Politecnico di Torino

Master's Degree in Aerospace Engineering

Master Thesis

Integrated Model-Based Systems Engineering methodology for design, analysis and simulation of an Environmental Control and Life Support System for an Analog Habitat

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JULY 2025

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Abstract

In human spaceflight, the ECLSS is an essential part of a mission, as it provides the necessary conditions for sustaining life within space habitats. Designing a long-duration human spaceflight mission requires developing a highly reliable and complex ECLSS, which must be integrated into the overall mission architecture. The traditional document-centric systems engineering approach might be inadequate for managing this level of complexity. In contrast, a Model-Based Systems Engineering (MBSE) methodology could significantly improve the design, management, and traceability of such a complex system. The ECLSS design process is highly iterative and recursive, involving the evaluation of technologies and system configurations through simulations, analysis tools, and hardware/software testing. To support the process, this thesis proposes an integrated MBSE approach that connects the system model to engineering analysis tools, enabling continuous performance assessment and iterative model refinement throughout the design phases. The main research contributions of this work are: (i) the development of a method that integrates a standard MBSE methodology with an arbitrary set of analysis or simulation tools while ensuring consistency and enabling automated system evaluation, and (ii) the demonstration of how an integrated MBSE approach can support the design of an ECLSS architecture. The effectiveness of this approach in supporting the design process is explored through its application to the preliminary design of an ECLSS for an Analog Habitat. The system model is developed using the Arcadia methodology implemented in the Capella modeling tool and is connected to an Equivalent System Mass (ESM) and reliability analysis tool, as well as to Virtual Habitat (V-HAB), a MATLAB-based simulation tool developed at the Technical University of Munich (TUM), specifically designed for the simulation of life support systems. As the design process progresses, more advanced engineering analyses can be integrated using the same method. This work highlights how an integrated MBSE approach can facilitate early validation and verification, enhance the detection and resolution of design issues, accelerate design iterations, reduce errors, and enable the rapid assessment of design changes. These capabilities enhance the overall efficiency and robustness of the ECLSS design process.

Keywords: Analog Habitat, Arcadia, Capella, Environmental Control and Life Support System, Human Spaceflight, Model Based System Engineering

Abbreviations

2BMS 2 Bed Molecular Sieve

4BMS 4 Bed Molecular Sieve

ACRS Advanced Carbon-Formation Reactor System

ACS Atmosphere Control and Supply

AES Air Evaporation Systems

AMCM Advanced Missions Cost Model

APC Air Polarized Concentrators

APCOS Aqueous Phase Catalytic Oxidation Post-Treatment System

AR Atmosphere Revitalization

ARCADIA ARchitecture Analysis and Design Integrated Approach

ASI Italian Space Agency

BPA Brine Processor Assembly

CAMRAS Carbon Dioxide and Moisture Removal Amine Swing-Bed System

CCAA Common Cabin Air Assembly

CDH Command and Data Handling

CDRA Carbon Dioxide Removal Assembly

CDF Poisson Cumulative Distribution Function

CELSS Controlled Ecological Life Support System

CHX Condensing Heat Exchanger

CFR Carbon Formation Reactor

CMS Carbon Molecular Sieve

COL Columbus Laboratory

CSA Canadian Space Agency

DDTE Design, Development, Test, and Evaluation

EDC Electrochemical Depolarization Concentration

ECLSS Environmental Control and Life Support System

ECLS Environmental Control and Life Support

EPBS End Product Breakdown Structure

ESA European Space Agency

ESM Equivalent System Mass

EVA Extravehicular Activity

FAI Federation Aeronautique Internationale

F2F Flow-to-Flow

FDS Fire Detection and Suppression

FoM Figures of Merit

FSP Food Storage and Preparation

GCRs Galactic Cosmic Rays

HEPA High Efficiency Particulate Atmosphere

HERA Human Exploration Research Analog

HESTIA Human Exploration Spacecraft Test-bed for Integration & Advancement

HLS Human Landing System

INCOSE International Council on Systems Engineering

ISS International Space Station

ITCS Internal Thermal Control System

KDPs Key Decision Points

LCC Life Cycle Cost

LEO Low Earth Orbit

LiOH Lithium Hydroxide

LSS Life Support Systems

MBSE Model-Based Systems Engineering

MCA Major Constituent Analyzer

MF Multifiltration

MS Modeling and Simulation

MSM Mass Spectrometer

NASDA National Space Development Agency

OGA Oxygen Generation Assembly

ORUs Orbital Replacement Units

P2F Phase-to-Flow

P2P Phase-to-Phase

PAB Physical Architecture Blank

PCA Pressure Control Assembly

PCBD Physical Components Breakdown Diagram

PCWQM Process Control and Water Quality Monitor

PDFB Physical Dataflow Blank

PFBD Physical Functions Breakdown Diagram

PID Proportional-Integral-Derivative

Pr(LOC) Probability of Loss Of Crew

PVMT Property Values Management Tools

RAX Radio Aurora Explorer

RH Relative Humidity

RO Reverse Osmosis

RSA Russia Space Agency

SAWD Solid Amine Water Desorption

SCWO Super Critical Water Oxidation

SCRA Sabatier Carbon Dioxide Reduction Assembly

SE Systems Engineering

SFWE Static Feed Water Electrolysis

SH Lunar Surface Habitat

SLS Space Launch System

SM Russian Service Module

SPWE Solid Polymer Water Electrolysis

SPE Solar Particle Events

TCCS Trace Contaminant Control Subassembly

TCCV Temperature Control and Check Valve

THC Temperature and Humidity Control

TIMES Thermoelectric Integrated Membrane Evaporation System

TOC Total Organic Carbon

TUM Technical University of Munich

TRL Technology Readiness Level

UPA Urine Processing Assembly

VAPCAR Vapor Phase Catalytic Ammonia Removal

VCD Vapor Compression Distillation

V-HAB Virtual Habitat

VV Verification and Validation

WM Waste Management

WM-WS Waste Management - Water Systems

WPA Water Processing Assembly

WRM Water Recovery and Management

WVE Water Vapor Electrolysis

Definitions

P_{total}	Total atmospheric pressure	[Pa]
p_{X}	Partial pressure of component X	[Pa]
RH(T)	Relative humidity at temperature T	[%]
$p_{\text{H}_2\text{O}}(T)$	Partial pressure of water vapor at temperature T	[Pa]
$p^{\circ}_{\text{H}_2\text{O}}(T)$	Saturated vapor pressure at temperature T	[Pa]
$m_{\text{water vapor}}$	Mass of water vapor in the air	[kg]
$m_{\text{dry air}}$	Mass of dry air	[kg]
$M_{\text{tech},i}$	Total mass of technology i	[kg]
$M_{\text{hw},i}$	Hardware mass of technology i	[kg]
$M_{\text{chg},i}$	Initial resource charge mass of technology i	[kg]
$M_{\text{cons},i}$	Mass of consumable resources of technology i	[kg]
$M_{\text{exp},i}$	Mass of process expendables of technology i	[kg]
$M_{\text{spare},i}$	Mass of spare parts of technology i	[kg]
$V_{\text{tech},i}$	Total volume of technology i	[m^3]
$V_{\text{hw},i}$	Hardware volume of technology i	[m^3]
$V_{\text{cons},i}$	Volume of consumable resources of technology i	[m^3]
$V_{\text{exp},i}$	Volume of process expendables of technology i	[m^3]
$V_{\text{spare},i}$	Volume of spare parts of technology i	[m^3]
$P_{\text{tech},i}$	Power consumption of technology i	[kW]
$THL_{\text{tech},i}$	Thermal heat load of technology i	[kW]
$CT_{\text{tech},i}$	Crew time of technology i	[h]
M_{ECLSS}	Total mass of the ECLSS	[kg]
V_{ECLSS}	Total volume of the ECLSS	[m^3]
P_{ECLSS}	Total power consumption of the ECLSS	[kW]
THL_{ECLSS}	Total thermal load of the ECLSS	[kW]
CT_{ECLSS}	Total crew time required by the ECLSS	[h]
CF_{VOL}	Conversion factor for volume	[kg/m^3]
CF_{PWR}	Conversion factor for power	[kg/kW]
CF_{TCS}	Conversion factor for thermal control system	[kg/kW]
CF_{CT}	Conversion factor for crew time	[kg/h]
ESM	Equivalent System Mass	[kg]
λ_i	Failure rate of component i	[1/day]
MTBF$_i$	Mean Time Between Failures for component i	[day]
$R_i(t)$	Reliability of component i at time t	[–]
$F_i(t)$	Failure probability of component i at time t	[–]
λ_{ECLSS}	Total failure rate of the ECLSS	[1/day]
$R_{ECLSS}(t)$	Reliability of the ECLSS at time t	[–]
Pr(LOC)(t)	Probability of Loss of Crew at time t	[–]
CM_{mission}	Number of crew members in the reference mission	[–]
$CM_{\text{technology}}$	Number of crew members the technology was designed for	[–]
$M_{\text{mol,i}}$	Molar mass of gas i	[kg/mol]
V	Cabin volume	[m^3]
R	Ideal gas constant	[J/(mol·K)]
T	Cabin temperature	[K]
SF	Safety factor	[–]
$\text{mass}_{\text{O}_2\text{,leak}}$	Mass of oxygen required to compensate leakage	[kg]
$\text{mass}_{\text{N}_2\text{,leak}}$	Mass of nitrogen required to compensate leakage	[kg]

$\text{mass}_{\text{O}_2,\text{repress}}$	Mass of oxygen required for repressurization	[kg]
$\text{mass}_{\text{N}_2,\text{repress}}$	Mass of nitrogen required for repressurization	[kg]
Total mass_{N_2}	Total storage mass of nitrogen	[kg]
Total mass_{O_2}	Total storage mass of oxygen	[kg]
tank ratio	Ratio of tank mass to stored mass	[kg/kg]
Total tank mass	Total tank mass (structure + stored fluid)	[kg]
$\text{Volume}_{\text{highPressure}}$	Volume of high-pressure tank	[m^3]
$\text{Volume}_{\text{cryogenic}}$	Volume of cryogenic tank	[m^3]
$\rho_{\text{cryogenic}}$	Density of cryogenic liquid	[kg/m^3]
$m_{\text{store,day}}$	Stored mass per day (excluding O_2/N_2)	[kg/day]
$\text{Volume}_{\text{other tank}}$	Volume of storage tank (excluding O_2/N_2)	[m^3]
ρ	Density of stored substance (excluding O_2/N_2)	[kg/m^3]
$\text{ESM}_{\text{spares},i}$	Equivalent System Mass including spares for technology i	[kg]
VI	Value Index	[–]

1 Introduction

Human spaceflight is one of the most significant achievements of the modern era. Since the 20th century, humanity has gradually gained experience in space flight, aiming to exploit the unique conditions of space for scientific, technological, and exploratory purposes.

Figure 1 illustrates the duration of NASA missions and reveals a clear trend: as experience in spaceflight has increased, missions have become progressively longer and more complex. NASA's programs have evolved from surviving in space to living in space, then working in space, and performing in space. This progress reflects the improvement of spaceflight technology and understanding, as well as growing ambitions in space exploration [1]. Following the Skylab missions, the development of the International Space Station (ISS) and the Chinese Space Station (Tiangong) began a new era of a permanent human presence in space.

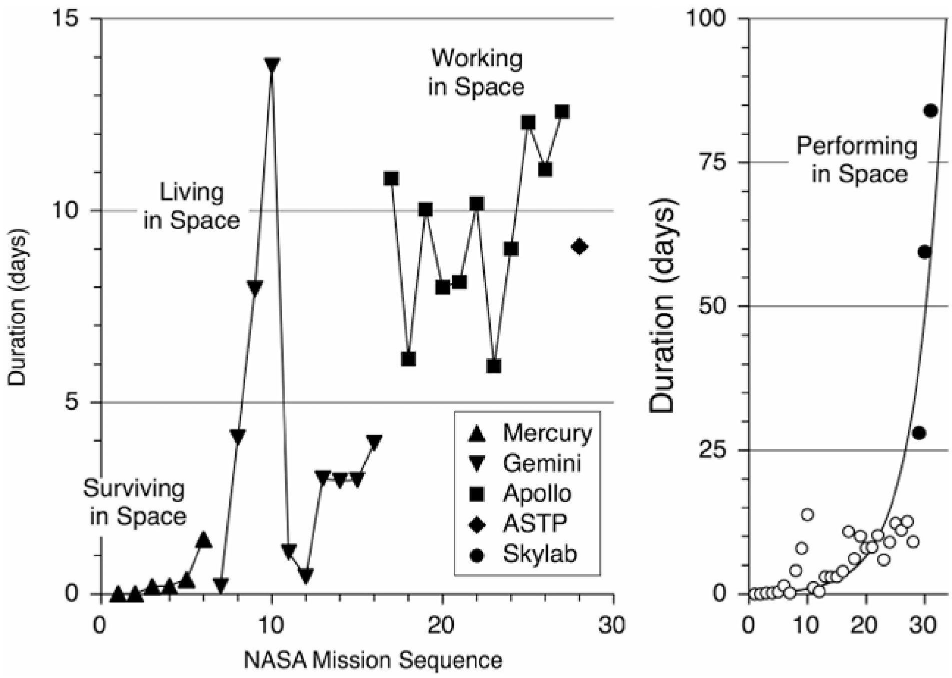


Figure 1: Duration of the NASA missions [1].

In the 21st century, ambitious goals of space exploration include establishing a permanent human presence on the Moon and sending humans to Mars [2]. As human spaceflights become longer, the missions become more complex and require greater reliability from all systems involved [3].

In human spaceflight, Environmental Control and Life Support System (ECLSS) is an essential part of the mission. This system provides a healthy, productive living and working environment inside spacecraft, space stations, and planetary habitats [4].

The ECLSS provides humans with essential resources and controls their environment. It is responsible for managing the atmosphere, water, waste, and food. Figure 2 illustrates the main functions and relationships among the ECLSS subsystems and their integration with other systems within the habitat. The diagram illustrates the system's overall complexity.

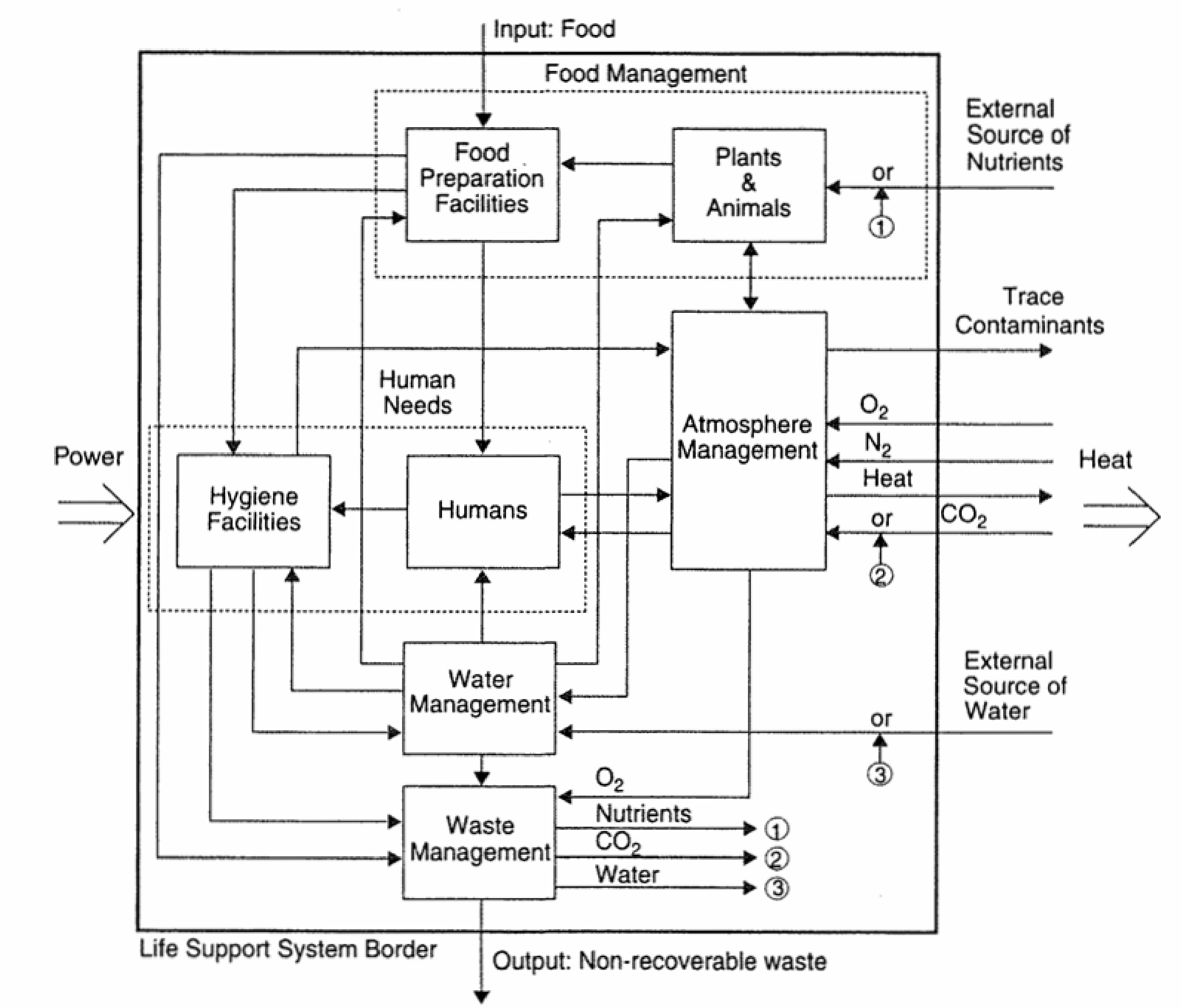


Figure 2: ECLSS functions and relationship [5].

Due to the critical functions performed by the ECLSS, designing a long-duration human spaceflight mission necessitates developing a complex, highly reliable system that is fully integrated into the broader mission structure [3].

As mission durations increase, the design of such complex systems becomes increasingly difficult to manage using the traditional document-centric systems engineering approach. This approach generates a large number of documents throughout the system's life cycle that present data without establishing explicit dependencies. The limitations of this approach become especially evident as the complexity of the system increases. The main challenges include a lack of traceability, difficult communication, high maintenance efforts, and limited scalability. For systems as complex as the ECLSS, this approach can be inefficient and error-prone [6, 7].

This thesis work investigates how Model-Based Systems Engineering (MBSE) can be used to overcome these limitations and enhance the management of complex systems. MBSE offers several potential benefits, including enhancing communication among stakeholders, improving understanding of the impacts of design changes, improving overall system comprehension, and facilitating early verification and validation. It also supports the early detection of design defects and helps resolve inconsistencies and discrepancies within the system design. Furthermore, MBSE can reduce costs and errors while saving time compared to the traditional document-centric approach [8].

The ECLSS design is recursive and iterative. It involves evaluating various system configurations, assessing alternative technologies, analyzing and simulating the system, and testing hardware and software [4]. The final architecture of the ECLSS depends heavily on the specific mission requirements and must be fully integrated with all of the spacecraft's or habitat's other systems.

This thesis proposes an integrated MBSE approach to support the design process of an ECLSS. This approach involves developing the ECLSS model in a modeling environment that accurately reflects the current state of the system architecture. The system model is connected to analysis and simulation tools, enabling continuous assessment of system performance and iterative refinement of the architecture throughout all design phases.

This work presents a method for integrating various types of analysis and simulation tools within an MBSE environment. The potential benefits of this integrated MBSE approach in supporting the ECLSS design process are illustrated through the preliminary design of the ECLSS for an Analog Habitat.

The system model is developed using the ARchitecture Analysis and Design Integrated Approach (ARCADIA) methodology and the Capella modeling tool. It is connected to analysis and simulation tools that are relevant for evaluating the performance and characteristics of the ECLSS during the preliminary design phase. Specifically, the model is linked to an Equivalent System Mass (ESM) and reliability analysis tool, as well as to Virtual Habitat (V-HAB), a life support system simulation tool developed at the Technical University of Munich (TUM) [9, 10]. The information obtained through these integrated analysis and simulation tools enables improvement and refinement of the system architecture. This approach can be extended to subsequent design phases by integrating more advanced engineering tools into the model using the same method. This work illustrates the potential of the proposed approach to improve the ECLSS design process by managing its complexity more effectively.

The thesis is structured as follows: Section 2 (*Background and Context*) provides an overview of the main concepts explored in this work. These include the history, future trends, and benefits of human spaceflight; human factors in spaceflight; analog habitats; and a detailed description of the Environmental Control and Life Support System, including its main functions and key design considerations. The section also introduces the Equivalent System Mass and the reliability analysis considered in this work, as well as the Virtual Habitat tool. Finally, the section provides background on systems engineering, Model-Based Systems Engineering, and the ARCADIA methodology.

Section 3 (*Research Problem*) outlines the challenges of the traditional document-centric systems engineering approach for designing the ECLSS, especially for long-duration missions. The section also describes the main advantages and limitations of integrating an

MBSE approach with engineering analysis tools. Based on this overview, the research questions that guide this work are presented.

Section 4 (*Proposed Integrated MBSE Approach for ECLSS Design Process*) presents the proposed integrated MBSE approach to support the ECLSS design process. It offers a detailed description of how each tool is integrated into Capella, as well as how these tools enable the evaluation and iterative refinement of the system architecture.

Section 5 (*ECLSS Design for an Analog Habitat*) presents the application of the proposed approach to the preliminary design of the ECLSS for an Analog Habitat, with the aim of illustrating its main potential benefits.

Section 6 (*Conclusions and Future Work*) summarizes the work's key outcomes and suggests possible future research directions.

2 Background and Context

This chapter aims to present a comprehensive overview of the context of this work, by providing a brief description of the main concepts explored throughout the thesis. This includes an overview of the challenges and opportunities related to human space exploration, with a particular focus on the ECLSS, and analog habitat simulators. The chapter also discusses the advantages and limitations of MBSE to support the design, analysis and verification of complex and integrated systems.

2.1 Human Spaceflight

"Human spaceflight include any space missions with humans as passengers or as on-board, active participants in spacecraft control or science" [3]. Since April 1961, when cosmonaut Yuri Gagarin became the first human to be launched into space, more than six hundred individuals have traveled beyond an altitude of 100 kilometers (where space begins, as arbitrarily chosen by the Federation Aeronautique Internationale (FAI)). Despite this number, only three countries have independently launched humans into space: Soviet Union/Russia, the United States, and China. In each of these nations, the development of human spaceflight has evolved progressively, with each successful mission building on the experience and lessons learned from previous flights [1]. Today, as spaceflights must be both safe and cost-effective, it is extremely important to understand how these countries achieved their goals, how missions are designed and executed, what major technical challenges must be overcome, and how to effectively organize the development and operation of such missions [3].

2.1.1 History of Human Spaceflight

The Soviet Union and Russia's Human Spaceflight Program

The first human spaceflight program was the Soviet Union's Vostok program started in 1961, which resulted in the first human in space, the first orbital flight around Earth, and the first full day spent in space by a human [11].

Building on Vostok's historic successes, in 1964 the Soviet Union initiated the Voskhod program, which consisted of two missions that carried multi-person crews into space and performed the first Extravehicular Activity (EVA) in human history.

An important milestone in Soviet human spaceflight came in 1967 with the introduction of the Soyuz spacecraft. Soyuz supported the operations of the Salyut and Mir space stations, and continues to play a key role today in servicing the ISS [11].

In 1971, the Soviet Union launched the Salyut program, a series of single-module space stations designed to host crews conducting military and scientific experiments. Building on the successes of Salyut, the Soviet Union developed Mir (shown in Figure 3), which was the first long-term space station composed of different modules. Operational from

1986 to 2001, Mir enabled a nearly continuous human presence in space for almost a decade [11].

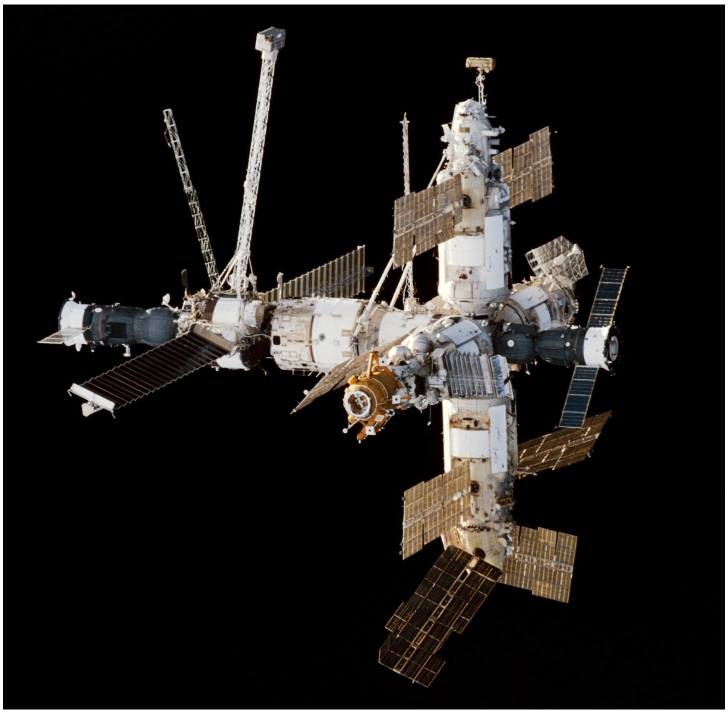


Figure 3: Mir space station [12].

The United States Human Spaceflight Program

The first U.S. human spaceflight program was Mercury, which included 25 missions, six of which carried astronauts between 1961 and 1963. Its primary objectives were to successfully place a human spacecraft into Earth orbit, evaluate the astronaut's ability to operate in space, and ensure the safe recovery of both the crew and the vehicle. Mercury was succeeded by the Gemini program, whose purpose was to prepare for future lunar missions by testing long-duration flights, performing orbital rendezvous and docking, refining re-entry techniques, and studying the physiological impacts of extended spaceflight on humans [13].

From 1961 to 1972, the US developed the Apollo program, the largest US program consisting of successful lunar landings and the safe return of astronauts to Earth. Apollo contributed to the advancement of technologies in support of national objectives in space, enabled the scientific exploration of the Moon, and enhanced humanity's ability to operate in the extraterrestrial environment [13]. Figure 4 shows the historic Apollo 11 Lunar Module docking with the Command Module before returning to Earth.

In 1973, the Skylab program marked America's first space station efforts, focusing heavily on solar observations and long-duration human missions. Meanwhile, the intense U.S. - Soviet competition, that had characterized the space race, evolved into cooperation, beginning with the Apollo-Soyuz Test Project in 1975. This collaborative effort became even more pronounced in the following decades, especially during the Space Shuttle era and the subsequent development of the ISS.

NASA's shuttle program, operational for over 30 years, completed 135 missions with five orbiters: Columbia, Challenger, Discovery, Atlantis, and Endeavour; and carried 355 individuals to space. As the first reusable spacecraft, the shuttle enabled routine access to Low Earth Orbit (LEO), deployed and repaired satellites, supported scientific research, and contributed substantially to the construction of the ISS [13].

Built between 1998 and 2011, the ISS is an unprecedented collaboration between the United States, the Canadian Space Agency (CSA), European Space Agency (ESA), Italian Space Agency (ASI), National Space Development Agency (NASDA), and the Russia Space Agency (RSA) [5]. It is a symbol of international collaboration, enabling not only research in microgravity, but also the advent of commercial activities in LEO and the advancement of technologies for future deep space exploration [13].

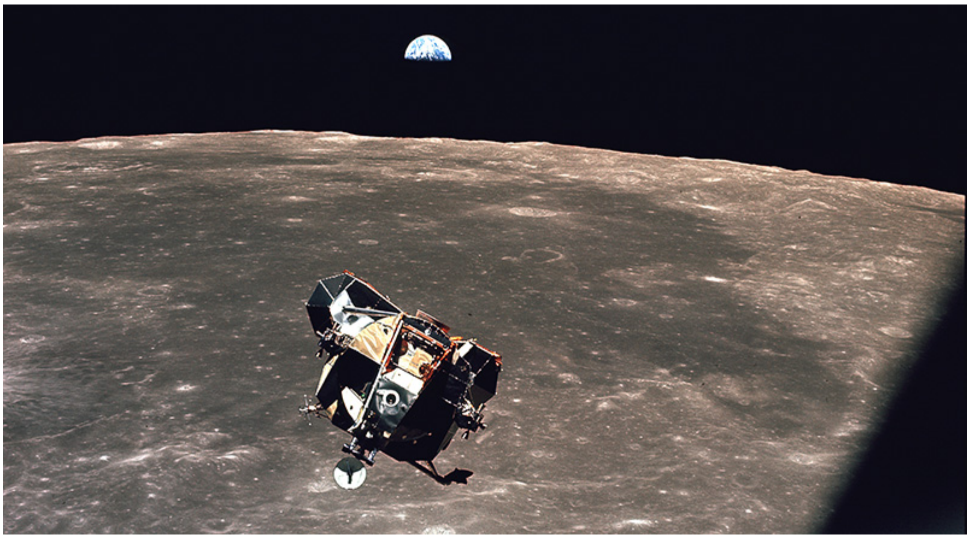


Figure 4: Apollo lunar module [13].

The Chinese Human Spaceflight Program

In 1992, the Chinese government initiated its human spaceflight program following a strategy composed of three steps [14]. The first step aimed to launch crewed spacecraft and develop fundamental human spaceflight technologies. The second focused on deploying space laboratories to achieve key technological breakthrough in EVA, orbital rendezvous and docking, and supporting short-term human habitation. The final stage involves the construction and long-term operation of a permanently crewed space station to enable a sustained human presence in space [14].

China successfully launched its first unmanned spacecraft, Shenzhou 1, in November 1999. On October 15, 2003, it reached a major milestone with the launch of Shenzhou 5, its first manned spaceflight [15]. With this achievement, China became the third country in the world to independently send humans into space, after the Soviet Union and the

United States. The mission, which lasted 21 hours and 22 minutes, marked the beginning of China's human spaceflight program [15].

Continuing its advancements, China launched its first prototype space station, Tiangong-1, in 2011 to test rendezvous, docking, and short-term crewed habitation. This was followed by Tiangong-2 in 2016, where two astronauts spent 30 days aboard during the Shenzhou-11 mission, successfully validating life support technologies essential for long-duration missions, setting the basis for a permanent space station [16].

In April 2021, China launched the Tianhe core module of its Tiangong modular space station, marking the start of the third stage of its human spaceflight roadmap. Additional modules were added in the following months, and the station reached full operational capacity in 2022. The Tiangong space station, shown in Figure 5, now supports a continuous human presence in LEO, hosting rotating crews and enabling a wide range of scientific experiments. With Tiangong, China has become the second nation after Russia/US to maintain a long-term human station in space, and has expressed interest in future international cooperation aboard the station [17].

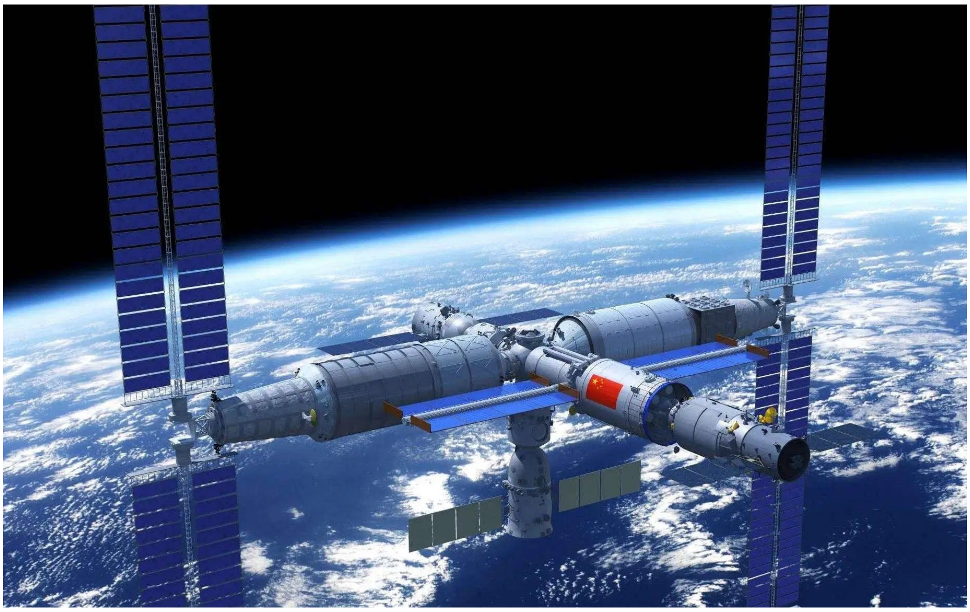


Figure 5: China's Tiangong space station [18].

The Future of Human Spaceflight and Space Commercialization

The centralized government-led approach that defined human space activities since the 1960s has gradually shifted over the past two decades. Today, government space agencies have been increasingly collaborating with private companies and engaging in international partnerships, reflecting a more collaborative and diversified model of space exploration [19]. Indeed, agencies such as NASA and ESA are moving towards partnerships with private companies such as SpaceX, Blue Origin, Northrop Grumman Systems Corporation and Axiom Space. The primary goal of these partnerships is to enhance collective capabilities in human spaceflight, to promote scientific innovation, to expand access to space, to reduce the cost of access to space, to foster innovation and to expand commercial activity beyond Earth orbit [20, 21].

NASA's Artemis program is an example of this new model of space exploration. The program aims to return humans to the moon, establishing the first long-term human presence. This will support scientific discovery, drive technological innovation, and provide critical experience for future human missions to Mars. Key mission objectives of Artemis program include: equality, technology, partnerships, long-term presence, knowledge and resources [22].

The Artemis program is based on four major elements: the Orion spacecraft, designed to carry astronauts through space; the Lunar Gateway, a space station that will orbit the Moon; the Human Landing System (HLS), intended to transport astronauts and equipment from the Gateway to the lunar surface; and the Space Launch System (SLS) [23].

The moon is a treasure of science, understanding its geological structure and history can reveal insights into planetary processes, the Earth-Moon system, and even the history of our Sun. Artemis astronauts will collect new data to deepen this understanding [23]. The target landing site for the Artemis missions is the lunar South Pole, a region characterized by deep craters, areas of constant sunlight, and permanent shadow. This location is particularly important because is known to contain deposits of water ice. In the future, these ice deposits could be integrated into the ECLSS of lunar habitats, supporting the establishment of a sustained human presence on the Moon [23]. Beyond the scientific, political and economic objectives, Artemis program aims to inspire the next generation of professionals and innovators, just as the Apollo missions inspired the current generation.

While the United States is leading the way toward establishing a long term human presence on the Moon through the Artemis program, other major nations are also shaping their own long-term visions for space exploration. Unlike U.S, Russia currently has no immediate plans to send cosmonauts to the Moon. In September 2022, however, Russia and China declared their intention to build a joint lunar base by the mid-2030s [11]. Over the past decade, emerging space nations such as India, with its Gaganyaan human spaceflight program [24], and the United Arab Emirates, which launched the Hope Probe to Mars in 2020 [25], have positioned themselves as serious players in space exploration, with ambitions for future human missions to the Moon and Mars.

2.1.2 Benefits of Human Spaceflight

Planning a space mission with humans on board, compared to a robotic mission, dramatically changes how the mission is designed, managed, and financed. Every element of the mission is heavily influenced by the presence of humans. Sending people into space introduces significant risks, higher costs, and increased complexity across the entire system. However, human presence add flexibility and adaptability impossible in robotic missions. Designing for human presence in space is more complex mainly due to safety and reliability, pressurized structures and dedicated subsystems, human factors and logistics [3].

Even though humans have been exploring space for over 60 years, the question remains: is it worth continuing to send humans into space, considering the significant risks, complexities, and costs involved [26]?

While geopolitical motivations were once the primary driver of human space exploration, today's justification is increasingly based on the broader benefits such missions can bring. The benefits of human spaceflight can be grouped into three categories: scientific benefits, practical non-scientific benefits, and intangible non-scientific benefits [26].

Scientific benefits: One of the main reasons for sending humans into space is to conduct scientific research. It is generally accepted that the benefits of such research outweigh the inherent risks and dangers [26]. Nevertheless, like human missions, robotic missions have provided an incredible return on scientific research, with notable examples including the Mars Rovers and the Pioneer and Voyager probes. However, the scientific value of human spaceflight lies in the ability to respond in real time to changing environments and unforeseen problems that can arise in space. The human presence brings flexibility, adaptability and manual skills that current unmanned technologies cannot match. This often results in complex tasks being completed more efficiently and in less time [27].

Beyond the advantages of human adaptability, the presence of astronauts in space is also essential for investigating the human body in microgravity, leading to the discovery of physiological processes and medical insights that cannot be observed on Earth, as well as fostering the development of new technologies aimed at improving quality of life. As stated in Bond and Wilson [28]: *"the human presence in space is a key factor in enabling new technologies to be tested in microgravity, leading to advanced solutions that provide benefits for power generation, transportation, safety and standard of living"*. Examples of important research and benefits arising from human spaceflight include advances in cancer research, osteoporosis studies, investigations into the decline in muscle performance due to prolonged inactivity and ageing, and microRNA research (other examples are discussed in [28].)

Practical non-scientific benefits: In addition to the scientific benefits, investing in human spaceflight offers significant practical non-scientific benefits, including the promotion of international cooperation and the enhancement of national prestige [26].

As presented in previous sections, since the Cold War human spaceflight has been seen as an instrument of "*soft power*" [29], capable of promoting national pride. The success of complex missions, such as the Apollo program, serves to enhance a nation's international reputation.

As well as enhancing national prestige, human space exploration is a natural focus for international cooperation. The Artemis program, for example, demonstrates this: *"54 countries have joined the accords and are committed to establishing a peaceful, prosperous future in space"* [22]. It provides a visible and powerful means of promoting global solidarity and building a more stable geopolitical environment. The involvement of several countries in human space exploration enhances cooperation, reduces risks, shares costs and facilitates technological exchange [27].

Intangible non-scientific benefits: Human space exploration is not only a demonstration of technological power, but also a testament to a nation's ability to mobilize resources and achieve ambitious collective goals, exemplifying "the best of our abilities", as President Kennedy once remarked.

Space exploration plays a crucial role in stimulating intellectual curiosity and promoting critical thinking throughout society. Not only does it address unprecedented scientific challenges, it also builds optimism and inspires the development of innovative solutions to complex societal problems [27]. One of the most important intangible benefits of human spaceflight, particularly evident in the Apollo program, is the inspiration of a new generation of engineers and scientists.

Programs such as Apollo have ignited a passion for science, engineering and exploration that has influenced the careers of countless individuals, including pioneers such as the founder of Amazon, who cited his fascination with Apollo as a major motivation [26]. In fact, one of the greatest benefits of human spaceflight is the challenge and complexity of carrying out such missions, which serves as a powerful source of inspiration for future generations.

2.1.3 Human Factors in Spaceflight

"The high costs and constraints involved in placing humans in space make people the most important "subsystem" within a mission" [3]. As discussed in the previous sections, planning a mission with humans on board adds significant complexity to the overall system. Therefore, human factors greatly affect the final system configuration.

Leaving Earth for space requires humans to adapt to entirely different environmental conditions. The main environmental factors to be considered in mission design to ensure human survival are: habitat atmosphere, radiation, acceleration, noise, vibration, metabolic parameters, microgravity and psychological effects [3]. The environmental context of a space mission is summarized in Figure 6.

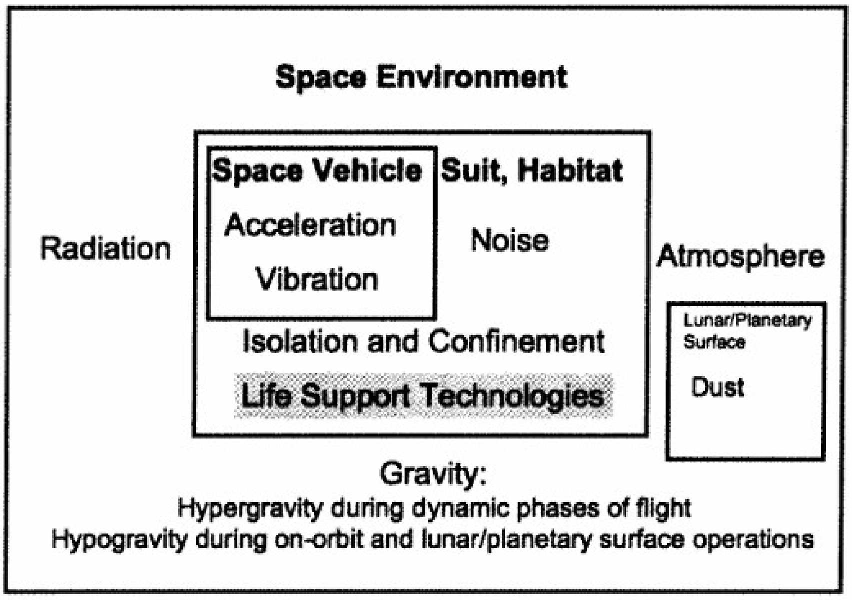


Figure 6: Overview of environmental factors [30].

Habitat atmosphere: Human spaceflight relies on pressurized structures and dedicated subsystems to provide life support and environmental protection. To sustain life, the system must continuously maintain appropriate atmospheric composition and temperature conditions. As stated by Wieland [4], *"The term atmosphere refers to the gas either surrounding a planet or contained within a sealed vessel, such as a space habitat"* and can be defined by the partial pressure p of its basic components:

$$P_{\text{total}} = p_{O_2} + p_{N_2} + p_{CO_2} + p_{H_2O} + p_{X_1} + p_{X_2} + \cdots + p_{X_n} \quad (1)$$

where P_{total} is the total pressure of the atmosphere. The primary atmospheric requirements for the mission are to maintain adequate total pressure and oxygen partial pressure. In addition, temperature and humidity must be maintained within appropriate ranges, while carbon dioxide and trace contaminant levels must remain sufficiently low.
To support human health, the partial pressure of O_2 in the atmosphere must remain sufficiently high, typically around 21.4 kPa at sea level, to prevent various physiological

problems. However, excessively high O_2 partial pressures can also be harmful, leading to conditions such as lung irritation and oxygen toxicity [4]. Figure 7 shows a NASA diagram illustrating the relationship between oxygen concentration, total pressure, and the physiological effects on humans when breathing the corresponding atmosphere. Mission designers must select and maintain oxygen partial pressure and total pressure values that fall within the light shaded area of the diagram to meet human physiological requirements. As shown in the diagram, the range of atmospheric conditions compatible with human survival extends from a total pressure of 103.1 kPa at 21% oxygen to a total pressure of 25 kPa at 100% oxygen (based on the sea level equivalent curve in the diagram).

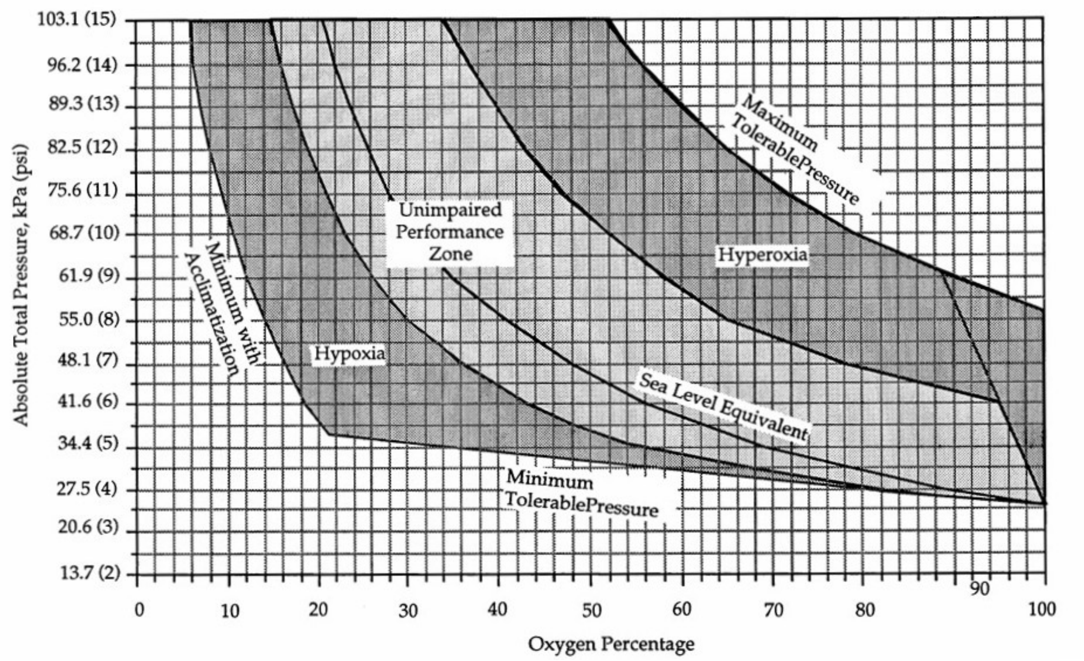


Figure 7: Physiological effects of oxygen concentrations [4].

Early US spacecraft used pure oxygen atmospheres to simplify life support systems and avoid the complexity of a two-gas system. However, after the Apollo 1 accident, in which an electrical spark caused a fatal fire that killed all three astronauts, the US switched to a nitrogen-oxygen atmosphere [4]. In fact, nitrogen is essential to inhibit the flammability of oxygen.

Based on these safety considerations, mission designers must carefully select atmospheric pressure and composition to meet both physiological and technical requirements. There are several advantages and disadvantages in using either a sea level atmosphere or a reduced pressure atmosphere in the cabin. Therefore, in addition to human physiological needs, the following factors must be taken into account when determining the total cabin pressure:

- Maintaining a total sea level pressure results in greater atmospheric losses caused by leakage, requires more structural mass to resist the higher pressure differential between the inside and outside of the habitat, and may complicate EVA preparations.

- Alternatively, lowering the total pressure below sea level causes voice communication over distances to become more challenging, increases the risk of fire due to the higher oxygen concentration, creates different conditions for mission experiments compared to Earth, increases material off-gassing and reduces heat transfer efficiency [3].

In addition to maintaining appropriate oxygen levels and total pressure, controlling carbon dioxide levels is critical for crew safety and mission success. In the habitat atmosphere, it is essential to keep CO_2 at a very low concentration to prevent adverse physiological effects. As CO_2 is produced by normal metabolic respiration, its levels would quickly rise to unacceptable concentrations in a confined environment unless some method of removal was employed. On Earth, the atmospheric concentration of CO_2 is about 0.0318 kPa, whereas in space habitats, acceptable levels range from 1.01 kPa for short-duration missions to 0.4 kPa for long-duration missions [3, 4].

In a habitat atmosphere, controlling the temperature and humidity is essential to providing a comfortable environment for the crew and preventing condensation on electronic components. In addition, moisture accumulation in any area can create favourable conditions for microbial growth [4]. The cabin's temperature and humidity are directly affected by sensible and latent heat. The mass of water vapor that must be condensed from the air is represented by latent heat, which is produced mainly by human metabolism and hygiene activities, while human metabolism and powered equipment generate sensible heat [31]. Temperature and Relative Humidity (RH) are closely related in their effect on human comfort: if the humidity is too low, crew members may experience drying of the nose, throat and other respiratory issues, while if the humidity is too high, a more common problem in space habitats, perspiration doesn't cool the crew properly, condensation on surfaces may occur and micro-organisms may grow more rapidly [3]. Historically, temperature and RH requirements have generally been the same for all space habitats, with temperatures typically ranging from 18.3 °C to 26.7 °C and RH between 25% and 75%. At high temperatures, a low relative humidity (RH) is required to facilitate evaporative cooling. On the other hand, at low temperatures, a high RH is preferred to minimize heat loss through evaporation and maintain comfortable conditions [4]. Figure 8 depicts the relationship between temperature, relative humidity[1], and humidity ratio[2].

[1]Relative humidity (RH) is the ratio of the amount of water vapor in the atmosphere to the maximum amount that the atmosphere can hold at a particular temperature. At a temperature T, the relative humidity can be defined as the ratio of the partial pressure of water vapor to the saturated vapor pressure:

$$\mathrm{RH}(T) = \frac{p_{\mathrm{H_2O}}(T)}{p^{\circ}_{\mathrm{H_2O}}(T)} \times 100$$

where $p_{\mathrm{H_2O}}(T)$ is the partial pressure of water vapor at temperature T and $p^{\circ}_{\mathrm{H_2O}}(T)$ is the saturated vapor pressure at the same temperature. The saturated vapor pressure corresponds to the partial pressure of water when the air–water mixture is at equilibrium, meaning that the rate of evaporation equals the rate of condensation. When the air cannot hold any more water vapor, it is said to have reached saturation [32].

[2]The humidity ratio is the ratio of the mass of water vapor in the air $m_{water\,vapor}$ to the mass of dry air $m_{dry\,air}$:

$$\text{Humidity ratio} = \frac{m_{water\,vapor}}{m_{dry\,air}}$$

The *comfort box*, highlighted in the Figure 8, represents the optimal environmental conditions for maintaining a stable and comfortable atmosphere suitable for human life.

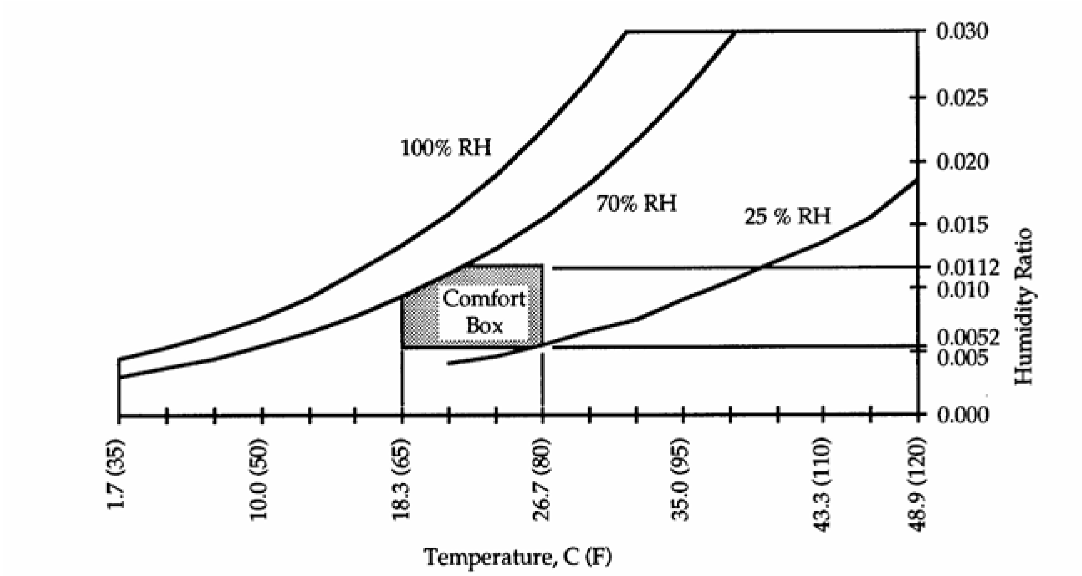


Figure 8: Temperature and RH ranges [4].

In addition, specific surface temperature limits must be maintained to prevent condensation and to avoid discomfort or injury to crew members. The acceptable temperature range for continuous contact with bare skin is approximately 4 °C to 45 °C [3].

In a microgravity environment, thermal convection and buoyancy are significantly reduced. This can result in the localized accumulation of carbon dioxide and airborne contaminants within the cabin. Effective ventilation is therefore essential to promote air mixing within and between modules, reduce thermal gradients and prevent the formation of stagnant zones. To ensure a safe and habitable environment, contaminant levels in the atmosphere must be kept below acceptable limits. The most critical contaminant to control is carbon dioxide, which is continuously produced by the crew. In addition, the system must remove micro-organisms, airborne particles, and trace chemical contaminants generated by both human activities and on-board equipment or materials [3, 4]. Another important atmospheric consideration for lunar or planetary missions is the presence of dust. Effective protection against dust is essential for both the health of the crew and the proper functioning of on-board equipment [30].

Radiation: As humans venture to the Moon and beyond, they will need reliable and effective protection against the serious threat of space radiation. The most hazardous aspect of the radiation is the effect of charged particles. In space, the main sources of these particles are [31]:

- Solar Particle Events (SPE): energetic protons released during coronal mass ejections from the Sun.
- Galactic Cosmic Rays (GCRs): high-energy atomic nuclei, mostly protons, originating outside the Solar System, probably produced by nova or supernova explosions.

- Van Allen radiation belts, which are areas of energetic particles that are confined to moving around the Earth's magnetic field lines.

Beyond the ozone layer, humans would be directly exposed to high levels of radiation. Therefore, radiation shielding is essential for future spacecraft and habitats to prevent health problems [30].

Acceleration: When planning a mission, designers must carefully consider the acceleration environment in relation to human tolerance. In particular, the focus is on linear acceleration, rotational acceleration, and impact. When analyzing acceleration effects, it is important to consider the direction of the force relative to the human body. Assuming the person is sitting upright, the x-axis corresponds to chest to back, the y-axis to side to side and the z-axis to head to seat [30]. Humans have the greatest tolerance to $\pm$ gx acceleration, so most high-g systems are designed to align crews along this axis. According to NASA-STD-3000, the acceleration during an emergency reentry should not be greater than ± 4 gx, ± 1 gy or ± 0.5 gz [3]. For rotational acceleration, untrained individuals can typically tolerate up to 6 rpm in any direction, although training can significantly increase this limit. Human tolerance to impact acceleration depends not only on the peak g-forces experienced, but also on the rate of application to reach the peak g.

Noise: As in Earth-like environments, noise reduction in the habitat is essential to preserve hearing, facilitate communication and ensure crew comfort. Therefore, typical noise sources such as motors, fans, pumps, valves, regulators and other equipment, including thrusters, must be considered by the mission designers [3].

Vibration: Vibration is typically classified as either whole-body or hand-arm, depending on the part of the body to which it is applied. Whole-body vibration over long periods of time causes the most severe physiological effects. It has a significant negative impact on human performance, particularly accuracy, which decreases with increasing frequency, intensity and duration of vibration [30]. Vibrations can combine with noise to cause problems such as stress, fatigue and reduced crew performance. This problem can be reduced by design choices such as adjusting equipment operating parameters, selecting alternative materials, applying lubrication or incorporating damping systems [3].

Metabolic parameters: From a thermodynamic perspective, humans are open systems that continuously interact with their environment by exchanging matter and energy. The main inputs are food, water, and oxygen, while the main outputs are heat and metabolic byproducts, such as carbon dioxide, sweat, urine, and feces. To sustain life, certain basic needs must be consistently met: an atmosphere of appropriate composition and temperature, access to clean water every few hours, and sufficient food. Figure 9 illustrates the typical values of the human metabolic input and output. These values are based on an average metabolic rate of 136.7 W per person and a respiratory quotient of

0.87 [3]. These values will increase with higher levels of physical activity [4]. As shown

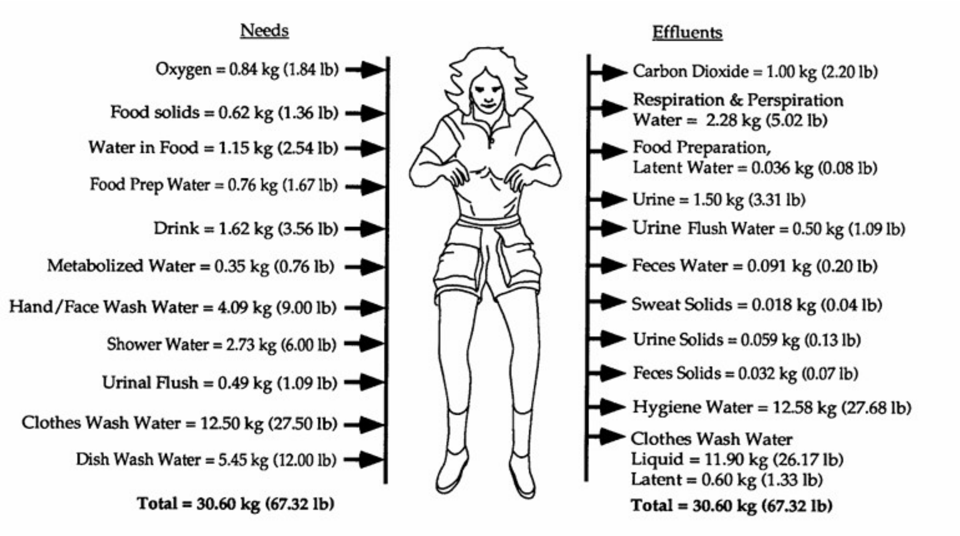


Figure 9: Human metabolic input and output per person per day [4].

in Figure 9, nominal oxygen (O_2) consumption per person is approximately 0.84 kg per day, although it can vary between 0.5 and 1.4 kg depending on individual factors and activity levels. Similarly, carbon dioxide (CO_2) production typically averages about 1 kg per person per day, but can vary from 0.65 to 1.5 kg [3]. In addition to metabolic needs, people also need potable water for hygiene, washing clothes and dishes. As shown in Figure 9, the daily water needs per person is significant (about 26.99 kg, 90% of the total resource needs). For long-duration missions, the design of an efficient water recycling system is essential, otherwise the total mass of consumables required would be prohibitively high. Humans also generate heat as a byproduct of metabolism, and the rate of this heat production varies depending on the individual and their level of physical activity. For example, the typical metabolic heat output of a resting astronaut is approximately 105 watts [3].

Microgravity: In space, microgravity poses serious challenges to human physiology, causing three main types of adverse effects: a reduced hydrostatic gradient leading to fluid redistribution, disturbances in vestibular functions leading to motion sickness, and a reduced load on weight-bearing tissues such as muscles and bones. Under Earth's gravity, body fluids are pulled downwards, resulting in higher blood pressure in the lower body and lower pressure in the upper body. In microgravity, this hydrostatic gradient disappears and fluids are redistributed evenly throughout the body, a phenomenon known as fluid shift. The kidneys interpret this redistribution as an excess of fluid and respond with increased urination, which can lead to dehydration. In addition, the heart experiences less resistance when pumping blood, leading to an increased and irregular heart rate and a gradual loss of heart muscle mass [31]. Vestibular function, or the capacity to perceive movement, is also impacted. The vestibular system is calibrated to work in a constant

[3]The respiration quotient is the ratio of the volume of carbon dioxide produced to the volume of oxygen consumed [33].

1-g environment on Earth. However, in space, this calibration is disrupted by the free-fall environment [30,31]. Prolonged exposure to microgravity also weakens both muscles, through loss of muscle mass, and bones, through significant calcium loss [30, 31]. These changes may not be a problem while the individual is in microgravity, but may become harmful when the individual returns to a higher-gravity environment. For short-term missions, experience has shown that regular exercise in microgravity is generally sufficient to prevent physiological changes from becoming operationally significant. However, it remains unclear how severe these effects could be on long-term missions, such as a journey to Mars. Some mission designers propose introducing artificial gravity in the range of 0.5 to 0.8 g to mitigate these problems. According to NASA-STD-3000, crew members on missions lasting more than 10 days in microgravity should perform physical activities to counteract these effects [3].

Psychological effects: When planning and designing space missions, especially long-duration missions, it is essential to consider the psychological effects on the crew. Excessive workloads can lead to physical exhaustion and moral fatigue. In addition, the extreme isolation of space can increase stress levels and, over time, lead to feelings of loneliness or depression. Living with the same people every day can further strain interpersonal relationships and negatively affect mental well-being [31]. Long-duration missions, such as those to Mars, will require careful attention to the psychological well-being of the crew and the development of effective support strategies. As human space missions extend over longer periods of time, the need for more stable, complex and human-center living and working environments will become increasingly important. Designers will be challenged to create habitats that not only support the crew's professional activities and social interactions, but also address a wider range of human needs [3].

2.2 Analog Habitats: Historical Review

Space habitats are advanced technological structures designed to support human life in extremely hostile and remote environments. The development of space habitats is a key project focus in the planning of long-term missions to the Moon or Mars. Sustaining human life in such a hostile environment requires precise design, careful planning and strict management protocols. Effective management of space habitats is therefore essential to ensure sustainability, crew safety and overall mission success. Habitat management includes life support systems, resource utilization, crew interactions, mental health, and operational protocols [34]. An example of a future space habitat is the Lunar Surface Habitat (SH) of the Artemis program, as shown in Figure 10.

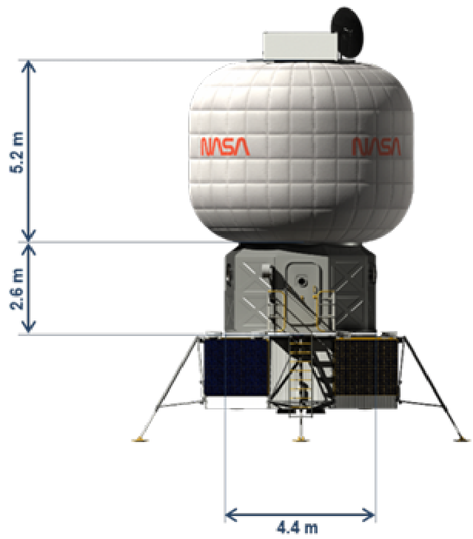


Figure 10: Lunar Surface Habitat of the Artemis program [23].

The design and management of space habitats relies heavily on experience, data and research gained from Analog Missions. *"An Analog Mission is a research method focused on investigating one or several aspects of crewed space missions using earthly real-life situations as an analogue to an off-world scenario"* [35]. These missions are typically conducted in terrestrial environments that closely simulate the physical and operational challenges of space. Before systems are implemented in actual space conditions, space agencies and their partners work with academic, industrial, and government institutions to test technologies and procedures in extreme terrestrial environments. Analog Missions therefore provide valuable insights into the strengths and limitations of proposed human exploration strategies [36]. Since the early days of space exploration, analog missions have played a key role in preparing for planetary surface operations, first for the Moon, and now for future deep space destinations such as an asteroid or Mars [36, 37]. The main element of an Analog Mission is the Analog Habitat: *"Analog habitat is a space adapted or designed to support analog missions and add more simulation and testing capabilities"* [35]. Over the past few decades, around twenty analogue habitats have been built around the world, allowing researchers to study habitat management strategies and evaluate technologies in a controlled environment [38]. Analog Habitats are therefore a powerful tool for studying and testing systems, human factors and strategies essential to the design of space habitats for future deep space missions. The knowledge gained from Analog Habitat studies not only improves the understanding of critical systems and human factors, but also significantly enhances the ability to mitigate risk during long duration space missions [34].

The benefits of Analog Missions for space exploration can be summarized as follows:

- **Realistic simulation:** Analog missions allow researchers to test technologies, protocols, and human factors in realistic scenarios that simulate actual space missions. These simulations help identify potential problems and refine solutions before they are implemented in space [34]. Therefore, Analog Habitat provide a platform to test operational procedures and determine the most effective combinations of procedures and team dynamics to successfully complete mission tasks [37].
- **Cost:** Analog Missions provide significant cost savings by facilitating low-budget testing and validation [34].
- **Risk reduction:** Analog Missions help reduce the risks of spaceflight by identifying and addressing potential problems in controlled environments. By testing hardware, procedures and human responses in these environments before flight, researchers improve mission safety and reliability [34].
- **Technological development:** Analog Missions facilitate the development of space habitat technologies. These missions help to increase their Technology Readiness Level (TRL)[4] through realistic testing [34, 37]. Analog Habitats are particularly essential for testing and validating ECLSS technologies. The development of future ECLSS relies on Analog Mission studies that investigate novel physico-chemical and bioregenerative technologies and their integration into habitat designs [38].
- **Human Factors:** As described in the previous section, the assessment of human factors is relevant in space exploration. To prevent cognitive or behavioural problems during these missions, it's important to take preventative measures [40]. By studying crew interactions and stressors in analog habitats, Analog Missions provide important insights into the social, physiological and psychological effects of long-duration spaceflight. These studies also allow the evaluation of psychological and interpersonal monitoring methods, many of which have been proven effective in actual flight operations [34, 37].

Many Analog Habitats have been built in recent decades, each with unique characteristics and specific mission objectives. These include the Antarctic research stations, Human Exploration Research Analog (HERA), the Mars-500 isolation experiment and Human Exploration Spacecraft Test-bed for Integration & Advancement (HESTIA), which will be used as an example in the following paragraphs. A comprehensive overview of Analog Habitats can be found in [38].

[4] *"Technology Readiness Level (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest"* [39].

Antarctica's climate, terrain and deep isolation closely mimics the conditions astronauts will encounter during long-duration space missions. It provides an ideal, accessible testbed for development and validation of prototype systems and technologies for lunar and Martian environments, as well as a natural analogue for behavioural health research, reflecting the psychological challenges of isolation. Antarctica is the location of various research stations, such as the American McMurdo Station and the Italian-French Concordia Research Station, shown in figures 11 and 12, respectively [41, 42].

Figure 11: McMurdo Station [43].

Figure 12: Concordia Research Station [44].

Human Exploration Research Analog (HERA) is a NASA analogue mission programme conducted in a habitat at the Johnson Space Center. The habitat, shown in Figure 13, is about 650 ft^2 (about 60 m^2), consisting of two floors and a loft. The HERA program simulates the isolation experienced during a space mission. The program's primary objectives are to study crew health, human factors, and communication [45].

Figure 13: Human Exploration Research Analog [46].

Mars-500 was a collaborative project between the European Space Agency (ESA) and the Russian Space Agency that simulated a journey to Mars within a habitat at the Institute of Biomedical Problems in Moscow, shown in Figure 14. The aim was to gather data and insights for future human missions to Mars by studying how long-term confinement affects humans, both psychologically and physically. Throughout the study, participants were subjected to a series of tests to assess the effects of isolation on stress levels, hormonal balance, immune function, sleep quality, mood, and the effectiveness of nutritional supplements [47].

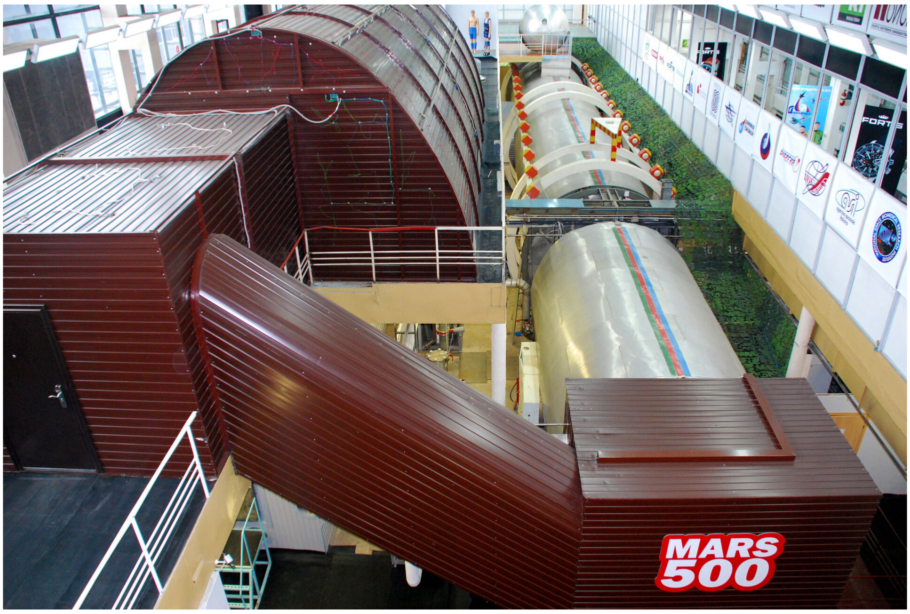


Figure 14: Mars 500 habitat [48].

Human Exploration Spacecraft Test-bed for Integration & Advancement (HESTIA) is a facility developed in support of the Gemini, Apollo, and SkyLab programs, shown in Figure 15. In the 1990s, HESTIA conducted several closed-loop tests of human ECLSS technology to advance the technology for the ISS [49]. HESTIA in the Gemini era, was necessary for testing environmental control and life support system, and evaluating concepts for human spaceflight habitation and structural designs. The facility provides capabilities for diverse research needs, such as data acquisition, monitoring and control systems, power distribution, fluid handling and atmospheric pressure management, and is now being prepared for reuse in support of future planetary deep space missions [38].

Figure 15: Human Exploration Spacecraft Test-bed for Integration & Advancement [38].

Analog conclusion

As the above-mentioned examples show, Analog Habitats have long been - and are foreseen to continue to be - excellent platforms for testing, research and validation in support of deep space mission design. As stated by Mane [34] *"Analog habitats are essential instruments for improving space research and establishing a sustained human presence beyond Earth because they encourage innovation, international collaboration, and public participation".* The lessons learned from these analogue environments will directly influence the development of future space habitat architectures.

2.3 Environmental Control and Life Support System (ECLSS)

As stated in the European Cooperation for Space Standardization, the ECLS is an:

> *"Engineering discipline dealing with the physical, chemical and biological functions to provide humans and other life forms with suitable environmental conditions. The objective of ECLS is to create a suitable environment by controlling the environmental parameters, providing resources, and managing waste products. It must also support special operations such as EVA, respond to environmental contingencies and provide health related services"* [50].

The Environmental Control and Life Support System (ECLSS) is *"a system that includes the hardware and software to perform the ECLS functions"* [50].

In human spaceflight, the ECLSS is an essential part of the mission, providing appropriate conditions for a physiologically acceptable environment for spacecraft, space stations or planetary habitat. As described in Section 2.1.3, the human being is an open system, exchanging matter and energy with the environment and naturally living within a life support system known as the "biosphere[5]" [52]. In space, the ECLSS ensures the biological autonomy of humans when separated from their original biosphere by attempting to replicate the critical functions of the complex, interconnected processes that occur on Earth [4].

Therefore, the system must provide humans with the resources they need and manage their output while maintaining an environment that is appropriate for them (see Section 2.1.3). It must also provide resources for activities such as hygiene, medical procedures, and scientific experiments [3]. To meet the requirements, the ECLSS must manage the atmosphere, water, waste and food.

The ECLSS is typically divided into five main functional areas [3, 52]:

- **Atmosphere management**, including atmospheric composition control, temperature and humidity control, pressure control, atmosphere regeneration, contamination control and ventilation;
- **Water management**, including the provision of potable and hygiene water, as well as the recovery and processing of waste water;
- **Food production and storage**, which includes the production and storage of food;
- **Waste management**, covering the collection, storage, and processing of human waste and other refuse;
- **Crew safety**, involving fire detection and suppression, and radiation shielding.

[5] *"Biosphere is a relatively thin life-supporting stratum of Earth's surface, extending from a few kilometres into the atmosphere to the deep-sea vents of the ocean. The biosphere is a global ecosystem composed of living organisms (biota) and the abiotic (nonliving) factors from which they derive energy and nutrients [51]."*

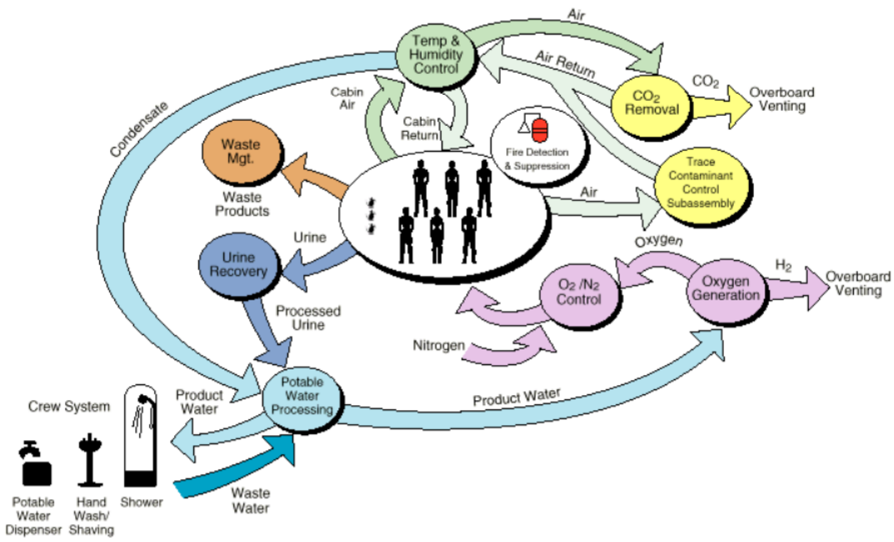


Figure 16: ECLSS flow diagram [53].

Figure 16 shows an ECLSS flow diagram illustrating the main functional areas of the system and the interactions between them. These functions can be divided into non-regenerative functions, which refer to processes that do not involve recycling, and regenerative functions, which are associated with the recycling of life support resources [52]. The following section examines the main functions of ECLSS in more detail, along with the technology options available to realize each function.

Beyond the primary purpose of sustaining human life in space, the configuration of an environmental control and life support system is heavily influenced by several requirements, including technological capabilities, human factors, mission scenarios, safety considerations, and cost constraints [52]. For example, an ECLSS configuration that works exceptionally well for a specific mission, such as a short-duration LEO mission where life support resources required are minimal, may be completely inappropriate for a different context, such as a long-duration lunar habitat that requires high autonomy, long-term reliability, and minimal resupply capabilities. Therefore, developing an ECLSS architecture is an iterative process that involves evaluating and comparing different technologies and system configurations based on specific mission requirements.

An ECLSS architecture based only on stored resources and without recycling processes is referred to as an *open loop* system, while an architecture that integrates recycling is referred to as a *closed loop* system.

In an **open loop** system, all the resources necessary for the mission are stored. There are two approaches that can be considered: launching all the necessary supplies at the beginning of the mission, or resupplying during the flight. An open loop ECLSS architecture is simpler and more reliable than a closed loop architecture, but the mass and volume of consumables increases linearly with mission duration and crew size, reaching a large system mass for long duration missions. Therefore an open loop system is ideal for short duration missions, avoiding the complexity and cost of recycling technology [4, 52].

A **closed loop** system is based on recycling an initial supply of life support resources. The *closure level* refers to how much of the total resources are provided by recycling.

Increasing the closure level reduces the need for resupply. The main advantage of this architecture is that, as the mission's duration and crew size increase, the increase in the total mass of the system is relatively small compared to the one of the open loop. However, this architecture is less reliable, more complex, more expensive and has higher thermal and power requirements than the open loop. For long duration missions, it is necessary to opt for a closed loop system to reduce its overall mass and volume [4, 52].

For example, the habitats of the Apollo spacecraft operated as open loop systems, while the International Space Station relies on a closed loop system [4].

Table 1: Reduction of relative supply mass by successive loop closure [52].

Step	**Method**	**Relative supply mass**
0	Open loop	100 %
1	Waste water recycling	45 %
2	Regenerative carbondioxide-absorption	30 %
3	Oxygen recycling from carbondioxide	20 %
4	Food production from recycled wastes	10 %
5	Elimination of leakage	5 %

As regenerative technologies are gradually introduced into the life support system, the need for resupply mass decreases significantly. This is shown clearly in Table 1, which outlines the relative resupply mass at different closure levels. It is evident that a system incorporating waste water recycling reduces the relative supply mass by more than 50% compared to an open-loop system. This substantial decrease is a consequence of the significant daily water requirements for human needs, as outlined in Section 2.1.3. For the other regenerative technologies, the reduction in supply mass is in the range of 5% to 15%. Increasing the closure level, decrease the resupply mass but also increases complexity, costs, energy consumption and reduces the overall reliability of the system.

2.3.1 ECLSS Functions

According to the NASA standard, the ECLSS is divided into several subsystems, which are listed in the Table 2:

Table 2: ECLSS subsystems [5, 54].

Subsystem	Function included
Temperature and Humidity Control (THC)	- Atmospheric Temperature Control - Atmospheric Humidity Control - Ventilation - Microorganisms and Airborne Particulate Contaminants Control - Equipment Cooling - Thermally Conditioned Storage
Atmosphere Control and Supply (ACS)	- Total Atmospheric Pressure control - Oxygen Partial Pressure Control - Atmosphere Constituents Storage - Relieve Overpressure - Respond to Rapid Decompression
Atmosphere Revitalization (AR)	- CO_2 Removal - CO_2 Reduction - O_2 Generation - Gaseous Contaminants Control - Monitoring Major Constituents
Water Recovery and Management (WRM)	- Hygiene Water Supply - Potable Water Supply - Water Storage - Urine Processing - Waste Water Processing - Water Quality Monitoring
Waste Management (WM)	- Metabolic Waste Management - Other Solid Waste Management - Liquid/Gaseous Waste Management
Fire Detection and Suppression (FDS)	- Fire Detection and Suppression
EVA Support	- Extravehicular Activity Support

The ECLSS also includes functions such as food storage and preparation, radiation protection, external dust removal, and gas distribution to user payloads [4].

Therefore, the ECLSS is made up of subsystems consisting of hardware and software, which together perform the ECLSS functions. As shown in Figure 17, non-regenerative functions are mainly found in four of the main subsystems: Atmosphere Control and Supply (ACS), Temperature and Humidity Control (THC), Fire Detection and Suppression (FDS) and Waste Management (WM)[6]. The regenerative functions, which represent the greatest technological challenge, are found in the Atmosphere Revitalization (AR) and Water Recovery and Management (WRM) subsystems [54].

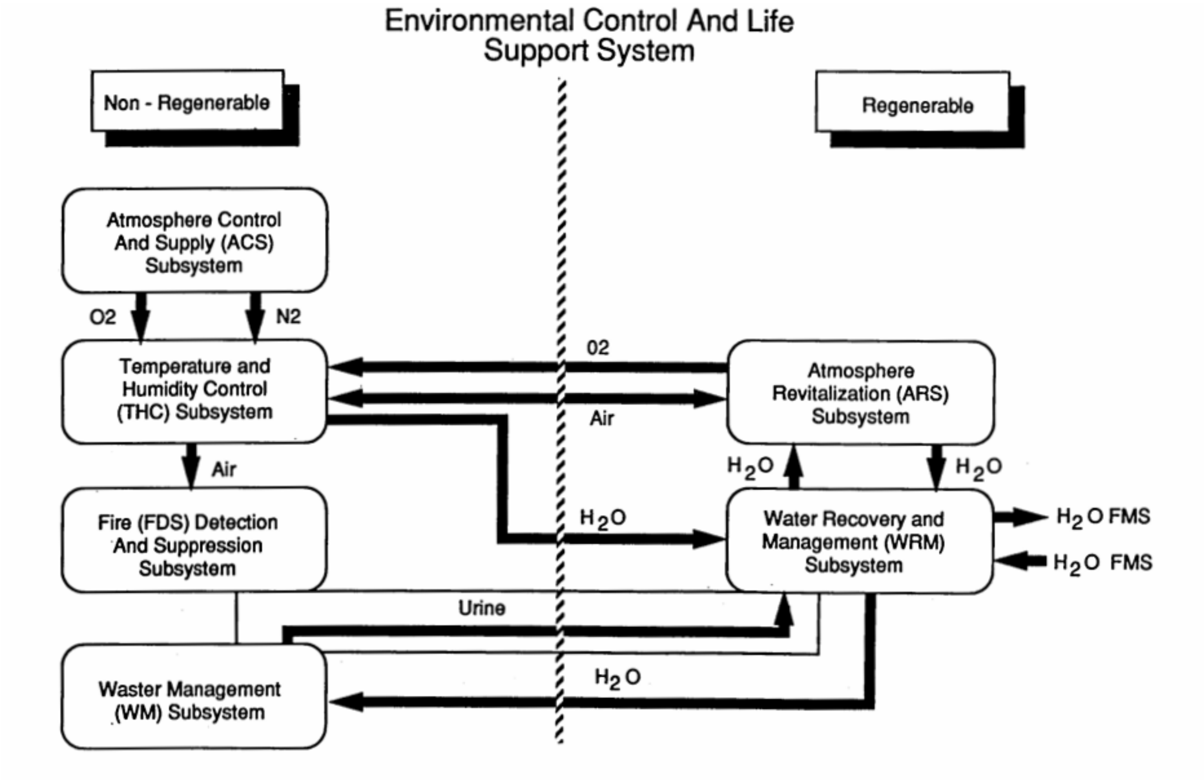


Figure 17: Regenerative and non-regenerative subsystems [54].

The following pages describe the main ECLSS functions for each subsystem. It is important to understand that the specific functions of the system are highly dependent on the mission scenario. Therefore, the ECLSS architecture definition will be different for each mission [4].

[6]In future deep space missions, advanced ECLSS could use technologies to recover products from waste. In this case, the WM will also perform regenerative functions.

Temperature and Humidity Control (THC) subsystem

The Temperature and Humidity Control (THC) subsystem is responsible for maintaining appropriate thermal and humidity conditions (see section 2.1.3) by regulating atmospheric temperature, controlling humidity, providing ventilation, cooling on-board equipment and ensuring thermally conditioned storage [52]. The subsystem is also in charge of controlling microorganisms and airborne particulate contaminants.

Atmospheric Temperature Control: Heat is removed from the cabin through ventilation, which circulates air through condensing heat exchangers. The heat is then dissipated into the outside environment through radiation or evaporation of a liquid [4].

Atmospheric Humidity Control: Maintaining appropriate levels of water vapor in the atmosphere is essential to prevent adverse physiological effects (see section 2.1.3), to avoid condensation on electronic components, and to prevent the accumulation of moisture, which provides an environment for microbial proliferation. A common problem in space habitats is excess humidity, which must be removed by condensation, absorption or adsorption [3, 4].

Ventilation: Ventilation is essential to ensure proper mixing of atmospheric constituents, allowing effective removal of CO_2, trace contaminants and heat. It also prevents the formation of stagnant regions, where oxygen can reach very low levels or carbon dioxide concentrations can become too high. Ventilation therefore plays a critical role in maintaining crew safety and comfort by circulating air both within and between modules [3,4].

Microorganisms and Airborne Particulate Contaminants Control: On Earth, airborne particulate contaminants are removed by gravity. In space, however, where gravity is negligible, such particles remain suspended and must be actively removed by filters integrated into the ventilation system (other methods include electrostatic precipitation and surface wiping). Similarly, microorganisms can spread rapidly in space habitats due to microgravity and continuous air circulation, so filters are also used to capture and control microbial contamination [3, 4].

Equipment Cooling: Electrical equipment generates heat that must be removed, either by forced convection of the atmosphere over the equipment or by conduction to a liquid-cooled surface [4].

Thermally Conditioned Storage: The THC subsystem also manages refrigerators and freezers, which are essential in space habitats for storing food, photographic film and experimental materials [4].

Atmosphere Control and Supply (ACS) subsystem

The composition of the atmosphere in a space habitat is planned during the design process based on several requirements (see section 2.1.3). The ACS must control the composition and pressure of gases in the atmosphere to ensure optimal crew and equipment performance. In a space habitat, oxygen is consumed by human metabolism and other processes, and cabin atmosphere is lost through leakage, airlock operation or use in experiments. It is therefore necessary to supply O_2 and N_2 to restore the cabin atmosphere to nominal conditions. The ACS is also responsible for relieving overpressure and responding to rapid decompression events [3, 4, 52].

Total Atmospheric Pressure Control and Oxygen Partial Pressure Control subsystem: Based on measurements of the cabin atmosphere's total pressure and O_2 partial pressure, the control system adds oxygen and nitrogen to reduce the difference between the actual pressure and the desired pressure. Control system can be either automatic or manual, or a combination of both, with the capacity to operate through pneumatic, mechanical, or electromechanical mechanisms [4].

Atmosphere Constituents Storage: Both open-loop and closed-loop ECLSS architectures require on-board storage of oxygen and nitrogen to regulate cabin pressure and composition. Even in closed-loop systems, reserves of O_2 and N_2 are essential to compensate for leakage and provide an emergency supply.

Relieve Overpressure: The system must ensure that the internal to external differential pressure remains below a specified limit. If overpressure occurs, the ACS will vent the cabin atmosphere to reduce the internal pressure.

Respond to Rapid Decompression: The ACS employs pressure sensor measurements to detect rapid atmospheric decompression events, such as those caused by meteoroid impacts [5]. The ACS is then required to restore the atmosphere using gas storage.

Atmosphere Revitalization (AR) subsystem

The objective of the Atmosphere Revitalization (AR) subsystem is to provide a breathable atmosphere for the crew by continuously controlling and regenerating the cabin atmosphere as needed. It must remove CO_2, reduce CO_2, generate oxygen, remove harmful trace contaminants generated by the crew and equipment, and monitor the major constituents of the atmosphere [5, 55].

CO_2 Removal: As discussed in section 2.1.3, carbon dioxide is the primary metabolic contaminant of a cabin atmosphere. Depending on the internal volume of the cabin and the number of crew members, high levels of CO_2 can accumulate quickly, so a method to remove it is necessary to avoid adverse physiological effects. The methods for removing CO_2 are based on absorption, adsorption, membrane separation or biological consumption [3, 4, 55].

CO_2 Reduction: For long duration missions, the system must reduce the CO_2 removed from the atmosphere to minimize the need for storage. There are several methods for reducing CO_2: electrochemical O_2 separation, biological methods, and methods based on the reaction of carbon dioxide and hydrogen at high temperature in the presence of a catalyst to produce H_2O. The reduction of carbon dioxide increase the closure level of the system [4].

O_2 Generation: For short-duration missions, the oxygen required by the crew is typically stored on board. For longer missions, however, the mass penalty of storing all the oxygen needed can be excessive, and oxygen generation is necessary. Available methods include water electrolysis, carbon dioxide electrolysis, and biological processes. Oxygen recovery from CO_2 can produce up to 0.74 O_2 kg per person per day, based on an average of 1 kg of exhaled CO_2 per crew member per day. Thus, oxygen recovery from CO_2 closes a large portion of the oxygen loop, limiting the need for storage for leak compensation and emergency use [4, 52].

Gaseous Contaminants Control: The AR subsystem must remove gaseous contaminants from the atmosphere. These contaminants include off-gassing materials, crew metabolic by-products, food preparation, housekeeping cleaners, and scientific experiments. Although the amounts of these contaminants may be small, they cannot be neglected for the safety of the crew. Passive contaminant control, such as material selection to reduce off-gassing, can reduce the amount of contaminants, but for long missions an active control system is required to remove these gases from the atmosphere [4, 52].

Monitoring Major Constituents: The primary components of a space habitat atmosphere are: N_2,O_2, H_2O and CO_2. Other gases, present in small amounts but also considered "major" because of their potential toxicity to the crew, are: H_2, CH_4, and CO. To maintain safe and stable environmental conditions, the AR subsystem must continuously monitor atmospheric major constituents and provide gas partial pressures to the control logic of other subsystems.

Water Recovery and Management (WRM) subsystem

The Water Recovery and Management (WRM) subsystem provides water for crew consumption, hygiene, and other on-board activities. For short-duration missions, water is typically stored in tanks; however, for long-duration missions, the volume and mass needed make this solution unfeasible. Because of the high cost of resupplying and the requirement of high purity for human consumption, water management is a critical technology for long-duration human spaceflight. Potable water can be produced either by fuel cells - where H_2 and O_2 are combined to produce electricity and water - or by waste water purification. The system must also ensure continuous monitoring and maintenance of water quality and distribute water to users [4, 52].

Hygiene and Potable Water Supply: The system must provide the crew with high quality potable water for consumption and hygiene water with relaxed quality requirements for dishwashing, showering, hand washing, commode or urinals, and clothes washing. As discussed in section 2.1.3, the daily water requirements per crew member, especially for hygiene needs, are significant and heavily influence the sizing and design of the ECLSS for long-duration missions. Water consumption also depends on mission characteristics, especially for EVA, where consumption can vary greatly depending on the design of the spacesuit [3].

Water Storage: Water storage must be designed to maintain potability throughout the mission. Water can be stored in tanks, but when gravity is too low to direct water to the outlet, the design requires alternative solutions. In microgravity, it is also hard to determine the amount of water remaining in the tank and to detect leaks [3, 4].

Urine Processing: Recovering water from urine increases the closure level of the system and reduces the amount of water that must be launched for the mission. Several technologies are available to recover water from urine, most of which are based on distillation methods. The recovered waste water is then further purified to produce potable water [52].

Waste Water Processing: Waste water to be treated includes condensate collected from cabin humidity, hygiene water, water processed from urine, and water from crew activities. The waste water is typically collected and treated to produce potable water. There are several purification methods available. The method selected depends on the origin of the wastewater and the required quality for the intended application [3, 4, 52].

Water Quality Monitoring: Monitoring water quality is essential to verify that the water purification process delivers acceptable quality water. Commonly monitored parameters include pH, ammonia content, total organic carbon, electrical conductivity, and microbial concentration. Less frequently monitored parameters include color, odor, turbidity, foaming, and heavy metal concentration [4, 52].

Waste Management (WM) subsystem

The Waste Management (WM) subsystem is responsible for the collection, treatment and storage of wastes generated on a space habitat. Waste includes metabolic wastes, other solid wastes, liquid wastes and gaseous wastes. For short-duration missions, these wastes are collected and stored or vented into space. For long-duration missions, however, the mass and volume required for storing all waste becomes excessive, and waste degradation may contaminate the habitat. Therefore, methods to recover useful products are needed [4, 52].

Metabolic Waste Management: For deep space missions, recovery of metabolic waste may be necessary to reduce the mass and volume of the system. Water from metabolic waste can be recovered by dehydration, and the solid portion can be converted to fertilizer for plants that would provide food for the crew. There are also processes to convert metabolic waste to carbon dioxide and water, which are then processed by the AR and WRM subsystems [4].

Other Solid Waste Management: Other solid waste consists mainly of paper and plastics, the recovery of this mass is essential for long-term missions [4].

Liquid/Gaseous Waste Management: Liquid waste includes urine and brine residues from the WRM processes. Oxidation processes exist to convert these wastes into usable products. Gaseous wastes include mainly CH_4, H_2S, H_2, CO, CO_2 and can be removed or converted to water and carbon dioxide [4].

Fire Detection and Suppression (FDS) subsystem

Fire is one of the most dangerous problems aboard any space habitat. As missions become longer, the probability of fire increases, so the potential for fire must be minimized. The FDS subsystem must detect the fire as soon as possible; detection methods include: smoke detectors and flame detectors. In the event of a fire, appropriate suppression methods must be provided. The fire will produce byproducts which may be hazardous for the crew, therefore it is essential that these byproducts are removed from the atmosphere [4, 52].

EVA Support

During EVA operations, crew members move from a high pressure environment (the cabin) to a much lower pressure environment (the suit). This change poses a potential risk because dissolved N_2 can form bubbles in body tissues and the blood stream, resulting in decompression sickness. To prevent this, crew members breathe pure O_2 in a hyperbaric chamber before EVA operations, which allows "washout" of N_2 from the body with each exhalation, reducing the risk of N_2 bubbles. The ECLSS must support EVA operations by providing the necessary environmental conditions for their execution [3, 4].

Other Functions

Food storage and preparation: The ECLSS is also responsible for food reserve management. Throughout the mission, food must be preserved until consumed, typically by dehydration, refrigeration, or freezing [4].

Radiation Protection: Crew radiation protection is considered part of the ECLSS. For long-duration missions, multiple strategies are required to provide adequate radiation shielding [4].

External Dust Removal: In planetary surface missions, dust poses a serious threat to both crew health and habitat hardware by reducing system reliability. Effective methods are needed to remove dust from spacesuits and clean hardware surfaces inside the habitat [4].

Gases Distribution to User Payloads: The ECLSS must supply oxygen and nitrogen, at the desired temperature, pressure, and flow rates, to the systems, crew, and payload interfaces [5].

2.3.2 ECLSS Technologies

ECLSS technologies may rely on physicochemical processes, biological processes, or a combination of both. Systems that include both types of processes are referred to as Controlled Ecological Life Support System (CELSS) [52].

Physicochemical technologies, which include fans, filters, physical or chemical separations, etc., have traditionally been used for life support. They are well understood, compact, have a fast response time, but typically have high energy demands and cannot contribute to food production. Biological technologies use living organisms, such as plants or microbes, to produce or break down organic molecules. While these technologies offer the potential for food production, they are less well understood, require more space and energy, require more maintenance, and have slow response times [3, 52].

In future space habitats, the integration of biological processes with physicochemical technologies can lead to a completely closed ecosystem, with closed loops for air, water, and carbon. Figure 18 shows an example of a gradual implementation of biological components into a physico-chemical life support system.

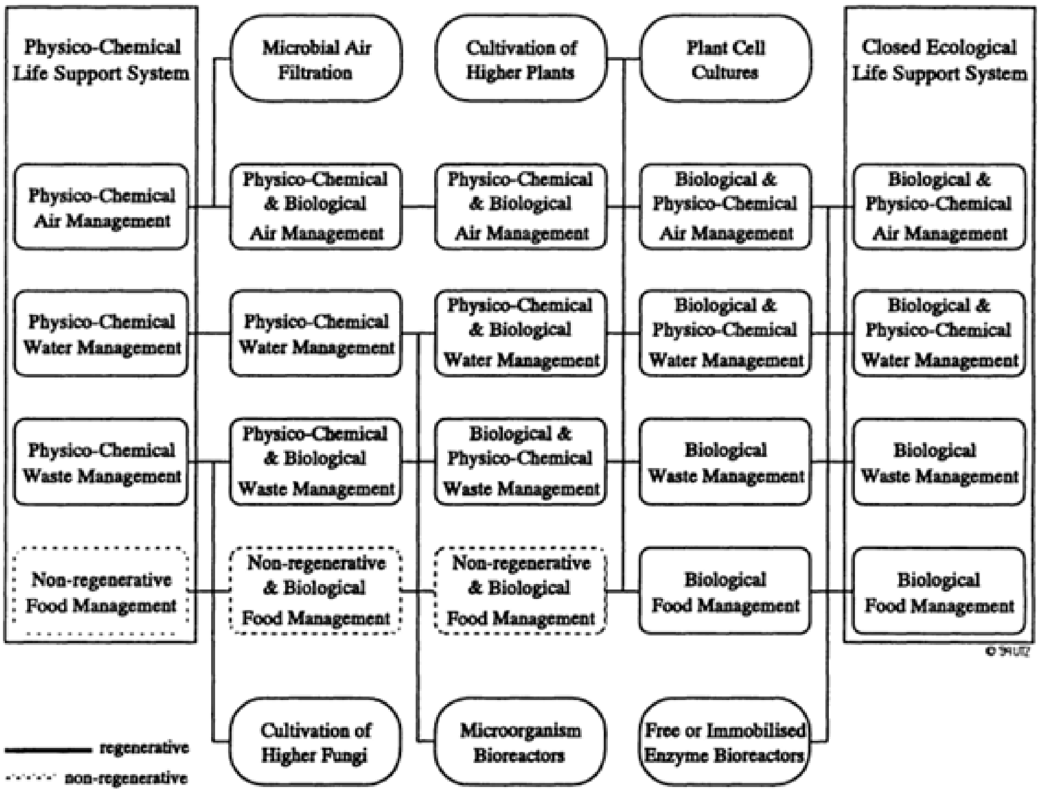


Figure 18: From a ECLSS to a CELSS [52].

Appendix A describes the main physicochemical and biological technologies associated with the ECLSS, which are designed to perform essential life support functions. For each function, there are often multiple technology options available. As a result, trade studies are typically conducted to compare candidate technologies based on factors such as power consumption, mass, volume, thermal load, TRL, reliability, safety, complexity, cost, and system integration considerations.

2.3.3 ECLSS Design Considerations, Constraints and Requirements

The development of an ECLSS is an iterative process that involves evaluations of technologies and system configurations, analysis and simulations of the system, and the testing of both hardware and software. During the design phase, several requirements, constraints, and considerations will affect the final system architecture. As shown in Figure 19, these include: technology considerations, human requirements, mission requirements, safety and reliability requirements, test requirements, flight requirements, cost requirements, system requirements and integration factors [4].

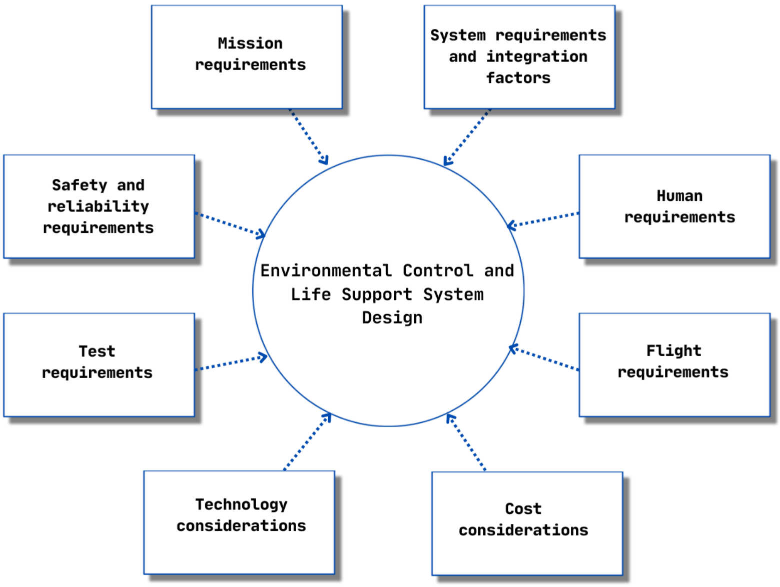


Figure 19: ECLSS design considerations.

Technology considerations: As described in the previous section, different technologies can perform the same ECLSS function. Therefore, it is necessary to identify the most suitable technologies by conducting top-level trade studies from the early design phases. Information on existing technologies in terms of mass, volume, power, thermal load, performance, safety, TRL, resupply, etc., is necessary to evaluate preliminary system configurations. The designer must comprehend the limitations of each technology, assess its ability to meet the specified requirements, and consider its impact on the overall system.

Human requirements: The basic purpose of any life support system is to sustain human life. Therefore, human requirements are the main factor in designing an ECLSS. These requirements can be grouped into three main categories: the need for an adequate environment, the supply of essential consumables and the management of human waste products [52]. Additional details on human factors relevant to ECLSS design are provided in the section 2.1.3. During the design phase, it is also important to consider "human-system" requirements, which relate to how the crew interacts with the hardware inside the habitat [4]. A well-designed interface for hardware that requires crew operation can facilitate maintenance tasks and enhance operational safety.

Mission Requirements: The mission profile (crew size, mission duration and location, habitat, etc.) is an important aspect that influences the architecture of an ECLSS. Crew size is one of the most important factors because it affects the system's metabolic requirements. However, the impact on mass, volume, power consumption, and thermal load does not necessarily increase linearly with the number of crew members. As mission duration increases, the need for consumables increases, while reliability and maintainability become more important. For long-duration missions, technologies that reduce the need for expendables and ensure high reliability become significantly more attractive. In addition, longer missions generally require a higher closure level, in order to reduce the need for resupply. Mission location is another key factor affecting ECLSS design. Habitats in LEO, on the Moon, or on Mars introduce different environmental conditions that affect hardware configuration. For example, the presence of gravity can simplify certain system components (such as liquid/gas separator) and improve reliability, but may also require more powerful pumps. Additionally, the design of an ECLSS for planetary habitats must consider the protection of the ECLSS hardware from dust. Habitat design aspects - such as module volume, leak rates, and EVA frequency - also have a direct impact on ECLSS performance and configuration. In addition to environmental and operational factors, mission requirements include payload requirements, logistics requirements, and requirements for growth. Payload requirements relate to the need for the ECLSS to support scientific or technical activities within the habitat during the mission. Logistics requirements relate to supply and maintenance. The system should be designed to minimize the number of components that require periodic replacement, as well as to standardize parts to minimize the number of spare units that must be stored. Finally, growth requirements address the need for the system to be adaptable to changes in configuration. Over time, the habitat may be expanded by adding modules or integrating new technologies. Therefore, the initial ECLSS architecture must be adaptable. It should have hardware and software interfaces that allow for future upgrades. Table 3 summarizes the major impacts on ECLSS design from the mission characteristics [3,4,52].

Safety and Reliability requirements: For human spaceflight missions, safety is one of the primary system design drivers. Potential safety risks and the consequences of component and operational failures must be identified and evaluated during the design process [4]. Some technologies are safer than others, and the selection process should prefer those that reduce risk. Equally important is the management of redundancy and spare units of the ECLSS technologies in order to ensure that the system maintains an acceptable level of safety throughout the mission.

Table 3: Impact on ECLSS design [52].

Mission Characteristics	**Impact on ECLSS Design**
Crew Size	Increasing the crew size increases the amount of consumables required.
Mission Duration	Increasing mission duration increases the amount of consumables and reliability required.
Cabin Leakage	An increase in cabin leakage necessitates an increase in the required resupply.
Resupply Capability	The more difficult the resupply, the greater the need for storage and reliability.
Power Availability	Due to limited power availability, passive or low-energy technologies are preferred.
Volume Availability	Space limitations require more compact technologies.
Transportation Costs	The high cost of transportation requires a decrease in system weight.
Gravity	Technologies must be designed to operate under the expected gravity conditions.
Contamination Source	Contamination requires implementing countermeasures and increasing system robustness.
In-Situ Resource Utilization	It decreases resupply needs.

Test Requirements: Throughout the development process, the performance of the ECLSS is validated by testing all the system assemblies in dedicated facilities [4]. In cases where testing involves humans, rigorous safety standards and procedures must be implemented. In this context, analog habitats play a key role in providing a means to simulate ECLSS operations and evaluate technologies under realistic, mission-like conditions, as discussed in the section 2.2.

Flight Requirements: After developmental testing, the design must be qualified for flight. This phase requires compliance with a wide range of specifications, including NASA and military related to design, manufacturing, testing, electronics, software, and other critical aspects of the system [4].

Cost Considerations: When selecting technologies, it is important to consider both development and operational costs. Development costs refer to the expenses required to make a technology ready for flight, while operational costs refer to the expenses of maintaining and operating the technology, including the costs of spare parts. The total investment required to develop a system is categorized as Design, Development, Test, and Evaluation (DDTE) costs. In addition, life cycle costs is the sum of DDTE, production costs, launch costs and the costs required to operate the system throughout its life [4].

System requirements and integration factors: In addition to the above requirements, ECLSS requirements must be addressed during the design process. These include total mass, volume, power consumption, thermal load, consumable and supply requirements, maintenance requirements, and interface requirements [4]. Interface requirements concern both the integration of the ECLSS subsystem and the integration with other habitat systems. It is essential to accurately define the interfaces between subsystems and between different technologies in order to develop a system capable of meeting all requirements. The selected technologies have a significant impact on system integration, which is an important design choice. Figure 20 shows an example of ECLS subsystem integration.

The ECLSS must also interact with the other systems of the habitat depending on the mission scenario. Therefore, it is also necessary to address the interface requirements of the ECLSS with the electrical power system, the thermal control system, the EVA system, the data and command processing system, the communications system, the guidance, navigation, and control system and the crew systems.

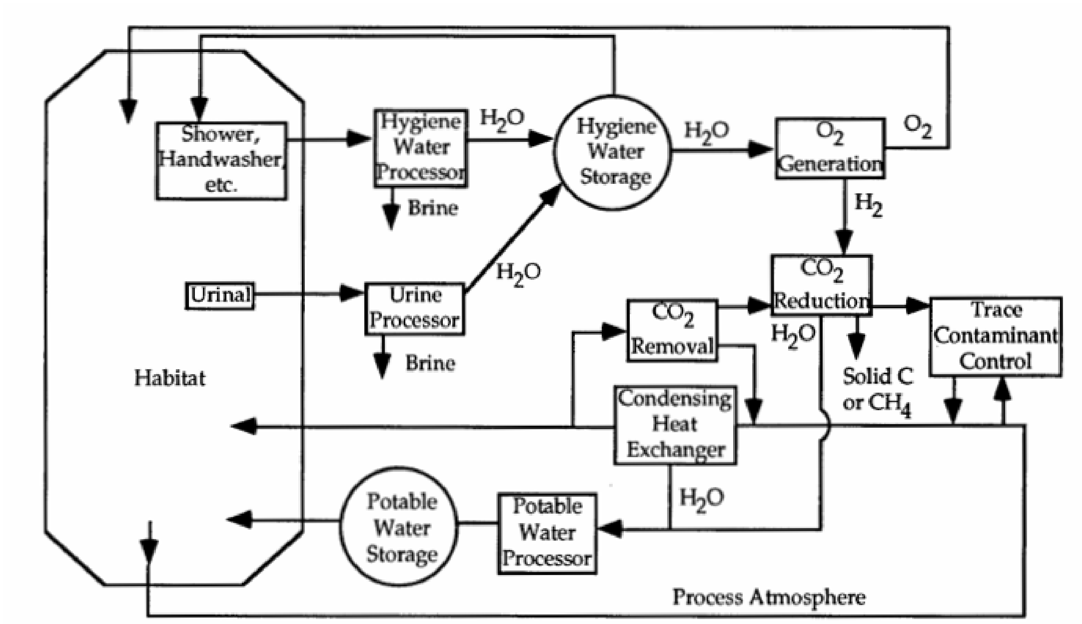


Figure 20: Integration of ECLS subsystems [4].

2.3.4 Equivalent System Mass, Reliability and Cost Analysis

In the early design phase of an ECLSS for a specific mission, trade studies of multiple system configurations are conducted to identify the optimal system architecture that meets all requirements. As shown in Figure 21, the conventional approach for a preliminary ECLSS design process involves defining a set of candidate system concepts. Each concept represents a possible system configuration aimed at providing an optimal solution based on the given requirements. These concepts are then analyzed, and the results are compared to identify the best evaluated design [56].

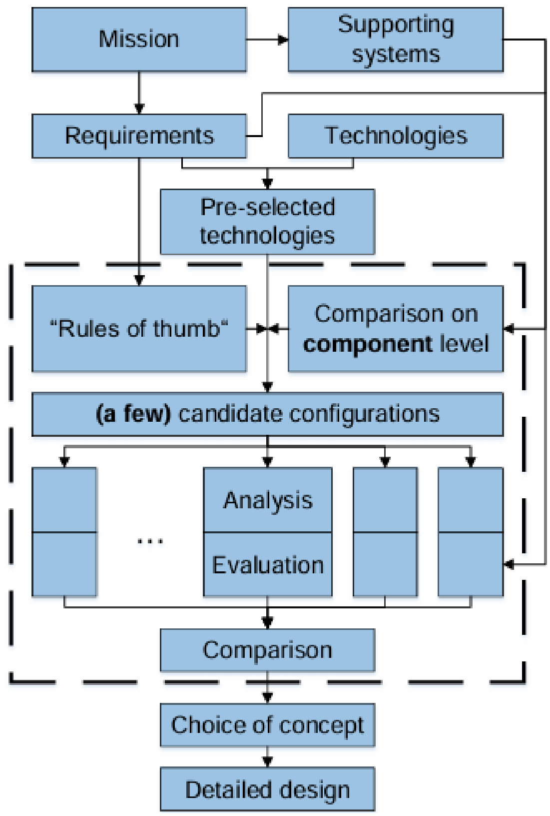


Figure 21: Convectional approach for a preliminary ECLSS design process [56].

System concepts are evaluated according to key criteria such as performance, safety, reliability, mass, cost and TRL.

To compare different system configurations or technologies, three important metrics can be considered from the beginning of the design process:

- Equivalent System Mass.
- Probability of Loss Of Crew.
- Life Cycle Cost

As discussed in Jones [57], The best life support system ensures the required performance and reliability level throughout the mission duration with the minimum ESM and Life Cycle Cost (LCC). Performance refers to how efficiently the system performs its intended functions and also the possible system's operational problems.

Equivalent System Mass (ESM)

As stated in Levri and Vaccari [58] "*The Equivalent System Mass (ESM) evaluates the mass of a system or subsystem and associated infrastructure costs, given a specific mission location, duration, and crew size. Determination of the ESM of a system or subsystem has five components: the actual system mass, the equivalent mass of the volume occupied, the equivalent mass of the power requirement, the equivalent mass of the cooling requirement, and the equivalent mass of the demands on crew time.*"

Traditionally, ESM has been used to compare different system configurations or technologies. The metric is simple to compute and easy to understand, but requires detailed information about the technologies [58].

To compute the ESM of an ECLSS, it is necessary to determine the physical and operational characteristics of each component of the system [3]. Physical characteristics include mass and volume of the specific technology while operational characteristics include power consumption, thermal heat load and crew time.

The following equation indicate that the total mass of a technology include an initial mass and a time-dependent mass:

$$M_{\text{tech1}} = M_{\text{hw1}} + M_{\text{chg1}} + (M_{\text{cons1}} + M_{\text{exp1}} + M_{\text{spare1}}) \cdot \text{mission duration} \tag{2}$$

Initial mass includes hardware mass M_{hw1} and initial resource charge M_{chg1} (such as the mass of oxygen inside the tank). While time-dependent mass include consumable resources M_{cons1}, process expendables M_{exp1} and spare parts M_{spare1} [3, 58]. The total mass of an ECLSS is:

$$M_{\text{ECLSS}} = M_{\text{tech1}} + M_{\text{tech2}} + \cdots + M_{\text{tech}N} \tag{3}$$

The equations for calculating volume are similar to those for mass, except that there is no equivalent volume to mass charge term, and the time-dependent volume is a function of the resupply interval rather than the mission duration [3, 58]:

$$V_{\text{tech1}} = V_{\text{hw1}} + (V_{\text{cons1}} + V_{\text{exp1}} + V_{\text{spare1}}) \cdot \text{resupply interval} \tag{4}$$

$$V_{\text{ECLSS}} = V_{\text{tech1}} + V_{\text{tech2}} + \cdots + V_{\text{tech}N} \tag{5}$$

While the total power consumption P_{ECLSS} in kW and the total thermal heat load THL_{ECLSS} in kW can be calculated using the following equations:

$$P_{\text{ECLSS}} = P_{\text{tech1}} + P_{\text{tech2}} + \cdots + P_{\text{tech}N} \tag{6}$$

$$THL_{\text{ECLSS}} = THL_{\text{tech1}} + THL_{\text{tech2}} + \cdots + THL_{\text{tech}N} \tag{7}$$

Another important operational characteristics is crew time, which is the total number of hours required for nominal operation and maintenance of the system [3]. Time is a valuable resource for the mission, and any time spent operating and maintaining the ECLSS subtracts from time available for primary mission activities. In the early design phases it is important to make an initial estimate of crew time based on the selected technologies, but in the ESM metric it is a minor contributor compared to the other characteristics [59]. Therefore, in addition to minimizing ESM and providing the required reliability, the designer should consider crew time during the design process to increase the total work time available for the mission purpose. Crew time can be calculated with the following equation:

$$CT_{\text{ECLSS}} = (CT_{\text{tech1}} + CT_{\text{tech2}} + \cdots + CT_{\text{tech}N}) \cdot \text{mission duration} \tag{8}$$

where CT_{ECLSS} is the total number of hours per day of crew time for a specific technology.

To calculate the total system ESM, the physical and operational characteristics described for each technology must be converted to an equivalent mass. Each mission has specific conversion factors that depend on the selected power and thermal control systems, as well as the habitat design. The ESM concept establishes mass as a shared unit for the major characteristics of the system, the idea is to determine what portion of the supporting systems, such as power and thermal control, are required to operate the ECLSS [3, 58]. The conversion factor for volume CF_{VOL} is expressed in $\frac{\text{kg}}{\text{m}^3}$, for power CF_{PWR} in $\frac{\text{kg}}{\text{kW}}$, for thermal heat load CF_{TCS} in $\frac{\text{kg}}{\text{kW}}$, and for crew time CF_{CT} in $\frac{\text{kg}}{\text{hour}}$.

Finally, the ESM can be calculated using the following equation:

$$\begin{aligned}\text{ESM} &= M_{\text{ECLSS}} + (V_{\text{ECLSS}} \cdot CF_{\text{VOL}}) \\ &\quad + (P_{\text{ECLSS}} \cdot CF_{\text{PWR}}) + (THL_{\text{ECLSS}} \cdot CF_{\text{TCS}}) + (CT_{\text{ECLSS}} \cdot CF_{\text{CT}})\end{aligned} \tag{9}$$

This metric allows different ECLSS configurations to be compared by plotting each ESM value against mission duration, providing valuable insight into the selection of a specific configuration. An example of this analysis is shown in Figure 22, which compares four ECLSS architectures: a non-regenerable physico-chemical (P/C) configuration, a regenerable (P/C) configuration, a hybrid P/C-biological configuration, and a CELSS [3, 52].

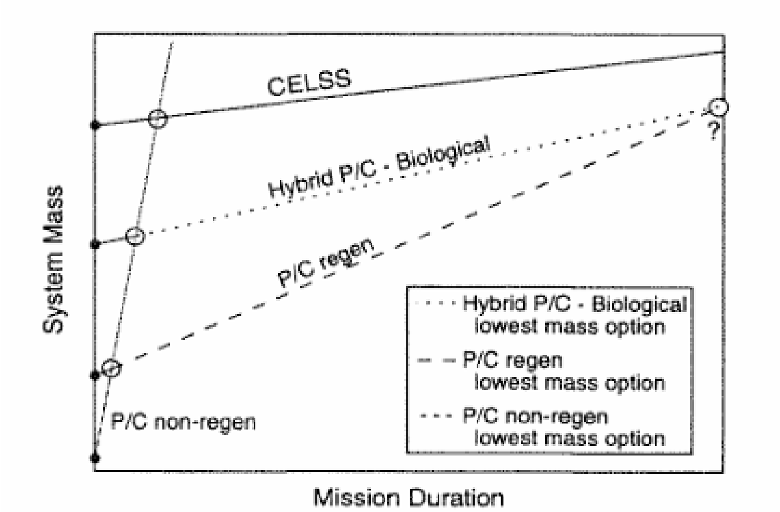


Figure 22: ESM vs mission duration [3].

These four approaches include ECLSS architectures that range from an open mass loop to closed water, oxygen, and food loops. It can be seen that as the mission duration increases, the ESM increases due to the time-dependent equivalent mass of the system. The initial mass of the four configurations is represented by the black points intersecting the y-axis. The white circles are the "break-even points" that represent the intersection of the two lines and indicate that as the mission duration increases, less mass is required to achieve a higher level of closure [52].

ESM analysis can be a valuable tool during the conceptual design of an ECLSS; however, it should not be used as the only metric for evaluating system configurations because it does not fully capture aspects such as safety, reliability, costs and performance capabilities [59].

Probability of Loss Of Crew (Pr(LOC))

Reliability is one of the most important factors in the design of an ECLSS. System design must includes reliability prediction, failure modes, effects analysis, risk analysis, and maintenance strategies in order to meet the safety requirements described above. Designers should minimize risk by incorporating safety and warning devices and establishing procedures [3]. Reliability also affects maintainability, probability of system failure, and ESM.

The components of an ECLSS are subject to frequent failures; in fact, the ECLSS on the ISS requires periodic replacement of subsystems using on-board Orbital Replacement Units (ORUs) to ensure uninterrupted operation [5].

Therefore, in the early design phases, it is important to predict the reliability of the system using reliability prediction models based on statistical methods. These models are used to compare design alternatives, evaluate design feasibility, identify potential failure areas and track reliability improvement [60].

To address the safety level of a system, it is necessary to estimate the failure rate of its technologies.

The failure rate λ_i is the number of failures per unit time period, given that the technology is operating at the beginning of the time period [61]. The failure rate is the inverse of the Mean Time Between Failure (the average time between critical failures):

$$\lambda_i = \frac{1}{\mathrm{MTBF}_i} \tag{10}$$

The reliability model provides designers with an estimate of the failure probability of the system based on the failure rates of each technology within the system. It also allows evaluation of how ESM and failure probability change when spares or redundancies are added. The reliability model considered in this work is based on the approach described by Jones [57], which assumes that adding a set of spare units for a given technology reduces its failure rate by one order of magnitude and increases its ESM by 50%. Redundancy is modeled using a Poisson distribution. More details on the reliability model and its implementation are given in the following sections.

As discussed in Jones [62], the reliability $R_i(t)$ is the probability that a technology will not fail before time t. Assuming the failure rate is constant, reliability is an exponential function:

$$R_i(t) = e^{-\lambda_i t} \tag{11}$$

A low failure rate of a technology is associated with a high MTBF, which leads to high reliability.

The failure probability $F_i(t)$ is the probability that a technology will fail before time t.

$$F_i(t) = 1 - R_i(t) \tag{12}$$

The total system failure rate is calculated as the sum of the failure rates of all subsystems, each determined by the sum of the failure rates of the individual technologies constituting the subsystem.

$$\lambda_{ECLSS} = \sum_{i=1}^{n} \lambda_i \tag{13}$$

where n is the number of the system technologies. While the reliability of the ECLSS is the product of all the subsystem reliabilities[7]:

$$R_{ECLSS}(t) = \prod_{i=1}^{n} R_i(t) \tag{14}$$

The failure probability of the system, also known as Probability of Loss Of Crew(t) is the probability that the ECLSS will fail before time t.

$$Pr(LOC)(t) = 1 - R_{ECLSS}(t) = 1 - \prod_{i=1}^{n} R_i(t) \tag{15}$$

Using equation 12, the Probability of Loss Of Crew (Pr(LOC)) can also be expressed as follows:

$$Pr(LOC)(t) = 1 - \prod_{i=1}^{n}(1 - F_i(t)) \tag{16}$$

To avoid risks and ensure acceptable safety levels, the Pr(LOC) must be less than a specified value. A reasonable Pr(LOC) is less than 0.001 for the all mission duration [57]. While achieving the required Pr(LOC) is generally less complex for short-duration missions, it becomes significantly more challenging as mission duration increases. The most effective ECLSS achieve the required Pr(LOC) while minimizing the Equivalent System Mass.

ECLSS technologies tend to have high failure rates, which means that achieving the required Probability of Loss Of Crew requires the integration of redundancy and spare parts into the system. While this strategy significantly improves reliability over the life of the mission, it also increases the ESM.

[7]This equation is correct if the system is composed of technologies in series. In other terms, the system operates if all of the technologies operate.

The Figures 23 - 24 show the ESM and Pr(LOC) plotted against mission duration for five different ECLSS architectures. The plots show the differences in mass and reliability of different system configurations based on storage, recycling, and various levels of redundancy and spares. It is clear that storage-based systems are inherently more reliable than recycling-based systems, especially for shorter missions. However, they have higher ESM as mission duration increases. In contrast, recycling-based systems reduce ESM for longer missions, but typically have higher failure rates, thus increasing Pr(LOC). The figures also show that adding redundancy and spares to recycling-based systems significantly improves reliability (reducing Pr(LOC)) but increases ESM [57]. These results highlight the importance of balancing mass constraints with reliability requirements in the initial design of life support systems for long-duration missions.

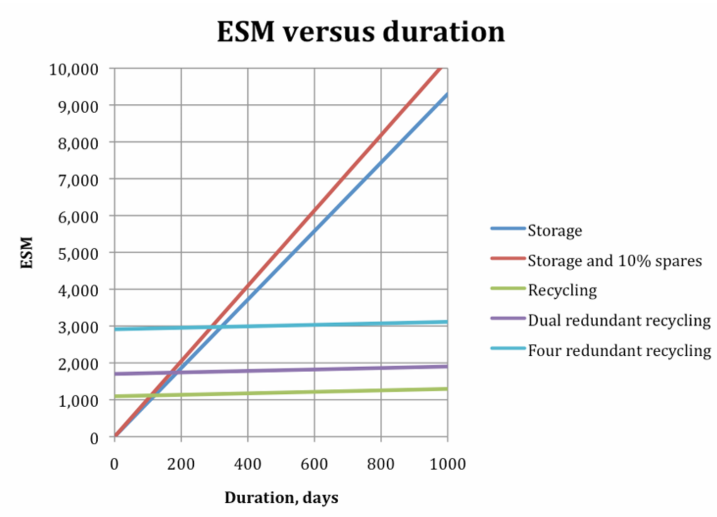


Figure 23: ESM versus duration for different ECLSS architectures [57].

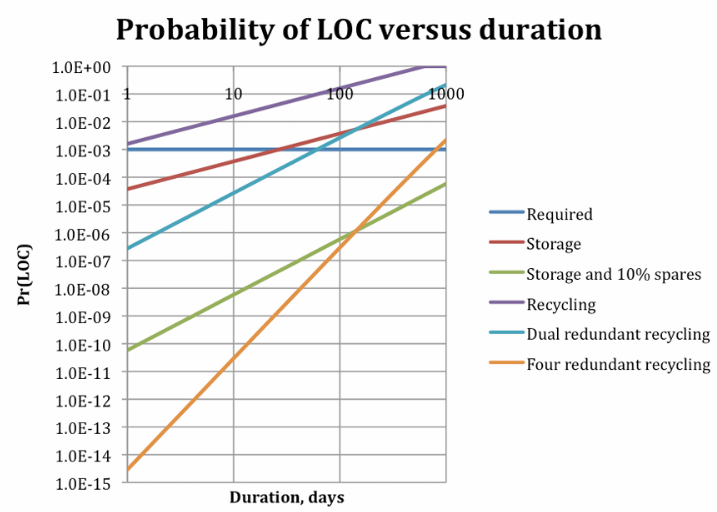


Figure 24: Pr(LOC) versus duration for different ECLSS architectures [57].

Therefore, this analysis provides valuable insights that support trade-offs between alternative system architectures. By using only the failure rates of individual technologies and a reliability model, designers can evaluate system reliability and maintenance demands early in the design process.

Life Cycle Cost (LCC)

The Life cycle cost includes the cost of *"Development of hardware and software, production, logistics support and personnel costs through development, acquisition, operation, support and where applicable, disposal"* [4].

As described in the previous section, the Life Cycle Cost is the sum of Design, Development, Test, and Evaluation costs, production costs, launch costs and operation costs.

It is evident that, increasing system reliability through redundancy and spares also increases overall system cost. For this reason, it is important to include cost analysis in the conceptual design phase of a system. Although ESM is often used as a measure of cost, given its direct relationship to launch costs, it does not take into account DDTE costs or operational costs [63].

In a conceptual design, DDTE and production costs can be estimated using the Johnson Space Center Advanced Missions Cost Model (AMCM) [63]. The AMCM cost in millions of 1999 dollars is:

$$Cost = 5.65 \cdot 10^{-4} Q^{0.59} M^{0.66} 80.6^{T} (3.81 \cdot 10^{-55})^{\frac{1}{Y-1900}} G^{-0.36} 1.57^{D} \qquad (17)$$

Where [63]:

- Q = Total quantity of development and production units.
- M = System dry mass in pounds.
- T = Mission type (2.13 for human habitat; 2.46 for crewed planetary lander).
- Y = Year of initial operation.
- G = The hardware generation (1 for a new design and 2 for a second generation).
- D = The estimated difficulty (0 for average and 2.5 for extremely difficult, and -2.5 for extremely easy).

Launch costs can be estimated at $25,000 per kilogram for LEO, and approximately $300,000 per kilogram for delivery to the Martian surface [63]. Based on ISS data, operational costs can be approximated as 11% of the DDTE cost per year [63].

These equations are useful in the early phases of the design process because they provide preliminary cost estimations that support initial trade-off decisions and system architecture. However, as the design progresses, more detailed and accurate cost analyses are required and must be integrated into the overall mission budget.

2.3.5 Virtual Habitat (V-HAB)

V-HAB is simulation tool which *"simulates on a system level the dynamics of entire mission scenarios for any given life support system including a dynamic representation of the crew"* [64]. The V-HAB project has been developed at the Technical University of Munich and is programmed in MATLAB using an object-oriented approach [65].

During the ECLSS design process, this tool allows designers to analyze the robustness and performance of a system configuration. These dynamic simulations offer insight into the system's behavior and the interactions between its subsystems. V-HAB also supports evaluations of the system based on criteria such as reliability, stability, and controllability, which are difficult or impossible to analyze using the traditional methods described in the previous section [64]. V-HAB is especially useful during the early design phases because it provides insights into how a system performs under different conditions, such as changes in environmental parameters or crew planners. It can also identify the potential impacts of integrating new technologies into systems, verify subsystem integration strategies, assist in operational planning by simulating EVAs and planning crew procedures [65]. Furthermore, V-HAB enables the simulation of subsystem and technology failures to evaluate the system's stability and robustness [64]. In addition to supporting system design, V-HAB can be used to analyze the feasibility of specific mission scenarios by verifying whether a given ECLSS architecture can meet the mission's operational requirements [65].

To validate the V-HAB tool, a model of the ISS was created and the simulation results were compared with flight data from the Columbus Laboratory (COL) and the Russian Service Module (SM), demonstrating excellent accuracy [66].

V-HAB is defined in a modular fashion so that any life support system architecture can be modeled and simulated. The modules of a Virtual Habitat simulation are: the Closed Environment Module, the Crew Module, the P/C Module and the Biological Module [64].

Closed Environment Module: As shown in Figure 25, this module includes all the simulation settings related to the mission and environment that need to be controlled. The module is divided into two main sections: boundary conditions and environment control.

Boundary conditions include mission planning parameters, such as mission duration and start conditions (the initial fill levels of consumable resources, like oxygen, water, and food). Boundary conditions also include habitat initialization, which defines the number and names of compartments of the habitat, as well as crew initialization, which specifies the number of crew members for each mission phase (depending on the mission scenario, crew members may change) [64].

Instead, Environment Control include Habitat layout, Life Support Systems (LSS) layout and LSS control. In the simulation, each habitat compartment is defined by its volume, temperature, pressure, and atmospheric composition. After the compartments are defined, connections between them are established. Then, life support systems (LSS) technologies and consumable storage tanks are assigned to each compartment and interconnected to define the overall system configuration. V-HAB also implements control systems that are designed to regulate key parameters, ensuring proper environmental and life support conditions throughout the mission [64].

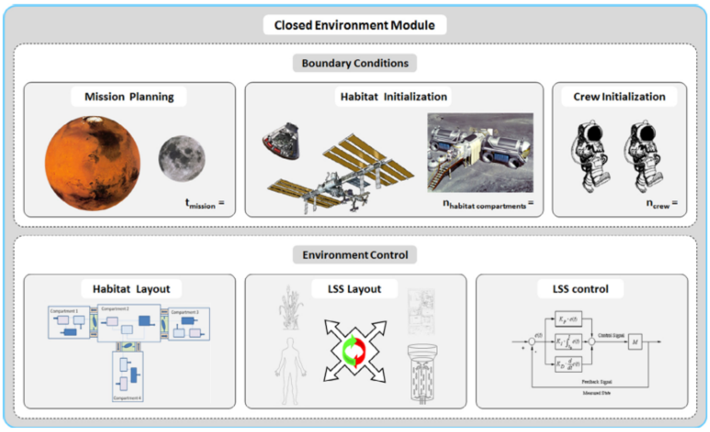


Figure 25: Closed Environment Module V-HAB [64].

Crew Module: The crew module includes the human model and the crew controller. Given that the crew continuously interacts with and affects the environmental conditions being simulated, the human model is a fundamental component of any life support system simulations. The human model is composed of layers, each corresponding to a specific physiological function of a human body as shown in Figure 26. The crew controller assigns each crew member a crew planner, which is a list of tasks to be performed at specific times during the mission [64].

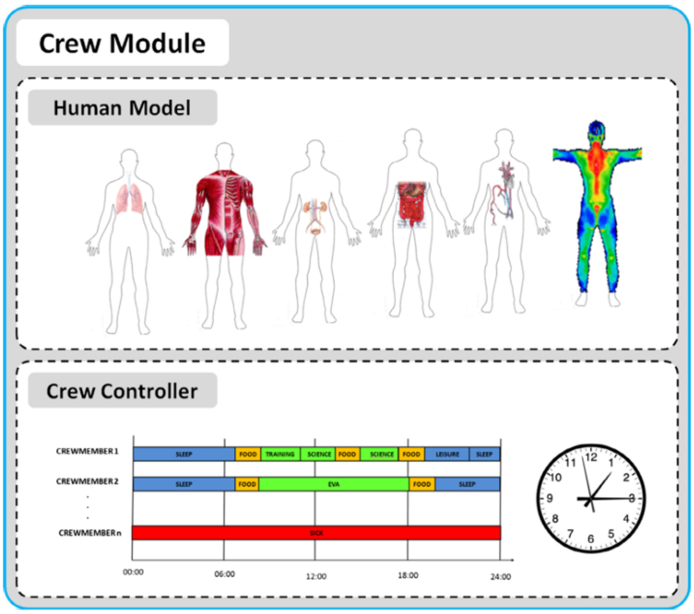


Figure 26: Crew Module V-HAB [64].

P/C Module: As shown in Figure 27, this module includes the four main ECLSS subsystems. The P/C module contains a library of models of specific ECLSS technologies that have been validated against test data. The crew and biological modules were also validated [64]. It is also possible to define a model of a new technology using the basic V-HAB components (tanks, pumps, valves, heaters, etc.).

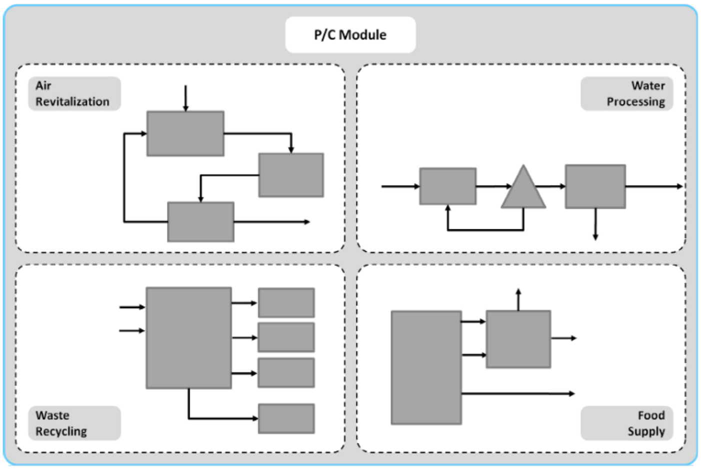


Figure 27: P/C module V-HAB [64].

Biological Module: As shown in Figure 28, V-HAB includes plant and algae models to simulate a CELSS.

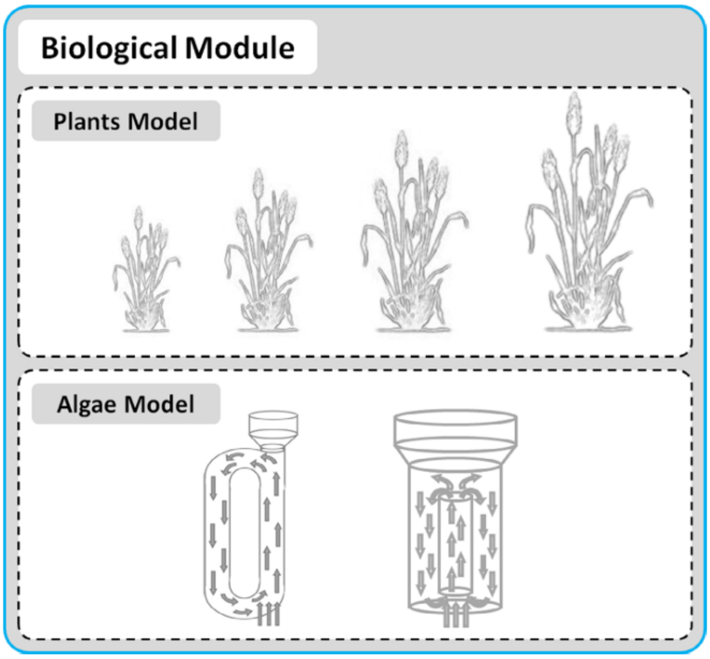


Figure 28: Biological Module V-HAB [64].

The MATLAB-based architecture of the V-HAB tool is shown in Figure 29. His structure consists of several layers, with each layer building upon the one below it. These layers are the infrastructure, the physical domains, a library of predefined models, and the user-defined ECLSS model [65].

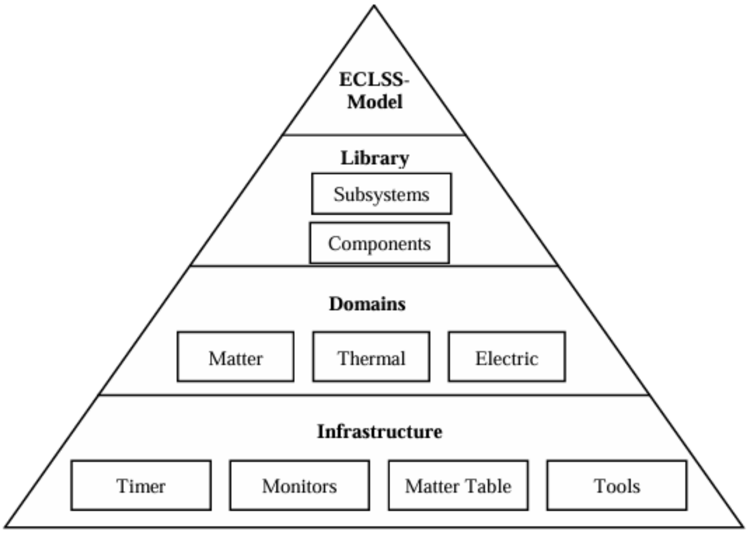


Figure 29: Basic structure of V-HAB [65].

The infrastructure layer establishes the basic framework for all V-HAB simulations. It provides an object-oriented structure that serves as the foundation for the other levels. This layer includes a timer that controls the execution and time progression of the simulation, monitors consisting of debugging observers and loggers for data collection, a matter table containing a database of the physical properties of various substances (for example, specific heat capacity, thermal conductivity, and density.), and tools consisting of functions that ease implementation of programming tasks [65].

The Domains layer contains the necessary classes for the three V-HAB physical domains: matter, thermal, and electric. Each domain has a similar structure consisting of stores (mass, thermal energy, or charge) and flows (mass flow, heat flow, or current). In the matter domain, the basic components used to store matter are called *stores*, which contain child objects called *phases*. *Matter flows* are the properties of moving matter inside the simulated system, and *matter processors* are the objects that can manipulate the matter content of other objects. There are three types of matter processors: Flow-to-Flow (F2F), Phase-to-Phase (P2P), and flow-to-phase/phase-to-flow. F2F processors can change the properties of a matter flow. P2P processors are used inside stores to transfer matter from one phase to another. Phase-to-Flow (P2F) processors are the interface between phases and flows [10]. In order to increase code maintainability and reduce bugs, the thermal and electric domains have a similar structure of the matter domain [65].

Together, the infrastructure and domain layers provide the framework necessary to model any physical process. For instance, a matter store could represent an oxygen tank, and the oxygen inside could be modeled as a phase. A F2F processor could model a fan that increases the pressure and temperature of a flow. P2P processor could model chemical reactions within a phase or phase transitions, such as condensation or adsorption [10].

In V-HAB, a *branch* is the framework for a link between two phases in the matter domain. Each branch of the model requires a numerical solver to perform the calculation of the flow rate given the current boundary conditions. There are different solvers in V-HAB, more information can be found in [9]. Thermal solvers are based on Peclet and Fourier laws and calculate the overall thermal resistance of thermal branches with conductors. In the electrical domain, solvers create and solve systems of linear equations that describe voltage drops across components in electrical branches and energy balances of electrical nodes [65].

The next layer is the V-HAB library, which contains predefined models of specific components, processes, and entire subsystems. The final layer is the user-defined ECLSS model.

With this structure, users can develop models to dynamically simulate the ECLSS at the desired level of detail with an arbitrary combination of library and/or user-defined models [65].

2.4 System Engineering

The International Council on Systems Engineering (INCOSE) define Systems Engineering *"a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods"* [67].

The Systems Engineering (SE) discipline was developed to manage and understand complexity, therefore is a fundamental approach to the design of complex aerospace systems. A *system* is composed of elements, including people, hardware, software, facilities, policies, and documents, as well as the relationships among them. These elements interact with one another to accomplish specific functions that satisfy identified needs [68, 69].

Systems Engineering can be defined as the scientific discipline of developing an operable system that meets requirements by balancing all engineering fields and ensuring that the design is not dominated by the perspective of a single one [69].

SE aims to design, develop, and operate a system in a way that achieves its intended purpose safely, while balancing performance, cost, schedule, and risk to achieve the most cost-effective outcome [69].

According to the Systems Engineering Handbook [69], the NASA SE approach consists mainly in three technical processes: system design, product realization and technical management. These processes are depicted in Figure 30, which shows the Systems Engineering *engine*, used to develop and realize the end products.

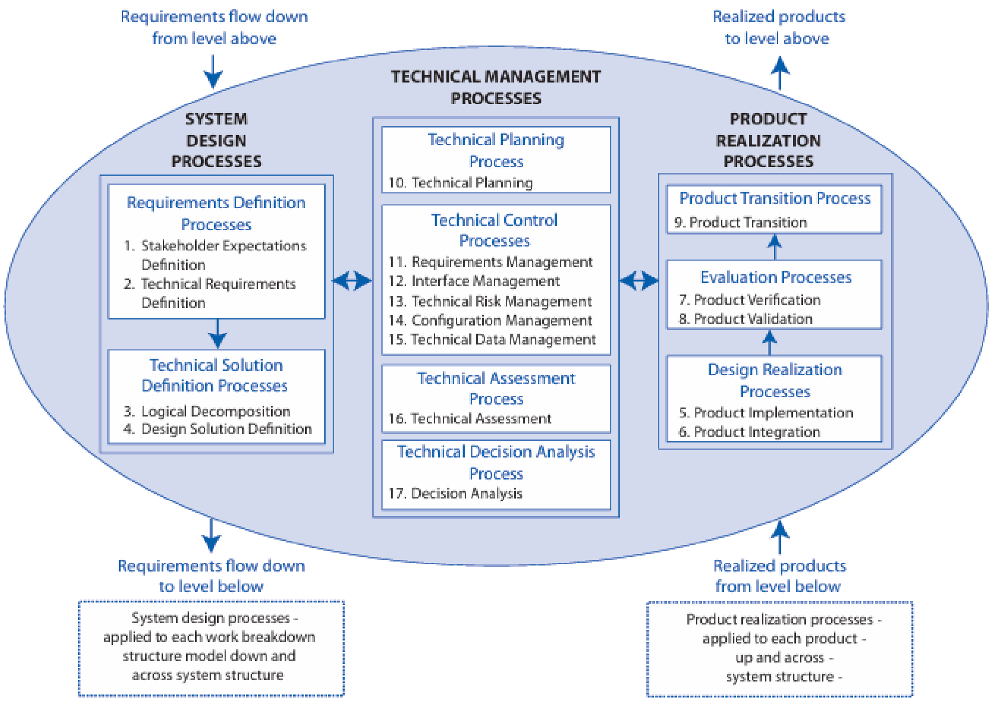


Figure 30: The Systems Engineering engine [69].

The system design processes include defining stakeholder expectations, creating technical requirements, and translating those requirements into a design that meets those expectations. These processes are employed for each product within the system architecture, from the highest to the lowest level. Because each product must be integrated into the overall system, designers define requirements that enable each product to operate within it.

Product realization processes include design realization, which involves the implementation and integration of the product, as well as verification and validation. These processes are applied at every level of system design, and products that meet expectations advance to the next level.

Technical management processes include developing technical plans for projects and managing requirements, interfaces, technical risks, configurations, and technical data. These processes also involve technical assessments and decision analysis [69].

These processes are used iteratively during system design to correct discrepancies by applying the same process to the same product. They are also used recursively through repeatedly applying them to design lower-level products or realize higher-level products within the system [69].

One of the fundamental concepts of systems engineering for managing complex systems is the project life cycle. It involves dividing a project into different phases, such as system conception, design and development, production and/or construction, distribution, operation, maintenance and support, and retirement. The life cycle consists of organizing all the steps required to complete a project into different phases [70]. Although the specific phases may vary between organizations such as NASA and ESA, the basic concept remains the same. Figure 31 shows the phases of the NASA project life cycle.

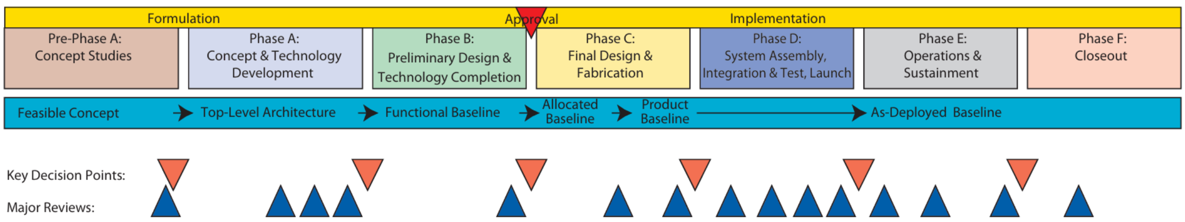


Figure 31: Project Life Cycle NASA [69].

Each phase is separated by Key Decision Points (KDPs). These are events at which decision authority determines if a program is ready to advance to the next life cycle phase. From Pre-Phase A to Phase C, the left side of the SE engine (design processes) is used iteratively and recursively to finalize all requirements and develop the final design. Phase D uses the right side of the SE engine (product realization processes) for the final implementation, integration, verification, and validation. Phases E and F employ the technical management processes of the SE engine to monitor performance, control configuration, sustain operations, and closeout the system. To ensure proper planning, control, assessment, and decision-making, these processes are also used in previous phases [69]. A detailed description of each phase can be found in the System Engineering Handbook [69].

The project life cycle can also be represented using the *V model*. Figure 32 illustrates the V model, which is a visual representation of the system development life cycle. It shows how the steps should be structured and describes the main activities that should be performed during the life cycle. The left side of the V represents the initialization and decomposition of requirements, as well as the creation of the system design. The base of the graph represents the implementation of the system, and the right side represents the integration of parts, system verification and validation, and operation and disposal [71].

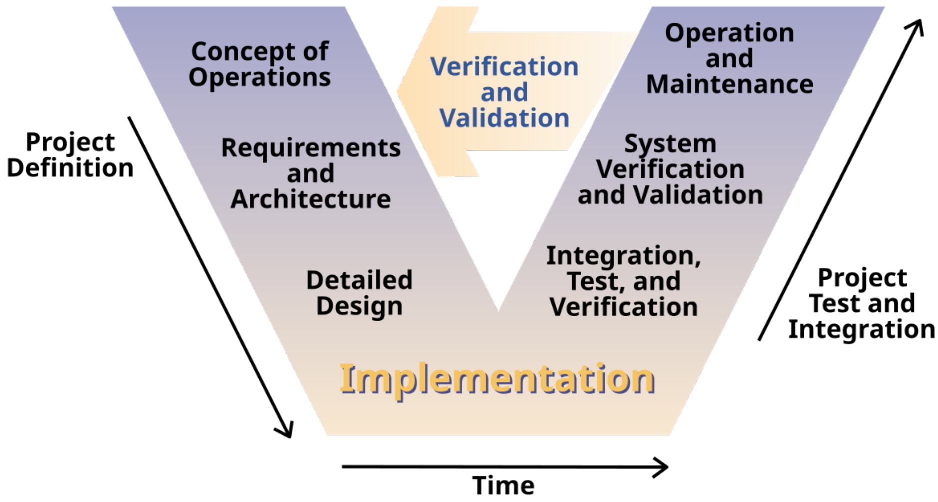


Figure 32: V model [72].

2.4.1 Model Based System Engineering (MBSE)

The International Council on Systems Engineering (INCOSE) define Model-Based Systems Engineering (MBSE) *"a 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"* [73].

According to Ramos et al. [74] *"a model is a representation of a selected part of the world, the domain of interest, that captures the important aspects, from a certain point of view, simplifying or omitting the irrelevant features"*. In MBSE, the *model* reflect the state of system development.

The MBSE approach is based on the definition of models for requirements elicitation, trade studies, design, analysis, verification, and validation of systems throughout their entire life cycle [6]. This approach aims to facilitate SE activities by developing a unified coherent model [74]. This approach uses models as a central element of the system development process.

Unlike MBSE, the traditional approach to systems engineering is document-centric. This approach produces a large number of documents throughout the system's life cycle. The data in these documents does not have explicit dependencies. This means that any change made to one document must be manually updated in all related documents. This manual process is error-prone and inefficient, especially for complex systems, which makes the document-centric approach too challenging [75]. For this reason, many engineering organizations are transitioning from document-centric to model-based approaches. Figure 33 depicts the differences between traditional document-centric systems engineering and model-based systems engineering.

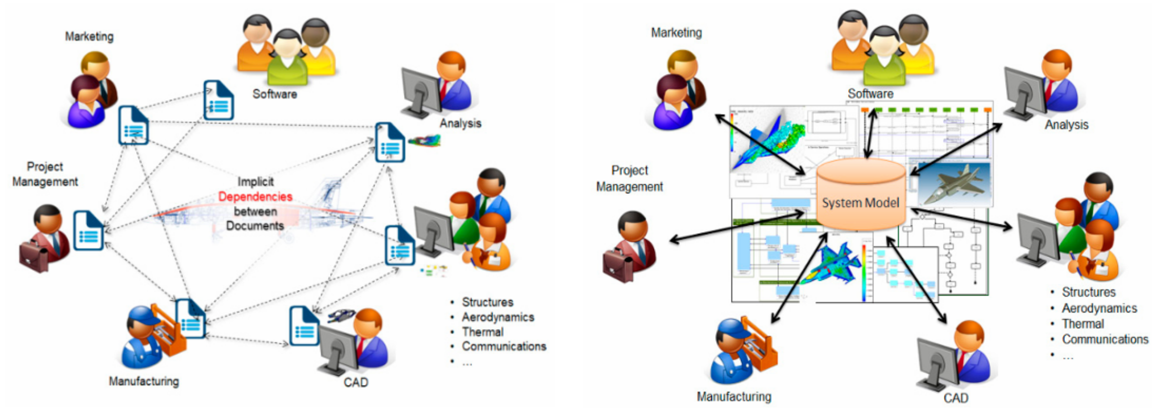


Figure 33: Document-centric system engineering (left); model-based system engineering (right) [75].

The MBSE methodology involves storing and managing all system-related data within the model. Unlike the traditional approach, the connections between elements in the model ensure consistency and enable automated propagation of design changes [75]. This approach helps engineering teams understand the impacts of design changes more readily, reducing errors and improving system understanding.

However, the objective is not to eliminate the use of documents; rather, it is to employ models to generate and validate data and information utilized in different viewpoints and artifacts, such as documents [8]. Therefore, a key objective of MBSE is to overcome the drawbacks of traditional document-centric systems engineering approach [8].

Moreover, a significant disadvantage of the traditional systems engineering approach is that errors in the initial requirements definition or decomposition are discovered late. This is because the requirements are defined on the left side of the V model (described in the previous section), while integration, Verification and Validation (VV)[8] are conducted on the right side of the V model. In contrast, each iteration of an MBSE model undergoes model validation, which checks that the model accurately describes the system, and model verification, which ensures that the model is precise enough to trust its predicted results [6]. This approach enables the earlier detection of defects, reducing time and costs [76].

A MBSE approach involves developing the model in a modeling language, which is available in a modeling tool. This model is depicted on graphical diagrams and contained in a model repository. This integrated model contains all relevant system information and

[8] *"Verification assures that a system is built correctly by assessing requirement compliance". "Validation assures system goals have been achieved by comparing a system's behavior to its needed or expected behavior".* [6]

is composed of interconnected modeling elements representing key system aspects [74]. With this structure, the engineering teams must 'speak' the same language and work on the same 'matter' corresponding to the system model [74]. The model is an abstract representation of reality at the start of the design process. Certain features can be ignored if they are irrelevant or not immediately important. As the design of the system progresses, these abstract models become increasingly concrete [6].

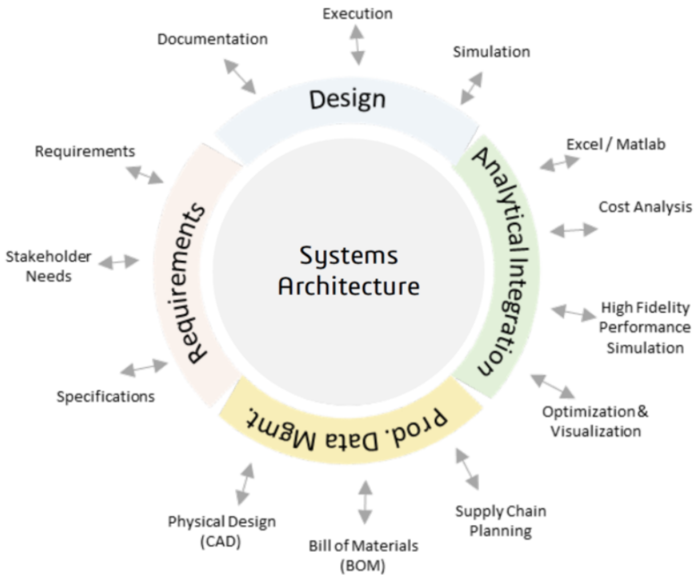


Figure 34: Model integration [76].

As depicted in Figure 34, this model can be integrated with other engineering tools (such as simulation, analysis, and hardware models) to address multiple aspects of systems. Linking these tools with the model provides insight into key characteristics of the system that would not be evident through the traditional approach alone. Integrated tools allow engineers to analyze a large number of system configurations against mission scenarios. This helps them identify key requirements and the most cost-effective design alternatives [74, 76].

The potential benefits of using MBSE can be summarized as follows:

- Improve communication among model designers and stakeholders [8, 74, 76].
- Increase the capacity to effectively manage system complexity [6, 8, 76].
- Improve the quality of the product and more understand of design change impacts [8, 76].
- Enhance knowledge capture and system understanding [8, 76].
- Facilitate early system verification and validation, and support early detection of design defects [8, 76].
- Provide mechanisms to enable deeper systems engineering without increasing costs [8, 76].
- Reduce costs, errors, ambiguity, and save time and resources [6].
- Resolve discrepancies and inconsistencies in system design [76].
- Ensure consistent and complete system model representation across missions and project phases [74].

2.4.2 ARChitecture Analysis and Design Integrated Approach (ARCADIA)

ARCADIA is a model-based engineering method developed by Thales for designing the architecture of systems, hardware, and software [77]. The ARCADIA method can be applied to complex systems to help identify customer needs, develop and share the product architecture with engineering stakeholders, validate and justify designs quickly, and facilitate integration, validation, and verification [78].

ARCADIA defines different perspectives/layers, depicted in Figure 35, that structure the implementation of an architecture: these include Operational Analysis, System Analysis, Logical Architecture, Physical Architecture, and End Product Breakdown Structure (EPBS).

To promote consistency, the ARCADIA method establishes an ontology[9] that captures concepts and their relationships. These relationships are essential for ensuring traceability and consistency in the system model. Each ARCADIA layer and its model elements are linked to the corresponding elements in the preceding and succeeding layers. This structured connection guarantees traceability between model elements and consistency between architectural views [79].

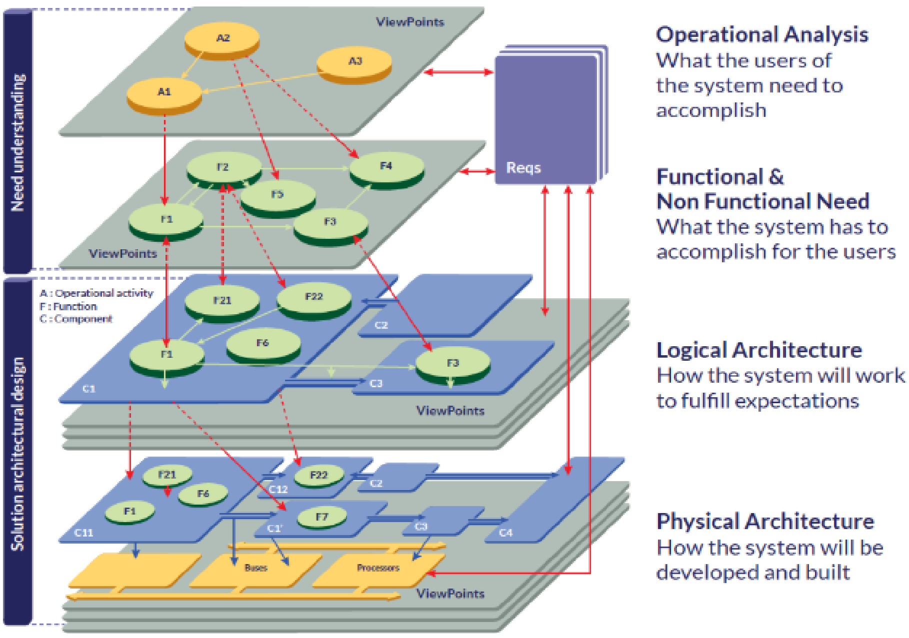


Figure 35: ARCADIA method [80].

[9] *"An ontology is a formal explicit conceptualization of a problem domain shared by stakeholders; it presents a controlled vocabulary that comprises a set of agreed upon terms (semantic domain) and rules for using and interpreting them within the domain"* [6].

As shown in Figure 35, the first two layers focus on understanding and formalizing needs, while the last three focus on developing the solution (i.e., the architectural design) [81].

Operational Analysis: What the users of the system need to accomplish.

The first layer involves examining customer needs, goals, and intended missions and activities. This analysis identifies the actors who will interact with the system and their respective goals, activities, and constraints. The required high-level operational capabilities can be modeled through this layer, and an operational needs analysis can be performed without the system being defined [79, 80].

System Analysis: What the system must achieve for the users.

This layer focuses on how the system, considered as a black box, can satisfy operational needs and determine the feasibility of the customer requirements. This involves carrying out an external functional analysis of the system in order to identify the system functions required [80, 82].

Logical Architecture: How the system will work to meet expectations.

This phase involves an internal functional analysis of the system to identify the subfunctions necessary for carrying out the chosen system functions from the previous phase. Logical components are identified to allocate the defined subfunctions. This layer implements the major decisions of the solution and ways to meet stakeholder expectations [82, 83].

Physical Architecture: How the system will be built.

This layer establishes the system's final architecture and how it should be implemented and integrated. Two types of physical components can be created to define the system architecture: a Behavior Physical Component, which is associated with physical functions and carries out part of the system's behavior (e.g., software components and data servers), and a Node, which is a Physical Component that provides the necessary material resources for one or more Behavior Components (e.g., processors, routers, and operating systems) [83, 84].

EPBS: What is expected from the provider of each component.

The goal of this level is to determine the specifications that each component must fulfill in order to meet the architectural design constraints and choices identified in previous phases [83].

In order to support the ARCADIA method, the operational engineering experts at Thales have developed the associated toolbox Capella [83]. Capella is a tool that provides the necessary notation and diagrams for creating models based on the ARCADIA method [79]. As shown in Figure 36, ARCADIA provides a modeling language and a modeling approach, and Capella is a tool designed to support this method and language.

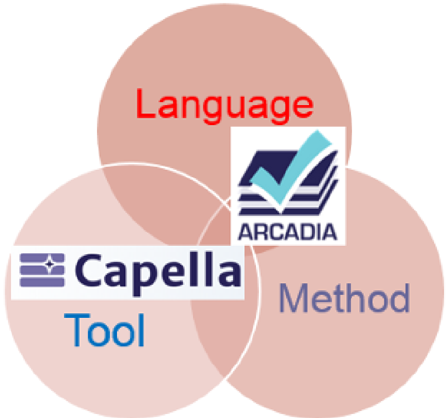


Figure 36: MBSE with ARCADIA Capella [77].

Capella offers various add-ons created to exploit the potential of MBSE [80]. Some of the most important are:

- Property Values Management Tools (PVMT) add-on: It allows end users to easily create data that can be addressed to the elements model.
- Requirements viewpoint add-on: It allows for requirements definitions and the importing of a set of requirements from a ReqIF file.
- Python4Capella add-on: This add-on enables interaction with the Capella model using Python. It is possible to create Python scripts to read and write from the Capella model.

Several other add-ons are described in [80].

3 Research Problem

As presented in Section 2.3, developing an Environmental Control and Life Support System is a complex, iterative process based on evaluating technologies and system configurations using simulation and analysis tools, as well as testing hardware and software [4]. The ECLSS is one of many systems designed for space habitats. However, it requires special attention because of its many critical functions.

Figure 37 shows the typical NASA spacecraft ECLSS development process. This process corresponds with the life cycle described in previous sections. The figure shows how the ECLSS design process is divided into distinct phases and clearly indicates the associated documentation and key review milestones.

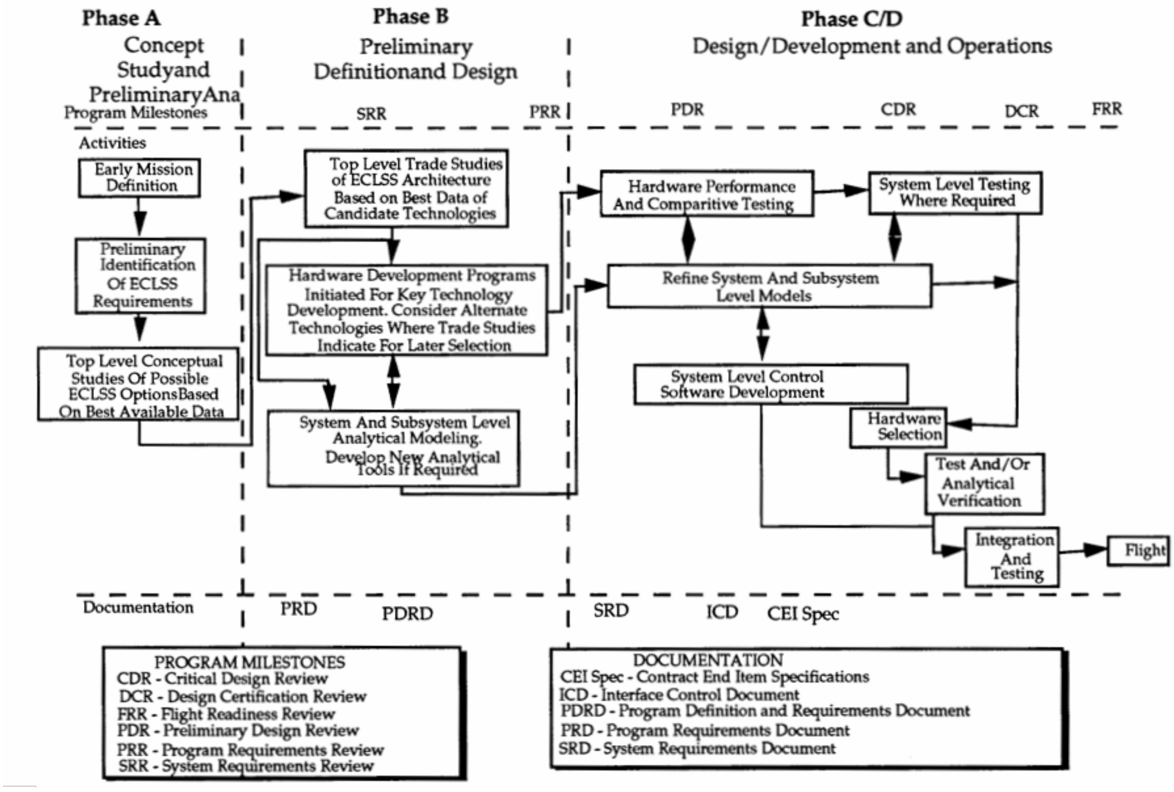


Figure 37: Typical NASA spacecraft ECLSS development process [4].

Phase A, also referred to as the Concept Study and Preliminary Analysis, involves early mission definition, preliminary identification of ECLSS requirements, and a project feasibility study. During this phase, concepts are created and preliminary analyses are performed to evaluate options.

Phase B, also referred to as the preliminary definition and design phase, involves revisiting and analyzing the preliminary concepts developed in Phase A through an iterative process. Trade study techniques are employed to compare each concept's capabilities to the system requirements.

Phases C and D involve design, development, and operational tasks.

The overall system configuration and interfaces are identified during the preliminary design process. This phase involves conducting trade studies of candidate technologies and their combinations to determine the most suitable architecture based on mission requirements.

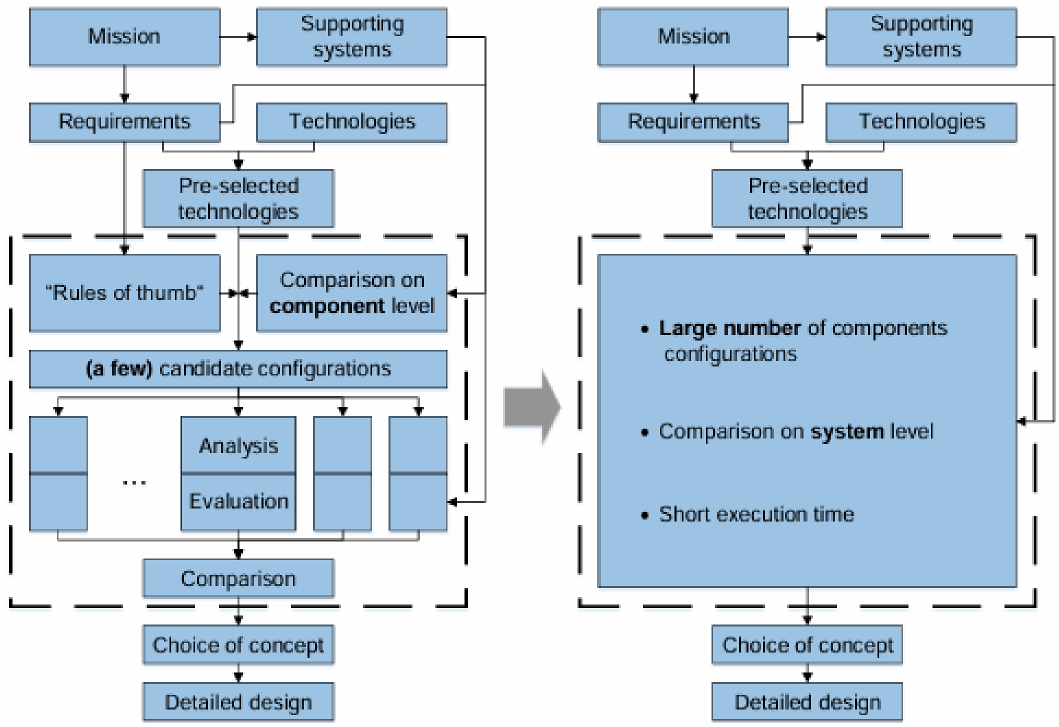


Figure 38: Conventional (left) and new (right) approach for a preliminary ECLSS design process [56].

The conventional approach for a top level trade studies of an ECLSS architecture performed in the preliminary definition and design process is shown in the left hand side in Figure 38. The mission defines the requirements and constraints through which appropriate technologies can be identified and implemented. A few candidate concepts are selected for examination and comparison. Each concept is evaluated based on ESM, reliability, and cost. The comparison process results in the selection of the best-evaluated concepts.

This approach can be a time-consuming, iterative process and since only a few candidate concepts are evaluated, it is uncertain whether the actual optimum is considered. Therefore, Binder et al. [56] proposed a new approach in their work, shown on the right-hand side of Figure 38, which compares a large number of component combinations at the system level with a short execution time in order to select the best options.

As shown in NASA life cycle (see Figure 37), these top-level trade studies may be conducted multiple times throughout the preliminary definition and design process since it is inherently iterative.

This traditional ECLSS development process is based on a document-centric approach. It involves documenting technical and programmatic requirements, design architecture, interface requirements, safety and reliability requirements, and verification requirements [4].

Section 2.4.1 discussed the main disadvantages of the document-centric systems engineering approach, which presents significant challenges when applied to complex systems. Designing an ECLSS for a long-duration mission requires greater system complexity and more stringent reliability requirements than existing ECLSS architectures. In such cases, a document-centric system engineering approach can be too challenging to manage effectively. As outlined in Section 2.4.1, the main drawbacks of the document-centric approach are a lack of traceability, difficulty integrating documents, and the need for manual updates to reflect design changes. As systems become more complex, these issues can lead to longer development times, an increased risk of errors, and higher overall costs.

Additionally, in the context of the project life cycle of typical NASA systems, Bajaj's work [85] identifies two major limitations of the traditional approach. The first involves the discontinuity of system analysis and simulation tools from the early design phases to the later phases. With the traditional approach, it is difficult to ensure that the analysis and simulation tools defined in different phases consistently represent the same system. The second refers to the lack of connection between the design and analysis/simulation models used in different phases. For example, between conceptual system design models and mathematical analysis models in the early phases, as well as between CAD and CAE models in the later phases.

These limitations highlight the need for a more integrated, model-centered approach to support the development of complex systems, such as the ECLSS, especially for long-duration missions. A MBSE approach enhances the ability to manage system complexity by improving communications, facilitating a quicker understanding of the impact of design changes, and increasing overall system comprehension. Additionally, MBSE supports early system verification and validation, enables the early detection of design errors, and ensures a consistent system representation throughout all phases of the project life cycle.

In order to exploit the benefits of the MBSE approach for the ECLSS development process, it is necessary to extend the system model to support connections with engineering analysis by means of Modeling and Simulation (MS) [86].

Simulation is a complex digital product that relies on simulation models, simulation tools, and computing hardware [87]. Since modeling is an essential part of a simulation, it is accurate to refer to simulations as Modeling and Simulation [88]. Engineering analysis through MS allows for the assessment of system performance during the design process, which supports decision-making.

Integrating a system model with MS tools presents several challenges. These include ensuring consistency between MBSE models and MS data, guaranteeing traceability between models and engineering analyses and system requirements, and ensuring tool compatibility throughout the entire process, since the model can be integrated with various engineering analysis tools [86].

However, the integration of system models with MS tools offers several key advantages in the system development process. These benefits include ensuring that simulations always reflect the latest system model version and enabling the automatic generation of analysis models from system models. This integration supports the early detection and resolution of design issues, reducing costs and effort when changes are inexpensive to implement. Furthermore, linking the model to simulations leads to more complete, unambiguous, and verifiable definitions of requirements [89]. As illustrated in Figure 39, engineers can use engineering analysis tools to assess whether a system meets requirements or if changes must be implemented.

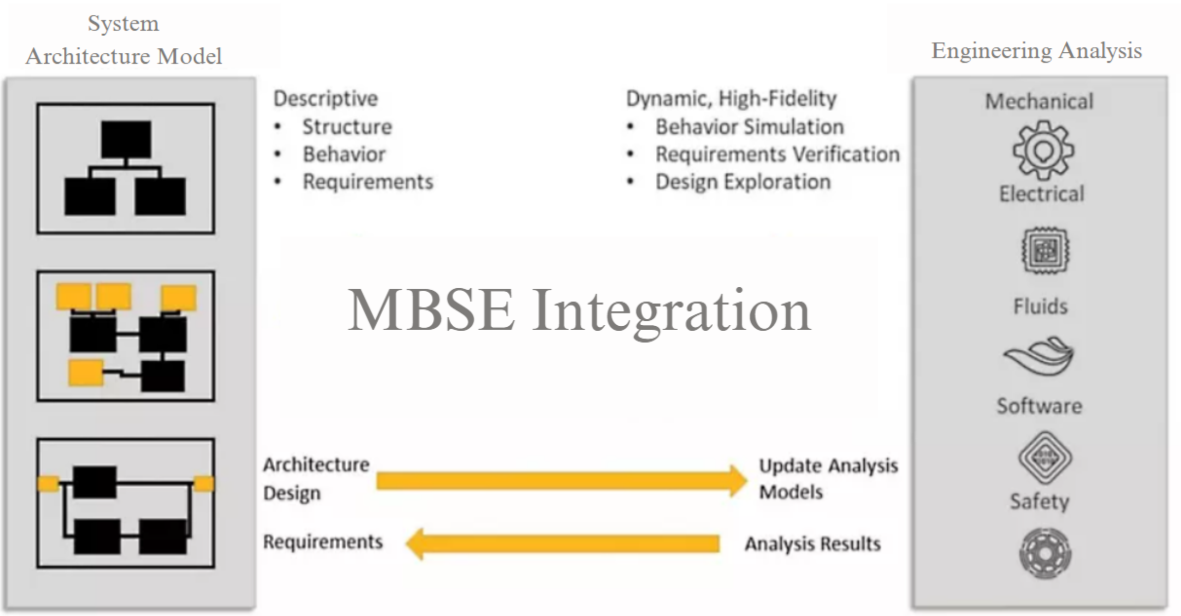


Figure 39: MBSE integration. Adapted from [90].

The connection between the system model and simulations enables the immediate evaluation of the impact of changes to the system. Additionally, integration reduces errors in the system development process and improves quality of design by increasing traceability between requirements, system architecture, and engineering analysis [89]. This integrated environment ensures the continuity of analysis and simulation tools across the different phases of the design process and maintains a consistent connection between the system model and its corresponding analysis and simulation models.

The benefits of integrating MBSE with MS tools have been documented by many projects:

- Lockheed Martin Space used an integrated MBSE approach to simulate the OSIRIS-REx spacecraft's mission trajectory. By integrating simulations into the system model, the team could quickly identify potential issues resulting from changes in mission requirements. They could also verify requirements and mission design parameters continuously throughout the spacecraft's life cycle. This approach resulted in a development process seven times faster than their previous methodology [91].
- Northrop Grumman Corp. implemented an integrated MBSE approach to design and optimize a Phased Array Antenna system. This methodology eliminated transcription errors, improved technical communication, and enhanced design quality and engineering productivity. It also reduced design and execution risks [92].
- In the work of Kaslow et al. [93], a model integrated with STK and MATLAB was

developed for the design of a Radio Aurora Explorer (RAX) Cubesat. The objective of this work is to demonstrate the power, scalability, and utility of MBSE tools and methods in supporting CubeSat mission design. Trade studies were performed using simulations and analyses to evaluate how design parameters impact mission performance, as well as to understand the system's behavior and how its components interact.

Considering the potential advantages of MBSE when integrated with analysis and simulation tools, this thesis proposes an integrated MBSE approach to support the design of an Environmental Control and Life Support System architecture.

To guide the development and assessment of this integrated MBSE approach, this thesis addresses the following research questions:

1. What method can be adopted to integrate a standard MBSE methodology with an arbitrary set of analysis or simulation tools while ensuring consistency and enabling automated system evaluation?
2. How can an integrated MBSE approach support the design process of an ECLSS architecture?

This work proposes a generalized approach for connecting a standard MBSE methodology with any engineering analysis tool. The proposed approach involves the extraction of system data and its architectural structure from the MBSE model. The extracted information can be used to perform system evaluation by providing the data as input to engineering analysis tools, or by converting the system model into an executable simulation model compatible with a target simulation environment.

The thesis aims to illustrate that, once all the necessary model data has been extracted, any required engineering analysis can be performed using this information. Additionally, this work aims to demonstrate the advantages of using an integrated MBSE approach to support the design of complex systems, such as the Environmental Control and Life Support System.

4 Proposed Integrated MBSE Approach for ECLSS Design Process

Designing an Environmental Control and Life Support System is a highly complex and iterative process. As discusssed in Section 2.3, the final architecture of the system is affected by several requirements, constraints, and considerations, which involve evaluating technologies and system configurations through analysis, simulation, and testing. The planning of a long duration human spaceflight mission to the Moon or Mars necessitates the design of a highly complex and reliable ECLSS, which must be integrated with a complex overall mission architecture. A traditional, document-centric systems engineering approach may be inadequate for handling this level of complexity. In contrast, a MBSE approach significantly improves the ability to manage and coordinate complex system architectures throughout the design process.

This section presents an integrated Model Based Systems Engineering approach to support the design of an ECLSS throughout the entire system life cycle. The proposed integrated approach involves connecting the ECLSS architecture model with analysis and simulation tools in order to evaluate system performance and iteratively refine the model itself. The effectiveness of this approach in supporting the design process is explored through an *end-to-end* case study design of an ECLSS for an Analog habitat.

In the integration process detailed in this section, the system model is integrated with engineering analysis tools, which are particularly relevant for supporting the early phases of the ECLSS design. As the design process progresses, more advanced analyses can be integrated using the same method. Thus, as presented in the following of this section, this integrated environment could effectively support the ECLSS design process throughout its entire life cycle. This environment enables engineers to perform analyses and simulations of the system automatically and directly from the model. These capabilities support early validation and verification, accelerate design iterations, reduce errors, and enable immediate assessment of the impact of changes on the system.

As discussed in Section 3, there are several challenges to effectively connecting engineering analysis tools with MBSE models. This work addresses these challenges and seeks to define an integrated model that mitigates them. The integration process involves extracting data from the system model and processing it to perform system analysis and simulation. It is designed to be independent of any MBSE methodology or analysis and simulation tool.

The following section provides a detailed description of the integration process developed to connect the MBSE model with engineering analysis tools. Subsequently, the methodology is applied to designing the ECLSS for an Analog Habitat, which proves its effectiveness in a realistic mission context.

During this work, the main benefits of the proposed approach will be discussed, as well as how it could support and enhance the ECLSS design process.

4.1 Integration Process

Figure 40 provides an overview of the proposed integration process, which defines an integrated MBSE model designed to support the development of an ECLSS throughout all phases of the design process. The integration process employs an iterative approach, whereby the ECLSS model is progressively defined by evaluating system characteristics through analysis and simulation tools. Based on the results, the requirements are reviewed and the system architecture is continuously refined.

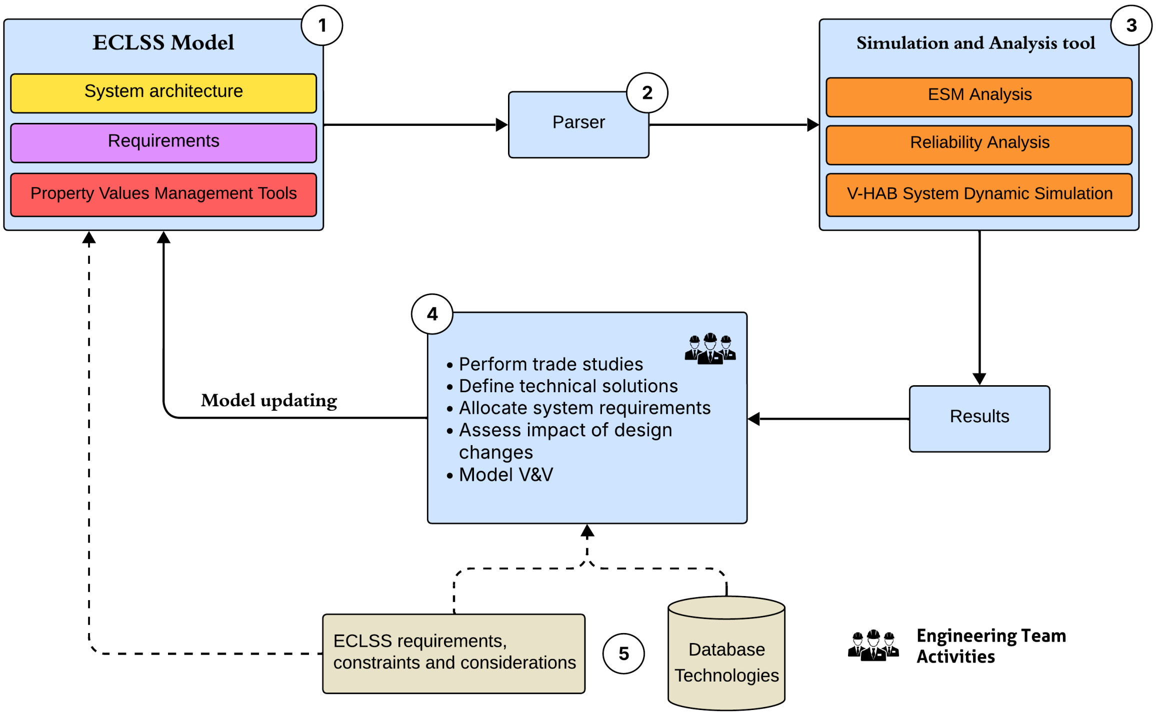


Figure 40: Integration process.

The main steps depicted in Figure 40 are the following:

1. The ECLSS model is developed using the ARCADIA methodology and implemented with the Capella modeling tool. As described in Section 2.4.2, ARCADIA is based on functional analysis and the allocation of functions to architectural components. This method aims to define and validate the system architecture iteratively. In Capella, diagrams represent specific views or extracts of the system model, allowing users to visually edit the model. A Capella diagram is a graphical representation of model elements, such as functions, logical or physical components, and functional/component exchanges [83]. This modeling environment accurately reflects the current state of the system architecture, which is progressively defined throughout the process. As discussed in Section 2.3, several high level requirements influence the ECLSS architecture, and the MBSE approach supports the elicitation of system requirements throughout the design process. Capella allows users to create requirement elements in the model and specify their status, relationships, and classifications. These elements can then be linked to model elements to ensure

traceability and consistency [94]. System simulation can be used to assess the status of requirements during the process. One of the most important parts of the integration process is the PVMT. The PVMT is a Capella add-on that allows users to define specific Property Values for model elements. These Property Values enrich the system architecture with additional information and support analysis and simulation of the system.

2. The connection between the ECLSS model in Capella and the analysis and simulation tools is established through a parser, which extracts necessary information from the model to perform system analyses and simulations. In this work, the parser is implemented in Python using the *Python Capella MBSE Tools* library [95]. This library enables access to model diagrams and elements, and supports the extraction and manipulation of the PVMT. Once the desired information has been extracted, it is possible to create the data structures required to establish the link between the system model and the analysis or simulation tools.

3. The data structure obtained from the model provides designers with all the information necessary to conduct any kind of analysis or simulation. The results provide insight into the system's key characteristics and address various aspects of its behavior. For this work, an ESM and reliability analysis tool was developed in Python to assess key metrics related to the system architecture. As described in Section 2.3, this analysis supports the assessment and selection of alternative system architectures. To evaluate the system performance, a Python tool has been developed that converts the system model into a V-HAB ECLSS model using the data extracted from the model. This tool enables automated evaluation of the system through dynamic simulation using V-HAB. The engineering analysis tools developed in this thesis are appropriate for the preliminary phases of the ECLSS design process. As the process progresses, more advanced simulations can be connected using the same approach.

4. Each analysis or simulation tool developed can be integrated into Capella using the Python4Capella add-on [96], which enables users to interact with the Capella model through Python. Uploaded scripts can be executed directly within Capella, enabling easy, automated system evaluation. After defining the system architecture, designers can run these scripts in the modeling environment to perform system-level analyses. By updating the system architecture, the proposed approach is capable of automatically executing the analysis on the new defined system architecture, ensuring consistency between the system model and the simulation environment. Designers can use the results of these analyses to perform trade studies, verify system requirements, evaluate the effects of design changes, and determine appropriate technical solutions. These evaluations improve understanding of the system's behavior and performance, allowing for more informed decisions throughout the design process.

5. As discussed in Section 2.3, several requirements, constraints and considerations

affects the final ECLSS architecture. These include: technology considerations, human requirements, mission requirements, safety and reliability requirements, test requirements, flight requirements, cost requirements, system requirements and integration factors. Throughout the design process, all these elements must be carefully considered by designers in order to properly define the system. To evaluate the system architecture using analysis tools, it is essential to have detailed information about the technologies that compose the system. In this work, a database of ECLSS technologies has been created that includes key parameters such as mass, volume, power consumption, thermal load, and resupply needs (see Appendix B.). These parameters are assigned to the technologies within the model using the PVMT add-on. The data are then extracted and used by the analysis tools to evaluate the system architecture.

The integrated MBSE model has the potential to support the development of the ECLSS throughout its entire life cycle. This approach allows designers to develop the system model and immediately perform analyses and simulations based on the defined architecture. Consequently, the system design can be refined continuously and iteratively.

The proposed integration process ensures that analysis and simulation reflect the latest system model, supports early detection of design issues, contributes to requirements verification, facilitates the assessment of design changes, and ensures continuity of analysis and simulation tools across the different phases of the design process.

Since this approach only involves extracting data from the model and processing it externally, it can be used to connect any MBSE methodology with any analysis or simulation tool. The following sections provide a detailed description of each step in the proposed integration process. The following elements of the process will be described: requirements, PVMT, parser, ESM and reliability analysis, and V-HAB dynamic simulation.

In Section 5, this process is applied to support the design of an ECLSS for an analog habitat.

4.1.1 Requirements

"A requirement is a statement that identifies a product or process operational, functional, or design characteristic or constraint, which is unambiguous, testable or measurable, and necessary for product or process acceptability" (ISO/IEC 2007) [97].

A MBSE approach facilitates the elicitation of requirements and supports their formal definition. In a MBSE tool, requirements element can be allocated to other model element enhancing consistency, traceability and early detection of requirement issues. Linking requirements to model elements facilitates verifying the system's correctness and completeness. Their validation is achieved through design verification and simulation [98].

Requirements can be created either directly within the modeling tool or imported from a requirements management tool (e.g., IBM Doors) [99].

In Capella, requirement elements can be defined through different modules [99]:

- The **module type** is used to define the type of module, such as a stakeholder or system requirement.
- The **requirement type** allows the category of the requirement to be defined. Requirements can be classified into different categories: functional, mission, interface, environmental, operational, human factor, logistics support, physical, product assurance induced, configuration, design and verification [100].
- The **relation type** is used to specify the relationship between one requirement element and other elements within the model. The different types of relationships between requirement and model elements are: trace, satisfy, copy, verify, validate, derive and refine [99].

It is also possible to associate attributes to requirements, for example, priority (high, medium, low) and status (draft, work-in-progress, reviewed). Each requirement is assigned a unique identifier according to the following format:

```
REQ-<TYPE>-<SYSTEM>-<SUBSYSTEM>-<NUMBER>
```

During the design process, engineering teams specify the modules that define the requirements and their priority attributes. The status of each requirement can be determined through system analyses and simulations. The integration process enables continuous verification of requirements, enhancing consistency and traceability while reducing errors.

Figures 41 - 42 show an example of a requirement definition in the Capella modeling environment. This example refers to a functional requirement related to the Atmosphere Revitalization AR subsystem of the ECLSS. The requirement modules and its associated attributes are defined as follows:

- **ID:** R-FUN-ECLSS-AR-001
- **Name:** CO_2 reduced
- **Text:** The system shall reduce the CO_2 to generate water.
- **Type:** Functional

- **Priority:** High
- **Status:** Work in progress
- **Relation type:** Satisfy

As shown in Figure 41, the requirement is allocated to the Node Physical Component *Sabatier* through a *Satisfy* relation. Additionally, Figure 42 shows a tabular representation of the requirements in Capella, which facilitates the review, management, and validation of the requirements. In the proposed integration process, once a requirement is defined, its status is assessed based on the results of the system's dynamic simulations.

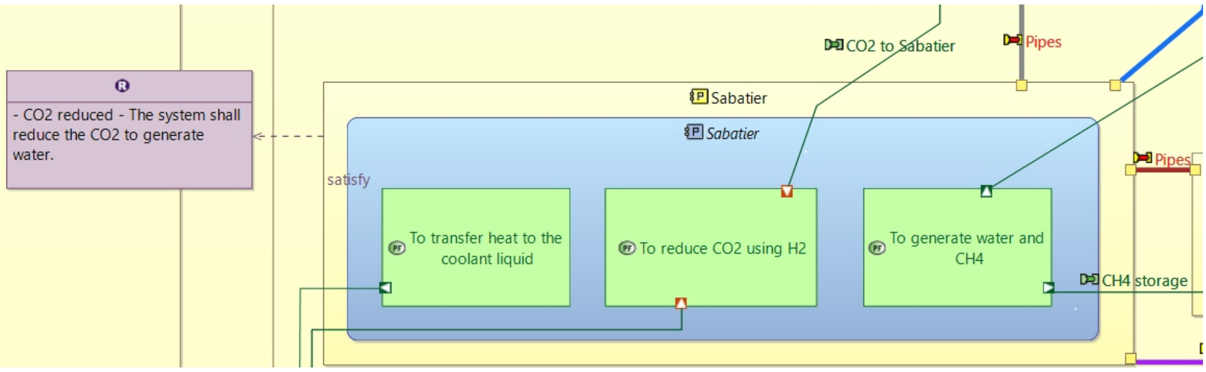


Figure 41: Requirement definition example.

	id	ReqIFName	ReqIFText	requirementType	Priority	Status
R	R-FUN-ECLSS-AR-001	CO2 reduced	<p>The system shall reduce the CO2 to generate water	functional	High	Work in progress

Figure 42: Requirements definition table.

4.1.2 Property Values Management Tools

In order to perform a system analysis or simulation, the model must contain all the necessary data. The Capella PVMT add-on was used to create and assign properties to the model elements. PVMT enriches the model with the data and information for defining the system architecture and enabling analyses and simulations. When defining Property Values to support the model integration process, it is important to consider the compatibility of the various analysis tools involved.

In Capella, Property Values can be created using the Configuration Property Values model editor, as shown in Figure 43. Within this environment, it is possible to define *domains* (represented by a blue notebook icon), which contain extensions (folder icon) and enumeration definitions (three blue circles icon). As shown in Figure 43, for each analysis/simulation tool (ESM and reliability analysis, V-HAB system dynamic simulation), a domain containing the necessary properties has been created.

Within a domain, multiple extensions can be created. Each extension defines a set of Property Values that can be assigned to model elements. An ARCADIA layer must be selected for each extension to determine where the associated properties can be applied. This ensures that the defined properties are applied only to elements within the chosen

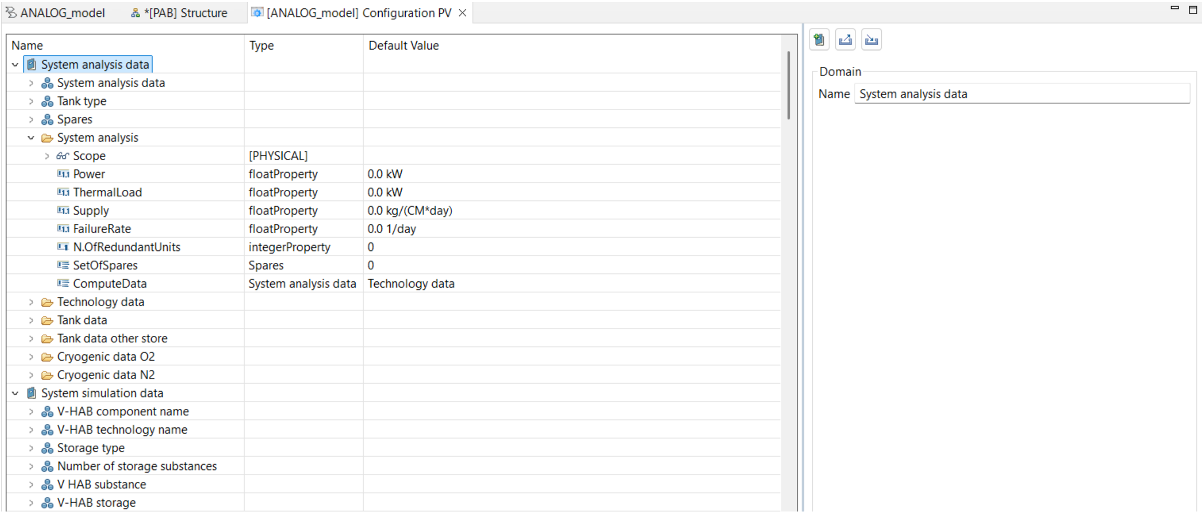


Figure 43: Configuration Property Values model editor.

layer (e.g., Operational Analysis, System Analysis, Logical Architecture, Physical Architecture or EPBS). Users can also specify the types of model elements within the selected layer to which the properties can be applied (e.g., Node Physical Component, Behavior Physical Component, or Physical Link for Physical Architecture). Additionally, users can specify property rules that restrict the application of the extension to elements that satisfy the defined criteria. As a result, extensions remain consistent with the model's structural hierarchy, preventing the assignment of properties to incompatible elements. An extension can contain the following property types: string, integer, float, boolean, and enumeration. The enumeration property allows selection of a specific enumeration literal defined within an enumeration definition.

Figure 44 shows an example of a domain definition created to better illustrate this concept. The domain includes one enumeration definition and two extensions.

The first extension, named *Storage Data*, can only be applied to Node Physical Components within the Physical Architecture layer (as defined by the scope and EClass rule). This extension defines several properties, including a string property that represents the storage name; an integer property that indicates the number of storage units; a float property that specifies the volume; a boolean property that specifies whether the storage is cryogenic; and an enumeration property that allows the selection of the storage type from a predefined list of literals (gas, liquid, or solid) defined in the enumeration definition called *Storage Type*.

The second extension, *Storage Gas Data*, can be applied to Node Physical Components in the Physical Architecture when certain conditions are met. It can only be applied to components when the value of the "Storage Type" property in the *Storage Data* extension is set to "Gas". In this case, the extension allows an additional float property representing pressure to be assigned to the component.

Figure 45 shows the Property Values view of a Node Physical Component named *Storage example*. In this view, the extensions created can be applied to different model elements. With the defined example domain, once a Node Physical Component is created within

Name	Type	Default Value
Domain_example		
Storage Type		
Solid		
Liquid		
Gas		
Storage data		
Scope	[PHYSICAL]	
EClass Rule	PhysicalComponent	
Storage_name	stringProperty	
NumberOfStorage	integerProperty	0
Volume	floatProperty	0.0 m^3
CryogenicStore	booleanProperty	false
Type	Storage Type	Solid
Storage gas data		
Scope	[PHYSICAL]	
EClass Rule	PhysicalComponent	
Property Rule	Type	= Gas
Pressure	floatProperty	0.0 Pa

Figure 44: Example PVMT configuration.

the Physical Architecture layer, the *Storage data* extension can be applied to it. If the user selects "Gas" as the storage type, the *Storage gas data* extension can also be applied to the same component. This example shows how to properly use the PVMT to enrich the model with all the necessary information.

(Physical Component) Storage example

Name	Value
Domain_example	
Storage data	
Storage_name	
NumberOfStorage	1
Volume	0.3 m^3
CryogenicStore	false
Type	Gas
Storage gas data	
Pressure	1.0E7 Pa

Figure 45: Storage Node Physical Component example.

The following sections detail the domains that were created to integrate the model with the analysis and simulation tools involved in this work. As the ECLSS design progresses, additional domains may be created to facilitate connections with other tools. During the definition of the domains, it is crucial to ensure consistency and compatibility between the model and the different tools.

In this work, all Property Values are applied to components in the Physical Architecture layer. However, as previously explained, properties can be applied to elements in any ARCADIA layer. All the Property Values created in this work to support the integration of the analysis and simulation tools are present in Appendix C.

4.1.3 Parser

To connect the system model with the engineering analysis tools, a parser was developed using the Python `capellambse` library [95]. The library allowed the extraction of all model elements and their relationships, as well as the Property Values defined through

PVMT. Having all the desired information of the model on Python enables the definition of the necessary data structure to perform any analysis or simulation.

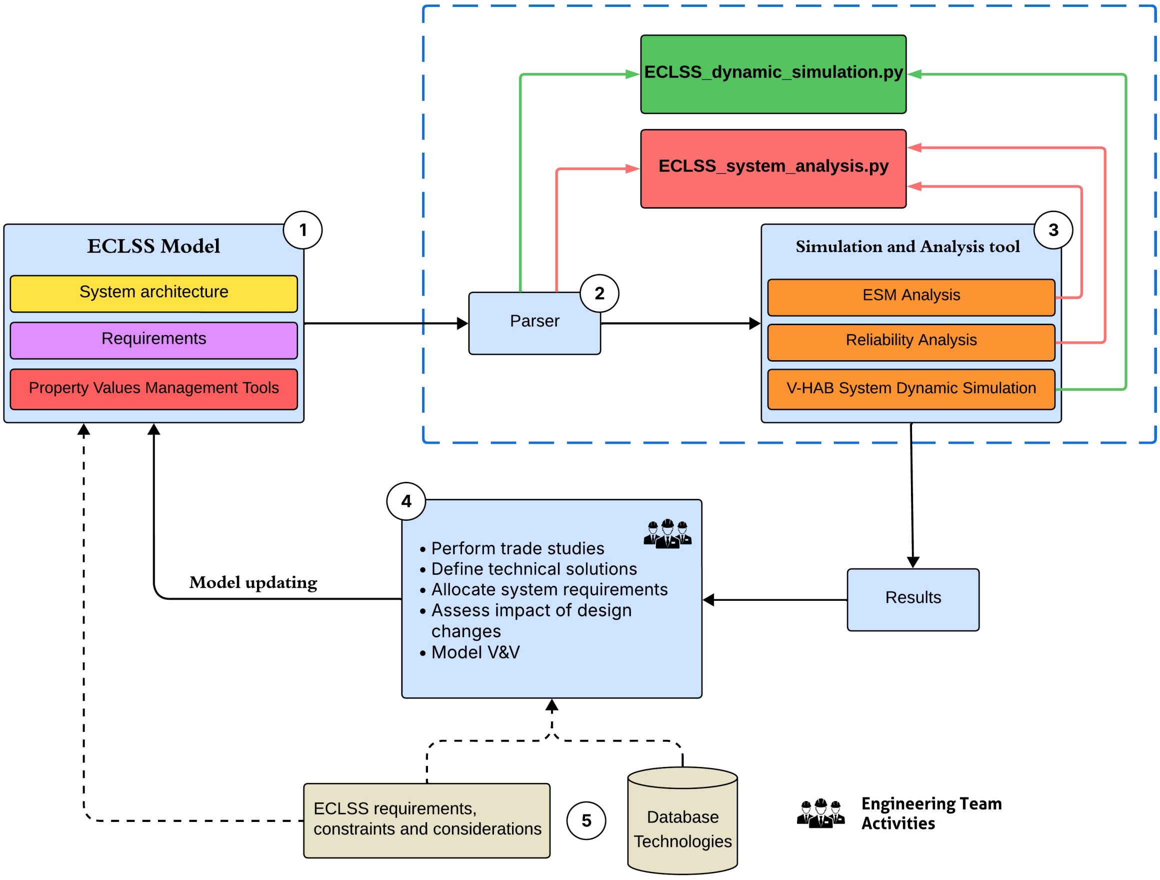


Figure 46: Parser and tools definition.

As shown in Figure 46, each Python code created and imported in Capella consists of a parser that extracts the necessary data and a second part that enables analysis or simulations. In this work, two different Python scripts have been defined:

- `ECLSS_system_analysis.py`: this script enables the execution of ESM and reliability analysis of the system architecture. The first part of the code extracts data from the model and creates the necessary data structure. The second part uses this structure to compute the ESM and the probability of loss of crew Pr(LOC) over time.
- `ECLSS_dynamic_simulation.py`: this script allows the conversion of the system model into a V-HAB model and the execution of a dynamic simulation under defined conditions. The first part of the code extracts and structures the data, and the second part uses this structure to convert the system model and run the simulation.

Each script is based on parser code and successive data manipulation to perform analysis or simulations. The following sections provide detailed descriptions of the ESM and reliability analysis script, the dynamic simulation script, and their direct implementation in Capella using the Python4Capella add-on.

4.1.4 ESM and Reliability Analysis

As discussed in Section 2.3, during the early phases of the design process, various system configurations and technologies are evaluated based on key criteria, such as performance, reliability, mass, cost, and TRL.

Traditionally, several metrics have been used to evaluate key aspects of an ECLSS system configuration. From the initial phases of the design process, it is essential to estimate the ESM and Pr(LOC) of the system architecture. As stated by Jones [57], "*The best design for a deep space life support system provides adequately for the crew, over the mission duration, with the required Pr(LOC), for the minimum ESM*".

As described in Section 2.3.4, the ESM accounts for the system's mass and associated infrastructure costs. It has traditionally been used to compare different system configurations or technologies. The probability that the ECLSS will fail before time t is represented by Pr(LOC)(t). This metric can support trade-offs and provide an estimate of system reliability.

This section details the tool developed in this work to calculate the ESM and the Pr(LOC) over time for the system architecture modeled in Capella. This analysis tool is especially useful in the early design phases because it allows for the comparison of different architectures, provides an initial system reliability assessment, and evaluates design feasibility. Although this analysis provides a preliminary estimation of system reliability, a comprehensive safety assessment is still necessary. As the design process progresses, defining failure modes, performing effects analysis, conducting risk analysis, and developing maintenance strategies becomes essential. These steps are necessary to ensure the system meets safety requirements.

To perform this analysis, the Python script `ECLSS_system_analysis.py` extracts the data assigned to the various technologies that compose the system architecture. The data is then used to calculate the ESM and the Pr(LOC) over time. The necessary input parameters, which are allocated to the Node Physical Components of the ECLSS model using the PVMT, include the crew size the technologies are designed for, as well as the mass, volume, power consumption, thermal load, resupply interval, failure rate, number of redundant units, and number of spare sets.

This analysis can be used to estimate the number of redundant units and spare sets needed to ensure that the system achieves the required reliability while minimizing overall mass. The other parameters for each ECLSS technology were collected from the literature and organized in the ECLSS database in the Appendix B.

The database includes the number of crew members that each technology is designed to support. For the purposes of this work, it is assumed that each technology scales linearly with crew size. A scaling factor is defined as the ratio of the number of crew members in the reference mission CM_{mission} to the number of crew members that the technology is designed to support $CM_{\text{technology}}$.

$$\text{Scaling factor} = \frac{CM_{\text{mission}}}{CM_{\text{technology}}} \tag{18}$$

This analysis neglects the contribution of crew time to the ESM calculation for each technology. However, as the design process progresses, it becomes crucial to evaluate crew time simultaneously with the maintenance strategy to maximize the total available work time for the mission's objectives.

The data necessary to perform the analysis are created using the PVMT, following the approach described in Section 4.1.2.

As shown in Figure 47, a constraint element has been created in the model to which various extensions have been applied. These extensions contain the necessary properties for analysis and simulation. Using this approach, users can input the required Property Values to perform the specified analysis or simulation. The properties showed in Figure 48 allocated to the *settings* element necessary for the system analysis tool are the desired total pressure in the cabin, desired O_2 partial pressure, desired N_2 partial pressure, desired temperature, crew members, total habitat volume, CF_{VOL}, CF_{PWR}, CF_{TCS} and the mission duration considered in the analysis. The simulation tool described in the following section also uses these properties. Special attention was given to ensuring compatibility between the two tools during the definition of these extensions.

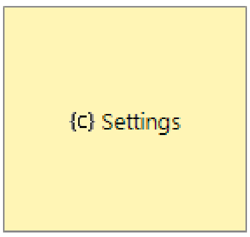
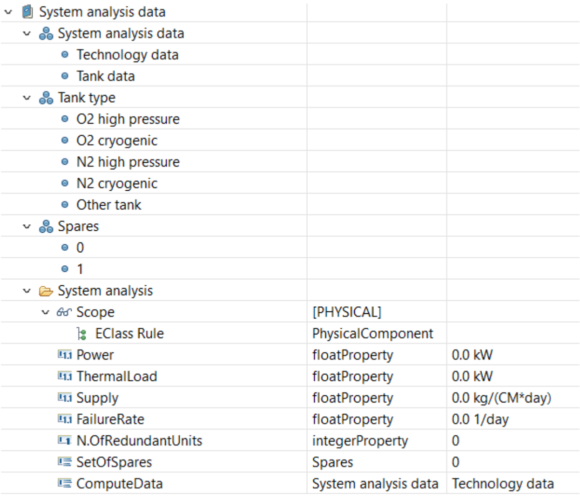


Figure 47: Settings (constraint model element).

Simulation and analysis data	
DesiredRatio_pO2_pTotal	0.2
DesiredTotalPressure	101325.0 Pa
DesiredO2PartialPressure	21000.0 Pa
DesiredN2PartialPressure	80000.0 Pa
DesiredCO2PartialPressure	325.0 Pa
DesiredTemperature	293.0 K
CrewMembers	2
FoodMassStore	100.0 kg
ComputeCrewData	true
TotalHabitatVolume	90.0 m^3
CF_power	192.0 kg/kW
CF_thermal	135.0 kg/kW
CF_volume	129.0 kW
MissionDurationAnalysis	1000 days
SimulationTime	7.0 days
Crew data	
MeanHeight	1.8 m
MeanAge	28 years
BreakfastTime	1
LunchTime	6
DinnerTime	15

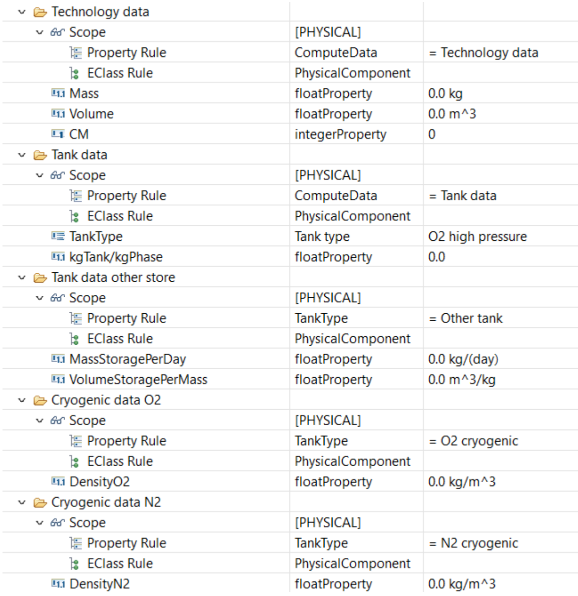
Figure 48: Settings data.

To apply the data to the different technologies necessary for the analysis, different extensions has been created, depicted in Figures 49 and 50. The following properties can be applied to all Node Physical Components: power consumption, thermal load, resupply interval, failure rate, number of redundant units, and number of spare sets. Additionally, the *ComputeData* enumeration property can be used to specify whether the physical component is a technology or a tank. If user select to compute technology data, the following properties can be applied: mass, volume and $CM_{\mathrm{technology}}$. Otherwise, it is possible to select the tank type and specify the ratio between the tank mass and the mass of the phase contained within it. Then, based on the selected enumeration literal in *Tank type* the corresponding phase properties can be defined.



System analysis data		
System analysis data		
Technology data		
Tank data		
Tank type		
O2 high pressure		
O2 cryogenic		
N2 high pressure		
N2 cryogenic		
Other tank		
Spares		
0		
1		
System analysis		
Scope	[PHYSICAL]	
EClass Rule	PhysicalComponent	
Power	floatProperty	0.0 kW
ThermalLoad	floatProperty	0.0 kW
Supply	floatProperty	0.0 kg/(CM*day)
FailureRate	floatProperty	0.0 1/day
N.OfRedundantUnits	integerProperty	0
SetOfSpares	Spares	0
ComputeData	System analysis data	Technology data

Figure 49: PVMT system analysis (1).



Technology data		
Scope	[PHYSICAL]	
Property Rule	ComputeData	= Technology data
EClass Rule	PhysicalComponent	
Mass	floatProperty	0.0 kg
Volume	floatProperty	0.0 m^3
CM	integerProperty	0
Tank data		
Scope	[PHYSICAL]	
Property Rule	ComputeData	= Tank data
EClass Rule	PhysicalComponent	
TankType	Tank type	O2 high pressure
kgTank/kgPhase	floatProperty	0.0
Tank data other store		
Scope	[PHYSICAL]	
Property Rule	TankType	= Other tank
EClass Rule	PhysicalComponent	
MassStoragePerDay	floatProperty	0.0 kg/(day)
VolumeStoragePerMass	floatProperty	0.0 m^3/kg
Cryogenic data O2		
Scope	[PHYSICAL]	
Property Rule	TankType	= O2 cryogenic
EClass Rule	PhysicalComponent	
DensityO2	floatProperty	0.0 kg/m^3
Cryogenic data N2		
Scope	[PHYSICAL]	
Property Rule	TankType	= N2 cryogenic
EClass Rule	PhysicalComponent	
DensityN2	floatProperty	0.0 kg/m^3

Figure 50: PVMT system analysis (2).

After allocating all properties to the components that compose the system, the data can be extracted from the model and processed for analysis.

In `ECLSS_system_analysis.py`, after extracting the data, the code computes the ESM for all physical components with system analysis properties associated.

The ESM for each technology is calculated using the following formula:

$$\begin{aligned} ESM_{\text{tech}_i} &= \text{mass}_i \cdot \text{scaling factor} \\ &+ CF_{\text{VOL}} \cdot \text{volume}_i \cdot \text{scaling factor} \\ &+ CF_{\text{PWR}} \cdot \text{power}_i \cdot \text{scaling factor} \\ &+ CF_{\text{TCS}} \cdot \text{thermal load}_i \cdot \text{scaling factor} \\ &+ \text{supply}_i \cdot CM_{mission} \cdot \text{mission duration} \end{aligned} \tag{19}$$

The mission duration is a time vector that ranges from zero to the value specified in the *MissionDurationAnalysis* property.

The ESM for a tank is calculated using the following formula:

$$\begin{aligned} ESM_{\text{tank}_i} &= \text{Total tank mass}_i \\ &+ CF_{\text{VOL}} \cdot \text{volume}_i \\ &+ CF_{\text{PWR}} \cdot \text{power}_i \\ &+ CF_{\text{TCS}} \cdot \text{thermal load}_i \\ &+ \text{supply}_i \cdot CM_{mission} \cdot \text{mission duration} \end{aligned} \tag{20}$$

The tank mass is calculated depending on the type of tank:

- **High pressure O_2/N_2**
- **Cryogenic O_2/N_2**
- **Other tank**

If the physical component under consideration is an oxygen or nitrogen tank, the code computes the required storage mass to compensate for both **leakage** and **repressurization** losses.

For this purpose, a cabin leakage rate of

$$0.23 \, \frac{\text{kg}}{\text{element} \cdot \text{day}}$$

is considered, as reported by Wieland [4]. It is assumed that this leakage consists exclusively of oxygen O_2 and nitrogen N_2, which reflect the cabin atmospheric composition of 21% O_2 and 79% N_2.

Based on these assumptions, the total mass required to compensate for leakage during the mission is calculated as:

$$\text{mass}_{O_2,\text{leak}} = 0.23 \cdot 0.21 \cdot \text{mission duration} \tag{21}$$

$$\text{mass}_{N_2,\text{leak}} = 0.23 \cdot 0.79 \cdot \text{mission duration} \tag{22}$$

To estimate the total mass of O_2 and N_2 required for repressurization, the ideal gas law is applied:

$$m = \frac{M_{\text{mol}} \cdot P \cdot V}{R \cdot T} \tag{23}$$

where:

- M_{mol} is the molar mass [kg/mol],
- P is the partial pressure of the gas [Pa],
- V is the cabin volume [m^3],
- $R = 8.314472\,\text{J/(mol}\cdot\text{K)}$ is the ideal gas constant,
- T is the cabin temperature [K].

The partial pressure, cabin volume, and cabin temperature values are taken from the property associated with the setting constraint. The repressurization mass for each gas is computed as:

$$\text{mass}_{N_2,\text{repress}} = \frac{M_{\text{mol},N_2} \cdot P_{N_2} \cdot V_{\text{cabin}}}{R \cdot T_{\text{cabin}}} \tag{24}$$

$$\text{mass}_{O_2,\text{repress}} = \frac{M_{\text{mol},O_2} \cdot P_{O_2} \cdot V_{\text{cabin}}}{R \cdot T_{\text{cabin}}} \tag{25}$$

The total storage mass, including leakage and repressurization compensation, is:

$$\text{Total mass}_{\text{N}_2} = (\text{mass}_{\text{N}_2,\text{leak}} + \text{mass}_{\text{N}_2,\text{repress}}) \cdot SF \tag{26}$$

$$\text{Total mass}_{\text{O}_2} = (\text{mass}_{\text{O}_2,\text{leak}} + \text{mass}_{\text{O}_2,\text{repress}}) \cdot SF \tag{27}$$

where SF is a safety factor assumed to be equal to 1.2, which accounts for uncertainties.

The total tank mass of oxygen or nitrogen is calculated using the tank ratio $\frac{kg}{kg}$, which is defined as the ratio of the tank's mass to the mass of the stored phase.

$$\text{Total tank mass} = \text{tank ratio} \cdot \text{Total mass} + \text{Total mass} \tag{28}$$

The volume of a tank is calculated differently depending on whether it is high-pressure or cryogenic.

$$\text{Volume}_{\text{highPressure}} = \frac{\text{Total mass} \cdot R \cdot T}{M_{\text{mol}} \cdot P}(1+\alpha) \tag{29}$$

$$\text{Volume}_{\text{cryogenic}} = \frac{\text{Total mass}}{\rho_{\text{cryogenic}}}(1+\alpha) \tag{30}$$

where α is a factor assumed to be equal to 0.1 to account for the tank structure.

If the Node Physical Component is not a high-pressure or cryogenic storage system for oxygen or nitrogen, then the user may provide the following information instead: the mass of the stored material per day $mass_{\text{store,day}}$ and the volume of the tank per unit of mass $\frac{1}{\rho}$. An example of this type of storage is the use of LiOH canisters for CO_2 removal. Therefore, the code compute the total mass and volume:

$$\begin{aligned}\text{Total tank mass}_{\text{other tank}} = \; & \text{tank ratio} \cdot \text{mass}_{\text{store,day}} \cdot \text{mission duration} \\ & + \text{mass}_{\text{store,day}} \cdot \text{mission duration}\end{aligned} \tag{31}$$

$$\text{Volume}_{\text{other tank}} = \frac{1}{\rho} \cdot \text{mass}_{\text{store,day}} \cdot \text{mission duration} \tag{32}$$

The `ECLSS_system_analysis.py` code uses these equations to compute the ESM for each system component.

As described in Section 2.3.4, in order to estimate the system's reliability and evaluate the impact of redundancy and spare parts on the ESM, must be defined a reliability model. Using the PVMT, users can assign a constant failure rate to each component. This value enables the calculation of the technology's reliability and failure probability.

This analysis considers a reliability model based on Jones's work [57], and is based on the following points:

- It is assumed that adding a set of spares, denoted by s, for a specific technology reduces its failure rate by a factor of ten. Therefore, assuming that the nine of ten failures will be repaired:
$$\lambda_{i,s} = \frac{\lambda_i}{10} \tag{33}$$
Adding a set of spares, increase also the ESM by 50%.
- Adding redundancy, denoted by r, to a specific technology increases its reliability, and this can be evaluated using the *Poisson Cumulative Distribution Function (CDF)*:
$$R_i(t) = \sum_{k=0}^{r} \frac{(\lambda t)^k}{k!} e^{-\lambda t} \tag{34}$$
The CDF estimates the probability that the number of failures occurring during a mission of duration t, with a failure rate of λ, will not exceed the number of available units ($r + 1$). This equation enable to compute the reliability of a technology with r reduntant units. Adding a redundant unit doubles the ESM of the technology, including the spares. If the technology does not have redundancy, its reliability is computed using the exponential function described in Section 2.3.4.

Using this reliability model, the ESM for each technology is calculated as follows:

$$\text{ESM}_{\text{spares,i}} = \text{ESM}_i \cdot (1 + 0.5 \cdot \text{spares}_i) \tag{35}$$

where spares_i denotes the number of spare sets (either zero or one), while redundancy_i represents the number of redundant units.

$$\text{ESM}_{total,i} = \text{ESM}_{\text{spares}_i} + \text{ESM}_{\text{spares}_i} \cdot \text{redundancy}_i \tag{36}$$

Denoting n the number of the technologies which compose the ECLSS, the total ESM of the system is:

$$ESM_{ECLSS}(t) = \sum_{i=1}^{n} ESM_{\text{total,i}} \tag{37}$$

Using the reliability equations, is possible to compute the failure probability of each technology $F_i(t)$ and calculate the Pr(LOC) of the system.

$$F_i(t) = 1 - R_i(t) \tag{38}$$

$$Pr(LOC)(t) = 1 - \prod_{i=1}^{n} (1 - F_i(t)) \tag{39}$$

Once the system architecture model is defined in Capella, the code extracts the necessary data and uses the described equations to compute the total ESM of the system and the

Pr(LOC) over time. This analysis offers valuable insights regarding the system architecture under consideration. It supports trade-off evaluations and assists in defining the system during the early stages of the design process.

Using the Python4Capella add-on, the script is imported in the Capella environment. This enables the user to execute the script directly within Capella. Using this method, designers can define the system model, perform the analysis, and obtain the results in the same tool.

After executing the code from Capella, all outputs are automatically saved and the following figures are generated: Total ESM over time, ESM over time by subsystem, and Probability of Loss Of Crew over time. Figures 51 - 52 - 53 show the results of the analysis for an example system architecture.

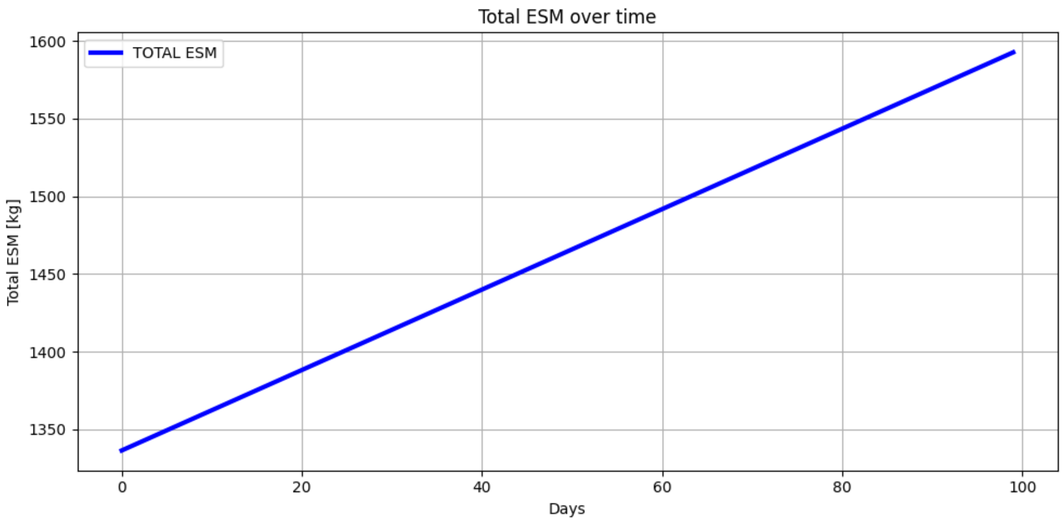


Figure 51: System analysis: ESM over time.

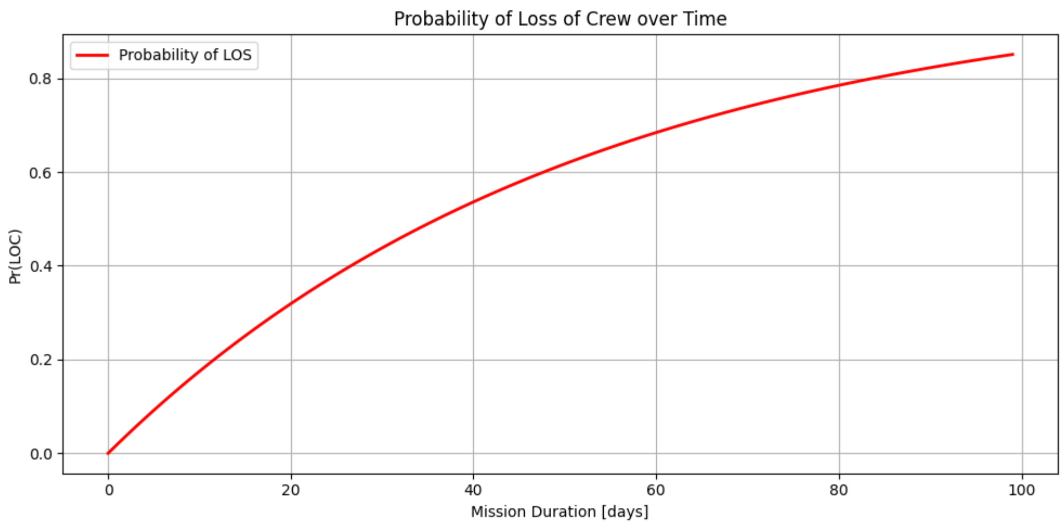


Figure 52: System analysis: Pr(LOC) over time.

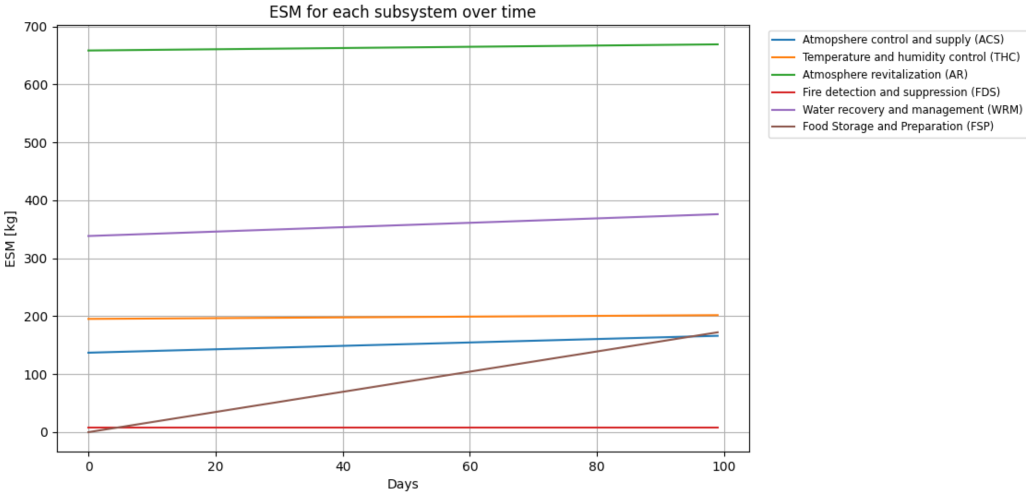


Figure 53: System analysis: ESM by subsystem over time.

Figure 54 shows the Python code that was imported to create the integrated model, as well as the console, which enables users to interact directly with Python within the Capella environment during analysis or simulation.

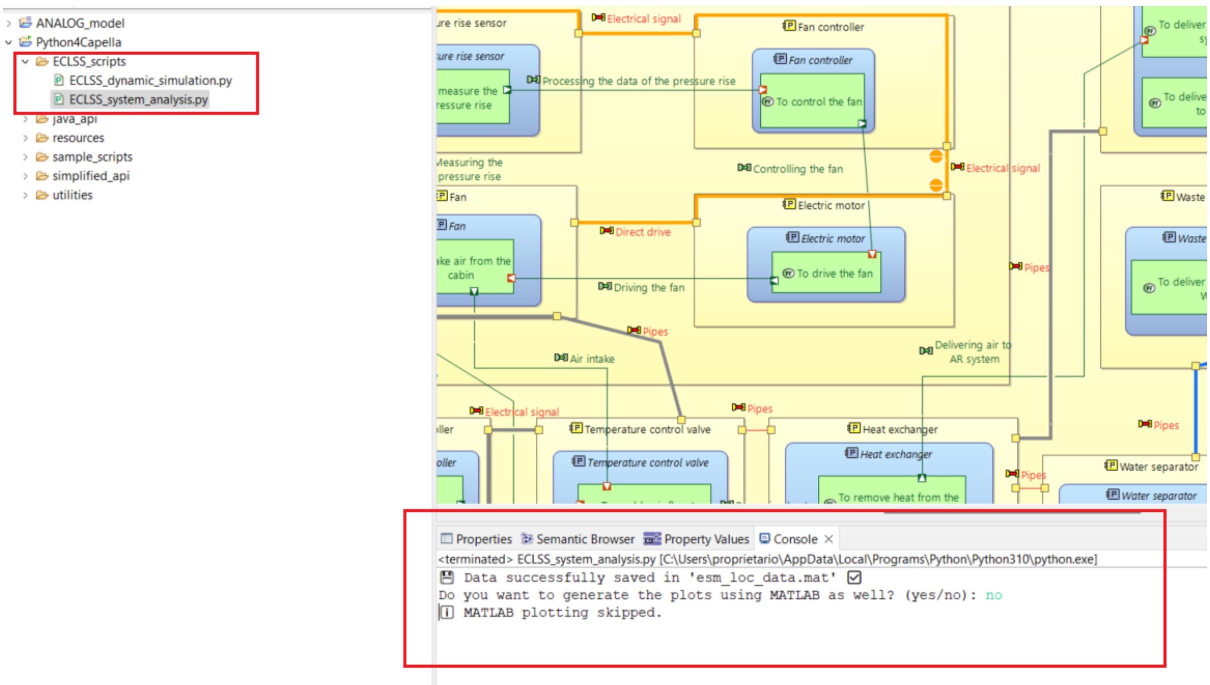


Figure 54: Console: system analysis.

The integrated model described in this section provides an easy, automated, and consistent way to analyze the system. It significantly reduces the time and effort required while effectively supporting the design process. The next section provides details on the system dynamics simulation tool and how it is integrated with the model. These simulations provide a more comprehensive view of system performance throughout mission duration, which complements the static ESM and reliability evaluation.

4.1.5 ECLSS Dynamic Simulation

The model is also integrated with V-HAB to continuously evaluate the performance of an ECLSS architecture throughout the design process. V-HAB performs dynamic simulations of the system for a specified mission scenario in order to investigate the robustness and overall performance of the system. These simulations support evaluating the system based on criteria such as reliability, stability, and controllability. They provide a deeper understanding of the system's behavior and the interactions between its subsystems. Multiple simulations under varying conditions, such as crew planner, cabin atmosphere composition, and other mission parameters, can be performed for the same system architecture to thoroughly assess system performance. For these reasons, these simulations, together with the ESM and reliability analysis, provide a comprehensive understanding of the system's characteristics, especially in the early design phases, which effectively supports the overall design process.

The model is integrated with V-HAB according to the method described in the previous section. Through PVMT, specific properties are assigned to each Node Physical Component of the model. The Python script `ECLSS_dynamic_simulation.py` extracts the data necessary for converting the Capella system architecture into the ECLSS V-HAB model. Then, it executes the simulation according to the specified mission scenario. This tool provides an easy, automated, and consistent way to simulate any ECLSS modeled in Capella. This integrated model enables designers to define the system architecture and easily perform dynamic simulations based on the specified mission scenarios. This approach facilitates the early detection of design issues and provides insight into the impact of design changes, supporting the system architecture definition. It also allows for continuous verification and validation throughout the design process, ensuring that the system meets its requirements. These simulations are essential for determining the status of the requirements defined in Capella.

Furthermore, since the V-HAB model is generated directly from the Capella model, this approach ensures consistency between the tools used in different design phases. This guarantees that the simulated model accurately reflects the defined system architecture. Together with the ESM and reliability analysis tools, this tool demonstrates that any type of simulation or analysis can be performed using the proposed approach.

To support the integration with the V-HAB tool, as well as the ESM and reliability analysis, a PVMT domain called *System simulation data* was created in the Configuration Property Values model editor. This domain contains the enumeration definitions and extensions necessary to convert the system model in a V-HAB model.

As shown in Figure 48, the *Simulation and analysis data* extension allows users to input all the necessary settings for the simulation and analysis tools. This includes key mission scenario parameters such as the desired ratio of oxygen partial pressure to total cabin pressure, desired total pressure, oxygen, nitrogen, and carbon dioxide partial pressures, desired cabin temperature, number of crew members in the habitat, amount of stored food, total habitat volume, and the mission duration to be simulated. In addition, the *settings* constraint element is associated with the *Crew data* extension, which allows specifying further parameters required by the V-HAB crew model. These include the average crew height and age, as well as the scheduled times for breakfast, lunch, and dinner[10]. Designers can change this properties and performing different simulation of the same system under different mission scenarios.

As shown in Figure 55, for each Node Physical Component (or Physical Actor for crew member) in Capella, it is possible to define the type of V-HAB element it corresponds to. These elements are: technology, component, storage and human. Depending on the type of element, different properties and data can be added necessary to define the model in V-HAB.

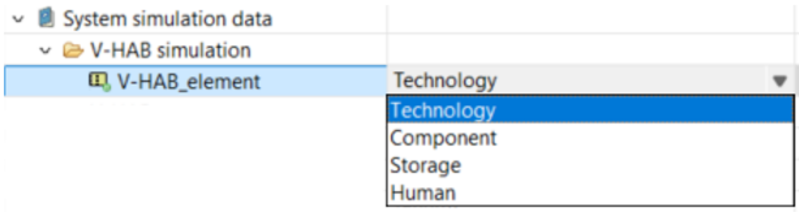


Figure 55: V-HAB element.

Human element: As shown in Figure 56, has been created a Physical Actor element in Capella to represent each crew member involved in the simulation. A dedicated model element can be defined for each crew member, to which specific properties are associated using PVMT, as illustrated in Figure 57. Each crew member can be assigned to a specific habitat module, and their activity schedule, referred to as the crew planner, can be specified. This includes key parameters such as the start time and duration of physical exercise and exercise intensity, as well as sleep start time and duration.

Figure 56: Crew member as Physical Actor.

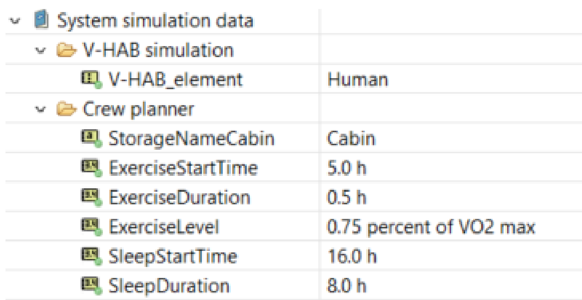


Figure 57: Extensions human.

Technology element: As shown in Figure 58, if the user selects the V-HAB technology element for a physical component, both the V-HAB technology type and its name can be specified. Available technologies that can be selected, based on those implemented in V-HAB, include: Common Cabin Air Assembly (CCAA), Bosch, Brine Processor Assembly, Carbon Dioxide and Moisture Removal Amine Swing-Bed System (CAMRAS), Carbon Dioxide Removal Assembly (CDRA), fuel cell, Oxygen Generation Assembly (OGA), Sabatier Carbon Dioxide Reduction Assembly (SCRA), Urine

[10]Since the habitat may consist of multiple modules, all of these data refer to the habitat as a whole.

Processing Assembly (UPA), and Water Processing Assembly (WPA)[11]. When defining the V-HAB model, it is also essential to provide the power consumption and CM properties for each technology. These values are specified within the *System Analysis Data* domain and are necessary to ensure the correct behavior and sizing of each technology V-HAB model. If the user selects *CCAA* as the technology, it is also possible to insert the necessary Proportional-Integral-Derivative (PID) [101] gain values for temperature control performed by the CCAA.

Name	Value
System analysis data	
System analysis	
Power	0.468 kW
ThermalLoad	0.468 kW
Supply	0.0 kg/(CM*day)
FailureRate	8.72E-4 1/day
N.OfRedundantUnits	0
SetOfSpares	0
ComputeData	Technology data
Technology data	
Mass	112.0 kg
Volume	0.4 m^3
CM	4
System simulation data	
V-HAB simulation	
V-HAB_element	Technology
V-HAB technology	
V-HAB_tech	CCAA
TechnologyName	CCAA 1
CCAA PID	
Gain_P	3.42
Gain_I	0.023
Gain_D	0.0

Figure 58: Extensions technology.

Component element: V-HAB includes also the implementation of basic ECLSS components, such as pressure regulators, pumps, fans, and filters. As shown in Figure 59, users can select these components directly within the model and specify their properties.

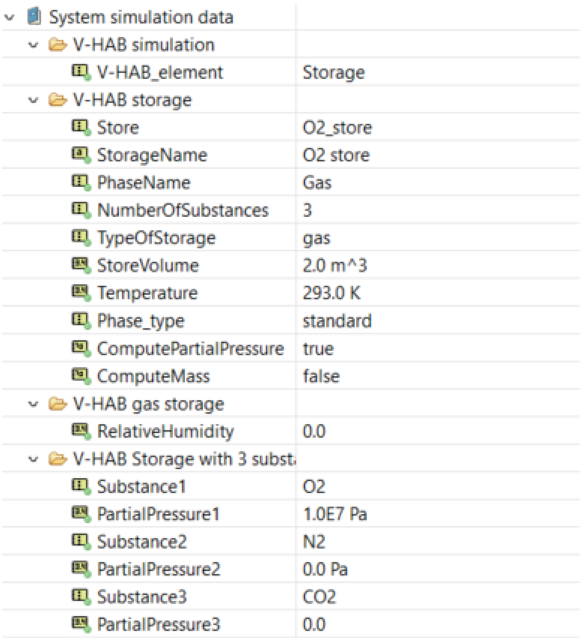
System simulation data	
V-HAB simulation	
V-HAB_element	Component
V-HAB components	
V-HAB_comp_name	SimplePressureRegulator
Simple pressure regulator data	
LimitPressure	300000.0 Pa

Figure 59: Extensions component.

[11] CDRA, OGA, SCRA, UPA, and WPA are the ISS technologies which refer respectively to 4 Bed Molecular Sieve (4BMS), Solid Polymer Water Electrolysis (SPWE), Sabatier, Vapor Compression Distillation (VCD), and Multifiltration.

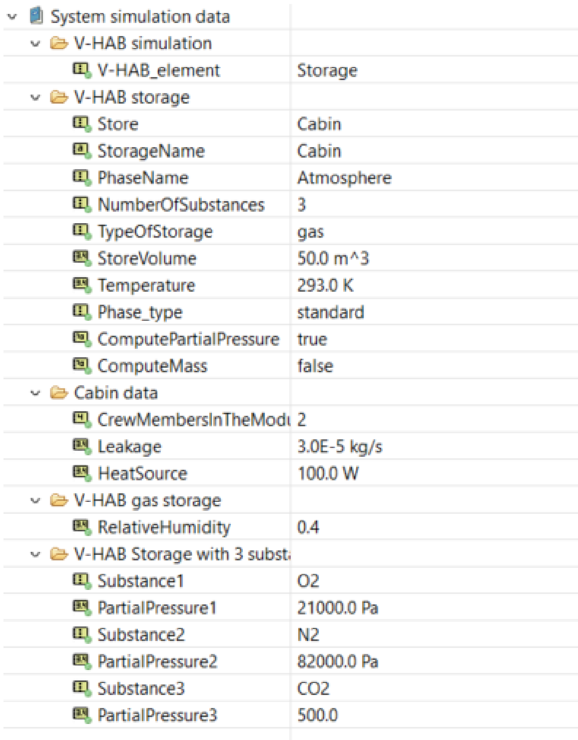
Storage element: As shown in Figure 60, several properties can be assigned to storage elements, including the storage type, storage name, phase type, number of substances in the phase, volume, temperature, and humidity. The phase composition can also be defined by specifying either the mass or the partial pressure of each substance.

In V-HAB, the cabin itself is modeled as storage. As depicted in Figure 61, when the *Store* property is selected as a "Cabin", additional properties can be defined, including the number of crew members located within the module, the module's leakage rate, and the associated heat sources. The "Cabin" storage's specified atmospheric composition constitutes the initial condition for the dynamic simulation.



System simulation data	
V-HAB simulation	
V-HAB_element	Storage
V-HAB storage	
Store	O2_store
StorageName	O2 store
PhaseName	Gas
NumberOfSubstances	3
TypeOfStorage	gas
StoreVolume	2.0 m^3
Temperature	293.0 K
Phase_type	standard
ComputePartialPressure	true
ComputeMass	false
V-HAB gas storage	
RelativeHumidity	0.0
V-HAB Storage with 3 subst.	
Substance1	O2
PartialPressure1	1.0E7 Pa
Substance2	N2
PartialPressure2	0.0 Pa
Substance3	CO2
PartialPressure3	0.0

Figure 60: Extensions storage.



System simulation data	
V-HAB simulation	
V-HAB_element	Storage
V-HAB storage	
Store	Cabin
StorageName	Cabin
PhaseName	Atmosphere
NumberOfSubstances	3
TypeOfStorage	gas
StoreVolume	50.0 m^3
Temperature	293.0 K
Phase_type	standard
ComputePartialPressure	true
ComputeMass	false
Cabin data	
CrewMembersInTheModu	2
Leakage	3.0E-5 kg/s
HeatSource	100.0 W
V-HAB gas storage	
RelativeHumidity	0.4
V-HAB Storage with 3 subst.	
Substance1	O2
PartialPressure1	21000.0 Pa
Substance2	N2
PartialPressure2	82000.0 Pa
Substance3	CO2
PartialPressure3	500.0

Figure 61: Extensions cabin.

Physical Path: In Capella, two Node Physical Component can be linked using the Physical Link element. It is also possible to create a Physical Path, an organized succession of Physical Links. As depicted in Figure 62, each Physical Path can be assigned a specific substance exchanged along that path. For example, oxygen is exchanged along the Physical Path connecting the O_2 tank and the cabin. Additionally, a constant flow rate can be defined between two components, or a gas control system implemented in V-HAB can be enabled for a given module. This control system is designed for regulating oxygen and nitrogen levels in the cabin atmosphere.

Additionally, the following Property Values related to the Internal Thermal Control System (ITCS) can be allocated to a constraint element: coolant store volume, coolant store temperature, coolant store mass, and coolant store pressure.

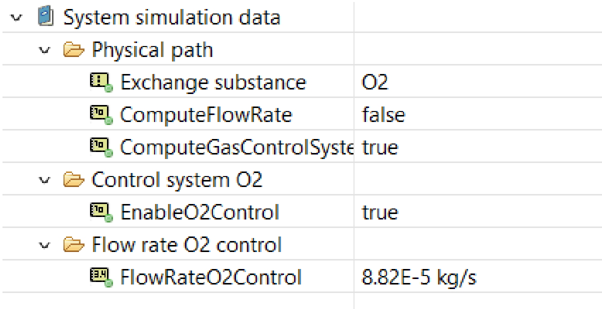


Figure 62: Extensions physical path.

The Configuration Property Value model editor, in which all of these extensions and enumerations are defined, is provided in Appendix C. The `ECLSS_dynamic_simulation.py` code extracts all the necessary PVMT data and model elements from the Capella architecture. The essential elements required to convert the system model into a V-HAB model are the Node Physical Components and the links connecting them. Based on this information, the code automatically generates the corresponding V-HAB model. Specifically, the Python script produces a MATLAB file that contains the V-HAB implementation of the system modeled in Capella. The simulation model is generated based on the known structure of V-HAB by manipulating and translating the system model data extracted from Capella.

Figure 63 illustrates the main elements of the system architecture and their equivalent representations in the V-HAB model, based on the allocated properties.

This section demonstrates how, knowing the structure of the target simulation tool, it is possible to create a code that can automatically convert a system architecture modeled in Capella into a simulation model in the desired tool. The integrated model provides significant support throughout the design process, especially in the early stages, by enabling rapid evaluation, early detection of design issues, and iterative refinement based on defined requirements.

In the defined integrated model, the steps to perform a dynamic simulation of the system are as follows:

1. Define the system architecture in Capella.
2. Use the Property Value view to assign Property Values to the *Settings* constraint element to specify the simulation and analysis data. This step allows defining all mission scenario parameters.
3. Assign the appropriate properties to each model element in Capella that corresponds to a component in V-HAB, as previously described.
4. Execute the Python script `ECLSS_dynamic_simulation.py` directly within the Capella environment.

After executing the Python script, the Capella console requests user interaction with the tool. As shown in Figure 64, the user is first asked to provide a name for the system model (e.g., `example1`). Then, the script then generates a corresponding MATLAB file for the V-HAB simulation model using this name (e.g., `example1.m`). After creating the

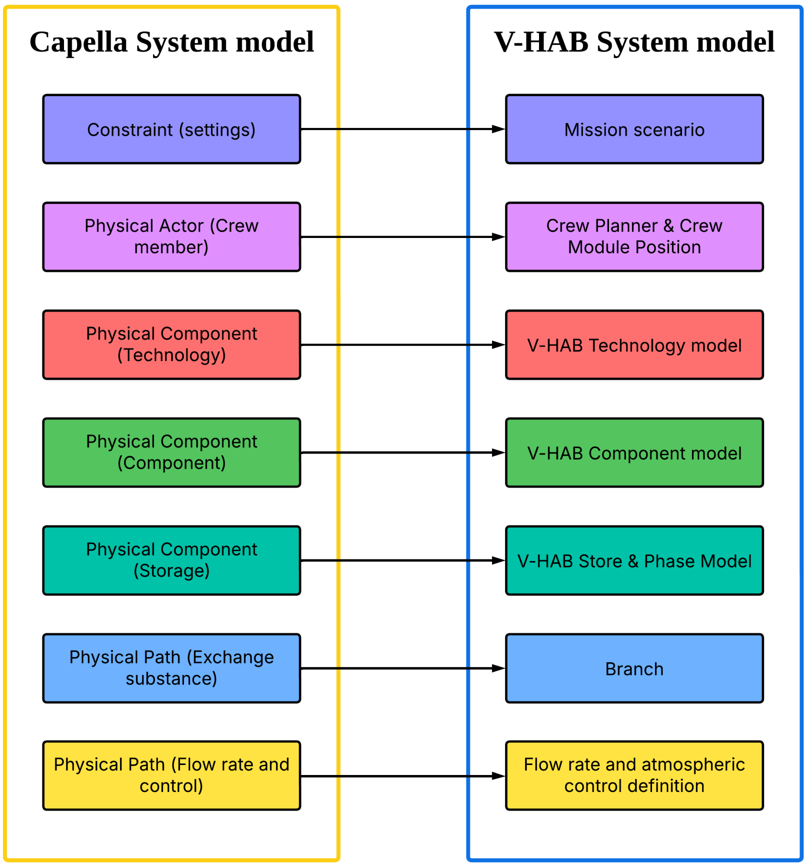


Figure 63: Model conversion.

model, the script asks if the system simulation should be executed. If the user confirms with `yes` the simulation is automatically launched in MATLAB.

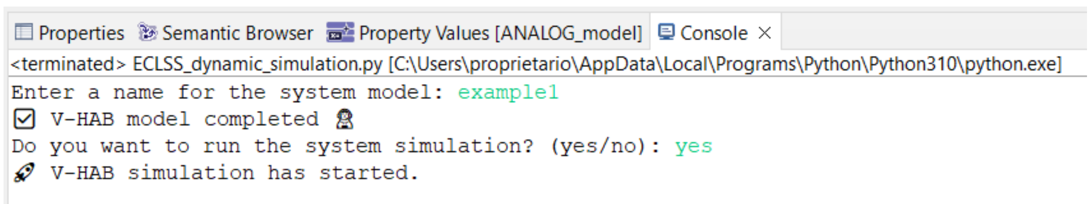


Figure 64: Console: dynamic simulation.

The dynamic simulation of the ECLSS for the specified mission scenario provides results for all system variables over time, for example: module temperatures, total and partial pressures, relative humidity, substance mass in storage tanks, flow rates between technologies, and power consumption. An example of the results that can be obtained from a simulation is depicted in Figures 65 to 69[12], which show the partial pressures of carbon dioxide, oxygen, and nitrogen in the cabin, the total pressure, the relative humidity, and the water mass inside the tank throughout the mission duration. These results offer a comprehensive understanding of the system's behavior and performance throughout the mission scenario.

[12]The simulation results refers to an example ECLSS architecture.

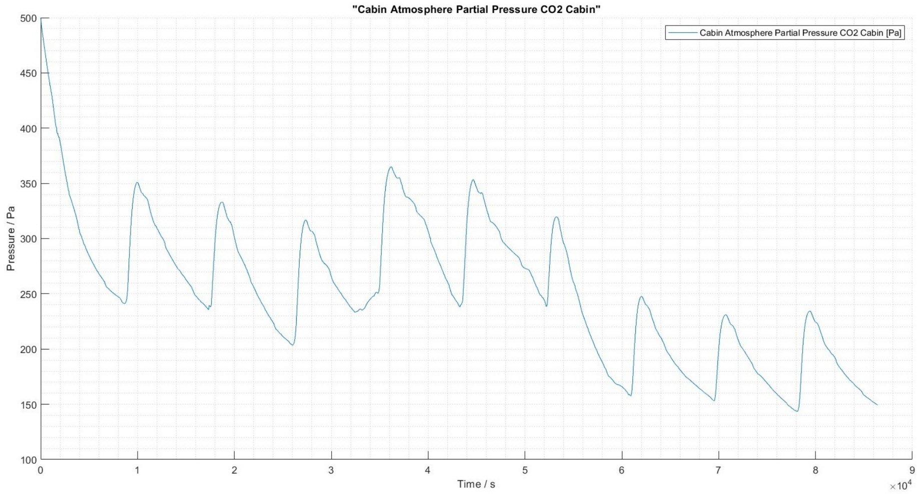


Figure 65: Simulation example: Partial Pressure CO_2.

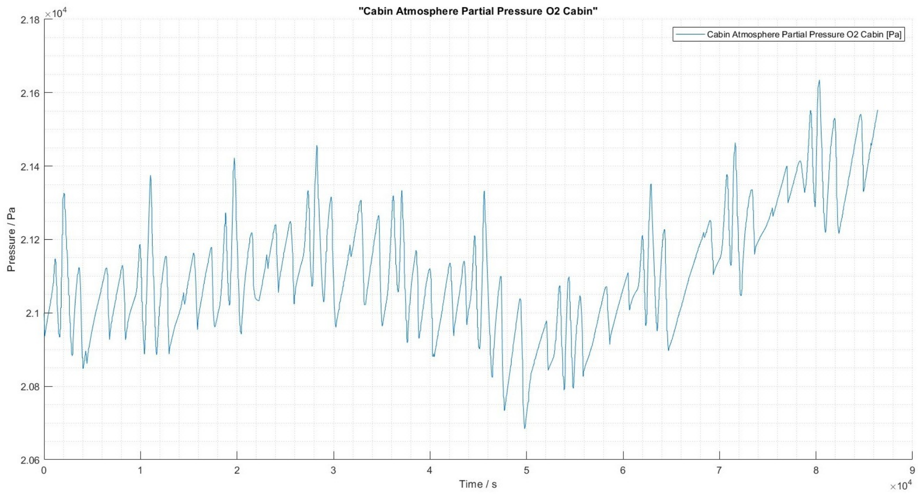


Figure 66: Simulation example: Partial Pressure O_2.

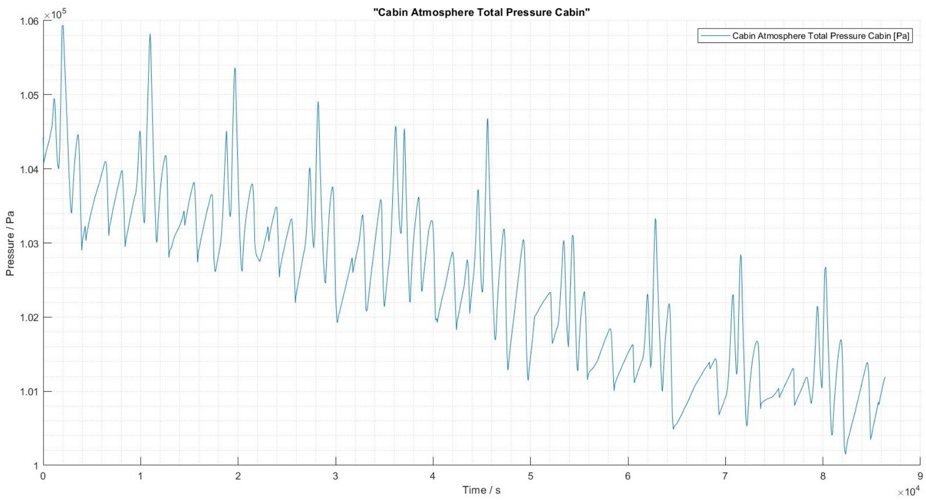


Figure 67: Simulation example: Total Pressure.

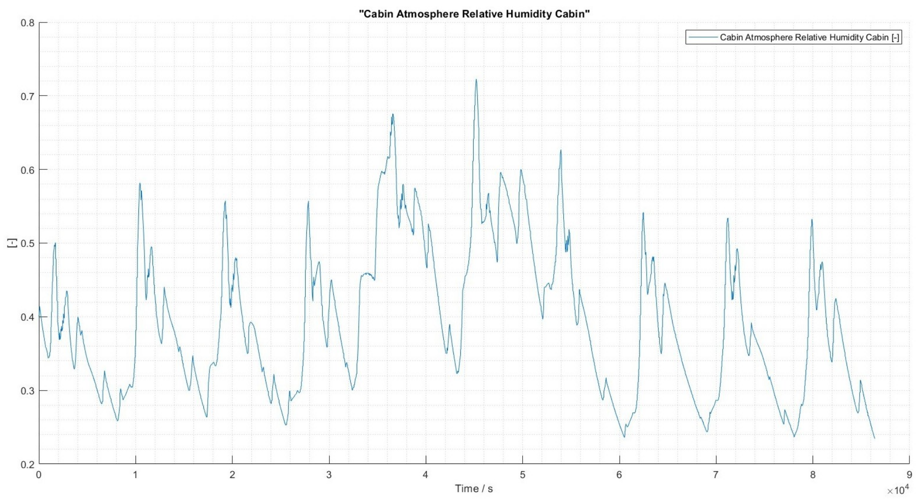


Figure 68: Simulation example: Relative Humidity.

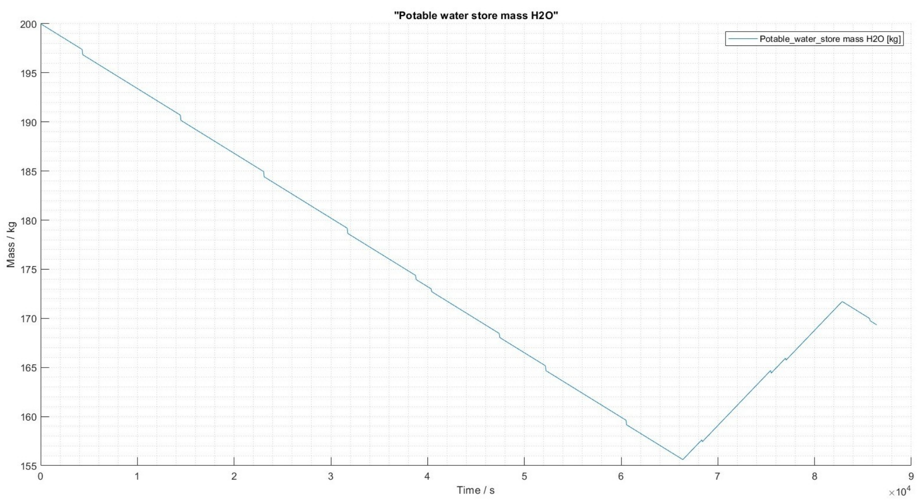


Figure 69: Simulation example: Water Tank Mass.

4.1.6 Integration Process Conclusion

The integration process described in this chapter demonstrates the feasibility and effectiveness of connecting a system architecture model to engineering analysis and simulation tools. Integrating tools such as the ESM and reliability analysis, and the V-HAB dynamic simulator illustrates how different evaluations can be performed using a single, consistent system model. The following chapter describes the application of the proposed integration process to the design of the ECLSS for an analog habitat. This practical application shows how integrated MBSE supports architectural definition, system evaluation, and design refinement within a realistic mission scenario.

5 ECLSS Design for an Analog Habitat

In this section, the integrated MBSE approach previously described will be applied to support the preliminary design of the ECLSS for an Analog Habitat. This case study will offer valuable insight into the potential advantages of the proposed approach.

5.1 Analog Habitat Design

The Analog Habitat involved in this work is a project of Politecnico di Torino. The project aims to build an habitat for space analog simulations. It exploits Analog Missions to test new technologies for human spaceflight, improve existing technologies and systems, study the effects of human metabolic activities on systems, and evaluate human-system interactions, among many other research objectives.

In the thesis of Perotti [102], a MBSE approach was adopted to support the design process of the mentioned Analog Habitat. The Habitat model has been developed using the ARCADIA method and implemented in Capella.

The first phase of this work involved defining the mission statement and primary objectives, conducting a stakeholder analysis, deriving secondary objectives, and defining mission requirements. This phase was supported by the ARCADIA method's Operational Analysis workflow. In this ARCADIA layer have been defined all the actors that interact with the system, their operational capabilities and activities, the interactions between the actors and activities, operational scenarios that described the capabilities, mission modes and states, and the definition of mission requirements. The requirements that have been specified are as follows:

1. *"The mission shall provide a mobility system, enabling transferability, provide independent power generation, command, data handling, and communication capabilities, and crew support facilities".*
2. *"The mission shall validate AI-assisted control systems, develop and validate innovative human-machine interface solutions, enable modularity and scalability for systems".*
3. *"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 ECLS systems".*

Successively, the ARCADIA System Analysis has been performed in order to define what the system must do and what are its external interfaces. This includes identifying system actors, defining missions and capabilities, defining system functions and functional exchanges, allocating functions to the system and its actors, describing capabilities using scenarios, and defining mission requirements.

Figure 70 shows the system functions created in the System Analysis related to the ECLSS. Perotti's thesis [102] thoroughly covers the functions of the other systems of the Analog Habitat, as well as the complete model.

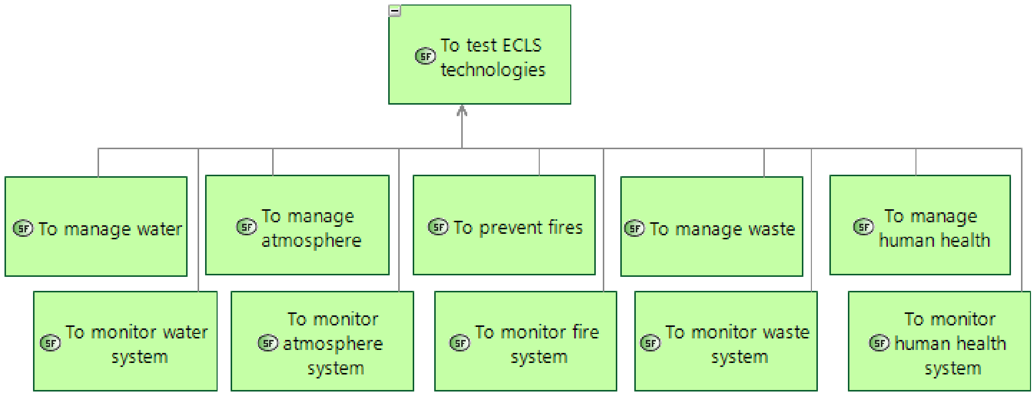


Figure 70: ECLSS functions System Analysis [102].

In the System Analysis layer, the system is considered a black box, while the Logical Architecture layer begins to decompose the system using structural elements called *logical components*. In the Logical Architecture layer, the system architecture is defined in order to meet the needs described in the Operational and System Analysis. As in the previous layer, a functional analysis is performed in the Logical Architecture to identify the behavior of the Logical Components.

Therefore this layer includes the creation of logical functions and functional exchanges, logical components with their allocated functions, and capabilities realizations have been described using functional chains and scenarios. Figure 71 shows the ECLSS functional tree while Figure 72 depicts a diagram including the logical components, the functions, the functional exchanges, and the functional chain related to the ECLSS.

Perotti's thesis [102] provides a thorough description of the Operational Analysis, System Analysis, and Logical Architecture conducted to support the design process of the Analog Habitat.

This work extends the Analog Habitat model described in Perotti's thesis by performing the Physical Architecture layer of the ARCADIA method for the ECLSS. The integrated approach described in the previous section will support the definition of the ECLSS architecture for the Analog Habitat. The ARCADIA method, integrated with analysis and simulation tools, will be applied iteratively to accurately define and verify the system architecture and associated requirements.

In the following sections, the application of the Physical Architecture layer of the ARCADIA methodology to define the ECLSS architecture will be described, as well as the trade-offs performed to choose between the different available technology options and the integrated analysis and simulation tools to support the design process. After the proposed integrated MBSE approach is presented to support the ECLSS design process, the developed architecture will be described, as it will be explained how to employ the proposed approach to support the design in subsequent design phases. This will involve integrating in the model more advanced engineering analysis tools and exploiting the full potential of the ARCADIA method.

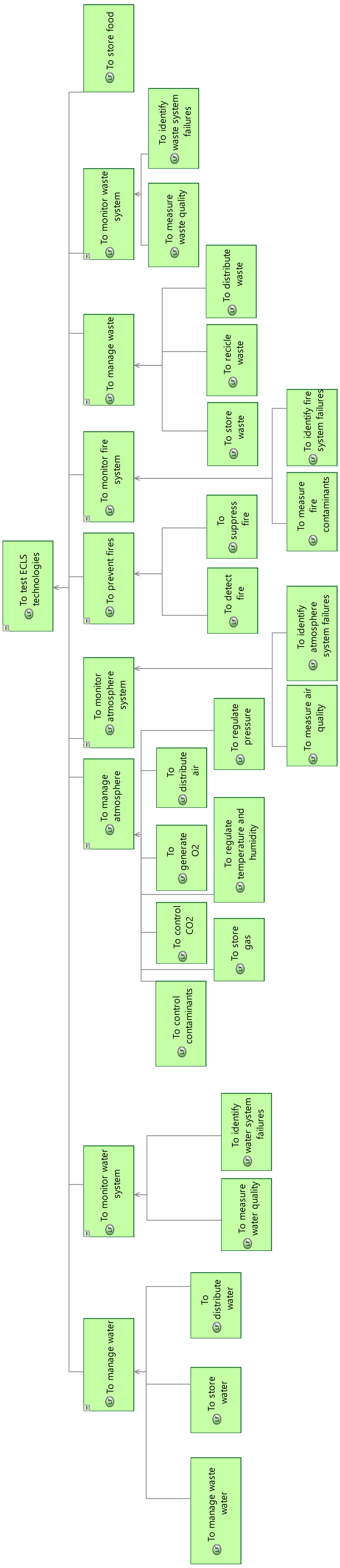


Figure 71: ECLS Technologies Root Logical Function [102].

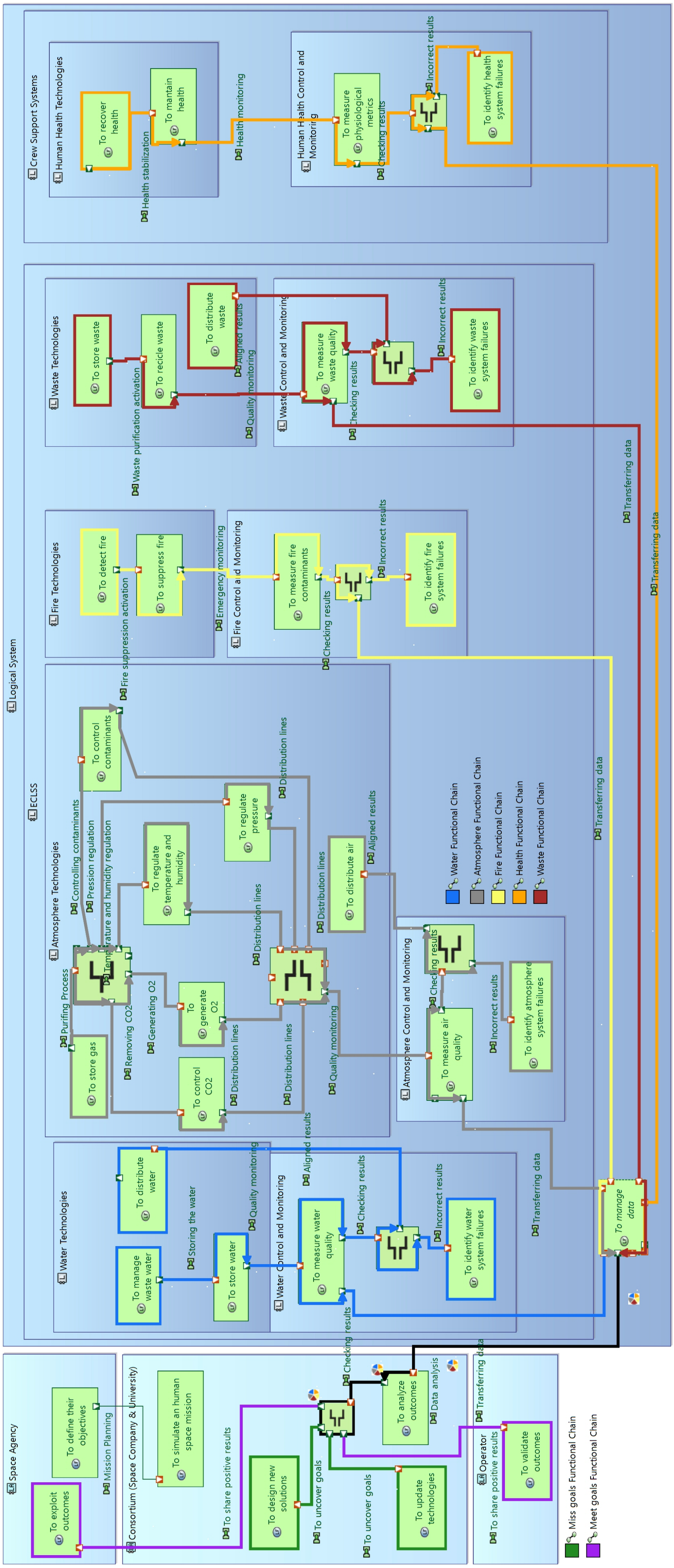


Figure 72: ECLS Technologies Structure [102].

5.2 ECLSS Model

The Logical Architecture layer of the Analog Habitat model, as defined in Perotti's thesis [102], involved the creation of structural elements called logical components, along with their properties and relations, for the entire Habitat system. According to the ARCADIA methodology, the Logical Architecture layer excludes all technological considerations or implementation choices, which are the main focus of the subsequent layer [84]. The Physical Architecture layer aims to define the real components that compose the system and to break down its functions.

In this work, the Physical Architecture layer of the ARCADIA method will be employed to define the architecture of the ECLSS. Figure 73, shows the main model elements of this perspective, which define the final architecture of the system. In this layer, new functions are added and allocated to Behaviour Components, which are physical components that perform these functions. Node Physical Components can also be created which provide the material resources needed for the Behavior Physical Components. A connection can be created between two Node Physical Components using the Physical Link element. It is also possible to create a Physical Path, which is a series of Physical Links [84].

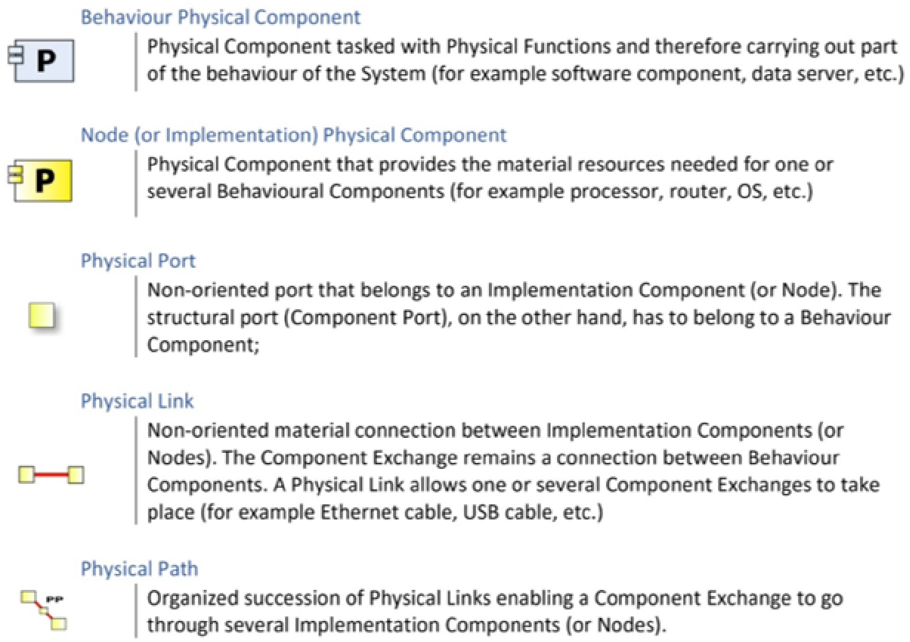


Figure 73: Physical Architecture concepts [84].

The main activities that can be performed in this layer to define the system architecture include defining new physical functions and functional exchanges, creating Node and Behavior Physical Components, allocating functions to Behavior Physical Components, defining Physical Links and Physical Paths, and realizing capabilities using functional chains and scenarios.

Different Capella diagrams are created during the process to perform these activities, easily edit the model, and provide a view of the system model.

The main diagram that can be created in this layer are:

- The Physical Functions Breakdown Diagram (PFBD) is a functional tree that contains all the functions created in the model. The concept is the same as the Functions Breakdown Diagram of the previous layers. To visually identify the functions related to the Physical Architecture, it is advised to change the color of the functions created in the previous layers from green to white [84].
- The Physical Dataflow Blank (PDFB) is a diagram which contains all the functions of the model with the related functional exchanges.
- The Physical Components Breakdown Diagram (PCBD) is a product tree related to the Beaviour Physical Components or to the Node Physical Components.
- The Physical Architecture Blank (PAB) is a diagram that enables the allocation of created functions to Behavior Physical Components, as well as the creation of physical links and paths. This diagram provides a powerful overview of the system architecture. Indeed, new physical functions, functional exchanges, and physical components can be identified and captured [84]. An example of the PAB diagram is showed in Figure 74.
- As in the previous layer, a capability realization can be described using functional chains and scenarios in specific diagrams.

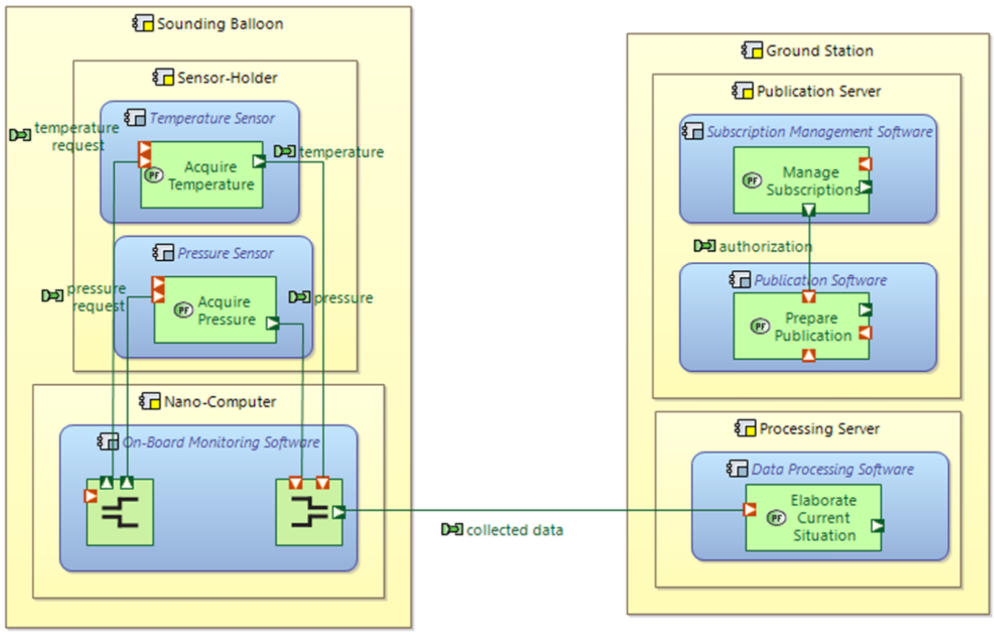


Figure 74: Physical Architecture Blank (PAB) example [80].

The Property Values previously specified necessary to perform simulations and analyses are associated with the Node Physical Components, Physical Paths, and Actors defined in the Physical Architecture layer.

With the integrated MBSE approach described in this work, the definition and verification of the ECLSS architecture is performed iteratively. More specifically, the system architecture is defined by carrying out activities related to the Physical Architecture layer and by analyzing and simulating the system iteratively. As explained in the previous section, requirement elements are also created during the system definition process and verified through the use of the integrated analysis and simulation tools.

Through this case study, this work aims to explore the potential benefits of integrating the ARCADIA methodology with analysis and simulation tools to support system architecture definition and verification.

5.2.1 Initial Design of the ECLSS Architecture

As discussed in Section 2.3, an ECLSS architecture is heavily influenced by several factors, including mission characteristics, systems and integration, human requirements, cost and technology considerations, safety and reliability, testing and flight requirements. During the design process, it is crucial for designers to consider these factors in order to accurately develop the ECLSS architecture. Among these factors, the mission characteristics have a significant impact on the ECLSS design. In fact, the ECLSS for a mission of a different duration, crew size, and location can have a completely different architecture. The following section will show that the overall system configuration and the selection of different technology options heavily depends on these mission factors.

The Analog Habitat considered in this work, consists of a single module, and one of the main research objectives is to *develop and test new ECLS systems* for future deep space missions. For this reason, the ECLSS architecture will be based on technologies that are better suited for long mission durations with two or three crew members in a single module, considering only physicochemical technologies[13].

Workflow

After transitioning the model element between Logical and Physical Architecture, development of the system could begin. Starting from the model element created in the previous layer, the activities related to the Physical Architecture were conducted as previously described. The system architecture is defined by iteratively performing these activities, mainly employing the Physical Functions Breakdown Diagram, the Physical Components Breakdown Diagram, and the Physical Architecture Blank. As previously discussed, in the ARCADIA method all the technology considerations and implementation choices are included in the Physical Architecture layer. As described in Appendix A, different technology options exist that can perform the same ECLS function but have different characteristics. Therefore, trade studies must be performed during the process to select the most suitable technologies that perform that specific function. For example, if the function *"To remove the CO_2 from the cabin atmosphere"* is created during the process, it is necessary to define a technology that can provide that function. In this case, the following step must be performed:

- Identify the technology alternatives.
- Perform a trade-off analysis.

[13] It is important to note that the proposed integrated MBSE approach can be applied to any ECLSS architecture that includes both physicochemical and biological technologies.

Therefore, in the first phase of the design process, during the development of the system architecture with the ARCADIA method, trade off studies are conducted to identify the best candidate technology for a specific function. Once the initial system configuration has been defined, the system will be analyzed in depth through integrated analysis and simulation tools. With this approach, once a first ECLSS architecture is proposed, the system can be iteratively developed through the ARCADIA method integrated with the ESM and reliability analyses, and the V-HAB simulations. These tools provide designers with meaningful information about the system, enabling them to perform trade-offs, define technical system solutions, allocate and verify system requirements, and assess the impact of design changes. They also facilitate continuous model verification and validation.

Trade Off Analysis

The main objective of a system engineer is to develop a system that performs its functions safely and in the most cost-effective way possible [69]. Designers must seek a balance of cost and effectiveness during the system development. Therefore, trade studies are a critical part of the system design process in order to identify the optimal configuration. In this work, different trade studies are performed to find the most cost-effectiveness technologies in the overall ECLSS architecture. Figure 75 depicts the different steps of the trade-off analysis considered in this thesis. A trade-off analysis is a method to accomplish design trade studies.

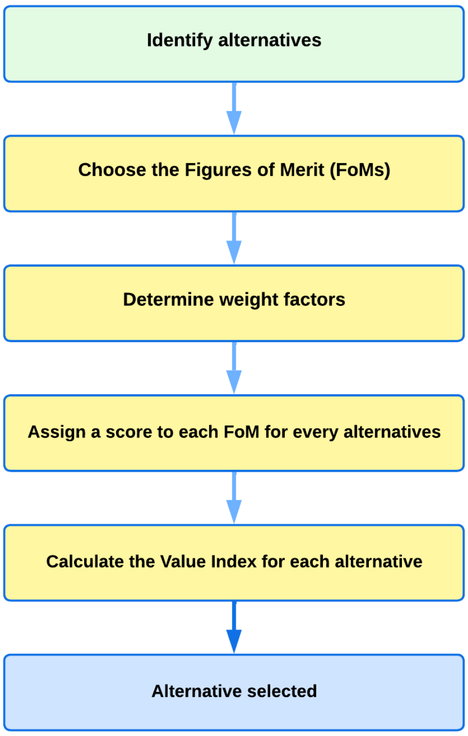


Figure 75: Trade-off analysis.

- The first step in a trade-off analysis is identifying the alternatives. For example, there are several alternatives for storing oxygen: high-pressure tanks, cryogenic tanks, and chemical compounds.
- The second step consists in choosing the Figures of Merit (FoM), which are the parameters or characteristics that are significant to evaluate the alternatives. Examples of these FoM are: safety, performance, cost, complexity, maintainability, and logistics support.
- The third step concern the definition of weight factors w_i, which establish how much each FoM is relevant in comparison with all others. For example, safety may be considered more important than complexity when choosing between alternatives.
- The fourth step is to assign a score P_i to each FoM alternative. The judgment criteria for this assignment should be as objective as possible. It is preferable that this score is determined by mathematical relationships, statistics or data and is elaborated on by the entire design team.
- The last step consists to calculate the Value Index VI for each alternatives using the following formula:

$$VI = \frac{\sum_{i=1}^{n_{pos}} P_i^{pos} w_i^{pos}}{\sum_{i=1}^{n_{neg}} P_i^{neg} w_i^{neg}} \tag{40}$$

  Where n_{pos} is the number of FoM for which a higher value indicates a more desirable or beneficial characteristic for the alternative, and n_{neg} is the number of FoM for which a higher value corresponds to a less desirable or negative characteristic. The alternative with the highest Value Index will be selected.

During the development of the system configuration through the Physical Architect activities, the described trade-off analysis is performed multiple times to select the best technologies for the specified mission from the alternatives.

As specified in Appendix A, for a specific function exists different physicochemical technologies regenerative and non-regenerative. As previously described, the referenced mission is a long-duration mission. Therefore, all non-regenerative technologies that would require a large amount of mass for a long-duration mission are excluded. Technologies with a TRL lower than 4 are also not taken into account.

Table 4 shows the technologies identified during the Capella architecture definition process that require trade studies, along with the options considered for each.

For all the trade-off analysis performed in this phase the following FoM has been considered: ESM, reliability, complexity, safety and TRL. In order to find the weight factors related to these FoM has been used the method showed in Table 5. The table lists the five defined FoM in both the first row and the first column. Each cell (excluding the diagonal) is assigned a value of 1 if the FoM in the row is considered more important than the FoM in the column and a value of 0 if otherwise. The diagonal elements are set to 1 by definition. The number of the weight factors is showed in Table 6. The weight factor associated with each FoM is calculated by dividing the number of cells set to 1 in its corresponding row by the total number of cells set to 1 in the entire matrix. As can be seen, safety is the most relevant FoM, as it has been considered more important than all the others. Following safety are TRL, ESM, complexity, and failure rate, which is considered the least relevant of the five.

Table 4: Trade studies.

Technology	Options
O_2 tank	- High pressure tank - Cryogenic tank
N_2 tank	- High pressure tank - Cryogenic tank
CO_2 removal	- 4 Bed Molecular Sieve (4BMS) - Solid Amine Water Desorption (SAWD) - Electrochemical Depolarization Concentration (EDC)
CO_2 reduction	- Sabatier - Bosch
O_2 generation	- Static Feed Water Electrolysis (SFWE) - Solid Polymer Water Electrolysis (SPWE)
Urine recovery	- Vapor Compression Distillation (VCD) - Thermoelectric Integrated Membrane Evaporation System (TIMES) - Air Evaporation Systems (AES)
Water process	- Multifiltration - Reverse Osmosis (RO)

Table 5: FoM comparison matrix.

	ESM	Failure rate	Complexity	Safety	TRL
ESM	1	1	1	0	0
Failure rate	0	1	0	0	0
Complexity	0	1	1	0	0
Safety	1	1	1	1	1
TRL	1	1	1	0	1

Table 6: Weight factors.

Parameter	Weight factor
ESM	0.200
Failure rate	0.067
Complexity	0.133
Safety	0.333
TRL	0.267

For each technology, the ESM is calculated with the formula described in the previous section and using the values of mass, volume, power, thermal load and resupply for each technology available in the database B. Each mission has specific conversion factors that depend on the selected power and thermal control systems, as well as the habitat design. In this preliminary phases of the design process of the Analog Habitat, is difficult to estimate these parameters. Therefore, the value of the conversion factor used in the lunar habitat mission example described in the book Human Spaceflight: Mission Analysis and Design [3] has been considered. Furthermore, the ESM calculated for this trade-off analysis was considered for each technology, excluding the contribution of a possible set of spares or redundancy that could increase the system's reliability. The FoM failure rate of each technology provides information about its reliability. While the FoM safety is not related to reliability, it is concerned with the potential hazards that such technologies can pose, such as flammable materials and gas leakage, which can result in toxic or explosive conditions.

After defining the weight factors, a score from 1 to 5 was assigned to each FoM for all the alternatives. The FoM ESM score is defined after calculating the equivalent mass for each alternative and is based on the difference between these values. The FoM failure rate is assigned based on the values of the failure rate that are available in the database (Appendix B) for each alternative. The FoM TRL score is assigned based on the technology readiness level of each technology. While the aforementioned FoM scores are based on mathematical relationships or technology data, the scores for the FoM complexity and safety are based on technology considerations summarized in Appendix A and described in detail in the literature. The final step in the trade-off analysis is to calculate the Value Index for each alternative using the formula 40. The FoM considered positive are the TRL and safety, while the negative are ESM, Failure rate and complexity. Indeed, a high TRL and safety value is more desirable for the technology, while a high FoM, failure rate, and complexity value is less attractive. For each trade-off analysis, the option with the highest Value Index has been chosen and integrated into the model. Tables 11 to 13 show the scores given to each technology in the various trade-off analyses. The "Value Index" column shows the resulting value for each alternative. The technology with the highest value, highlighted in green, is selected for each analysis.

Table 7: Trade-off scores and Value Index for O_2 tank options.

O_2 tank	ESM	Failure rate	Complexity	Safety	TRL	Value Index
High pressure tank	2	2	1	3	5	3.5
Cryogenic tank	2	3	5	4	5	2.105

Table 8: Trade-off scores and Value Index for N_2 tank options.

N_2 tank	ESM	Failure rate	Complexity	Safety	TRL	Value Index
High pressure tank	3	2	1	3	5	2.692
Cryogenic tank	2	3	5	4	5	2.105

Table 9: Trade-off scores and Value Index for CO_2 removal options.

CO_2 removal	ESM	Failure rate	Complexity	Safety	TRL	Value Index
4BMS	4	2	2	5	5	2.5
SAWD	3	2	3	3	4	1.824
EDC	2	3	3	2	3	1.467

Table 10: Trade-off scores and Value Index for CO_2 reduction options.

CO_2 reduction	ESM	Failure rate	Complexity	Safety	TRL	Value Index
Sabatier	2	2	4	3	5	2.188
Bosch	4	4	2	4	3	1.600

Table 11: Trade-off scores and Value Index for O_2 generation options.

O_2 generation	ESM	Failure rate	Complexity	Safety	TRL	Value Index
SFWE	4	2	2	4	4	2.000
SPWE	3	2	3	4	5	2.353

Table 12: Trade-off scores and Value Index for urine recovery options.

Urine recovery	ESM	Failure rate	Complexity	Safety	TRL	Value Index
VCD	3	2	3	5	5	2.647
TIMES	2	2	4	5	3	2.312
AES	4	1	2	4	2	1.647

Table 13: Trade-off scores and Value Index for water process options.

Water process	ESM	Failure rate	Complexity	Safety	TRL	Value Index
Multifiltration	4	2	1	5	5	2.812
RO	1	1	4	4	2	2.333

The technologies selected from these trade studies are: oxygen high pressure tank, nitrogen high pressure tank, 4BMS, Sabatier, SPWE, VCD and Multifiltration. After the trade studies, the selected technologies are modeled in Capella and integrated into the whole architecture, creating the related functions, functional exchanges, Physical Components, Physical Links, and Physical Paths. Figure 76 shows a portion of the PAB diagram related to the AR technologies. It is possible to note the functions, functional exchanges, Physical Components, and Physical Links created to implement in the model the selected technologies. Each alternative considered in the trade studies is integrated into the system differently. For example, the Sabatier process for CO_2 reduction technology requires CH_4 storage, while the Bosch process requires C storage. Therefore, understanding how a specific technology is integrated into the system is key in the design process. The following sections will describe the overall system configuration, providing a clearer understanding of the technologies' complete integration.

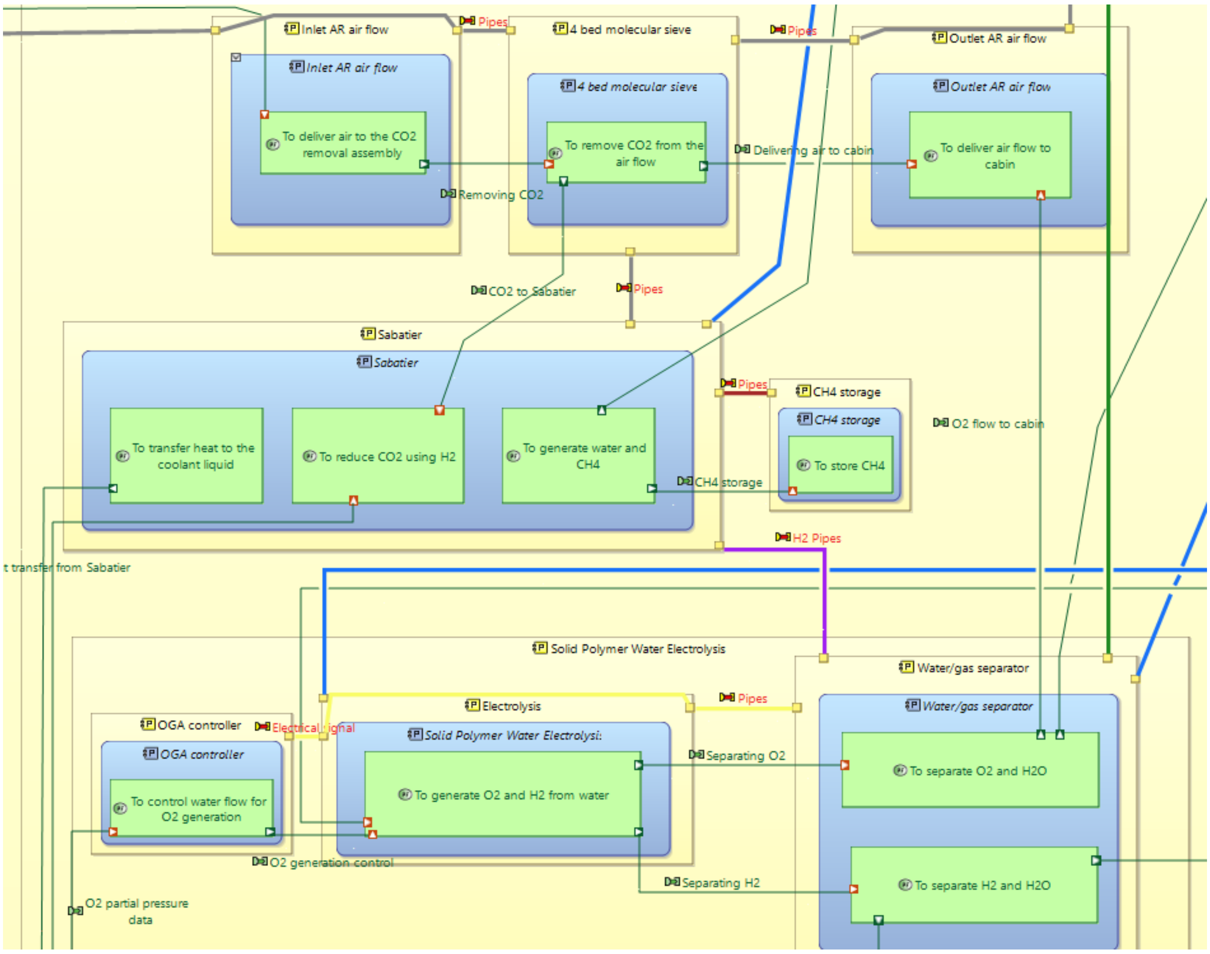


Figure 76: Part of the PAB diagram.

Therefore, after completing the various trade studies, activities related to Physical Architecture are performed to define the initial configuration of the ECLSS. The following section will describe all the diagrams created to support the process.

Because the design process is iterative by nature, configurations defined in the initial phases may be modified as the process evolves. Later stages may include additional trade studies that use more advanced analytical methods or simulation tools to refine the design and support decision-making.

During the definition of the architecture, different system requirements elements are created and allocated to different Node Physical Component. As shown in Figure 77, the ECLSS requirements are divided into different folders, each one related to an ECLSS subsystem: Atmosphere Control and Supply (ACS), Temperature and Humidity Control (THC), Atmosphere Revitalization (AR), Waste Management (WM), Food Storage and Preparation (FSP), Fire Detection and Suppression (FDS) and Water Recovery and Management (WRM). The name, ID, text, requirement type, status, and priority have been defined for each requirement. These characteristics can be modified during the design process. For example, the status of each requirement can be evaluated using the V-HAB simulation or other simulation and analysis tools. Figures 78 and 79 show the requirements created during the process.

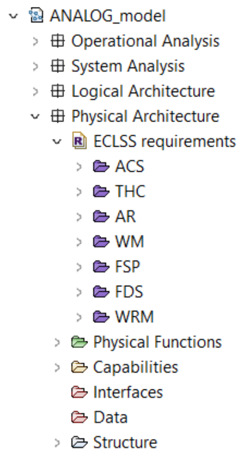


Figure 77: Requirement element folders.

	ReqIFIdentifier	ReqIFText	Priori...	Status
	R-FUN-ECLSS-ACS-001	The system shall control the total atmospheric pressure in the crew cabin to remain close to the specified target pressure.	High	Work in progress
	R-FUN-ECLSS-ACS-002	The system shall vent the cabin atmosphere as necessary to prevent overpressure.	High	Work in progress
	R-FUN-ECLSS-ACS-003	The system shall provide enough resources to compensate the atmospheric leakage during nominal operation and for a decompression event.	High	Work in progress
	R-FUN-ECLSS-ACS-004	The system shall add nitrogen to the cabin atmosphere as needed to compensate for leakage losses.	High	Work in progress
	R-FUN-ECLSS-ACS-005	The system shall add nitrogen to the cabin atmosphere to restore nominal conditions following a decompression event.	High	Work in progress
	R-FUN-ECLSS-ACS-006	The system shall control the oxygen partial pressure in the crew cabin to remain close to the specified target pressure.	High	Work in progress
	R-FUN-ECLSS-ACS-007	The system shall add oxygen to the cabin atmosphere as needed to compensate for leakage losses.	High	Work in progress
	R-FUN-ECLSS-ACS-008	The system shall add nitrogen to the cabin atmosphere to restore nominal conditions following a decompression event.	High	Work in progress
	R-FUN-ECLSS-ACS-009	The system shall monitor the total atmospheric pressure in the cabin.	High	Work in progress
	R-FUN-ECLSS-ACS-010	The system shall distribute O2 and N2 for systems and payload	High	Draft
	R-FUN-ECLSS-THC-001	The system shall maintain the atmospheric temperature in the crew cabin between 291.5 K and 299.8 K during normal operations.	High	Work in progress
	R-FUN-ECLSS-THC-002	The system shall allow the crew to select the atmospheric temperature within the acceptable operational range.	High	Work in progress
	R-FUN-ECLSS-THC-003	The system shall remove sensible heat from the cabin atmosphere as needed during normal operations.	High	Work in progress
	R-FUN-ECLSS-THC-004	The system shall maintain the atmospheric relative humidity in the crew cabin within the range of 25% to 70%, regardless of the current mission phase.	High	Work in progress
	R-FUN-ECLSS-THC-005	The system shall remove moisture from the cabin atmosphere as needed during normal operations.	High	Work in progress
	R-FUN-ECLSS-THC-006	The system shall ensure that the ventilation of the cabin atmosphere maintains airflow within defined nominal ranges during normal operations.	High	Draft
	R-FUN-ECLSS-THC-007	The system shall remove heat to support fire detection and suppression operations.	High	Draft
	R-FUN-ECLSS-THC-008	The system shall remove airbone particulate contaminats and microorganisms.	High	Draft

Figure 78: ACS and THC requirements.

	ReqIFIdentifier	ReqIFText	Priority	Status
	R-FUN-ECLSS-AR-001	The system shall maintain the CO2 partial pressure below a specified threshold under nominal conditions.	High	Work in progress
	R-FUN-ECLSS-AR-002	The system shall remove gaseous atmospheric contaminants.	High	Work in progress
	R-FUN-ECLSS-AR-003	The system shall reduce the CO2 to generate water.	High	Work in progress
	R-FUN-ECLSS-AR-004	The system shall generate O2 from water.	High	Work in progress
	R-FUN-ECLSS-AR-005	The system shall measure the partial pressures of the gases present in the cabin atmosphere.	High	Work in progress
	R-FUN-ECLSS-WM-001	The system shall collect waste and urine	High	Work in progress
	R-FUN-ECLSS-FSP-001	The system shall supply food to the crew as required.	High	Work in progress
	R-FUN-ECLSS-FDS-001	The system shall detect and suppress fires within the crew cabin.	High	Work in progress
	R-FUN-ECLSS-WRM-001	The system shall collect and supply potable water	High	Work in progress
	R-FUN-ECLSS-WRM-002	The system shall control the water quality.	High	Work in progress
	R-FUN-ECLSS-WRM-003	The system shall collect waste water	High	Work in progress
	R-FUN-ECLSS-WRM-004	The system shall distribute water to the crew, payload and systems.	High	Work in progress
	R-FUN-ECLSS-WRM-005	The system shall process waste water into potable water.	High	Work in progress
	R-FUN-ECLSS-WRM-006	The system shall process urine into waste water.	High	Work in progress
	R-FUN-ECLSS-WRM-007	The system shall process brine into water vapor.	High	Work in progress

Figure 79: AR, WM, FSP, FDS and WRM requirements.

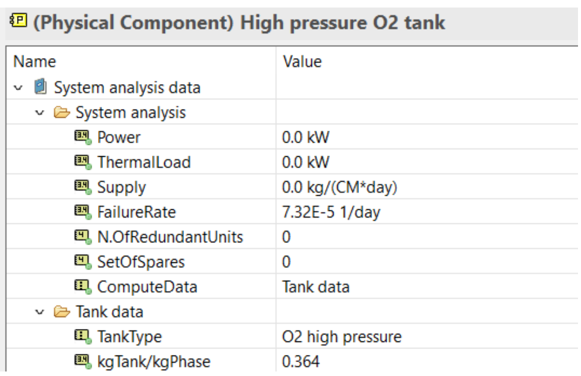
5.2.2 ESM and Reliability Analysis

After the initial system configuration is defined, the model is continuously refined using integrated analysis and simulation tools, which provide valuable insights into the system performance. This approach offers a simple, effective way to evaluate the system directly from the model.

Therefore, the configuration of the system is updated and verified continuously using the ARCADIA methodology, integrated with engineering analysis tools. These tools can also be used to evaluate several system configurations, allowing designers to assess the most effective one.

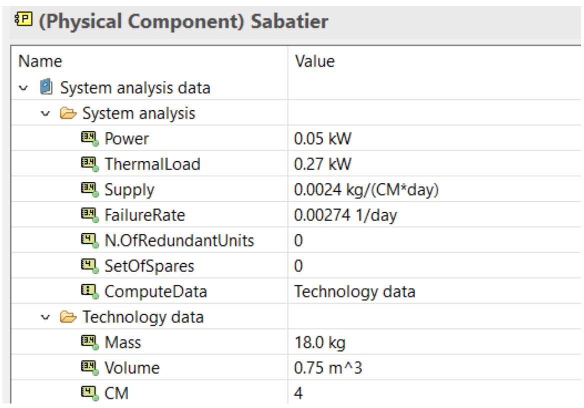
For the ECLSS model developed in this work, after defining the first system configuration, the Property Values related to the data of each technology represented by the Physical Node Component are added. Thus, all the necessary data for the implemented analysis and simulation has been included in the model.

Figures 80 and 81 show examples of Property Values associated with two Physical Node Components: the high-pressure O_2 tank and the Sabatier. These values are required for the ESM and reliability analyses. For each technology in the system configuration, the necessary values for the analysis are assigned. The data used in the model are available in the database (see Appendix B). Section 4.1.4 provides a detailed description of the Property Values needed for the analysis, as well as the procedure to compute the ESM and the Pr(LOC) over time for the Capella model.


(Physical Component) High pressure O2 tank

Name	Value
System analysis data	
System analysis	
Power	0.0 kW
ThermalLoad	0.0 kW
Supply	0.0 kg/(CM*day)
FailureRate	7.32E-5 1/day
N.OfRedundantUnits	0
SetOfSpares	0
ComputeData	Tank data
Tank data	
TankType	O2 high pressure
kgTank/kgPhase	0.364

Figure 80: High pressure O_2 tank: system analysis Property Values


(Physical Component) Sabatier

Name	Value
System analysis data	
System analysis	
Power	0.05 kW
ThermalLoad	0.27 kW
Supply	0.0024 kg/(CM*day)
FailureRate	0.00274 1/day
N.OfRedundantUnits	0
SetOfSpares	0
ComputeData	Technology data
Technology data	
Mass	18.0 kg
Volume	0.75 m^3
CM	4

Figure 81: Sabatier: system analysis Property Values

As has been described in section 4.1.4, important information about the system can be obtained by performing this kind of analysis of the system configuration defined in the Physical Architecture. The analysis outputs are the ESM of the system and the Pr(LOC) over time. During the initial phases of the ECLSS design process, it is important to develop a system architecture that ensures the required performance and reliability levels throughout the mission duration with the minimum ESM [57].

This analysis provided important estimates of system reliability during the initial design phases. It can be used to determine design feasibility, evaluate different system configurations for trade studies, and determine the number of redundant units and sets of spare parts for each technology.

Figures 82 and 83 depict the results of the ESM and reliability analyses performed directly in Capella. These analyses are related to the system configuration defined in previous steps. In the first configuration, the Property Values for the number of set of spares and the number of redundant units are set to zero for all technologies.

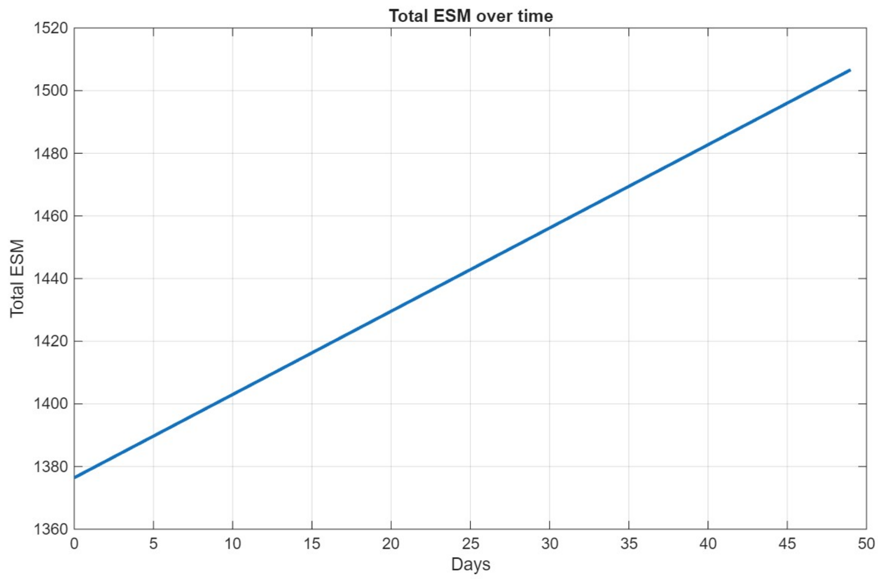


Figure 82: ESM over time of the system configuration.

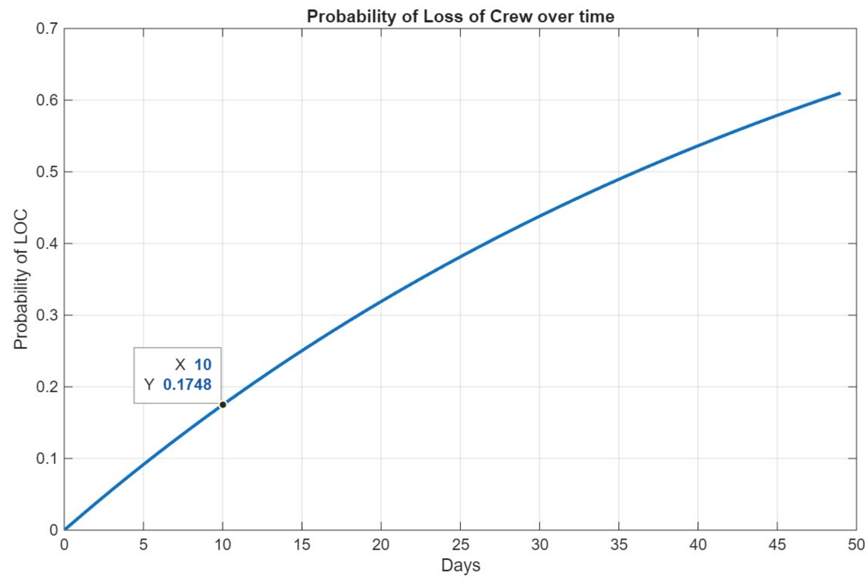


Figure 83: Pr(LOC)) over time of the system configuration.

As shown in Figure 82, the ESM of the system increases linearly with time due to the consumables and expendables required by the system architecture. Since the defined ECLSS is based on recycling technologies, the slope of the line is relatively small compared to an ECLSS relying on storage technologies, which require a great mass of the system for a long duration mission. For this configuration, the ESM for a mission duration of ten days is approximately 1400 kg, whereas for a mission duration[14] of fifty days, the ESM is around 1500 kg.

Figure 83 shows the variation of Pr(LOC) over time. Clearly, the probability of system failure is relatively high, even for short missions. Indeed, after ten days, the Pr(LOC) of the initial system configuration is 0.1748 (17.48%). As stated in Jones [57], a reasonable value for Pr(LOC) over the course of the entire human spaceflight mission is 0.01, while for the ECLSS it is 0.001. As the database (see Appendix B) clearly shows, ECLSS recycling technologies have a high failure rate and are subject to frequent failures. For this reason, the ECLSS on the ISS requires periodic replacement of subsystems with onboard ORUs to ensure uninterrupted operation [5]. As indicated in Section 2.3.4, the system's reliability can be increased including a set of spare for the different technologies and/or redundant units in the configuration. As described, this also increases the ESM of the system. Another option is to include technologies with low failure rate in the system architecture, or to incorporate highly reliable storage. However, adding storage increases the ESM, especially for long mission durations. For example, in the work of Jones [57], which focused on deep space human spaceflight missions, it was found that the most effective way to achieve the required reliability for long-duration missions is to combine storage and recycling technologies. Therefore, designers must conduct trade studies to determine the appropriate system configuration, as well as the necessary set of spares and redundant units, for each technology. The optimal system architecture depends heavily on the duration and reliability requirements of the mission. In summary, this analysis aims to identify a system configuration that ensures mission reliability while minimizing ESM.

As discussed, the ECLSS of the Analog Habitat primarily relies on regenerative technologies, which are appropriate for long-duration missions. However, since the Analog simulations are significantly shorter than actual space missions, the reliability requirements for the system are adjusted accordingly. Given that multiple Analog Missions will be conducted to support different research objectives, each simulation will have a limited duration. As a result, the reliability analysis in this study focuses on the first twenty days of operation. As shown in Figure 83, Pr(LOC) increases over time. Therefore, achieving a configuration that meets the reliability requirements for the Analog Missions is more feasible. This also enables the selection of system configurations with relatively low ESM. Additionally, the reliability requirements for the Analog Habitat are intentionally less stringent than those for a deep space mission. This decision is motivated by two factors: reducing the ESM and associated costs and the fact that, unlike in space, a system failure on Earth results in an emergency scenario that can be mitigated through an established evacuation plan. In such cases, the crew can be safely evacuated from the habitat.

As shown in Figures 84 and 85, a further analysis of different system configurations has been carried out. The figures compare the ESM and Pr(LOC) values over time for four

[14] As described in the previous section, it is possible to define the mission duration in days using the settings in the Capella model for this analysis.

configurations:

1. The initial configuration without any spare or redundant units.
2. One set of spares added to all technologies.
3. One redundant unit per technology.
4. One set of spares and one redundant unit are applied to all technologies[15].

This comparison was conducted to understand the impact of spares and redundancy on the ESM and reliability of the system. The figures show the value of these two metrics up to 1,000 days to better understand the differences.

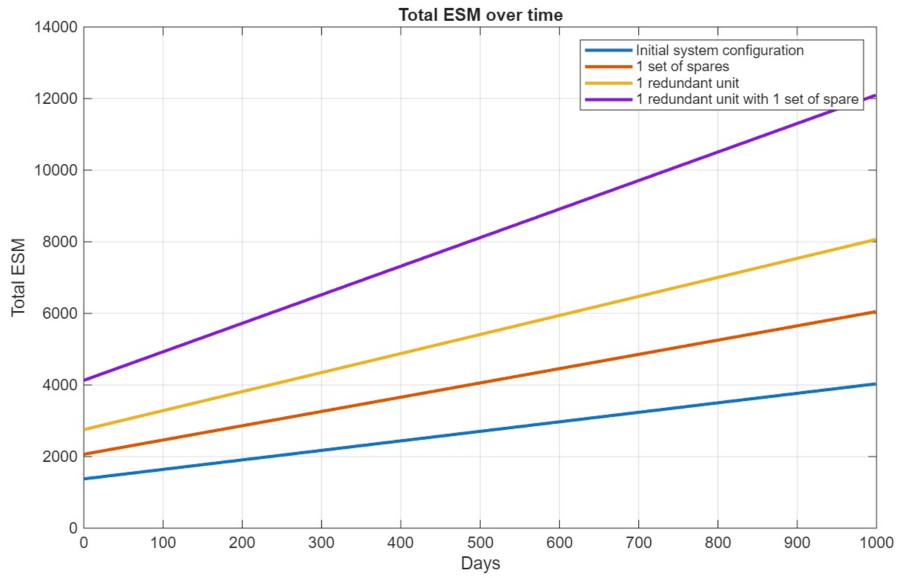


Figure 84: ESM over time for different configuration.

In the reliability model considered for this analysis, considering for a technology a set of spare increase its ESM by half while a redundant unit double its ESM. Figure 84 shows the ESM for the four configuration considered.

It is evident that including spares or redundancy in the model to increase the system's reliability also increases its ESM. Including spares results in a smaller increase in ESM than accounting for redundancy. Furthermore, the difference in ESM between configurations increases over time.

As shown in Figure 85, the Pr(LOC) is high since the first days of the mission for the initial system configuration. However, including redundancy or spares reduces the probability of a system failure. For missions shorter than 76 days, it can be observed that the configuration with redundancy results in a lower Pr(LOC) than the configuration with spares. For longer missions, however, the probability of failure in the redundant configuration increases significantly, reaching nearly 100% after 600 days. In contrast, the configuration with spares exhibits a slower, less abrupt increase in Pr(LOC) over time. For this reason, the Analog Mission, which lasts less than 76 days, may be better

[15] As described in Section 4.1.4, if a technology includes one redundant unit, then the full set of spares considered for the main unit is also included.

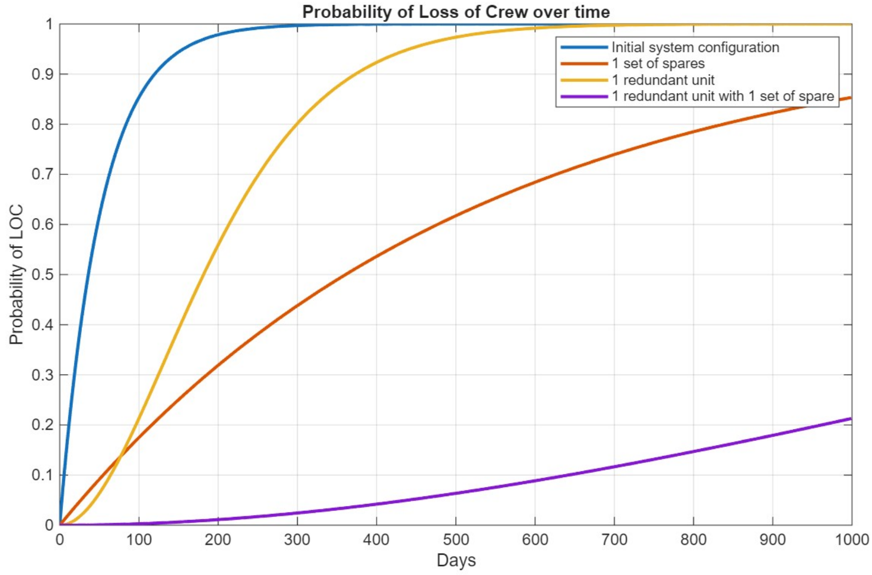


Figure 85: Pr(LOC) over time for different configuration.

suited for redundancy. However, this significantly increases the ESM and costs. Instead, considering redundancy and spares for all technologies results in a high ESM value but a very low Pr(LOC) over time. Indeed, this configuration reaches a Pr(LOC) value of 0.0028 at 100 days. This architecture therefore has high reliability for the duration of an Analog Mission, but significantly increases the ESM and costs.

Figures 86 and 87 compare two additional configurations, referred to as configurations A and B. In both cases, the number of set of spares or reduntant units assigned to each technology was determined by evaluating its mass, volume, power consumption, thermal load, and especially its failure rate. Technologies with higher failure rates were prioritized for including spares or redundant units. However, if a technology has a high ESM, the number of redundant units is limited to avoid an excessive ESM.

Configuration A includes the following technologies with one set of spares: Pressure Control Assembly (PCA), CCAA, 4BMS, Sabatier, SPWE, VCD, Process Control and Water Quality Monitor (PCWQM) and Multifiltration. All others have zero redundancy or spares.

Configuration B includes the following technologies with one set of spares: PCA, oxygen and nitrogen high pressure tank, CCAA, Major Constituent Analyzer (MCA), Trace Contaminant Control Subassembly (TCCS) and PCWQM. While the following technologies have a redundant unit with one set of spares: 4BMS, Sabatier, SPWE, VCD and Multifiltration. All others have zero redundancy or spares.

As Figures 86 and 87 show, Configuration B has a higher ESM than Configuration A but provides greater reliability. Specifically, after ten days, the difference in ESM between the two configurations is approximately 1200 kg. Meanwhile, the Pr(LOC) is 0.0233 for Configuration A and 0.0033 for Configuration B for a ten-day mission. The configuration A has a lower ESM than the fully redundant configuration and than the configuration with all technologies with a set of spares. Configuration B has a high ESM but a low Pr(LOC).

In addition to the increased costs associated with a higher ESM, adding redundant units generally involves higher costs than including spare parts.

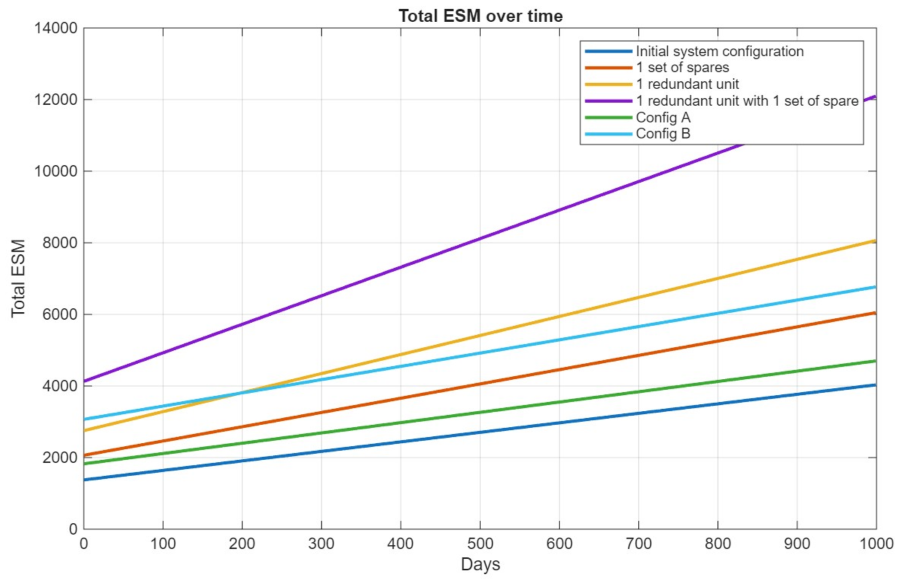


Figure 86: ESM over time for different configuration.

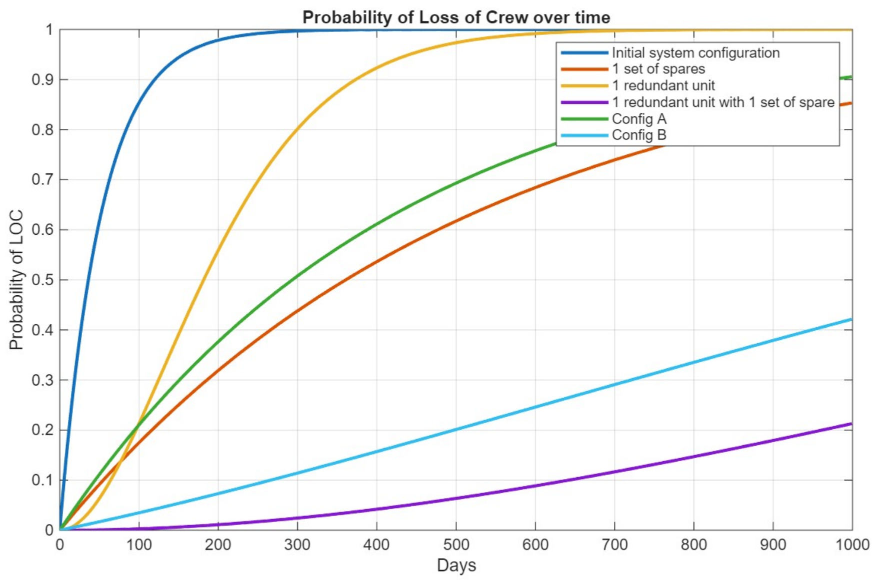


Figure 87: Pr(LOC) over time for different configuration.

Figure 88 shows a detailed view of the Pr(LOC) graphs over time, emphasizing the Pr(LOC) values of the various configurations for a 10-day mission. Table 14 shows the Pr(LOC) values for all configurations analyzed.

To summarize, the configurations with the lowest ESM are the initial system configuration, the configuration with a single set of spares for each technology, and Configuration A; however, these options are less reliable. The three configurations that include redundancy and set of spares offer the highest reliability, but they also have significantly higher ESM and overall system costs.

Based on this analysis, configuration A has been identified as the most appropriate for the Analog Habitat in question. This configuration has the lowest ESM and costs due to its exclusive use of spares rather than redundant units, except for the initial system configuration. For a short-duration analog mission, such as the one considered in this study, this system configuration provides the appropriate level of reliability throughout the mission.

These analog simulations last only a few hours or a few days, as shown in Figure 88, Configuration A exhibits a low Pr(LOC) for such short durations. This justifies proceeding with the design process based on Configuration A, as it offers the lowest ESM and overall cost while maintaining an adequate level of reliability.

Table 14: Values of Pr(LOC) for different configurations for a 10-day mission.

Configuration	**Pr(LOC)(10 days)**
Initial system configuration	0.1748
1 set of spares	0.0190
1 redundant unit	0.0029
1 redundant unit with 1 set of spares	2.9E-5
Config A	0.0233
Config B	0.0033

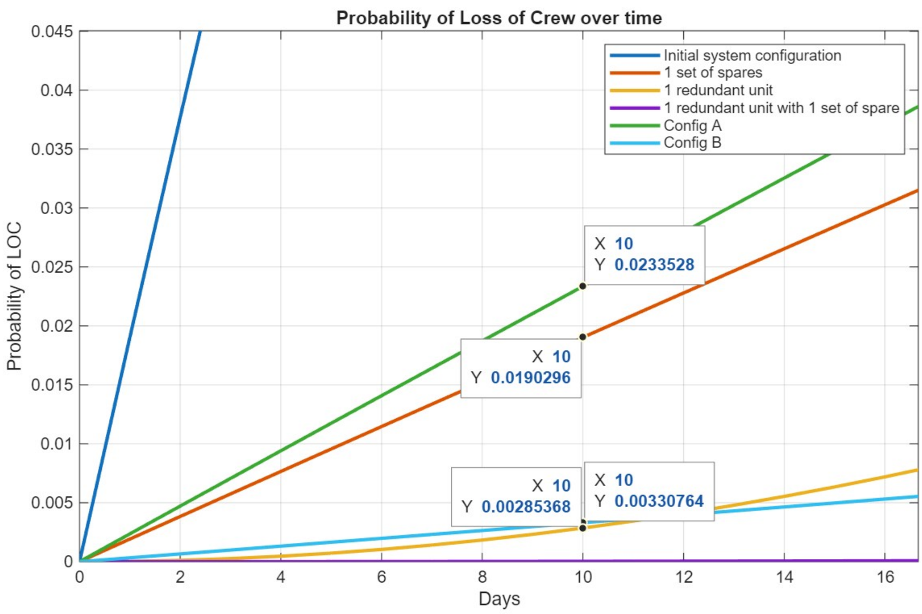


Figure 88: Zoomed-in view of the Pr(LOC) graphs over time.

Figures 89 and 90 illustrate the variation of the two ECLSS metrics, over time for the chosen configuration. The total ESM is 1829.12 kg for a one-day analog mission and 1883.77 kg for a 20-day mission. Similarly, Pr(LOC) increases from 0.00236 after one day to 0.04616 after twenty days.

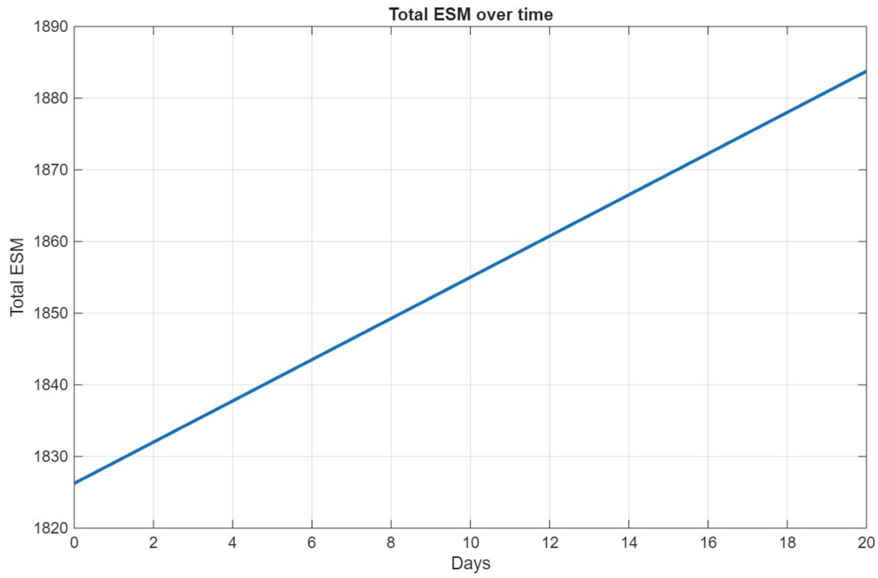


Figure 89: ESM over time for the chosen configuration.

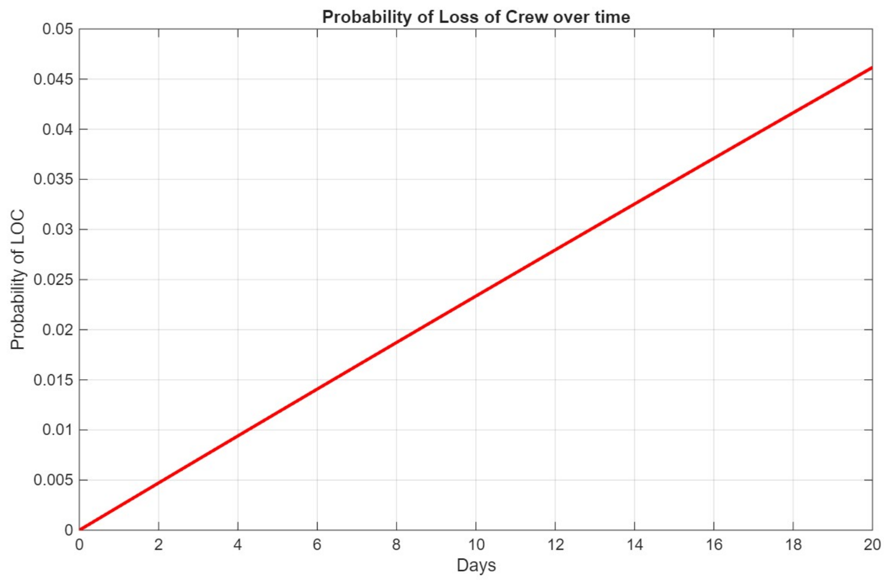


Figure 90: Pr(LOC) over time for the chosen configuration.

Figure 91 illustrates the variation in ESM over time for each ECLSS subsystem. For a mission duration of around 500 days, the subsystems with the highest ESM, in order from highest to lowest, are: Atmosphere Revitalization (AR), Water Recovery and Management (WRM), Temperature and Humidity Control (THC), Atmosphere Control and Supply (ACS), Waste Management (WM), and Fire Detection and Suppression (FDS).

Although the Food Storage and Preparation (FSP) subsystem initially contributes less, it shows the greatest increase in ESM over time. Around day 580, the FSP becomes the dominant contributor to total ESM, surpassing all other subsystems. The WRM and ACS subsystems also display significant growth, indicating their increasing impact as the mission duration extends.

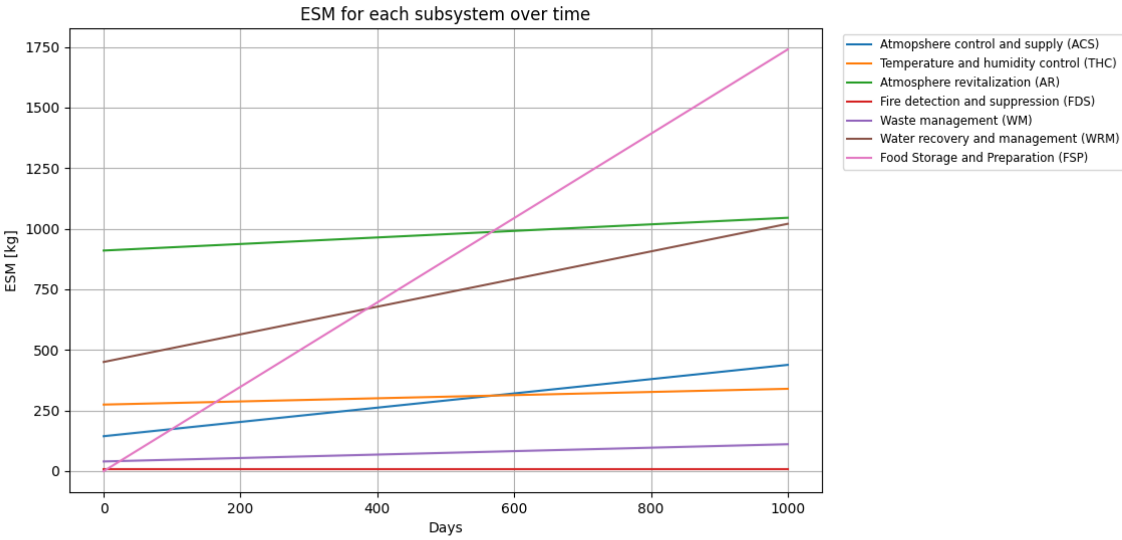


Figure 91: ESM over time for each ECLSS subsystem.

As demonstrated in this section, the tool that performs this analysis provides designers with meaningful information about the system. This tool can be applied continuously during the ECLSS design process to obtain important information about the system. Some applications include:

1. This analysis can be used to evaluate the feasibility of a system and mission. Once the proposed system configuration for a specific mission is analyzed, the results provide a useful estimation of the system's reliability and ESM, which can be used to assess the system's feasibility.
2. Different system configurations can be compared, especially during the conceptual design phase, by performing trade studies using computed metrics.
3. Once defined a system architecture, this tool can be used to estimate its reliability and update the system adding redundancy and spares to define the system with the desired characteristics.
4. It can be used to explore the system performance for different missions.
5. These analyses enable verification of imposed mass and reliability requirements.
6. This tool also identifies subsystems requiring special attention in subsequent design phases, especially with regard to maintenance planning and failure management.

As the design process progresses, it becomes essential to conduct detailed analyses, including failure mode identification, effects analysis, risk assessment, and maintenance strategy definition. The ESM and reliability evaluations presented here can provide a solid foundation for these future steps.

5.2.3 ECLSS Dynamic Simulations

After defining the system architecture in Capella with the activities related to the Physical Architecture layer of the ARCADIA methodology, it is possible to perform dynamic simulations of the system using V-HAB. The tool developed in this work allows the V-HAB dynamic simulation to be started directly from within the Capella tool. This approach minimizes errors in the V-HAB model definition and decreases the time needed to update the model when the system configuration changes in Capella. Thus, the tool offers a consistent, automated approach to support the system architecture definition with the MBSE methodology.

As described in Section 4.1.5, the tool developed in this work allows designers to execute multiple dynamic simulations of the system for a given mission scenario. These simulations allow for the analysis of key aspects of the system, such as robustness, performance, stability, and controllability. The results can support a variety of systems engineering activities, including trade studies between different architectural options, requirement verification, system properties assessment, and mission feasibility analysis. They also contribute to the continuous verification and validation of the system throughout the development process. These simulations provide a deeper understanding of system behavior under varying conditions, enhancing decision-making and strengthening the MBSE approach.

As described in the previous section, after defining the architecture, it is possible to use the PVMT to add the necessary data to each technology to perform the dynamic simulation of the system. After defining the architecture with all the necessary technology information for the simulation, the model can be enriched with mission scenario data and the simulation can be initiated using the tool developed in this work. When the dynamic simulation code is executed, the Capella system model is automatically converted into a V-HAB model, and the simulation can start.

First ECLSS Simulation

The first simulation conducted for the ECLSS architecture, described in the previous sections, involves a seven-day Analog Mission with two crew members inside the module.

Table 15 shows the Property Values defined in the *settings* constraint, related to the key parameters of the simulation. For this first analysis has been chosen to simulate the sea level atmosphere inside the module.

The desired partial pressure values defined in the model serve as reference inputs for the ECLSS control systems. As will be explained in the next section, the OGA uses the difference between the actual oxygen partial pressure and the ratio $\frac{P_{O_2}}{P_{total}}$ and their respective reference values to regulate oxygen production. The OGA then increases or decreases the amount of oxygen generated and injected into the cabin to minimize the error. Similarly, the PCA monitors errors in oxygen and nitrogen partial pressures and introduces the necessary amounts of each gas from their respective tanks. Temperature regulation is managed by the CCAA, which employs a PID controller to actuate the Temperature

Control and Check Valve (TCCV), aiming to minimize the difference between the actual and desired temperature.

As shown in Table 15, the model also allows the user to specify the initial food mass storage, average crew height and age, as well as scheduled times for breakfast, lunch, and dinner.

Table 15: System Simulation settings.

Parameter	**Value [Unit]**
Desired $\frac{P_{O_2}}{P_{total}}$	0.207 [-]
Desired total pressure	101325.0 [Pa]
Desired oxygen partial pressure	21000.0 [Pa]
Desired nitrogen partial pressure	80000.0 [Pa]
Desired carbon dioxide partial pressure	325.0 [Pa]
Desired temperature	293.0 [K]
Number of crew members	2 [-]
Initial food mass storage	100.0 [kg]
Total atmosphere habitat volume	90.0 [m^3]
Simulation duration	7.0 [days]
Mean crew height	1.8 [m]
Mean crew age	28 [years]
Breakfast time	1 [hour]
Lunch time	6 [hours]
Dinner time	15 [hours]

A Physical Actor has been created for each crew member in the model and assigned the properties that define their crew planner, as shown in Table 16. These simulations can also be used to establish the crew planner during the design process. If the model includes different modules of the habitat, it is possible to assign crew members to specific modules.

Table 16: Crew Member Planner Settings.

Parameter	**Crew Member 1**	**Crew Member 2**
Exercise start time	5.0 [h]	9.0 [h]
Exercise duration	0.5 [h]	0.5 [h]
Exercise intensity	0.75% of VO_2 max	0.75% of VO_2 max
Sleep start time	16.0 [h]	16.0 [h]
Sleep duration	8.0 [h]	8.0 [h]

Table 17 reports the initial values of the partial pressures of oxygen, nitrogen, and carbon dioxide, as well as the initial relative humidity, cabin leakage rate, and internal heat generated by operating electronics inside the cabin.

Table 17: Initial Cabin Conditions.

Parameter	Value
Initial Partial pressure of O_2	21000.0 [Pa]
Initial Partial pressure of N_2	80000.0 [Pa]
Initial Partial pressure of CO_2	325.0 [Pa]
Initial relative humidity	0.4 [-]
Leakage rate	3.0×10^{-6} $[\frac{kg}{s}]$
Heat source	100.0 [W]

As described in Section 4.1.5, all physical storage components in the model must be assigned the necessary information to accurately define the corresponding V-HAB elements. For the high-pressure gas tanks has been considered a pressure of 1E7 Pa and a volume of 2 m^3 for both oxygen and nitrogen. In this initial simulation, the water tank is defined with an initial mass of 200 kg and a volume of 1 m^3. These dynamic simulations determine the necessary amounts of water, nitrogen, and oxygen for a given mission. Thus, these simulations help select the appropriate mass, pressure, and volume for the respective tanks.

The PID controller gain values used by the CCAA for temperature regulation are as follows:

- Proportional gain (P) = 3.42
- Integral gain (I) = 0.023
- Derivative gain (D) = 0

Based on the temperature variation inside the module during the simulation, these gains can be adjusted to achieve the desired dynamic response.

Moreover, in the Physical Path from both the oxygen and nitrogen tanks to the cabin, the flow rates are set to 8.82E-5 $\frac{kg}{s}$ for oxygen and 2.16E-4 $\frac{kg}{s}$ for nitrogen, respectively. These gases are injected into the cabin when the partial pressure of oxygen or nitrogen falls below a certain threshold. The specific threshold depends on the desired total cabin pressure.

In Capella, users must specify the properties of the coolant fluid required by technologies involving active thermal control. The following parameters are defined for the coolant store:

- Coolant store volume: 1 m^3
- Coolant store temperature: 277 K
- Coolant store mass: 1 kg
- Coolant store pressure: 100000 Pa

After the simulation is completed, time-series plots can be generated for all relevant system variables. These plots include key environmental parameters, such as temperature, partial pressures of gases, and relative humidity in the cabin, as well as system-level variables, such as the mass or pressure of fluids stored in tanks, flow rates between technologies, and the power consumption of each technology. Since each subsystem is specifically modeled in V-HAB, internal variables specific to each technology can be accessed and visualized . This level of detail allows for a detailed analysis of system-level performance and individual component behavior.

Total pressure: Figure 92 shows the total atmospheric pressure values inside the module during the simulation. Initially, the total pressure is 101325 Pa, decreasing to a stabilized value of approximately 99000 Pa after about two days. This behavior is mainly caused by the control systems that regulate the injection of oxygen and nitrogen into the cabin. Furthermore, if the total pressure exceeds the desired value by more than 4000 Pa, the PCA vents some of the atmosphere from the habitat to the outside to reduce the pressure and prevent overpressure. The total pressure remains close to the desired value, which indicates that the system effectively regulates the total atmospheric pressure inside the module. However, refining the control strategy could improve performance further and reduce deviations from the target pressure.

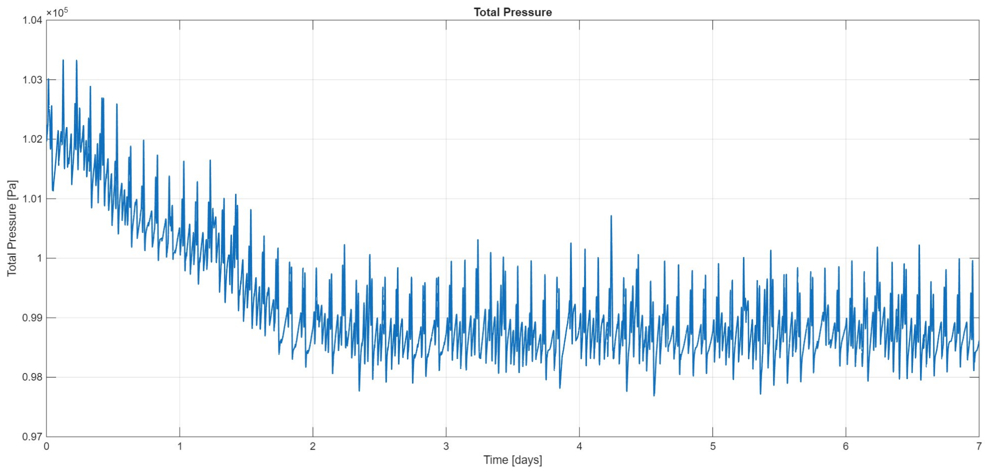


Figure 92: Total Pressure.

Oxygen partial pressure: During the simulation, the crew's metabolic activity primarily consumes oxygen, while a smaller amount is lost due to system leakage. Two different control system regulate the injection of oxygen inside the cabin:

- The PCA injects oxygen into the cabin when the partial pressure of oxygen falls below the defined threshold, which is the desired partial pressure minus 2000 Pa.
- The OGA generates and injects oxygen into the cabin when the partial pressure of oxygen drops below the defined threshold of the desired setpoint minus 2000 Pa. Conversely, when the partial pressure exceeds the setpoint plus 2500 Pa, the system significantly reduces the oxygen injection rate to mitigate fire hazards. For intermediate conditions, a nominal injection rate is applied.

Figure 93 shows the oxygen partial pressure during the simulation. The pressure increased because the oxygen production rate from the OGA is higher than the rate of oxygen consumption or loss. This behavior is primarily caused by the cabin's relatively large volume (90 m^3), which contains a significant amount of oxygen at the simulated pressure. Consequently, the crew's oxygen consumption rate only has a limited effect on the partial pressure of oxygen over time. In contrast, if the cabin had the same pressure but a smaller volume, the available oxygen mass would be lower. The same consumption rate would therefore lead to a much faster decrease in oxygen partial pressure.

Throughout the simulation, only the OGA control system was active because the partial pressure never dropped below the PCA's lower activation threshold. After about seven days, the partial pressure reached the upper limit of the OGA control system's range. As a result, the injection rate was decreased. The ECLSS effectively controls the pressure by maintaining the oxygen partial pressure close to the desired value. However, adjusting the control thresholds of the OGA and PCA systems could improve the overall performance and dynamic response of the system.

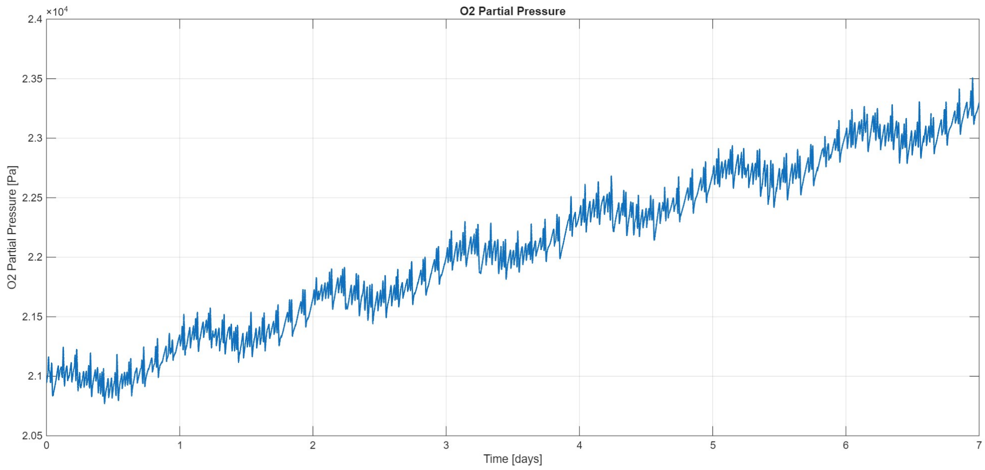


Figure 93: O_2 Partial Pressure.

Nitrogen partial pressure: Figure 94 depicts the evolution of the N_2 partial pressure during the simulation. The pressure decreases due to leakage, so the PCA injects nitrogen into the cabin when the total atmospheric pressure drops below the threshold. The threshold is defined as the desired total pressure minus 3000 Pa. Therefore, nitrogen is added to maintain the total pressure, as previously discussed. Adjusting this control system's characteristics could improve its ability to maintain total pressure closer to the target value.

Carbon dioxide partial pressure: Figure 95 depicts the evolution of the CO_2 partial pressure during the simulation. As the plot shows, the system can maintain carbon dioxide levels below 400 Pa. This is the acceptable limit for a short-duration mission, as discussed in Section 2.1.3. The crew generates CO_2, which reaches a peak during periods of physical activity. The 4BMS unit then removes the CO_2, and it is further reduced through the Sabatier reaction.

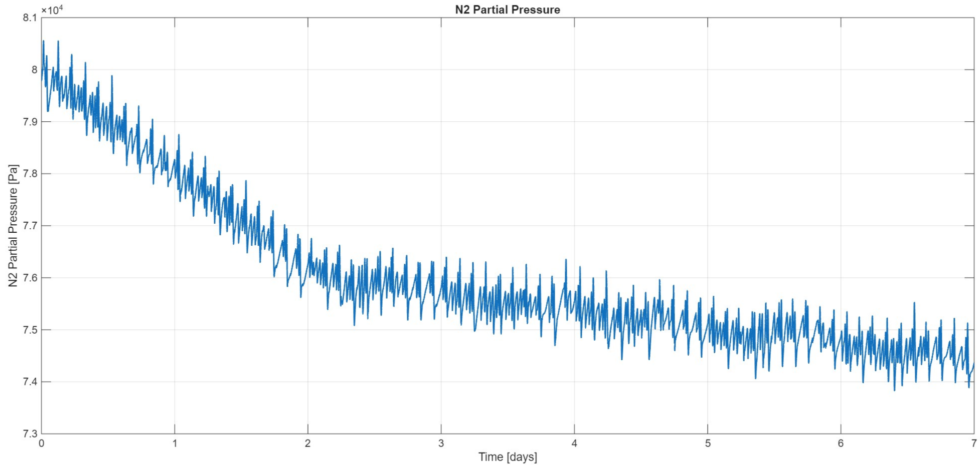


Figure 94: N_2 Partial Pressure.

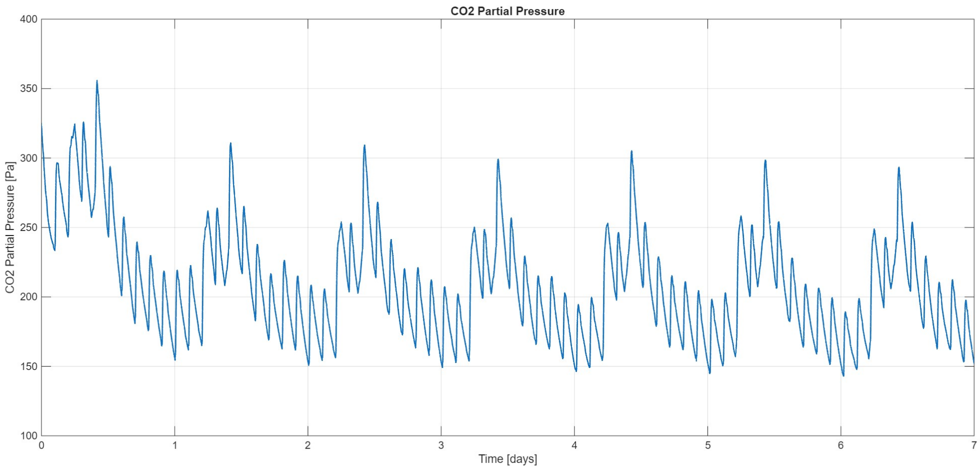


Figure 95: CO_2 Partial Pressure.

Temperature: Figure 96 illustrates the evolution of the cabin temperature during the simulation. The CCAA effectively maintains the temperature close to the target value, with oscillations generally remaining within a small range. Tuning the CCAA's PID gains could improve dynamic behavior by reducing the amplitude and frequency of the oscillations, thereby improving the system's dynamic response.

Relative humidity: Figure 97 illustrates the relative humidity levels inside the cabin during the simulation. Throughout the entire mission, the relative humidity remains below 70%, demonstrating the CCAA's effective humidity control. Both temperature and relative humidity values consistently fall within the comfort range defined in Section 2.1.3. The peaks in relative humidity during its evolution are related to the times when the crew performs physical activities.

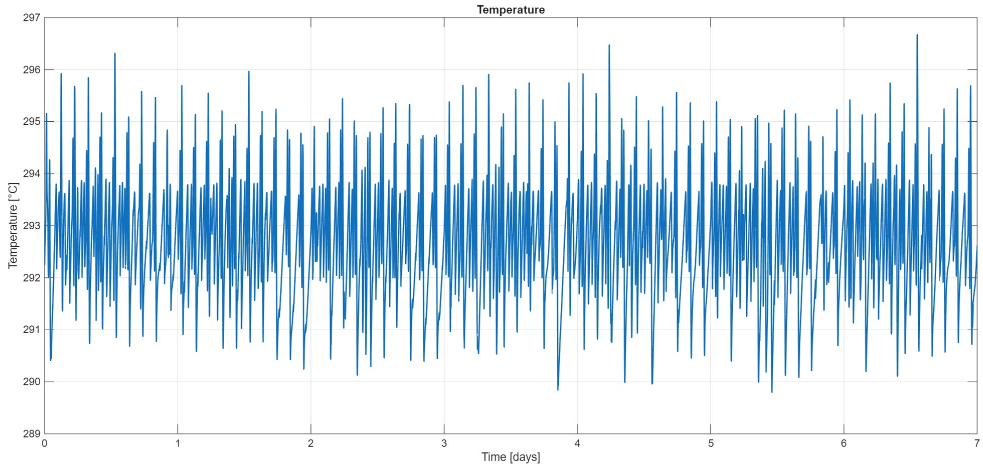


Figure 96: Temperature.

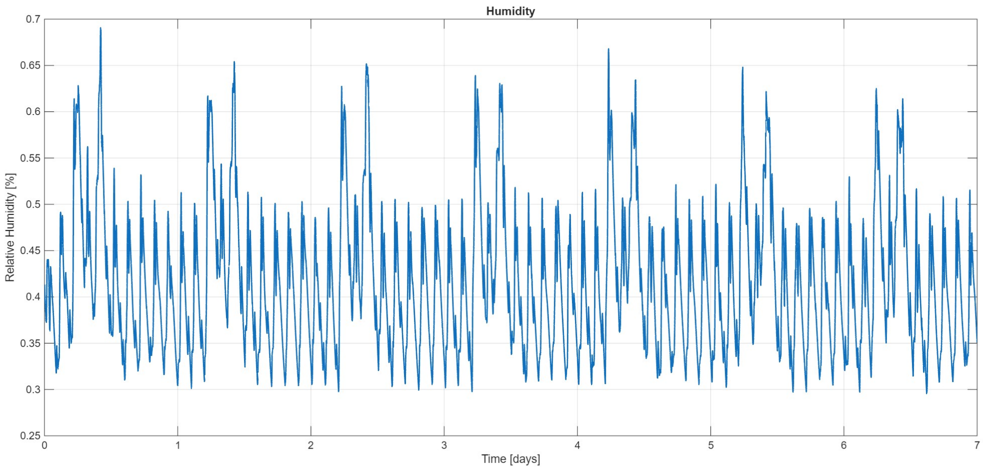


Figure 97: Relative Humidity.

Mass of N_2 in the high pressure tank: Figure 98 shows the decrease in nitrogen mass in the high-pressure tank during the mission. For the first two days, the nitrogen mass remains constant. Once the total cabin pressure falls below the predefined threshold, the PCA begins injecting nitrogen into the cabin to maintain pressure levels. Consequently, the nitrogen mass in the tank decreases as it is used to keep total pressure above the required limit. This simulation enables the evaluation of the necessary nitrogen mass for the mission.

Mass of water in the tank: Water is consumed in the habitat by the crew for drinking and hygiene purposes, as well as by the OGA, which uses it to produce oxygen through electrolysis. However, the system is equipped with regenerative technologies that enable a high degree of water recovery and reuse. Figure 99 illustrates the variation in water mass within the tank throughout the mission. Water is continuously consumed throughout the mission. The figure shows a periodic evolution of the water inside the tank. The increase in water mass correspond to the activation of the WPA. The WPA treats wastewater collected in the system and produces potable water, which is then returned to the tank for reuse. This analysis is essential for planning missions, as it allows engineers to estimate the minimum amount of water needed on board for a given mission duration. In this simulation, the initial water mass is set at 200 kg, decreasing to approximately 160 kg over the course of a seven-day mission. Therefore, the system must be capable of storing at least 40 kg, the minimum required amount, to ensure continuous operation throughout the mission.

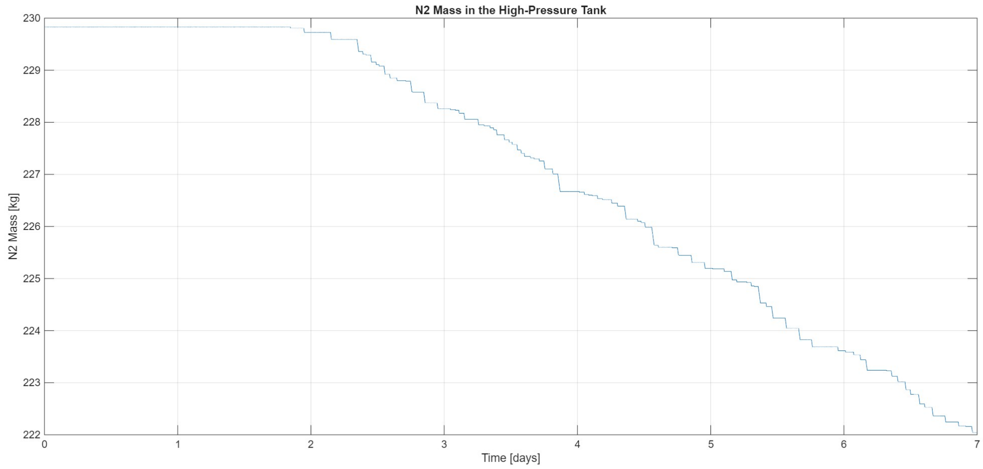


Figure 98: N_2 Mass in the High-Pressure Tank.

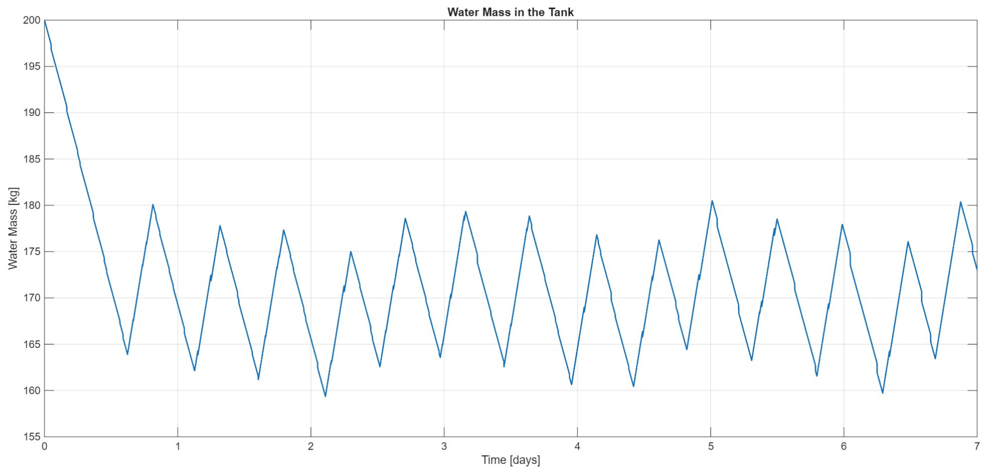


Figure 99: Water Mass in the Tank.

Power budget: Figure 100 presents the power budget of the system throughout the simulated mission. The power budget represents the system's total power consumption, which is calculated as the sum of the power used by each technology. This output is a key result of the simulation because it can be directly compared with the total available power during the mission, ensuring that energy demands remain within operational limits. Thus, this tool is useful for both system analysis and for the mission design. Figure 101 shows a zoomed-in view of the power budget during the first day of the simulation, providing a clearer visualization of the system's power consumption profile.

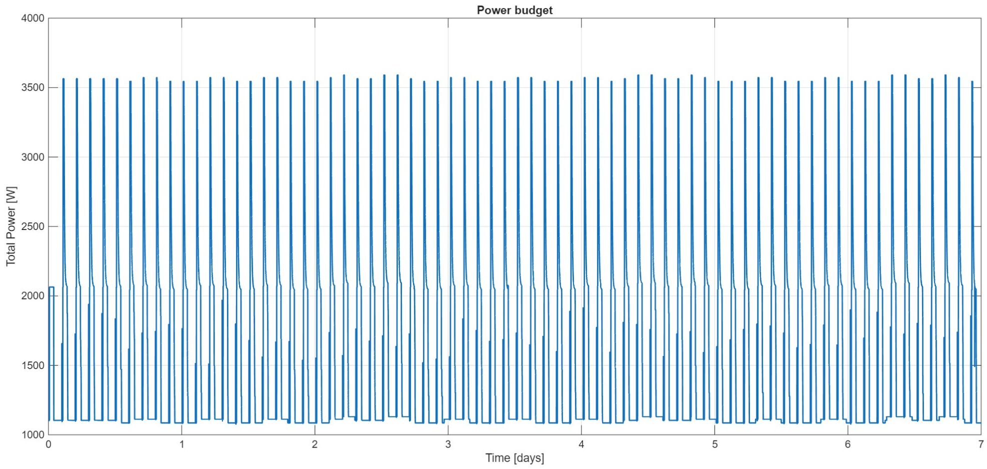


Figure 100: Power Budget Overview.

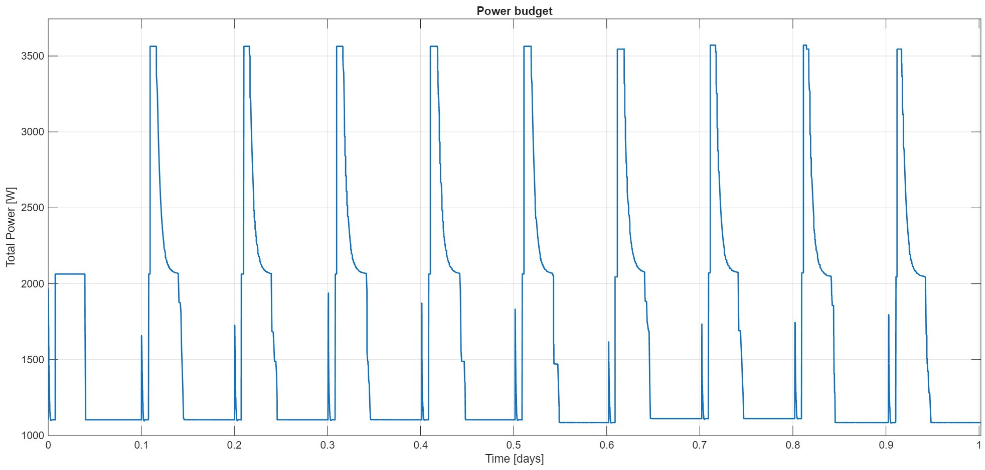


Figure 101: Zoomed View of the Power Budget.

The system's various technologies have different power consumption profiles throughout the simulation. Depending on their operational phase, each subsystem can be in standby mode, in which it consumes minimal power, or active mode, in which power consumption is at its maximum. Additionally, some technologies have variable power consumption profiles depending on the process being executed. For instance, the OGA's power consumption varies according to the electrical current used for oxygen production during electrolysis. Therefore, the power budget, determined by the activation patterns of each subsystem, exhibits a quasi-periodic profile. Total power consumption ranges from a minimum of approximately 1200 W to a maximum of around 3500 W. Accurately estimating this preliminary power budget is crucial for the initial design of the habitat's electrical power system.

Figures 102 and 103 show the power consumption of the main technologies within the system throughout the simulation. The components with the highest power demand are the SCRA and CDRA (specifically the 4BMS and Sabatier), followed by the OGA, CCAA, Brine Processor Assembly (BPA), WPA, and UPA. The CCAA and BPA exhibit constant power consumption throughout the simulation. In contrast, the OGA maintains a constant power consumption until the oxygen partial pressure exceeds the upper threshold. At this point, it switches to a minimal power state, indicating a reduction in oxygen generation. The SCRA and CDRA are activated several times during the simulation for short periods. In contrast, the UPA and WPA remain active for longer intervals.

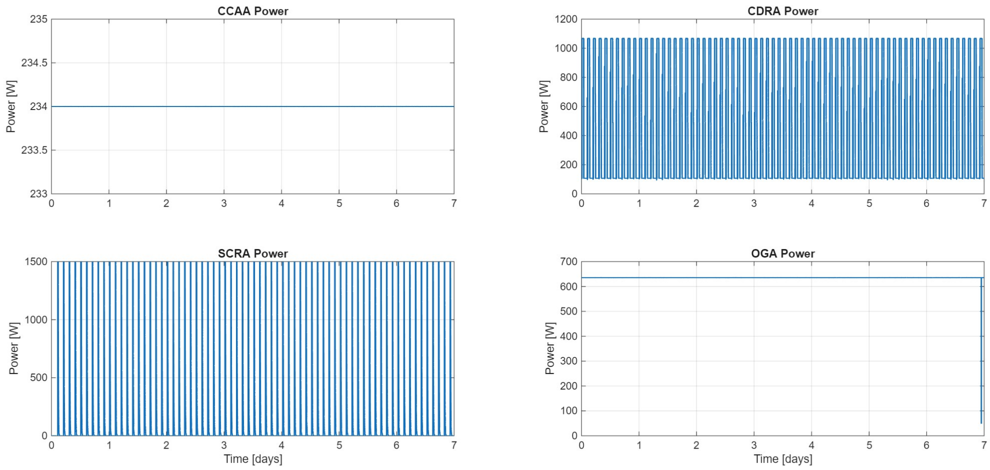


Figure 102: Power consumption of CCAA, CDRA, SCRA and OGA.

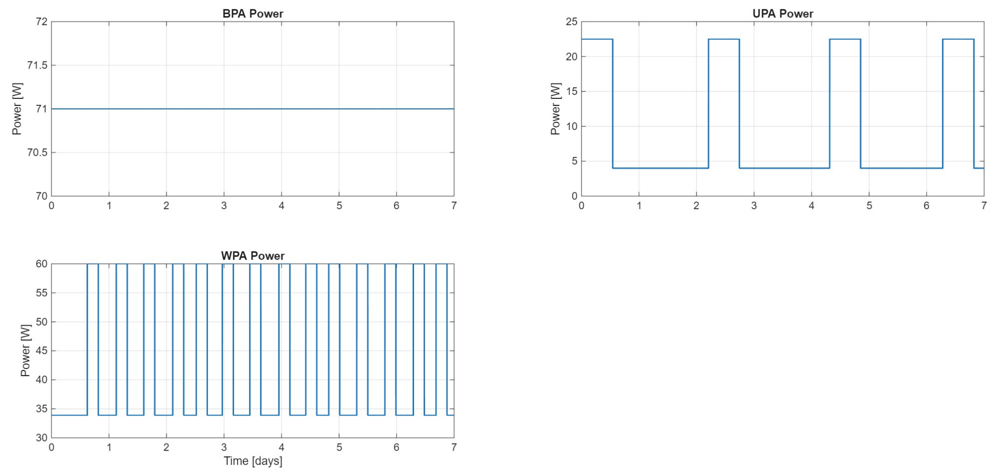


Figure 103: Power consumption of BPA, UPA and WPA.

PCA and OGA control system

The previous simulation provided valuable insights into the performance, stability, and controllability of the system. As discussed, adjusting the control logic of both the PCA and OGA can reduce deviation from the desired setpoints for total pressure, oxygen and nitrogen partial pressures.

The control logic is modified as follows:

- The PCA injects oxygen from the tank into the cabin when the partial pressure of oxygen drops below the desired value minus 500 Pa. It also injects nitrogen into the cabin when the total pressure falls below the desired value minus 1000 Pa. The PCA also controls atmospheric venting when the total pressure exceeds the desired value plus 4000 Pa.
- The OGA generates oxygen at its maximum power when the O_2 partial pressure drops below the desired value minus 1000 Pa. Decreased oxygen generation occurs when the partial pressure rises above the desired value plus 500 Pa.

These changes were implemented and a simulation was performed for a four-day mission using the same simulation settings of the previous analysis.

As Figures 104 through 105 show, the modified control logic for the two technologies enables the system to maintain the desired total pressure and partial pressures of O_2, N_2, and CO_2 throughout the mission with greater precision.

Figures 106 through 109 show the evolution of the main subsystems' power consumption, as well as the overall power budget. In particular, the OGA's power consumption profile highlights the effect of the new control logic; the OGA's power consumption decreases each time the oxygen partial pressure exceeds the defined threshold.

Therefore, the V-HAB simulation tool enables analysis of the system's controllability starting in the conceptual design phase. This allows for the early identification of control strategies that ensure stable and robust performance under varying mission conditions.

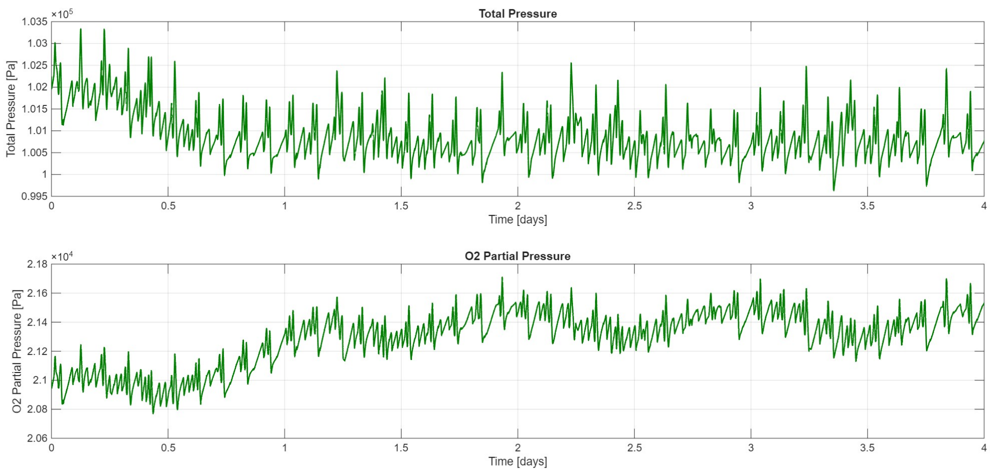


Figure 104: Total and O_2 Partial Pressure over Time.

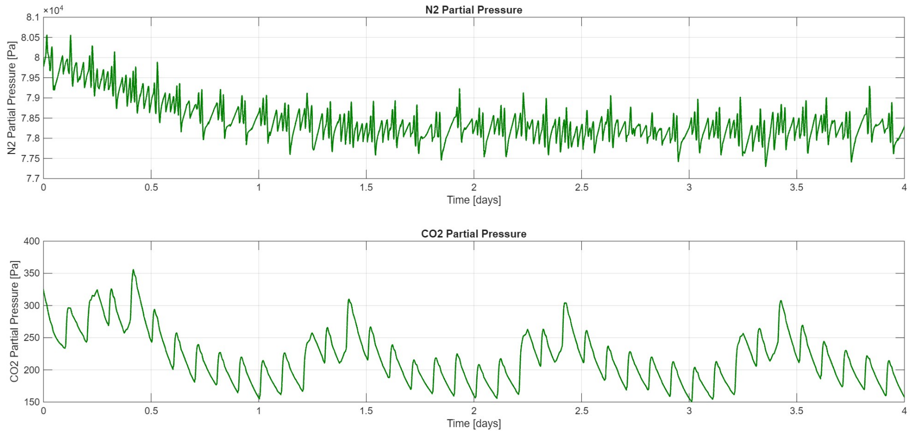


Figure 105: N_2 and CO_2 Partial Pressure over Time.

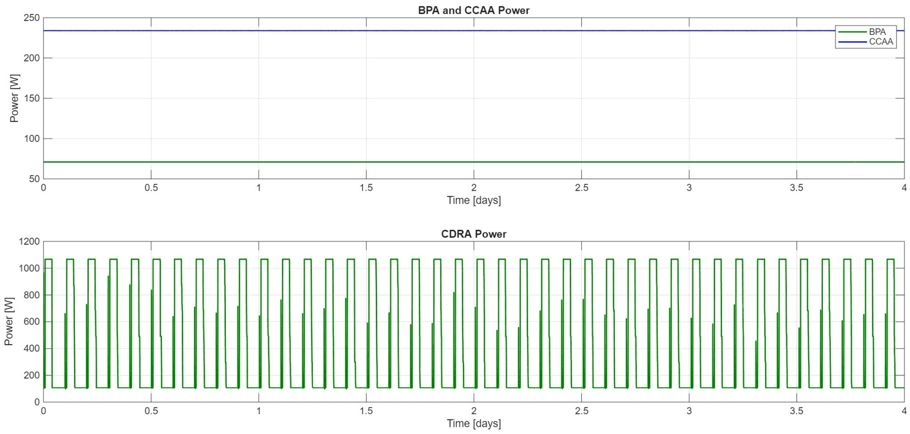


Figure 106: Power Consumption: BPA, CCAA, and CDRA.

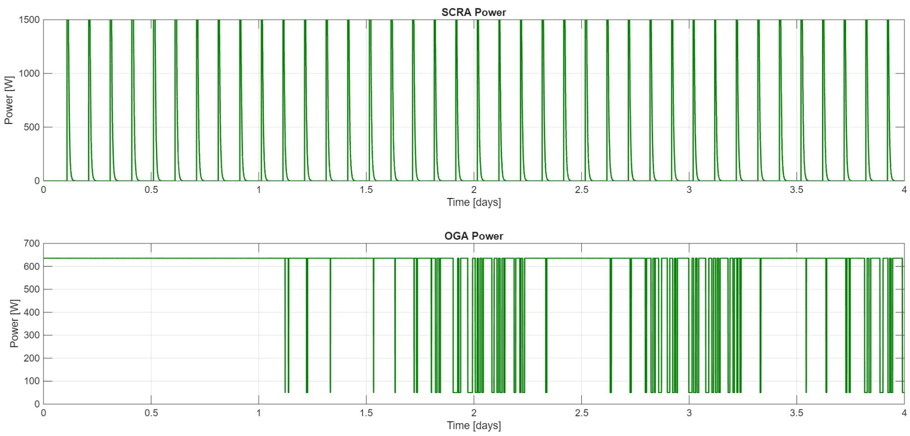


Figure 107: Power Consumption: SCRA and OGA.

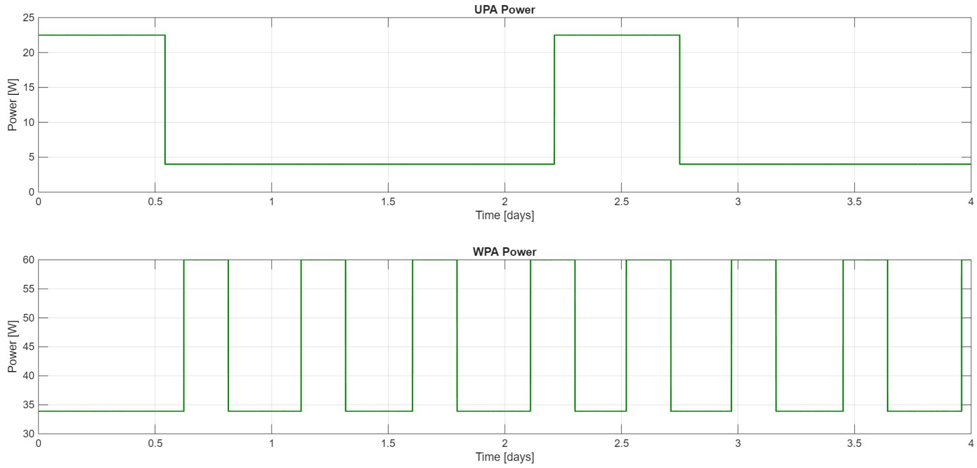


Figure 108: Power Consumption: UPA and WPA.

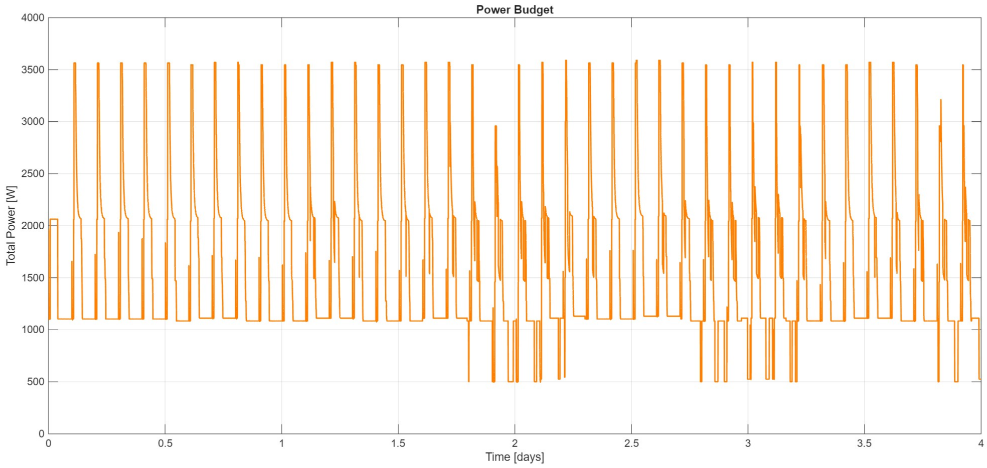


Figure 109: Power Budget over Time.

Simulations for different total pressure in the module.

The system's performance, stability, and robustness can be evaluated through various simulations, which can be conducted to assess different operating conditions and control strategies.

One of the main objectives of the Analog Habitat project is to simulate different total pressure conditions inside the habitat to enable various research studies. Consequently, the ECLSS must be capable of operating effectively under reduced pressure scenarios. Three different simulations were performed to assess the system's performance under these conditions. Based on the diagram in Section 2.1.3, which defines the acceptable range of total pressure and oxygen level to avoid human physiological issues, specific combinations of total and oxygen partial pressures were selected. These combinations are summarized in Table 18. The simulation is for a three-day mission, while the other settings are the same as in the previous simulation.

Table 18: Total pressure and oxygen partial pressure values for each simulation

Simulation	**Total Pressure [Pa]**	**O_2 Partial Pressure [Pa]**
Sim 1	101325	21000
Sim 2	89300	20539
Sim 3	79050	21343.5

As Figures 110 through 114 show, the variables evolve similarly across all three simulations. These simulations show that the system can perform its functions correctly, even in a cabin environment with reduced total pressure. Figures 110 through 112 show the evolution of total pressure, as well as the partial pressures of oxygen and nitrogen. The results show that the system is capable of controlling the pressure in each simulated cabin scenario.

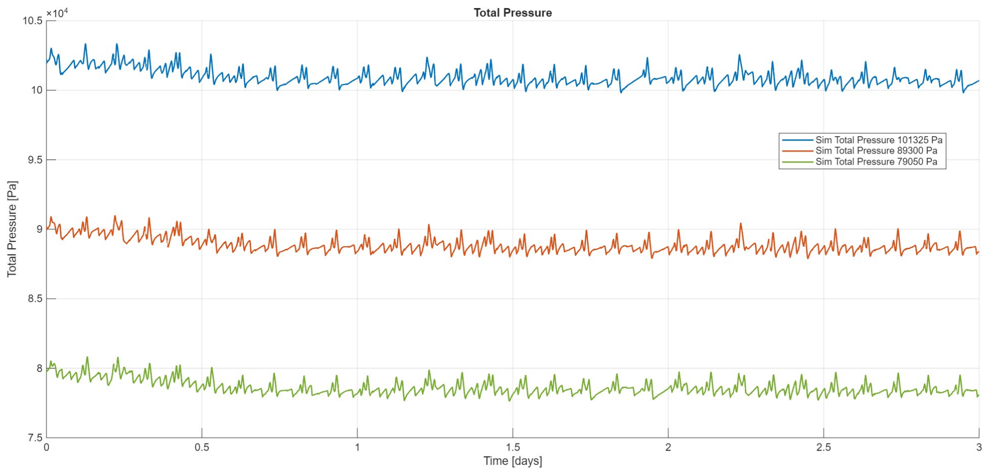


Figure 110: Comparison of total cabin pressure.

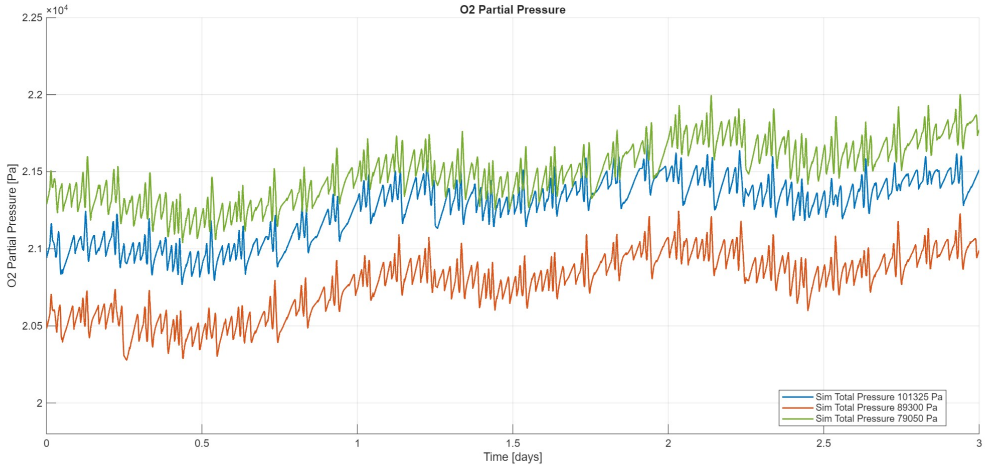


Figure 111: Comparison of O_2 partial pressure.

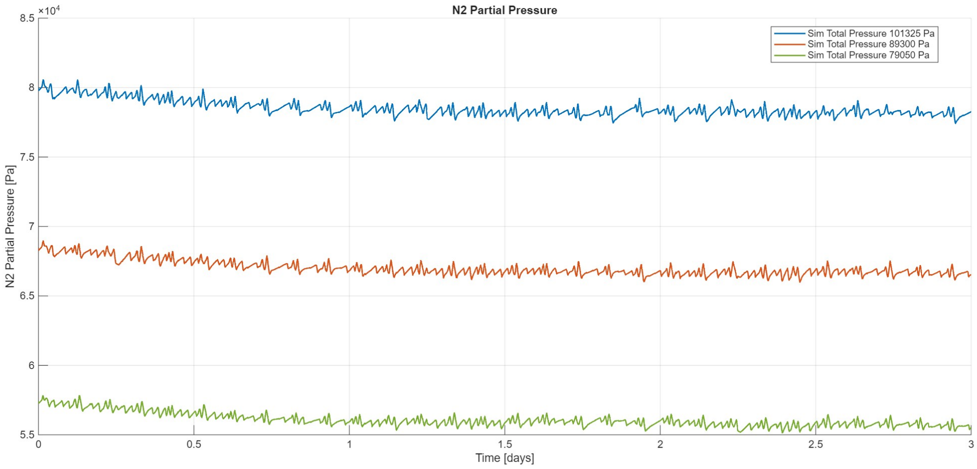


Figure 112: Comparison of N_2 partial pressure.

Figure 113 shows the carbon dioxide partial pressure for each simulation. The results indicate that, as cabin pressure decreases, the system can maintain lower levels of CO_2 in the atmosphere. This occurs because the airflow through the CCAA remains constant throughout the simulations. Since the 4BMS processes the air exiting the ECLSS to remove CO_2, a constant airflow at lower total pressure results in a lower CO_2 partial pressure. Future work should determine how each subsystem or technology operates under varying initial conditions where system properties (e.g., flow rates) adapt or change accordingly.

Figure 114 illustrates how the mass of nitrogen in the high-pressure tank decreases to maintain the desired total pressure inside the cabin. In each simulation, the total pressure drops below the control system threshold around the same time, activating the PCA to inject nitrogen and restore the pressure level. After three days, the total amount of nitrogen consumed is nearly the same across all three scenarios. However, higher simulated pressure levels result in greater nitrogen consumption. This suggests that increasing the target pressure would proportionally increase the nitrogen required to maintain stable conditions over time. Further insight into this behavior could be obtained by extending the simulation period to several more days or weeks. All simulations were performed under the assumption of a constant leakage rate. However, leakage is directly proportional to internal cabin pressure. Therefore, scenarios with higher cabin pressure would likely experience greater mass loss over time. Therefore, future simulations should consider pressure-dependent leakage equations to better capture the system's dynamic behavior under varying pressure conditions.

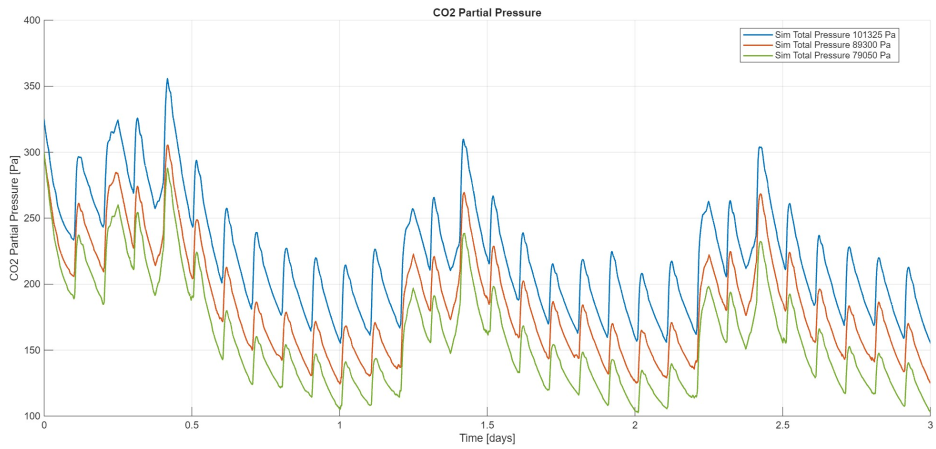


Figure 113: Comparison of CO_2 partial pressure.

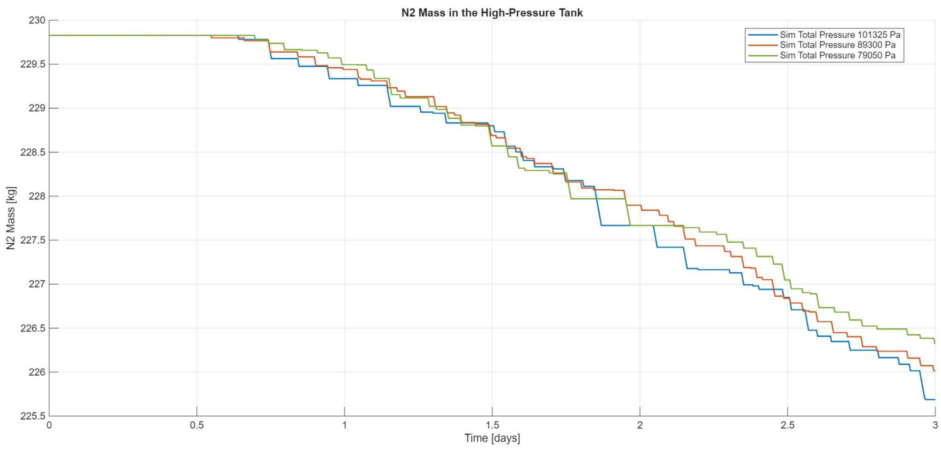


Figure 114: Comparison of N_2 mass in the high-pressure tank.

Figure 115 shows the power budget for all three simulations. Overall, the power consumption appears similar across the different cases, with the main difference being the time at which the OGA shuts down.

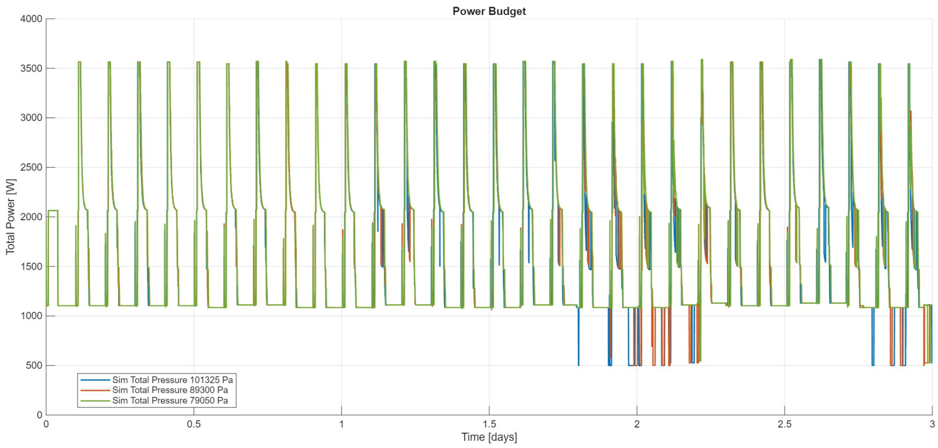


Figure 115: Comparison power budget.

Requirements verification

As discussed previously, the MBSE approach enables the elicitation of requirements during the definition of the system model. The previous section presented the requirements element created within the Physical Architecture layer of the ARCADIA methodology. The status of each requirement can be evaluated through simulations performed with the V-HAB tool. Using this integrated MBSE approach to continuously define and verify requirements allows for earlier detection of defects, reduces errors, decreases development time, and improves system understanding from the early design phases.

Therefore, during the preliminary phase of designing the ECLSS, each requirement defined in Capella can be verified using the results of the system architecture's dynamic simulation, as discussed earlier. For example, the simulation results confirm that the system is capable of fulfilling the requirement element allocated to the PCA that states, *"The system shall control the total atmospheric pressure in the crew cabin to remain close to the specified target pressure."* Consequently, its verification status in Capella can be set to "Reviewed."

Figures 116 and 117 show the requirement editing view in Capella, where the characteristics of a requirement element can be defined and modified. As discussed, based on the results of the dynamic simulations performed using V-HAB, the status of some requirements has been set to "Reviewed." The status of other requirements, which could not be verified using the analysis and simulation tools considered in this work, has been set to "Draft" or "Work in Progress."

Therefore, several requirements have been reviewed during this conceptual design phase. These requirements will be continuously verified and refined as the design progresses. This approach ensures consistency and traceability throughout the entire system design process.

	ReqIFIdentifier	ReqIFText	Status	Priority
	R-FUN-ECLSS-ACS-001	The system shall control the total atmospheric pressure in the crew cabin to remain close to the specified target pressure.	Reviewed	High
	R-FUN-ECLSS-ACS-002	The system shall vent the cabin atmosphere as necessary to prevent overpressure.	Reviewed	High
	R-FUN-ECLSS-ACS-003	The system shall provide enough resources to compensate the atmospheric leakage during nominal operation and for a decompression event.	Reviewed	High
	R-FUN-ECLSS-ACS-004	The system shall add nitrogen to the cabin atmosphere as needed to compensate for leakage losses.	Reviewed	High
	R-FUN-ECLSS-ACS-005	The system shall add nitrogen to the cabin atmosphere to restore nominal conditions following a decompression event.	Reviewed	High
	R-FUN-ECLSS-ACS-006	The system shall control the oxygen partial pressure in the crew cabin to remain close to the specified target pressure.	Reviewed	High
	R-FUN-ECLSS-ACS-007	The system shall add oxygen to the cabin atmosphere as needed to compensate for leakage losses.	Reviewed	High
	R-FUN-ECLSS-ACS-008	The system shall add nitrogen to the cabin atmosphere to restore nominal conditions following a decompression event.	Reviewed	High
	R-FUN-ECLSS-ACS-009	The system shall monitor the total atmospheric pressure in the cabin.	Reviewed	High
	R-FUN-ECLSS-ACS-010	The system shall distribute O2 and N2 for systems and payload	Draft	High
	R-FUN-ECLSS-THC-001	The system shall maintain the atmospheric temperature in the crew cabin between 291.5 K and 299.8 K during normal operations.	Reviewed	High
	R-FUN-ECLSS-THC-002	The system shall allow the crew to select the atmospheric temperature within the acceptable operational range.	Work in progress	High
	R-FUN-ECLSS-THC-003	The system shall remove sensible heat from the cabin atmosphere as needed during normal operations.	Reviewed	High
	R-FUN-ECLSS-THC-004	The system shall maintain the atmospheric relative humidity in the crew cabin within the range of 25% to 70%, regardless of the current mission phase.	Reviewed	High
	R-FUN-ECLSS-THC-005	The system shall remove moisture from the cabin atmosphere as needed during normal operations.	Reviewed	High
	R-FUN-ECLSS-THC-006	The system shall ensure that the ventilation of the cabin atmosphere maintains airflow within defined nominal ranges during normal operations.	Draft	High
	R-FUN-ECLSS-THC-007	The system shall remove heat to support fire detection and suppression operations.	Draft	High
	R-FUN-ECLSS-THC-008	The system shall remove airbone particulate contaminats and microorganisms.	Draft	High

Figure 116: Capella Requirement elements editing view: ACS and THC.

	ReqIFIdentifier	ReqIFText	Status	Priority
	R-FUN-ECLSS-AR-001	The system shall maintain the CO2 partial pressure below a specified threshold under nominal conditions.	Reviewed	High
	R-FUN-ECLSS-AR-002	The system shall remove gaseous atmospheric contaminants.	Draft	High
	R-FUN-ECLSS-AR-003	The system shall reduce the CO2 to generate water.	Reviewed	High
	R-FUN-ECLSS-AR-004	The system shall generate O2 from water.	Reviewed	High
	R-FUN-ECLSS-AR-005	The system shall measure the partial pressures of the gases present in the cabin atmosphere.	Draft	High
	R-FUN-ECLSS-WM-001	The system shall collect waste and urine	Reviewed	High
	R-FUN-ECLSS-FSP-001	The system shall supply food to the crew as required.	Reviewed	High
	R-FUN-ECLSS-FDS-001	The system shall detect and suppress fires within the crew cabin.	Draft	High
	R-FUN-ECLSS-WRM-001	The system shall collect and supply potable water	Reviewed	High
	R-FUN-ECLSS-WRM-002	The system shall control the water quality.	Draft	High
	R-FUN-ECLSS-WRM-003	The system shall collect waste water	Reviewed	High
	R-FUN-ECLSS-WRM-004	The system shall distribute water to the crew, payload and systems.	Draft	High
	R-FUN-ECLSS-WRM-005	The system shall process waste water into potable water.	Reviewed	High
	R-FUN-ECLSS-WRM-006	The system shall process urine into waste water.	Reviewed	High
	R-FUN-ECLSS-WRM-007	The system shall process brine into water vapor.	Reviewed	High

Figure 117: Capella Requirement elements editing view: AR, WM, FSP, FDS and WRM.

V-HAB Conclusion

As discussed in this section, the integrated V-HAB simulations in the MBSE approach provide designers with a powerful tool to support the ECLSS design process from the beginning of the conceptual design phase. In this work, the tool was used to verify the performance, stability, and robustness of the system, while also improving its controllability. Additionally, the results of these simulations supported the verification of system requirements. In addition to verifying system performance, stability, and controllability, this tool supports a wide range of system-level analyses throughout the design process. It enables the comparison of different ECLSS architectures, trade studies between different technologies, the evaluation of mission feasibility, and the assessment of design choices based on their impact on system performance in the desired mission scenario. The tool also enables sensitivity studies, such as evaluating how initial conditions or crew schedule planning affect system behavior. Furthermore, it can simulate different mission profiles to evaluate how the same system performs under varying operational conditions. These capabilities provide valuable insights into the system's robustness and stability across different contexts. Reliability and fault management can be explored by simulating system failures, such as the loss of specific technologies or increased cabin leakage. This helps identify failure modes and supports the early development of mitigation strategies. Finally, as previously discussed, the simulation provides the system's power budget for the specified mission. These data can be used to compare with available onboard energy to support habitat architecture-level trade-offs.

Several types of analyses can be conducted using V-HAB, providing information that can enhance the overall system design, beginning in the conceptual design phase. Automating the conversion of the Capella model into a V-HAB simulation model reduces errors and development time during the model definition phase. Therefore, integrating Capella with V-HAB allows for automated, consistent simulations that align with the system architecture. This supports efficient and reliable system analysis from the early design stages.

5.2.4 Preliminary ECLSS Architecture

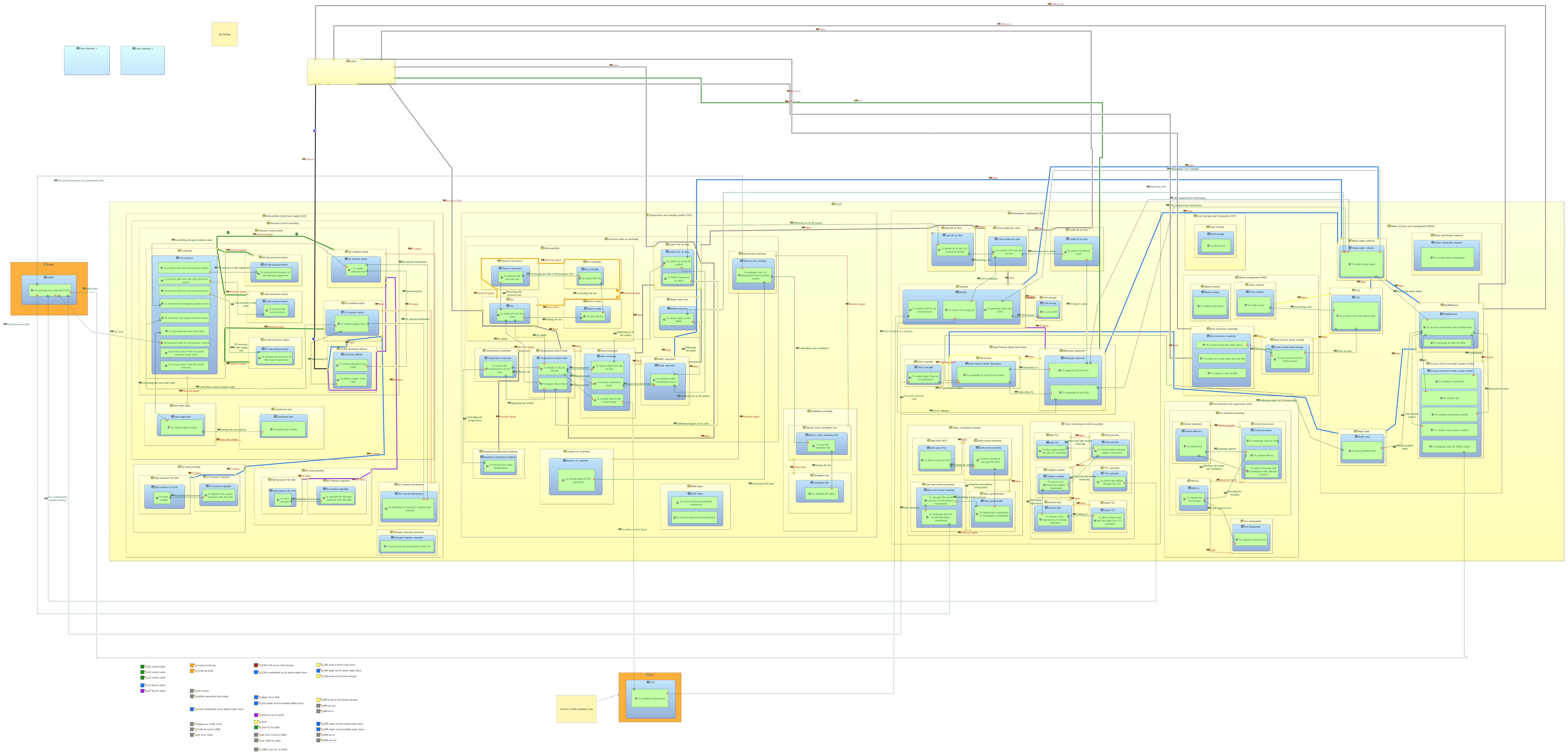
In conclusion, the integrated MBSE approach described in this work enabled the definition of a preliminary ECLSS architecture for the Analog Habitat. As described in this section, integrating the ARCADIA methodology with the ESM and reliability analysis, as well as dynamic simulations, supported the development of the system configuration. The resulting architecture reflects the outcomes of the iterative process described in Section 4.1. As discussed, this integrated approach allowed for the continuous refinement of the system configuration. With this approach, the aim was to develop an ECLSS architecture that would meet the required performance, reliability, and operational objectives for the Analog Habitat. This preliminary system architecture could be further developed using the integrated MBSE approach defined in this work. New engineering analysis tools could be integrated, or the tool previously described could be enhanced for the subsequent design phases.

Figure on page 139 illustrates the main diagram created in the Physical Architecture perspective of the ARCADIA methodology related to the ECLSS.

It provides a complete overview of the system architecture defined in this work. This diagram provides a comprehensive representation of the Node and Behavioral Physical Components and their allocated functions, as well as the Physical Links and Physical Paths. It illustrates how the various technologies and subsystems are integrated with one another. As shown in the diagram, the ECLSS is modeled as a Node Physical Component containing several other Node Physical Components that represent its subsystems. Each subsystem includes the technologies and elements that constitute its structure. The lower-level Node Physical Components provide the material resources required by the Behavioral Physical Components, which perform the allocated functions. The diagrams represent two Physical Actors corresponding to the crew members, as well as the cabin, which is modeled as a Node Physical Component. Additionally, the diagram shows the constraint elements to which Property Values are assigned for analysis and simulation tools. Other Analog Habitat systems — the Command and Data Handling (CDH) system and the Internal Thermal Control System (ITCS) — are also included and modeled as Node Physical Components (highlighted in orange in the diagram). These elements were introduced to define the links between these systems and the ECLSS subsystems. As described in the previous sections, all Property Values required to perform the integrated analysis and simulation tools are associated with the Node Physical Components, Physical Actors, and Physical Paths shown in these diagrams.

Another important diagram created in Capella during the process is the PFBD, which illustrates all the functions defined in the model for the ECLSS. The diagram presents a functional tree, which provides an overview of the entire system from a functional perspective. High-level functions related to the ECLSS are split into lower-level functions. Since these high-level functions are complex, they are decomposed into simpler, more specific functions during the modeling process. As a result, different branches are created from each high-level function. This view clearly identifies the basic functions that the system must perform. The functions shown in this diagram are those allocated to the Behavioral Physical Components depicted in the PAB diagram. The other important diagram is the PCBD, which illustrates all the Node Physical Component defined during the design process for the ECLSS. This breakdown provides a comprehensive view of all the elements that compose the system. As shown, the ECLSS Node Physical Component is decomposed into its main subsystems. Each subsystem is then divided into its respective technologies and parts, which illustrates the system's complete physical structure. A detailed description of each technology modeled as a node physical component is provided in Appendix A.

In summary, the Physical Architecture diagrams were developed iteratively throughout the design process by applying the ARCADIA methodology, conducting trade studies analyses, and performing system simulations. This integrated MBSE approach enabled the creation of a coherent and consistent ECLSS architecture. The use of the Capella tool ensured full traceability between requirements, functions, physical components, and other model elements, thus supporting system validation and future development.



5.2.5 Schematic of the ECLSS Architecture

Figure 118 provides a schematic representation of the system architecture defined in this work. In this illustration, the main processes of the system and the key technologies involved can be clearly visualized. The relationships between each component of the system and the types of matter they exchange are easily identifiable, providing an immediate understanding of the system's main resource exchanges and interactions. As shown in the legend, each arrow representing a matter flow is colored according to the type of matter exchanged. This makes identifying the interfaces between different technologies easier.

This graphical representation provides an immediate and intuitive overview of the system architecture and its primary resource flows.

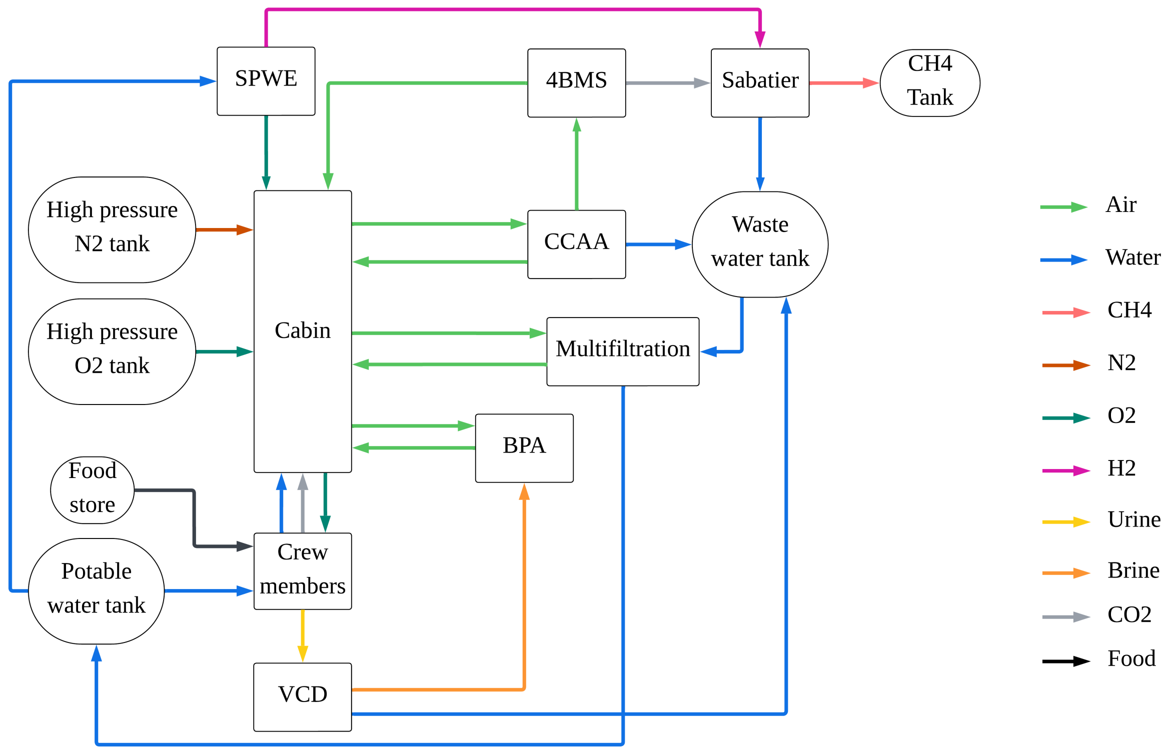


Figure 118: Schematic of the ECLSS architecture.

6 Conclusions and Future Work

Designing an Environmental Control and Life Support System for human spaceflight is a highly multidisciplinary, iterative, and recursive process fully integrated with the development of all other space habitat systems. The ECLSS architecture is strongly influenced by the mission scenario. As the duration of the mission increases, the required performance and reliability of the system, and the integration between the ECLSS and the other habitat systems, significantly increase the complexity of the design process.

This work explored the application of Model Based Systems Engineering to take advantage of its potential benefits in supporting the complex design process of the ECLSS. The main objective of this thesis was to define an integrated MBSE approach to effectively support the design of the ECLSS throughout its lifecycle, overcoming the primary limitations associated with the traditional document-centric systems engineering approach, particularly when applied to complex systems. This approach also addresses limitations - e.g., the ones identified by Bajaj et al. [85] -, such as the difficulty to ensure that analysis and simulation tools defined in different design phases consistently represent the same system and the lack of connection between design and analysis/simulation models throughout the development process.

These limitations highlight the need for defining a single, coherent system model within which can be managed and integrated all analysis and simulation tools.

This thesis addressed the identified research questions by defining and applying an integrated MBSE approach for the design of an ECLSS architecture. In response to the first research question, the proposed method demonstrated that a standard MBSE methodology can effectively be integrated with arbitrary analysis and simulation tools, while maintaining consistency and enabling automated system evaluation. Regarding the second question, the case study of an Analog Habitat illustrated how this integrated approach can enhance the ECLSS design process.

The approach presented in this work is based on the definition of the system model supported by the integration with external analysis and simulation tools, which contributes to the development of the system architecture. The system model reflects the state of the system architecture and is refined iteratively throughout the design process using information obtained from the integrated tools. As discussed, these analyses and simulations offer valuable insights into system performance, reliability, controllability, and other important aspects. Therefore, based on the system information obtained from these engineering analyses, designers can perform trade studies, define technical solutions by modifying the system architecture, allocate and verify requirements, verify and validate models, and support other key systems engineering activities. The method developed to integrate external tools in the modeling environment ensures consistency between the system model and related analyses or simulations, guarantees traceability of system data related to these tools, and ensures tool compatibility throughout the entire development process. The integrated MBSE approach ensures that simulations and analyses consistently reflect the latest version of the system model. These are executed directly from the model, with all necessary system information extracted and used by the tools to derive meaningful characteristics of the system modeled in Capella. It also allows for the automated execution of simulations and analyses. Designers can execute scripts imported into Capella that are associated with these tools to conduct the desired analysis or simulation. Then, either the system model is automatically converted into a simulation environment or the system data is used directly for analysis. These features reduce the time and errors associated with setting up analyses and simulations. As outlined in the Analog Habitat case study, in this integrated environment, once a system configuration is defined, analyses and simulations can be easily and immediately executed to obtain information about the system and rapidly understand the impact of design changes. Moreover, this integrated environment supports the early detection and resolution of design issues during the design process by enabling verification and validation of the system from the beginning of the design process. Furthermore, it contributes to the verification of requirements in the initial design phases. Considering all these benefits, the proposed approach has the potential to significantly enhance the ability to manage complexity in the design of systems such as the ECLSS.

In this work, the integrated MBSE approach has been applied to support the preliminary design of the ECLSS for an Analog Habitat to explore its advantages. An ESM and reliability analysis, and the Virtual Habitat tool were integrated into the system model. These analyses provided valuable insights into the system, especially during the initial design stages. These tools are useful for understanding the behavior of the system architecture modeled in Capella, as they provide key information on system performance, reliability, robustness, stability, controllability, and overall mission feasibility. As shown in the case study, these tools can support a wide range of system-level analyses during the preliminary design phase, including comparisons between different ECLSS architectures, technology trade studies, sensitivity analyses, and further investigations. Furthermore, the results of these analyses and simulations allow requirements to be allocated and verified in Capella from the early stages of the design process. Therefore, this approach allows for the iterative definition of the system architecture, potentially improves design quality and enhances the ability to manage complexity overall.

The proposed integrated MBSE approach has been defined to support the design process of the ECLSS throughout its entire life cycle. As the design process evolves, more advanced analysis and simulation tools can be integrated into the model using the same method. This allows the system architecture to be refined as more detailed information becomes available. For instance, Property Values related to CAD parameterization can be assigned to each physical component in the model. Similarly, parameters necessary for automatically executing CFD or FEM simulations can be stored directly within the model. Therefore, future work could involve integrating the system model with advanced engineering analysis tools in order to evaluate the effectiveness of this approach and assess how it could improve the design process further. As a result, with this approach, the model can be connected to various engineering tools and serve as a central repository for all system information, potentially supporting the design throughout its entire lifecycle.

All the main outcomes, models and codes of this work are available in a public repository - under GPLv3 license (see `https://www.gnu.org/licenses/gpl-3.0.html`) - at the following link: `https://gitlab1.polito.it/aer-se-public/mbse-framework-eclss`.

A ECLSS Technologies Description

A.1 Physicochemical Technologies

This appendix describes the main technologies associated with the following subsystems:

- Temperature and Humidity Control (THC)
- Atmosphere Control and Supply (ACS)
- Atmosphere Revitalization (AR)
- Water Recovery and Management (WRM)
- Waste Management (WM)
- Fire Detection and Suppression (FDS)

For some functions, several technologies may be available. In such cases, the main differences between them are highlighted.

A.1.1 Temperature and Humidity Control (THC)

In space, temperature is controlled by transferring internal and external heat loads to a water coolant loop. Humidity is typically removed through condensation, absorption, or adsorption. For humidity control, the main existing technologies are the CAMRAS and the CCAA.

Carbon Dioxide and Moisture Removal Amine Swing-Bed System (CAMRAS)

CAMRAS is used to remove CO_2 and moisture from cabin air. The device employs a pair of interleaved beds that are filled with SA9T, which is a particular type of sorbent which is composed of plastic beads that are highly porous and coated with an amine. SA9T has been demonstrated to be a highly effective CO_2 sorbent, exhibiting a strong affinity for water vapor. A linear multi-ball valve is employed to regulate the flow of air and vacuum to the adsorbing and desorbing beds. The adsorbing bed absorbs CO_2 and H_2O from the cabin air, while the desorbing bed is subjected to vacuum to desorb and vent the collected gases. This technology is only suitable for short-duration missions that do not require the recycling of CO_2 and H_2O. As a result, CAMRAS can be used in systems based on storage rather than recycling. The system offers advantages such as low mass and volume, no need for cooling, and minimal power consumption [103].

Common Cabin Air Assembly (CCAA)

The CCAA is one of the main components of the ISS, it is used to control the temperature and the humidity inside the module. Figure 119 shows a diagram of the CCAA.

As shown in Figure 119, filtered air is extracted from the cabin atmosphere through the ORU inlet, which consists of a fan that moves air through the CCAA. Temperature is controlled by the TCCV, which operates on a PI control scheme based on the difference between the actual cabin temperature and the desired temperature. The control logic adjusts the valve position to split the airflow between the CHX and the bypass duct. The portion of the air passing through the CHX is subjected to heat and moisture removal.

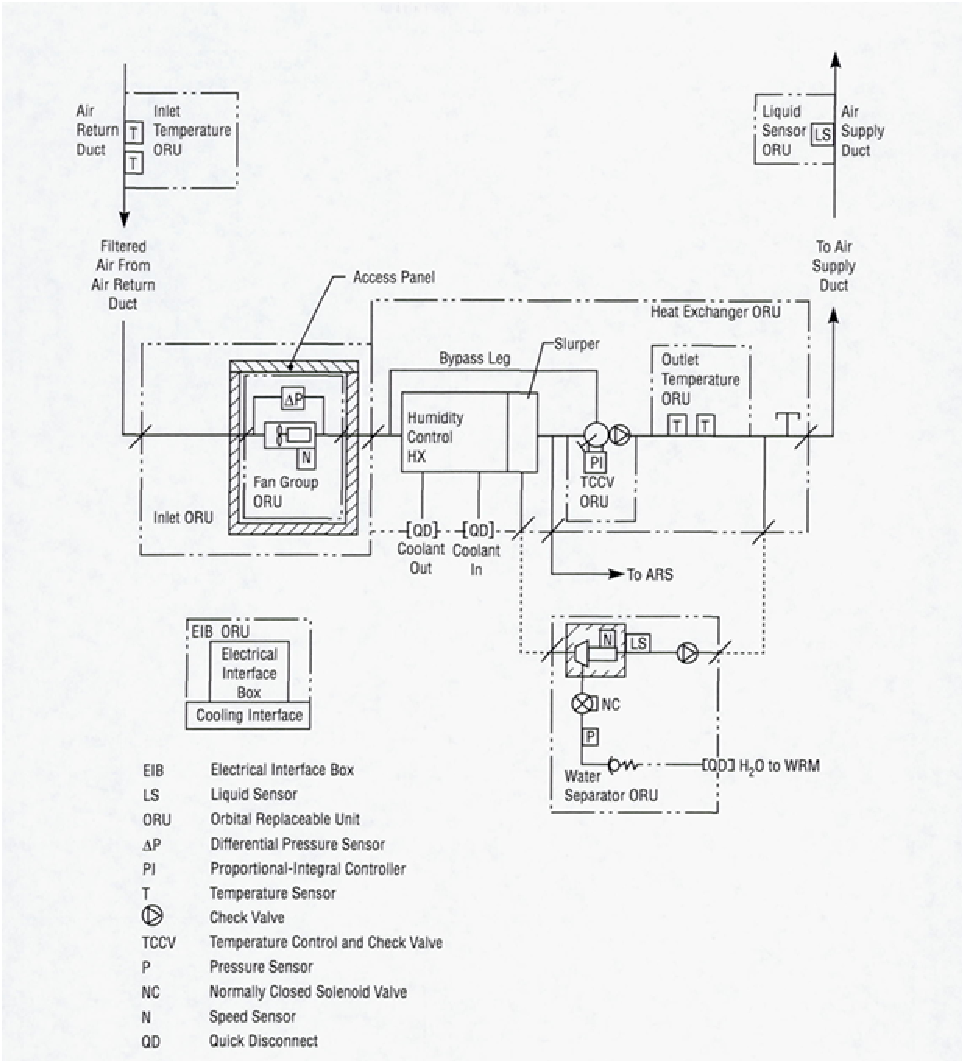


Figure 119: Common Cabin Air Assembly process schematic [5].

Then, the bypass air and CHX airflow are delivered to the cabin or other subsystems. Condensed moisture and air are drawn through the water separator. There, the condensate is separated from the air and delivered to the WRM subsystem.

In this process, heat is removed from the air and transferred to the coolant water loop. Meanwhile, moisture removal is achieved in three steps:

- Decrease the air temperature below the dew point to condense water in the CHX.
- Formation of a condensate film.
- Separation of the condensate film from the air stream.

A component known as a slurper separates the condensate film from the airflow. This component is integrated into the air outlet side of the CHX. The condensate film is carried by airflow to slurper holes, where negative pressure drains it and directs it to a water separator. Figure 120 depicts the CHX slurper.

The CCAA has greater mass, volume, power consumption, and cooling requirements compared to CAMRAS, but it enable for recycling of both water and air.

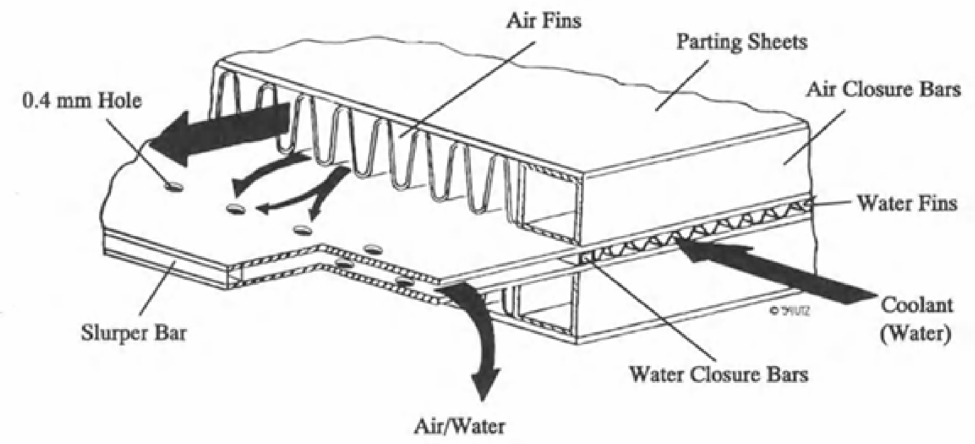


Figure 120: CHX slurper [52].

Ventilation Hardware

The hardware required for ventilation includes fans, ducting, and isolation valves. The main differences between the options is the type of fan based on power consumption, noise, and vibration [3]. It is necessary to provide ventilation both within the module and between modules.

Microorganisms and Airbone Particulate Contaminants Control Hardware

The common methods for removing airborne particulate contaminants are High Efficiency Particulate Atmosphere (HEPA) filters, electrostatic precipitation and wiping surfaces where dust particles accumulate. While, the main methods for removing microorganisms are chemical disinfectants, ultraviolet light, and HEPA filters [4]. The replacement of filters is necessary after a specified period of utilization. Consequently, the filter's total mass increases over time.

A.1.2 Atmosphere Control and Supply (ACS)

The ACS subsystem consists of hardware and software associated with the storage, distribution, and pressure control of atmospheric gases. It also includes components related to vent and relief capability and habitat repressurization. In the ISS, the main component of the ACS is the Pressure Control Assembly (PCA), which controls the injection of N_2 and O_2 into the cabin. Figure 121 illustrates a functional diagram of the ACS subsystem.

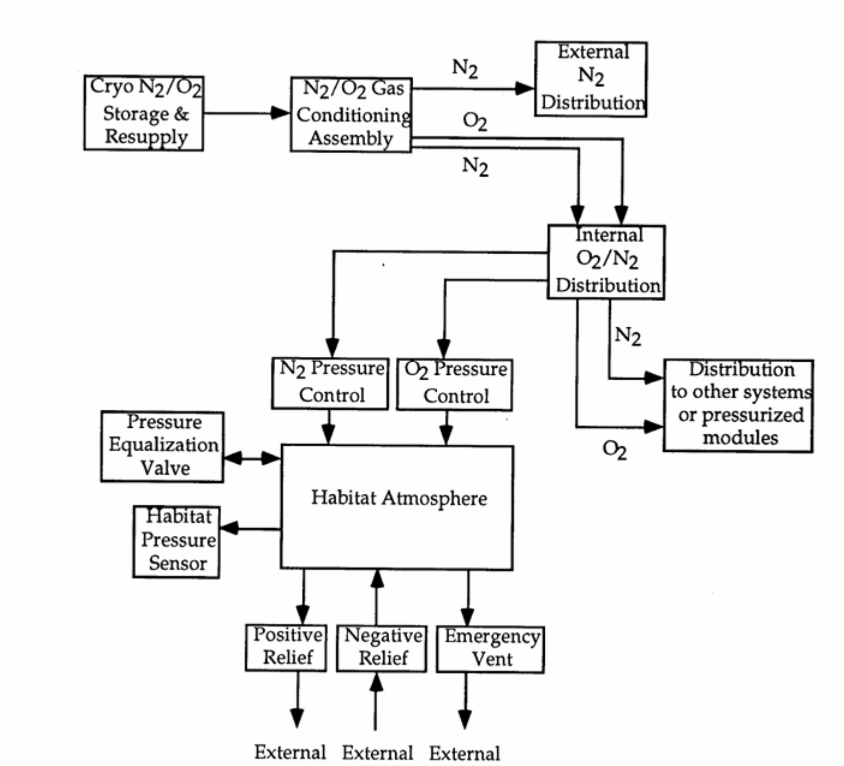


Figure 121: ACS functional diagram [4].

To perform its functions, the ACS uses gas storage tanks, valves and regulators, all managed by control algorithms using data from pressure sensors and from the Major Constituents Analyzer. The following options are available for gas storage: Storage in chemical compounds, high pressure storage and cryogenic storage [52].

High Pressure Storage

High pressure storage systems are commonly used to store atmospheric gases such as oxygen and nitrogen. The high pressure allows a significant reduction in tank volume. However, increasing storage pressure requires thicker tank walls, and since gases become less compressible at higher pressures, the benefits of extreme compression are limited. An optimum pressure to volume ratio is typically achieved at a pressure of a few million pascals [52]. This type of storage is particularly suitable for small volumes of gas where the mass and volume savings of cryogenic techniques cannot be achieved [4]. Although high-pressure storage systems are simple, robust, and insensitive to ambient heat, redundancy is required from a safety perspective to reduce risk [104]. Another critical factor is material compatibility. For example, titanium reacts with oxygen and is not a suitable material for oxygen tanks [4].

Cryogenic Storage

Cryogenic storage is commonly used for large volumes of gases, such as oxygen and nitrogen, because it can provide higher storage densities than high-pressure gas storage. By storing these fluids at cryogenic temperatures, it is possible to reduce both the storage volume and the pressure inside the tank. This results in lower tank mass and improved safety since high operating pressure are avoided. However, cryogenic tank design presents unique engineering challenges. The most important factors are effective thermal insulation to minimize boil-off losses and tank venting for pressure relief. Additionally, microgravity introduces complexities, such as making fluid delivery more difficult and accurately measuring the remaining fluid amount particularly challenging [4, 52, 104].

Chemical Compounds

An alternative method of storing gases is to use chemical compounds in which oxygen and nitrogen are combined with other elements. Chemical compounds have been used for many applications, including cabin repressurization, leakage makeup, and emergency operation, especially when long-term storage or standby is required [52].

Compounds that contain oxygen that can be released in a breathable form can be divided into three groups:

- Alkali and alkaline earth peroxides, superoxides, and ozonides
- Alkali and alkaline earth chlorates and perchlorates
- Hydrogen peroxide

The first group of compounds release oxygen through chemical reactions with carbon dioxide and water, the second group works by decomposing sodium chlorate to sodium chloride and oxygen. Hydrogen peroxide provides oxygen through a two-step process: it first must be decomposed into water and oxygen, and the resulting water can then be electrolyzed to produce additional oxygen [4]. For example, the Mir station combines resupply and perchlorate candles to ensure redundancy and to meet peak oxygen demands when visiting crews are on board [3].

Nitrogen can be stored as liquid hydrazine and catalytically dissociated when needed. This method requires significantly less volume compared to storing nitrogen as a compressed gas or cryogenic fluid [4].

A.1.3 Atmosphere Revitalization (AR)

The AR subsystem technologies are related to: CO_2 removal, CO_2 reduction, O_2 generation, control of gaseous contaminants, and monitoring of major constituents.

There are many technologies for removing CO_2, each with advantages and disadvantages for different mission scenarios and requirements. The main technology options for CO_2 removal are

- Regenerative Technologies:
  - 4 Bed Molecular Sieve (4BMS)
  - 2 Bed Molecular Sieve (2BMS)
  - Solid Amine Water Desorption (SAWD)
  - Electrochemical Depolarization Concentration (EDC)
  - Air Polarized Concentrators (APC)
  - Osmotic Membranes
  - Electroactive Carriers
  - Metal oxides
  - Carbonate
  - Ion-exchange electrodialysis
- Non-Regenerative Technologies:
  - Lithium Hydroxide (LiOH)
  - Sodasorb
  - Superoxides
  - CAMRAS

4 Bed / 2 Bed Molecular Sieve

The Four-Bed Molecular Sieve (4BMS) system consists of two adsorbing beds - a desiccant bed for water vapor removal and a zeolite molecular sieve for trapping CO_2. These operate in parallel with two identical beds in the desorption mode. In the process, depicted in Figure 122, the air passes through the desiccant bed, which removes the water vapor to protect the CO_2 bed from water vapor. The air then passes through a precooler, which removes heat generated during water vapor adsorption. This cooled air then enters the carbon dioxide adsorption bed where CO_2 is removed. The air then moves to the desorbing desiccant bed, where it is re-humidified before returning to the cabin [52]. There are no special safety hazards associated with this concept. The materials are not flammable, so gas leakage cannot result in toxic or explosive conditions [104].

The 2BMS is similar to the 4BMS, but it uses a Carbon Molecular Sieve (CMS) to remove CO_2. Unlike zeolites, CMS materials are not affected by water vapor. This enables direct CO_2 adsorption without the need for a separate desiccant bed. This simplifies the system and reduces the 4BMS to a 2BMS. In addition, CMS desorbs CO_2 at a lower temperature than zeolite, resulting in lower power consumption. However, while the 4BMS is a well-established and mature technology, the 2BMS is still in a relatively early stage of development [52].

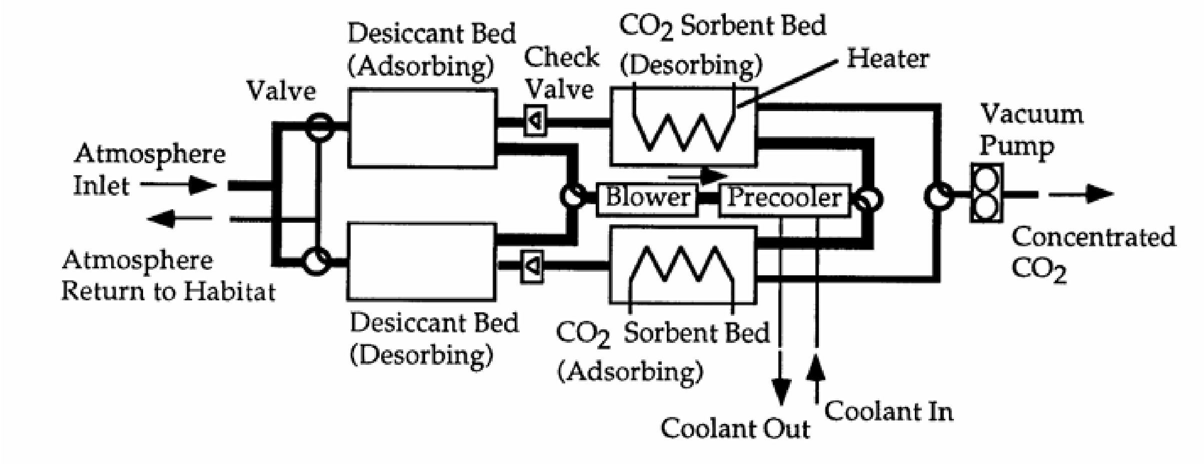


Figure 122: 4 Bed Molecular Sieve [4].

Solid Amine Water Desorption (SAWD)

The main components of the Solid Amine Water Desorption (SAWD) are the canisters containing the resin absorbents and a steam generator (see Figure 123). The resin captures carbon dioxide from the atmosphere, and steam is utilized to regenerate the resin by removing the absorbed CO_2. The resin absorbs CO_2 through a two-step chemical process: first, it reacts with water to form a hydrated amine, which then reacts with CO_2 to form a bicarbonate compound. To regenerate the resin, steam heat is applied to break the bicarbonate bond releasing the CO_2 and recovering the amine for further use [52]. Solid amine tends to degrade relatively quickly over time (amine degradation may yield toxic vapors), resulting in more frequent replacement of the absorption beds. In addition, the SAWD system imposes additional demands on the ECLSS because it requires hygiene water for operation. This water is eventually released as vapor into the Temperature and Humidity Control (THC) system, increasing the load on the condensing heat exchanger [52].

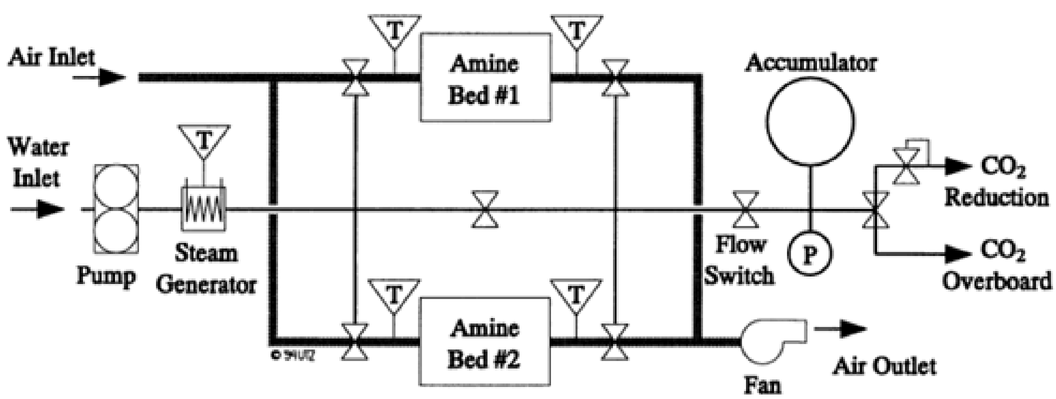


Figure 123: Solid Amine Water Desorption [52].

Electrochemical Depolarization Concentration (EDC)

The Electrochemical Depolarized Carbon Dioxide Concentrator (EDC) removes CO_2 by reacting hydrogen and oxygen with carbon dioxide in an electrochemical cell, producing two separate outlet streams, as shown in Figure 124. The stream from the anode side contains a high concentration of CO_2 along with some hydrogen, while the stream from the cathode side consists of air with a reduced concentration of CO_2 which is then returned to the cabin atmosphere [52]. The overall reaction is:

$$CO_2 + \frac{1}{2}O_2 + H_2 \longrightarrow CO_2 + H_2O + \text{electrical energy} + \text{heat} \tag{41}$$

The main advantages of EDC are that the rate of CO_2 removal can be controlled simply by changing the operating electric current and the generated direct current power can be used by other ECLSS subsystems. However, EDC has several drawbacks. The most significant mass penalty is indirect and comes from the power requirements of the oxygen generator, which must produce the oxygen consumed during the process. In addition, the technology generates water vapor, which increases the load on the THC subsystem, requires a cooling system, and demands a supply of H_2. EDC also poses a safety risk, as hydrogen leakage into the cabin could pose a fire or explosion hazard [52, 104].

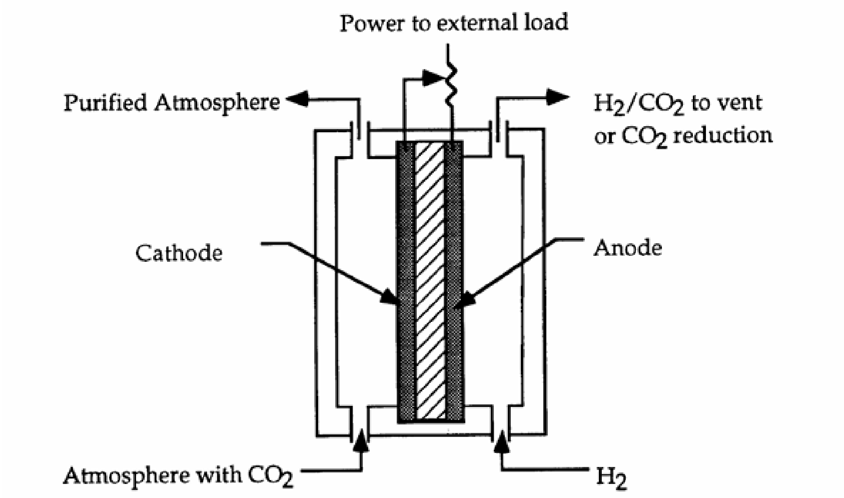


Figure 124: Electrochemical Depolarization Concentration [4].

Air Polarized Concentrators (APC)

The APC is essentially an EDC that does not require hydrogen for the CO_2 removal process and incorporates an O_2/CO_2 separator. It is safer than the EDC, although hydrogen is no longer available in the outlet stream to support CO_2 reduction. Power consumption is significantly higher without hydrogen; however, the APC can operate with or without hydrogen to optimize power efficiency while maintaining safety. Although switching between modes can reduce energy consumption and improve safety, it also accelerates the degradation of the electrode catalyst. In addition, the presence O_2/CO_2 separators increases the mass, power consumption, volume and overall complexity of the system compared to the EDC.

Other regenerative technologies for CO_2 removal - such as osmotic membranes, electroactive carriers, metal oxides, carbonate systems, and ion exchange electrodialysis - generally have either a low technology readiness level (TRL) or lower performance compared to the previously described methods. A detailed description of these technologies can be found in [52].

Lithium Hydroxide (LiOH)

In an open-loop ECLSS, carbon dioxide is usually removed from cabin atmosphere as it flows through a canister that contains a packed bed of lithium hydroxide (LiOH) granules [52]. The chemical reaction involved can be represented as a:

$$2\,\mathrm{LiOH} + \mathrm{CO_2} \longrightarrow \mathrm{Li_2CO_3} + \mathrm{H_2O} \tag{42}$$

Once used, the LiOH is not recovered; instead, the canisters are replaced with new absorbent material. On average, about 2 kg of LiOH is needed to absorb one person's daily CO_2 output. Therefore, LiOH-based CO_2 removal is suitable for short-duration missions, but is not feasible for long-duration missions due to its significant mass penalty. LiOH remove also trace contaminants and odors from the atmosphere [52].

Other non-regenerative technologies, such as Sodasorb and superoxides, have an overall performance inferior to that of lithium hydroxide (LiOH). Detailed descriptions of these methods can be found in [4, 52], while the CAMRAS has been discussed previously.

To increase the closure level of an ECLSS, carbon dioxide must be removed from the cabin atmosphere and then reduced to useful components within the system. Consequently, the CO_2 output from the carbon dioxide removal process becomes the input to the CO_2 reduction process. The recycling of oxygen from CO_2 will provide a maximum of 0.74 kg O_2/(man-day) from an average of 1 kg CO_2 exhaled per man per day. Therefore, the recovery of oxygen from carbon dioxide closes a significant part of the oxygen cycle. The main CO_2 reduction technologies are:

- Bosch
- Sabatier
- Advanced Carbon-Formation Reactor System (ACRS)
- CO_2 Electrolysis
- Superoxides

Bosch

The Bosch CO_2 reduction process, shown in Figure 125, is based on the reaction of carbon dioxide with hydrogen at high temperature (700-1000 K) in the presence of a catalyst. This reaction produce solid waste carbon, water and heat:

$$\mathrm{CO_2} + \mathrm{H_2} \longrightarrow \mathrm{C} + 2\,\mathrm{H_2O} + \mathrm{heat} \tag{43}$$

Hydrogen and carbon dioxide are compressed and heated before the contact with the catalyst bed. Typically, only about 10% of the CO_2 is reacted in a single pass, so it is necessary to recirculate the outlet gas back into the reactor [4]. The produced water may be stored and then processed to hygiene water or used to generate oxygen, while the heat has to be removed by the thermal control system.

Key advantages of the process include the potential to achieve 100% conversion efficiency and no overboard venting of gases. However, the system also has significant drawbacks: it requires high operating temperatures, requires frequent maintenance due to the periodic replacement of the catalyst cartridge, and the reactor is limited to semi-batch operation of the catalyst beds [52].

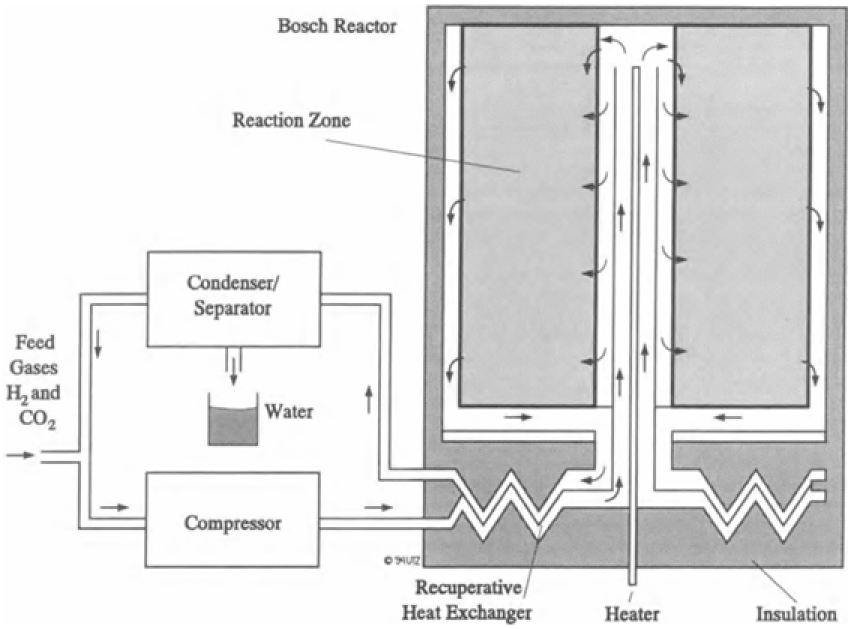


Figure 125: Bosch CO_2 Reduction Process [52].

Sabatier

The Sabatier CO_2 reduction process, shown in Figure 126, is based on the reaction of hydrogen and carbon dioxide at high temperature (450-800 K) in the presence of a ruthenium catalyst on a granular substrate, producing methane and water. In this reaction, carbon dioxide is first hydrogenated to carbon monoxide, and then the carbon monoxide is hydrogenated to methane in a second step. The overall reaction is shown below:

$$CO_2 + 4\,H_2 \longrightarrow CH_4 + 2\,H_2O + \text{heat} \qquad (44)$$

For the process, the required hydrogen can be obtained from water electrolysis and the heat must be managed by the thermal control system. The water can be processed into hygiene water or used to produce oxygen, while the methane can be used for propulsion, vented to space, or converted to H_2 and solid carbon by pyrolysis [4]. The H_2 produced by pyrolysis can be used by the Sabatier reactor.

The main advantages of this process are: reliable operation, significant savings in mass, power and volume compared to Bosch, short start-up time and single pass efficiency greater than 99%. However, there are also some drawbacks. The recycled water may contain dissolved gases, such as N_2, CH_4, and CO_2, N_2 is vented with CH_4, and the catalyst is vulnerable to contamination by solid amine vapors. Additionally, the storage or venting of CH_4 must be managed. [52].

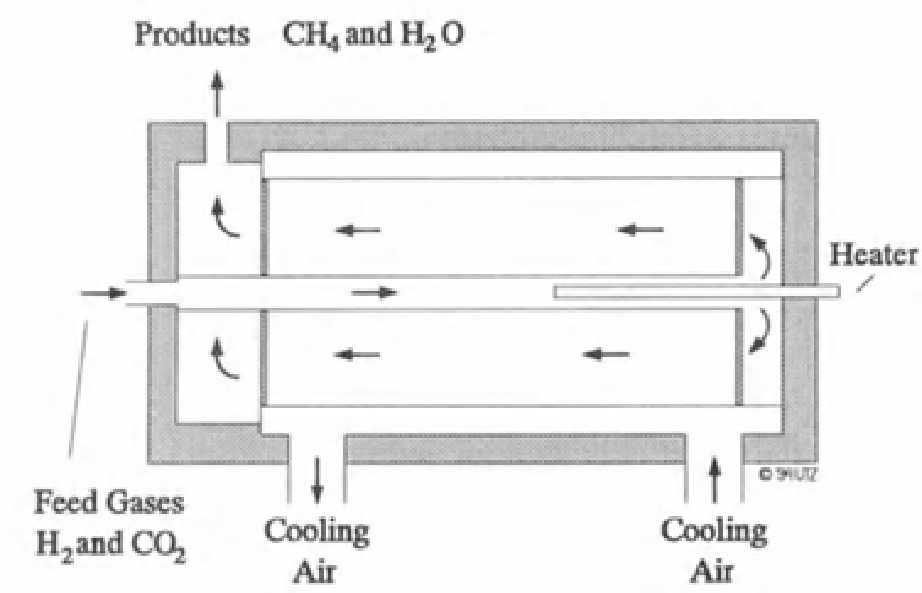


Figure 126: Sabatier CO_2 Reduction Process [52].

Advanced Carbon-Formation Reactor System (ACRS)

The ACRS includes a Sabatier reactor, a gas/liquid separator that removes water from the methane, and a Carbon Formation Reactor (CFR) that reduces the methane to carbon and hydrogen [4,52]. The CFR compacts carbon more effectively than the Bosch process; however, it operates at temperatures above 1144 K [52], which must be reduced before the ACRS becomes feasible. This technology is a potential candidate for carbon dioxide reduction in long-duration space missions, but it has not yet been fully developed [61].

CO_2 Electrolysis

The CO_2 electrolysis uses a solid oxide electrolyte to both reduce CO_2 and regenerate O_2. Carbon dioxide is taken directly from the CO_2 concentrator and electrolyzed to produce O_2. This technology is capable of electrolyzing both CO_2 and water vapor, producing enough oxygen to meet a person's metabolic needs and compensate for habitat cabin leakage. Therefore, the overall AR subsystem may be simpler and have lower mass, volume and power consumption. The reaction is:

$$CO_2 + H_2O \longrightarrow CO + O_2 + H_2 \tag{45}$$

The resulting CO is then catalytically decomposed into solid carbon and CO_2, with the O_2 recycled back to the electrolysis unit. However, technological challenges, such as ineffective high temperature (above 1140 K) ceramic-to-ceramic seals, have inhibited the development of O_2 electrolysis from reaching the same level of maturity as the SPWE and SFWE systems (described later) [52].

Superoxides

Both alkali and alkaline earth metal superoxides are solid chemicals that can provide oxygen and remove carbon dioxide from the atmosphere [52]. An example is potassium superoxide (KO_2), which reacts with moisture in the air to produce oxygen (O_2) and potassium hydroxide (KOH). The KOH then absorbs carbon dioxide from the atmosphere. The overall reaction is:

$$4\,\mathrm{KO_2} + 3\,\mathrm{H_2O} + 2\,\mathrm{CO_2} \longrightarrow 2\,(\mathrm{K_2CO_3} \cdot \frac{3}{2}\,\mathrm{H_2O}) + 3\,\mathrm{O_2} + \text{heat} \qquad (46)$$

The theoretical capacity of KO_2 is 0.309 kg of CO_2 absorbed per kilogram of sorbent, and it produces 0.388 kg of O_2 per kilogram of sorbent [52]. There are handling challenges, however, as superoxides are hygroscopic and react with water to release both oxygen and heat, potentially enough to ignite combustible materials. In addition, KO_2 can cause irritation to the eyes and respiratory tract [4].

In addition to CO_2 electrolysis and superoxides, the main technologies for oxygen generation are

- SFWE
- SPWE
- Water Vapor Electrolysis (WVE)

Static Feed Water Electrolysis (SFWE)

The SFWE electrolyzes water to O_2 and H_2. The process, shown in Figure 127, consists of vaporizing water through a membrane into an aqueous KOH electrolyte. Oxygen is produced at the anode of the electrolysis cell, and hydrogen is produced at the cathode [4]. The process is not 100% efficient, and heat is generated that must be removed [52].

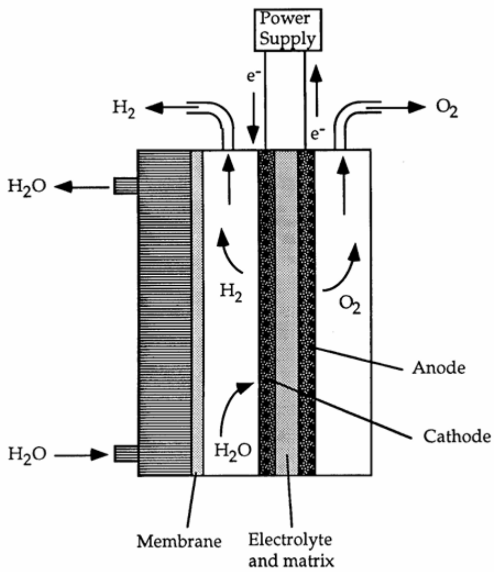


Figure 127: Static Feed Water Electrolysis process [4].

Static Polymer Water Electrolysis (SPWE)

The SPWE electrolyzes water into O_2 and H_2. The process shown in Figure 128 uses a solid polymer electrolyte to electrolyze water. This process is similar to SFWE, but more complex due to the need for liquid/gas separators [4, 52].

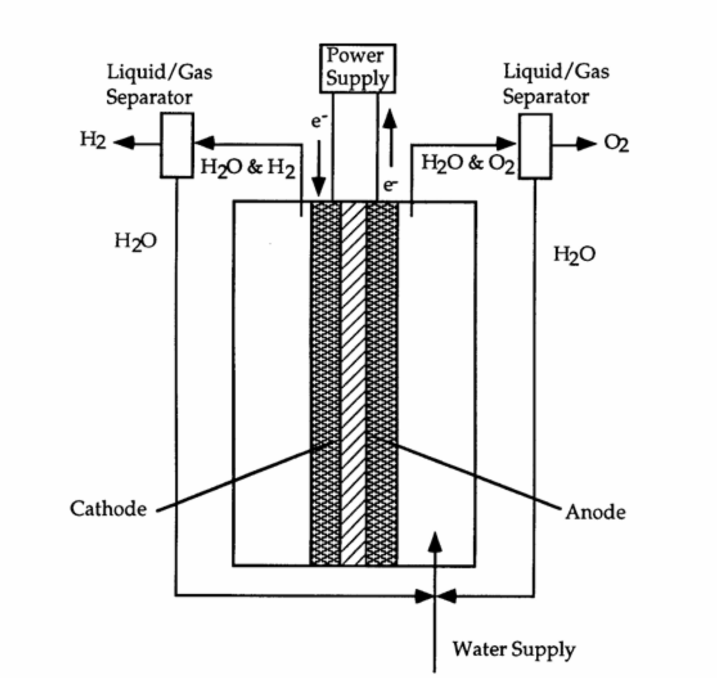


Figure 128: Static Polymer Water Electrolysis process [4].

Water Vapor Electrolysis (WVE)

The Water Vapor Electrolysis (WVE) system electrolyzes water vapor directly from the cabin air to generate oxygen and hydrogen. The process operates continuously, with oxygen returned to the cabin and hydrogen separated for disposal. The process, shown in Figure 129, is simple and reliable; however, to provide adequate oxygen, nearly all of the water vapor must be extracted from the atmosphere [4, 52].

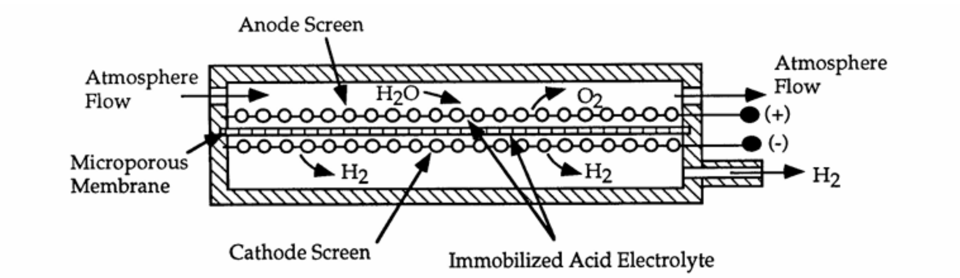


Figure 129: Water Vapor Electrolysis process [4].

The Atmosphere Revitalization (AR) subsystem must control the gaseous contaminants in the atmosphere to protect the crew. Removal of gaseous contaminants can be achieved by several approaches, including oxidation, absorption, and adsorption [4].

Trace Contaminant Control Subassembly (TCCS)

An example of gaseous contaminant removal and disposal technology is the ISS Trace Contaminant Control Subassembly.

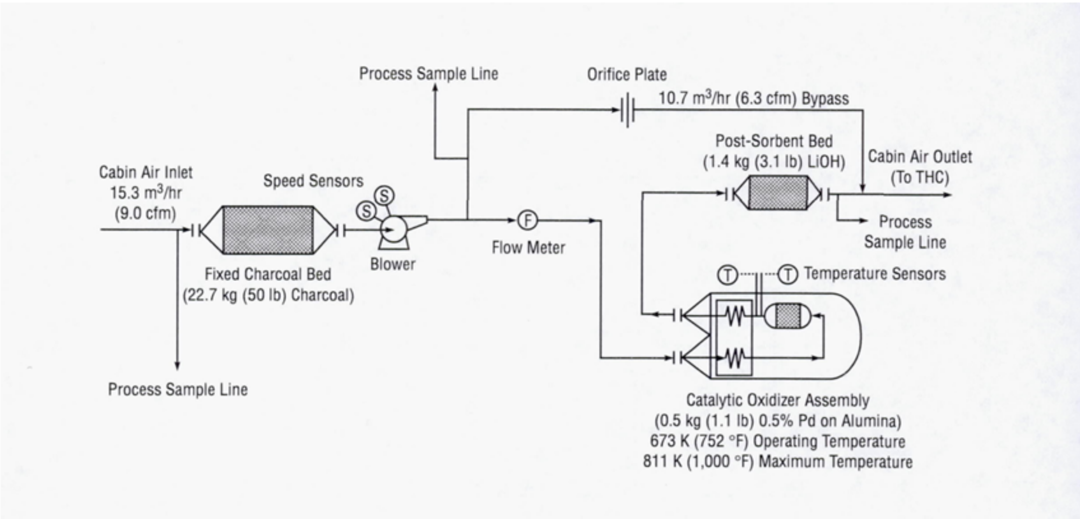


Figure 130: Trace Contaminant Control Subassembly [5]

As shown in Figure 130, the air first passes through the charcoal bed to remove contaminants with a high molecular weight. A blower and a flow meter located downstream of the charcoal bed control the airflow rate. Next, a portion of the air passes through a high-temperature catalytic oxidizer to eliminate low-molecular weight contaminants, such as CH_4, H_2, and CO. Then, the air enters a LiOH bed to absorb acidic byproducts generated during the oxidation process before it returns to the atmosphere. [5].

One of this technology's major advantages is its ability to control many different types of non-specific airborne contaminants, both organic and inorganic. The main disadvantage is related to the expendable charcoal beds, which require periodic replacement and resupply [52].

Major Constituent Analyzer (MCA)

In a space habitat, it is necessary to monitor the major atmospheric constituents, and there are numerous methods available. On the ISS, the Major Constituent Analyzer performs the following tasks [5]:

- Provides continuous monitoring of the major atmospheric constituents.
- Provides oxygen and nitrogen partial pressures to the CDH system used by the Atmosphere Control Subsystem (ACS).
- Monitors the performance of the CDRA and TCCS by measuring the partial pressures of CO_2 and CH_4.
- Compares the measured partial pressures to predefined acceptable ranges.

The MCA process is shown in Figure 131. As described in Wieland [5]: "*The MCA operates by drawing a sample past the single-focusing magnetic sector Mass Spectrometer (MSM) inlet leak where gas is drawn into an ion source and the gas molecules are ionized. The ions are then accelerated by an electron field and pass into a shaped magnetic field where they are dispersed by molecular weight. The dispersed ion beams are focused into Faraday current collectors by resolving slits. The collected currents are proportional to the partial pressures. Molecules not collected are absorbed by an ion pump. Air not admitted into the MSM is returned to the AR rack by a pump.*"

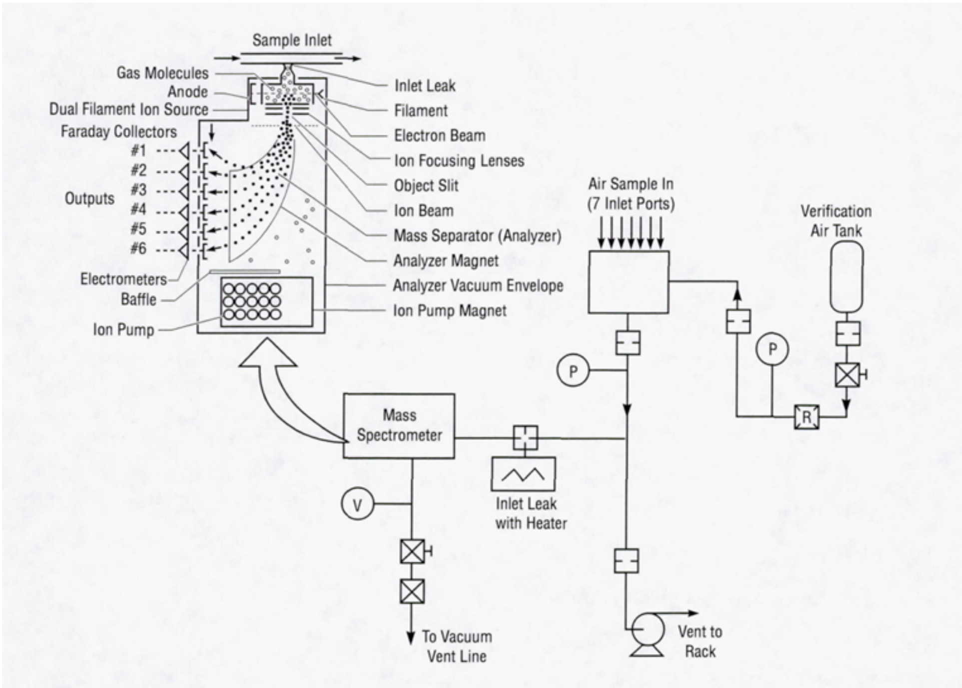


Figure 131: Major Constituent Analyzer [5].

The MS is capable of distinguishing compounds with different molecular weights. However, it cannot distinguish between compounds of the same molecular weight, such as CO and N_2. In such cases, an additional method is required to detect at least one of them. Nondispersive infrared spectrometry is one option for identifying CO [4].

A.1.4 Water Recovery and Management (WRM)

The WRM subsystem is extremely important in the ECLSS architecture, especially for long-duration missions where water requirements are very challenging. The main technologies of the WRM are related to urine processing, waste water processing and water quality monitoring.

For urine, the simplest approach is to collect it in a container and then vent it to space, but this method leads to loss of mass and can result in contamination of external surfaces [4]. The main developed urine processing technology are[16]:

- Vapor Compression Distillation (VCD)
- Vapor Phase Catalytic Ammonia Removal (VAPCAR)
- Thermoelectric Integrated Membrane Evaporation System (TIMES)
- Air Evaporation Systems (AES)
- Aqueous Phase Catalytic Oxidation Post-Treatment System (APCOS)
- Super Critical Water Oxidation (SCWO)

Vapor Compression Distillation (VCD)

In the VCD process, shown in Figure 132, waste water flows into a rotating drum at reduced pressure where the water evaporates. The vapor is then compressed and condenses on the surface in direct thermal contact with the evaporator. The resulting heat flux from the condenser to the evaporator is enough to evaporate the same amount of water that is being condensed. [52]. This allows the VCD process to operate as a thermally passive system, requiring no active temperature control. The evaporator, condenser, and condensate collector are rotated to provide zero gravity phase separation. With this method, more than 96% of the water can be recovered and the remainder is discharged as brine. Wastewater pre-treatment and post-treatment may be required to ensure high quality water [52].

The VCD produces slightly higher quality water and processes higher flow rates than the TIMES, but incorporates rotating components, generates gaseous product that must be vented, and requires brine storage [52].

Vapor Phase Catalytic Ammonia Removal (VAPCAR)

VAPCAR is a process that combines evaporation with high temperature catalytic oxidation of the volatile impurities that vaporize along with the water. Evaporation occurs through hollow fiber membranes, then the process includes two catalyst beds: in the first bed, ammonia is oxidized to nitrous oxide (N_2O) and N_2, and volatile hydrocarbons are oxidized to CO_2 and H_2O. In the second bed, N_2O is catalytically decomposed to N_2 and O_2. Figure 133 Shows a diagram that simplifies the VAPCAR process [4, 52].

The overall water quality of this process is higher than VCD or TIMES and it doesn't need any pre-treatment. However, the process has a high power consumption and a low technology level [52, 105].

[16] The technologies related to waste water processing or urine processing can, in most cases, also be used to process urine or waste water, respectively [4].

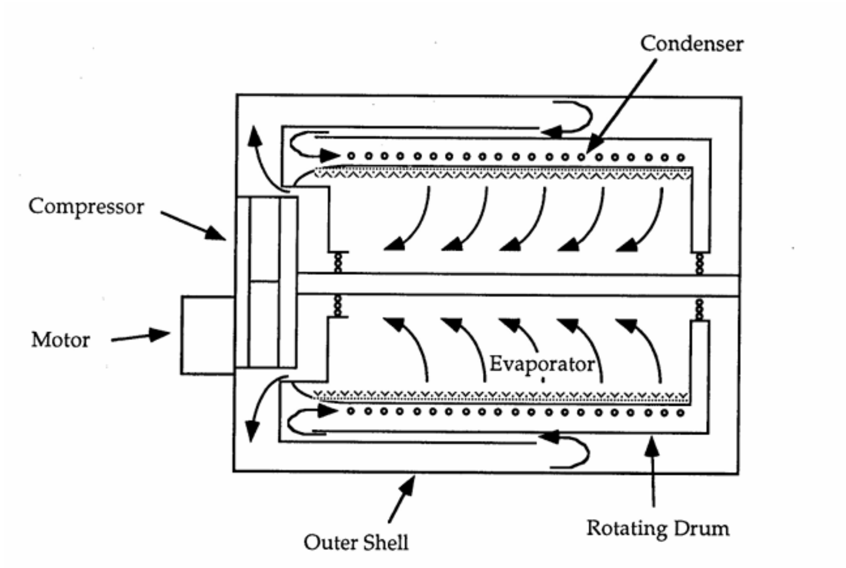


Figure 132: VCD process [4].

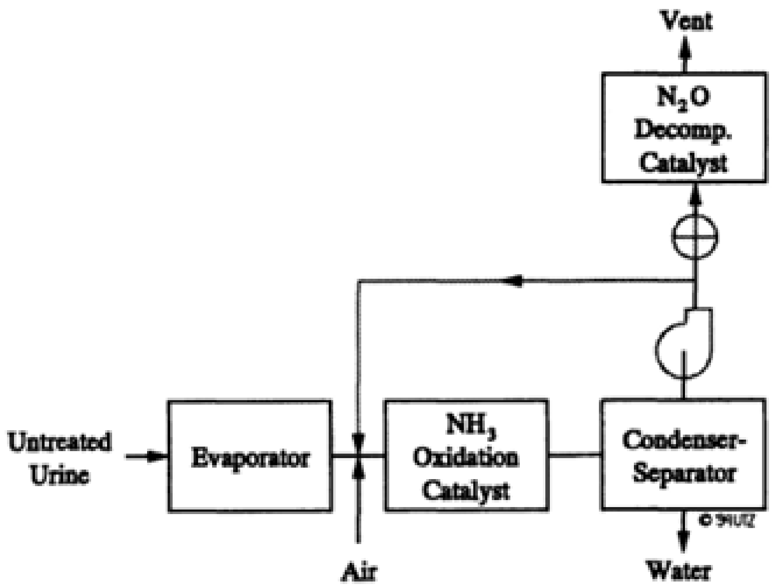


Figure 133: VAPCAR Process [52].

Thermoelectric Integrated Membrane Evaporation System (TIMES)

The TIMES operates by heating wastewater to 339 K using a heat exchanger, as shown in Figure 134. The water is then forced through a hollow fiber membrane, where a reduced pressure (17.02 kPa or 2.47 psia) on the outer surface of the membrane facilitates evaporation. A thermoelectric heat pump transfers heat from the condenser to the evaporator to support the process [4].

The process can recover up to 93% of the water. Waste fluid is contained within hollow fiber membranes in the evaporation section, making the process safer. There are no moving parts in the process, but it requires pre-treatment of urine, water quality is inferior to VCD, it's not as energy efficient as VCD and requires high maintenance time [52].

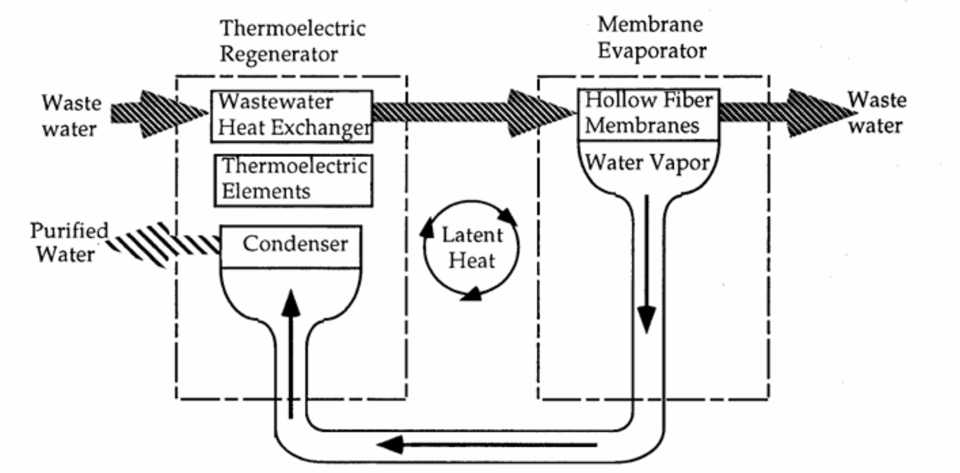


Figure 134: TIMES Process [4].

Other urine processing technologies include the Air Evaporation System (AES), the Aqueous Phase Catalytic Oxidation Post-Treatment System (APCOS), which serves as a wastewater post-treatment method [52], and Supercritical Water Oxidation (SCWO), which will be discussed later in the Waste Management subsystem section, as it is primarily used for the destruction of organic compounds.

Water used by crew members, processed urine, and water recovered from systems such as CCAA condensate must be purified to meet acceptable quality standards. The major competing regenerative technologies for potable and hygiene water processing are:

- Multifiltration (MF)
- RO

Multifiltration (MF)

The multifiltration process, shown in Figure 135, consists of a particulate filter upstream of six unibeds in series. Each unibed consists of an adsorption bed (activated carbon) and an ion exchange resin bed. The process first removes particulates by filtration. Then, suspended organic contaminants in the waste water are removed by passing through an activated carbon bed, and inorganic salts are removed by cation and anion exchange resin beds [52]. Microbial control is achieved by heating the entire technology to 347 K [4, 52].

This technology is simple and required very little development for use in space, but the process does need expendables to regenerate the ion exchange beds and a suitable regeneration scheme for the activated charcoal [4].

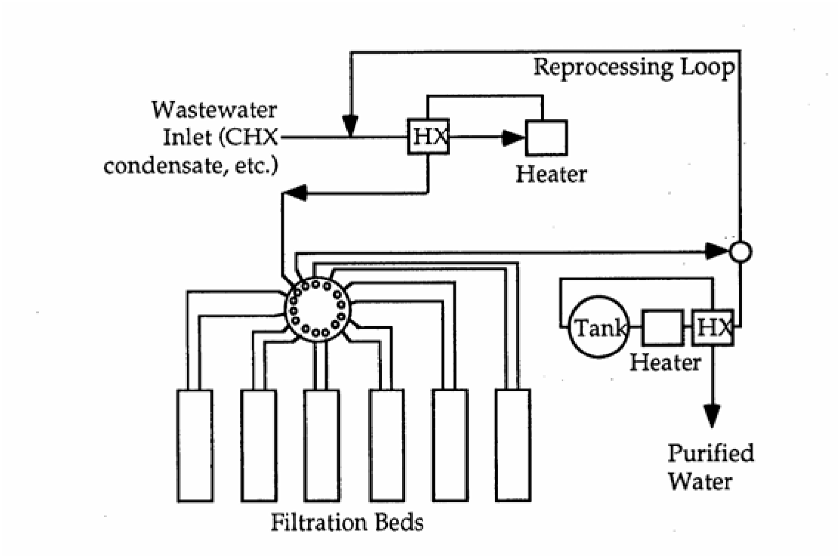


Figure 135: Schematic of Multifiltration water processor [4].

Reverse Osmosis (RO)

In this process, shown in Figure 136, waste water is first forced through an ultrafiltration membrane to remove suspended solids and macromolecules, allowing water and low-molecular weight substances to pass through. The waste water is then pressurized to between 690 and 5500 kPa, forcing the water through a semi-permeable membrane and leaving most ions and larger organic compounds behind. The quality of the purified water is high, energy consumption is low, and there is no need for a gas-liquid phase separator in microgravity. However, high pressure and pre-treatment makes the system more complex [4, 52].

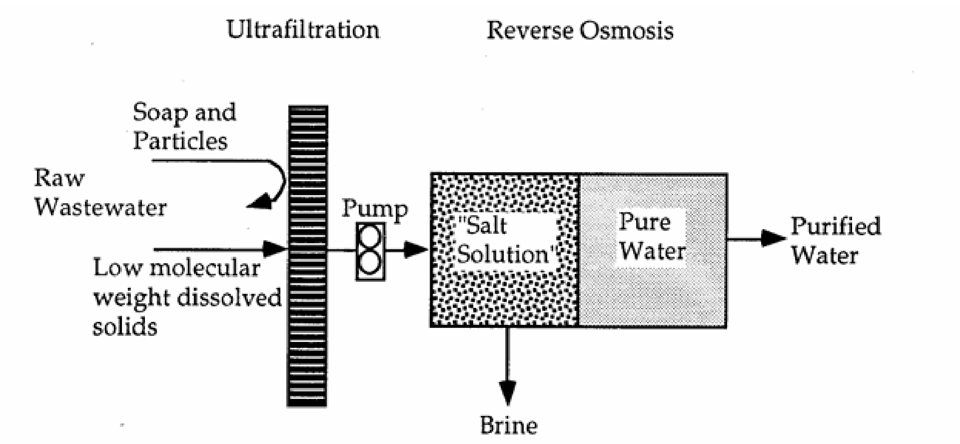


Figure 136: Reverse Osmosis process [4].

Other water purification methods include electrodialysis and electrolysis fuel cells. For more information on these processes, see [4, 52].

Water Quality Monitoring

Once purified, potable and hygienic water must meet specific quality standards to ensure the safety of the crew. To achieve this, water quality monitoring must be automatic, with the most critical parameters measured either continuously or at regular intervals. These measurements can be made using commercially available sensors. As shown in Figure 137, water samples used for measurements requiring calibration with chemical standards are not returned to the main supply to avoid contamination. Typically, less than one percent of the total water is used for these measurements. As described previously, key parameters that require frequent monitoring include pH, ammonia content, Total Organic Carbon (TOC), electrical conductivity and microbial concentration [4, 52].

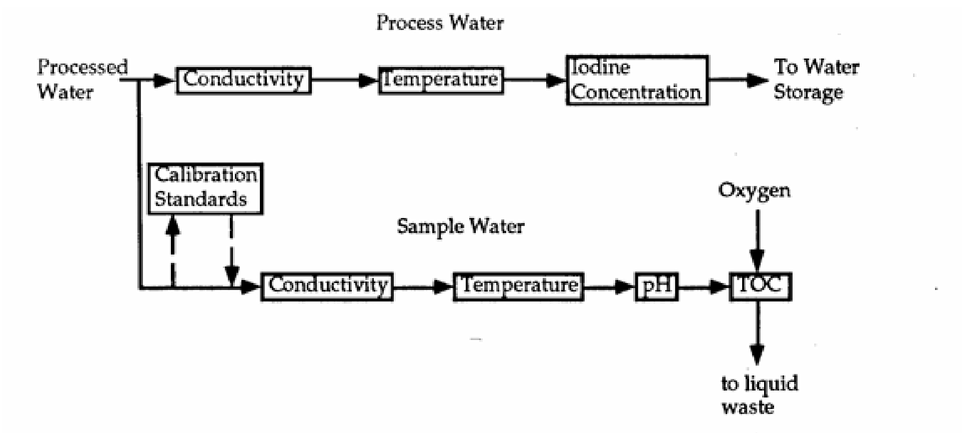


Figure 137: Water Quality Monitoring Process [4].

A.1.5 Waste Management (WM)

The WM subsystem must manage waste from the WRM and AR subsystems, food preparation waste, feces, EVA waste, and other waste associated with crew members. The waste management process follows this sequence: collection and separation, fractionation, stabilization or storage, and recycling when appropriate.

For short-term missions, waste is simply collected and stored, but for longer missions, the mass and volume required to store all the waste may be unacceptable, so processes to recycle the waste must be considered. The main processes include: Super Critical Waste Oxidation (SCWO), Wet Oxidation, Combustion / Incineration, Electrochemical Oxidation and Waste Management - Water Systems (WM-WS). Recycling wastes with these processes can reduce the mass and volume required, especially for long missions, but they still have a low TRL [4, 52] (a detailed description of these processes can be found in [52]). NASA is currently seeking to develop new waste recycling technologies for deep space missions to reduce system mass and volume, converting waste into usable products [106].

Brine Processor Assembly BPA

In recent years, NASA has developed the Brine Processor Assembly (BPA), a technology that recovers water from the urine brine produced during urine processing. This technology has been demonstrated on the ISS, increasing the overall water recovery to more than 98%. This process helps close the water loop, which is especially important for deep space missions. The BPA utilizes cabin air and relies on existing spacecraft hardware, including the cabin CHX and TCCS, to minimize mass, volume, and system complexity. Specifically, the BPA uses forced convection of cabin air coupled with an ionomer membrane water process to recover up to 80% of the available water from 22.5 liters of brine over a 26-day cycle [107]. In the process, the disposable BPA bladder receives the brine from the urine process. The BPA's dual-layer bladder performs two functions: safely containing toxic contaminants and providing water recovery. The inner layer holds the liquid but allows water vapor and some trace contaminants to pass through its microporous membrane. The outer ionomer layer also allows water vapor to escape but holds most contaminants. Heated cabin air flows over the bladder, collecting the vapor, which is then condensed by the ISS's existing condensing heat exchanger (the CCAA's CHX) [107].

A.1.6 Fire Detection and Suppression (FDS)

The FDS subsystem is responsible for detecting fires in the space habitat, alerting the crew through alarms, and providing the necessary tools to extinguish the fire. In space missions, it is critical that detection is prompt to allow the crew sufficient time to activate suppression procedures. Fire detection generally relies on two types of sensors: smoke detectors and flame detectors. Various fire suppression methods are available, including the use of water, foam, carbon dioxide, nitrogen, halon, or even depressurization of the habitat [4].

A.2 Biological Technologies

As demonstrated in the previous sections, the use of regenerative physicochemical technologies in a life support system enables closure of the water and oxygen loops. For future space habitats, it will be essential to close the carbon loop, the final component of a closed-loop life support system. This will only be possible through the development of advanced life support systems capable of recycling metabolic waste and producing food [52].

The Controlled Ecological Life Support System (CELSS) relies on two categories:

- **Chemosynthetic Systems:** These systems are based on microorganisms, such as hydrogen bacteria, that contain the stable enzyme hydrogenase, which allows them to produce food with a protein content of 70-85%. The necessary inputs for this process include urine, magnesium and iron salts, oxygen and carbon dioxide.
- **Photosynthetic Systems:** In these systems, autotrophs absorb the carbon dioxide exhaled by heterotrophs, including humans, and produce the oxygen that these organisms consume. For example, algae such as Chlorella convert carbon dioxide and water into oxygen and biomass through photosynthesis, as described by the equation:

  $$CO_2 + H_2O + \text{Light} \longrightarrow O_2 + \text{Biomass} + \text{Heat} \tag{47}$$

  Some of the edible biomass consumed by humans is converted to carbon dioxide and water, while the rest is partially oxidized and expelled in urine, feces, and sweat. One clear advantage of growing food in space is that plants can also regenerate the atmosphere [52].

Physicochemical subsystems are required to support these biological processes to create a Controlled Ecological Life Support System. A CELSS has several advantages over fully physicochemical systems. A CELSS creates a more Earth-like environment, which can have a positive effect on crew psychology. It also produces fresh fruits and vegetables, improving both dietary variety and taste. From a logistical aspect, a CELSS greatly reduces the need for resupply by producing almost all essential life support resources. The plant or algae growth unit is the largest component of a CELSS contributing to food production, oxygen generation, carbon dioxide absorption, and liquid and solid waste processing.

Some of the most important biological subsystems in an CELSS are: microorganisms, algae and higher plants.

Microorganisms

In CELSS, microorganisms can be used to support several critical functions: they can contribute to food production, atmospheric regeneration, and waste treatment. One of the main advantages of using microorganisms is their very fast growth rate and high harvest index. Microorganisms are also a source of single-cell proteins. However, a major limitation is that they contain relatively high levels of nucleic acids, which can be harmful to humans in excessive amounts. For this reason, a crew member should not consume more than 50 grams of microorganism dry mass per day [3].

Algae

Algae convert carbon dioxide to oxygen and are rich in vitamins and proteins; however, their integration into a CELSS presents several challenges. It is generally not recommended that algae constitute more than 20% of a person's diet, and maintaining and harvesting algae over long periods of time is technically difficult [3].

Higher plants

Plants are capable of providing most of the essential nutritional requirements of humans, including calories, proteins, fats, carbohydrates, minerals, vitamins, and trace elements. When higher plants are integrated into a life support system, they not only provide food, but also contribute to atmospheric revitalization (by consuming water and carbon dioxide from the environment and converting them to carbohydrates and oxygen) and to water regeneration (as the water transpired by plants can be collected and reused for hygiene or potable water). Integrating higher plants into the CELSS architecture for long-duration missions can significantly reduce the need for large storage and resupply costs. Key environmental parameters to be considered in the design of a plant production system include: temperature, light intensity and duration, spectral composition, atmospheric carbon dioxide concentration, irrigation, water quality, plant protection, fertilization, and cultivation techniques [52].

The advantages and disadvantages of biological systems are summarized in the table 19.

Table 19: Advantages and disadvantages of biological systems [52].

Biological Agent	**Advantages**	**Disadvantages**
Microorganisms	- Convert organic waste materials to water, CO_2 and usable plant nutrients.	- Use oxygen; - Slow process; - Unknown control mechanisms.
Algae	- Convert CO_2 to O_2. - Simple, stable system.	- Unpalatable. - Indigestible.
Higher Plants	- Convert CO_2 to O_2. - Provide food. - Provide water via transpiration.	- Production of biomass. - High power and volume. - Considered unreliable.

B Database ECLSS Technologies

This appendix presents the data collected for each ECLSS technology considered in this study.

B.1 Temperature and Humidity Control (THC) Database

Table 20: THC database.

Technology	**CM**	**Mass [kg]**	**Volume** $[m^3]$	**Power [kW]**	**Thermal load [kW]**	**Resupply** $[\frac{kg}{CM \cdot day}]$	**Failure rate** $[\frac{1}{day}]$	**Ref.**
Resistance Temperature detector	4	0.0455	8.20E-05	0.001	0.001	0	-	[5]
CCAA	4	112	0.4	0.468	0.468	0	8.72E-04	[5, 108]
Avionics Air Assembly	4	12.4	0.034	0.1125	0.1125	0	-	[5, 108]
Intermodule Ventilation Fan	4	9.2	0.0093	0.055	0.055	0	-	[5, 108]
Intermodule Ventilation Valve	4	5.1	0.0099	0.006	0.006	0	-	[5, 108]
Bacteria Filter Assembly	4	4.6	0.121	0	0	0.0326	1.20E-07	[5, 108]

B.2 Atmosphere Control and Supply (ACS) Database

Table 21: ACS database.

Technology	**CM**	**Mass [kg]**	**Volume** $[m^3]$	**Power [kW]**	**Thermal load [kW]**	**Resupply** $[\frac{kg}{CM \cdot day}]$	**Failure rate** $[\frac{1}{day}]$	**Ref.**
Pressure Control Assembly	4	22	0.062	0.018	0.018	0	1.92E-03	[5, 109]
Manual Pressure Equalization Valve	4	1.2	0.0014	0	0	0	1.44E-04	[5, 109]
Nitrogen Interface Assembly	4	7.5	0.0122	5.50E-03	5.50E-03	0	-	[5]

Table 22: ACS: tank data.

Technology	**Tank ratio** $[\frac{kg\,tank}{kg\,element}]$	**Failure rate** $[\frac{1}{day}]$	**Ref.**
O_2 Tank High Pressure	0.364	7.32E-05	[57, 104]
O_2 Tank Cryogenic Liquid	0.429	2.98E-04	[104, 108]
N_2 Tank High Pressure	0.556	7.32E-05	[4, 104, 108]
N_2 Tank Cryogenic Liquid	0.524	2.98E-04	[4, 104, 108]

B.3 Atmosphere Revitalization (AR) Database

Table 23: AR: Carbon dioxide removal technologies.

Technology	**CM**	**Mass [kg]**	**Volume** [m^3]	**Power [kW]**	**Thermal load [kW]**	**Resupply** [$\frac{kg}{CM \cdot day}$]	**Failure rate** [$\frac{1}{day}$]	**Ref.**
4 Bed Molecular Sieves	4	201	0.39	0.86	0.86	0.008	2.99E-03	[56, 57]
2 Bed molecular sieves	3	48.1	0.26	0.23	0.23	0	-	[52]
Solid Amine Water Desorption	3	51.3	0.21	0.454	0.454	0.00466	3.46E-03	[52, 56, 110]
Electrochemical Depolarization Concentration	4	44.4	0.0713	0.148	0.336	0.003	5.21E-03	[52, 56, 110]
LiOH	1	0	1.23E-03	3.00E-03	0	1.75	3.60E-05	[3, 57]

Table 24: AR: Carbon dioxide technologies.

Technology	**CM**	**Mass [kg]**	**Volume** [m^3]	**Power [kW]**	**Thermal load [kW]**	**Resupply** [$\frac{kg}{CM \cdot day}$]	**Failure rate** [$\frac{1}{day}$]	**Ref.**
Sabatier	4	18	0.75	0.05	0.27	0.0024	2.74E-03	[56, 57]
Bosch	4	102.1	0.3	0.95	0.313	0.007	0.01224	[56,111]
ACRS	3	180	0.3	0.4	0.15	–	0.01488	[52,111]

Table 25: AR: O_2 Generation technologies.

Technology	**CM**	**Mass [kg]**	**Volume** $[m^3]$	**Power [kW]**	**Thermal load [kW]**	**Resupply** $[\frac{kg}{CM \cdot day}]$	**Failure rate** $[\frac{1}{day}]$	**Ref.**
Static Feed Water Electrolysis	3	54.6	0.057	1.09	0.27575	0	1.51E-03	[112]
Solid Polymer Water Electrolysis	7	113	0.14	1.47	1.47	0.018	2.10E-03	[56,111]

Table 26: AR: MCA and TCCS.

Technology	**CM**	**Mass [kg]**	**Volume** $[m^3]$	**Power [kW]**	**Thermal load [kW]**	**Resupply** $[\frac{kg}{CM \cdot day}]$	**Failure rate** $[\frac{1}{day}]$	**Ref.**
Major constituent analyzer	4	54.7	0.439	0.0876	0.0876	0.00833	1.55E-05	[5, 108]
Trace contaminant control	4	78.2	0.272	0.1746	0.1746	0.0167	1.15E-05	[5, 108]

B.4 Water Recovery and Management (WRM) Database

Table 27: WRM: water tank data.

Technology	**Tank ratio** $[\frac{kg\,tank}{kg\,element}]$	**Failure rate** $[\frac{1}{day}]$	**Ref.**
Water Storage	0.02	0	[3]

VAPCAR, TIMES, and AES are designed for a specified wastewater processing rate, expressed in $\frac{\text{kg}}{\text{day}\cdot\text{WW}}$, and they have a resupply requirement expressed in $\frac{\text{kg}}{\text{day}}$.

Table 28: WRM: urine process technologies.

Technology	**CM**	**Mass** [kg]	**Volume** $[m^3]$	**Power** [kW]	**Thermal load** [kW]	**Resupply** $[\frac{kg}{CM \cdot day}]$	**Failure rate** $[\frac{1}{day}]$	**Ref.**
Vapor compressor distillation	8	128	0.37	0.09	0.09	0.06	3.71E-03	[57,113]
Vapor Phase Catalytic Ammonia Removal	50.9 $\frac{kg}{(day\,WW)}$	412	1.57	2.38	2.38	0.005 $\frac{kg}{day}$	4.57E-03	[56,114]
Thermoelectric Integrated Membrane Evaporation System	20 $\frac{kg}{(day\,WW)}$	68	0.23	0.17	0.17	0.05 $\frac{kg}{day}$	4.57E-03	[52,114]
Air Evaporation Systems	7.64 $\frac{kg}{(day\,urine)}$	45.3	0.15	0.578	0.577	0.071 $\frac{kg}{day}$	1.20E-03	[56,115]

Table 29: WRM: water process data.

Technology	**CM**	**Mass [kg]**	**Volume** [m^3]	**Power [kW]**	**Thermal load [kW]**	**Resupply** [$\frac{kg}{CM \cdot day}$]	**Failure rate** [$\frac{1}{day}$]	**Ref.**
Reverse osmosis	4	8.5	0.056	0.02	0.015	0	1.16E-03	[52,115]
Multifiltration	10	476	2.25	0.3	0.3	0.13	4.39E-03	[57]

Table 30: WRM: water quality monitoring data.

Technology	**CM**	**Mass [kg]**	**Volume** [m^3]	**Power [kW]**	**Thermal load [kW]**	**Resupply** [$\frac{kg}{CM \cdot day}$]	**Failure rate** [$\frac{1}{day}$]	**Ref.**
Process Control Water Quality Monitor	4	38	0.051	0.03	0.03	0	3.17E-04	[5, 115]

B.5 Waste Management (WM) Database

Table 31: WM: Super Critical Wet Oxidation data.

Technology	**CM**	**Mass [kg]**	**Volume** [m^3]	**Power [kW]**	**Thermal load [kW]**	**Resupply** [$\frac{kg}{CM \cdot day}$]	**Failure rate** [$\frac{1}{day}$]	**Ref.**
Super Critical Wet Oxidation	4	694	2.12	1.44	0.36	0	-	[52]

Table 32: WM: BPA data.

Technology	**CM**	**Mass [kg]**	**Volume** [m^3]	**Power [kW]**	**Thermal load [kW]**	**Resupply** [$\frac{kg}{CM \cdot day}$]	**Failure rate** [$\frac{1}{day}$]	**Ref.**
BPA	4	14.1	0.15	0.142	0.142	0.0355	-	[116]

B.6 Fire Detection and Suppression (FDS) Database

Table 33: FDS: technologies data.

Technology	**CM**	**Mass [kg]**	**Volume** $[m^3]$	**Power [kW]**	**Thermal load [kW]**	**Resupply** $[\frac{kg}{CM \cdot day}]$	**Failure rate** $[\frac{1}{day}]$	**Ref.**
Portable fire estinguisher	4	6.8	0.0405	0	0	0	0	[5]
Fire detection assembly	4	1.5	0.0028	0.00148	0.00148	0	0	[5]

C Configuration PV Model Editor

Figures 138 to 140 show the enumeration definitions and extensions that were created to support model integration with the ESM and reliability analysis, and V-HAB. The order follows a layout that goes from left to right and from top to bottom.

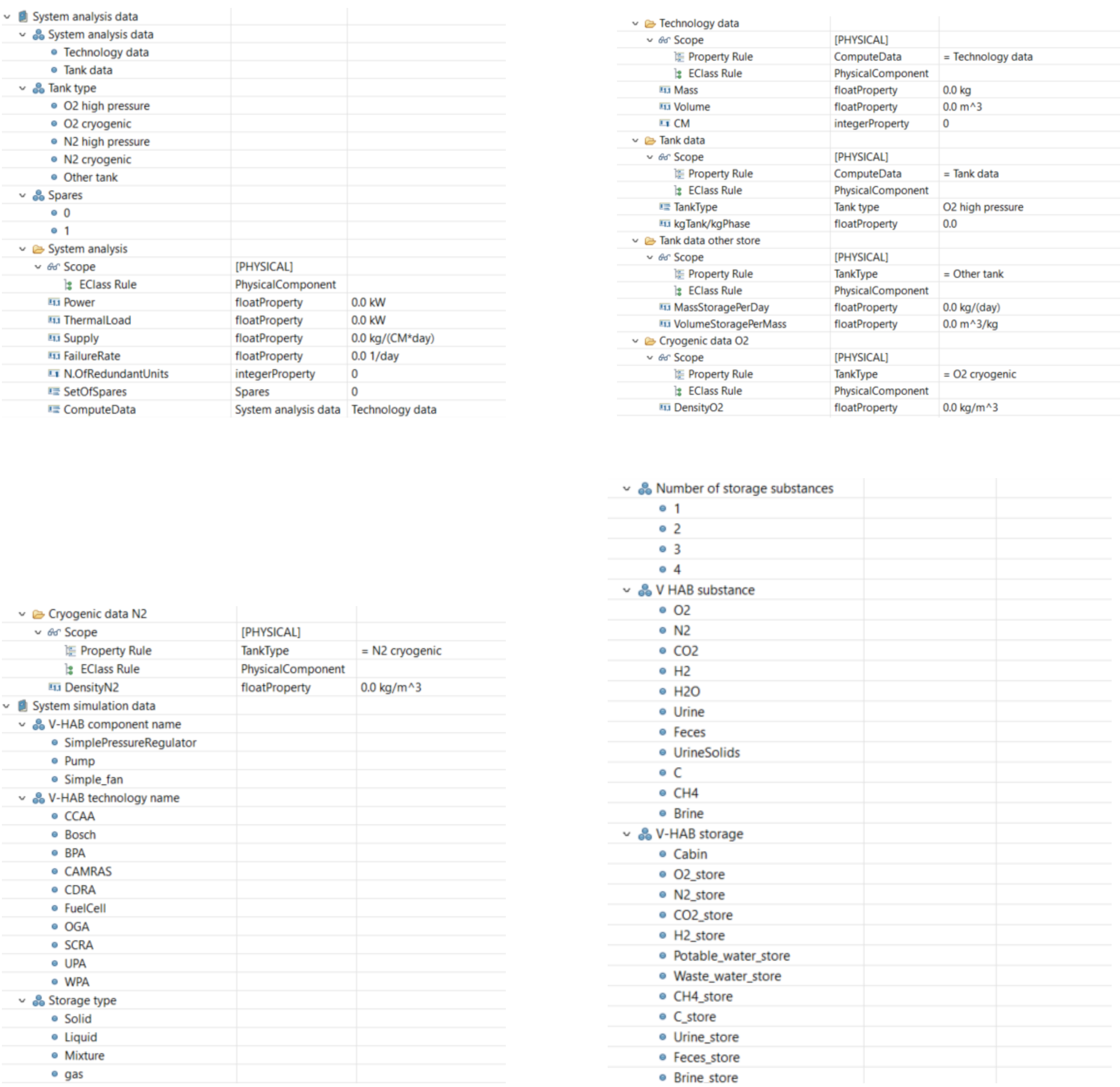


Figure 138: Configuration PV model editor (1).

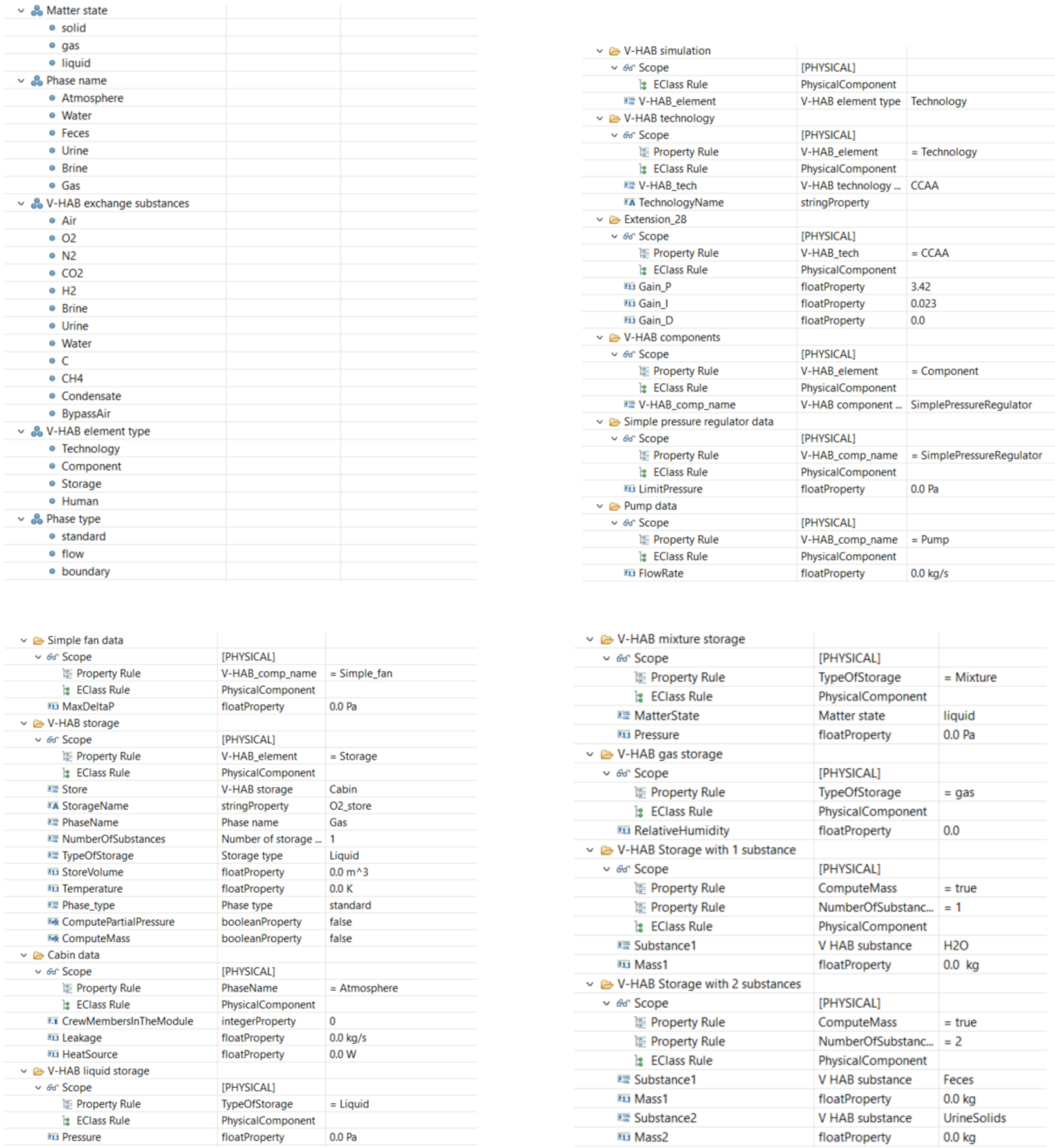


Figure 139: Configuration PV model editor (2).

V-HAB Storage with 3 substances		
Scope	[PHYSICAL]	
Property Rule	ComputeMass	= true
Property Rule	NumberOfSubstanc...	= 3
EClass Rule	PhysicalComponent	
Substance1	V HAB substance	Urine
Mass1	floatProperty	0.0 kg
Substance2	V HAB substance	H2O
Mass2	floatProperty	0.0
Substance3	V HAB substance	UrineSolids
Mass3	floatProperty	0.0
V-HAB Storage with 4 substances		
Scope	[PHYSICAL]	
Property Rule	ComputeMass	= true
Property Rule	NumberOfSubstanc...	= 4
EClass Rule	PhysicalComponent	
Substance1	V HAB substance	H2O
Mass1	floatProperty	0.0 kg
Substance2	V HAB substance	Urine
Mass2	floatProperty	0.0 kg
Substance3	V HAB substance	Feces
Mass3	floatProperty	0.0 kg
Substance4	V HAB substance	UrineSolids
Mass4	floatProperty	0.0 kg
V-HAB Storage with 1 substance (gas)		
Scope	[PHYSICAL]	
Property Rule	NumberOfSubstanc...	= 1
Property Rule	ComputePartialPres...	= true
EClass Rule	PhysicalComponent	
Substance1	V HAB substance	O2
PartialPressure1	floatProperty	0.0 Pa

V-HAB Storage with 2 substances (gas)		
Scope	[PHYSICAL]	
Property Rule	ComputePartialPres...	= true
Property Rule	NumberOfSubstanc...	= 2
EClass Rule	PhysicalComponent	
Substance1	V HAB substance	O2
PartialPressure1	floatProperty	0.0 Pa
Substance2	V HAB substance	O2
PartialPressure2	floatProperty	0.0 Pa
V-HAB Storage with 3 substances (gas)		
Scope	[PHYSICAL]	
Property Rule	ComputePartialPres...	= true
Property Rule	NumberOfSubstanc...	= 3
EClass Rule	PhysicalComponent	
Substance1	V HAB substance	O2
PartialPressure1	floatProperty	0.0 Pa
Substance2	V HAB substance	O2
PartialPressure2	floatProperty	0.0 Pa
Substance3	V HAB substance	O2
PartialPressure3	floatProperty	0.0
V-HAB Storage with 4 substances (gas)		
Scope	[PHYSICAL]	
Property Rule	ComputePartialPres...	= true
Property Rule	NumberOfSubstanc...	= 4
EClass Rule	PhysicalComponent	
Substance1	V HAB substance	O2
PartialPressure1	floatProperty	0.0 Pa
Substance2	V HAB substance	O2
PartialPressure2	floatProperty	0.0 Pa
Substance3	V HAB substance	O2
PartialPressure3	floatProperty	0.0 Pa
Substance4	V HAB substance	O2

Simulation and analysis data		
Scope	[PHYSICAL]	
EClass Rule	Constraint	
DesiredRatio_pO2_pTotal	floatProperty	0.24
DesiredTotalPressure	floatProperty	0.0 Pa
DesiredO2PartialPressure	floatProperty	0.0 Pa
DesiredN2PartialPressure	floatProperty	0.0 Pa
DesiredCO2PartialPressure	floatProperty	0.0 Pa
DesiredTemperature	floatProperty	0.0 K
CrewMembers	integerProperty	2
FoodMassStore	floatProperty	100.0 kg
ComputeCrewData	booleanProperty	false
TotalHabitatVolume	floatProperty	0.0 m^3
CF_power	floatProperty	0.0 kg/kW
CF_thermal	floatProperty	0.0 kg/kW
CF_volume	floatProperty	0.0 kW
MissionDurationAnalysis	integerProperty	0 days
SimulationTime	floatProperty	1.0 days
Crew data		
Scope	[PHYSICAL]	
Property Rule	ComputeCrewData	= true
EClass Rule	Constraint	
MeanHeight	floatProperty	0.0 m
MeanAge	integerProperty	0 years
BreakfastTime	integerProperty	0
LunchTime	integerProperty	0
DinnerTime	integerProperty	0

ITCS data		
Scope	[PHYSICAL]	
EClass Rule	Constraint	
CoolantStoreVolume	floatProperty	0.0 m^3
CoolantStoreTemperature	floatProperty	0.0 K
CoolantStoreMass	floatProperty	0.0 kg
CoolantStorePressure	floatProperty	0.0 Pa
Physical path		
Scope	[PHYSICAL]	
EClass Rule	PhysicalPath	
Exchange substance	V-HAB exchange su...	Air
ComputeFlowRate	booleanProperty	false
ComputeGasControlSystem	booleanProperty	false
Flow rate		
Scope	[PHYSICAL]	
Property Rule	ComputeGasContro...	!= true
Property Rule	ComputeFlowRate	= true
EClass Rule	PhysicalPath	
FlowRate	floatProperty	0.003 kg/s
Control system O2		
Scope	[PHYSICAL]	
Property Rule	ComputeFlowRate	!= true
Property Rule	ComputeGasContro...	= true
Property Rule	Exchange substance	= O2
EClass Rule	PhysicalPath	
EnableO2Control	booleanProperty	false
Flow rate O2 control		
Scope	[PHYSICAL]	
Property Rule	EnableO2Control	= true
EClass Rule	PhysicalPath	
FlowRateO2Control	floatProperty	8.8268E-5 kg/s

Control system N2		
Scope	[PHYSICAL]	
Property Rule	ComputeFlowRate	!= true
Property Rule	ComputeGasContro...	= true
Property Rule	Exchange substance	= N2
EClass Rule	PhysicalPath	
EnableN2Control	booleanProperty	false
Flow rate N2 control		
Scope	[PHYSICAL]	
Property Rule	EnableN2Control	= true
EClass Rule	PhysicalPath	
FlowRateN2Control	floatProperty	2.16017E-4 kg/s
Crew planner		
Scope	[PHYSICAL]	
Property Rule	V-HAB_element	= Human
EClass Rule	PhysicalComponent	
StorageNameCabin	stringProperty	Cabin
ExerciseStartTime	floatProperty	5.0 h
ExerciseDuration	floatProperty	0.5 h
ExerciseLevel	floatProperty	0.75 percent of VO2 max
SleepStartTime	floatProperty	16.0 h
SleepDuration	floatProperty	8.0 h

Figure 140: Configuration PV model editor (3).

References

[1] G. Clément and A. P. Bukley, “Human space exploration – From surviving to performing,” *Acta Astronautica*, vol. 100, pp. 101–106, July 2014.

[2] International Space Exploration Coordination Group, “Global Exploration Roadmap Supplement,” October 2022. https://www.globalspaceexploration.org/wp-content/isecg/GER_Supplement_Update_2022.pdf Accessed: 2025-07-12.

[3] W. J. Larson and L. K. Pranke, *Human spaceflight: mission analysis and design.* Space technology series, McGraw-Hill, 1st ed., 1999.

[4] P. O. Wieland, *Designing for human presence in space: an introduction to environmental control and life support systems*, vol. 1324. National Aeronautics and Space Administration, Office of Management, 1994.

[5] P. O. Wieland, “Living together in space: the design and operation of the life support systems on the international space station,” tech. rep., NASA Marshall Space Flight Center, 1998.

[6] A. M. Madni and M. Sievers, “Model-based systems engineering: Motivation, current status, and research opportunities,” *Systems Engineering*, vol. 21, no. 3, pp. 172–190, 2018.

[7] MG Techsoft, “Transitioning from document-centric to model-centric systems engineering,” 2022. https://mgtechsoft.com/blog/transitioning-document-to-model-centric-engineering/ Accessed: 2025-07-09.

[8] T. Huldt and I. Stenius, “State-of-practice survey of model-based systems engineering,” *Systems engineering*, vol. 22, no. 2, pp. 134–145, 2019.

[9] C. O. Daniel Kaschubek and J. Schnaitmann, “V-hab documentation.” https://wiki.tum.de/display/vhab Accessed: 2025-05-15.

[10] C. Olthoff, D.Pütz, J. Schnaitmann, “Dynamic life support system simulations with v-hab,” in *Deutscher Luft-und Raumfahrtkongress 2015*, 2015.

[11] Astronomy Magazine, “A brief history of soviet and russian human spaceflight,” 2023. https://www.astronomy.com/space-exploration/a-brief-history-of-soviet-and-russian-human-spaceflight/ Accessed: 2025-04-18.

[12] Wikipedia contributors, “Mir — wikipedia, the free encyclopedia,” 2025. https://en.wikipedia.org/wiki/Mir Accessed: 2025-05-06.

[13] NASA, “60 years and counting: Human spaceflight,” 2018. https://www.nasa.gov/specials/60counting/spaceflight.html Accessed: 2025-04-18.

[14] China Manned Space Agency, “About cms,” 2024. https://en.cmse.gov.cn/aboutcms/#:~:text=In%20september%201992%2C%20chinese%20government,carry%20out%20space%20application%20experiments Accessed: 2025-06-05.

[15] Institute of Science and Technology, “A brief history of the chinese manned space programme,” 2022. https://istonline.org.uk/resources/a-brief-history-of-the-chinese-manned-space-programme/ Accessed: 2025-04-18.

[16] SpaceNews Staff, "China set to carry out controlled deorbiting of tiangong-2 space lab," 2019. https://spacenews.com/china-set-to-carry-out-controlled-deorbiting-of-tiangong-2-space-lab/ Accessed: 2025-04-18.

[17] A. J. Daisy Dobrijevic, "China's tiangong space station: A guide," 2023. https://www.space.com/tiangong-space-station/ Accessed: 2025-04-18.

[18] A. Jones, "China lays out big plans for its new tiangong space station," 2022. https://www.space.com/china-big-plans-tiangong-space-station Accessed: 2025-05-06.

[19] G. Autry and P. Marquez, "The commercial space age is here," *Harvard Business Review*, February 2021. https://hbr.org/2021/02/the-commercial-space-age-is-here Accessed: 2025-04-19.

[20] Axiom Space, "Axiom space and esa sign memorandum of understanding for future collaboration," 2023. https://www.axiomspace.com/release/esa-partnership Accessed on April 19, 2025.

[21] R. Bardan, "Seven us companies collaborate with nasa to advance space capabilities," 6 2023. https://www.nasa.gov/news-release/seven-us-companies-collaborate-with-nasa-to-advance-space-capabilities Accessed: 2025-04-20.

[22] NASA, "Artemis," 2024. https://www.nasa.gov/humans-in-space/artemis Accessed: 2025-04-19.

[23] S. Creech, J. Guidi, and D. Elburn, "Artemis: An Overview of NASA's Activities to Return Humans to the Moon," in *2022 IEEE Aerospace Conference (AERO)*, (Big Sky, MT, USA), pp. 1–7, IEEE, Mar. 2022.

[24] Indian Space Research Organisation, "Gaganyaan programme," 2025. https://www.isro.gov.in/Gaganyaan.html Accessed: 2025-04-20.

[25] UAE Space Agency, "Emirates mars mission – hope probe," 2025. https://www.emiratesmarsmission.ae. Accessed: 2025-04-20.

[26] M. Shelhamer, "Why send humans into space? Science and non-science motivations for human space flight," *Space Policy*, vol. 42, pp. 37–40, Nov. 2017.

[27] R. J. Rovetto, "Defending spaceflight – The echoes of Apollo," *Space Policy*, vol. 38, pp. 68–78, Nov. 2016.

[28] P. Bond and A. Wilson, *Benefits of human spaceflight.* No. 230 in ESA BR, Noordwijk: ESA Publications Div, 2005.

[29] D. A. Mindell, S. A. Uebelhart, A. A. Siddiqi, and S. Gerovitch, *The Future of Human Spaceflight: Objectives and Policy Implications in a Global Context.* Cambridge, MA: American Academy of Arts and Sciences, 2009.

[30] P. M. Jones and E. Fiedler, "Human factors in space exploration," Tech. Rep. NASA/TM-2011-11268, NASA Ames Research Center, 2011. Chapter draft for *Review of Human Factors and Ergonomics*, Volume 6.

[31] S. Corpino, "Space environment and its effects on humans." Course slides for "Aerospace Systems", Politecnico di Torino, 2024.

[32] J. Zhang, H. Zhang, J. Wu, and J. Zhang, "Relative Humidity (RH) Effects on PEM Fuel Cells," in *Pem Fuel Cell Testing and Diagnosis*, pp. 201–223, Elsevier, 2013.

[33] S. M. Exams, "Respiratory quotient (rq)," 2024. `https://www.savemyexams.com/a-level/biology/cie/25/revision-notes/12-energy-and-respiration/12-1-energy/respiratory-quotient-rq/` Accessed on June 4, 2025.

[34] S. Mane, "Theoretical overview on space analog habitat management," *International Journal of Enhanced Research in Science, Technology & Engineering*, vol. 13, pp. 27–32, 04 2024.

[35] L. Orzechowski, "What is an analog mission?," 2024. `https://lunares.space/what-is-an-analog-mission/` Accessed: 2025-05-02.

[36] NASA, "Analog missions," 2025. `https://www.nasa.gov/analog-missions/` Accessed: 2025-05-02.

[37] G. G. De La Torre, G. Groemer, A. Diaz-Artiles, N. Pattyn, J. Van Cutsem, M. Musilova, W. Kopec, S. Schneider, V. Abeln, T. Larose, F. Ferlazzo, P. Zivi, A. De Carvalho, G. M. Sandal, L. Orzechowski, M. Nicolas, R. Billette De Villemeur, A. P.-L. Traon, and I. Antunes, "Space Analogs and Behavioral Health Performance Research review and recommendations checklist from ESA Topical Team," *npj Microgravity*, vol. 10, p. 98, Oct. 2024.

[38] C. Heinicke and M. Arnhof, "A review of existing analog habitats and lessons for future lunar and Martian habitats," *REACH*, vol. 21-22, p. 100038, Mar. 2021.

[39] NASA, "Technology readiness levels." `https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/` Accessed: 2025-05-03.

[40] F. Pagnini, D. Phillips, K. Bercovitz, and E. Langer, "Mindfulness and relaxation training for long duration spaceflight: Evidences from analog environments and military settings," *Acta Astronautica*, vol. 165, pp. 1–8, Dec. 2019.

[41] NASA, "Antarctic stations." `https://www.nasa.gov/mission/antarctic-stations/` Accessed: 2025-05-03.

[42] NASA, "Concordia research station." `https://www.nasa.gov/mission/concordia/` Accessed: 2025-05-03.

[43] Wikipedia contributors, "Stazione mcmurdo — wikipedia, l'enciclopedia libera," 2025. `https://it.wikipedia.org/wiki/Stazione_McMurdo` Accesso: 6 maggio 2025.

[44] Institute of Polar Sciences, National Research Council (ISP-CNR), "Concordia research station," 2025. `https://www.isp.cnr.it/index.php/en/infrastructures/research-stations/concordia` Accessed: 6 May 2025.

[45] NASA, "Human exploration research analog (hera)." `https://www.nasa.gov/mission/hera/` Accessed: 2025-05-03.

[46] NASA, "Human exploration research analog (hera)," 2025. https://www.nasa.gov/hera-about-hera/ Accessed: 6 May 2025.

[47] European Space Agency, "Mars500 study overview." https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Mars500/Mars500_study_overview. Accessed: 2025-05-03.

[48] European Space Agency (ESA), "Das mars500-habitat in moskau," 2011. https://www.esa.int/ESA_Multimedia/Images/2011/11/Das_Mars500-Habitat_in_Moskau Accessed: 6 May 2025.

[49] NASA, "Hestia facility capabilities." https://www.nasa.gov/missions/analog-field-testing/hestia-facility-capabilities/ Accessed: 2025-05-03.

[50] European Cooperation for Space Standardization (ECSS), "Space engineering - environmental control and life support (ecls)," Tech. Rep. ECSS-E-ST-34C, ESA-ESTEC, Requirements & Standards Division, Noordwijk, The Netherlands, July 2008.

[51] Encyclopedia Britannica, "Biosphere," 2025. https://www.britannica.com/science/biosphere Accessed: 2025-05-04.

[52] P. Eckart, *Spaceflight life support and biospherics*. No. 5 in Space technology library, Torrance, Calif: Microcosm Press, softcover reprint ed., 1996.

[53] NASA, "Space station regenerative eclss flow diagram," 2017. https://www.nasa.gov/image-article/space-station-regenerative-eclss-flow-diagram/ Accessed: 2025-05-04.

[54] C. Ray and A. Adams, "Environmental control and life support system," in *Technology for Space Station Evolution Workshop*, (Dallas, Texas), NASA, Marshall Space Flight Center, 1990. Presented January 16–19, 1990.

[55] L. Vega, "Environmental Control and Life Support (ECLS) Systems," in *Handbook of Bioastronautics* (L. R. Young and J. P. Sutton, eds.), pp. 1–11, Cham: Springer International Publishing, 2020.

[56] T. Binder, E. Nathanson, S. Belz, and S. Fasoulas, "Efficient Evaluation Method of System Concepts for Preliminary ECLSS Design Studies," in *44th International Conference on Environmental Systems*, 2014.

[57] H. Jones, "Design and Analysis of a Flexible, Reliable Deep Space Life Support System," in *42nd International Conference on Environmental Systems*, (San Diego, California), American Institute of Aeronautics and Astronautics, July 2012.

[58] J. A. Levri, D. A. Vaccari, and A. E. Drysdale, "Theory and Application of the Equivalent System Mass Metric," tech. rep., NASA, July 2000.

[59] M. Swickrath, M. Anderson, and R. Bagdigian, "Parametric Analysis of Life Support Systems for Future Space Exploration Missions," in *41st International Conference on Environmental Systems*, (Portland, Oregon), American Institute of Aeronautics and Astronautics, July 2011.

[60] G. Sharma and R. N. Rai, "Reliability modeling and analysis of environmental control and life support systems of space stations: A literature survey," *Acta Astronautica*, vol. 155, pp. 238–246, Feb. 2019.

[61] H. Jones, "Reliability Analysis of Carbon Dioxide Reduction Systems," in *41st International Conference on Environmental Systems*, (Portland, Oregon), American Institute of Aeronautics and Astronautics, July 2011.

[62] H. Jones, "Life Support Dependability for Distant Space Missions," in *40th International Conference on Environmental Systems*, (Barcelona, Spain), American Institute of Aeronautics and Astronautics, July 2010.

[63] H. Jones, "Methods and Costs to Achieve Ultra Reliable Life Support," in *42nd International Conference on Environmental Systems*, (San Diego, California), American Institute of Aeronautics and Astronautics, July 2012.

[64] M. Czupalla, A. Zhukov, J. Schnaitmann, C. Olthoff, M. Deiml, P. Plötner, and U. Walter, "The Virtual Habitat – A tool for dynamic life support system simulations," *Advances in Space Research*, vol. 55, pp. 2683–2707, June 2015.

[65] D. Pütz, C. Olthoff, J. Schnaitmann, and U. Water, "Development Status of the Virtual Habitat (V-HAB) Simulation System," in *49nd International Conference on Environmental Systems*, July 2019.

[66] P. Ploetner, M. S. Anderson, M. Czupalla, M. K. Ewert, C. M. Roth, and A. Zhukov, "Status of the Correlation Process of the V-HAB Simulation with Ground Tests and ISS Telemetry Data," in *43rd International Conference on Environmental Systems*, (Vail, CO), American Institute of Aeronautics and Astronautics, July 2013.

[67] International Council on Systems Engineering (INCOSE), "Systems engineering definition," 2025. `https://www.incose.org/about-systems-engineering/system-and-se-definitions/systems-engineering-definition`, Accessed on June 4, 2025.

[68] M. H. Sadraey, *Aircraft design: a systems engineering approach*. Aerospace series, Chichestet, West Sussex: Wiley, online-ausg ed., 2013.

[69] S. J. Kapurch, *NASA systems engineering handbook*. Diane Publishing, 2010.

[70] H. Abuamara, P. Badzey, W. Chang, F. Lawler, J. Mancera, P. Marbach, D. Mason, H. Nguyenhuu, M. Salimi, J. Silvas, and S. Tseng, *Systems Engineering Jr. Handbook*. INCOSE LA Chapter and The Creativita Institute, 2015. Version 1.0.

[71] S. M. B. Malaek, A. Mollajan, A. Ghorbani, and A. Sharahi, "A New Systems Engineering Model Based on the Principles of Axiomatic Design," *Journal of Industrial and Intelligent Information*, vol. 3, no. 2, 2014.

[72] Wikipedia contributors, "V-model," 2024. `https://en.wikipedia.org/wiki/V-model` Accessed: 2025-05-22.

[73] INCOSE, "Mbse initiative," 2024. `https://www.incose.org/communities/working-groups-initiatives/mbse-initiative` Accessed: 2025-05-17.

[74] A. L. Ramos, J. V. Ferreira, and J. Barcelo, "Model-Based Systems Engineering: An Emerging Approach for Modern Systems," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 42, pp. 101–111, Jan. 2012.

[75] A. M. Madni and S. Purohit, "Economic Analysis of Model-Based Systems Engineering," *Systems*, vol. 7, p. 12, Feb. 2019.

[76] L. E. Hart, "Introduction to model-based system engineering (mbse) and sysml." Presented at the INCOSE Delaware Valley Chapter Meeting, July 2015. https://www.incose.org/communities/working-groups-initiatives/mbse-initiative Accessed: 2025-05-17.

[77] P. Roques, "Mbse with the arcadia method and the capella tool," in *8th European Congress on Embedded Real Time Software and Systems (ERTS 2016)*, 2016.

[78] S. Bonnet, J. Voirin, D. Exertier, and V. Normand, "Modeling system modes, states, configurations with Arcadia and Capella: method and tool perspectives," *INCOSE International Symposium*, vol. 27, pp. 548–562, July 2017.

[79] H. Castro, "Mbse with arcadia method step-by-step: Operational analysis," 2023. https://www.linkedin.com/pulse/mbse-arcadia-method-step-by-step-helder-castro/ Accessed: 2025-05-19.

[80] Thales Group, "Arcadia method overview," 2025. https://mbse-capella.org/arcadia.html Accessed: 2025-05-19.

[81] S. Bonnet, J. Voirin, V. Normand, and D. Exertier, "Implementing the MBSE Cultural Change: Organization, Coaching and Lessons Learned," *INCOSE International Symposium*, vol. 25, pp. 508–523, Oct. 2015.

[82] H. Castro, "Mbse with arcadia method step-by-step: System analysis," 2023. https://www.linkedin.com/pulse/mbse-arcadia-method-step-by-step-system-analysis-helder-castro/ Accessed: 2025-05-19.

[83] J.-L. Voirin, *Model-based system and architecture engineering with the arcadia method.* Elsevier, 2017.

[84] H. Castro, "Mbse with arcadia method step-by-step: Physical architecture," 2023. https://www.linkedin.com/pulse/mbse-arcadia-method-step-by-step-physical-helder-castro/ Accessed: 2025-05-19.

[85] M. Bajaj, D. Zwemer, R. Peak, A. Phung, A. G. Scott, and M. Wilson, "SLIM: collaborative model-based systems engineering workspace for next-generation complex systems," in *2011 Aerospace Conference*, (Big Sky, USA), pp. 1–15, IEEE, Mar. 2011.

[86] A. Busch, E. Vidana, and A. Luc, "Connecting mbse to spacecraft modeling & simulation," in *Proceedings of the Model-Based Space Systems and Software Engineering Workshop (MBSE2024)*, 05 2024.

[87] H. Sohier, P. Lamothe, S. Guermazi, M. Yagoubi, P. Menegazzi, and A. Maddaloni, "Improving simulation specification with MBSE for better simulation validation and reuse," *Systems Engineering*, vol. 24, no. 6, pp. 425–438, 2021. Publisher: Wiley.

[88] A. D'Ambrogio, "M&s and mbse: Individual challenges and mutual opportunities," in *Proceedings of the 12th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH 2022)*, (Lisbon, Portugal), 2022.

[89] Altair, "Integrating system models with simulation improves design quality and engineering productivity," 2019. https://altair.com/docs/default-source/resource-library/phoenix-integration---mbse-overview.pdf?sfvrsn=ab2ca091_3 Accessed: 2025-05-21.

[90] Ansys, "Model-based systems engineering (mbse) explained," 2025. https://www.ansys.com/blog/model-based-systems-engineering-explained Accessed: 2025-05-24.

[91] L. M. Space, "Modelcenter + lockheed martin space," tech. rep., Ansys, 2021. https://www.ansys.com/content/dam/resource-center/case-study/modelcenter-lockheed-martin-space-case-study.pdf Accessed: 2025-05-21.

[92] Northrop Grumman, "Modelcenter + northrop grumman," tech. rep., Ansys, 2021. https://www.ansys.com/content/dam/resource-center/case-study/modelcenter-northrop-grumman-case-study.pdf Accessed: 2025-05-21.

[93] D. Kaslow, G. Soremekun, H. Kim, and S. Spangelo, "Integrated model-based systems engineering (MBSE) applied to the simulation of a CubeSat mission," in *2014 IEEE Aerospace Conference*, pp. 1–14, IEEE, 2014.

[94] iExcelarc, "How to capture textual requirements in capella – complete step-by-step guide," 2022. https://iexcelarc.com/how-to-capture-textual-requirements-in-capella-complete-step-by-step-guide/ Accessed: 2025-05-25.

[95] Digitale Schiene Deutschland – Digitalisierung Bahnsystem, "py-capellambse: A Python 3 Headless Implementation of Capella," 2025. https://dsd-dbs.github.io/py-capellambse/ Accessed: 12 July 2025.

[96] PolarSys / Eclipse Foundation, "Capella MBSE Tool – Add-Ons," 2025. https://mbse-capella.org/addons.html Accessed: 12 July 2025.

[97] SEBoK Editorial Board, "Requirement (glossary)," 2024. https://sebokwiki.org/wiki/Requirement_(glossary) Accessed: 2025-05-27.

[98] H. Castro, "What is model-based systems engineering?," 2022. https://www.linkedin.com/pulse/what-model-based-systems-engineering-helder-castro/ Accessed: 2025-05-27.

[99] H. Castro, "Formalizing textual requirements in a model to improve communication between stakeholders," 2023. https://www.linkedin.com/pulse/formalizing-textual-requirements-model-improve-between-helder-castro-tlage/ Accessed: 2025-05-27.

[100] ESA, "Ecss-e-st-10-06c: Space engineering – technical requirements specification," tech. rep., European Cooperation for Space Standardization (ECSS), Noordwijk, The Netherlands, Mar. 2009. Version C, 6 March 2009.

[101] C. Knospe, "Pid control," *IEEE Control Systems Magazine*, vol. 26, no. 1, pp. 30–31, 2006.

[102] M. Perotti, "Design of an analog for human space exploration using a mbse approach," master's thesis, Politecnico di Torino, 2025.

[103] A. B. Button and J. J. Sweterlitsch, "Amine Swingbed Payload Testing on ISS," tech. rep., NASA Johnson Space Center, 2014. 44th International Conference on Environmental Systems.

[104] W. Locks, "Trade-off study and conceptual designs of regenerative advanced integrated life support systems (AILSS)," Tech. Rep. NASA CR-1458, NASA, 1970.

[105] H. W. Jones, J. W. Fisher, L. D. Delzeit, M. T. Flynn, and M. H. Kliss, "Developing the Water Supply System for Travel to Mars," in *46st International Conference on Environmental Systems*, 2016.

[106] NASA, "Recycling in space: Waste handling in a microgravity environment challenge," 2020. https://www.nasa.gov/missions/station/recycling-in-space-waste-handling-in-a-microgravity-environment-challenge/ Accessed: 2025-05-10.

[107] L. K. Kelsey, P. Pasadilla, and T. Cognata, "Closing the Water Loop for Exploration: 2018 Status of the Brine Processor Assembly," in *48st International Conference on Environmental Systems*, 2018.

[108] A. J. Hanford, "Exploration life support baseline values and assumptions document," tech. rep., NASA, 2006.

[109] R. Barker and M. Yakut, "Parametric study of manned life support systems. volume 3-computational procedures final report, jul. 1967-aug. 1968," tech. rep., NASA, 1969.

[110] G. Detrell, E. Gríful I Ponsati, and E. Messerschmid, "Reliability versus mass optimization of CO2 extraction technologies for long duration missions," *Advances in Space Research*, vol. 57, no. 11, pp. 2337–2346, 2016.

[111] H. W. Jones, "Using the system complexity metric (SCM) to compare CO2 removal systems," in *50th International Conference on Environmental Systems*, 2021.

[112] F. Schubert and R. Wynveen, "Technology advancement of the static feed water electrolysis process," tech. rep., NASA, 1977.

[113] T. T. Chen and J. J. Sweterlitsch, "Trade study analysis of a cryogenic oxygen architecture for lunar outpost life support," in *51st International Conference on Environmental Systems*, 2022.

[114] M. Flynn, F. Beganovic, A. D. Reyes, C. Flores, S. Choi, and J. Hink, "Planetary water recycling systems trade study," in *49th International Conference on Environmental Systems*, 2019.

[115] B. Schreck, "Feasibility analysis of a life support architecture for an interplanetary transport ship," master's thesis, Technische Universität München, 2017. RT-MA 2017/05.

[116] D. L. Carter and A. F. Gleich, "Selection of a brine processor technology for nasa manned missions," in *International Conference on Environmental Systems*, ICES-2016-014, 2016.