD	Define Logical Architecture Functions
3	LDFB	Define Functional Exchanges
4	LCBD	Define Logical Components
5	LAB	Allocate Logical Functions to Logical Components
6	LFCD/FS/ES	Describe Capability Realizations with Functional Chains and Scenarios

The approach followed in the Logical Analysis is essentially the same as in the previous steps, with the progressive addition of elements, among actors, functions and the initial system components.

6.1 Capabilities

Once the content developed during the System Analysis phase has been transferred, sub-capabilities of the previously defined capabilities are typically specified. However, since the Logical Analysis may require modifications by those responsible for conducting the subsequent analysis, PA, and further steps of design and dimensioning, this step has been omitted. In this case, the sub-capabilities are the same of the defined system capabilities, subsection 5.2.

In this section, for each step, four different diagrams will be presented, illustrating the LA of all the previously defined capabilities, subsection 5.2. Specifically, these diagrams are structured as follows:

- ECLS Technologies
- Human Environment Interactions and Crew Support Facilities
- AI, Human Machine Interfaces, and System Modularity and Scalability
- Mobility and Utility Systems

At this stage, the elements and level of detail become increasingly significant, following the same procedural approach as in the previous steps. The foundation established thus far is further refined to achieve a higher degree of definition. In practice, the names of these four diagrams correspond to the capabilities previously analyzed and defined.

The LA has been created in four distinct representations to improve usability and organization. Even though the diagrams are categorized differently, they are all equal in importance and serve the same purpose, each playing a role in defining and finalizing the overall design. This does not mean that specific elements are missing; instead, they are present and collectively guarantee the fulfillment of the specified capabilities.

6.2 Logical Functions and Functional Exchanges

The next step involves further refining the functions related to the capabilities and defining their functional exchanges.

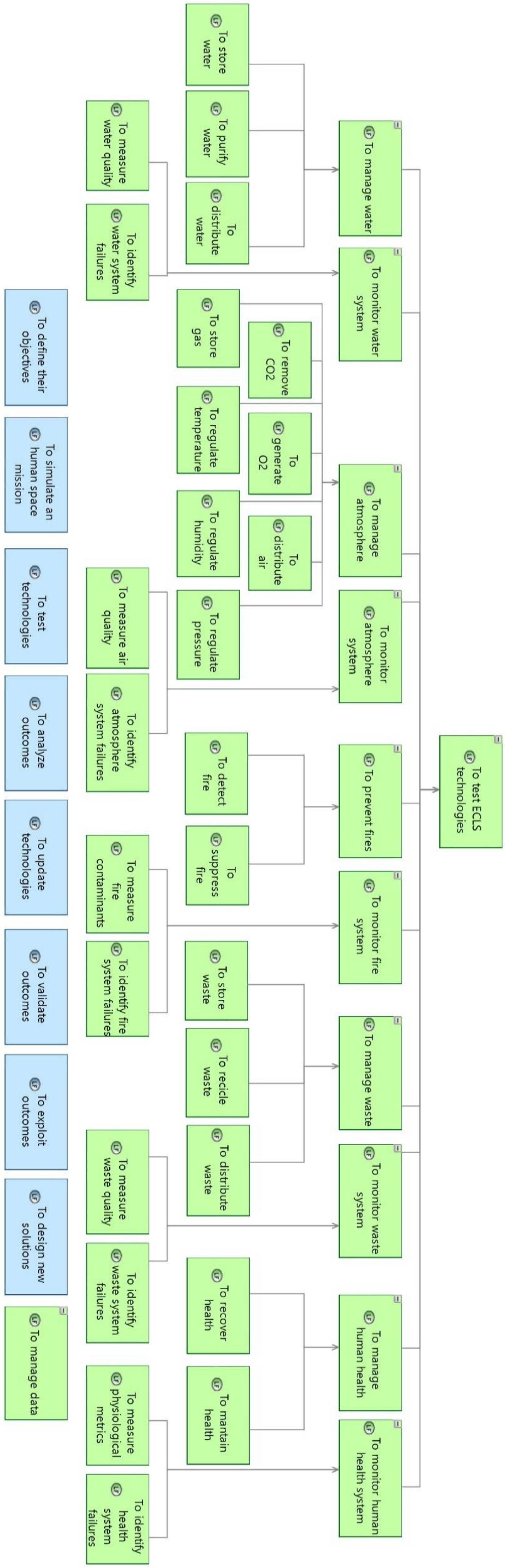
As shown in the subsequent PDFs, the functions associated with actors, in blue, have remained identical to those defined in the previous steps, subsection 4.3 and subsection 5.3, while all other system functions, in green, have been further expanded, resulting in an increasingly branched tree structure.

The Logical Structure, subsection 6.4, diagram currently showcases only the newly established system functions. It is designed to encompass all functions to aid in understanding, enhance readability and organization, and demonstrate the progression of the structure through various stages.

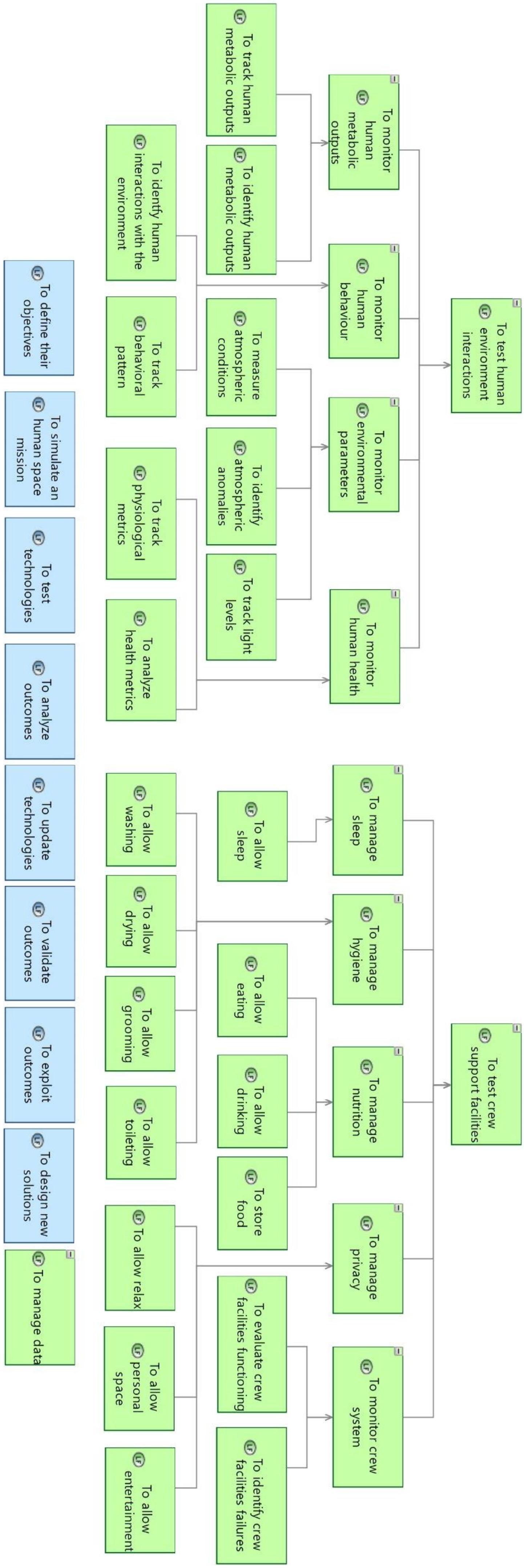
Regarding functional exchanges, this step was first implemented in the Logical Structure, subsection 6.4. In the relative diagrams, organizing and positioning elements, both functions and exchanges, becomes increasingly complex due to the decision to include the entire functional tree. For this reason, given their approximate nature and low quality, they have been omitted at this stage.

In subsection 6.4, a detailed explanation will be provided regarding the definition of the new functions and how they interact with each other. This will help in comprehending the underlying logic more effectively. In few words, the operational functions and monitoring functions, outlined in subsection 5.3, have been elaborated upon. This represents a significant step as it defines more precise functions that encompass the essential features of the technologies that will undergo testing.

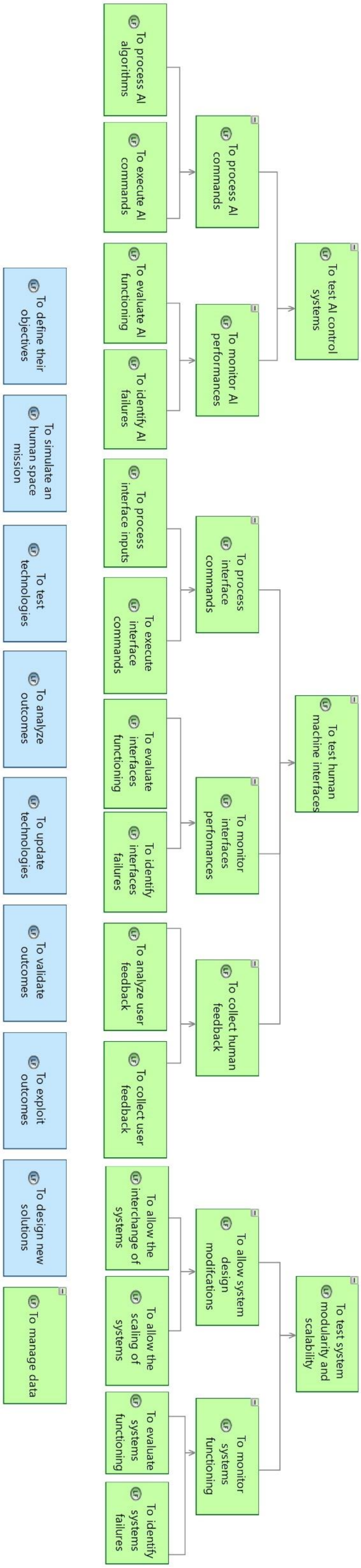
[LFBD] ECLS Technologies Root Logical Function



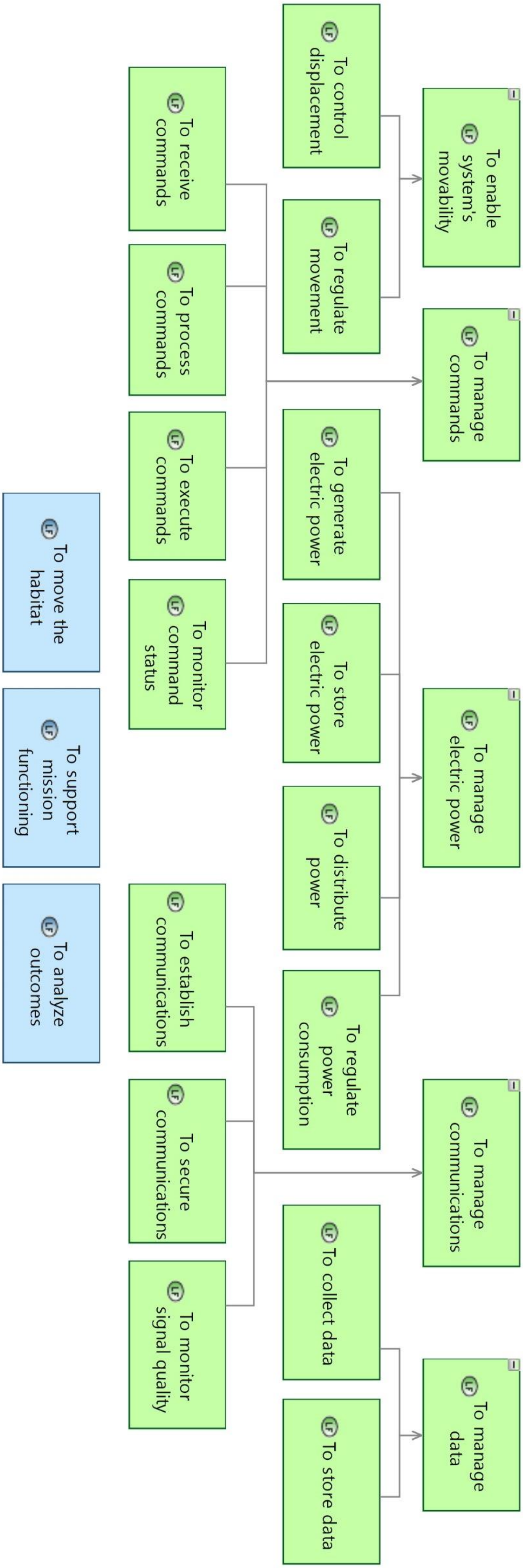
[LFBD] Human Environment Interactions and Crew Support Facilities Root Logical Function



[LFBD] AI, Human Machine Interfaces and System Modularity and Scalability Root Logical Function



[LFBD] Mobility and Utility Systems Root Logical Function



6.3 Logical Components

At this stage, as previously mentioned, given the numerous functions defined even for a single capability, the system components are introduced. These components represent systems that fulfill specific functions, grouped based on their similarity in purpose. In particular, functions are categorized into the following domains for each of the four classifications specified earlier, with a corresponding representation of the nature of the components, along with the actors and entities defined so far, clearly illustrated.

- ECLS Technologies
  - Water
  - Atmosphere
  - Fire
  - Health
  - Waste

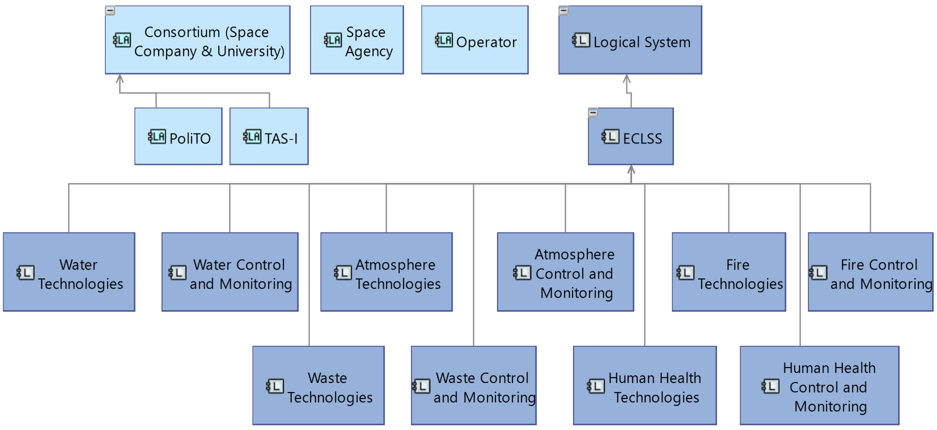


Figure 6.1: [LCBD] ECLS Technologies Components.

- Human Environment Interactions and Crew Support Facilities
  - Atmosphere
  - Health
  - Sleep and Privacy
  - Hygiene
  - Nutrition

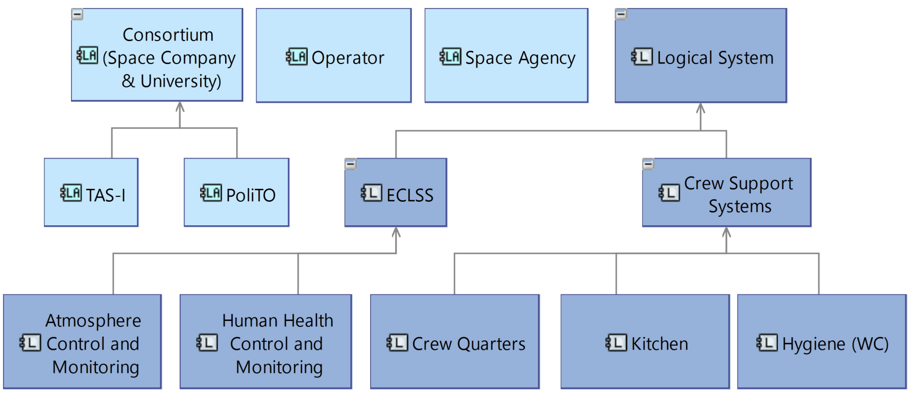


Figure 6.2: [LCBD] Human Environment Interactions and Crew Support Facilities Components.

- AI, Human Machine Interfaces, and System Modularity and Scalability
  - AI
  - Interfaces

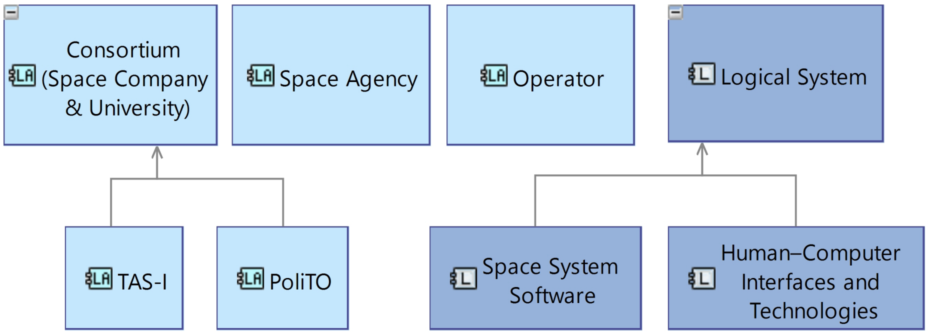


Figure 6.3: [LCBD] AI, Human Machine Interfaces and System Modularity and Scalability Components.

- Mobility and Utility Systems
  - Motion
  - Power
  - Communications
  - Command
  - Data

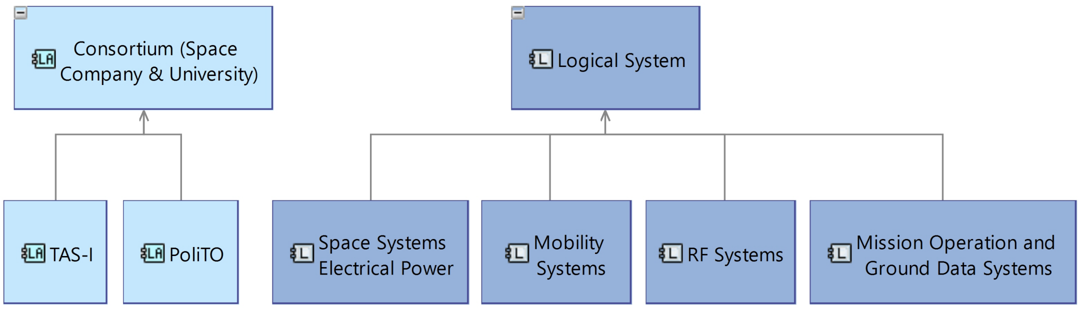


Figure 6.4: [LCBD] Mobility and Utility Systems Components.

In most cases, the naming of components follows the ESA Technology Tree [68]. Nonetheless, there are discrepancies in the definitions of components and sub-components compared to the ESA Technology Tree. To resolve this issue, the approach taken is to select the most appropriate naming conventions from the reference document that pertains to the specified components.

Specifically, in Figure 6.1, the components have been defined using the same logic as the functions in the SA, subsection 5.3, with each domain of responsibility within the ECLSS having an operational component and a monitoring component.

In Figure 6.2 and Figure 6.3, the defined components are linked to the entirety of the function blocks, both operational and monitoring, as defined in subsection 5.3. In Figure 6.4, the component is unique and specific due to the absence of the monitoring aspect. This does not mean that monitoring is absent, but rather that it is of a different nature compared to the other functions.

As shown in Figure 6.1 and Figure 6.2, during the design of the two different categorizations, certain functions share identical components, such as 'Atmosphere' and 'Human Health'. Although these components are presented within two different categorizations, it was considered that the same systems could handle both the functions related to life support technologies and those related to the analysis of human-environment interactions. This approach enables a design with fewer components while enhancing efficiency and multidisciplinary functionality.

Nonetheless, as in this step, and in subsequent phases, despite the presence of identical components, the two categorizations will always be presented separately to ensure better readability and usability of the study diagrams, which are already dense with elements.

6.4 Logical Architecture

The Logical Architecture follows the same approach as the SA, ensuring a clearer identification of the actors and entities involved in specific roles. Furthermore, this phase emphasizes how components contribute to the execution of specific functions and how they interact through functional exchanges.

For the first time, Capella™'s elements such as 'split' and 'gather' are introduced to define instances where certain functions lead to multiple possible functional sequences or where specific functions must be executed simultaneously, such as for regulating atmospheric parameters in the simulated environment. As illustrated in the following PDFs, various pathways and functional chains begin to emerge, leading to distinct outcomes.

Moreover, as in the SA, the logical architecture incorporates functional chains to offer clear and readable diagrams, presenting how a specific functional path flows.

In the following subsections, each of the four diagrams is analyzed individually, further detailing the logic behind the functions defined in subsection 6.2.

6.4.1 ECLS Technologies Architecture

This section defines the structure related to the 'ECLS Technologies' capability. The following functional chains are identified within this diagram:

- Water Functional Chain - Blue

  This functional chain pertains to the processing, storage, and distribution of water within the habitat, both for human consumption and for hygiene purposes, which are essential for overall health.

  The functional chain is categorized into two main parts: 'Water Technologies' and 'Water Control and Monitoring', as seen in Figure 6.1. This division is consistently maintained throughout the subsequent functional chains. The concept behind this classification is to assign one component to handle operational tasks and another component to manage monitoring tasks, specifically focusing on 'water management'.

  The process starts by storing water that is deemed contaminated. Later on, the water is purified using specific technologies and methods that will be determined in subsequent phases. The effectiveness of the purification process is assessed through monitoring.

  Once the water meets the required purification criteria, it is distributed through a specially designed system. On the other hand, if the quality standards are not met, the monitoring system must detect any possible error. Key stakeholders like the 'Space Company' and 'University' will tackle these challenges, which may include creating new technologies, adjusting current systems or introducing alternative solutions.

  This quality control process is also applied to the other functional chains within this diagram.

  Once the water quality is measured, in addition to the aforementioned evaluations, the collected data are analyzed. Based on the results, the process branches into two distinct functional chains, which are not only common to other functional chains within this diagram but also extend across other test diagrams.

  These two functional chains are the following ones.

- Miss Goals Functional Chain - Green

  This functional chain encompasses functions entirely related to the actors in cases where the results of the data analysis from various systems are negative and do not comply with the predefined objectives and requirements. Specifically, this chain involves improving technologies and systems and/or re-designing new solutions to enhance performance and achieve compliance with the mission's objectives and requirements.

- Meet Goals Functional Chain - Purple

  Conversely, this chain is activated when the results are positive. It encompasses functions related to collaborations with external entities such as 'Space Agency' and 'Operator', which can further exploit and validate the obtained results within the simulated mission.

- Atmosphere Functional Chain - Grey

  This functional chain focuses on regulating atmospheric conditions in a living space to establish and sustain a suitable environment for people while ensuring harmony with current systems and technologies.

  The components are 'Atmosphere Technologies' and 'Atmosphere Control and Monitoring'.

  The initial step involves gathering and storing polluted air resulting from human activities in the surroundings. Subsequently, the air is purified by eliminating carbon dioxide, producing oxygen, and controlling temperature, pressure, and humidity. Following purification, the air quality is evaluated by the monitoring system. If the set criteria are met, the purified air is circulated throughout the living space. In cases where the parameters do not align with the required standards, the system must identify potential malfunctions.

  As with the water functional chain, data is collected and analyzed to determine appropriate actions based on the results obtained, following the same methodology outlined earlier.

- Fire Functional Chain - Yellow

  The functional chain described here focuses on preventing fires in living spaces to ensure safety and reduce fire risks.

  The components are 'Fire Technologies' and 'Fire Control and Monitoring'.

  The first step involves recognizing possible fire risks like smoke or minor sparks. This is followed by implementing preventive actions and firefighting protocols, which will be detailed in later stages of the design process. After extinguishing the fire, the contamination levels resulting from the fire are evaluated to determine if the emergency situation has been completely addressed.

  If the contamination levels are within acceptable limits, no further action is required, but the collected results are analyzed in the same manner as other functional chains. If the levels exceed safety thresholds, the system must identify potential failures and determine corrective actions.

- Health Functional Chain - Orange

  This functional chain is dedicated to overseeing the well-being of individuals in the living environment, guaranteeing healthcare and general welfare during the mission.

  The components are 'Human Health Technologies' and 'Human Health Control and Monitoring'.

  The process begins with providing medical treatment if necessary, followed by maintaining health through physical exercises, treatments, and medical analyses, which will be further detailed in subsequent phases.

  Subsequently, physiological parameters are scrutinized to evaluate the health condition of the person. In cases where the outcomes indicate sound health, no further interventions are necessary, although external entities still review the gathered information. However, if the results are unfavorable, the system must pinpoint potential shortcomings, identify areas for enhancement, and suggest tailored treatments.

- Waste Functional Chain - Red

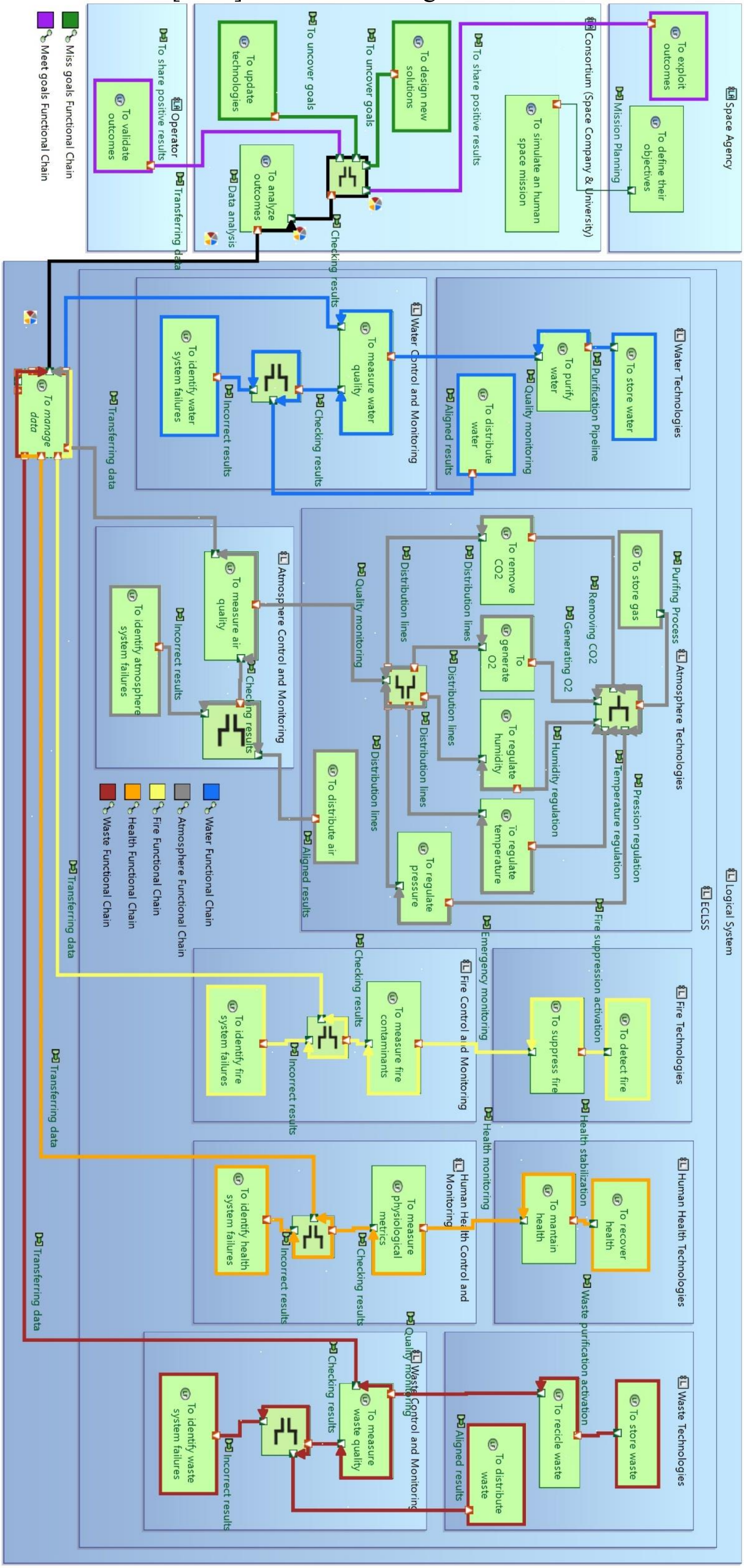
  This functional chain is centered on managing waste within the living environment. Its objective is to sustain a livable habitat by repurposing waste produced by humans, their consumption, and technological actions. The aim is to establish an effective system that repurposes resources efficiently.

The components are 'Waste Technologies' and 'Waste Control and Monitoring'.

The procedure commences with the collection of waste, followed by its recycling. After recycling, the recovered materials are assessed for their quality and potential for reuse. If they meet the necessary criteria, the materials are reintegrated into the habitat and allocated to the appropriate technologies for utilization. In cases where the quality falls short of the required standards, the system must identify any potential failure.

As with the other functional chains, data is collected and analyzed to determine appropriate actions based on the obtained results, following the methodology outlined previously.

[LAB] ECLS Technologies Structure



6.4.2 Human Environment Interactions and Crew Support Facilities Architecture

This part defines the structure related to the 'Human Environment Interactions and Crew Support Facilities' capabilities. The following functional chains are identified within this diagram:

- Miss Goals Functional Chain - Green

  This functional chain is activated when system analysis indicates that the predefined objectives and requirements have not been met. It involves refining existing technologies and designing new solutions to address failures and optimize performance.

  The first step involves the consortium, which consists of the 'Space Company' and the 'University', identifying unmet objectives. Together, these entities assess the performance of the system to pinpoint areas that need improvement. After analyzing the data, they proceed to upgrade technologies and create innovative solutions to improve the success rate of missions.

  Once new developments are made, the outcomes are reassessed. The results are either incorporated into system improvements or, if failures persist, subjected to further refinement as explained in the previous diagram.

- Meet Goals Functional Chain - Purple

  This functional chain is activated when system analysis confirms that the predefined objectives and requirements have been met. It focuses on validating and exploiting positive outcomes for further applications.

  The process starts with the consortium sharing positive results obtained from the system's performance evaluation. These results are then transmitted to the 'Operator' and the 'Space Agency' for validation and further exploitation in the context of the mission.

  By collaborating with external entities, validated solutions can be further applied and refined in operational scenarios, contributing to future technological advancements and mission optimizations as explained in the previous diagram.

- Human Functional Chain - Blue

  This functional chain is centered on exploring the relationship between humans and their environment, with the goal of understanding and examining the mutual impact they have on each other.

  The component involved is 'Human Health Control and Monitoring'.

  The process commences by recognizing the metabolic products produced by humans to evaluate how astronauts adjust to and engage with their surroundings. This involves overseeing their performance efficiency throughout the mission and observing any physiological alterations that may occur. Furthermore, the system assesses their interactions with the environment to study their behavioral tendencies and routines, pinpointing any possible adjustments in their behavior and investigating the root causes behind them.

  All these processes are complemented by the continuous collection and monitoring of physiological metrics throughout the mission. As described previously, all data is gathered and analyzed by external actors to determine the necessary course of action, whether in response to positive or negative outcomes.

- Environment Functional Chain - Red

  This functional chain delves into the correlation between individuals and the atmospheric circumstances in their living environment. Its goal is to recognize and scrutinize the influence of environmental elements on human well-being and vice versa.

  The component involved is 'Atmosphere Control and Monitoring'.

  The initial step involves pinpointing and evaluating the atmospheric conditions, including the artificial lighting within the living space. The quality of artificial lighting can have a significant impact on human health. It is crucial to take into account factors such as the hue and design of the interior of the living space, particularly for extended space expeditions, to comprehend how individuals react to these stimuli.

In case any irregularities are identified, the system needs to ascertain whether they result from environmental factors or underlying system glitches. If no irregularities are detected, the gathered data is archived and examined by external entities to ensure ongoing monitoring and adjustments to uphold optimal atmospheric conditions.

Beyond the functional chains, the system also includes crew facilities, which encompass the following components and their respective functions:

- Crew Quarters

  Crew quarters are responsible for managing sleep and relaxation for crew members, ensuring they have a personal space that also allows for entertainment and psychological well-being. This is essential for maintaining the overall health of astronauts throughout the mission cycle.

- Hygiene - WC

  This facility is dedicated to personal hygiene management, including washing, drying, and addressing the crew's standard physiological needs.

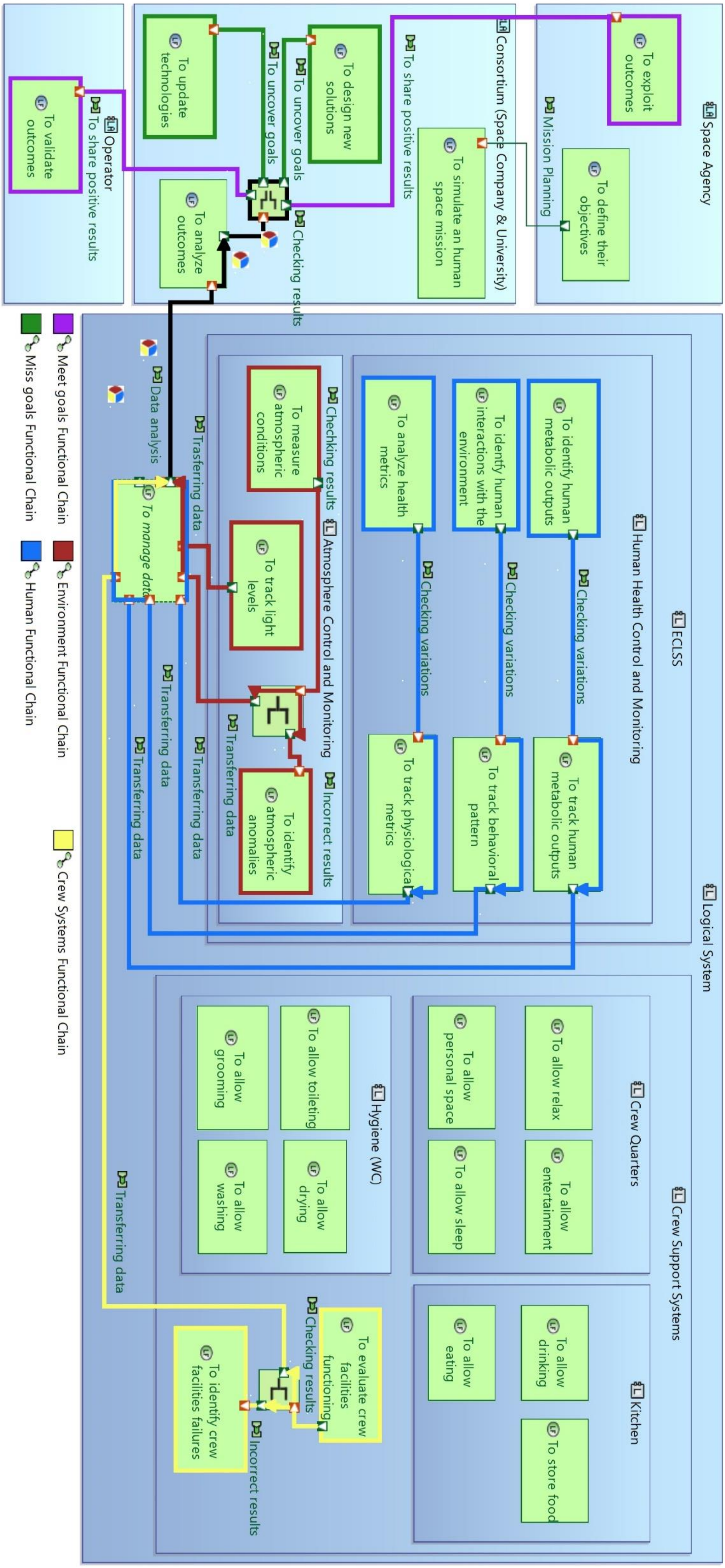
- Kitchen

  Kitchen ensures nutrition by providing food and drinks, properly stored.

Additionally, these systems are continuously evaluated to monitor their performance, identifying and addressing potential failures as needed, as shown in the yellow functional chain, called 'Crew Systems Functional Chain'.

As with the other functional chains, data is collected and analyzed to determine appropriate actions based on the obtained results, following the methodology outlined previously.

[LAB] Human Environment Interactions and Crew Support Facilities Structure



6.4.3 AI, Human Machine Interfaces and System Modularity and Scalability Architecture

This part defines the structure related to the 'AI, Human Machine Interfaces and System Modularity and Scalability' capabilities. The following functional chains are identified within this diagram:

- Miss Goals Functional Chain - Green

  As previously explained.

- Meet Goals Functional Chain - Purple

  As previously explained.

- AI Functional Chain - Blue

  This functional chain relates to the utilization and operation of artificial intelligence AI that aid in managing the system.

  The component involved is 'Space System Software'.

  The sequence initiates with the handling of AI algorithms, proceeded by their application and activation. Subsequently, after the execution of AI directives, an assessment is conducted to gauge their performance and efficacy in mission tasks. In cases where deficiencies or breakdowns are detected in the outcomes, the system is required to recognize potential issues and rectify them accordingly.

  Similar to the functional chains mentioned earlier, data is gathered and assessed to determine the suitable course of actions based on the acquired findings, following the same approach as previously delineated.

- Interfaces Functional Chain - Red

  This functional chain manages the human-machine interactions, ensuring efficient communication between users and the technology.

  The component involved is 'Human-Computer Interfaces and Technologies'.

  The process starts with the processing of interface inputs, followed by their implementation and execution. Once the interface commands are executed, their functionality and effectiveness in mission operations are evaluated. If the results indicate inefficiencies or failures, the system must identify potential malfunctions and implement corrective measures.

  As with the previously described functional chains, data is collected and analyzed to determine the appropriate actions based on the obtained results, following the same methodology outlined earlier.

- User Feedback Functional Chain - Yellow

  This functional chain ensures the collection and analysis of user feedback to improve system interfaces.

  The process begins with collecting feedback from users interacting with the system. This data is then analyzed to assess the effectiveness of current implementations.

  As with the previously described functional chains, data is collected and analyzed to determine the appropriate actions based on the obtained results, following the same methodology outlined earlier.

  After analyzing the data, the system checks if any changes are needed to improve scalability and compatibility with other systems. If modifications are necessary, they are implemented to enhance the system. Once the system has been refined, it undergoes another evaluation to guarantee the best possible user experience and performance.

- Systems Functional Chain - Orange

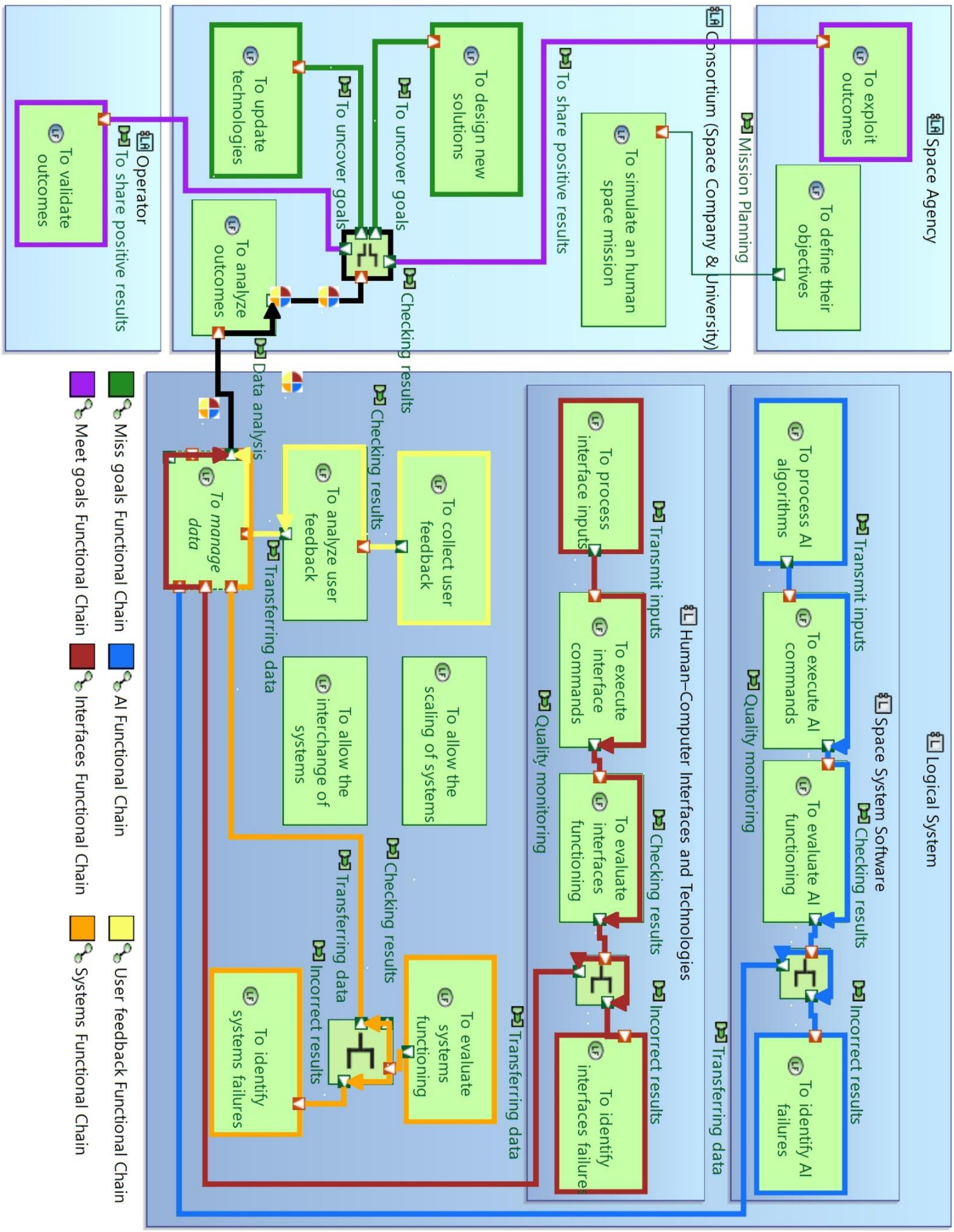
  This functional chain concerns the evaluation and monitoring of overall system performance to ensure reliability and efficiency.

  The process begins with the evaluation of system functionality. If the results confirm that the system is operating correctly, the data is stored and utilized for further optimization.

  Based on the analysis, the system determines whether modifications are required. If necessary, adjustments are made to enhance the scalability and interchangeability of systems. The refined system is then re-evaluated to ensure optimal user experience and performance.

  If failures are detected, the system must identify the root causes of these failures. This iterative process ensures continuous improvement and stability of the habitat's technological ecosystem.

[LAB] AI, Human Machine Interfaces and System Modularity and Scalability Structure



6.4.4 Mobility and Utility Systems Architecture

This section defines the structure related to the 'Mobility and Utility Systems' capabilities. The following functional chains are identified within this diagram:

- Moving Functional Chain - Red

  This functional chain manages the mobility systems with the objective of ensuring the ability to easily relocate the analog habitat from one environment to another during various simulation missions, maintenance activities, or as required.

  The component involved is 'Mobility Systems'.

  The process starts with the consortium's decision to move the habitat, which subsequently triggers the system to regulate its movement and control its displacement within the predefined environment, site, or location.

- Supporting Functional Chain - Green

  This functional chain ensures mission support by managing power distribution, data handling, communications and command execution.

  The components involved are 'Space System Electrical Power', 'RF Systems' and 'Mission Operation and Ground Data Systems'.

  The process begins with the consortium providing operational support to the mission.

  - Energy Management

    The first step involves regulating the electrical power consumption according to the habitat's operational needs. Then, electrical energy is generated using technologies and procedures that will be defined in later stages. Finally, the generated energy is stored and distributed to the necessary subsystems.

  - Communications Management

    The communication system is first established and secured against potential interferences. Subsequently, the quality of the signal is continuously monitored to ensure reliability.

  - Command Management

    The process begins by receiving commands, which are then processed and executed. After that, the system monitors the status of each command to check if it has been executed, is currently being processed, or is still pending.

  Data handling is managed in the following functional chain.

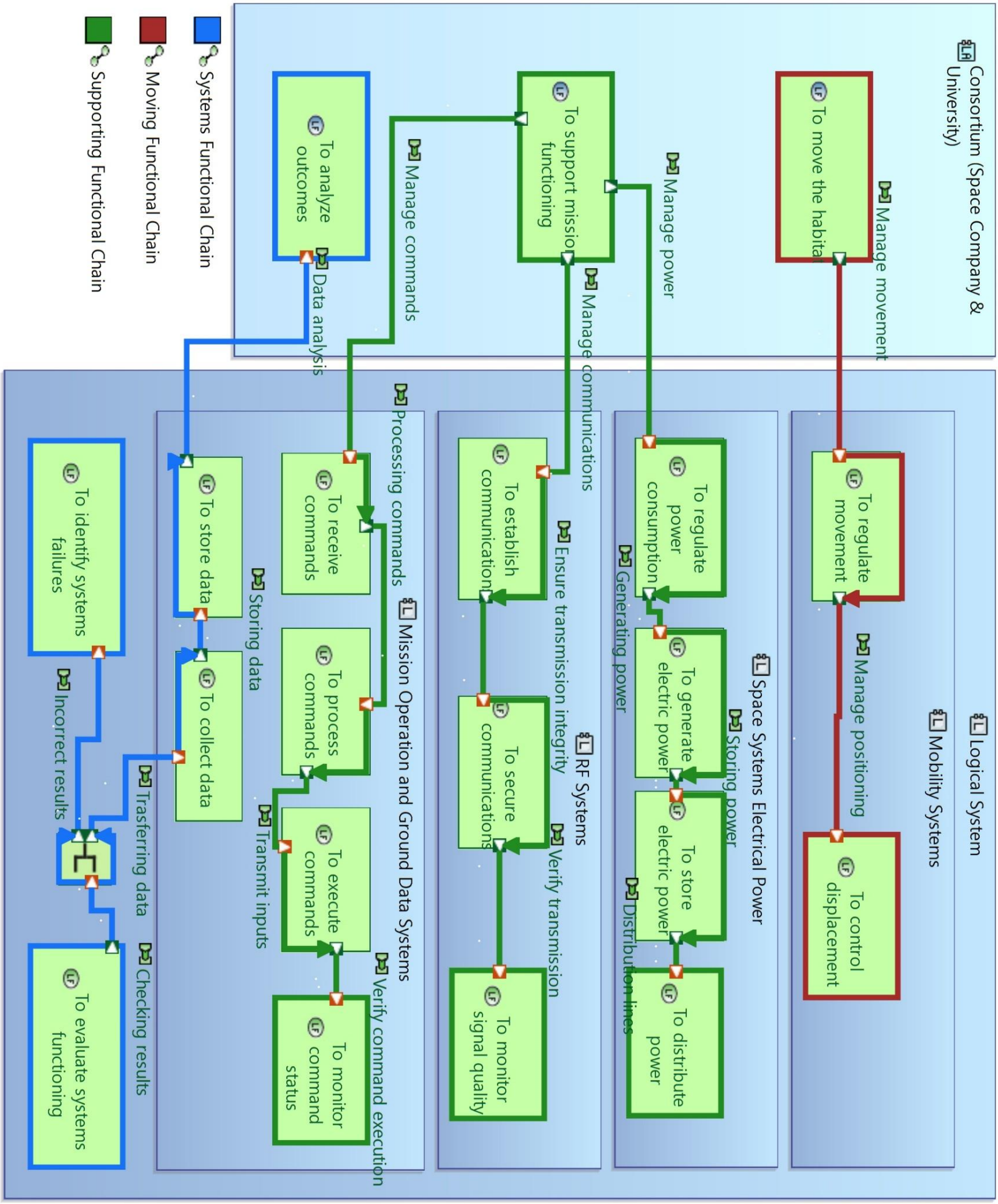
- Systems Functional Chain - Blue

  This functional chain concerns the evaluation and monitoring of overall support system performance.

  The process begins with valuating system functioning. If the results confirm that the system is operating correctly, the collected data is stored and subsequently analyzed by the consortium.

  If failures are detected, the system must identify the root causes of these failures. This iterative process ensures continuous improvement and stability of the habitat's technological ecosystem.

[LAB] Mobility and Utility Systems Structure



6.5 Logical Scenario

At this point, the Logical Scenario plays a crucial role in defining the temporal dimension, providing insight into how the multiple functions are executed, in what sequence, and by whom.

The scenario becomes increasingly complex and extensive. However, when correctly structured, it facilitates both ease of interpretation and modification when necessary, ensuring coherence with the logical structure.

In the current phase, scenarios are established for each capability, following the same patter in the OA and SA phases, as examples in subsection 5.2. As no further enhancements have been implemented in the capabilities since the System Analysis phase, this phase will also feature eight scenarios. However, only one scenario will be thoroughly examined, as the analysis in this phase does not introduce significant new insights compared to what was covered in the previous phase, subsection 6.4, aside from the inclusion of the time factor.

These scenarios are notably more intricate and detailed than those in the OA and SA phases. Therefore, it is essential to analyze at least one 'testing' scenario and the two 'supporting' scenarios comprehensively to elucidate all aspects of this diagram type. This level of scrutiny was not deemed necessary earlier due to the straightforward nature of the analyses in the preceding steps, section 4 and section 5, which involved minimal elements in their scenarios.

Scenarios that are not detailed in this section can be found in subsection D.3.

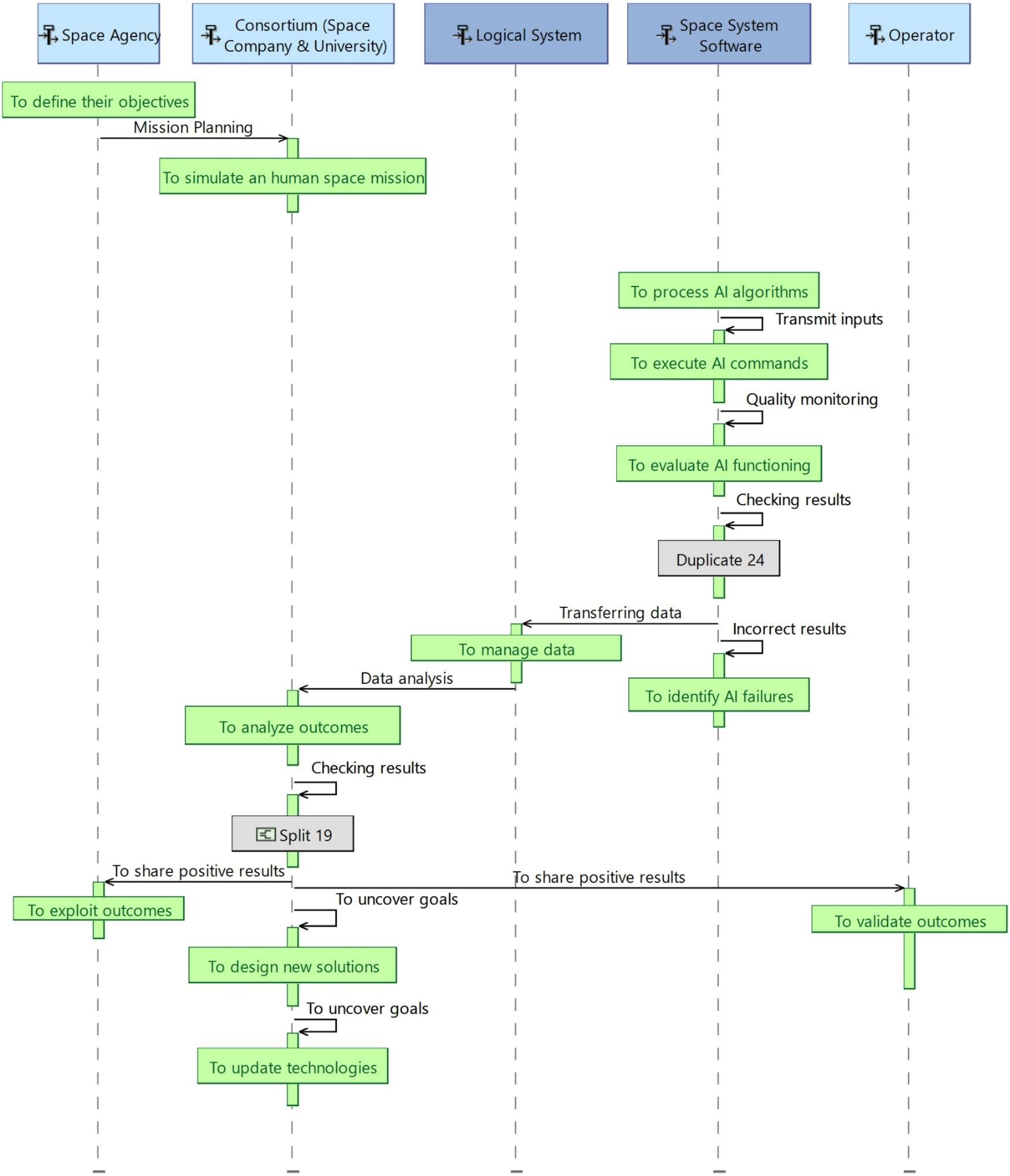
One particular scenario, known as the '[ES] AI Logical Scenario', as followed, is examined and displayed as a PDF for better visualization. While the concluding part, concerning the analysis of the results, remains consistent across all scenarios concerning the technologies under evaluation, there is a clear increase in the number of components. These visual representations are beneficial for observing the functional sequences outlined in subsection 6.4 separately, from their initiation to their conclusion.

The operational process begins with the 'Space Agency', which is a potential partner of the consortium, defining the mission goals. Collaborating with the consortium, they will plan the simulation of a human space mission, focusing on testing specific aspects related to the use and integration of AI capabilities, in this case.

Within the 'Space System Software' element, there will be equipment for processing and carrying out AI instructions, as well as tools for monitoring these instructions. In cases where the data meets safety and approval criteria, the overall system, known as the 'Logical System', will not require any further intervention but will gather the data for later analysis. However, if the outcomes do not meet the standards, the 'Space System Software' will need to pinpoint the system's failure points, rectify the errors and implement measures to prevent similar issues in the future.

The reanalyzed data will be divided into two paths. In case of a positive outcome, external entities like the 'Space Agency' and third-party 'Operators' will use and confirm it. However, if the outcome is negative, there will be a requirement to update the existing systems. This update may involve implementing new machine learning software and/or AI command processing systems.

[ES] AI Logical Scenario

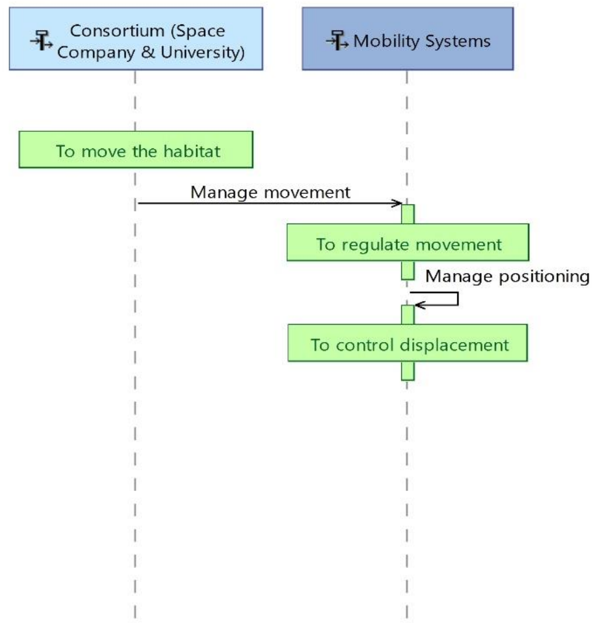


Instead, in the context of support scenarios, the '[ES] Mobility Systems Logical Scenario' is characterized by a concise presentation of key elements, as previously illustrated in subsection 6.4. The scenario commences with the consortium's decision to relocate the habitat and the corresponding system responsible for overseeing this relocation, which involves regulating and monitoring the habitat's position.

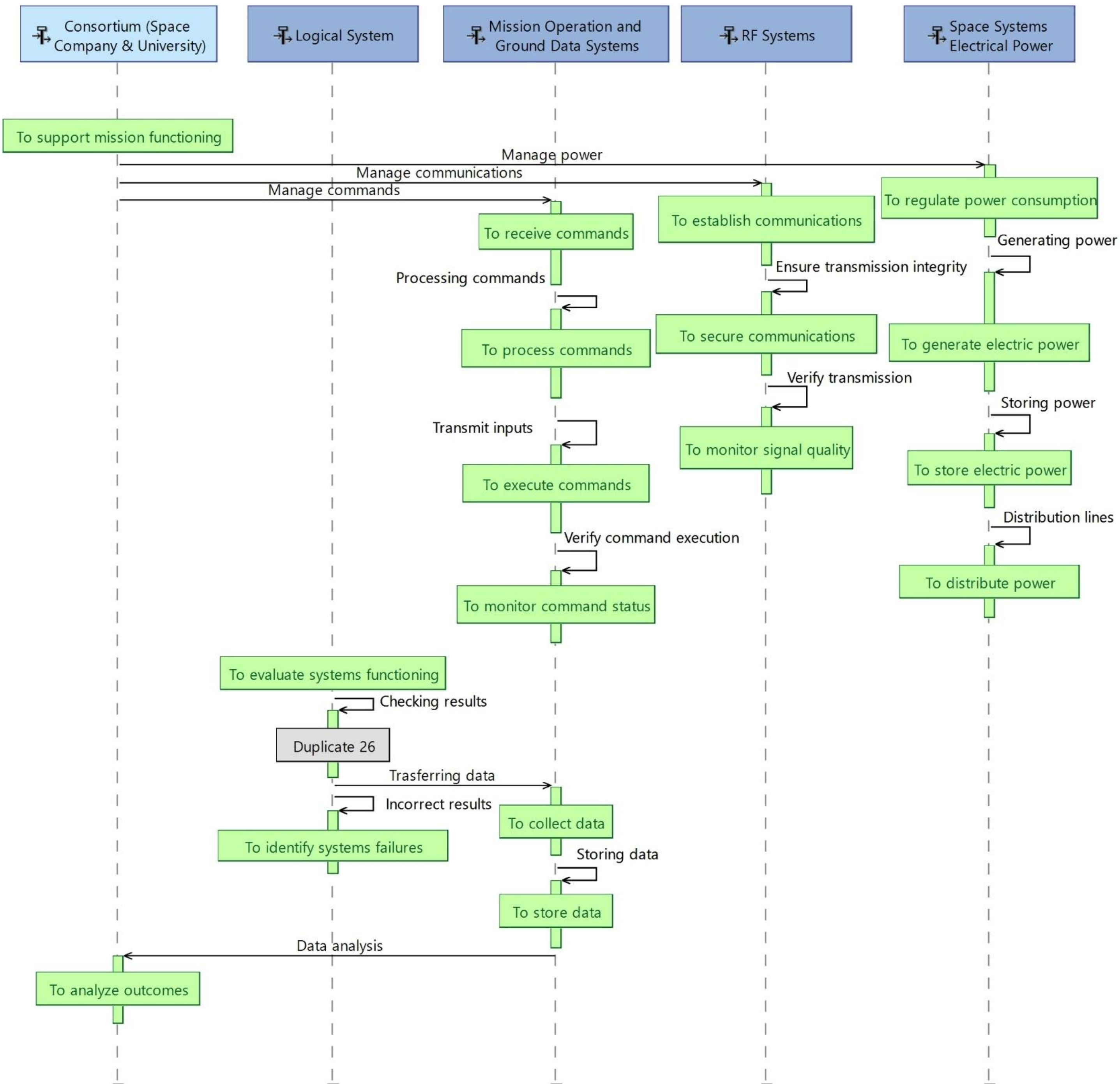
On the other hand, the '[ES] Utility Systems Logical Scenario' illustrates the simultaneous execution of processes related to electrical energy management, communications and commands, each accompanied by its functional interactions outlined in subsubsection 6.4.4. Subsequent to this, a comprehensive assessment of all systems' operations will be conducted, encompassing the detection of potential malfunctions if needed, in adherence to appropriate procedures for data management, gathering and analysis. This aspect stands as another critical facet in supporting the simulation mission.

These two scenarios are proposed in succession.

[ES] Mobility Systems Logical Scenario



[ES] Utility Systems Logical Scenario



These scenarios provide a more direct and easy-to-understand view to ensure that everything defined so far has been coherently structured, both in the complexity of the entire system and in its uniqueness, which is difficult to identify in subsection 6.4.

This concludes the design phase of this project. The Physical Analysis, along with the dimensions and progress of the entire project, will be carried out in future studies and developments. The capabilities of Capella™ allow for easy reworking and addition of new parts to further and effectively develop the project.

7 Physical Analysis PA

As previously stated, this phase will not be considered in the scope of this project. However, it is presented to provide a comprehensive overview of the ARCADIA methodology and to potentially encourage future extensions or improvements to this work.

During the Logical Architecture phase, the main focus is on defining the structural elements of the system, referred to as Logical Components, including their properties and relationships. This phase intentionally does not consider any specific technologies or implementation details. The goal of the Physical Architecture phase is to progress from this conceptual representation to an actual implementation by specifying the concrete system components [69].

Capella™ offers a systematic process to support this transition, which is similar to the methods used in earlier phases like moving from Operational Analysis to System Analysis and from System Analysis to Logical Architecture. This method enables the creation of Physical Functions that correspond to Logical Functions while preserving Functional Exchanges and Functional Chains [69].

The main activities involved in the Physical Architecture phase include:

- Defining the final system architecture and functional decomposition.
- Deploying behavioral components within the concrete system structure.
- Considering the reuse of existing model elements to optimize development.

The following Table 7.1 presents the expected key activities involved in the Physical Analysis layer.

Table 7.1: Physical Analysis Steps [69].

Step	**Diagram**	**Description**
1	CRB	Capabilities Realization at Physical Architecture layer
2	PFBD	Define Physical Functions
3	PDFB	Define Physical Functional Exchanges
4	PCBD	Define Behavioural and Physical Nodes
5	PAB	Allocate Functions to Behavioural Nodes and Physical Nodes Components
6	PFCD/FS/ES	Describe Capability Realizations with Functional Chains and Scenarios

8 Conclusion

In this research project, an analog space habitat was developed using a Model-Based Systems Engineering, MBSE, approach with the support of Capella™ software. The main goal was to establish a testing ground for crucial technologies essential for human space exploration. This initiative aimed to reduce risks and enhance solutions by conducting thorough testing before implementing them in actual space missions.

Various existing analog simulations like MARS 500, HI-SEAS, and CHAPEA were reviewed to identify their limitations and potential contributions. The focus was particularly on Environmental Control and Life Support Systems, ECLSS, due to their critical role in supporting human life in space. After conducting this analysis, the project stakeholders were assessed to understand their needs, expectations and goals. By examining these stakeholders, initial macro-functions, functional exchanges, and logical components were identified in an initial functional analysis. This comprehensive functional analysis was crucial in handling the system's complexity during the following design phases.

The design process followed the ARCADIA methodology, structuring the project into distinct yet interconnected phases: Operational Analysis OA, System Analysis SA, and Logical Analysis LA. This methodical approach enabled a gradual progression from a conceptual grasp of the mission context to a clearly defined system architecture.

During the OA phase, crucial actors and entities like space agencies, private companies, and universities were identified, along with their respective activities and interactions. Subsequently, in the SA phase, these elements were transformed into system elements, defining first system functions and their interfaces, defining the expected system behavior. Finally, the LA phase focused on establishing the internal structure of the system by introducing logical components and functional chains to elucidate interdependencies and streamline operations, by the incorporation of 'split' and 'gather' elements, enhancing the accuracy of representing the system's internal processes.

While there has been significant progress, there are still various obstacles that need to be addressed. Transitioning from abstract representations to concrete implementations will require the Physical Analysis, PA, phase, which was not covered in this study. This phase is crucial for defining the actual system components and their technological specifications.

To improve coherence and operational efficiency, it will be also essential to further refine the logical functions and integrate them into the system components. Moreover, extensive testing and simulations are necessary to validate and optimize the design, evaluating the system's performance under realistic operating conditions.

Additionally, ongoing advancements in Capella™ will improve the accuracy and functionality of the model. The theoretical framework described in the , such as the Functional Tree and Product Tree, will act as a foundation for potential enhancements and technological progress.

In conclusion, this thesis presents a detailed framework for creating an analog space habitat by utilizing the MBSE approach and Capella™. The outcomes establish a strong basis for upcoming progress, presenting a systematic approach to habitat design and supporting the overarching objective of enhancing human space exploration. The system crafted in this research could potentially function as a dependable tool for validating technology, training astronauts, and engaging in scientific outreach activities. This further underscores the importance of analog missions in space exploration.

APPENDICES

A Radiation

This appendix provides a brief overview of radiation levels and the doses that can be absorbed by humans, along with their potential consequences. Radiation is measured in millisieverts (mSv), the unit of measurement for equivalent radiation dose in the international system of units of measurement. The equivalent dose quantifies the biological damage caused by radiation to an organism. The equivalent dose has the same dimensions as the absorbed dose, which is measured in gray (Gy) or energy per unit mass.

$$1Sv = 1Gy = 1\frac{J}{kg} \tag{A.1}$$

Subsequently, some subdivisions of doses and their related consequences are presented in Figure A.1 and Figure A.2.

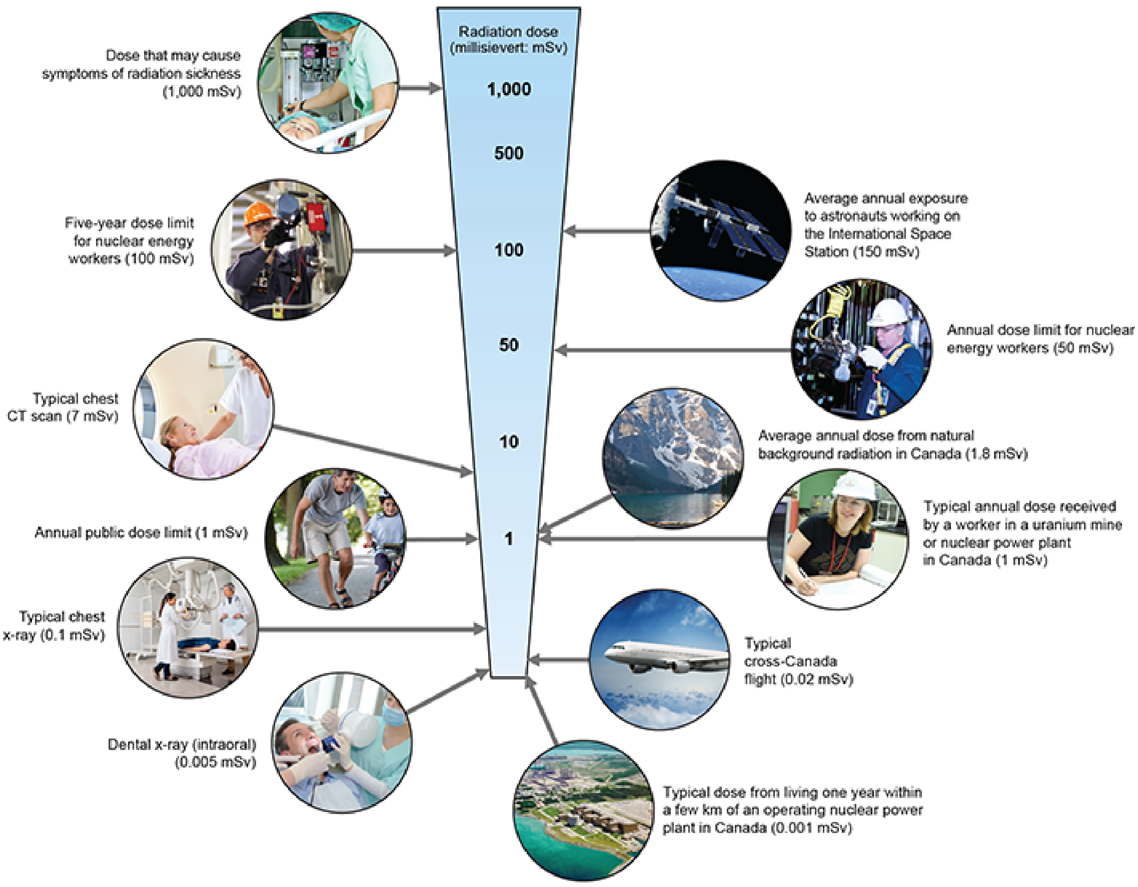
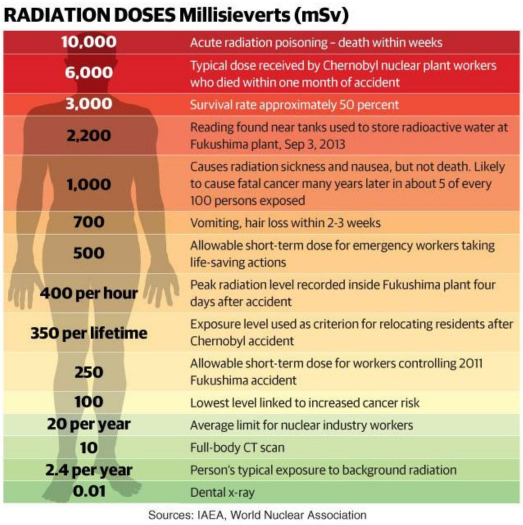


Figure A.1: Radiation Dose Examples [70].

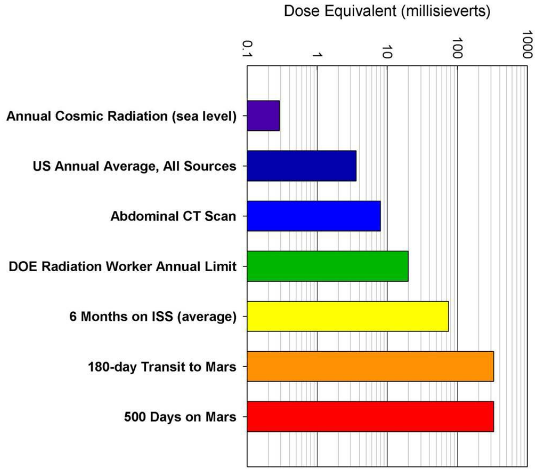


RADIATION DOSES Millisieverts (mSv)

10,000	Acute radiation poisoning - death within weeks
6,000	Typical dose received by Chernobyl nuclear plant workers who died within one month of accident
3,000	Survival rate approximately 50 percent
2,200	Reading found near tanks used to store radioactive water at Fukushima plant, Sep 3, 2013
1,000	Causes radiation sickness and nausea, but not death. Likely to cause fatal cancer many years later in about 5 of every 100 persons exposed
700	Vomiting, hair loss within 2-3 weeks
500	Allowable short-term dose for emergency workers taking life-saving actions
400 per hour	Peak radiation level recorded inside Fukushima plant four days after accident
350 per lifetime	Exposure level used as criterion for relocating residents after Chernobyl accident
250	Allowable short-term dose for workers controlling 2011 Fukushima accident
100	Lowest level linked to increased cancer risk
20 per year	Average limit for nuclear industry workers
10	Full-body CT scan
2.4 per year	Person's typical exposure to background radiation
0.01	Dental x-ray

Sources: IAEA, World Nuclear Association

(a) Radiation consequences [71].



(b) Radiation examples [72].

Figure A.2: Others Studies.

B ECLSS Components

This appendix provides a detailed analysis of the components and processes employed in Environmental Control and Life Support Systems, ECLSS, across three key temporal stages: historical implementations, current usage aboard the International Space Station, ISS, and prospective technologies being studied or tested for future missions. The analysis underscores both the immense complexity of developing highly advanced and mutually compatible processes and the practical constraints posed by current technological limitations.

B.1 Past Architecture

First, the summary Table B.1 is presented, outlining the historical ECLSS technologies utilized in U.S. and U.S.S.R./Russian space habitats. For the United States, the table includes technologies from the Mercury, Gemini, Apollo Command Module, Apollo Lunar Module, Skylab, Orbiter, and Spacelab programs. For the U.S.S.R./Russian missions, it includes technologies from the Vostok, Voskhod, Soyuz, Salyut, and Mir programs. A complete representation of these systems can be found in the referenced bibliography [39].

Table B.1: Historical ECLSS for U.S. and U.S.S.R./Russian Space Habitats [39].

Subsystem	USA	Russia
Thermal and Humidity Control	Heat exchangers CHX Electrical heaters Air duct/wall heaters	Liquid/air heat exchanger CHX — —
Heat exchange and ventilation	Coolant loop flow system radiators	Dehumidifier —
Equipment cooling	Cold plates High-emmitance coating Thermal capacitors	External Radiators — —
Atmosphere monitoring	Carbon monoxide sensor Draeger tubes CO	Gas analyzer (O_2,CO_2, H_2, CO) —
Gas storage	O_2/N_2 Storage tank O_2/N_2 Storage bottles	O_2/N_2/air storage —
Cabin ventilation	Fan Ventilation ducts	Fan Ventilation ducts
CO_2 removal	LiOH canister Molecular sieve canister	LiCl/LiOH canister/bed Reaction Oxygen regenerator
Gas recovery	—	Chemical cartridges of KO_2
O_2 generation	— — —	Chemical cartridges of KO_2 Water electrolysis Solid fuel Oxygen generator
Trace contaminant control	Activated charcoal — —	Filters Activated charcoal Catalytic chemical absrbents
Water processing	Vent waste water Condensate water stored Waste water stored	Vent waste water Condensate water stored Vapor diffusion distillation
Water monitoring	Iodine sampler	Water analyzer
Water storage and distribution	Tank pressurized bladder Cylindrical stainless steel tanks	Tank pressurized bladder Elastic polyethylene container
Water system microbial control	Chlorine/Iodine in water	Silver in water
FDS - Suppressant	Aqueos gel/Halon bottles	Portable extinguishers

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	Depressurize the cabin	—
FDS – Detection	Ultraviolet detectors Ionization smoke sensors	Optical sensors Ionization smoke sensors
WM – Fecal/urine handling	Bags Commode storage container Waste water tank for urine	Plastic/metal container Commode storage container Air stream collects both

B.2 Present and Future Architecture

Secondly, a selection of the technologies currently in use aboard the ISS is summarized in Table B.2 on the left, providing an overview of how these systems have evolved over time and their practical application in what remains, to date, the only long-duration human spaceflight mission. A complete list of these technologies, U.S. and Russian ISS segment, is provided in the reference [39].

Additionally, Table B.2 on the right presents some of the ongoing projects and future developments involving various innovative and enhanced technologies aimed at supporting upcoming lunar missions and, potentially, beyond. The objective is to offer a high-level overview of the technologies being researched and developed. For a more in-depth understanding and specific technical details, further information is available in the referenced literature [73].

Table B.2: Current and Future ECLS Technologies [39],[73].

Subsystem	**ISS**	**Development**
Thermal and Humidity Control	CHX — —	CHX with hydrophilic coating Additive manufacturing CHX Laser processed CHX
Heat exchange and ventilation	Cold Plates Heat exchanger Freon/water coolant loop	— — —
Equipment cooling	Fan	—
Atmosphere monitoring	Major constituents analyzer Anomaly gas analyzer — — —	Spacecraft atmosphere monitor Air quality monitor FlIR griffin trace gas monitor Tunable laser spectrometer Laser aim monitor
Gas storage	Cryogenic O_2 and N_2 storage	—
Cabin ventilation	Fan Vent	— —
CO_2 removal	Four bed carbon dioxide scrubber Thermal amine scrubber — — — —	Ionic liquid system Liquid amines Carbon dioxide deposition Rapid cycle adsorption Multi-sorbents Air-cooled adsorption
Gas recovery	Bacteria scroll filter Methane pyrolysis Bosch carbon reactors Sabatier reactions Carbon vapor deposition	Methane processor assembly ISS Sabatier upgrades — — —
O_2 generation	Oxygen generation assembly O2/N2 resupply tank for EVAs —	Static Vapor Feed Electrolysis Advanced OGA High-pressure O_2 generation

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	—	Compress low p 2 to high p
	—	Ceramic O_2 generation
Trace contaminant control	Activated charcoal Catalytic oxidizer Sorbent/filter	New sorbents Hydrogen chloride sorbents Airborne particulate monitor
Water processing	Water processor assembly Urine processor assembly Sabatier reactor — —	WPA upgrades Potable water dispenser UPA upgrades Planetary urine processor Wastewater bioreactors
Water monitoring	Measuring carbon content Conductivity compare samples — —	Conductivity silver sensor Fluorescent materials Organic carbon analyzer Water impurity monitor
Water storage	Metal Tanks	—
Water system microbial control	Iodine in water Silver in water — — —	Bromine and Chlorine Ultraviolet Silver XX Hydrogen peroxide Dormancy
FDS - Suppressant	CO2 extinguishers Depressurizing cabin	Argon inhibitor —
FDS – Detection	Photoelectric smoke detetors Thermal smoke detetors	— —
WM – Fecal/urine handling	Toilet with urine recycling Alternative fecal canister Hard-sided Fecal canister	Waste management system — —
Care and health maintenance	Advanced exercise device Space Treadmill Shower, Washing/dryer machines	European exercise device Blue lights —
Medical monitoring	Vital signs & blood analysis Radiation area monitor Ultrasound imaging Ocular and cardiovascular tests	Real time mobility assessments Crew health/perfomance data — —
Medical emergency equipment	Fluid loading protocols Medical Kits Blood pressure glucose metrics Automated external defibrillator Portable breathing apparatus Medical suction device	Optimizing fluid loading Intravenuos fluid generation Medical inventory system Electronic health record Multifunctional medical device Pharmacy
Telemedicine capabilities	Video link remote consultation Medical imagin Psychological support	— — —
FSP	Freeze-dried food pouches Ready to eat meals —	Incorporate crop growth Food intake tracking systems Others projects

Finally in subsubsection B.2.1, an overview of regenerative technologies and processes currently under study is provided, with a particular focus on regenerative food production programs. These advancements have the potential to redefine the state of the art in life support systems for space exploration. However, the subsubsection B.2.1 also highlights the persistent technological and operational limitations, emphasizing the importance of balancing ambitious objectives with the practical constraints of current and near-future capabilities.

B.2.1 Food Storage and Preparation FSP

Specifically, ensuring an adequate, nutritious and sustainable food supply is a fundamental challenge for long-duration space missions, particularly for future Mars exploration. Astronauts currently rely on pre-packaged food systems, primarily consisting of freeze-dried food pouches that require rehydration and ready-to-eat meals stored in flexible containers. These packaging solutions are specifically designed to be lightweight, to minimize waste and to preserve food safety and quality throughout the mission [73].

As NASA prepares for missions beyond low Earth orbit, adjustments to the current space food system are crucial to meet the challenges of long-duration space travel [40]. To do this, there are various obstacles.

One significant challenge is ensuring that space food can remain utilizable for extended periods. While current space food can last 1-3 years, missions to Mars, for example, may require food with a shelf life of at least 5 years. Research is concentrating on improving shelf food life without compromising nutritional content. Although the idea of cold storage is being considered, it presents challenges due to limited resources [74].

Another aspect concerned maintaining a balanced diet and ensuring crew members find the food acceptable are also key concerns. Limited and monotonous food options during long missions can lead to weight loss and can reduce crew appetite. Exploring the integration of crop production for in-flight food production is a way to provide fresh produce and enhance dietary variety [74].

Lastly, to meet time constraints, it is essential for meal preparation to be efficient and simple. Future systems are being developed to reduce preparation time while ensuring meals efficiency [74].

In parallel, NASA has to work on advancing technologies to overcome limitations in resources such as mass, volume, water and power. Some examples are specialized crop production units, designed for microgravity conditions, water recycling and oxygen production systems. NASA is also aiming to decrease the water content of prepackaged foods to reduce reliance on external resupply efforts [74].

All these efforts due to the fact that the success of space missions in the long term relies on ensuring the health and performance of astronauts. Research is continuously being conducted to enhance the space food system to address these requirements. NASA's goal is to create a robust and efficient food system that can support astronauts during extended space journeys [74].

With NASA programs, there are also many relevant programs that are proposed with a brief analysis, to give an additional understanding of this aspect, in succession:

- VEGGIE - NASA [75]
- MELISSA - ESA [48]
- EDEN - DLR [76]
- SpaCEA - CSA [77]

B.2.2 VEGGIE - 2014 to today

The Veggie vegetable production system was developed and launched to the ISS as part of the VEG-01 series, which aimed to validate the hardware for growing crops in microgravity.

The Veggie system, developed by ORBITEC, is a low-mass, low-power plant growth chamber designed for space environments, requiring minimal crew time while offering expandable capacity for effective food crop production [75].

Launched to the ISS in 2014, Veggie was installed in the ISS's Columbus module. Veggie operates with a power supply of approximately 70 watts, powering the lighting and fans, and facilitating cooling air circulation for the lighting array [75].

Veggie uses a LED lighting array featuring red, blue, and green wavelengths, along with a fan to circulate cabin air through the system. The hardware's flexible, transparent bellows can be adjusted to accommodate various crops and growth phases, as shown in Figure B.1. The system includes a passive wicking irrigation mechanism, designed with a 2-liter reservoir to hydrate plant pillows [75].

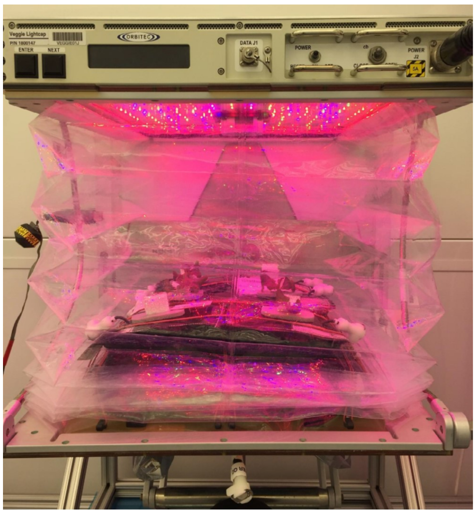


Figure B.1: VEGGIE HARDWARE [75].

In the VEG-01 series, half of the plant pillows were filled with a substrate size of 600 μm-1 mm, while the other half contained a blend of 600 μm-1 mm and 1-2 mm substrates. The seeds were germinated in the pillows, glued into place with guar gum, and sealed in gas-impermeable bags for transport. Upon arrival on the ISS, the pillows were hydrated with potable water through a quick-disconnect system and periodically tended by the crew. Operations included adjusting light intensity and fan speed, thinning seedlings, and carrying out periodic watering and photography [75].

Researches Conducted

The initial experiments of VEG-01 concentrated on cultivating 'Outredgeous' red romaine lettuce and 'Profusion' zinnia plants to evaluate their growth and blooming in space. These tests highlighted significant challenges related to irrigation, with the lettuce not receiving enough water and the zinnias being overwatered. The crew manually watered the plants, leading to improved growth, and the lettuce grown met safety standards for consumption. Despite encountering some fungal issues, two zinnia plants managed to survive and bloom [75].

The VEG-01 series offered valuable insights into the performance of systems, human aspects, plant microbiology, and the chemistry of plants cultivated in microgravity. These discoveries are contributing to the enhancement of future equipment and the advancement of our knowledge regarding plant growth in space [75].

In continuation of the VEG-01 project, the VEG-03 experiment was conducted with the goal of enhancing plant growth conditions on the ISS. This experiment specifically concentrated on cultivating 'Outredgeous' lettuce and 'Tokyo Bekana' Chinese cabbage due to their nutritional benefits and sensory qualities. To optimize yield, a method known as cut-and-come-again was employed for harvesting the crops [75].

NASA is working on implementing a new powered watering system to tackle irrigation issues and enhance oxygen distribution. This system is expected to decrease the workload for the crew members and promote consistency in crop growth.

The upcoming experiments, VEG-04 and VEG-05, will investigate the effects of varying light ratios and fertilizer compositions on the development and nutritional content of leafy greens and dwarf tomatoes in a microgravity environment [75].

These advancements are geared towards establishing a robust and effective food production system to support astronauts during extended space missions.

Conclusion

The Veggie system aboard the ISS is contributing significantly to our understanding of growing food in space, addressing the challenges posed by microgravity on plant growth. Data from the VEG-01 and VEG-03 experiments have highlighted the need for improved irrigation systems and a deeper understanding of the interaction between plant growth, water, and nutrient delivery in space. Ongoing and future experiments will continue to refine the system, making space-grown food a viable option for long-duration missions, such as those to Mars, and further advancing space agriculture research.

B.2.3 MELISSA - 90s to today

The Micro-Ecological Life-Support System Alternative, MELISSA, project aims to develop closed and regenerative life-support systems for long-duration space missions. Inspired by terrestrial aquatic ecosystems, MELISSA processes organic waste such as urine and carbon dioxide, to provide essential resources like food, water and oxygen in a closed-loop system.

The project consists of five main sub-processes that simulate the complex ecological interactions necessary for sustaining life in space. These five steps concerned different type of bacteria as thermophilic anoxygenic bacteria, photo-heterotrophic bacteria, nitrifying bacteria, photosynthetic bacteria and higher plants. All these actors react all together to contribute to food production, oxygen release and water generation, completing the closed-loop system alongside the crew by recycling CO_2 into oxygen and providing essential nutrients [48].

MELISSA is comprised of four compartments, all related among them. They are:

- Solid Organic Waste Processing - Compartment C1

  In this compartment, thermophilic bacteria carry out anaerobic digestion on organic waste such as feces, kitchen scraps and plant leftovers. Through this process, the waste is transformed into volatile fatty acids, minerals and CO_2. These by-products are then directed to Compartment C4 to support photosynthesis [48].

- Liquid Organic Waste Processing - Compartment C2

  Rhodospirillum rubrum bacteria process volatile fatty acids and liquefied organic matter from C1 in an environment without oxygen. To enhance CO_2 recovery, an electrochemical reaction can be integrated into this system, leading to the redirection of the recovered CO_2 to C4 [48].

- Ammonium and Mineral Processing - Compartment C3

  Nitrifying bacteria process the ammonium and minerals from C2, as well as the urine from the crew, converting the ammonium into nitrate. Oxygen from C4 is essential for this process, and the nitrate and minerals produced help in promoting plant growth in C4 [48].

- Plant and Algae Growth - Compartment C4

  Split into two sections, C4a and C4b, this area utilizes cyanobacteria in C4a to transform CO_2 into oxygen and food. In C4b, higher plants are grown to generate food and release oxygen. Through transpiration, clean water is produced for the crew, guaranteeing the reuse of CO_2 and the production of oxygen for breathable air [48].

All the compartments and their reports are detailed in the Figure B.2.

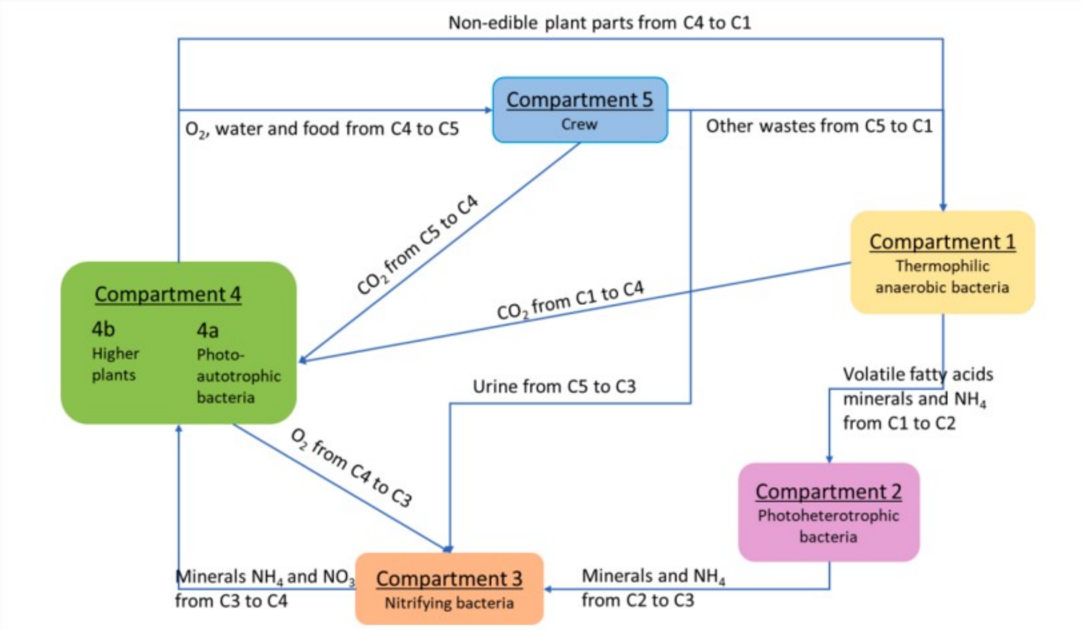


Figure B.2: MELISSA Loop [48].

Conclusion

The MELISSA project represents a pioneering effort to develop closed-loop life support systems that recycle organic waste into essential resources. By addressing challenges related to nutrient recovery, water management, and system integration, MELISSA is poised to play a critical role in supporting long-term human exploration of space.

B.2.4 EDEN - 2016 to today

The EDEN-ISS, shown in Figure B.3, project offers important knowledge about space agriculture, especially for the ISS.

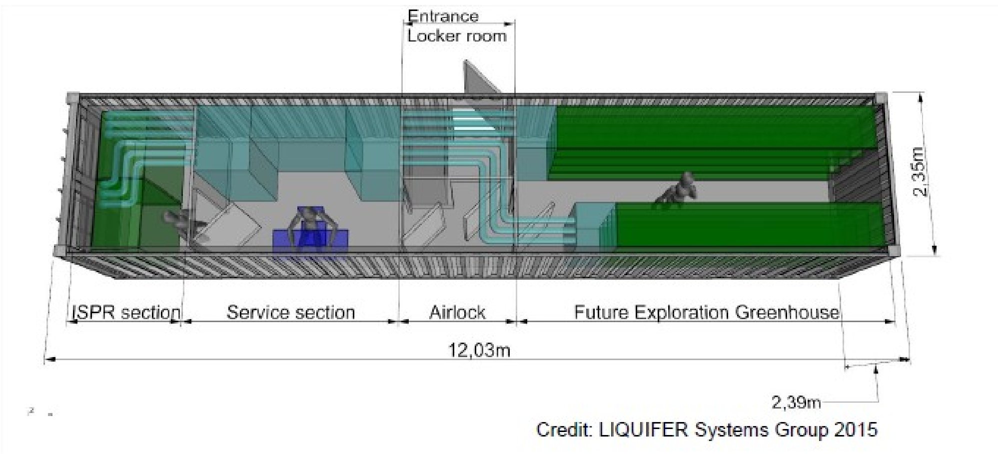


Figure B.3: EDEN ISS Structure [76].

The main goal of the EDEN-ISS project is to enhance space agriculture through the experimentation of plant growth systems in Antarctica. This initiative is crucial for preparing for upcoming experiments on the ISS. The plant growth system is designed to work harmoniously with ISS operations and provides different setups, ranging from a quarter rack for subsystem tests to a full rack equipped with multiple growth chambers [76].

The International Standard Payload Rack, ISPR, shown in Figure B.4 is a compact cultivation unit with a growing area of 0.5-1.0 m^2, depending on its configuration. In contrast, the Future Exploration Greenhouse, a part of the EDEN-ISS Mobile Test Facility, provides a larger growing area of approximately 31 m^3 in volume and 12 m^2 for crop cultivation. This expanded setup allows the greenhouse to test a broader range of crops and higher yields, thereby exploring the psychological benefits of plant-based environments for isolated crews [76].

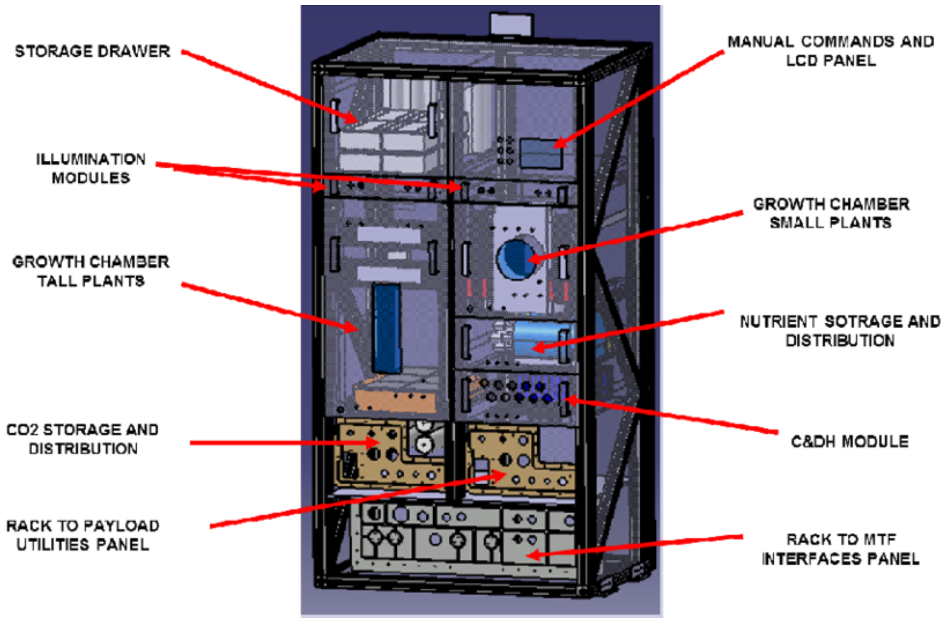


Figure B.4: ISPR [76].

Within the ISPR system, there are designated areas for power, command, data handling, nutrient storage, and distribution. Each growth chamber is equipped with its own lighting and air management system. Additionally, a control panel for manual monitoring and adjustment is incorporated into the setup [76].

Additionally, in this program a method has been created to choose the most suitable plants for growing in space. This method takes into account factors such as growth traits, engineering limitations, nutritional requirements and psychological aspects. It involves a systematic process that includes a scoring mechanism to assess and rank plants, guaranteeing they fulfill the particular demands of space expeditions [76].

When applied to the ISS and the greenhouse at Neumayer III station in Antarctica, this method gives preference to vegetables and herbs that yield top-notch fresh produce. By focusing on these crops, the method enhances food cultivation, promotes the well-being of astronauts, and paves the way for future progress in space farming [76].

Conclusion

In conclusion, the careful selection of crops based on objective criteria is critical to meeting the nutritional, psychological, and operational needs of long-duration space missions. The methodologies developed in the EDEN-ISS project are helping to improve food production capabilities, enhance astronaut well-being, and lay the groundwork for future advancements in space agriculture.

B.2.5 SpaCEA - 2014 to today

The SpaCEA project presents a small plant growth chamber, as shown in Figure B.5, that is simple to produce and put together.

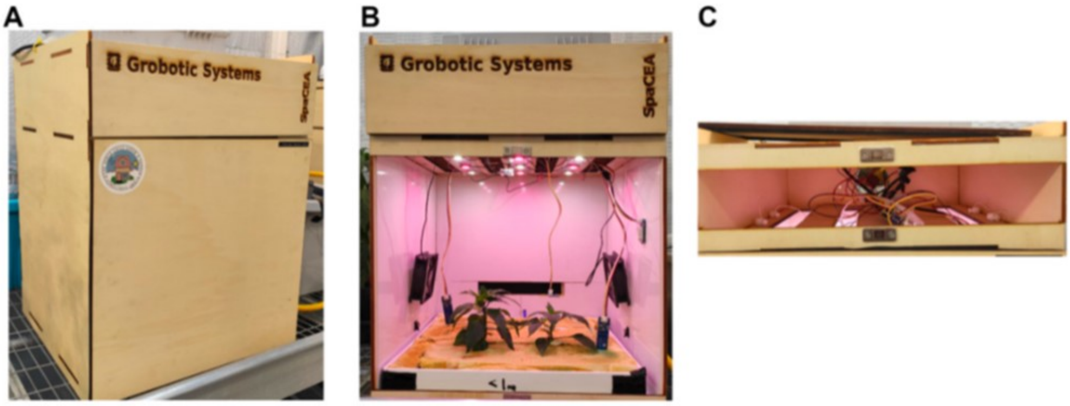


Figure B.5: SpaCEA Chamber [77].

Taking cues from the Grobot alpha chamber by Grobotic Systems, this chamber provides a 40 cm^3 area for plants to grow. It includes customizable LED lighting, fans for ventilation, a built-in camera, environmental sensors and an automatic watering system. The design is modular, enabling easy assembly and is managed by an microcontroller along with specialized software [77].

SpaCEA offers an open-source plant growth protocol, that helps in controlling growth conditions and collecting data. The manufacturing process involves using distributed production methods and sharing digital schematics to lower expenses and enable customization at a local level. For instance, parts such as the chamber chassis are made by laser-cutting durable materials, making assembly simple even without specific skills. The electronic components can either be bought pre-assembled or manufactured locally using open-source design files, which encourages adaptability and innovation within the community [77].

Moreover, the BRIDGES framework, used in SpaCEA Chamber, combines biological and physicochemical processes to promote sustainable food production in various settings, such as space. It establishes consistent testing conditions to streamline monitoring, automation, connectivity and data gathering in experiments on plant growth. This approach guarantees harmonization with SpaCEA and other research platforms, thereby propelling the development of plant-centric life support systems for extended space missions [77].

Conclusion

Through the integration of technological advancements, open-source approaches, and sustainable design concepts, projects like Veggie, APH, SpaCEA, and BRIDGES not only improve astronaut well-being but also lay the groundwork for future agricultural systems beyond Earth.

C Functional Analysis

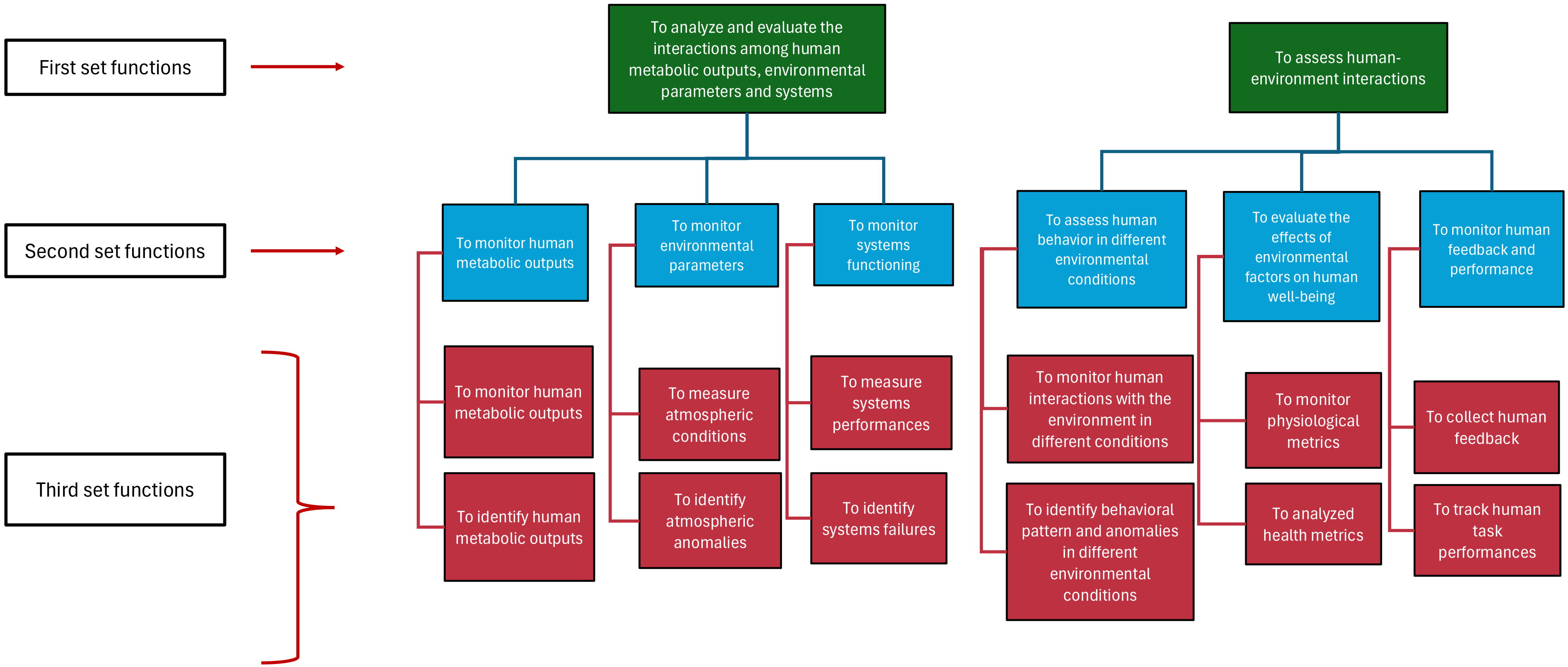
This appendix presents the second part of the theoretical framework, which serves as the foundation for the actual design process in Capella™. Ideally, this work should be carried out only partially before being further developed within Capella™, based on the elements identified in section 3, provided that the preceding phases have been correctly executed. However, it has been included here because the not the all design phases are conducted in Capella™. Consequently, these representations and models may prove valuable for future developments, as they explicitly outline the initial conceptual framework established in this project.

Following the work conducted in section 3, the theoretical framework aims to identify the potential functions and, consequently, the products, components, and systems that the overall system must incorporate to achieve the mission objectives. As previously mentioned, this work should ideally be performed only partially and not in excessive detail, serving merely as a foundation for the subsequent work in Capella™, which is expected to make the process more efficient, intuitive, and streamlined, provided it is correctly executed. Capella™ has been specifically designed to simplify and accelerate this phase, avoiding the lengthy and sometimes complex process described in the following sections.

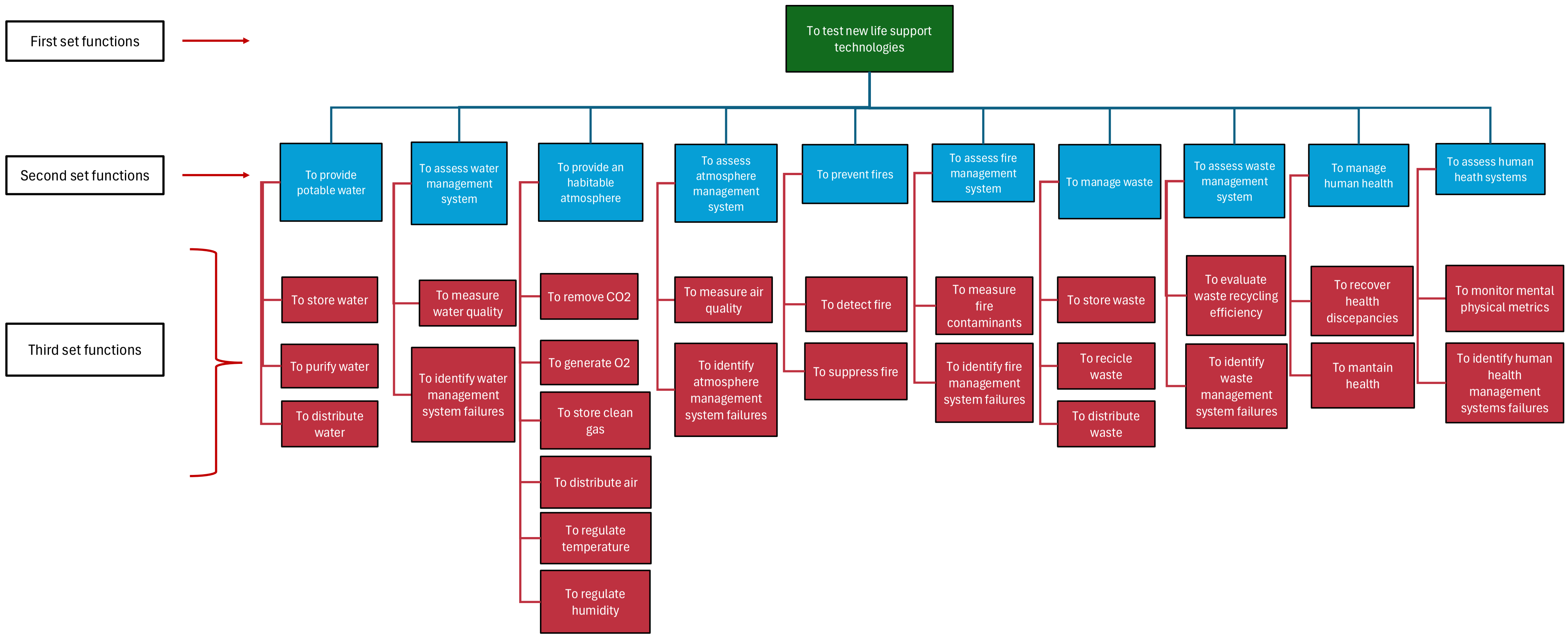
The Functional Tree and Product Tree, derived from the mission objectives, are therefore presented.

C.1 Functional Tree

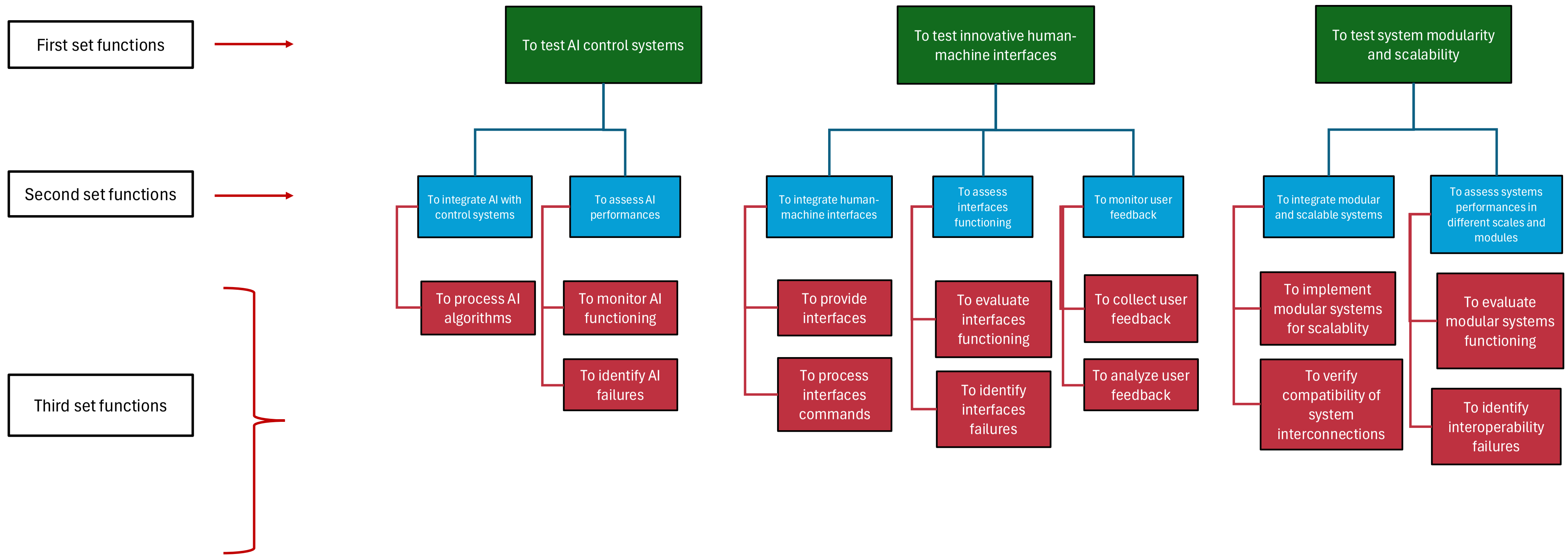
Three different sets of functions are presented, ranging from high-level functions to more specific and lower-level ones.

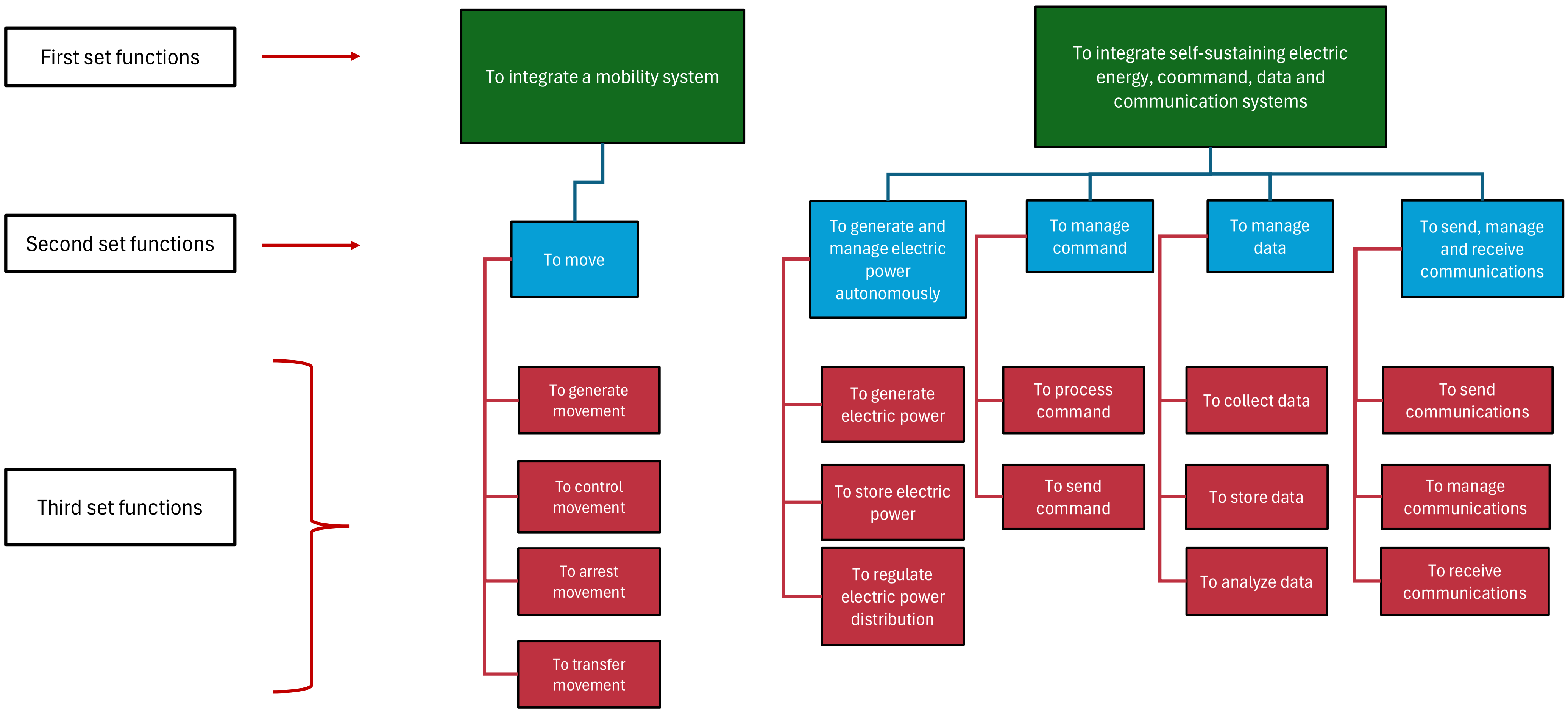


First set functions
Second set functions
Third set functions
To analyze and evaluate the interactions among human metabolic outputs, environmental parameters and systems
To assess human-environment interactions
To monitor human metabolic outputs
To monitor environmental parameters
To monitor systems functioning
To assess human behavior in different environmental conditions
To evaluate the effects of environmental factors on human well-being
To monitor human feedback and performance
To monitor human metabolic outputs
To identify human metabolic outputs
To measure atmospheric conditions
To identify atmospheric anomalies
To measure systems performances
To identify systems failures
To monitor human interactions with the environment in different conditions
To identify behavioral pattern and anomalies in different environmental conditions
To monitor physiological metrics
To analyzed health metrics
To collect human feedback
To track human task performances



First set functions
Second set functions
Third set functions
To test new life support technologies
To provide potable water
To store water
To purify water
To distribute water
To assess water management system
To measure water quality
To identify water management system failures
To provide an habitable atmosphere
To remove CO2
To generate O2
To store clean gas
To distribute air
To regulate temperature
To regulate humidity
To assess atmosphere management system
To measure air quality
To identify atmosphere management system failures
To prevent fires
To detect fire
To suppress fire
To assess fire management system
To measure fire contaminants
To identify fire management system failures
To manage waste
To store waste
To recicle waste
To distribute waste
To assess waste management system
To evaluate waste recycling efficiency
To identify waste management system failures
To manage human health
To recover health discepancies
To mantain health
To assess human heath systems
To monitor mental physical metrics
To identify human health management systems failures


First set functions
Second set functions
Third set functions
To test AI control systems
To integrate AI with control systems
To assess AI performances
To process AI algorithms
To monitor AI functioning
To identify AI failures
To test innovative human-machine interfaces
To integrate human-machine interfaces
To assess interfaces functioning
To monitor user feedback
To provide interfaces
To process interfaces commands
To evaluate interfaces functioning
To identify interfaces failures
To collect user feedback
To analyze user feedback
To test system modularity and scalability
To integrate modular and scalable systems
To assess systems performances in different scales and modules
To implement modular systems for scalablity
To verify compatibility of system interconnections
To evaluate modular systems functioning
To identify interoperability failures


First set functions
Second set functions
Third set functions
To integrate a mobility system
To move
To generate movement
To control movement
To arrest movement
To transfer movement
To integrate self-sustaining electric energy, coommand, data and communication systems
To generate and manage electric power autonomously
To generate electric power
To store electric power
To regulate electric power distribution
To manage command
To process command
To send command
To manage data
To collect data
To store data
To analyze data
To send, manage and receive communications
To send communications
To manage communications
To receive communications

C.2 Product Tree

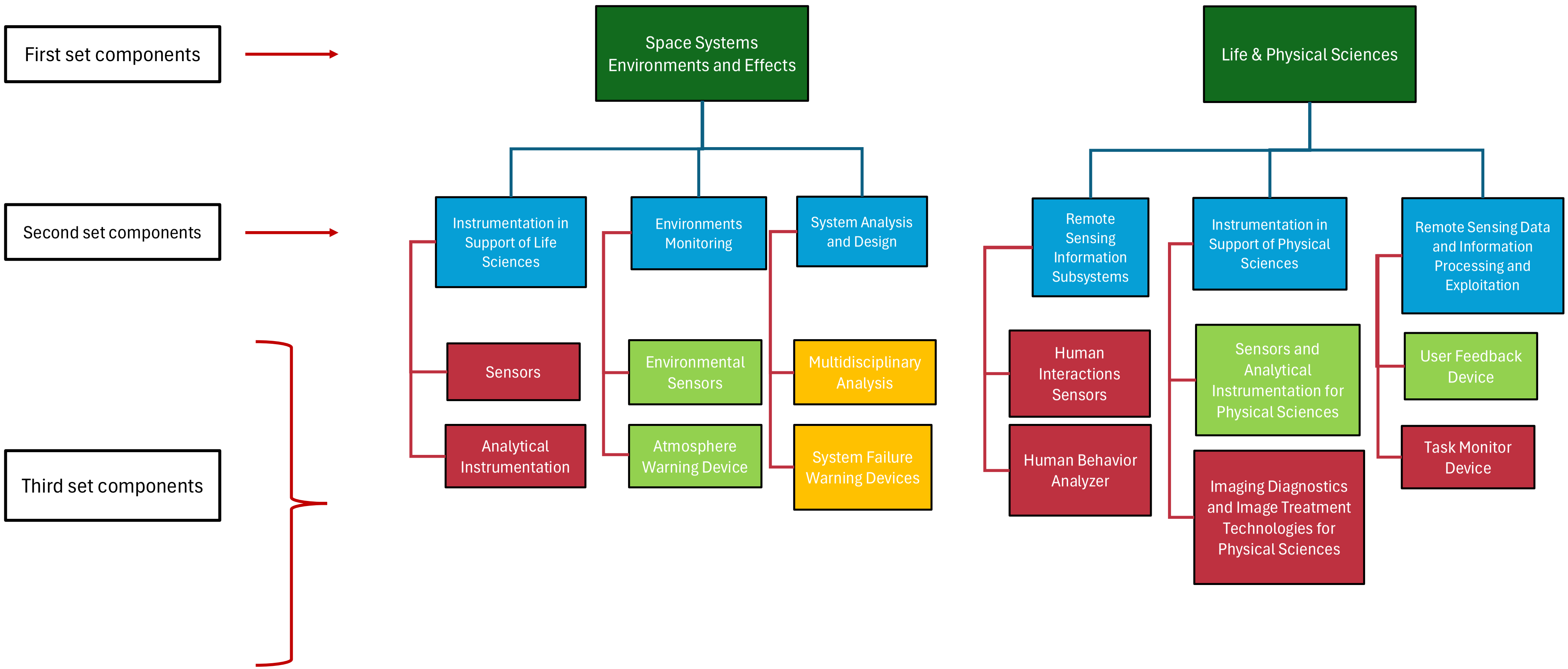
The Product Tree is presented based on the three sets of functions described earlier. Whenever possible, the naming of the products has been carried out in alignment with the functions defined in the Functional Tree while following the ESA Technology Tree [68] descriptions.

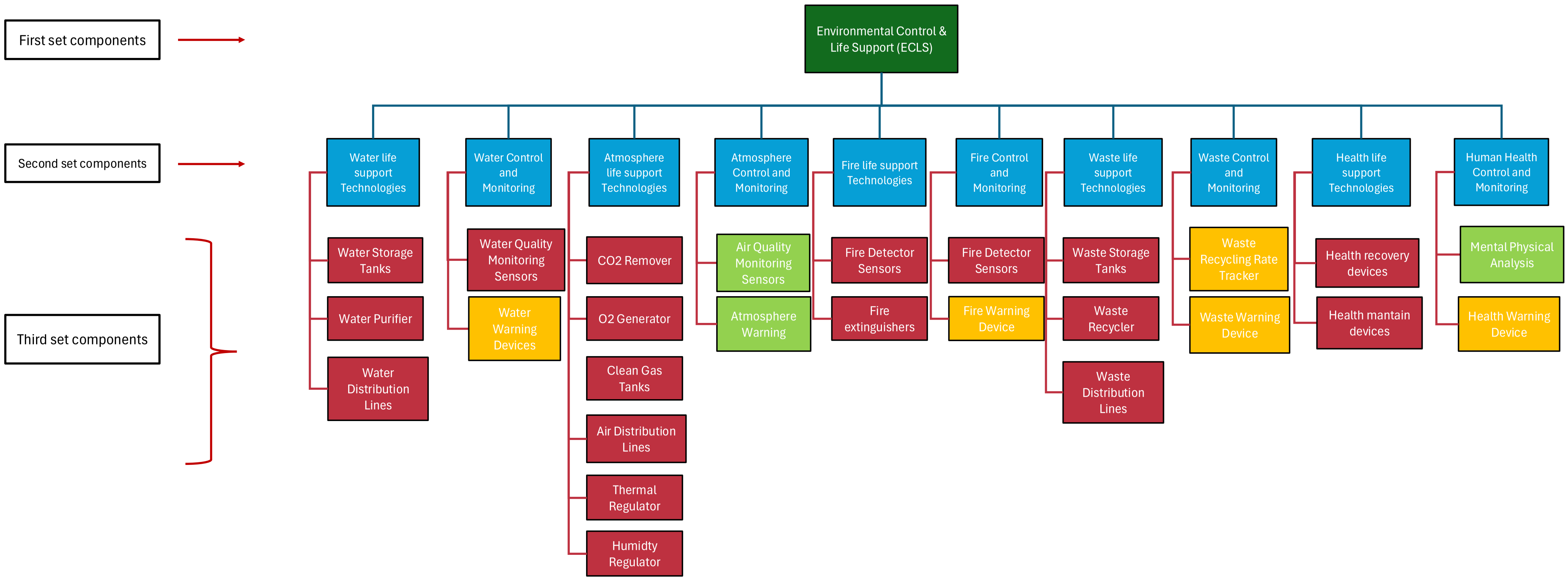
The ESA Technology Tree includes numerous components for each technology category. However, in this document, only the names corresponding to the functions defined within this work are used. These may be incomplete and require further revisions or iterations, as will later be performed in Capella™.

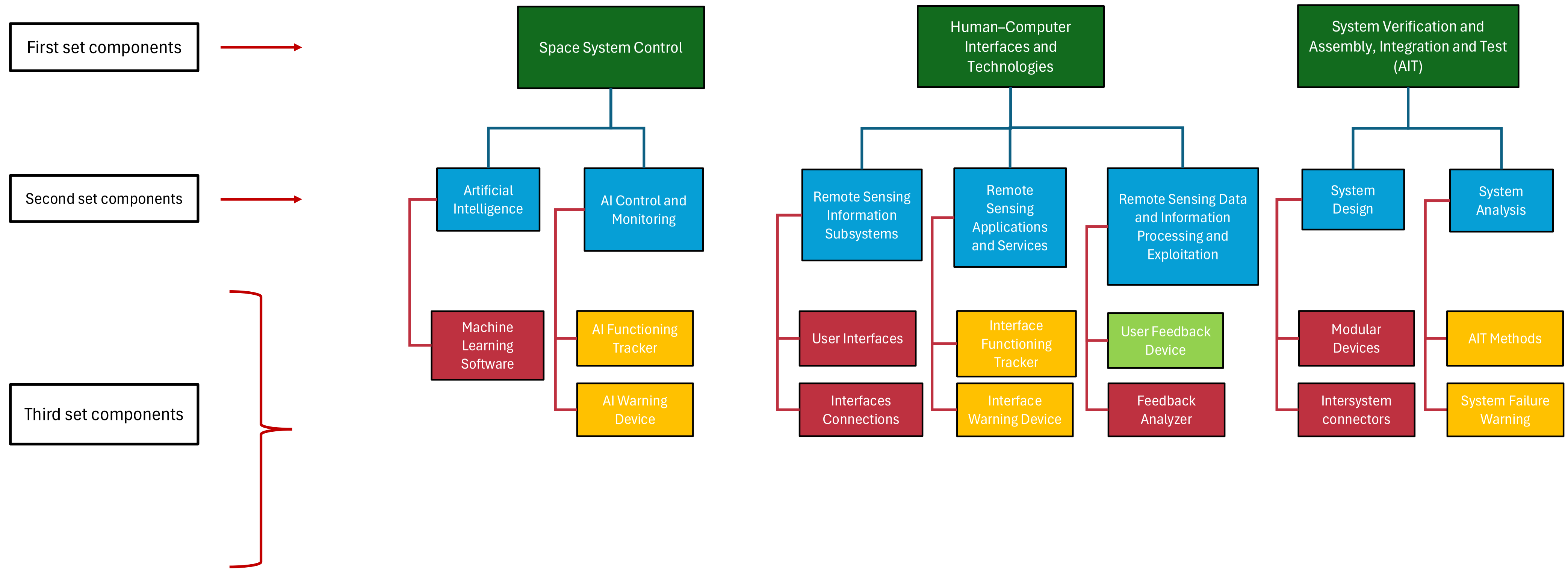
Initially, the functions were defined, which has led to some misalignment with the described components and their respective groupings. Additionally, the definitions of components and sub-components do not entirely align with those in the ESA Technology Tree. To address this, the adopted approach seeks to choose the most suitable naming conventions from the reference document concerning the defined components.

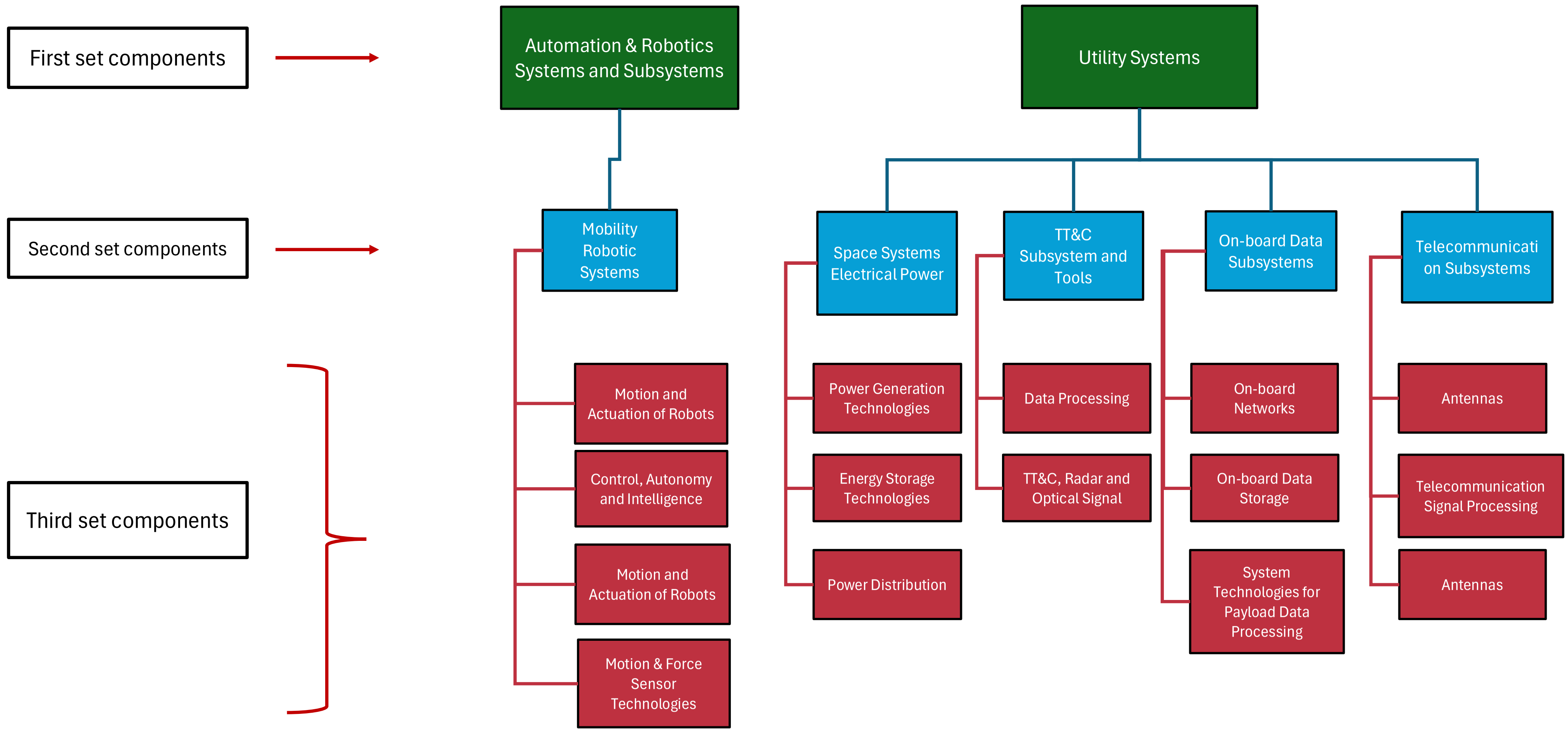
Products highlighted in green are duplicated or can be considered redundant. Products highlighted in yellow could potentially be grouped into two unified products. For example, a single alarm system for all systems in case of malfunction and/or a unified monitoring system to ensure the proper functioning of all systems.

It is important to note that this phase is precisely what the MBSE approach aims to avoid. However, it is included here in the hope that it may serve as a foundation for potential and valuable future improvements.


First set components
Second set components
Third set components
Space Systems Environments and Effects
Instrumentation in Support of Life Sciences
Environments Monitoring
System Analysis and Design
Sensors
Analytical Instrumentation
Environmental Sensors
Atmosphere Warning Device
Multidisciplinary Analysis
System Failure Warning Devices
Life & Physical Sciences
Remote Sensing Information Subsystems
Instrumentation in Support of Physical Sciences
Remote Sensing Data and Information Processing and Exploitation
Human Interactions Sensors
Human Behavior Analyzer
Sensors and Analytical Instrumentation for Physical Sciences
Imaging Diagnostics and Image Treatment Technologies for Physical Sciences
User Feedback Device
Task Monitor Device


First set components
Second set components
Third set components
Environmental Control & Life Support (ECLS)
Water life support Technologies
Water Storage Tanks
Water Purifier
Water Distribution Lines
Water Control and Monitoring
Water Quality Monitoring Sensors
Water Warning Devices
Atmosphere life support Technologies
CO2 Remover
O2 Generator
Clean Gas Tanks
Air Distribution Lines
Thermal Regulator
Humidty Regulator
Atmosphere Control and Monitoring
Air Quality Monitoring Sensors
Atmosphere Warning
Fire life support Technologies
Fire Detector Sensors
Fire extinguishers
Fire Control and Monitoring
Fire Detector Sensors
Fire Warning Device
Waste life support Technologies
Waste Storage Tanks
Waste Recycler
Waste Distribution Lines
Waste Control and Monitoring
Waste Recycling Rate Tracker
Waste Warning Device
Health life support Technologies
Health recovery devices
Health mantain devices
Human Health Control and Monitoring
Mental Physical Analysis
Health Warning Device


First set components
Second set components
Third set components
Space System Control
Artificial Intelligence
AI Control and Monitoring
Machine Learning Software
AI Functioning Tracker
AI Warning Device
Human–Computer Interfaces and Technologies
Remote Sensing Information Subsystems
Remote Sensing Applications and Services
Remote Sensing Data and Information Processing and Exploitation
User Interfaces
Interfaces Connections
Interface Functioning Tracker
Interface Warning Device
User Feedback Device
Feedback Analyzer
System Verification and Assembly, Integration and Test (AIT)
System Design
System Analysis
Modular Devices
Intersystem connectors
AIT Methods
System Failure Warning


First set components
Second set components
Third set components
Automation & Robotics Systems and Subsystems
Mobility Robotic Systems
Motion and Actuation of Robots
Control, Autonomy and Intelligence
Motion and Actuation of Robots
Motion & Force Sensor Technologies
Utility Systems
Space Systems Electrical Power
Power Generation Technologies
Energy Storage Technologies
Power Distribution
TT&C Subsystem and Tools
Data Processing
TT&C, Radar and Optical Signal
On-board Data Subsystems
On-board Networks
On-board Data Storage
System Technologies for Payload Data Processing
Telecommunicati on Subsystems
Antennas
Telecommunication Signal Processing
Antennas

D Capella Diagrams

This appendix presents the diagrams developed in Capella™ that were not referenced during the analysis. In particular, it includes scenarios similar to the one presented for technology testing, Figure 5.6, which were omitted in the OA, section 4, SA, section 5, and in the LA, section 6, to avoid redundancy but are provided here for the sake of completeness.

In the OA and SA, scenarios are identical as observed in the analysis. The only difference lies in the technologies being evaluated, while the design stages maintain consistent features.

Conversely, in the case of LA, each scenario is distinct. The decision to put the remains scenario in appendix was made to focus on describing a single scenario during the analysis, avoiding excessive emphasis on the descriptions. The rationale applied to the main scenarios can also be extended to the logical scenarios presented in this appendix.

D.1 Operational Analysis Diagrams

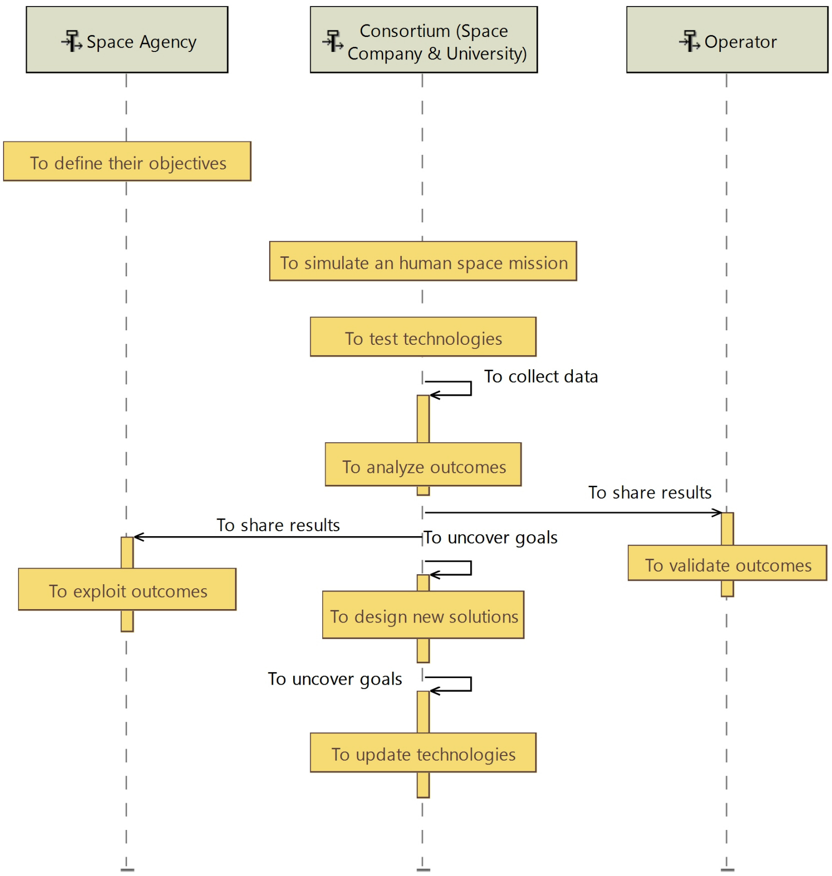


Figure D.1: [OES] Support Technologies Scenario.

D.2 System Analysis Diagrams

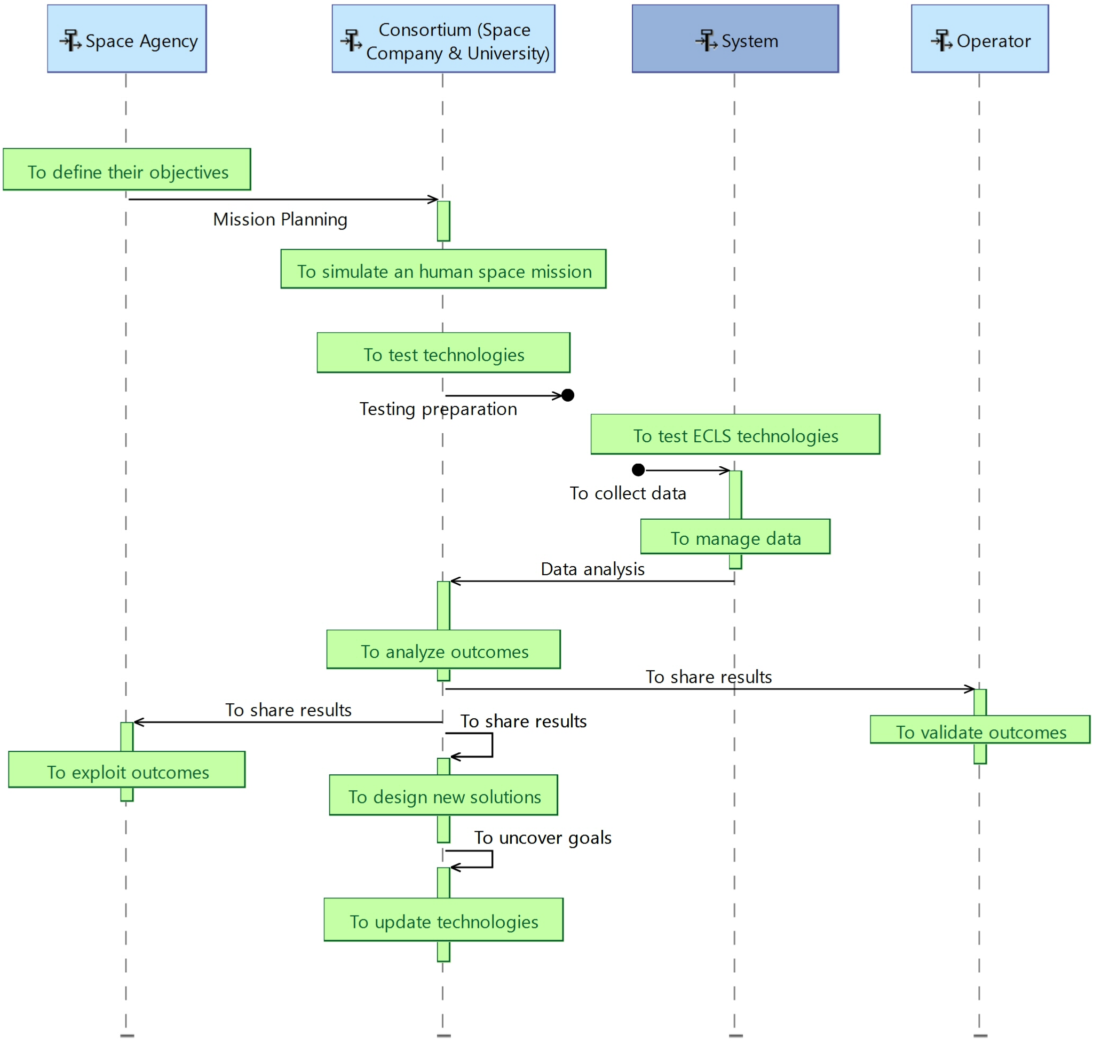


Figure D.2: [ES] ECLS Technologies Scenario.

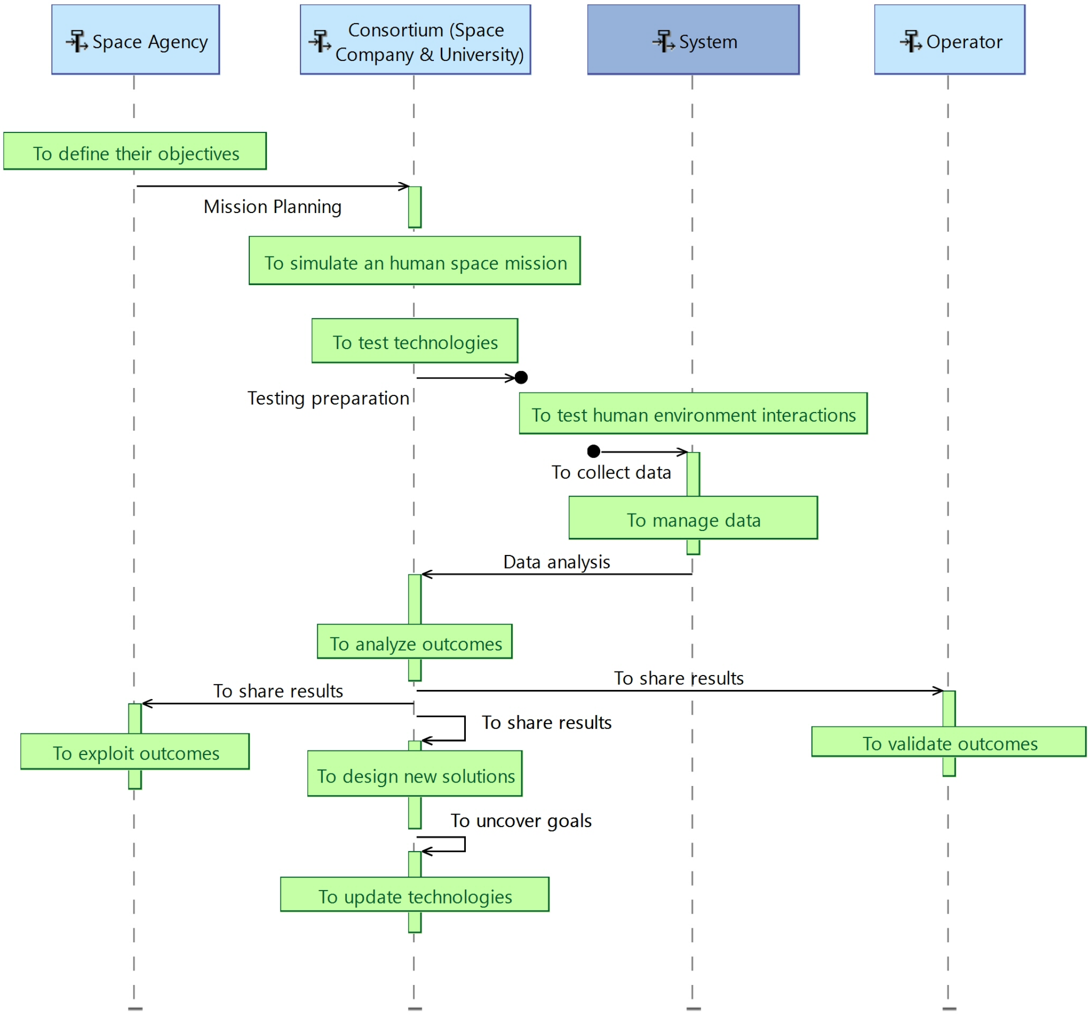


Figure D.3: [ES] Human Environment Interactions Scenario.

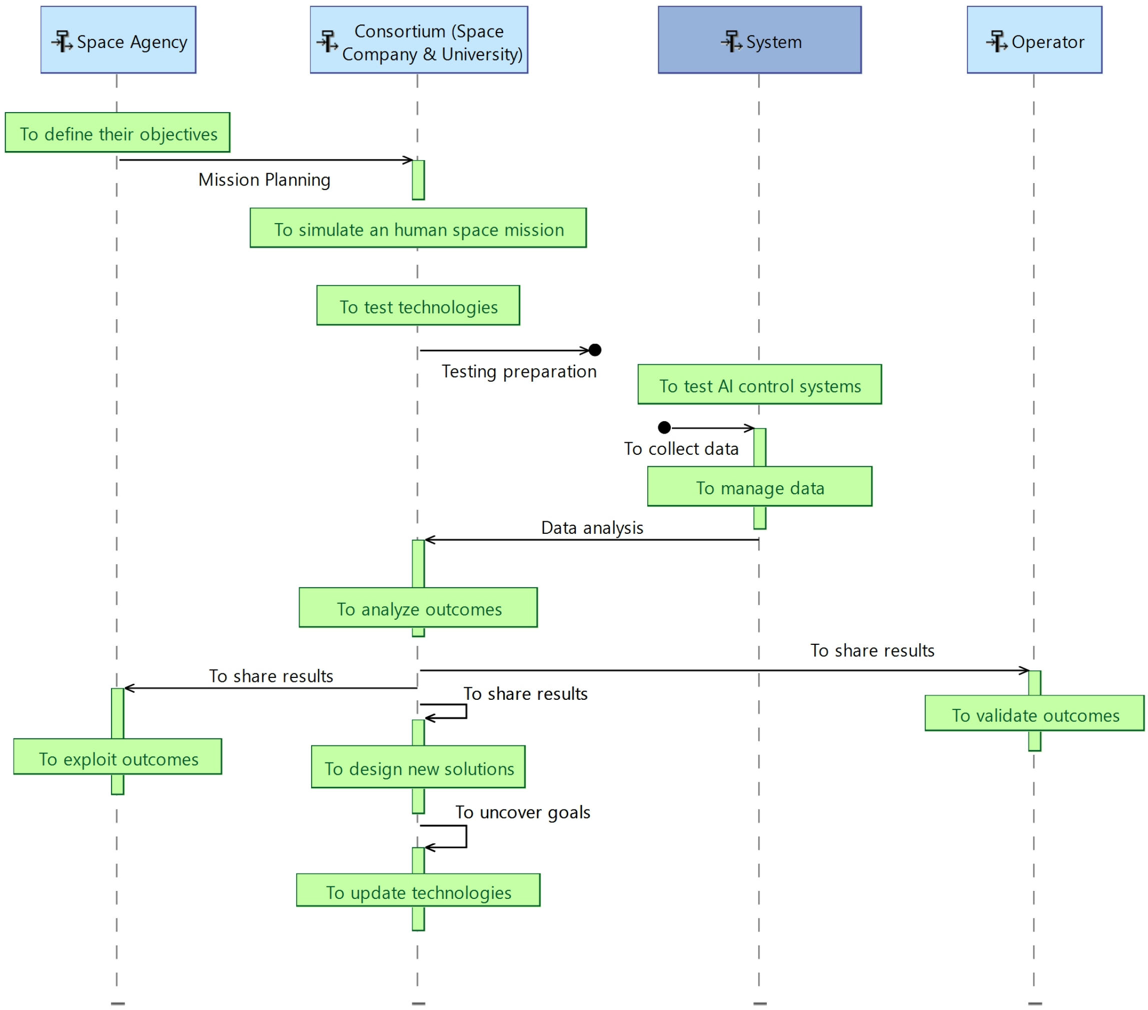


Figure D.4: [ES] AI Scenario.

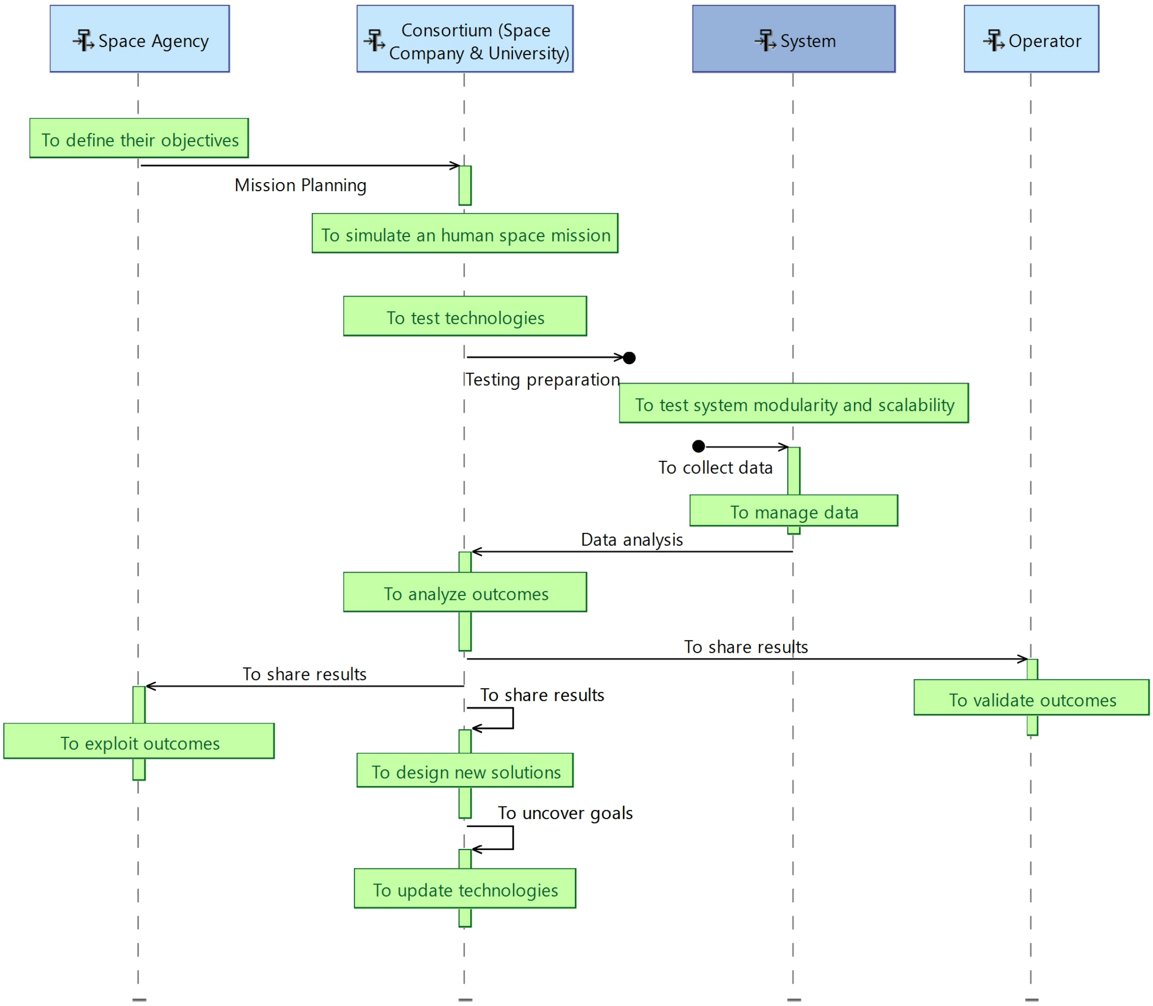


Figure D.5: [ES] System Modularity and Scalability Scenario.

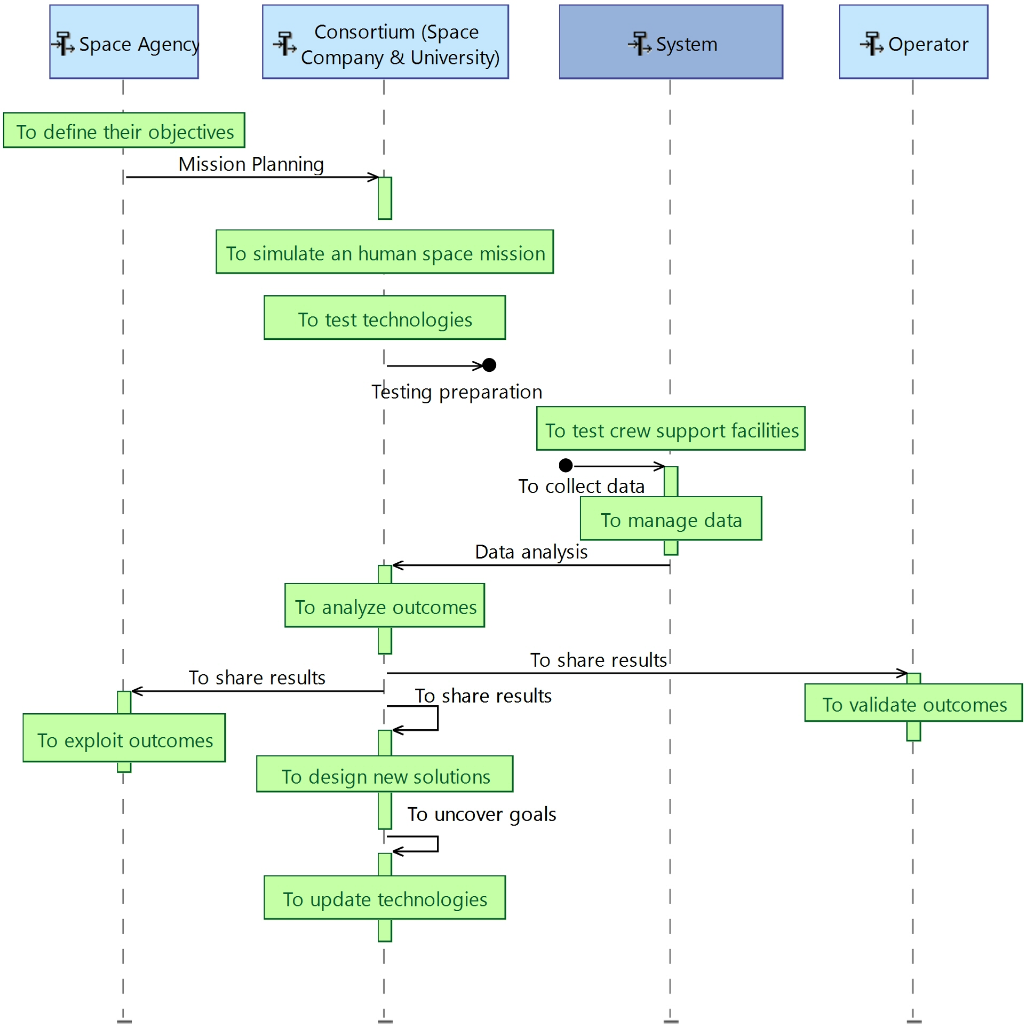
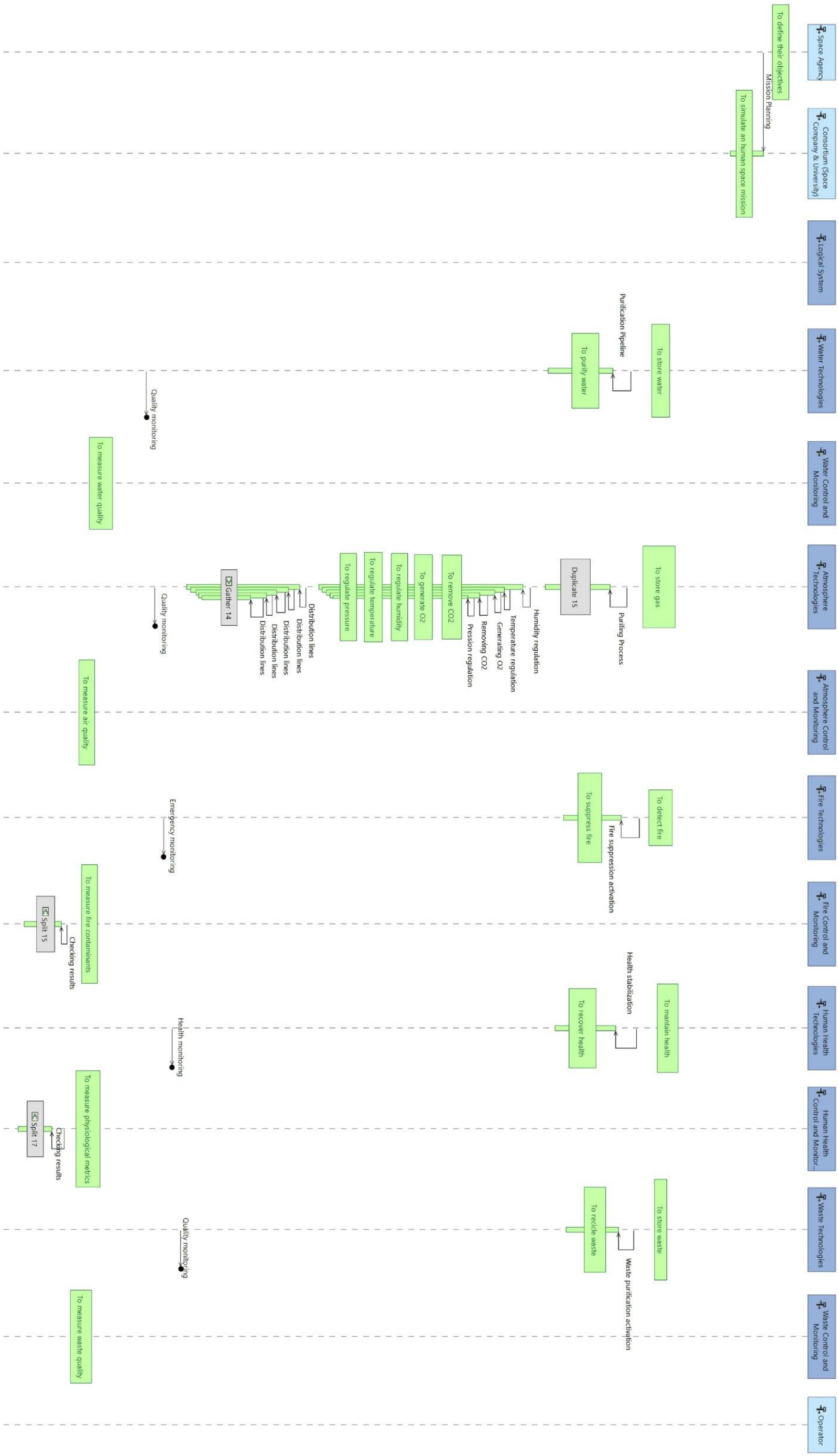
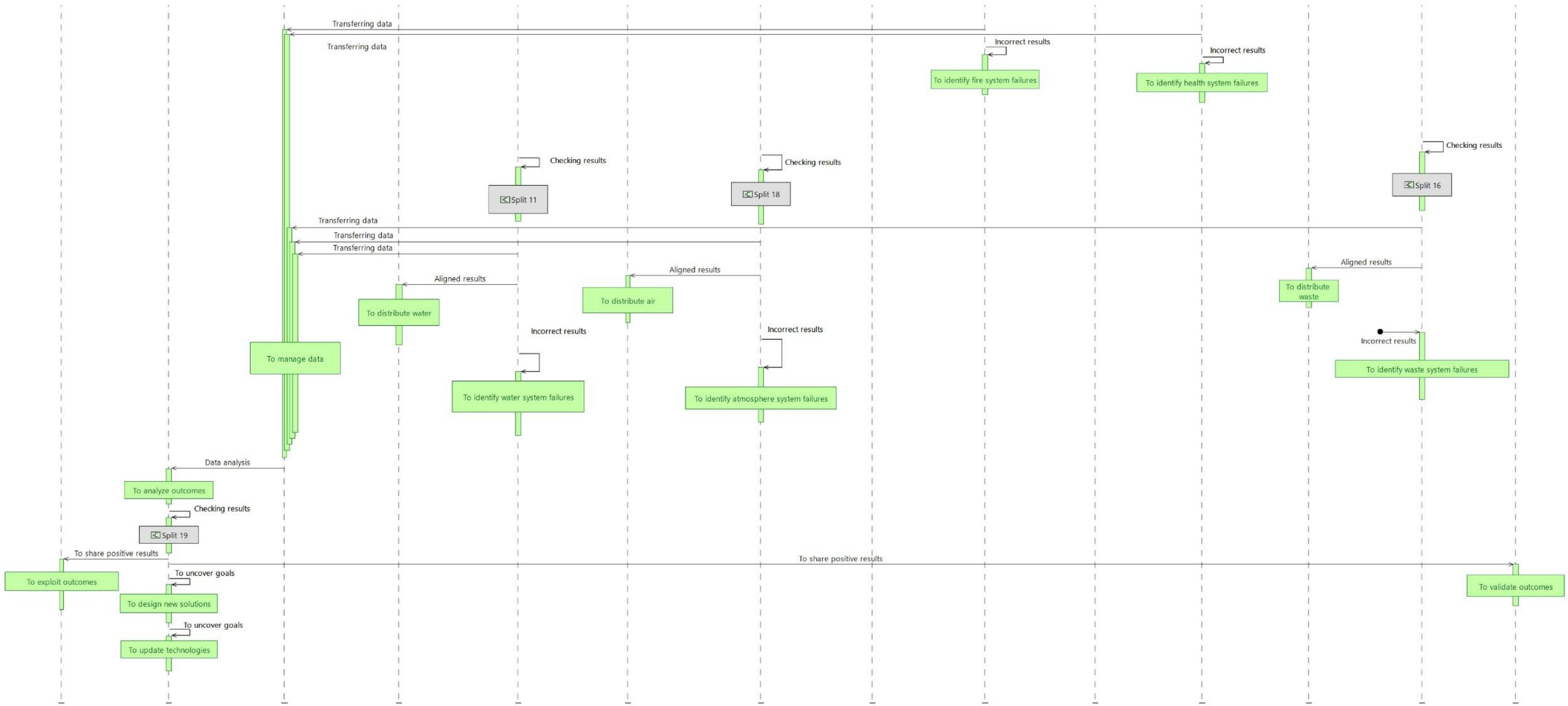


Figure D.6: [ES] Crew Support Facilities Scenario.

D.3 Logical Analysis Diagrams

[ES] ECLS Technologies Logical Scenario

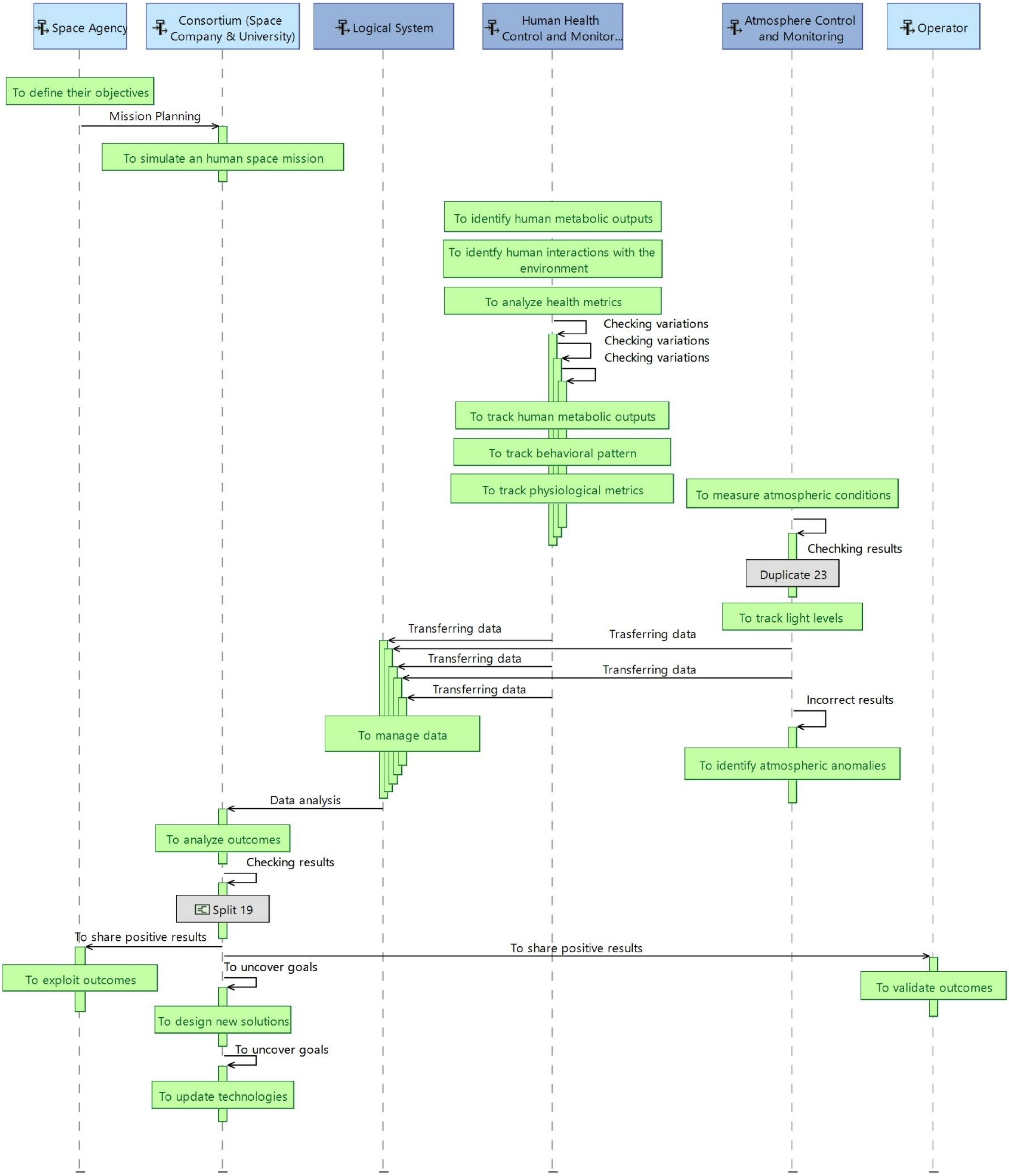




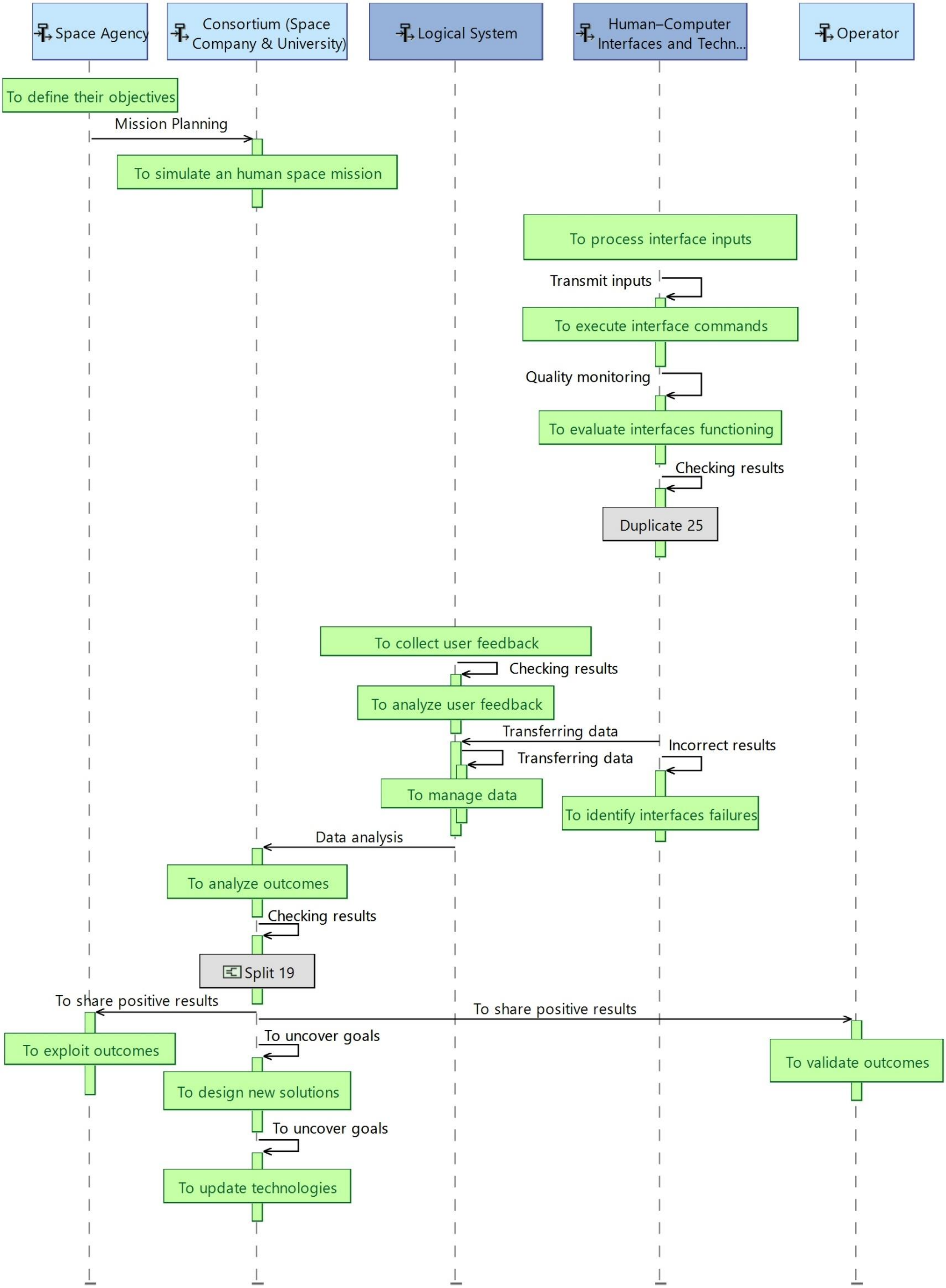
Transferring data
Transferring data
Incorrect results
To identify fire system failures
Incorrect results
To identify health system failures
Checking results
Split 11
Checking results
Split 18
Checking results
Split 16
Transferring data
Transferring data
Transferring data
Aligned results
To distribute water
Aligned results
To distribute air
Aligned results
To distribute waste
To manage data
Incorrect results
To identify water system failures
Incorrect results
To identify atmosphere system failures
Incorrect results
To identify waste system failures
Data analysis
To analyze outcomes
Checking results
Split 19
To share positive results
To exploit outcomes
To share positive results
To validate outcomes
To uncover goals
To design new solutions
To uncover goals
To update technologies

[ES] Crew Support Facilities Logical Scenario

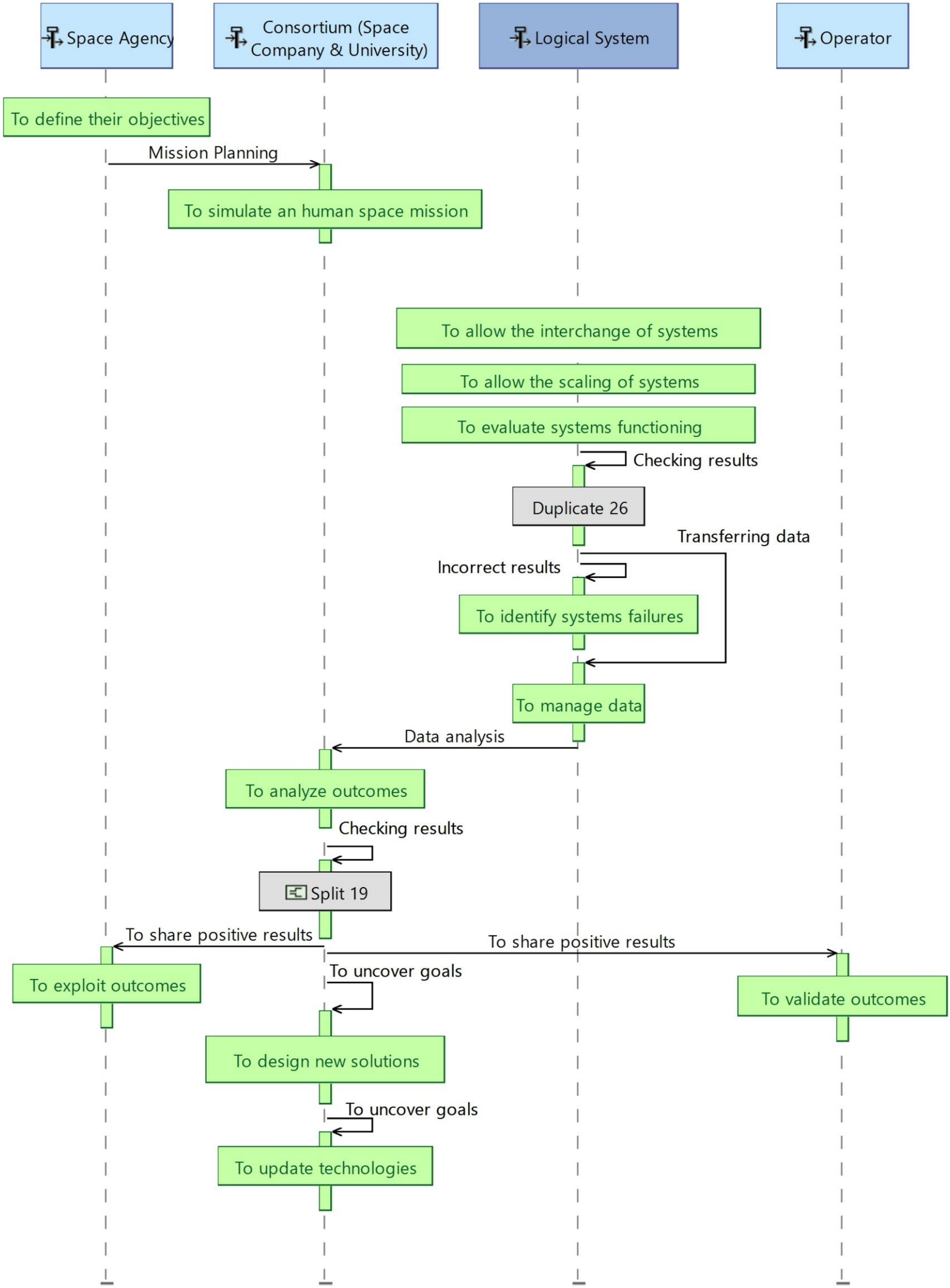
[ES] Human Environment Interactions Logical Scenario



[ES] Human Machine Interfaces Logical Scenario



[ES] System Modularity and Scalability Logical Scenario



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