Politecnico di Torino

Master's Degree in Aerospace Engineering

Master Thesis

Integrating Operational Concepts with Model-Based Systems Engineering Methodology for the Design of a Lunar Habitat: Design by Operations

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Abstract

Nowadays, the push for space exploration has returned stronger than ever: a considerable segment of the global economy orbits around the space industry, with the private sector assuming an increasingly significant role and entailing a constellation of new possibilities and dynamics. In this context, one of the most challenging goals is the human space exploration, whose final goal is the human exploration and colonization of Mars. In order to achieve this significant objective, the first step to face is the return of the humans on the Moon.

This Thesis – conducted in collaboration with ALTEC (Aerospace Logistics Technology Engineering Company, Turin, IT) – investigates and describes the process of derivation of a functional architecture for a permanent Lunar Habitat model, whose presence will be an enabling factor for the future prolonged human presence on the Lunar surface. Its design, characterized by complex and multidisciplinary nature, must encompass all the crucial aspects involved in a mission of this complexity level, since the very beginning. One of these fundamental perspectives is the operational one: the aim of this Thesis is to obtain a functional design compatible with operational concepts of the system, in an integrated model. For this reason, this Thesis' work adopts the Model-Based Systems Engineering paradigm, and in particular the ARCADIA methodology, supported by Capella tool: this allows to derive a system model characterized by several fundamental perspectives and analysis, in a completely traceable process.

This Thesis analyzes the key challenges of long-duration human missions on the Moon, reviews the lunar environment, and introduces the Systems Engineering and MBSE frameworks central to the analysis.
The core of this work analyses the ARCADIA process applied to the functional design of the Lunar Habitat, from the Stakeholders analysis and mission objectives identification to the achievement of a functional architecture that reveals the main high level elements of the system – up to the subsystem level. This functional analysis is integrated and parallel to operational evaluations, which consists into the definition and description of system's Concept of Operations and Operative Modes.
Finally, the Thesis discusses the main achievements and design results, outlining the work's strengths, its limitations and possible future developments: from this work, further analyses on the model can be performed, from the derivation of the physical design of the system and its components to the lower-level development and integration of operational concepts and other critical perspectives. The continuation, integration and deepening of this model is allowed by the ARCADIA method and its intrinsic traceability.

Keywords: Model-Based System Engineering, ARCADIA, Lunar Habitat, Functional Analysis, Concept of Operations, Operative Modes

Context of the Work

This Thesis is developed within the Space It Up (SIU) project: it consists of a strategic partnership involving 33 entities from both the research and industrial sectors, among which Politecnico di Torino, ALTEC, Leonardo, Thales Alenia Space, Istituto Nazionale di Fisica Nucleare (INFN) and more. The purpose of this consortium is to boost Italian space technology for the exploration and exploitation of space, generating concrete benefits for the planet and humanity [1]. In particular, this Thesis work is conducted within the context of Spoke 8 – *Robotic and Human exploration of extraterrestrial habitats, architectures and infrastructures.*

1 Introduction

Human nature is characterized by a constant need for exploration, which leads to the identification of new frontiers and the development of technologies, in order to understand the universe enhance life on Earth and in space. In recent times, the push for space exploration has returned stronger than ever after Apollo missions: a substantial proportion of the global economy orbits around the space industry, which has witnessed the entry of the private sector, hence a constellation of new possibilities and dynamics. This is exemplified by the growing space tourism market, the development of commercial launch systems that service both government and private sectors, and the increasing use of privately financed space-based science [2]. In Figure 1 the SpaceX's vision for the future of human exploration is shown.

Figure 1: SpaceX vision for the future of human space exploration [3].

In this new exciting landscape, one of the most challenging goals is the return of the human space exploration, which entails the nowadays final goal: the human exploration and colonization of Mars.
The first step in order to achieve this significant objective, is the return of the humans on the Moon. The Moon is our closest planetary body – roughly three days' flying time away – with almost instantaneous communication with Earth. A strategic view of space exploration places Moon and Mars in proper order, to allow the experimentation of technologies and methodologies on the Moon before Mars, with reduced logistic challenges [4]. In this context, Figure 2 results illustrative, showing NASA's scope map for human exploration of Moon and Mars.
Several countries are exploring the possibility of establishing a permanent human presence on the Moon, with particular interest in the Lunar South Pole: recent orbiting missions have revealed that the poles may contain water and its believed that solar wind particles are trapped there. The water and volatile chemicals hold information on the history and chemistry of the inner Solar System and potentially provide resources for future exploration. Furthermore, this area is permanently sunlit, enabling uninterrupted power generation and reducing the necessity for energy storage. This, in turn, facilitates the generation of alternative power during lunar night [5, 6].

The effort required to face this challenge and to ensure the safety of astronauts is huge: human-rated transportation to the Moon, descending and landing technologies, lunar habitats, power systems, protection systems, exploration vehicles and resources are only few of the fundamental elements needed, including extremely complex human factors involved in missions of this nature.

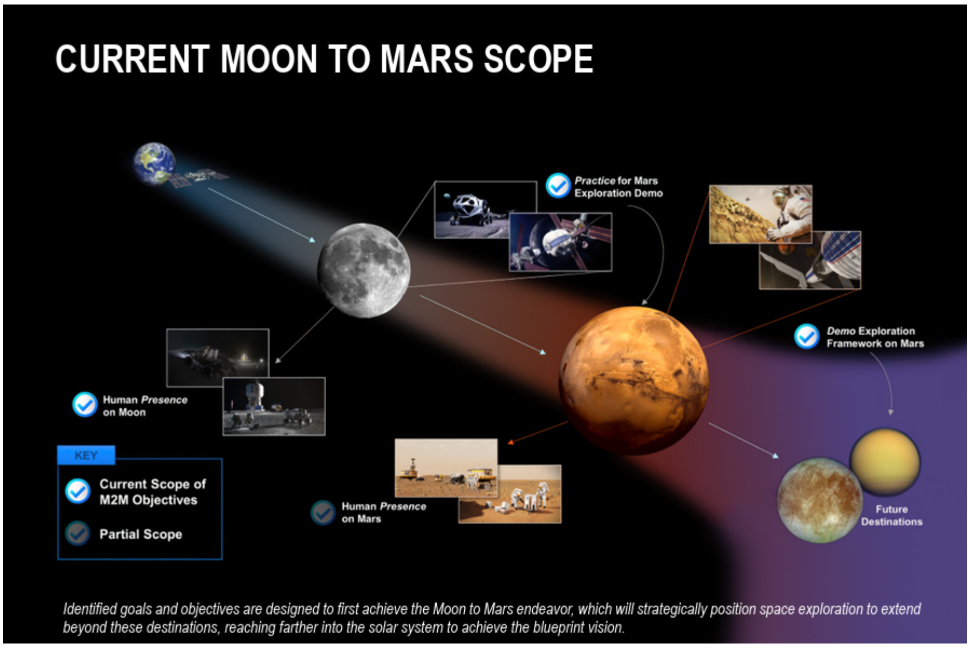

Figure 2: NASA's Moon to Mars scope map [7].

In this context, the presence of a pressurized Habitat becomes an enabling factor for the prolonged human presence on the Lunar surface. Its design, characterized by its complex and multidisciplinary nature, must encompass all the crucial aspects involved in a mission of this complexity level, since the very beginning. As the following Sections will illustrate, the lunar environment is characterized by specific features that make the survival of humans critical. it is essential to involve into the design phases, since the first ones, all the elements that allow to obtain the desired final product, not only in systems terms but also in operative and logistic sense. Model Based System Engineering (MBSE) discipline allows to do this, conducting accurate analysis during the development of the system model and ensuring that all the features and needs of the mission are taken into account. This value is incredibly important nowadays for the management and designing of complex systems' and missions' features.

This Thesis, conducted in collaboration with ALTEC – Aerospace Logistics Technology Engineering Company (Turin, IT) – will discuss the process of derivation of a Lunar Habitat model, up to a definition level in which the principal elements of the system have been identified. In particular, the value of this work lies in the absolute traceability of the process, starting from the very beginning with context and challenges evaluations, and deriving a system that meets and involves all the complexities of the case, including operations evaluations.

The Thesis is structured as follows: Section 2 provides an overview of the lunar environment, with a brief discussion of its main characteristics, followed by an historical summary of the human exploration of the Moon and future goals. Then, several concepts for a surface habitat are presented, with particular focus on the Artemis program's Surface Habitat as an illustrative case study. In conclusion, Systems Engineering discipline is described, outlining its definition and its role in mission development. In particular, this Thesis adopts the Model-Based Systems Engineering (MBSE) approach, applying the ARchitecture Analysis and Design Integrated Approach (ARCADIA) methodology: hence, this and other important methodologies are described, providing an overview of the MBSE approach's possibilities.

Section 3 presents the Research Problem of this Thesis, summarizing the challenges that MBSE allows to face during the design process.

Section 4 describes the definition of the Lunar Habitat model, hence the ARCADIA methodology's steps followed in order to obtain the desired system for the resolution of the Research Problem. In particular, the section starts with the analysis of the context and with a stakeholders analysis, which permits to identify their needs and values, from which the main mission goals and the high level mission requirements are derived. Then, the section follows the ARCADIA methodology, describing the implementation of the results of the Stakeholders' analysis on Capella and proceeding with functional-driven analysis.

Section 5 illustrates the parallel transverse modeling concepts related to system's operations integrated in the system design, performed in collaboration with ALTEC, including high level Concept of Operations (ConOps) and System's Operative Modes (OMs).

Section 6 concludes the Thesis, summarizing its main findings and highlights and its future directions.

2 Context: the Moon Challenge and the MBSE approach

The dream of inhabiting the Moon is part of human history: the mankind looked up to the Moon for all its existence, until the possibility of reaching the Moon became real, on more recent times, in 20th century. First lunar base studies were conducted in the 1940s and 1950s, and between 1969 and 1972 United States (U.S.) astronauts spent a total time of about 80 Extra Vehicular Activity (EVA) hours on lunar surface, with six successful Apollo landing missions [8]. Mission Apollo 17 marked the end of an era, but not the end of the humankind on the Moon.
Nowadays, about 50 years after the last man walked on the Moon, the interest in returning to the Moon is stronger than ever, and concrete missions are being developed in order to make this happen. NASA Artemis program and China's plans are clear: humans will get back to the Moon with astronauts before 2030 (in Figure 3 a concept art) [9, 10].

Figure 3: A NASA artist's illustration of Artemis astronauts working on the Moon [10].

In this context, it is important to understand the main characteristics of the Earth's natural satellite, and how the complexity level that derives from these can be managed. Thus, this Section begins with an overview of the lunar environment and explains how its hostile features influence the complexity of the design of a surface module.
The second part of the Section consists in an overview of the intense relationship between humans and the moon, and by the description of possible surface module concepts developed through past and recent studies will be provided. Finally, an overview of the System Engineering (SE) discipline occurs, including its definition and characteristics; in this context, the Section describes the SE approach adopted by this Thesis: the Model Based System Engineering (MBSE). The main methodologies included in this approach are summarized, and ARCADIA, the methodology used for this Thesis' work, is described before its application in Section 4.

2.1 The Lunar Environment

The differences between Earth and Moon are evident both in physical structure and environment: some of these diversities provide unique opportunities for Moon exploitation, for research and space exploration [6].
Besides this, Earth and its natural satellite have strong bonds: tidal resonance between Earth and Moon locks the Moon's rotation with one face always towards the Earth, and the other one always hidden. Therefore, this side of the Moon is shielded from the Earth's electromagnetic noise. Also, the friction generated by the tidal phenomenon causes energy dissipation: this provokes the slowdown of Earth rotation around its axis – about 1.46 seconds per century. To keep the angular momentum of the Earth-Moon system constant, our satellite moves outward about 3.8 cm per year [11, 12].

The Moon is a celestial body with a mass about 81 times smaller than Earth's, and presents smaller density and radius - about 1/4 the Earth's one. The lunar orbit around Earth presents an average major semi-axis of about 384400 km, with 5% of variation, an average sidereal period of 27.32166 days ± 7 hours and an average velocity of 1.023 km/s. The orbital eccentricity is subjected to variations too: the average eccentricity is 0.05900489, with orbital stretches with a period of 31.8 days, known as Lunar Evection phenomenon [12]. Other fundamental characteristics are reported in the Table 1 below.

Table 1: Physical comparison of Moon and Earth [4, 11, 13].

Property	**Moon**	**Earth**
Mass	$7.35310^{22}\ kg$	$5.97610^{24}\ kg$
Radius	$1738\ km$	$6371\ km$
Surface area	$37.910^{6}\ km^2$	$510.110^{6}\ km^2$
Mean density	$3.34\ g/cm^3$	$5.517\ g/cm^3$
Gravity at equator	$1.62\ m/sec^2$	$9.81\ m/sec^2$
Escape velocity at equator	$2.38\ km/sec$	$11.2\ km/sec$
Sidereal rotation time	27.322 days	23.9345 hr
Day length	29.5 Earth days	1 Earth days hours (hrs)
Inclination of orbit	$6°41'$	$23°28'$
Mean surface temperature	107°C day; -153°C night	22°C
Temperature extremes	-246°C to 127°C	-89°C to 58°C
Atmosphere	$10^4\ molecules/cm^3$ day, $2 \times 10^5\ molecules/cm^3$ night	$2.5 \times 10^{19}\ molecules/cm^3$
Surface atm pressure	0	$101.3\ kPa$
Seismic energy	$2 \times 10^{10}\ (or\ 10^{14})\ J/yr$	$10^{17} - 10^{18}\ J/yr$
Magnetic field	0	$24 - 56\ A/m$

As Table 1 shows, there are some significant differences that need to be deepened in the context of this thesis: firstly, the average temperatures are extreme for human survival as well as the thermal excursion between day and night, about 5°C/hour. This represents a

challenge in particular for materials used in systems, besides for the astronauts survival. In addition, the lunar operative environment provides a negligible atmosphere, as well as magnetic field: these two characteristics implicate more exposure to radiations and the absence of breathable air for humans.
At equator, the gravity is about 1/6 than on Earth: this has to be considered in structure definition and in logistics planning, in addition to the consequences to human body and capabilities.

2.1.1 Thermal Environment

Used to the livable and moderate thermal excursions on Earth, the design of a system that has to survive and operate within the Moon thermal condition is all but trivial. The Moon environment presents a long day/night cycle – about 2 weeks each – which means long periods of extremely high or low temperatures. During the transition from lunar day to night, a rapid temperature drop occurs, resulting in about 260°C of excursion, or more. As discussed in [14], the lunar thermal environment around a potential surface module is the result of:

- Heat fluxes given by the Sun: it is the amount of power that passes through a given distance from the Sun. The nominal value at Moon distance is the Solar Constant and its average value is 1358 W/m^2.
- Reflected lunar albedo flux: the Moon's albedo – its reflectivity – is less than 10%. This means that the other 90% of incipient solar radiation heats up the surface.
- Infrared radiation flux directly from the Moon itself, which acts as a gray body source at the temperature of the surface, which varies according to surface region coordinates and to the time in the day/night cycle.

At Apollo 15 site ($26°N$, $\sim 3.6°E$) the maximum temperature reached was $101°C$, with a minimum of $-181°C$, while at Apollo 17 site ($20°N$, $30.6°E$) it was $10°C$ higher [11]. According to NASA [13], temperatures near the Moon's equator can rise over 121°C in daylight and then drop to -133°C at night. The surface regions are critical: in deep craters near the Moon's poles – in permanent shadow – NASA's Lunar Reconnaissance Orbiter has measured temperatures lower than -246°C; it is in these places that are sited ice deposits that may be billions of years old.
The temperature at lunar noon varies throughout the year with the variation of the distance from the Sun, increasing about 6°C from aphelion to perihelion. Figure 4 shows an interesting thermal map in this sense, providing a visualization of the yearly average surface temperature of the lunar south polar region.

In these conditions, particular care has to be adopted in design phase considering efficient heat management solutions in order to maintain acceptable operative temperatures, and to select highly elastic materials, even more if directly exposed to these extreme temperatures cycles [4].
An interesting spark has to be considered: it has been identified a large difference between mean surface temperature and the thermal conditions just few centimeters below. At the Apollo 15 site, the mean temperature at a depth of 35 cm was 45 °C higher than that

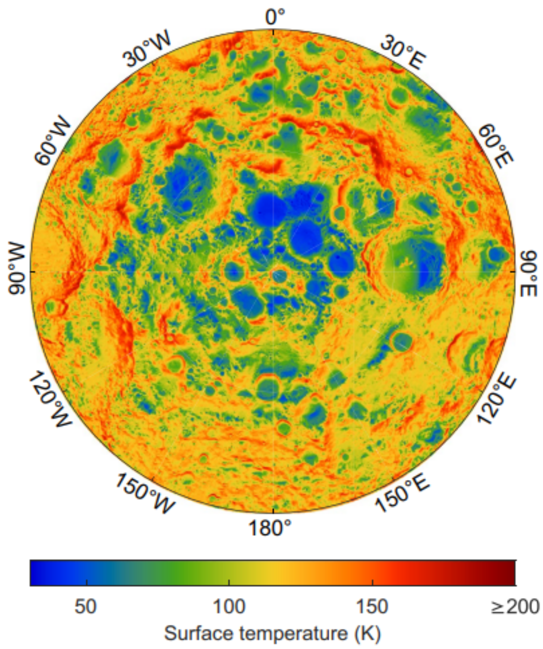

Figure 4: Yearly average surface temperature of the lunar south polar region above 80°, measured by Lunar Reconnaissance Orbiter Diviner with a resolution of 240 m/pixel [15].

of the surface; at the Apollo 17 site, the difference detected was 40 °C. This mean temperature increase along with the increase of depth is related mostly to the temperature dependence of thermal conductivity of the topmost 1 to 2 cm of lunar soil. Thermometers buried 80 cm below the lunar surface showed no perceptible variation in temperature related to the lunar day/night cycle: below these depths thermal gradients should reflect heat flow from the lunar crust. It is noteworthy that a layer of about 30 cm of regolith is sufficient to dampen out the $\sim 260°C \div 280°C$ of excursion into an only ~ 3°C variation: this means that an option for a lunar habitat module is to perform an In Situ Resource Utilization (ISRU) activity to exploit lunar regolith, in order to shield the system from the thermal fluctuations linked to the day/night cycle. This kind of solution, on the other hand, should elaborate an efficient method for the waste heat dissipation. [11]

2.1.2 Regolith

Apollo Astronauts Neil Armstrong and Alan Bean respectively stated

"*The fine surface material is a powdery, graphite-like substance that seems to be dominantly sand to silt size. When this material is in con tact with rock, it makes the rock slippery. This phenomenon was checked on a fairly smooth, sloped rock. When the powdery material was placed on the rocks, the boot sole slipped easily on the rock, and the slipping was sufficient to cause some instability of movement. Otherwise, traction was generally good in the loose, powdery material.* " - [16]

"*After lunar liftoff [...] a great quantity of dust floated free within the cabin. This dust made breathing without the helmet difficult, and enough particles were present in the cabin atmosphere to affect our vision. The use of a whisk broom prior to ingress would probably* *not be satisfactory in solving the dust problem, because the dust tends to rub deeper into the garment rather than to brush off*" - [17]

These two testimonies, directly from two renowned NASA astronauts, provide a significant introduction to the subject of this Section, the lunar soil, known as *regolith*, formed over billions of years ago, primarily due to continued impact by meteoroids and larger rocks [4].
The lunar regolith contains at least 20% silicon, 40% oxygen, and 10% metals, and, as it is possible to realize from the quotes above, the presence of regolith results in a harshly dusty environment, as possible to see in Figure 5. In fact, lunar surface soil is composed of very fine particles - $< 100\ \mu m$, in analogy with terrestrial volcanic ash or silt -, sharp and highly abrasive [14]. In particular, the *dust* is the portion of regolith that is $< 20\ \mu m$ in size, and represents the 20% of the volume by weight [4].

The regolith is a serious reason of concern for different motives, regarding both human and machine. Firstly, as emerges from Astronaut Bean's words, the dust contamination of cabin air makes difficult to breath without protections: from a physiological point of view, the concern about the dust is that it can enter the lungs, interact with blood and be carried throughout the body, potentially causing damage in particular if smaller than $2.5\ \mu m$[4]. Also, it increases the level of complexity of operations.
On the other hand, a photoelectric charge in the conductivity of the particles causes them to levitate and adhere to surfaces, resulting in a complication for the dust removal: this is a problem that can involve almost all the systems on the lunar surface – habitat, solar arrays, hatch seals, joints and interlocks, EVA suits, and radiators are just few examples – since it can cover and obscure camera lenses, interfere with mechanisms and reduce visual field if raised. Lunar regolith is much sharper than terrestrial counterparts, due to the bombardment of the surface by micrometeoroids over millions of years. This sharper shape results in more abrasive properties, which means that long term exposure, in addition to coverage and interference with systems parts, causes significant degradation phenomena [4, 18]. In all cases, during design phases, this aspect must be considered, involving shielding solutions to limit premature parts consumption, and thus maintenance and repair interventions.

National Aeronautics and Space Administration (NASA) and Lunar Science Innovation Institute (LSII) explored both active and passive strategies for regolith shielding: active methods require power and actuation, whereas passive approaches rely on surface modification or dust-tolerant materials and coatings. An example of a passive method analyzed involves the modification of surface with laser ablative patterning to prevent the adhesion of dust particles, while an active solution has been developed by NASA's Kennedy Space Center, applying dynamic electric fields to loft dust from surfaces [18].

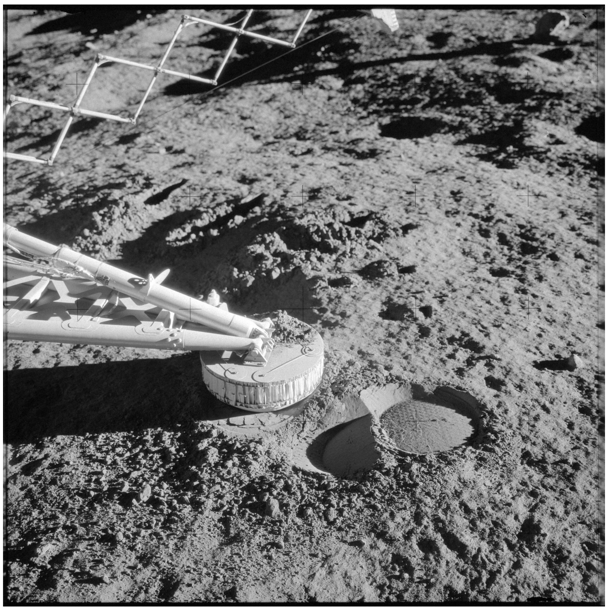

Figure 5: Landing gear mark left by Surveyor 3, Apollo 12, in April 1967, photographed on 21 November 1969 [19].

Moreover, lunar regolith does not represent only a reason of concern: it also preserves valuable information about the Moon and beyond. Trapped in the solid fragments composing regolith, there are atoms from the Sun and cosmic ray particles from beyond the solar system. The information obtainable from regolith samples regard the composition and early history of the Sun as well as of the cosmic rays, and the rate at which meteoroids and cosmic dust have bombarded the Moon – and, by inference, the Earth – in its history [11].
In addition, the lunar regolith can represent an important resource for future human outposts on the Moon: including ISRU operations, layers of regolith on a surface module can be used as thermal protection – reminding that 30 cm of regolith is sufficient to dampen out the 260°C-280°C of excursion into an only 3°C variation – and radiation shielding, as will be deepen later in this dissertation.

2.1.3 Radiations

The radiation exposure can be measured in milliSieverts [mSv], and in general it is possible to state that it increases with the mission scenario level [1]. The usual radiation dosage humans are subjected to is about 3.6 mSv per year on Earth [20]; in human flight LEO missions, such as on ISS, despite the Earth's magnetic field protection, it is possible to notice an increment of the exposure to $80 - 160$ mSv in six months [20], respectively at solar maximum and minimum. In this context, huge countermeasures are not necessary – pharmacological protection, monitoring and vehicle hull are sufficient.
Increasing the scenario level, the exposure becomes even more important, reaching maximum dosages in the interstellar space context – besides the enormous radiation levels in

[1]Mission scenarios: MS1 Near-Earth orbits, MS2 Interplanetary flight – transit –, MS3 Moon, MS4 Mars

Van Allen radiation belts, which must be surpassed as fast as possible. From scenarios MS2 to MS4, measures for radiation protection like shielded areas or magnetic deflectors must be taken [21]. In the perspective of human arrival on Mars, it results that only the 6-months trip to Mars would mean 300 mSv of radiation exposure for the crew, with a total of 600 mSv for the round-trip. Assuming that the crew would spend 18 months on the surface waiting for the planets to realign to make the journey back to Earth possible, they will be exposed to an additional 400 mSv, for a total exposure of about $1,000$ mSv. [20]
Intense analysis must be carried on in order to find effective solutions, responding to safety guidelines. As an example, in 2021 NASA introduced a new standard for its astronauts safety, establishing the maximum dosage reachable by an astronaut over its career to 600 mSv [18].

In order to understand the risks that a permanence on the Moon can implicate, it is important to have an overview about the Space Radiation Environment. The most concerning kind of radiation and currently the most serious danger for astronauts that will be involved in at least MS2 missions, are the *Cosmic radiations*. These are also the least known, as most missions to date are MS1 missions and are therefore shielded from cosmic radiation by the Earth's magnetic field.

It is possible to identify different kind of cosmic radiations, of different energy levels [21, 22]:

- **Solar Wind**: continuous release of energized protons and electrons - including gamma and X rays - from the solar corona.
- **Solar Particle Events (SPE)**: these radiations are given by particles from the Sun, and can be low to medium energy particles. They are also known as *Solar Flares* or *Eruptions* and consist in high energy emissions – protons, neutrons, gamma and X rays and UV radiation – involving all the layers of the solar atmosphere. These events occur most often during the solar cycle maximum, reaching peaking values, but in general are difficult to predict in occurrence and duration.
- **Galactic Cosmic Rays (GCR)**: these are the most concerning kind of cosmic radiation, as consist in penetrating protons and heavy nuclei – up to 1000 MeV – coming from outside the Solar System and related to star explosion. Also in this case they are difficult to predict in occurrence, duration and strength, but in general it is possible to state that they are of continuous occurrence, omnidirectional and variable with solar cycle. In particular, lower GCR levels occur during solar maximum.
- **Van Allen Belts**: this area around the Earth is composed by an inner and an outer belt, and presents extremely high levels of radiation, as mentioned above, given by trapped protons and electrons due to the interaction of the cosmic rays and the terrestrial magnetic field.
- **Jovian electrons**: these are particles of Jovian origin transported and modulated to contribute to electron intensities in the heliosphere, especially at Earth.

The consequences of astronauts radiation exposure, in certain conditions, can be fatal. During an hypothetical mission, the short-term effects can consist in acute syndromes such as nausea, vomiting, fatigue and, in more dangerous cases, bleeding. Long term health impacts can result in severe consequences such as increased cancer morbidity or mortality risk, DNA damages, changes in cognition and motor function, behavior or neurological disorders [21, 22]. All these risks can and must be mitigated with effective shielding solutions considered from the very beginning of the design of systems and planning of the activities.

On the Moon, the lack of atmosphere and the negligible magnetic field result in particular radiation vulnerability.
While few centimeters of wall thickness can shield alpha and beta radiation, and according to NASA [22] the adoption of $5-20\,\mathrm{g/cm^2}$ aluminum and polyethylene is effective in SPE protection, the GCRs shielding is the real challenge: 1 GeV proton has a range of about 2 m in regolith, with secondary particles released due the primary particles collisions which penetrate deeper. In fact, the high energy particles, from the collisions within habitat materials and lunar regolith, produce secondary radiation that is more dangerous than the primary one [4].
The best way to shield from ionizing radiation is to provide as much physical material between a person and the source of radiation as possible: dense and thick material are ideal but imply significant amounts of mass. Aluminum and polyethylene are the most commonly used shielding materials: they provide an average 50% reduction in dosage levels from SPE radiation. GCRs radiations do not respond to shielding, with only an average 7% reduction in dosage levels. Additionally, secondary radiation is produced within tissues, further reducing any benefits of shielding [22].

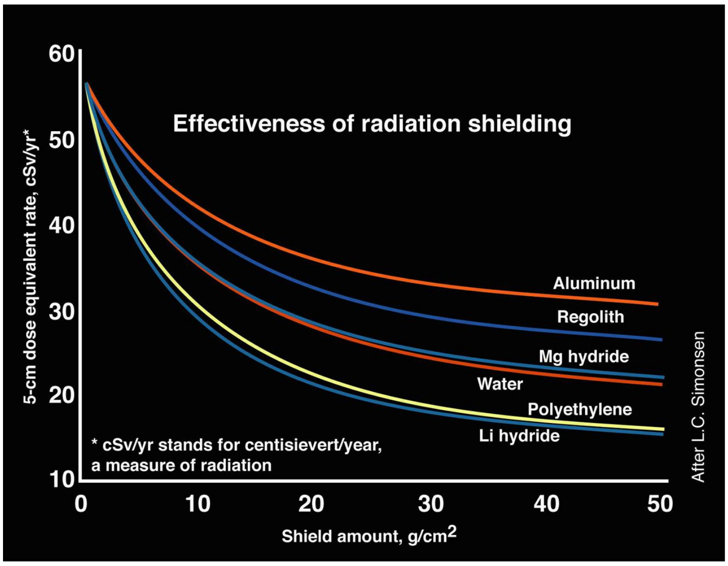

Figure 6: Effectiveness of different materials used for radiation shielding [23].

In Figure 6 the behavior of different shielding materials is shown: it is possible to notice that materials with lower atomic mass, such as Lithium Hydride and Polyethylene, present superior shielding properties, as they have a higher density of nuclei which block radiation more effectively. Furthermore, they produce less and weaker secondary radiation [24]. Water presents a similar behavior: the involvement of water for a radiation shielding system is an interesting point, since in a human mission water is constantly

and necessarily present onboard – so the recycle system of water itself could be directly involved in radiation shielding system. *Hydrogel* is an alternative to the use of water for this purpose [25].
Just like water walls protection system, another active method could consist into a magnetic shielding around the habitat [18]. Another interesting solution involves the use of regolith: the heavy nuclei of GCRs usually are stopped by ionization energy losses within 10 cm of the lunar surface, so shielding of a few g/cm^2 is usually adequate to remove most of these highly ionizing heavy GCR nuclei. The lighter nuclei, instead, which consist in protons and alpha particles for the main part, are very penetrating and with secondary particles can extend for meters into the lunar surface. According to Benaroya at al. [4] a 0.5 m regolith layer – assuming a regolith density of $1.5\,g/cm^3$ - reduces the radiation exposure to slightly less than half of the annual dose limit, while according to Wiley [5], an effective shielding solution against radiation is a layer of 0.5-3 m of regolith.

2.1.4 Partial gravity

As mentioned above in this Section, the lunar gravitational acceleration at equator is about $1.62\,m/s^2$, that is about 1/6 the terrestrial gravity acceleration g: this means that the same structure will have six times the weight-bearing capacity on the Moon as it would on the Earth. Hence, the same loads can be supported with about 1/6 of structural strength: this has implications on design possibilities and in particular on structures, which will be able to extend themselves over much greater distances [4].
The partial gravity does not only influence systems: in fact, the main point of concern regards astronauts. In the human space exploration context, the reduced gravity is to consider into mission, systems and operations definition, due to its effects on astronaut's organisms. It is well known nowadays, thanks to many years of experimentation on International Space Station (ISS), that the human body, in a condition of lasting permanence in low gravity environment, starts an adaptational process which involves mainly cardiovascular, neuro-vestibular and musculo-skeletal systems.
In summary, the fluids in human body are shifted upwards, causing a complex network of effects all over the organism [21, 26]:

- **Cardiovascular system**: the main effects are space anemia [2], cardiovascular deconditioning [3], body mass atrophy, cardiac atrophy [4] and reduced aerobic capacity, fundamental to perform daily activities, in particular during EVAs. To mitigate these effects, the astronauts must perform daily physical exercise and favorite blood circulation in lower body with Lower Body Negative Pressure devices, Gravity Suits or Artificial Gravity of centrifuges, for example.
- **Musculo-skeletal system**: the main effects in this case are loss of mass, volume and force of muscles, which can be mitigated during the mission with integrators consumption and daily workout. The most concerning effect regards the skeletal system: in low gravity conditions, accelerated osteoporosis occurs [5], weakening the

[2] The total blood levels result reduced.
[3] The cardiovascular systems is in a permanent loosen condition.
[4] The heart, as well as the body, results reduced in dimensions.
[5] On Earth, a healthy young subject loses 1-2% of skeletal mass per decade, while in ISS microgravity

astronaut's bones, in particular in lower body. The loss of skeletal mass increases also the risk of kidney formation.
These consequences on this system influence the activities during the mission and the mission definition itself: it is still unknown how the skeletal system can be affected by missions longer than one year, and nowadays the countermeasures adopted are mostly empiric and not so efficient.

- **Neurovestibular system**: one of the most critical aspects involves the neurovestibular system, which involves the reinterpretation of the sense of translation and inclination by the otoliths. This causes frequent disorientation and Space Motion Sickness (SMS), which imply illness due to the adaptational process such as nausea, vomiting, cold sweats, loss of appetite. However, Spaceflight Associated Neuro-Ocular Syndrome (SANS) is the real concern for astronauts, considered second in severity only after the radiation effects. Probably due to the higher intracranial pressure, astronauts after an extended period in micro gravity conditions report reduced sight, visual scotoma and migraine. Basing on today's knowledge of this syndrome, SANS results irreversible and without effective countermeasures. Despite this, to favorite the blood circulation in lower body also in this case is recommended.

These effects increase in severity with the decrease of gravitational acceleration, hence on the Moon they are expected to be less acute than on the ISS. Still, it is important to conduct experiments and analysis on the human organism reactions during the permanence in new gravity conditions. For these reasons, considering these elements in mission, system and operations definition is essential to permit astronauts to live and explore in the best conditions possible: medical equipment and support must be present in order to allow daily workout sessions, following the example of ISS today 7. A lunar habitat system should guarantee these necessities.

Figure 7: ESA astronaut Samantha Cristoforetti runs on the ISS [27].

conditions the same subject loses 1-2% of bone's mass per month, continuing also after the return on Earth for a certain period [21].

2.1.5 Other characteristics

The lunar environment is also characterized by other significant features that condition the mission and system design, such as vacuum, seismic activity and meteoroid bombardment.

Meteoroid Bombardment The term *meteoroid* is used for a naturally occurring solid body, traveling through space, that is too small to be called asteroid or a comet. Meteoroids with diameters less than about 1 mm – and with masses less than about 10^{-2} g– are commonly classified as micrometeoroids. When a meteoroid pass through an atmosphere and its parts are recovered on the surface, these are called *meteorites* [11]. During 1960s missions, Lunar Orbiters collected data about velocities and frequencies of meteoroid impacts. These Orbiters were pressurized semicylinders made of 0.025 mm metal with pressure-sensitive switches to record perforation by meteoroids. After these measurements, a rate of 0.16 perforations per m^2 had been concluded. This is about half the perforation rate estimated by Explorer spacecraft in Near Earth Orbit (NEO): this result is given by the terrestrial gravity force, which attracts more elements and increases their velocity, making the impacts more penetrating [11].
As near Earth calculations result, the velocities of meteoroids at Moon have been estimated about $13 - 18\ km/sec$. In particular, the meteoroids flux presents an increase of small meteoroids – $< 1\ \mu m$ – from the Sun, and a smaller enhancement of larger meteoroids – $> 1\ \mu m$– coming from the the direction in which the Earth is traveling. This means that the impact distribution and probability is not uniform on the Lunar surface: in particular, the Moon's face towards Earth's motion in its orbit around the Sun is more exposed to larger and hazardous meteoroids [11], worsen by the absence of atmosphere which could stop them from striking the surface. According to Wiley [5], in a lunar habitat system context, a layer about 0.5 m of regolith on the system would be an effective shielding against micrometeoroids.

Atmosphere The bare atmosphere present on Moon, in particular its *Exosphere*, it is very different from the terrestrial one, since is characterized by near vacuum conditions (Figure 8). Molecules around the Moon are so few and far between each other that they travel long distances without running into anything. In fact, the Moon's atmosphere contains about one million billion – 10^{15} – times fewer molecules per cubic centimeter than Earth's does, due to the minor lunar mass – hence gravity field – and the absence of active sources of atmospheric gases, present on Earth.
The major constituents of the lunar atmosphere are neon, helium, argon and tiny fraction of hydrogen. Helium is mostly derived from the solar wind, but 10% may be radiogenic and lunar in origin. Argon is mostly 40Ar derived from the radioactive decay of lunar 40K (only about 10% of the Argon is 36Ar of solar wind origin).

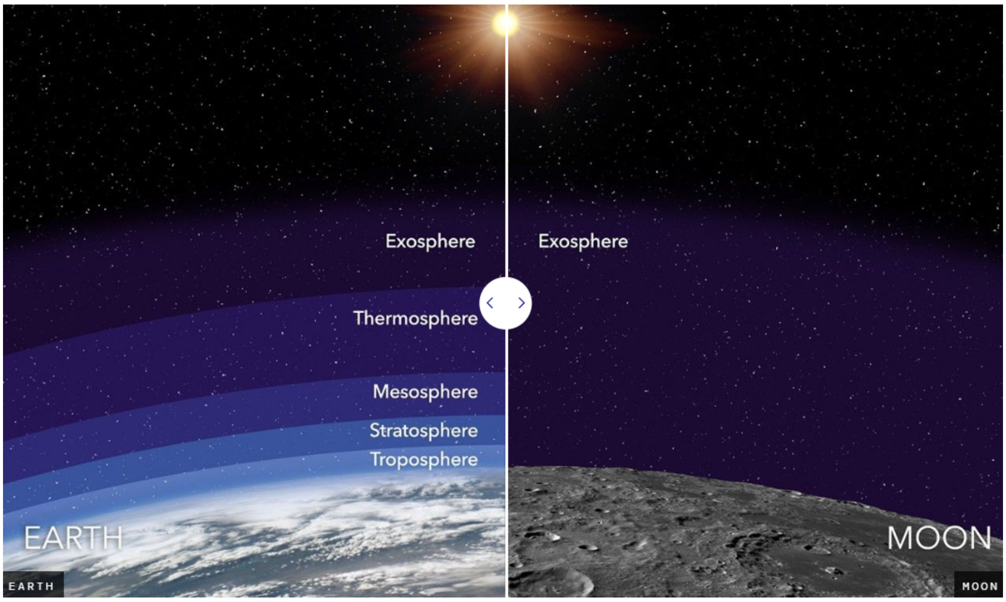

Figure 8: Earth and Moon atmospheric layers in comparison – not in scale [28]

Resulting in an atmospheric pressure of 2.96×10^{-15} *atm* [29], with a first approximation the lunar environment can be considered essentially vacuum. This vacuum environment precludes the use of many common materials whose strength properties result reduced by the *outgassing* phenomenon, which consists in the leak of gasses from the material itself [14]. This can degrade the materials' properties and functioning, such as astronomic lenses and solar panels. For this reason, all the materials involved in the mission must be tested and qualified for space application, in order to prevent this risk.
The vacuum environment also make the surface-to-surface contacts much more abrasive, due to the absence of an air layer. The increase in dynamic friction would cause fusion at the interfaces, aggravated by the fact that the vacuum is a bad conductor of heat. Wear-and-tear on all moving parts is also worsen by the higher abrasiveness, requiring a more intense maintenance activity [30].
Another interesting problem concerns possible blasting: the high pressure generated by the explosion would affect the surrounding area in a way that is difficult to predict. All these considerations affect the operation definition [30].

Seismic Activity During Apollo missions several research activities about the lunar seismic activity had been conducted. This resulted in almost 8 years of passive seismometers measurements, which could detect ground movement of less than 1 *nm*.
The release of seismic energy from the Moon is quite small, about 7 orders of magnitude lower than the Earth's, only $210^{10} J/yr$ compared to Earth's $10^{17} - 10^{18} J/yr$ [11][5]. The higher value in Table 1 comprehends the possibility that larger but rarer moonquakes did not occur during the 8 years of measurements. In this time of research the largest recorded moonquakes had Earth-equivalent magnitudes of about 4.
The source of seismicity on the Moon include the monthly *deep-focus moonquakes* caused by Earth-Moon tidal stresses, a few stronger – but rarer – *shallow moonquakes* due to tectonic processes and *meteorite impacts*, very widely in energy [11]. In conclusion, seismic

strengthening doesn't seem necessary for structures on the Moon.

2.2 Human Exploration of the Moon: Historical Overview

Lunar exploration began in the 1950s, when the U.S. and the Union of Soviet Socialist Republics (USSR) competed for the spaceflight dominance, also known as *Space Race*, during the Cold War – lasted from 1947 to 1991.
The Space Race started as an arms race between the U.S. and the USSR, the two major global powers after World War II: in this context, rocket technology demonstrated its potential in modern warfare, and advanced and powerful technology of ballistic missiles was developed by both Countries. This, in short time, gave way to the Space Race. The competition became particularly heated when the USSR achieved the first successful satellite launch, Sputnik 1, in 1957, and then when succeeded in sending the first human into space: he was Yuri Gagarin with the orbital flight of Vostok 1, on April 12, 1961. This led the U.S. to two important events. Firstly, president Eisenhower reacted to Sputnik recommending to the U.S. Congress to establish a nonmilitary agency to conduct space activities, which brought to the birth of National Aeronautics and Space Administration (NASA) on July 29, 1958. Later, in Gagarin's flight response, on May 25, 1961, President John F. Kennedy delivered a 46-minutes speech formally titled *Special Message to Congress on Urgent National Needs*. After requesting that Congress expand funding of space activities, Kennedy's worlds became history [31]:

"I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the Earth. No single space project in this period will be more impressive to mankind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish"

U.S. required huge efforts to gain ground in this competition, which saw many important goals achieved by USSR: the first satellite flight in 1957, the first animal in space – the dog Laika – in 1957, the first probe in flyby the Moon with Luna 1, the first impact on the Moon with Luna 2 and hidden-side photos of the Moon made by Luna 3, in 1959, and the first human in space in 1961. At the Kennedy's speech time, U.S. accomplished the first American astronaut flight only few weeks earlier, with Alan Shepard on Explorer 1. The methodology and expertise of the team involved by NASA, allowed to reach incredible results in only few years. Mercury and Gemini missions prepared the way: Mercury missions developed hardware for safe spaceflight and return to Earth, with six crewed missions between 1961 and 1963. Then, NASA introduced Gemini, which consisted into the development of a two-astronauts spacecraft: during Gemini missions, between 1964 and 1966, spacecraft control, rendezvous, docking and EVAs were improved, reaching the record time of two weeks in space [32].
But the final goal was reached by the Apollo program, which goals included: [33].

- Establishing the technology to meet other national interests in space.
- Achieving preeminence in space for the United States.

- Carrying out a program of scientific exploration of the Moon.
- Developing human capability to work in the lunar environment.

Before the landing of first humans on the Moon, several missions were conducted [33].

Apollo 1, first known as Apollo 204, meant to be the first crewed flight of the program, scheduled to launch February 21, 1967, but astronauts Virgil Grissom, Edward White and Roger Chaffee tragically lost their lives when a fire swept through the command module. This postponed crewed launches in order to investigate and clarify the causes. No missions or flights were ever designated Apollo 2 or 3.

Apollo 4, in November 1967, was an unmanned missions which consisted in the first all-up test of the three stages of Saturn V rocket, and carried a payload of an Apollo Command and Service Module (CSM) into Earth Orbit (EO). The mission was deemed a successful test.

Apollo 5, in January 1968, was an uncrewed mission which sent the Lunar Module-1 payload into EO by a launch vehicle composed of a Saturn IB first stage and a Saturn S-IVB second stage. The Apollo lunar module's first flight test was called a complete success and ascent/descent propulsion systems and the ability to abort a lunar landing and return to orbit were demonstrated.

Apollo 6, in April 1968, was designed to be the final qualification of the Saturn V launch vehicle ad Apollo spacecraft for crewed Apollo missions, consisting in three stage Saturn V, the Apollo CSM and a boilerplate Lunar Module. During the mission three major problems occurred, including dynamic instability and loss of structural panels from the lunar module adapter, the premature shut down of two engines of the second stage, not allowing to reach the planned EO, and a failure to third stage propulsion system.

Apollo 7,in October 1968, was the first successful crewed Apollo mission, which demonstrated the crewed CSM performance and mission support facilities. Wally Schirra, Donn Eisele and Walt Cunningham were the astronauts protagonists of this successful flight.

Apollo 8, in December 1968, was a crewed missions which demonstrated Lunar landing preparation capabilities. In this mission three astronauts, Frank Borman, James Lovell Jr. and William Anders, were sent to Lunar orbit in order to perform 10 orbits and test the systems, such as communication and navigation ones. For the first time humans went beyond the EO, and the mission resulted in a success.

Apollo 9, in March 1969, consisted in the first crewed flight of the full Apollo spacecraft in EO. On the other hand, the engineering test of the first crewed Lunar Module was performed. In addition, tests of flight equipment and the EVA mobility unit were conducted. All prime mission objectives were met. All major spacecraft systems were successfully demonstrated. The few off-nominal conditions that developed did not affect achievement of the major goals.

Apollo 10, in May 1969, saw astronauts Thomas Stafford, John Young, and Eugene Cernan test all the components for a lunar landing mission, except landing on the Moon. It was the first flight of a complete, crewed Apollo spacecraft to operate around the Moon. All mission objectives were achieved and the landing on the Moon was the last step, ready to be done.

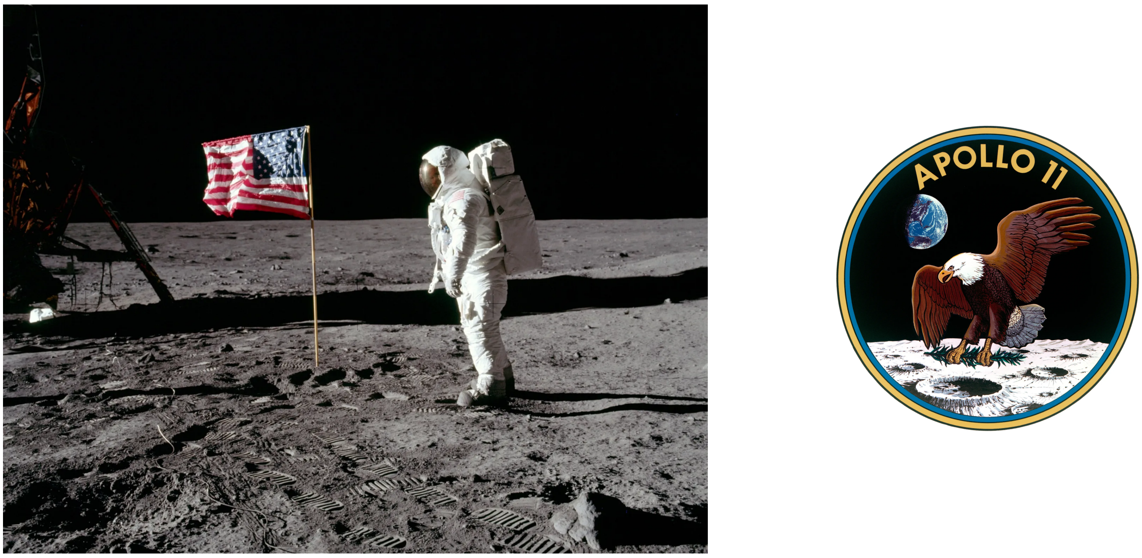

Figure 9: On left, astronaut Buzz Aldrin stands on the Moon facing a U.S. flag during Apollo 11 mission in July 1969. On right, Apollo 11 mission logo. [33]

2.2.1 Humans on the Moon

The national goal set by President Kennedy was accomplished with Apollo 11: on July 20, 1969 the astronauts Neil Armstrong and Buzz Aldrin stepped onto the Moon (Figure 9).

"Houston, Tranquility Base here. The Eagle has landed."

Both the astronauts ranged up to 300 feet from the lunar module – *The Eagle*, protagonist of the official Apollo 11 logo represented in Figure 9– deploying the Early Apollo Scientific Experiments Package (EASEP) experiments and gathering samples of lunar surface. The entire EVA phase lasted more than two and a half hours.
Armstrong and Aldrin spent 21 hours and 36 minutes on the Moon's surface. After a rest period that included seven hours of sleep, the the two astronauts turned back to the Columbia CSM with ascent stage, reaching the pilot Micheal Collins. Re-entry procedures started July 24, and after a fight of 195 hours, 18 minutes, 35 seconds – about 36 minutes longer than planned – Apollo 11 splashed down in the Pacific Ocean.
As historically Neil Armstrong said, this represented *"one small step for a man, one giant leap for mankind"*: the first, and surely not the last.

After Apollo 11 success, several Apollo missions brought back humans on the Moon. USSR never managed to land their astronauts on the lunar surface.

Apollo 12 was the second crewed lunar landing mission, which on November 19, 1969 brought the crew Charles Conrad Jr., Alan L. Bean and Richard F. Gordon Jr. back to the Moon. The mission included mainly an extensive series of lunar exploration tasks and the deployment of the Apollo Lunar Surface Experiments Package (ALSEP), which was to be left on the Moon's surface to gather seismic, scientific and engineering data

throughout a long period of time. Two EVAs were performed. During the first one, Conrad spent three hours, 39 minutes outside Intrepid LM, during which he collected lunar surface samples and deployed both the S-band communication antenna and the solar wind experiment, while Bean was assigned to mount the TV camera on a tripod, with an EVA of two hours and 58 minutes. The ALSEP instrumentation and SNAP-27 Radioisotope Thermoelectric Generator (RTG) were deployed within an arc of 600 to 700 feet of the LM, with satisfactorily functioning.
The second EVA included the collection of rock and dirt samples, the retrieval of few pounds of randomly selected selenological samples, and further probing of two areas to retrieve lunar material from depths up to 32 inches below the surface. In addition, the crew retrieved the TV camera and stored it in the LM for return to Earth. In this case, Conrad and Bean ranged up to 1300 feet from Intrepid. During the exploration, the astronauts discussed their findings by voice communication with geologists in Houston, who provided advice about which samples to retrieve. This EVA lasted three hours and 48 minutes.
In the same day, Intrepid ascended to lunar orbit and reunited with the Yankee Clipper CSM, hence with Gordon. After the transfer to the CSM, the ascent stage jettisoned and deorbited to impact the moon, providing predictable impact data for the ALSEP seismometer: strong signals lasted for more than a half hour, and weaker signals ceased about one hour later. On November 24, Apollo 12 ended splashing down in the Ocean Pacific after 10-day flight.

Apollo 13, on April 11, 1970, was intended to be the third human mission on the Moon, but was prevented by the explosion of an oxygen tank during the transfer to the Moon. The loss of oxygen made the fuel cells useless, resulting in eventual loss of all electrical power and water. The lunar landing was officially excluded, so the mission new goal was to bring back the crew alive. Along with the extreme shortage of water and electrical power, the crew also encountered dangerous levels of carbon dioxide. The crew rescue involved the Lunar Module as *lifeboat*, becoming central for the crew survival, providing the sufficient oxygen, power and life support.
The ground support staff and engineers' incredible capabilities were the key to the successful return of astronauts Jim Lovell, Fred Haise and Jack Swigert, and this mission is remembered as *the successful failure*, an incredible example of failure and crisis management.

Apollo 14, launched on January 31, 1971, was dedicated to accomplish the mission objectives that Apollo 13 didn't achieve: the exploration of Fra Mauro region, deployment of ALSEP and other scientific instruments, lunar field geology investigations, collection of samples and communication testing, besides engineering and operational evaluations of hardware and techniques, and photographs of environment. All these mission activities were accomplished by the crew Alan B. Shepard Jr., Edgar D. Mitchell and Stuart A. Roosa, with two EVAs performed by Shepard and Mitchell, with a total of nine hours and 24 minutes of activities outside the Lunar Module – a record EVA time by a lunar landing crew – and a new distance-traveled record of approximately 9000 feet.

Apollo 15, launched on July 26, 1971, was the first mission capable of a longer stay time on the Moon - almost three days thanks to modifications of Lunar Module - and that involved the utilization of a Lunar Roving Vehicle (LRV), which allowed faster and wider transfers. The main mission objectives regarded lunar surface science, lunar orbital science and engineering-operational evaluations. In this case, the target area was the Hadley-Apennine region. Another key mission objective was the release of a Particles and Fields subsatellite from the CSM just before the return to Earth. Its purpose was to study the Moon's mass distribution and gravitational anomalies, the particle environment near the Moon and the interaction between the lunar and terrestrial magnetic fields.

Apollo 16, launched on April 16, 1972, carried on the research and exploration activities on the lunar surface, in particular in Descartes region. Just like the previous Apollo missions, its main objectives were to inspect and sample surface terrain, deploy and activate the fourth ALSEP and conduct in-flight experiments and photographic tasks from lunar orbit. In addition, zero gravity experiments, engineering evaluations of spacecraft and equipment were performed, and the LRV was improved.

Apollo 17, launched on December 7, 1972, was the last Apollo mission. This time, the region of interest was the Taurus-Littrow highlands and valley, due to the presence of rocks both older and younger than those previously analyzed in other Apollo missions. Also in this case the stay time of the crew on the lunar surface was increased – part of the so known J-type missions – and involved extended hardware capability, larger scientific payload capacity and a battery-powered LRV. The mission objectives were analogous to the previous missions' ones, but in addition heat flow experiment, lunar seismic profiling, lunar surface gravimeter analysis and lunar atmospheric composition experiments were performed. Also, biomedical experiments included Biostack II and BIOCORE, which studied the effects of radiation on microorganisms, living cells and mice.
Apollo 17 ended with the splashdown in the Pacific Ocean, 12 days later. It was December 19, 1972, and Eugene Cernan and Harrison Schmitt were the last humans on the Moon [33].

2.2.2 After Apollo Program

In the wave of the success of Apollo landings, in 1969 the Space Task Group (STG) appointed by President Richard M. Nixon presented *"The Post-Apollo Space Program: Directions for the Future"*, to propose the NASA development of new systems and technologies for future programs. This report included several programs, such as a Mars mission, the establishment of a lunar orbiting space station, a lunar base, an Earth-to-orbit transportation system and a 50-person Earth orbiting space station. Facing with the geopolitical reality of the time, President Nixon decided that those planes were too grandiose and far too expensive. In September 1970, reductions in NASA's budget forced the cancellation of several Apollo missions, until the closure of Apollo program with Apollo 17.
In January 1972 President Nixon directed NASA Administrator to develop the Space Transportation System, also known as *Space Shuttle*. 12 years later, the space station program was approved, then evolved into the multinational partnership called the *International Space Station* [34].
The political and social interest for the human space exploration declined rapidly due

to new priorities: the space exploration required huge economic effort, and as Apollo 1 and 13 demonstrated, it could be very dangerous too. On the other hand, these efforts didn't produce immediate results that were appreciated by the public and politicians. The Space Shuttle program marked the temporary end of lunar exploration efforts, as NASA shifted its focus toward reusable spacecraft and operations in Low Earth Orbit.

In December 2017 NASA announced ARTEMIS program, whose main objective is to bring back astronauts on the Moon. Nowadays, the future perspective of human space exploration is exciting: with ARTEMIS program, which in turn consists of four missions, the humans will be back to the Moon with new technologies for space transportation, the Orion spacecraft, a new lunar space station – the lunar Gateway – and several lunar surface technologies which will permit long stay times and intensive lunar exploration – e.g. exploration vehicles, lunar habitats, Extravehicular Mobility Units (EMUs) .
With this new achievements, new frontiers will be more accessible and closer: first of all, the first humans on Mars.

2.3 Lunar Habitat concepts

In this Thesis' context the high level definition of a lunar habitat will be discussed, thus it is important to provide an overview of the results of past and recent studies, which propose several solutions for habitat concepts up to the accomplishment of long stay time, scientific research and exploration goals. In addition, essential considerations regarding the presence of crew will be discussed.

2.3.1 Inflatables structures

The first possible concept presented consists into a pillow-shaped structure in fiber composites that, once on the lunar surface, would be inflated with pressurized gas. This solution allows to save volume during transportation and to perform a rapid system erection in situ. According with the previous discussion about lunar environment, in this case the shielding properties are provided by a layer of regolith, with accommodation for sunlight inlet [30].
Another pressurized membrane structure proposed is constructed of a double-skin membrane filled with structural foam, and supported by a pressurized torus-shaped substructure. Also in this case, the shielding capability is provided by a layer of regolith upon the habitat. The system erection consists into the spreading of the uninflated structure upon the appropriately shaped ground, to proceed with the injection of foam and then the pressurization of the internal compartment.
In both cases, the floors of the structures are intended to be filled with compact soil, in order to provide stability and a flat bottom surface: this operation is quite thorny, since the interior of the habitat must be dust-free [30]. An example of Inflatable habitat concept is shown in Figure 10: the artist author of the image has depicted along with the inflatable habitat a construction shack and related solar shield, connecting tunnel regolith bags for radiation protection, thermal radiation experimental six-legged walker, solar power system for the lunar oxygen pilot plant and other elements [30].

2.3.2 Erectable structures

In this case the structure involves rigid or semi-rigid structures, designed to be transported in parts or compressed, and assembled or deployed on the lunar surface by astronauts or robotic systems. This concept can consist into [30]:

- Modular truss structures that provide three-dimensional frameworks - e.g., tetrahedral, hexahedral, octahedral - that serve as both habitation modules and expansion platforms.
- Shuttle tank-based modules, which would consist in the use of the liquid oxygen tank portions of the space shuttle external tank assembly for a basic lunar habitat. Modifications of the tank would take place in Low Earth Orbit (LEO), proceeding with the installation of living quarters, equipment and Environmental Control and Life Support System (ECLSS), for example. Then, the habitat would be transported to the Moon.

Figure 10: Inflatable habitat concept developed during the Lunar Base Systems Study undertaken by the Advanced Programs Office in the Engineering Office at Johnson Space Center during the period 1986–1988. The study was performed by the Advanced Programs personnel with contractor support from Eagle Engineering, Inc. and Lockheed Engineering and Sciences Co. (NASA graphic number S89-26097 March 1989). [30]

In general, a modular approach is suggested in order to include the possibility to expand the habitat, according to future needs and improvement capabilities of the outpost.

2.3.3 Lava Tubes and Mobile bases

One of the possible options include the realization of an outpost situated under the lunar surface, in a *lava tube* [30]. The lunar lava tubes are significantly larger and more sinuous than terrestrial analogs, and typical widths and depths of tubes can be estimated in the hundreds of meters, with overall lengths of a few kilometers. Lava tube roof thicknesses seem to be more than sufficient to shield radiation and meteorite impacts, and would provide in general a well protected environment, with a temperature unaffected by diurnal surface variations, constant to -20°C. [35]

Another idea is to use pressurized rovers as permanent or semi-permanent bases, providing the advantage to move sites if necessary. On the other hand, the size of the settlement is very limited and activities such as farming and manufacturing become almost impossible [30].

2.3.4 Artemis Surface Habitat

The best example of lunar habitat in advanced design level is the SH in development for the NASA's Artemis program, which will be employed for the stabilization of an Artemis Base Camp, in further missions. A concrete base camp will mark the beginning of a sustained human presence on the Moon, enabling exploration and scientific research in a manner comparable to the ISS one, thus with an important reuse factor. In addition, a base camp will allow to simulate and evaluate Mars conditions of long stay, testing systems and operations. Besides the SH, the Artemis base camp will involve other fundamental elements, such as the Lunar Terrain Vehicle (LTV) and the Pressurized Rover (PR).

According to NASA [18],

> *"the Surface Habitat is a fixed surface habitat, offering a home base for astronauts, a hub for communications, a science facility, an EVA equipment repair site, a waste processing facility, a supply hub, a surface operation base and a test bed for sustained surface presence and preparation for Mars missions."*

The SH is designed to support a crew of two astronauts for approximately 30 days, and occasionally a crew of four during crew swap-outs occurring mid-mission. In future SH evolutions, it will be possible to support the stay of four astronauts for 60 days. To accomplish these durations of stay, the SH must be self sufficient in power generation and management, in communications with both Earth, surface and orbital assets, and in environmental management and astronauts' life support. In particular, this final point is a critical point and sees the presence of an advanced Environmental Control and Life Support System (ECLSS), with the necessity of regenerative capability: water recovery system is included, together with oxygen generation. [18]

The habitat structure consists into a two-story inflatable section arranged vertically,

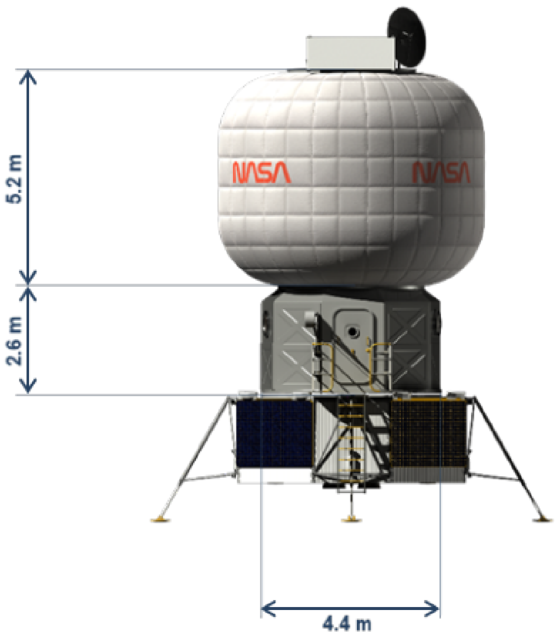

Figure 11: Artemis SH with representative dimensions [18]

with a metallic core and lower metallic section, with the ingress/egress of the module that allows inlet and outlet of EVA crew and logistics. A two-chamber airlock between the outer EVA hatch and the interior section is present, in which can be performed the EMU maintenance. Micro-meteoroids and orbital debris impact resistant material is used for the structure, as well as Multi Layer Insulation (MLI) materials [18].

The Thermal Control System (TCS) involves active solutions consisting in a low temperature loop, medium temperature loop, two radiators using HFE 7200, a sublimator for

cooling prior to deployment, and fluid pumps for transporting the waste heat.
The Power System generates power with GaAs cells solar arrays, designed for a life of 15 years, and the energy storage is performed by a regenerative fuel cells system.
The habitat is designed for a total life of 15 years, with 10 years of operation [18].

2.4 Systems Engineering

System Engineering (SE) is the discipline that allows the management of the complexity levels characteristic of the space engineering field. The origin of this term dates back to Bell Telephone Laboratories in the early 1940s, and sees its very first applications during World War II. According to Hall [36], the first attempt to teach the discipline of System Engineering as we know it today came in 1950 at Massachusetts Institute of Technology (MIT) by Mr. Gilman, Director of Systems Engineering at Bell [37].
The *evolutionary forces* that brought to the definition of a proper discipline at that time, according to Hall [36], were :

- **Complexity**: the principal causative factor, though not exhaustive, was given by the development of increasingly complex systems. The complexity concept refers in part to the number and kinds of components in the system, in part to the relations between them. The development of this kind of engineering was needed not only for over all planning capabilities, but also for the necessity of a method allowing long range development of the systems: this induced increased interest in the methods by which efficient planning and design could be accomplished in complex situations where no other scientific discipline could.
- **Expanding Needs and Environment**: the environment of a system includes all external factors that can affect it and which are affected by the system itself, including the state of technology, economic factors and other systems, as an example. In the middle of the 20th century, innovations and growth of the technologies and of knowledge provided a new dynamic environment, creating a difficult problem of maintaining a close link between the availability of the new art and its application to human needs. Needs for new systems expanded more rapidly than ever, and technical decisions and high level compromises, often in face of large uncertainties, were needed.
- **Scientific and Engineering Manpower**: since 1951, an acute shortage of technically trained people was registered, colliding with the expanding needs and environment as above. This lack of resources brought organizations to study their own methods in order to improve what they had. It was learned that through technical planning it was possible to prevent costly mistakes in the development phase.

In the same dissertation, Hall defined System Engineering as a function with five phases [36, 37, 38]:

1. **System Studies**, or program planning
2. **Exploratory Planning**, including problem definition, objectives selection, system synthesis, best system selection and results communication. It is the first phase of project planning.

3. **Development Planning**, a more detailed phase 2.
4. **Studies During Development**, which represents the first Action phase, and includes the development of parts of the system and the integration and testing of these parts.
5. **Current Engineering**, the second Action phase, which takes place while system is operational and being refined.

In the contemporary era, the world is undergoing perpetual transformation. Social, economic, political and physical environment, alongside with technology and science fields, are strictly interconnected and in dynamic relationships. The acceleration of technology advancements obtained in the last century is incomparable, impacting the nature of systems solutions. Nowadays, System Engineering is a fundamental discipline perfectly integrated in all the system's lifecycle, whose interdisciplinarity allows to include representation and considerations from each discipline and each affected stakeholder. Systems engineering must guide and orchestrate the overall technical effort including hardware, software, test, and specialty engineering to ensure the solution satisfies its stakeholder needs and expectations [39].
In general, the main tasks of SE consist into [38]:

- **Stakeholders analysis**: it is the responsibility of the system engineer to define, balance and integrate the stakeholders' goals, purpose and success criteria, as well as customer needs, operational concepts and required functionalities definition, from the outset of the development cycle.
- **Lifecycle model**: the system engineer establishes an appropriate lifecycle model, process approach and governance structures, based on the levels of complexity, uncertainty and variety.
- **Solution concepts and Architectures development**
- **Requirements and Solution Architecture definition** for each phase of the endeavor.
- **Design synthesis, system Verification and Validation**
- **System Integration and Trade-off Analysis**: the system engineer must balance all the factors in solution and problem domains in order to achieve a satisfactory outcome.

An interesting perspective of the *Systems Engineering Engine* is provided by NASA in its System Engineering Handbook [40], illustrated by Figure 12.

The main processes defined in this "engine" regard System Design, Technical Management and Product Realization. Each process receives in input and provides in output requirements and products from and to other levels. All the processes are characterized by strong *iterative* and *recursive* features.

System Design Processes start with the definition and baseline of stakeholders expectations, from which derives the technical requirements generation. With this, working on the definition of a technical solution is possible, performing a logical decomposition of requirements obtained and converting them into a design solution which can satisfy the stakeholders expectations. This processes are applied to each product of the system, from the top to the bottom of the structure. This Thesis follows the steps of this process,

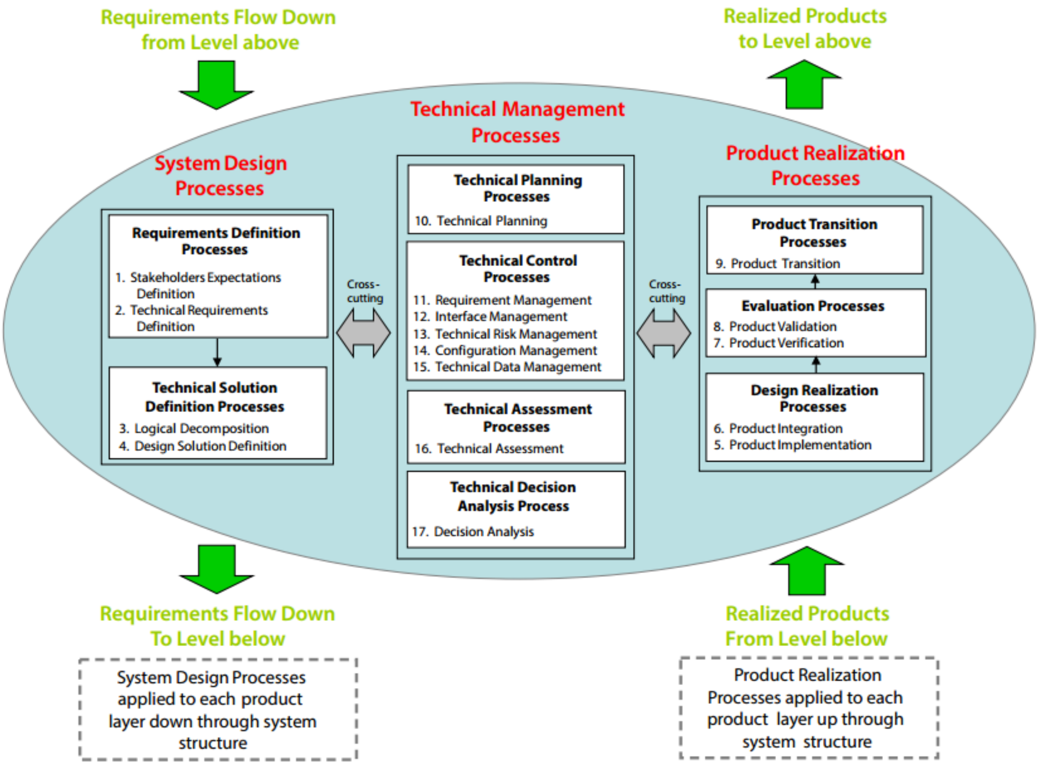

Figure 12: The System Engineering Engine [40].

at high level.

Product Realization Processes are applied to each product in the system structure, starting from the lowest level to the highest integrated level. These processes allow to obtain the design solution for each product, then subjected to verification and validation processes. When successful, follows the product transition, obtaining a solution that meet stakeholders expectations.

Technical Management Processes are employed to establish and evolve technical plans and to manage interfaces, risks, configuration and technical data. The requirement management is always involved, and support in decision making and technical assessment is provided through the project development.

2.4.1 Definitions

International Council on Systems Engineering (INCOSE), in its *"Systems Engineering Vision 2035"* [38], offers the following definition of System Engineering:

> *"Systems Engineering is 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."*

Results important to clarify some key aspect of this statement, following the INCOSE definitions [38].

Transdisciplinary approach points out the ability of System Engineering to "transcend" all of the disciplines involved, organizing the effort around a common purpose, sharing the learning and understanding of the context. A transdisciplinary approach is needed when the problem cannot readily be “solved” and the best that can likely be achieved is instead a “resolution”.

Integrative Approach is considered suitable for less complex, highly precedented situations involving a limited number of stakeholders, where a clear solution path exists, and it relies on traditional multi- and interdisciplinary methods of systems engineering. In contrast, a transdisciplinary approach becomes necessary in unprecedented or highly complex contexts.

Engineered System indicates a system designed or adapted to interact with an anticipated operational environment to achieve one or more intended purposes while complying with applicable constraints [41].

Systems principles and concepts represent the means by which systems thinking and the systems sciences permeate systems engineering, such as mental models, system archetypes and mapping, abstraction, etc.

In the context of this Thesis, results interesting to report also the definition of System Engineering given by NASA [40]:

"Systems Engineering is defined as a methodical, multi-disciplinary approach for the design, realization, technical management, operations, and retirement of a system."

In INCOSE *"Systems Engineering and System Definitions"* [41] a very general definition of System is provided:

"A system is an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not."

Systems can be either **physical** or **conceptual**, or a combination of both, and their properties emerge from the parts or elements which compose it, and their individual properties, together with the relationships and interactions between and among the constituents, the system and the environment. In particular, in case of physical system, composed of matter and energy, it is said that it exhibits a certain *behavior*. Instead, if the system is conceptual, so composed of information and knowledge elements, it exhibits a certain *meaning*.

Another fundamental definition in Systems science regards Open and Closed Systems. Always according do INCOSE definitions [41], it is possible to distinguish **open systems** and **closed systems**, depending on the relationship they have with its environment. When a system is closed, it is completely isolated from its environment. On the other hand, an open system has flows of information, energy, and/or matter between the system and its environment, and which adapts to the exchange. In systems engineering, all physical systems of interest are inherently open. Nevertheless, in particular cases it may be practical to treat a system as closed, provided that no significant external relationships or interactions are involved. However, this is not the case in the present Thesis.

An useful definition o of **complexity** can be provided as follows [41]:

"A complex system is a system in which there are non-trivial relationships between cause and effect: each effect may be due to multiple causes; each cause may contribute to multiple effects; causes and effects may be related as feedback loops, both positive and negative; and cause-effect chains are cyclic and highly entangled rather than linear and separable."

In these means, the whole system results non deterministic, ambiguous or chaotic, even if the individual relationships within the system are well understood. Complexity is a *property* of the system, and a major goal of SE is to reduce the "perceived complexity" by the use of valid models.
Contemporary complex systems, such as the one examined in this Thesis, encompass significant autonomous activities and operations. They should not merely react to events, but must also be able to anticipate and adapt. Becomes fundamental the concept of **Anticipatory System**, defined as:

"A physical system that has an internal model of itself and its environment and an internal decision-making function, enabling it to anticipate potential changes in the environment and make appropriate adaptations to be ready for the anticipated change."

As result, the behavior of this kind of systems depends upon the anticipated *future states* or *future inputs* generated by an internal predictive model.

In the SE work, part of the "Systems Engineering Engine" meets the concepts of validation and verification. According to NASA [40]:

*"**Verification** of a product shows proof of compliance with requirements that the product can meet each "shall" statement as proven though performance of a test, analysis, inspection, or demonstration (or combination of these)."*

In other words, verification is a process which tests the product relating back to the approved set of requirements, and can be performed at different stages in the product life cycle. Without a verified baseline and appropriate configuration controls, later modifications can be costly or cause problems.

*"**Validation** of a product shows that the product accomplishes the intended purpose in the intended environment that it meets the expectations of the customer and other stakeholders as shown through performance of a test, analysis, inspection, or demonstration."*

Validation, on the other hand, tests the product relating back to the Concept of Operations document. The tests are conducted under realistic conditions - real or simulated - and the purpose is to determine the effectiveness of the product for its intended use during the mission. Validation can be performed in each phase, on phase products, which means that both models and final products can be subjected to validation testing.

2.5 Model-Based Systems Engineering

As part of the dynamic condition of the modern world, system engineering itself is passing through an evolution process. In particular, INCOSE Vision 2020 [42], published in 2007, presented the concept of Model-Based Systems Engineering (MBSE), a new approach to system engineering intended to enhance the efficacy of its processes in the face of increasingly sophisticated technologies.
Traditionally, system engineering is based on documents, but systems – and surely space systems – are becoming too elaborate to manage with documents alone: text descriptions are not sufficient to describe behavior of all the mission workings, which are increasingly complex and full of exceptions and dependencies.
Model Based System Engineering (MBSE) provides suitable tools to create models of systems, in order to support system requirements, design, analysis, verification and validation activities, covering the whole life cycle. In this way, system evaluations based on advanced and complete models are possible, with an absolute traceability and fully digitalized, replacing the document-centric approach [42]. Models of MBSE facilitate collaboration among stakeholders and encourage questioning of assumptions and constraints. In addition, models can be verified in simulation environments as part of verification testing, reducing cost and effort of physical testing [43].

At beginning of 2000s one of the most significant inhibitors to widespread of this approach was the lack of standards and tool interoperability. The first emerging modeling standards were the Unified Modeling Language (UML) [44] and Systems Modeling Language (SysML) [45] adopted by Object Management Group (OMG) in 2006 and the ISO 10303233 Application Protocol: Systems Engineering and Design (AP233) [42]. SysML is a general purpose graphical modeling language for specifying, designing, analyzing and verifying complex systems, implemented in some MBSE support tools.
The goal for the future of the systems engineering established in 2007, according to INCOSE, was to "*[...] extend MBSE to modeling domains beyond engineering models to support complex predictive and effects-based modeling. This will include the integration of engineering models with scientific and phenomenology models, social, economic, and political models and human behavioral models*" [42].

Today, MBSE is being officially adopted and gradually integrated by the main entities and organizations in engineering industry, and in particular in space sector. ESA itself supports the implementation of this approach, adopting it as default baseline approach to all new mission studies carried out by Preparation elements of ESA's Discovery, Preparation and Technology Development (DPTD), since 2021. Missions Euclid, Plato, Ariel, ClearSpace-1, TRUTHS, the European Large Logistics Lander, Mars Sample Return, Argonaut, Earth Return Orbiter and Galileo have all benefited from the MBSE approach. ESA Technology Strategy states: [46]

> *"MBSE and the digital spacecraft are important contributors to the improvement of development time and cost efficiency targets. In particular, industrial actors have recognised the added value of MBSE in streamlining the design, development, deployment and verification of space systems."*

Furthermore, CGI and OHB studied a way to harmonize the different approaches of ESA and large space companies (Airbus Defence and Space, Thales Alenia Space and OHB System), in order to create an MBSE Handbook (2023). The aim was to maximize the potential for different MBSE approaches to work together efficiently, ensuring a continuous flow of MBSE-related information between stakeholders. [46]

According to INCOSE, in many industries systems engineering is still mainly document-based, but the new emphasis on digital model-based approach is opening new opportunities. Other model-based standards such as the Systems Modeling Language (SysML) and the Unified Architecture Framework (UAF) are continuing to evolve to provide a standard way to support model-based systems engineering for systems and enterprises [39]. Artificial Intelligence (AI) and Autonomous Systems are increasingly present and necessary in the modern technology environment, and their complex behavior cannot be supported by the classic system engineering methods: even their social and ethical implications need to be considered as part of the design. The new techniques in development will no longer be merely advanced supporting methods and approaches: they are rapidly becoming a necessity.

In the future vision of INCOSE, by 2035 systems engineering will be model-centric, with a vast library of reusable elements, enabling efficient exchanges with stakeholders in order to define and update needs and technologies, and providing the essential methodologies to manage the increasing complexity and risk levels during the whole lifecycle. This approach will allow to include in design and evaluations crucial elements like artificial intelligence and human-system integration, providing virtual models updated in real time, hence a virtual reality-based, immersive design and exploration space [39].
By 2035, a family of unified, integrated MBSE-System Modeling and Simulation (SMS) framework will exist, taking advantage of digital twins and which will be possibly evaluated down through manufacturing, maintenance, updates and decommissioning.

2.5.1 MBSE methodologies

A *methodology* is defined as a collection of related processes, methods and tools. Thus, a MBSE methodology can be characterized as the collection of processes, methods and tools used to support the systems engineering discipline in a model-based approach. A summary description of some of the main MBSE methodologies surveyed in INCOSE 2008 Report and used in the today's industry is provided in this section, following some fundamental definition [43]:

- A **Process** is a logical sequence of tasks performed to achieve a particular objective. In other words, describes *what* is done, without specifying how.
- A **Method** consists of techniques for performing a task. In this case, *how* a task is performed is described. At any level, processes tasks are performed using methods. However, each method is also a process itself, with a sequence of tasks to be performed for that particular method.
- A **Tool** is an instrument that enhances the efficiency of a task, applied to a particular method and, if properly used, should facilitate the accomplishment of the *how*. Most tools are computer- or software-based.
- An **Environment** consists into the external conditions or factors that influence and are influenced by the system. The purpose of a project environment should be to integrate and support the use of tools and methods used. Thus, the environment enables or disables the *what* and *how*.

Object-Oriented Systems Engineering Method(OOSEM) Object-Oriented Systems Engineering Method (OOSEM) evolved in the mid of 1990s at the Software Productivity Consortium in collaboration with Lockheed Martin Corporation, then strongly sustained by INCOSE [47]. This methodology integrates a top-down, model-based approach that uses Object Management Group™ (OMG) SysML to support specification, analysis, design, and verification of systems. Furthermore, facilitates integration with object-oriented software development, hardware development, and test [48].
The main development activities included by OOSEM are the following ones, also shown in Figure 13:

- Stakeholders Needs Analysis
- System Requirements Definition
- Logical Architecture Definition
- Candidate Architecture Systhesis
- Alternatives Optimization and Evaluation
- System Verification and Validation

A dedicated process framework tool for OOSEM does not exist; however, tool support for OOSEM can be provided by COTS-based OMG SysML tools and associated requirements management tools. In order to support the full system lifecycle, other tools should be integrated with the SysML and requirements management tools, such as configuration management, performance modeling, and verification tools [48].

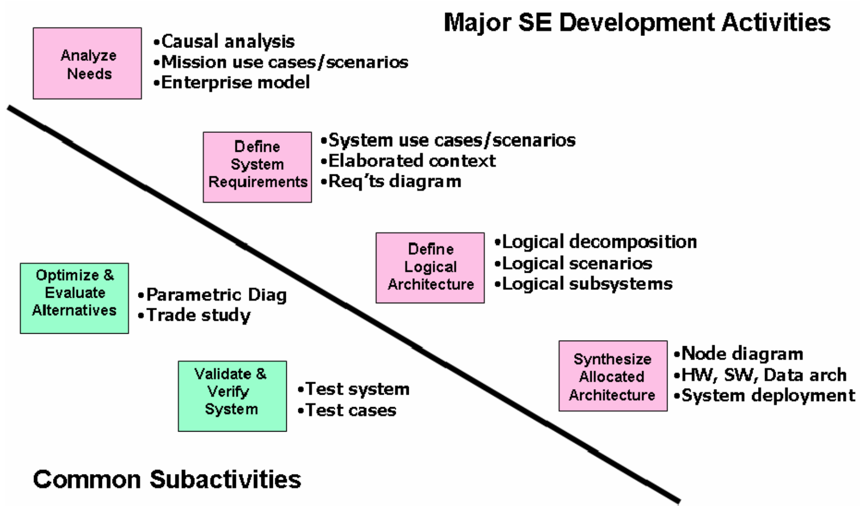

Figure 13: OOSEM Activities and Modeling Artifacts. [48].

Harmony-SE Harmony-SE is a subset of Harmony [49], a larger integrated systems and software development process, developed at ILogix, Inc., now IBM Teleologic. Harmony integrated systems and software development process is very close to the classical V lifecycle development model, and its system engineering component is in the upper left side of the process. The key objectives are:

- Identify / derive required system functionality.
- Identify associated system states and modes.
- Allocate system functionality / modes to a physical architecture.

Harmony-SE modeling approach uses OMG SysML artifacts, and is defined as a "service request-driven" modeling approach: this means that system structure is described by means of SysML structure diagrams using blocks as basic structure elements, which communicate basing on services requests. Provided services are at the receiving part of service requests and state/mode change or operations (activities) are described as operational contracts. Functional decomposition is handled through decomposition of activity operational contracts. The work products of this Methodology are shown in Figure 14 include [48]:

- Requirement Analysis
- System Functional Analysis
- Architectural Design

No process framework tool exists for Harmony-SE, but tool support is provided by IBM Telelogic via the Telelogic Tau and Telelogic Rhapsody product offerings.

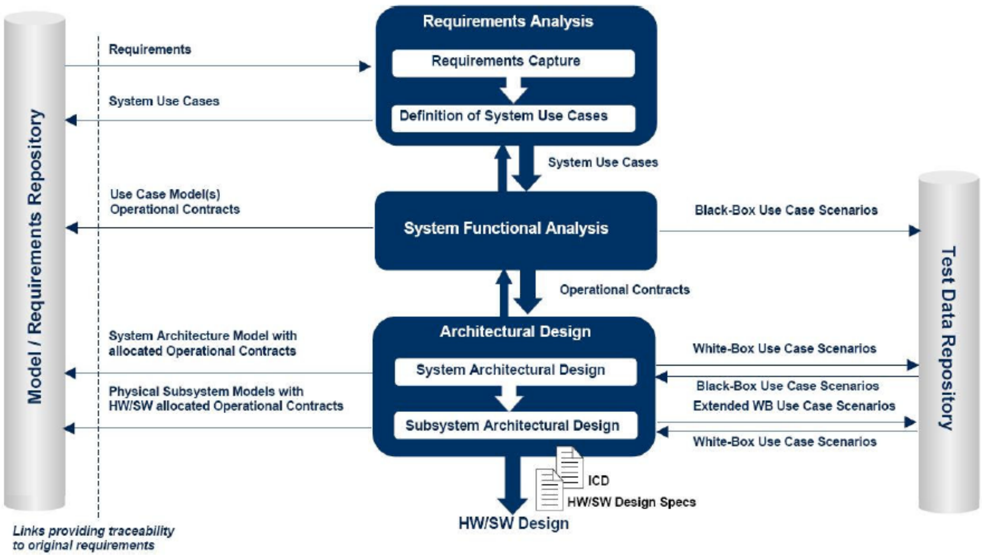

Figure 14: Harmony-SE Process Elements. [48].

Object-Process Methodology(OPM) Object-Process Methodology (OPM) is a "*formal paradigm to systems development, lifecycle support, and evolution*" [43]. In December 2015, OPM was ratified as ISO/PAS 19450:2015 [50], a Publicly Available Specification of the International Organization for Standardization (ISO), establishing OPM as an international standard for systems modeling.

OPM combines formal and simple visual models – Object-Process Diagrams (OPDs) – with constrained natural language sentences – Object-Process Language (OPL) – to express a function, structure and behavior of systems in a single model. In OPM point of view, everything can be considered as either an *object* - something that exists or has the potential of existence - or a *process* - pattern of transformation applied on a object. The *state*, instead, represents a situation of an object [43, 48].

System developing process includes four high level main stages, also shown in Figure 15:

- Requirement Specifying
- Analyzing and Designing
- Implementing
- Using and Maintaining

OPM is supported by OPCAT software [51], which includes System Overview, the Current State, Future Goals, Business or Program Constraints, and Hardware and Software Requirements. In addition, OPCAT has facilities for animated simulation, requirements management, and other advanced features [43].

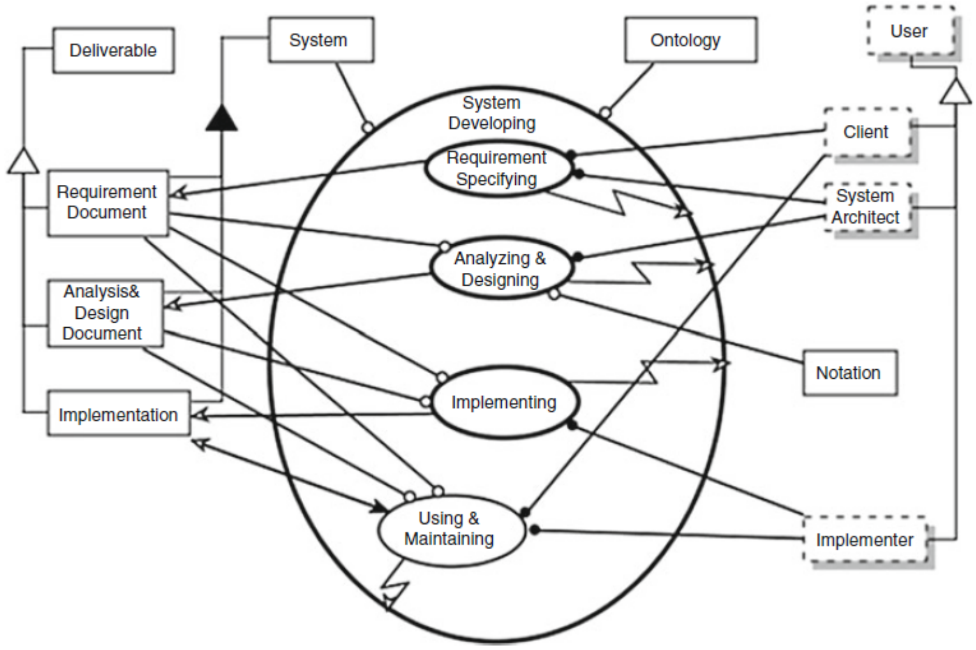

Figure 15: Zooming into System Developing [43].

ARChitecture Analysis and Design Integrated Approach (ARCADIA) ARCADIA methodology was developed by Thales company since early 2000s, and reached the public domain in 2010. Its development, along with its supporting tool, Capella, is still ongoing today. The releasing into public domain of the method elements and those of the Capella modeling tool, as open source by the Polarsys industrial working group within the Eclipse Foundation, occurred in 2015.
ARCADIA is defined by Voirin [52] as *a structured engineering method for defining and verifying the architecture of complex systems*, allowing to perform since the beginning of the definition phase, the activities that will provide a solution that satisfies all the identified requirements. All the information produced by engineering, describing requirement and solution, are within a single model, shared by all the actors involved. The models relative of each engineering level – system, subsystem, mechanical design, electronics, software – and trades are deducted/validated/linked between each other, allowing Co-engineering activities between the different levels supported by a multi-perspective approach.

Since this is the Methodology used for the development of this Thesis' work, a dedicated section will follow, in order to deepen its characteristics and processes.

2.5.2 ARChitecture Analysis and Design Integrated Approach (ARCADIA)

As stated before in this dissertation, ARCADIA presents a **multi-perspective approach**, which allows to derive the desired system model integrating different points of view. In particular, these perspectives are represented by the following layers of the model's structure [52]:

1. **Operational Analysis (OA)**: this perspective analyses the system under operational users point of view. The system engineer in this analysis identifies the actors that will interact with the system, their goals, activities, constraints and interactions.

   "What system users must achieve"

2. **System Analysis (SA)**: this perspective allows to build an external functional analysis, based in the operational analysis results and on textual input requirements. In this way, necessary functions of the system or system services are obtained as consequence of the users needs and requirements.

   "What the system must achieve for users"

3. **Logical Analysis (LA)**: this is the perspective/layer in which the system starts to emerge, in response to the need expressed by the previous analysis. Hence, the functional analysis is deepened into an internal system functional analysis, which describes the functions to be performed and assembled in order to implement the service functions identified in the previous phase.

   "How the system will work to meet expectations"

4. **Physical Analysis (PA)**: in this perspective the objective is the same than the LA's one, but it defines the finalized architecture of the system, as it should be completed and integrated, explicating all the behavioral components that perform the system's identified functions.

   "How the system will be built"

Between each perspective, their elements are connected to each other through traceability and justification connections. Figure 16 shows the layers and a schematic representation of their connections.

One of the most fundamental benefits of MBSE methods, like ARCADIA, supported by a modeling tool, like Capella, is the strong traceability of the processes. Thanks to the links between elements of each perspective, every result can be traced back to higher levels and other perspective's elements. This facilitates, for instance, the tracking of the provenance of a physical model element in a bottom-up manner to the entity in question, thereby providing a comprehensive rationale for the element's inclusion and definition within the architecture.

ARCADIA is a methodology that consists into a **function-driven** modeling. Hence, the solution architecture will be defined and justified with respect to the functional analysis. According to Voirin (2018):

"Functional analysis constitutes the major support for the understanding and the expression of need in ARCADIA, as well as for the definition of the expected behavior of each system component during the design stage."

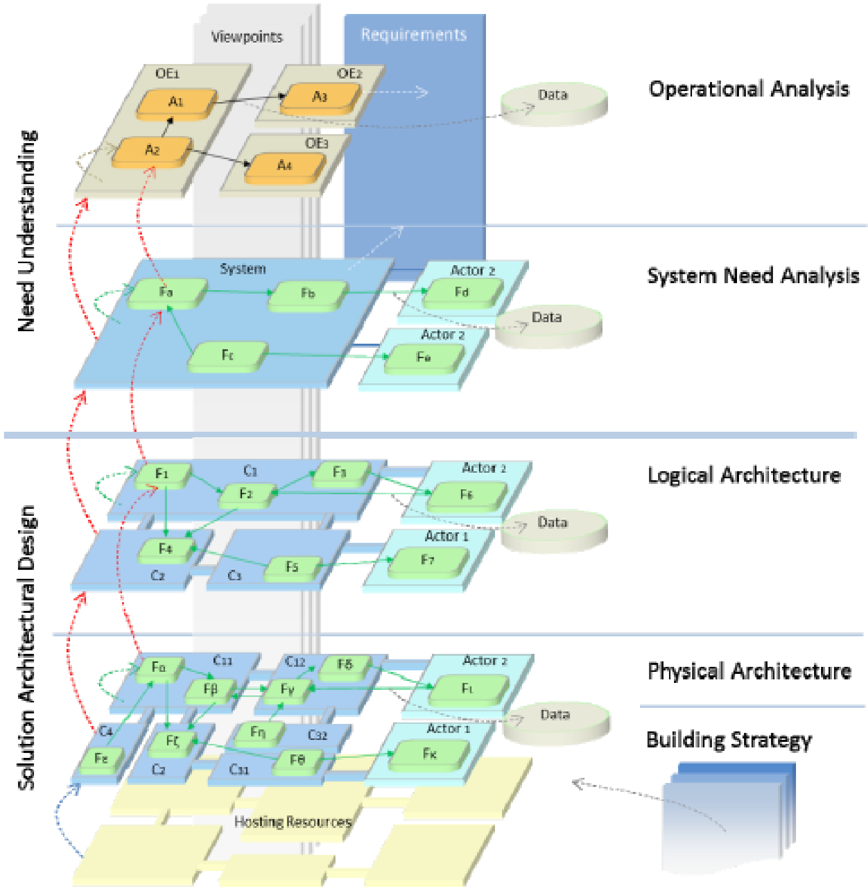

Figure 16: Main views and perspectives structuring the ARCADIA approach [52].

In each of the main perspectives, different functional analyses are established, each one satisfying the specific objectives of its layer. In this context, results essential to provide *function* definition [52]:

"A function is an action, an operation or a service performed by one of the key players (actors), the system or one of its components, contributing to its behavior."

The term *Behavior* in this context consists into a set of partial functional views: each view represents a specific perspective, but always correlated and consistent with each other.
Each function is defined by its name, its outputs and inputs, and can be decomposed into child functions or subfunctions. The relationships between functions are called *functional exchanges*, and gradually build up a graph of functional dependencies also known as *data flow*, which constitutes the first of the functional views.
On Capella is also possible to highlight the *functional chains*, which consist in paths that draw attention on specific subset of functional dependencies.
Functional chains can be enriched with chronological dimension, creating related *scenarios*, which focus on the temporal positioning of the activity of functions and their exchanges. Scenarios can be defined between functions or between system/its components and external actors [52].

Another functional view in ARCADIA methodology concerns the concept of *modes* and *states*, which can be defined with different level of detail and allocated to system and its elements. A *mode* characterizes a chosen context in which an actor, the system or its components can be found, hence its behavior in this context. On the other hand, a *state* characterizes an incurred context in which an actor, the system or its components can be found, hence its behavior in this context. The behavior is often defined by functions available in the mode or state in consideration.
It is possible for a scenario to make reference to a mode or state in order to indicate the transition at any given time.
States and modes associated with an element are generally defined by a state or mode machine, which describes them and possible transitions between them, as well as the conditions of these transitions [52].

Once a finalization step has been completed, it is imperative that the various perspectives of a functional analysis are delineated and integrated with each other in a coherent manner. This approach is essential in fostering the model's overall consistency and robustness.

In Section 4 the ARCADIA methodology and its perspectives are deepened by the dissertation of the development of a Lunar Habitat model on Capella, up to a Logical Analysis perspective. In Section 5 considerations of operations are described, with elaboration of ConOps and Operative Modes that are parallel and integrated with the system design analyzed in Section 4.

3 Research Problem

"A lunar base will first be an engineering and medical laboratory, for the study of extraterrestrial infrastructure development and for the creation of a safe environment for human habitation. Access to lunar resources will drive industrial activity.[...] Second, it will be a site for the scientific study of the Moon and the Solar System. [...] Resources recovered on the Moon will be used to support the manufacture of items needed locally, as well as of use beyond the Moon." – Benaroya (2017) [4]

In Section 2 the main characteristics of the Lunar environment and a general overview of possible permanent Lunar Habitats have been described.
The design of a system intended to operate on the Moon continuously for a long time and which interfaces with astronauts is characterized by a high level of complexity, since it must guarantee not only the survival of the systems but also humans' health, thus extremely high levels of safety and reliability are required. The design of the system is surely not the only critical aspect to ensure the success of the mission: the operational effectiveness is another fundamental point to permit the achievement of mission goals, and faces several challenges including logistics and autonomous operations.
The main challenges that must be considered during the design of a Lunar Habitat are briefly described in this Section, and will be further deepened in Sections 4 and 5.

Lunar Night survival: although the current goal is to establish a lunar base in the South Pole of the Moon, which provides an almost continue luminosity on tall peaks [5], it is important to consider that the lunar habitat could face extended periods of lack of power due to eclipse periods. This drives to energy storage needs, and considerations on the system's operative modes (Section 5), including the possibility to vary heat rejection capabilities [18].

Dormancy: a lunar habitat will not be continuously crewed. The system shall be able to survive extended periods of dormancy, which can range from months to years. To achieve this purpose, a key factor for a lunar habitat consist into autonomous operations. In this kind of phases, the system will conserve water and waste autonomously, will be able to manage failures and to ensure correct re-activation after a dormant period. This characteristic is also fundamental in a Mars base optics, which more than ever will pass through uncrewed long periods [18], considering that an Earth-Mars transfer will last about six months.

Habitability: in the context of human space exploration, mission objectives do not depend only on the systems functioning and on the pure survival of the astronauts. To make an environment, and in this case the system itself, habitable, means to ensure the astronaut's psychophysical health and comfort, which must be regarded as a fundamental variable for mission success, on par with the performance of any critical subsystem. Only in this way, the crew will be able to perform the intense schedule of activities along the mission, avoiding the risk to incur into mission failures due to the low habitability of the system. To illustrate this point, it is vital to emphasize the significance of maintaining effective communication with Earth, particularly with relatives. This is crucial in order to effectively cope with the psychological challenges associated with distance and feelings of isolation that can arise in such circumstances. In the same way, as an example, the system must guarantee privacy and comfort space, as well as the appropriate levels of lighting and noise. Also the activity planning and demands must be carefully analyzed, ensuring their psychophysical sustainability [5].

EVAs and Rover docking: in a realistic perspective of lunar base, the habitat will interact strictly with at least a pressurized rover for longer explorations. This means that the habitat design must consider the capability to provide a docking system, pressurized atmosphere and resource transfer between habitat and rover. In this scenario, the habitat would be used to process wastewater from the pressurized rover and provide potable water, oxygen for EVA charging and resources [18]. Furthermore, the designated habitat must be equipped with the necessary infrastructure to facilitate Extra Vehicular Activity (EVA) procedures, that can support the preparation and maintenance of Extravehicular Mobility Unit (EMU). This includes the provision of a suitable ingress/egress mechanism.

Outfitting: with an outfitting process a structural system is transformed into a usable system, by the installation of its subsystems and equipment. In the lunar habitat case, it will provide a livable and safe environment to the crew, and enable activities execution. The outfitting process shall be planned in order to minimize crew time and safety concerns, and the partial gravity must be considered for operations plans. The ability to outfit new system capabilities in subsequent missions is also needed [18].

Logistics: the logistic support to a permanent Lunar habitat is an intrinsic challenge of system design. First of all, the delivery of the habitat itself involves complexity in operations due to the high masses to be delivered by cargo landers. Furthermore, the habitat must be resupplied with a certain cadence (Section 5) in order to receive resources for crew survival as food, water and gasses, but also spares, payloads and new equipments and system's parts. These resupplies will be composed by landing of cargo and then by its transfer from the lander to the habitat by crew, which can represent challenging operations.

Maintenance: the maintenance plan is a key factor for a mission of this logistical complexity. In particular, repair of external systems will require Extra Vehicular Activities or robotic servicing capabilities. it is fundamental that the system design considers the maintainability of the entire system, allowing the access of all its parts, including the external ones, and hence the development of processes and procedures to support the maintenance activities. With longer mission durations and sustained operations on the lunar surface, returning to Earth should no longer be considered the primary mitigation strategy for system failures. The ability to repair external systems and assets in situ will enable recovery from major faults [18].

Safety: one of the most difficult and essential points in the design of a system like this is to guarantee the safety of the astronauts. Design for safety requires experience and skill; in fact, it represents one of the most challenging fields in the system development and design. In this Thesis, this field won't be deepen, but it is inevitable to consider that this kind of system shall involve key failure management systems and safety protocols directly integrated into the system itself. According to Wiley and Pranke [5], generally, in priority order, designers should:

1. Design for minimum risk: the design shall eliminate hazards; when this is not possible, the risk must be reduced to an acceptable level.
2. Incorporate safety devices: the risks can be reduced also adding automation or other design features or devices
3. Develop procedures and training: standardize cautions and, where necessary, certify people in tasks and activities.

In this context, the Research Problem of this Thesis is the development of a functional design of a Lunar Habitat, considering the main challenges and characteristics that have been previously described in this dissertation. The aim is not only to achieve a system design in itself: in this Thesis the final functional architecture obtained shall provide the basis to develop a system compatible with its operative life, from logistics needs – the capability of Pressurized Rover docking, for instance – to Operative Modes development. For this reason, this Thesis involves also a parallel integration of operative evaluations that will be described in Section 5: this *transverse modeling*, as will be called, is fundamental to ensure the effectiveness of the operations, allowing to save time and money, and to reach mission objectives pursuing more exploration and research activities.
This multi-perspective design process is possible thanks to the MBSE approach, in particular following the ARCADIA methodology, previously mentioned. This methodology, supported by the utilization of Capella tool, permits to derive a complex functional architecture involving several critical aspects for the design, including operative once, in a completely traceable way: in fact, every element present in the model can be traced back to the entire chain of design made since preliminary evaluations.

In Sections 4 and 5 the Research Problem will be resolved. In particular the Section 4 will describe the design process of the system, starting with Stakeholders' expectations and needs analysis and proceeding with mission objectives identification and then with the functional derivation of the system, up to subsystem level. In this Section, the design already involves also elements derived from the parallel integration of operative evaluations, which will be explained in Section 5.

4 Lunar Habitat system model with ARCADIA

This Section applies the ARCADIA method, briefly summarized in the previous Section, to the development of a system model of a Lunar Habitat, basing on the main concepts discussed so far. It will be possible to explore in greater depth the ARCADIA perspectives and activities, and to show how these are implemented within the Capella tool.

The first part of the Section, namely Subsections 4.1 and 4.2, covers the only activities not directly supported by Capella and which provide the foundation for the subsequent Operational Analysis and the initiation of the modeling work on Capella.
The model is then developed up to Logical level in Subsections 4.3, 4.4 and 4.5, with the aim of identifying the main subsystems and elements of the system under a functional point of view. Even if the system design is described separately from the operational evaluations discussed in Section 5, it has to be clarified that already in this Section elements included in the system design are derived from operational integration of ConOps and Operative Modes described and deepened in Section 5, as the two processes has to be intended as parallels.

Subsection 4.1 concerns an high level Stakeholders analysis, fundamental to identify the main needs and expectations to satisfy with the final product, proper of classical preliminary activities of mission design.

Subsection 4.2 presents the Mission Statement that describes the mission, from which the main mission objectives are derived. The final set of objectives is integrated with secondary objectives derived from the Stakeholders analysis discussed in Subsection 4.1, and in particular through the identification of the main stakeholders' values, which result in objectives. Finally, Mission and System Functional Requirements are reported.

Subsection 4.3 starts to describe the design process following the ARCADIA methodology. In this subsection, the external actors involved into the operative phase of the mission are identified and their main activities are allocated and analyzed.

Subsection 4.4 represents the first proper approach to the desired system. Basing on the results obtained in the previous phases, a system functional analysis is derived from the mission objectives and the first functional architecture is achieved.

Subsection 4.5 describes the ultimate level of detail reached in this Thesis, and explores further the functional analysis begun with the System Analysis. Finally, a Logical Architecture of the system is achieved, with the identification of the main elements of the system – the future subsystems – which allow the execution of the allocated functions.

4.1 Stakeholders Analysis

The process of stakeholder analysis constitutes the preliminary stage in the design and realization of a product. The purpose of this process is to identify the stakeholders and their intended use of the system. The primary steps in this process are the identification of stakeholders and the understanding of their needs and values, hence their expectations [40].

4.1.1 Stakeholders Identification

According to NASA [40], a Stakeholder is:

"A group or individual that is affected by or has a stake in the product or project"

Some of these stakeholders are *key stakeholders*, which are key players for the project/product. Additionally, the composition of the stakeholders' group may also encompass services and supply providers, as well as parties who are affected by or have a vested interest in the outcomes of the project or product. Results important that the list of stakeholders is identified at the outset of the process, as well as the primary stakeholders will exert the most significant influence over the project.

Consequently, first of all the main groups of stakeholders have been identified.
In this context, **Space Agencies, Space Industry** and **Astronauts** are the so-called *key stakeholders*, whose influence is the most significant for the project.
Secondary Stakeholders' groups have been identified, whose influence and interest can be significative in different phases of the project: **Research Centers, Universities, Regulatory authorities** and **Public administration entities**.
In Figure 17 a qualitative representation of the levels of Influence and Interest of the Stakeholders' groups mentioned above is shown.
It is important to note that key stakeholders – Space Agencies, Space Industry and Astronauts – are those who possess both the highest levels of interest and influence. These individuals are also referred to as *Promoters*.
On the other hand, Regulatory Authorities and Public Administration entities have an high influence but low interest in the project: they are also known as *Latents*.
Stakeholders with high level of interest in the product or project but low influence, in this case Research Centers and Universities, are called *Defenders*.
Finally, classes of stakeholders which present both low levels of interest and influence – media and industries not directly involved in space industry, for example – are referred to as *Apathetics*. As this class of stakeholders exerts a negligible influence on the project, it will not be the subject of further discussion in this dissertation, but could include, as an example, Energy Industry or Biomedical Industry, interested in advanced researches in respective fields for space applications.

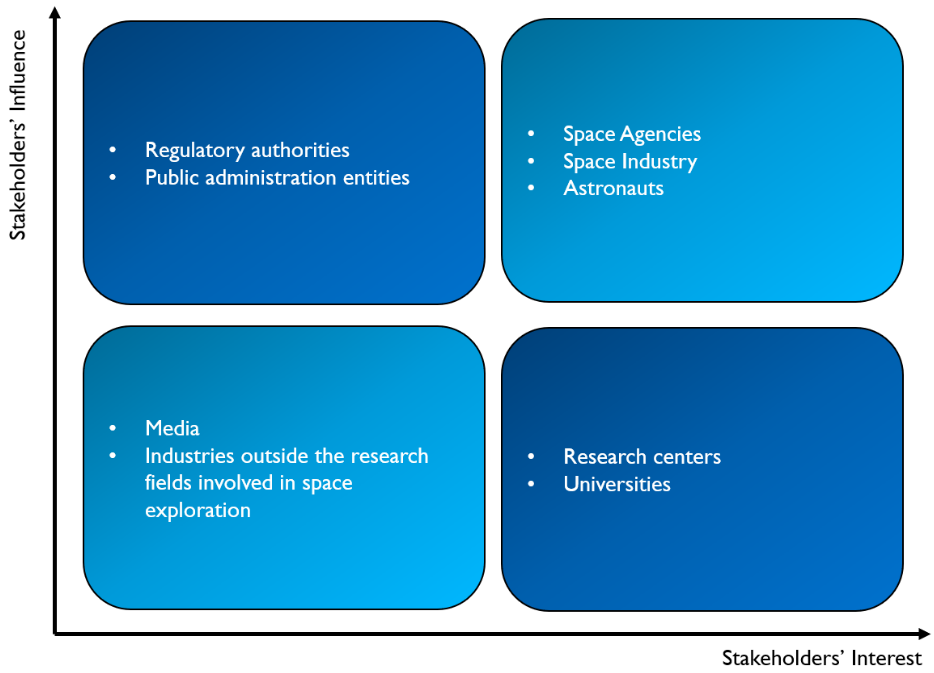

Figure 17: Stakeholders Interest - Influence diagram

In order to analyze the expectations of the stakeholders, in particular Promoters' ones, fitting examples of specific stakeholders have been identified, considering an European perspective. These are reported in Table 2:

Table 2: Stakeholders classification.

Stakeholders class	Stakeholders group	Stakeholders
Promoters	Space Agencies Space Industry Astronauts	ESA, ASI Thales Alenia Space, Leonardo, Altec Astronauts
Defenders	Research Centers Universities	CNR-INFN, CNR-DSB, C.I.R.A, ENEA Politecnico di Torino [7]
Latents	Regulatory Authorities Public Administration entities	UNOOSA, ITU, IAEA MUR, Regions
Apathetics	Media & Other Industries	–

[7]Politecnico di Torino is here representative of a broader category which includes all Italian and European Universities active in Aerospace sector

4.1.2 Stakeholders Expectations Analysis

The understanding of key stakeholders' expectations for the project is crucial in the system engineering process, since it provides the foundation upon which all the SE work depends. The result of this process will be the achievement of mission objectives and requirements.
In order to do this, defining concepts of *need* and *value* is fundamental.

A **Need** is a single statement which answers to the question "What problem are we trying to solve?". Hence, it should relate to the problem that the product is supposed to solve, but not the solution. [40]

A **Value** identifies the utility that stakeholders obtain in exchange for their contribution to the project. This statement answers to the question "What is the worth of the outcome?".

For each Stakeholder identified, needs and values have been described, as shown in Tables 3, 4 and 5.

Table 3: Promoters Needs and Values.

Promoters	**Needs**	**Values**
Agenzia Spaziale Italiana (ASI)	Testing and evaluation of technologies for space exploration missions.	Technological and scientific return in human space exploration field, enduring human presence on the Moon, autonomous operations, high quality of data.
European Space Agency (ESA)	Research, technological development, preparation for space exploration missions; Astronauts training and medical research; Astronomical research; Testing and evaluation of technologies for space applications and telecommunications.	Technological and scientific return in human space exploration and telecommunications fields, advancements in medical field, enduring human presence on the Moon, autonomous operations and extensible systems, high quality of data.
Thales Alenia Space	Testing and evaluation of technologies, and infrastructures for human flight and human exploration.	Technological and scientific return in human space exploration field, technological test and verification.
Leonardo	Testing and enhancement of its technologies for telecommunications, AI, electronics and robotics.	Technological return by the application of its technologies on the Moon, data security and technological adaptability, technological test and verification.

Continued on next page

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Promoters	Needs	Values
ALTEC	Testing and improvement of tools for engineering and logistics supporting planetary exploration missions.	Technological enhancement of engineering and logistics services to support lunar mission operations; technological and operational test and verification.
Astronauts	Optimal working conditions for carrying out activities during the mission.	High level of safety, improvement of comfort and privacy, ease of interfaces, survival.

Table 4: Defenders Needs and Values.

Defenders	Needs	Values
Consiglio Nazionale delle Ricerche (CNR)-Istituto Nazionale di Fisica Nucleare (INFN)	Research in particle physics and technology development.	Astroparticells research, scientific return and quality of data.
Consiglio Nazionale delle Ricerche (CNR)-Dipartimento di Scienze Biologiche (DSB)	Research in Biological Sciences fields.	Scientific return from research of biological behavior on the Moon, human psychophysical behavior in extreme conditions, advancements in medical field, quality of data.
Centro Italiano Ricerche Aerospaziali (CIRA)	Research and technological development for Aerospace applications.	Technological return and adaptability to other Aerospace application.
ENEA - Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile	Research of innovative technological solutions for sustainable economic development.	Technology return and scientific knowledge on energy production field, adaptability of technologies to terrestrial applications.
Politecnico di Torino	Testing and Research of new technologies in Aerospace, Mechatronics and Biomedicine fields.	Technological and scientific return, technological adaptability to other fields.

Table 5: Stakeholders Needs and Values.

Latents	Needs	Values
United Nations Office for Outer Space Affairs (UNOOSA)	Development and oversight of international space treaties and conventions compliance.	International laws compliance and space legislation enhancement.
International Telecommunication Union (ITU)	Definition and strengthening of telecommunication standards.	International telecommunications standards compliance and enhancement.
International Atomic Energy Agency (IAEA)	Research and development of safety standards and minimization of risk related to radiation exposure.	Safety standards compliance for human health and regulations enhancement.
Ministero dell'Università e della Ricerca (MUR)	Coordination of Italian scientific and technological research.	Italian prestige in the global space sector, technological return and adaptability to terrestrial fields.
Italian Regions	Local technological research and development support, promotion of economic growth and innovation.	Local prestige in space sector, economic and technological return, adaptability to terrestrial applications

The values identified in this analysis can be summarized with the following set of principal values:

- **Habitability**: as defined in Section 3, the mission guarantees the appropriate comfort and privacy conditions, ensuring a good crew's psychophysics health.
- **Ease of Interfaces**: the crew interfaces with systems involved in the mission without excessive complexities.
- **Operational Availability**: the mission's operative phase is logistically and functionally sustainable and effective.
- **Data Quality**: the data produced by the mission present high quality levels.
- **Autonomous Operations**: the mission involves systems with autonomous capabilities.
- **Adaptability**: the mission's results are adaptable to both other space missions and Earth applications.
- **Standards Accomplishment**: the mission accomplishes international standards.
- **Extensibility**: the systems involved in the mission allow future extensions and upgrading.
- **Human Survival**: the mission ensures the crew survival.
- **Technology Return**: the mission provides technology return.
- **Scientific knowledge Return**: the mission provides scientific knowledge return.
- **Economic Return**: the mission has an economic return.

4.2 Mission Statement, Objectives and Requirements Definition

The subsequent phase involves the primary objectives definition and the translation of the stakeholders' analysis of needs and values into mission elements. As previously stated, this process will result in the definition of mission objectives and requirements.

According to NASA [40], an **Objective** represents a specific output that the mission -or systems- must achieve. Generally, objectives should meet four criteria:

- **Specificity**: objectives should be specific enough to provide clear directions to all figures involved, including customers.
- **Measurability**: objectives should be measurable, quantifiable and verifiable.
- **TBDs**: objectives To Be Defined (TBD) may be included until deeper studies and evaluations occur.
- **Results-oriented**: objectives should be results-oriented focusing on desired outputs and outcomes, not on methods used to achieve them.

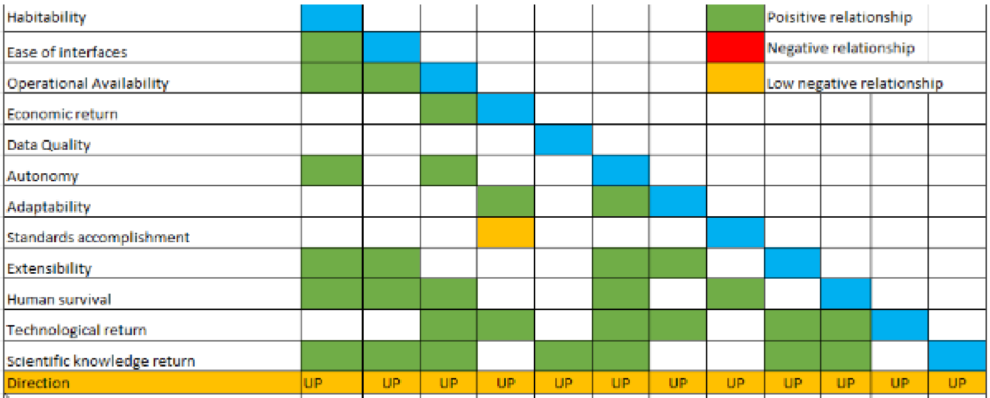
The primary mission objectives can be derived from the mission purpose itself, described by the *Mission Statement*:

"To ***establish enduring human presence*** *on the Moon in a mission that* ***ensures survival*** *and* ***autonomous operations***, ***enables research*** *and* ***exploration activities***, *and serves as* ***preparatory test bench*** *for future colonization goals on Mars."*

From the key concepts highlighted in the statement, it is possible to define the **primary mission objectives**:

1. To enable a prolonged human presence on the lunar surface
2. To guarantee astronauts survival under all circumstances
3. To enable autonomous activities without crew intervention
4. To enable research and exploration activities
5. To represent a bench test for the future human exploration missions on Mars

This set of mission objectives can be enriched by another group of objectives directly derived by the Stakeholder Analysis discussed in Subsection 4.1. An useful tool that allows to identify the most incisive Stakeholder's values in the project is the **Quality Function Deployment (QFD)**.
This tool consists into the initial allocation of a numerical value between 1 and 5 to each stakeholder – their *weight* in the project – followed by the assignment of the weight from 1 to 10 that each Stakeholder allocates to each value identified by Stakeholder's analysis. In addition, in the top of the QFD it is possible to highlight the relationship between values: if two values are in a *positive relationship*, in other words they favorite each other, a *green* mark is assigned; otherwise, is their relationship is *low negative* or *negative*, *yellow* and *red* marks are allocated, respectively.
In Figure 18 the executed Quality Function Deployment (QFD) is shown.



Stakeholders	Values(1-10) / Stakeholder weight (1-5)	Habitability	Ease of interfaces	Operational Availability	Economic return	Data Quality	Autonomy	Adaptability	Standards accomplishment	Extensibility	Human survival	Technological return	Scientific knowledge return
ASI	5	10	9	10	4	8	10	7	6	10	10	9	8
ESA	5	10	9	10	4	8	10	7	6	10	10	9	8
Astronauts	5	10	10	10			9		6	8	10	7	7
Politecnico di Torino	3					10		7		6	10	10	10
Thales Alenia Space	4	10	9	9	4		10	6		8	10	8	
ALTEC	4	8	9	10	4		10	6		8	10	10	
Leonardo	4	8	8	10	4		10	7		7	10	10	
UNOOSA	2								10		10		
ITU	2								10				
MUR	2				6			9				10	10
International Atomic Energy Agency (IAEA)	2								10		10	6	8
Italian Regions	2				9			8				7	
CNR - INFN	1					10							10
ENEA	1							10				6	6
CIRA	3							8		5		10	6
CNR - Dipartimento di Scienze biomediche	1					10		10			10	10	10
	Score	254	244	266	118	130	265	245	150	265	350	359	225
	Ranking (Importance)	6	8	3	12	11	4	7	10	4	2	1	9

Figure 18: Quality Function Deployment (QFD)

As it is possible to notice on the top of the QFD, possible conflicts can derive from the relationship between Economic return and Standards accomplishment. The risk of higher costs due to standards measures must be considered.

The Stakeholders' values with higher impact on the mission, according to this analysis are:

1. Technology Return
2. Human Survival
3. Operational Availability
4. Autonomous Operations
5. Extensibility
6. Habitability

These can be traduced into other Mission Objectives [8] (Table 6):

Table 6: Stakeholders' main values to Mission Objectives

Value	**Mission Objective**
Habitability	To ensure habitable conditions
Operational Sustainability	To ensure system's continuous functioning
Extensibility	To enable system's future extensions and upgrading

Finally, Table 7 shows all the Mission Objectives obtained:

Table 7: Mission Objectives

Mission Objectives	
ID	**Objective**
MO1	To enable a prolonged human presence on the lunar surface
MO2	To guarantee astronauts survival under all circumstances
MO3	To enable autonomous activities without crew intervention
MO4	To enable research and exploration activities
MO5	To represent a bench test for the future human exploration missions on Mars
MO6	To ensure habitable conditions
MO7	To ensure systems continuous functioning
MO8	To enable systems' future extensions and upgrading

As previously mentioned, Stakeholders' expectations can also be transformed into *Requirements*, expressed as *shall* statements which enable the description of all inputs and

[8]Since human survival, technology return and autonomous operations are already included by the primary set of Mission Objectives, their repetition would be redundant

outputs, the required relationships between them, including constraints, and system interactions with operators, maintainers, and other systems [40]. In this instance, at this point of the dissertation, *Mission Requirements* (Table 8) are derived directly from Mission Objectives, some of which can be translated to functions of systems involved in the mission: these are named *System Functional Requirements* (Table 9).

Table 8: Mission Requirements

Mission Requirements	
ID	**Requirements**
R-MIS-001	The mission shall be operative before TBD
R-MIS-002	The mission shall operate on Lunar South Pole (TBC) surface
R-MIS-003	The mission shall demonstrate technologies and operations for human Mars exploration
R-MIS-004	The mission shall sustain crewed operative phases up to TBD periods
R-MIS-005	The mission shall sustain uncrewed operative phases up to TBD periods
R-MIS-006	The mission shall include in situ research and exploration activities

Table 9: System Functional Requirements

System Functional Requirements	
ID	**Requirements**
R-FUN-001	The system shall ensure the survival of a crew of TBD astronauts for a TBD period.
R-FUN-002	The system shall enable autonomous operations
R-FUN-003	The system shall enable both human exploration and research activities
R-FUN-004	The system shall ensure habitable conditions
R-FUN-005	The system shall enable future extensions and upgrading
R-FUN-006	The system shall ensure continuous functioning

At this point of dissertation it is possible to proceed with the description of the ARCADIA layers' analysis, sustained by Capella tool, which allow to derive the system that satisfies all the mission objectives and requirements just obtained.

4.3 Operational Analysis

"What system users must achieve"

Operational Analysis layer in Arcadia methodology aims to capture what system users must achieve, enabling the exploration of user needs in order to ascertain the most effective solutions. One of the most particularities of this perspective is that *Operational Analysis (OA) should not mention the system, so as not to bar itself from potentially interesting alternatives for achieving the satisfaction of customer needs*. Hence, the aim is to avoid *a priori* assumptions about the resulting system, hence the risk of exclude other potential effective solutions [52]. Only later in the methodology's perspectives, will emerge the system and its role, in particular since System Analysis (SA) (Subsection 4.4). The main activities to achieve during the OA are:

- To define missions and required operational capabilities
- To perform analysis of the operational needs

4.3.1 Operational Entities and Actors

The first step in this analysis is to **capture Operational Entities and Actors**, which will represent the users of the system. On Capella, Entities and Actors are defined as follows:

- **Operational Entities**: Entity belonging to the real world whose role is to interact with the system being studied or its users.

- **Operational Actors**: Particular case of a (human) non decomposable operational entity.

The actors and entities involved in this analysis include both space and ground segments elements which interact with the system. In terms of space segment, the Crew and Pressurized Rover (PR), which physically interact with the system on the Moon, are considered, as well as Lunar Orbiters[6] that enable the communication between the system and Earth. Regarding ground segment, the elements/actors on Earth which support the mission and collect data are included. In particular, according to NASA, [53], the primary elements of a Ground System are the ones included in Table 10.

Basing on the main elements identified in Table 10, other actors and entities relevant for this case of study are identified, including Astronauts' Families, Medical doctors and Psychologists, and several Control Centers that interface directly with astronauts and the Space Segment, providing mission and system's support during the operative phase [11]. In addition, engineering centers are included, since could be required the involvement of specific engineering support during the mission.

[6]The importance of interaction of PR and Lunar Orbiters with the system derives from operational considerations that will be discussed in Section 5

[11]It is important to specify that Families and Specialists in support to the crew communicate with the space segment through channels provided by Control Centers. Nevertheless, in this model these are considered separately from the Control Centers in order to facilitate the visualization of the different kinds of activities performed by these actors and to focus on the activities strictly proper of Control Centers during the operative phase of the system

Table 10: Primary Elements of a Ground System [53]

Primary Elements of a Ground System	
Element	**Function**
Ground Stations	Telemetry, tracking, and command interface with the system
Ground Networks	Connection between multiple ground elements
Control Centers	Management of the system's operations. Mission Control Center (MCC), Spacecraft Operations Control Center (SOCC) and Payload Operations Control Center (POCC) are included.
Remote Terminals	User interface to retrieve transmitted information for additional processing. In this dissertation are named also End Users.

Figure 19 shows the **Operational Entities Breakdown Diagram**, which represents the Entities and Actors identified for this mission and implemented on Capella.

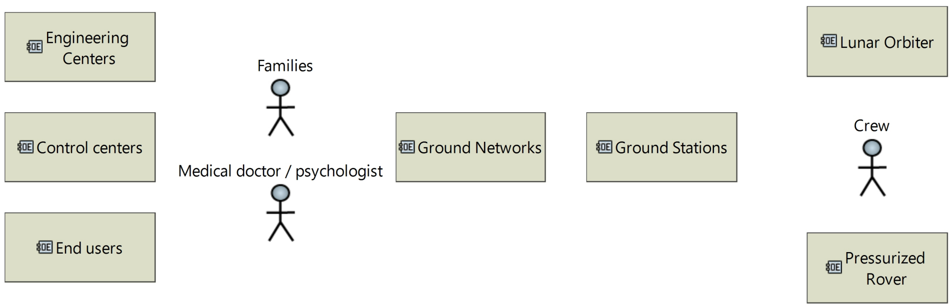


Figure 19: Operational Entities Breakdown Diagram (OEBD)

4.3.2 Operational Capabilities

An Operational Capability (OC) is defined as the *capability of an organization to provide a high level service, leading to an operational objective being reached.* Each OC can involve more entities and actors, so they will be connected in the diagram. The OCs identified are directly derived from the Stakeholders' Analysis and Mission Objectives definition previously discussed, as shown in Table 11.

The resulting diagram is the Operational Capabilities Blank (OCB), shown in Figure 20. In particular, the following allocations have been performed:

- **To ensure human survival and habitability**: this capability obviously involves the crew itself, which must survive its mission on the Moon, and PR that allows, among all, to resupply the habitat with essential resources for the crew stay. Also, the Control Centers must ensure that the mission planning and the systems involved are compatible with the survival of astronauts. Through Control Centers, besides the engineering support provided by Operators, the survival is supported

Table 11: Operational Capabilities derivation

Objectives	Operational Capability
• The mission will enable a prolonged human presence on the lunar surface • The mission will guarantee astronauts survival under all circumstances • The mission will ensure habitable conditions	To ensure human survival and habitability
• The mission will enable autonomous activities without crew intervention • The mission will ensure systems continuous functioning • The mission will enable systems' future extensions and upgrading	To ensure long term functioning and upgrading
• The mission will represent a bench test for the future human exploration missions on Mars • The mission will enable research and exploration activities	To enable research and exploration activities

by the regular communication with Medical doctors, and the recurrent communication with psychologists and families favorites the permanence on the Moon. Also, Engineering Centers dedicated to the engineering support have an important involvement into astronauts survival, ensuring the appropriate functioning of the systems, hence the crew safety.

- **To ensure long term functioning and upgrading**: the crew, during crewed phases, support the correct functioning of the system on the front line, monitoring, maintaining and upgrading it in situ. The PR with its logistic resupplies provides spares, items and new equipment for the system's functioning and upgrading. Lunar orbiters allow a consistent communication with Earth, where Engineering Centers and Control Centers, also through Ground Stations, monitor autonomous operations and intervene in case of remote maintenance or emergencies.
- **To enable research and exploration activities**: these are carried out first of all by the crew during the lunar mission, with the fundamental support of the PR, which allows to reach greater explorations ranges and hence to collect more samples for research. In addition, end users perform research activities on Earth using data produced during the mission and received by the Control Centers.

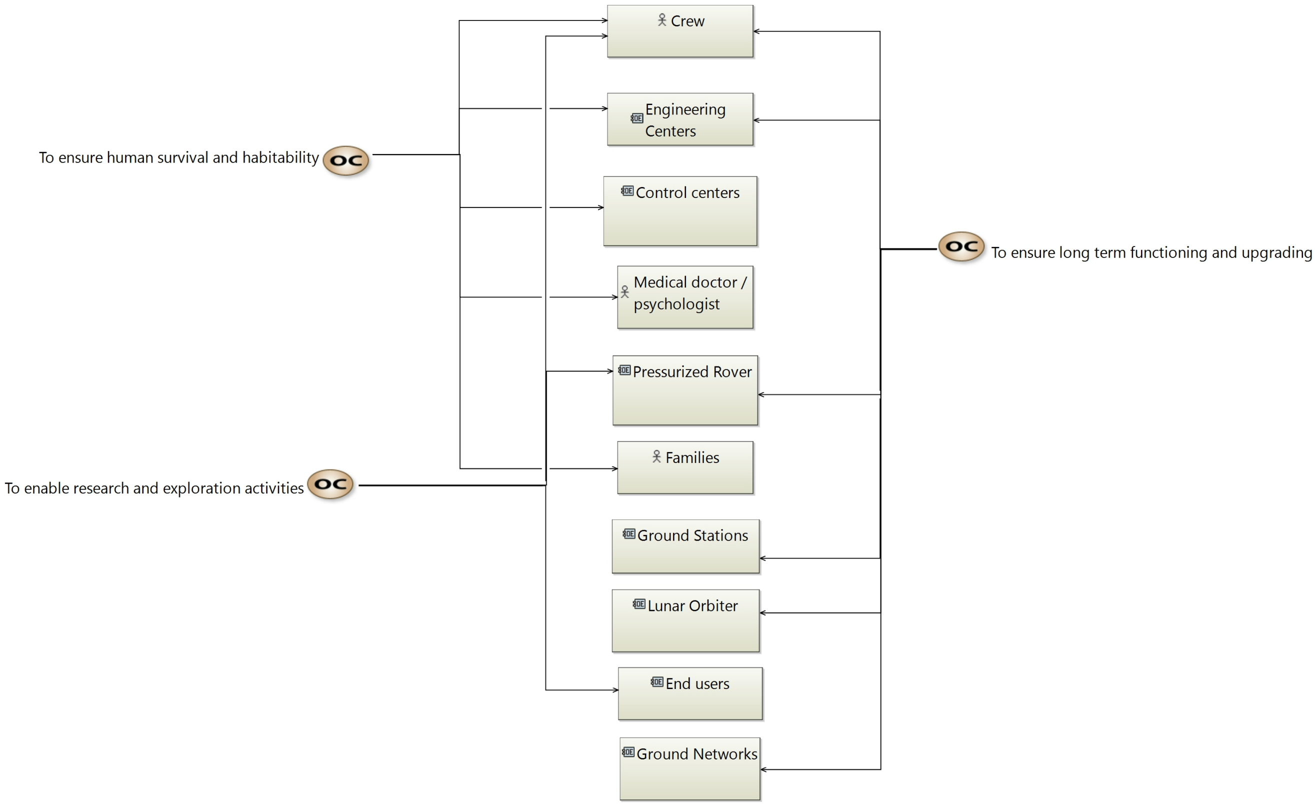


Figure 20: Operational Capabilities Blank (OCB)

4.3.3 Operational Activities

With these elements defined, it is possible to build a first architecture that represents the main high level activities performed by each Entity and Actor during the operative phase of the system, named Operational Activities. These deepen the concepts described above, and provide a clearer idea of the relations between activities and Entities themselves. This architecture is shown in Figure 21, with the Operational Architecture Blank (OAB).

In this architecture Lunar Orbiters and Ground Stations are the interfaces for data and commands communications between Ground facilities and Space segment, allowing uplink and downlink with consistent availability, visibility, and higher data rates for surface users [54]. These data and commands are distributed between Earth facilities and handled by Ground Networks.
Thanks to these communication and data handling activities, Control Centers can support the mission and astronauts' work, with the assistance of Engineering Centers, which perform trend analysis and provide specific engineering support if required. More in detail, Control Centers provide general engineering support to the mission and its systems, and obviously to the crew. They manage emergencies, monitor the systems functioning and support the crew survival not only through the correct functioning of systems, but also through mission and activities planning, and medical support by professional figures.
The main activities that astronauts accomplish during the mission, besides basilar surviving activities, regard systems maintenance and outfitting, exploration and research activities – supported by the utilization of the Pressurized Rover (PR) – and other daily

activities which can include personal communications with family, daily work out and off duty activities, following a precise schedule provided by Control Centers. Together with the regular communication with loved ones, a psychological support is provided by professional figures through Control Centers, in order to ensure the psychological health of astronauts.

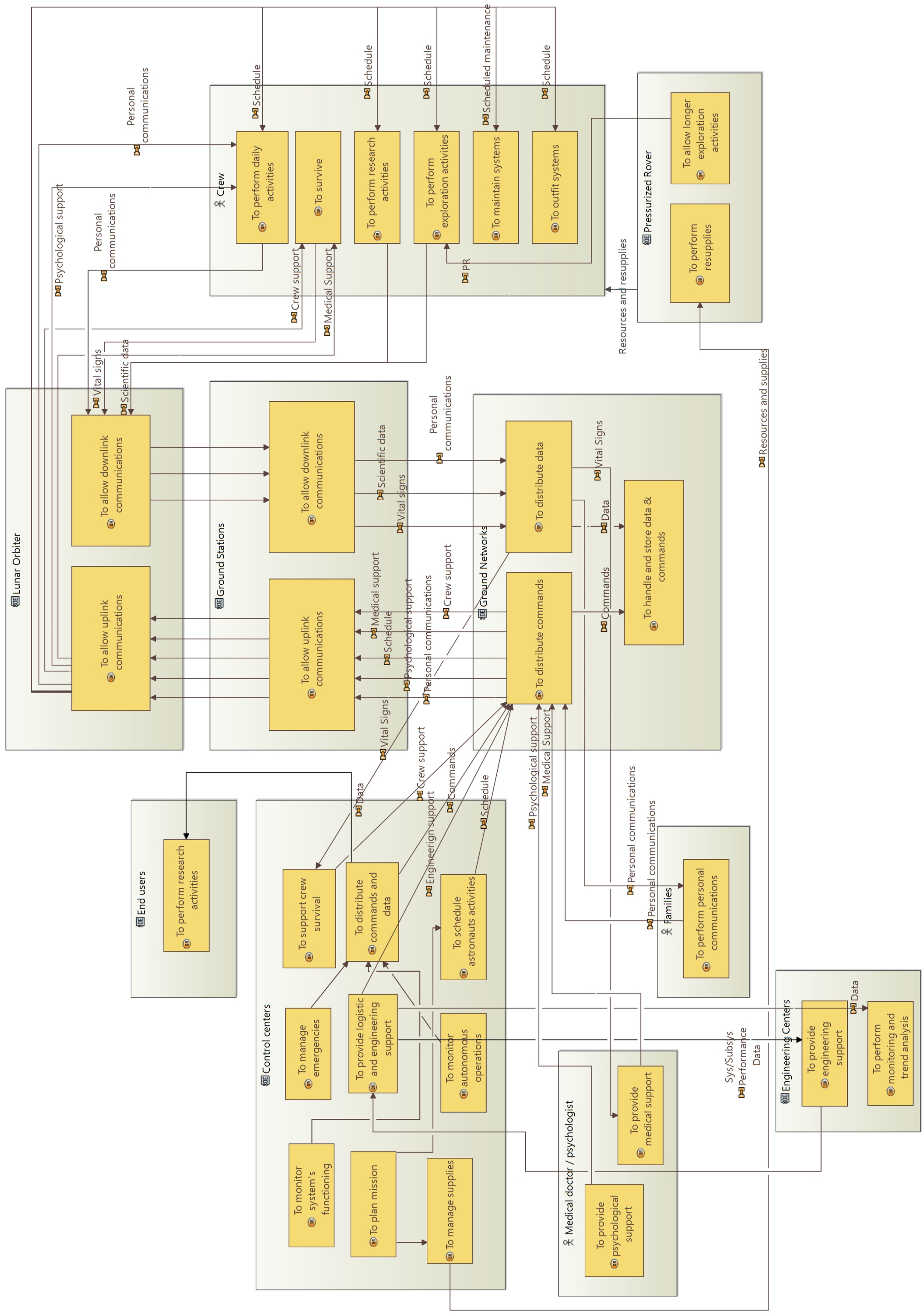


Figure 21: Operational Architecture Blank (OAB)

4.4 System Analysis

"What the system must achieve for the users"

So far in this Section the analysis focused on the needs of the different stakeholders and users of the product, without ever mention the system in the model. With the System Analysis (SA), the System of interest begins to emerge, starting from the Operational Capabilities identified during the OA. Essentially, the SA identifies the **required system's functions**, including the functional exchanges that exist to accomplish the users' activities, excluding any implementation choice or details [52]. This perspective focuses on the system itself as a black box, in order to define how it can satisfy the former operational needs, and builds an external *functional analysis*, based on the OA, and which is analyzed in this Subsection.

4.4.1 Mission and System Capabilities

The first step, which provides continuity and connects the following analysis with the OA, is to identify **Mission Capabilities** and **System Capabilities**:

- **Mission Capabilities** answer the question *What is the purpose of the system?*, and coincide with the Operational Capabilities identified in OA.
- **System Capabilities** answer the question *What services shall the System provide?*, and derive from the Mission Capabilities, providing the base of main functionalities that the system must perform.

Figure 22 shows this process, in a diagram called Mission Capabilities Blank (MCB).

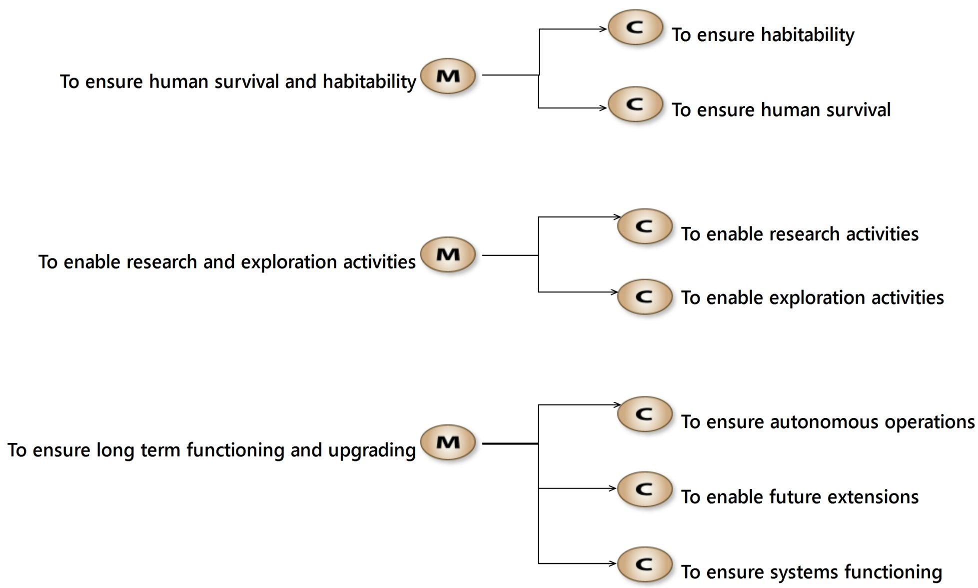


Figure 22: Mission Capabilities Blank (MCB)

4.4.2 System Functional Tree

As mentioned, the System Capabilities provide essentially the main functional groups that the desired system must accomplish, so they are transitioned to *Root System Functions*. Before the allocation of each function to System Actors or Components, a functional derivation of lower level functions is performed, building a first High Level **Functional Tree**, called System Function Breakdown (SFBD).

In Figure 23 the first three functional arms of the SFBD are shown.

The first arm from left, is the functional arm relative to ensuring Human Survival.
To guarantee the crew survival, the system must provide the basic human necessities: water and hygiene needs are translated into water and waste management functionalities[7]. In line with the concepts discussed in 2 and 3, the system must shield astronauts from radiation exposure typical of the lunar environment, and must provide autonomous emergencies management functionality in order to automatize safety protocols and enhance the safety of the astronauts. Finally, the system must be able to manage the vital signs of astronauts, in order to contribute in supporting their health during the mission.

The arm in the middle shows the functional arm relative to the Autonomous Operations functionalities of the system. In particular, the system must be able to manage some of the habitat characteristics without a continuous human intervention, both from Earth and Moon, allowing to dedicate more time to research and exploration, and to survive dormancy periods. Consequently, the system must be able to conserve resources and to manage habitat atmosphere autonomously, including regolith shielding. Finally, the system must manage failures without human intervention.

The third functional arm concerns the ability of the system to function properly for long periods. This means that it must include traditional functionalities of a space system, such as communications, electrical power, commands, data and thermal management. In addition, in order to favorite a longer operative life, the system must be able to monitor and control itself, and shall enable maintenance actions across all its parts and components.

In Figure 24 the fourth and fifth functional arms are shown. In particular, the one on the left concerns the ability of the system to ensure an Habitable environment inside the system: this means to provide livable space, so with internal spaces appropriate to move and live comfortably, and to provide psychological comfort conditions, such as privacy and the appropriate levels of lightening and noise, as will be detailed in next Subsection 4.5.
On the right, is explicated the capability of the system to enable extensions and upgrading: this allows to obtain a system with gradual more advanced capabilities and which permits to perform more research and exploration activities. To accomplish this, the system shall provide a modular structure which can be extended by the addition of further modules, thanks to appropriate interfaces.

Finally, the last two arms of SFBD regard the ability of the system to enable Research ad Exploration activities. In particular, to perform researches astronauts need space and

[7]Food and atmosphere management are included in Autonomous Operations functional arm.

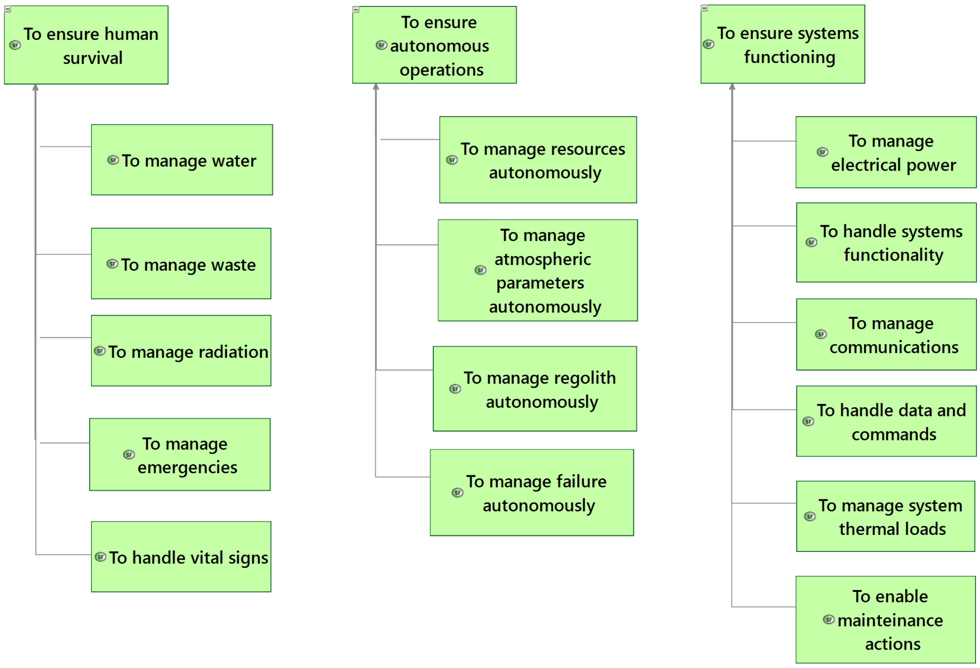


Figure 23: The first three functional arms of SFBD. From left to right: (a) Human Survival functional arm (b) Autonomous Operations functional arm (c) Systems Functioning functional arm.

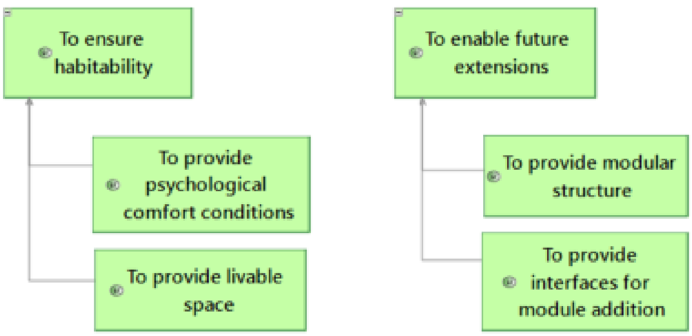


Figure 24: The fourth and fifth functional arms of SFBD. From left to right: (a) Habitability functional arm (b) Extensibility functional arm.

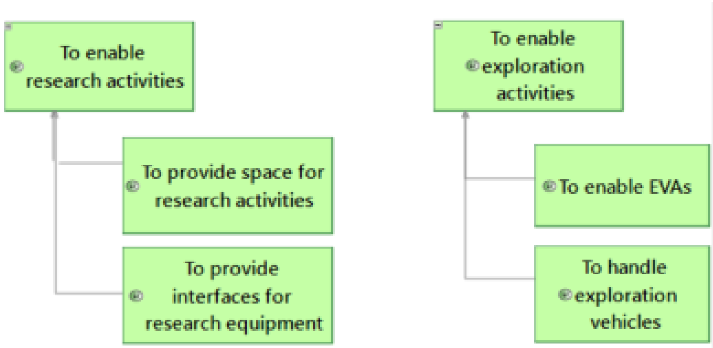


Figure 25: The sixth and seventh functional arms of SFBD. From left to right: (a) Research activities functional arm (b) Exploration activities functional arm.

scientific equipment, so the system shall provide sufficient internal space and equipment interfaces. On the other side, to enable exploration activities, the system must enable to properly perform Extra Vehicular Activitys (EVAs), and to manage the docking and the support of exploration vehicles.

The entire Tree, also called System Function Breakdown (SFBD), is shown in Appendix B.

4.4.3 System Functional Architecture

Once the high level functions have been identified, it is possible to produce the final diagram of this layer, which consists into a *Functional Architecture*. This architecture shows the functional allocations to the desired System, and to involved Actors. All these functions involve *functional exchanges*.
In practice, the architecture diagram, called System Architecture Blank (SAB), is an integrative representation of the SA, and allows to visualize an initial high level functional architecture of the system.
In Figure 26 the System Architecture Blank (SAB) diagram obtained is shown.

As mentioned, the system starts to emerge from this analysis, and in particular it is represented by the dark blue element in the middle, which interfaces with the actors and entities previously identified in OA, now called *System Actors*, in light blue [8].
The functions allocated to the System are the same from the SFBD, and the functions allocated to System Actors are the Operational Activities transitioned to System Actors' functions. The lines between the functions represent the functional exchanges, which are the elements exchanged between actors and system, and between functions themselves. Thanks to this architecture, it is possible to make evaluations on system's functionalities, and if these appropriately support all the crew functions and necessities. As an example, the astronauts to survive need water, resources, breathable atmosphere, regolith and radiation shielding: these are provided by System's functions which allow to conserve resources, manage water, radiation, regolith and atmosphere. In addition, the system

[8] The actors who directly interface with the system are the Crew, PR and Lunar Orbiters, but the other actors have been represented too in order to explicit more complete functional paths

provides an emergencies support to the crew, and resources are provided by resupply activities performed by the PR.
The crew doesn't only require in input elements by the system, but also provide outputs: due to their daily activities and survival, astronauts produce water and waste, which will be managed by the system, and by performing research activities they produce data which will be managed by the system and communicated to Earth. These data are distinguished into scientific data from researches, and vital signs from astronauts' health monitoring during daily activities and medical researches. These vital signals are then elaborated by the system, which can provide a preliminary support to astronauts health, and communicated to Earth. Here, these data are analyzed and a remote medical support is provided by professional figures, as well as psychological support.
These are not the only kind of data handled: the system also provides updated Housekeeping data both to Earth and, if present, to the Crew. These data are monitored by system itself, which can manage autonomously failures, and by Control Centers and astronauts, which can decide to intervene with maintenance activities.
Other elements can be extracted from the diagram, such as the system's modular structure and the related interfaces which allow the Control Centers to evaluate and program future system's extensions, but also the possibility of the astronauts to perform daily activities, researches and exploration thanks to the docking of a Pressurized Rover, to the capability to allow EVAs and to the inner spaces provided by the system.

4.5 Logical Analysis

"How the system will work to meet expectations"

This perspective constitutes the ultimate level of detail of the system outlined in this Thesis. The resulting architecture of this analysis, commonly called Logical Architecture, implements important decisions of the solution in terms of principles of construction and ways to fulfill the expectations of stakeholders [52]. The Logical Analysis (LA) level of detail is achieved further decomposing the previous SA perspective, allowing to derive *abstract* components. The Logical Architecture is therefore a general abstracted vision of the system, which will be used in future works as a base to develop the system's physical structure.

4.5.1 System Logical Functions Tree

The System Functions derived in SA are now referred as **System Logical Functions**, and are represented in a branched-out functional tree, called Logical Function Breakdown (LFBD), represented in Figures 27 and 28: since the LFBD presents dimensions far too substantial to be visualized in these pages, the tree is divided in two halves, and single branches are discussed. The LFBD in its entirety can be visualized in Appendix C.

To ensure habitability consists into the provision of livable space and psychological comfort conditions, as seen in SFBD. In particular, these are decomposed as follows.

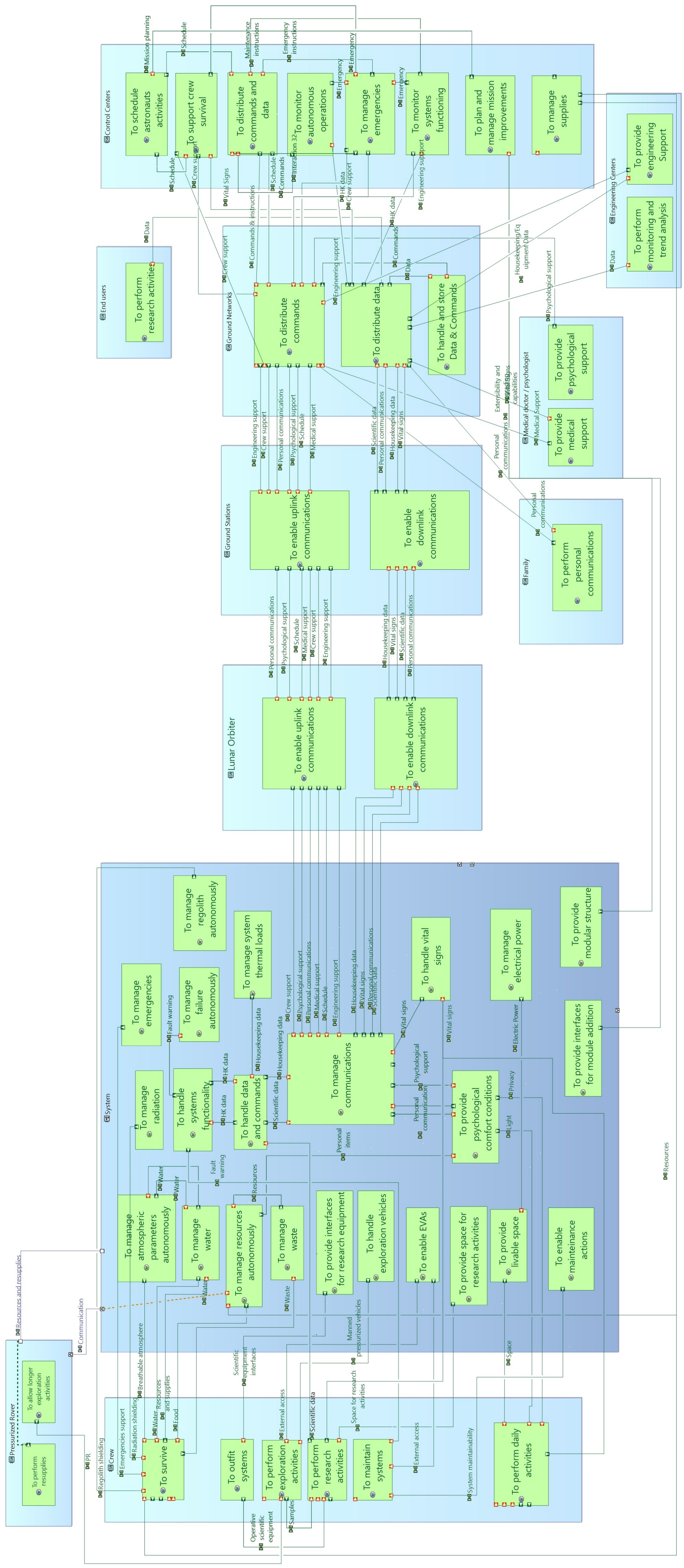


Figure 26: System Architecture Blank (SAB)

In order *to provide psychological comfort conditions*, it is essential that the system guarantees personal communication channels to astronauts, allowing them to maintain regular contact with their families. Furthermore, it is fundamental to ensure crew's privacy by providing designated private spaces, and to maintain optimal environmental conditions to ensure their comfort, for example maintaining suitable lighting and noise levels.
Finally, *to provide livable space* means that the system must guarantee internal spaces up to allow astronauts' comfortable movements and postures, and shall guarantee the presence of specific essential areas dedicated to hygienic services.

To ensure autonomous operations is a fundamental characteristic to support the astronauts' activities and to survive dormancy periods. The four main functional groups that are explicated in this branch are strictly related to the main autonomous operations required to the system to survive and self-maintaining during dormancy periods. Other autonomous operations related to human survival and system functioning assurance can be found all over the LFBD. In particular:
To manage failures autonomously the system must be capable of detecting and identifying potential failures, thereby preventing their propagation and subsequent occurrence of other failures, and, ultimately, resolving the existing failures by human or autonomous commands. These concepts are also reported by NASA in its Fault Management Handbook [55], named Failure Detection, Containment and Response. Further analysis and definitions of Failures and Faults Management could be integrated in future iterations and perspectives of this model, such as Failure Recovery and Fault Diagnosis, Identification and Isolation.
To conserve resources autonomously is essential in the context of long-duration crewed missions, with the objective of ensuring the presence of the required resources in optimal conservation conditions. Furthermore, the system must be able to conserve the residual resources also during dormancy periods in order to favor their optimal management and exploitation[9].
To manage regolith shielding autonomously consists into an active ability of the system to monitor and control regolith levels in cabin atmosphere. This is essential not only for astronauts' health during their permanence in the Habitat, but also for the correct system functioning during both crewed and dormant periods. In these terms, the system shall include an effective regolith shielding capability, and must be able to monitor the cabin atmosphere's contamination and to eliminate inner regolith outwards.
Finally, *To manage atmospheric parameters autonomously* is a crucial aspect for a system designed to be crewed for consistent periods. The system's ability to control the atmosphere in cabin is fundamental as well for the system preservation. The atmosphere management functionality includes monitoring and control activities, such as the control of humidity, temperature and pressure levels. According with Chambliss and Henninger [56], the system must be able to control composition and trace contaminants, provide ventilation and to manage CO2 and O2. Within the Logical Architecture Blank (LAB),

[9] In this functional branch, as well as resources autonomous conservation, could be included the autonomous conservation of waste. However, this functionality is reported under the Human Survival functional arm in order to explicit the direct relationship between human survival's outputs and the need of a complete waste management system.

in the next Subsection, will be possible to analyze the logical structure and exchanges between these functions.

To ensure systems functioning , as previously mentioned in Subsection 4.4, represents the the ability of the system to function properly for long periods. Traditional system functionalities are explicated, and a preliminary mention to the maintainability of the system is included:
To manage electrical power means that the system must be able to generate, store, convert and distribute electrical power in order to make it available to subsystems and equipment. An important characteristic of this functionality – and consequently of the related future subsystem that will be derived – is that the system shall adapt to different sun lightning conditions, and so shall regulate the power distribution and exploitation basing on the sunlight availability. This will emerge in Section 5, with the dissertation of system's Operative Modes (OMs).
To handle data and commands is the ability of system to elaborate, store and distribute data and commands. This represents one of central functionality of the system, as it allows to data and commands to flow between subsystems.
To handle systems' functionality means that the system must be able to monitor its own status, and to actively control its functionalities to maintain a nominal functioning, if necessary. This means that the system is able to actualize commands. In addition, interfaces between system and crew must be provided, in order to allow the crew to monitor system's performance and to provide direct commands.
To manage communications regards the ability of the system to provide downlink and uplink communication capabilities, hence to send and receive data, commands and communications to and by Earth. In addition, a lunar base must be able to communicate with other systems on the lunar surface – with the PR for example – thus intra-lunar communication function is included.
To enable maintenance actions is a crucial aspect for a space system designed for a long operative life, and whose safety is fundamental to guarantee crew survival. With a sustained presence on the lunar surface, all supporting assets and external elements will require a certain degree of maintenance and repair, scheduled or not. In case of necessity of maintenance actions, the system must be designed in order to ensure the access to all its parts: this facilitates the operations and maximizes scientific outputs and crew productivity [18]. The maintenance activities can be performed by astronauts, who will require the appropriate equipment, or by autonomous systems in order to avoid specific dangerous and complex EVA activities.
To manage system thermal loads concerns the management of the thermal loads that involve the system in its entirety. The system cannot only be able to manage the cabin temperature, but must guarantee the respect of operative and survival temperature limits of each subsystem. This management consists into the collection, rejection, storage, provision and transfer of heat fluxes between the interior and exterior of the habitat.

To ensure human survival is one of the most important and challenging goals – and so root functions – of the Habitat. In this functional arm are reported only the main

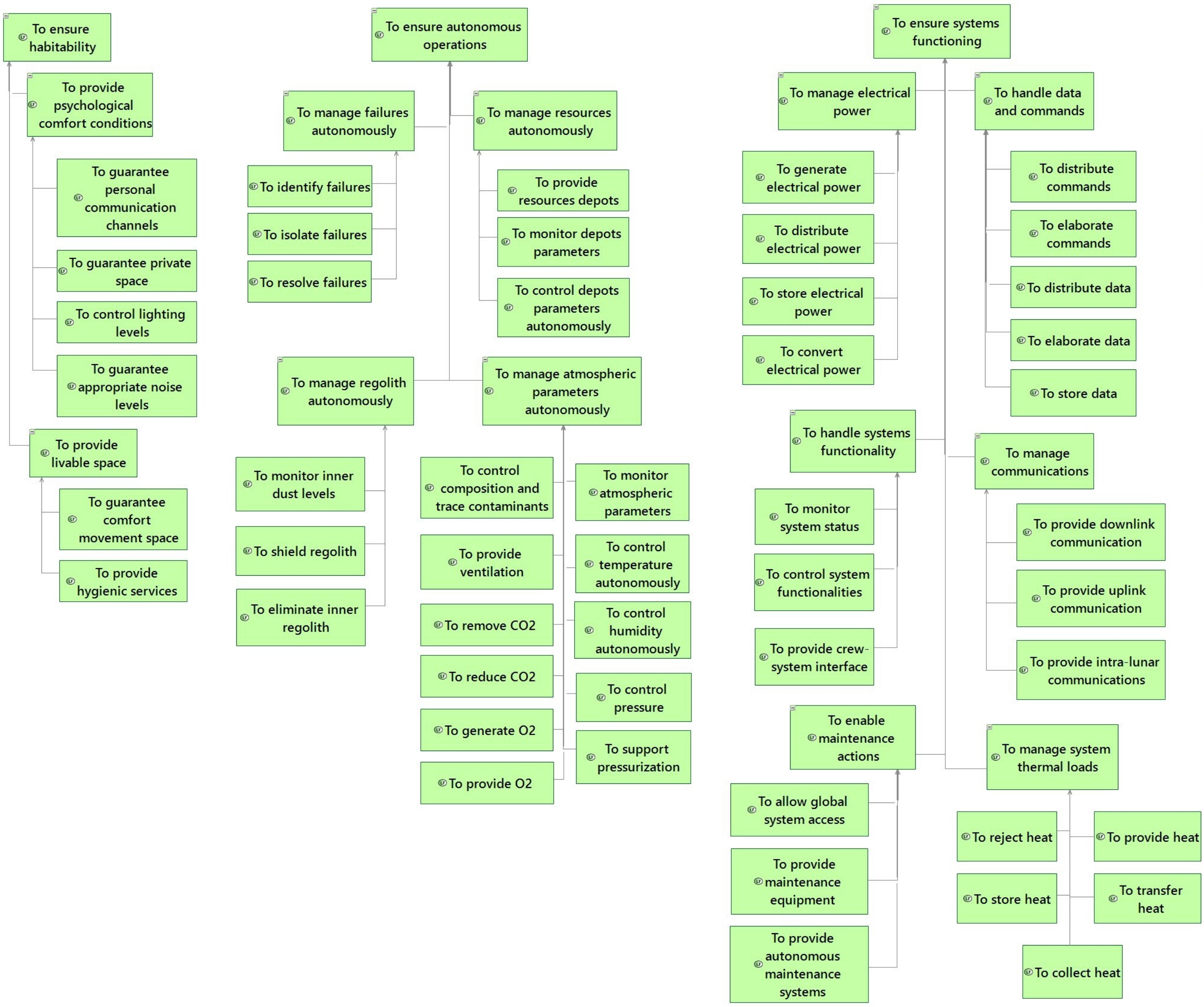


Figure 27: The first three functional arms of LFBD. From left to right: (a) Habitability functional arm (b) Autonomous operations functional arm (c) System functioning functional arm

groups of functions strictly relative to the human survival aim, but as it has been possible to notice so far, the survival of the crew is intrinsic in several other functional branches – in breathable atmosphere management and in resources conservation, for example. To support the human survival the system must provide other fundamental functionalities:
To manage water is essential for this goal. In addition to the necessity of drinkable water, the crew needs water destined to hygienic use – in the specific areas dedicated to hygienic services provided by the related function seen previously. Humans do not only require water in input, but also provide it in output daily with hygienic services utilization and by sweat, in addition to possible water utilization by payloads. This is traduced into the system's necessity to manage water: this means that the habitat shall be able to recover the water by hygienic services, space suits, payloads and atmosphere, in order to recycle it and redistribute it. In the context of crewed space systems meant for long missions, it is imperative to reason as much as possible in terms of closed loops able to recycle and produce in situ necessary resources: this means that the water produced by crew life in the system shall be used to produce new water, ready to be used. From a functional perspective, the habitat must be capable of processing, storing and distributing water, in addition to monitoring its quality.
To manage waste functionality follows the same principle of water management: in a almost closed loop perspective, waste must be considered into recycling loops that allow to recover essential resources. At this level of detail, this traduces into a waste recycling function, which is not further decomposed. In future analysis this could be evolved basing on the kind of recycle system chosen. In addition, a crucial aspect to be considered is the capability of the system to store in optimal conditions both recyclable and not recyclable waste. These functionalities are strictly linked to the autonomous conservation function seen above, part of Autonomous Operations arm. These conservation aspects are crucial to safeguard against the formation of biomass, which, in further levels of detail, will traduce into the introduction of detection and mitigation solutions [18].
To handle vital signs means that the system must support the crew and also monitor the vital signs of astronauts, which are collected daily by the provided medical equipment. In this way, in addition to the professional support of medical personnel from Earth, the system itself can monitor in situ the regularity of health conditions of astronauts, and provides to the crew a general feedback of the monitoring activity through an interface dedicated to life support.
To manage radiation is essential to ensure the survival of the crew, as discussed in Section 2. This means that the system must include an effective radiation shielding, and a continuous monitoring activity of radiation levels shall be conducted, in order to ensure the allowed exposure of astronauts[10].

To enable exploration activities is crucial for the pursuit of mission objectives and to allow the astronauts to perform their research activities. This means that the crew must be able to leave the habitat and to explore lunar surface, also with vehicles dedicated to exploration, pressurized or not, such as PR and LTV. In particular:

[10]In this dissertation, a passive radiation protection system is currently considered, since active methods are still too immature to be implemented. In future iterations, however, active protection could be included by introducing a dedicated control function.

To handle exploration vehicles means that the habitat shall be a "port" where vehicles can be docked and resupplied. This is particularly important for pressurized vehicles, which allow to cover longer distances from the habitat and which can be used for logistic resupplies of the habitat at the beginning of crewed phases (Section 5). In addition to the provision of cabin-rover access and docking mechanisms, the system can provide maintenance support.
To enable Extra Vehicular Activities EVAs the system must include a specific volume dedicated to the EVAs preparation and access to the external environment. Consistently with the ISS structure [57], and in particular with its Joint Airlock, the system must include the possibility to nominally depressurize to vacuum a specific volume in order to begin the EVA[11] and the provision of space for stowage, recharging, suiting don/doff and servicing of EMUs[12]. In addition, the system shall provide support to the crew during EVA, as an example providing dedicated communication channels or tracking and monitoring the exploration activity ongoing.

To enable research activities the system must provide space and interfaces. In particular:
To provide space for research activities means that the system provides test-benches in order to outfit the required equipment and payloads. This is strictly related to the next function which provides interfaces.
To provide interfaces for research equipment consists into the provision of electrical, data and fluid interfaces necessary for the functioning of payloads and equipment.

To enable future extensions is a crucial aspect in planning improvements and system upgrades, and involves:
To provide modular structure which permits to add new modules. This characteristic will allow the habitat to evolve, increasing internal spaces and functionalities, enhancing the research and astronauts capacity. In particular, the system shall present modular connection nodes to permit these expansions. Furthermore, these connections must be compatible with standard mechanisms in order to facilitate these implementations and the relative operations.
To provide interfaces for module addition is fundamental in this context: the system shall guarantee continuity of interfaces between modules, providing standardized electrical, fluid and mechanical interfaces.

[11]This volume will be called Crew Lock
[12]This volume will be called Equipment Lock

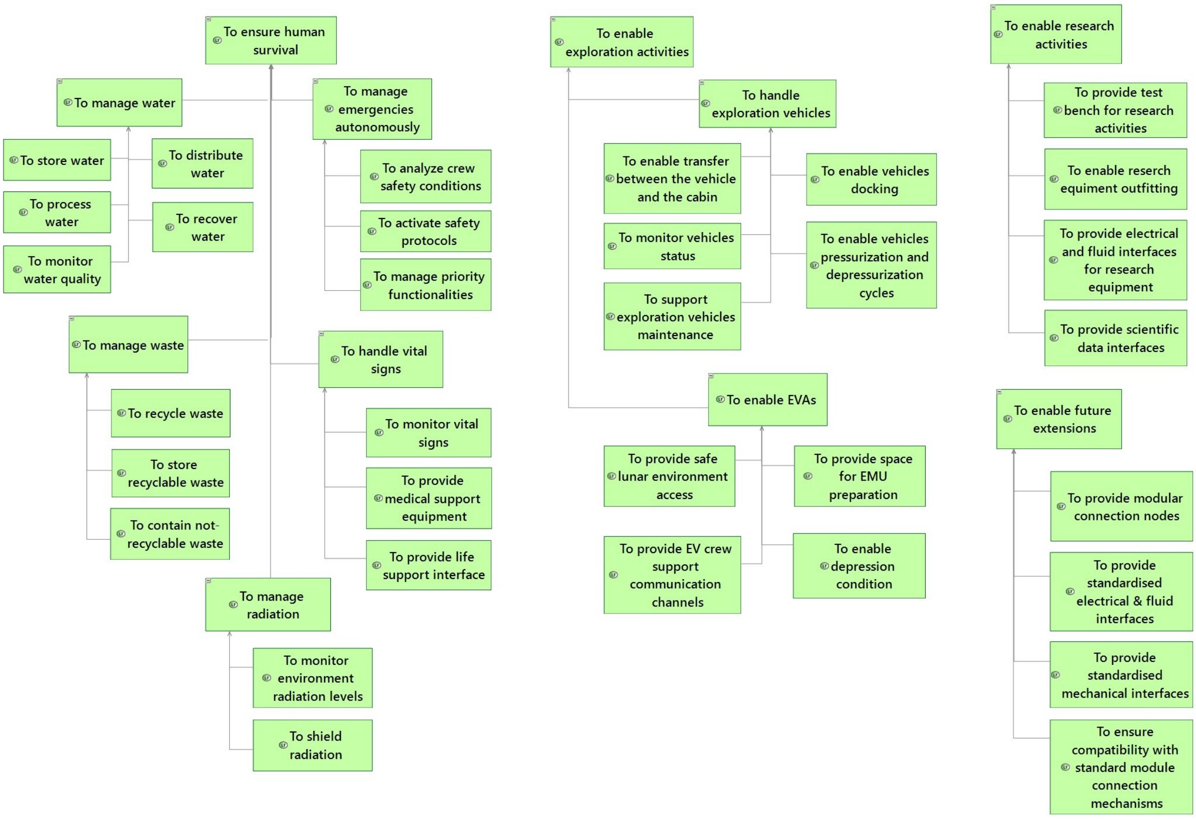


Figure 28: The last four functional arms of LFBD. From left to right: (a) Human Survival functional arm (b) Exploration activities functional arm (c) Research activities functional arm (d) Extensibility functional arm

4.5.2 System Logical Architecture

The result of the functional derivation described above is finally traduced into the Logical Architecture Blank (LAB), which represents the final diagram of the system's solution obtained. Essentially, this is a more detailed version of SAB, in which functional exchanges between actors and system are explicated. In particular, in this diagram the identification of *Logical Components* emerges for the first time, which are defined by a group of several logical functions. The term *Component* is understood here in the general sense, as a constituent of the system at this level; in future, it will can be implemented as subsystem, equipment, software, etc [52].

The LAB obtained presents dimensions not compatible with the format of this Thesis, making it impossible to be readable in its entirety. In the following pages, the discussion will be supported by a series of extracts with Figures 30, 31, 32 and 29. In Appendix D the LAB in its entirety is shown, only to provide a global visualization of the complexity of the diagram.

The Ground Segment's identified actors – now called Logical Actors, transitioned directly from the previous perspectives – with their allocated functions are located on the top of the diagram, with the same functional exchanges contained in SAB. These are connected to the Space Segment thanks to the interaction between Ground Stations and Lunar Orbiters. This is shown in Figure 29 fragment. All these elements, together with Crew and Pressurized Rover actors, are represented in light gray in order to be distinguished from the System, which is composed by the Logical Components in blue color [13].

A possible lecture of this diagram is given by following some of the main functional exchanges – characterized by green color – which involve different logical components, functions and actors. In addition, these paths can include *Component Exchanges* in indigo color, which represent elements exchanged between logical components and not between proper functions, and *Port Allocations* with dotted lines, which connect component ports with functions.

Life Support The first capability of the system that is going to be analyzed is the life support one, which allows the astronauts *to survive*. This is mainly explained by the interactions and functional exchanges between the *crew* and the logical component named *Environmental Control and Life Support System*, to which the functions strictly related to the life support of the crew are allocated. As shown in Figure 30 and 31, the inputs and outputs provided to and by the crew during its life in the system are:

- **Resources and supplies**: these are provided to the system by Earth, through the docking of the PR for logistic resupplies, and to the crew by the system itself, which presents *Depots* able to monitor and control stocking parameters, and to provide the required resources to astronauts. In addition, thanks to the presence of a *Waste Management System*[14], waste can be recycled in order to maximize the resource availability and their exploitation during crewed periods. It is possible to notice that, in this context, the Crew actor has been enriched of a new function, which is *To operate waste sorting*: in this way, all the waste produced by the crew is sorted and distinguished into Recoverable and Non-recoverable waste. The system is hence provided of two different types of *Waste Depots*, whose purpose is to contain recoverable or not waste in optimal conditions. Recoverable organic waste is also produced by the crew during daily life. All the recoverable waste is then processed by *Waste Management System* in order to produce new resources.

- **Hygiene and Water**: the system, within its ECLSS, includes *Hygienic Services*, which allow the crew to perform daily hygienic activities. Organic waste is not the only following output of these activities, which involve the fundamental use of water. The *Water management system* provides hygienic and potable water to

[13] To facilitate the lecture of the diagram, the general System block is omitted, displaying the interaction directly between Ground Segment elements and the logical components, but it is important to notice that the blocks in blue and gray colors are characterized by different levels.

[14] During dissertation is important to keep in mind that all the elements described are abstract components. The associated names evidently remind to physical subsystems and components, but in this perspective are not treated as physical elements.

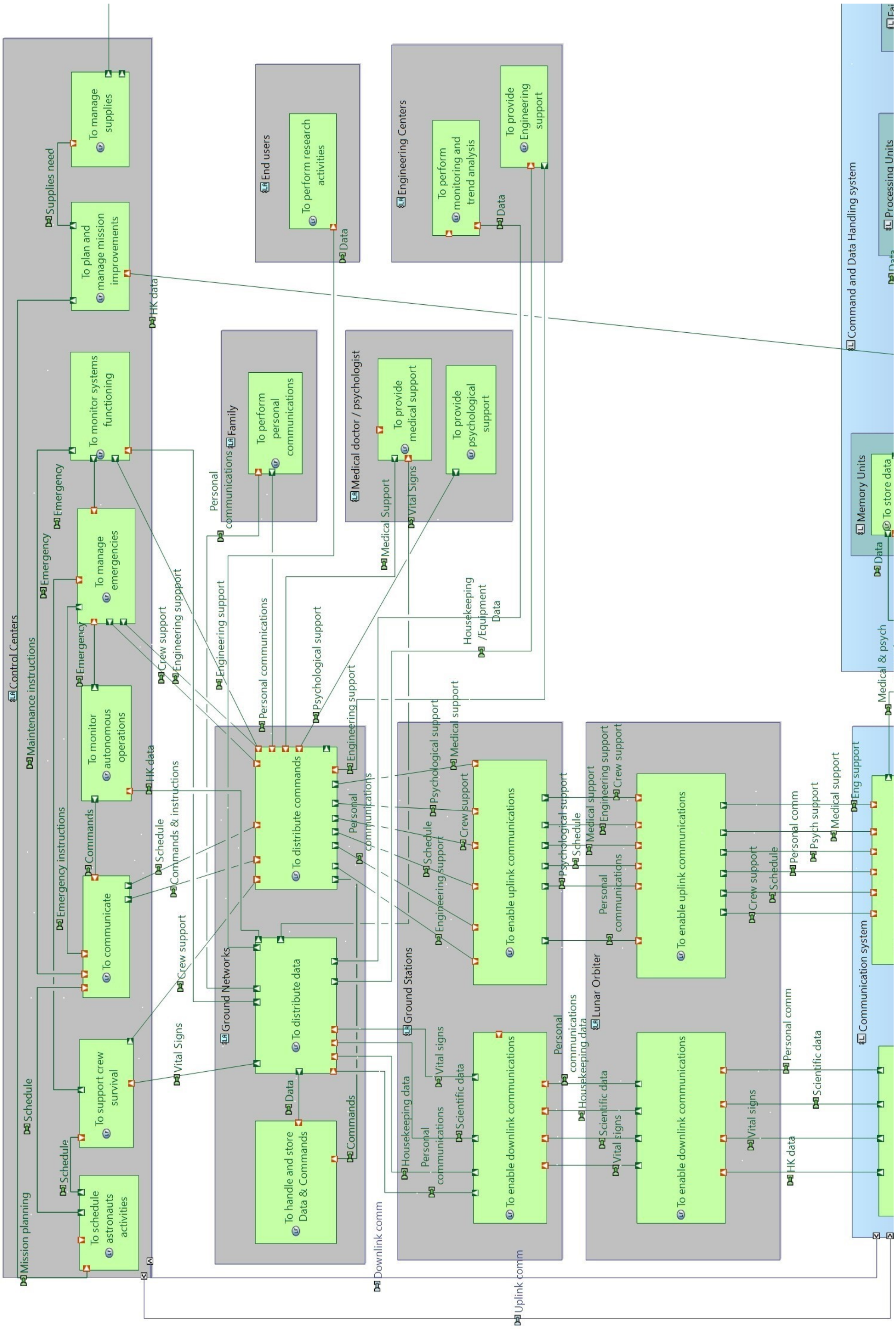


Figure 29: LAB: Ground Segment fragment

services and crew, involving a *water recycling system* that processes water collected by human outputs, payloads and atmosphere and make it usable for drinking, other hygienic activities, and cabin atmosphere control. In addition to the recycling system, the water management system includes *Water Tanks* for the water storage, and *Water Distribution Lines* for the distribution of usable water from tanks.

- **Atmosphere**: it is essential to provide a livable atmosphere to the crew. This goal is reached mainly by the *Environmental Control System* part of ECLSS, which is composed by: *Radiation Shielding System*, *Regolith Shielding System* and *Cabin Atmosphere Control System*. In particular, the third one is an active element which combines the monitoring and control activities on atmospheric parameters of the cabin, so pressure, temperature and humidity are continuously – and autonomously – monitored and controlled, as well as atmosphere's composition and trace contaminants. Thanks to a ventilation capability, the cabin air is constantly renewed, removing CO2 excesses and providing Oxygen. By the provision of water by the water management system, this is processed by electrolysis, obtaining Oxygen and Hydrogen: the first one is led into the cabin, while the Hydrogen is used for the reduction of CO2 collected by the cabin's atmosphere. From this process, water is obtained and recovered by the water management system. Furthermore, dust levels within the cabin are monitored, and the system is able to eliminate the insinuated regolith.
  Other important functions allocated to the Environmental Control System involve the lightning levels control and the noise regulation, critical for the performance of daily activities and important contribution to psychological health and habitability of the system.

- **Vital signs and medical support**: the constant monitoring of the state of health of astronauts during their mission is a key aspect for their survival, and also for research purposes. As part of their daily activities, astronauts will perform monitored physical training and health checks: these activities are possible due to the provision of medical support equipment[15], part of the so-called *Crew Support Unit*. This Unit refers to those elements of system which are dedicated to the support of crew's health and collection of vital signs. In fact, through the daily use of medical equipment, crew's vital signs are collected and monitored by the crew and the system itself, providing a first preliminary feedback through a dedicated interface. Though, the most significant medical support comes from Earth: the vital signs are elaborated by the *Command and Data Handling System (CDHS)* and then distributed to the *Communication System*, which sends them to Lunar Orbiters and then to Earth, where through Ground Stations and Networks are provided to *Medical doctors*. In this way, medical specialists send in uplink medical support to astronauts, following the same reverse functional path up to the Crew Support Unit.

- **Safety protocols**: the last input to the crew's survival function involves the Safety

[15]Medical support equipment include training equipment, since physical exercise is integral part of astronauts' medical prescriptions

protocols provided by the ECLSS, and in particular by its logical component called *Emergency Management System*. This element of the system, as its name reveals, is is responsible for the management of emergencies, thereby ensuring the safety of the crew in critical conditions. When a failure occurs, the system must be able to analyze if the conditions represent a risk for crew's health and for system's integrity: if these could be compromised, safety protocols are autonomously activated in order to make the crew safe, if present, and a prioritization of the system functionalities is performed in order to optimize this process. Fire detection and control capabilities are surely part of this system, as an example.

Psychological support The psychological health of the astronauts is necessary for the accomplishment of their mission objectives and to face long periods on the Moon. The system considers this aspect and, as Figure 32 shows, its *Structure* provides internal spaces designed to guarantee comfortable movements and postures, and privacy areas for personal daily activities. One of these activities is surely to communicate with relatives on Earth: for this reason, the *Communication System* provides channels dedicated to personal communications, and through the *Crew Support Unit* astronauts can obtain psychological support by specialists on Earth (Figure 30 and 29). Another significant factor is provided by the regulation of noise and lightning levels anticipated above, which allow the astronauts to rest efficiently.

Scientific data and exploration
The research and exploration activities that the crew must perform during its stay on the lunar surface are supported by the system mainly by the logical components *Laboratory support* and *Exploration Vehicles Support*. In particular, as shown in Figure 32, the system allows to outfit a laboratory space, providing interfaces and the test benches: with the scientific equipment outfitted the crew can perform the researches activities producing scientific data, which are processed, stored and distributed by the *Command and Data Handling System (CDHS)* and then communicated to Earth by the *Communication System*. Finally, the scientific data are distributed to *End Users* and *Control Centers* (Figure 29). The scientific equipment installed inside the system is surely used for the analysis of samples collected during exploration activities: these are possible considering a system *Structure* including a volume dedicated to the exit (and entrance) from the system. As mentioned during the description of LFBD, this volume is composed by Equipment lock and Crew lock, which together permit to create a depressurized environment and to manage the EMUs. In this way, the astronauts are able to leave the habitat and to return to it, safely (Figure 32).
The habitat can also support the docking operations of PR: the logical component related to this group of functionalities includes a docking system and a hold door which allows the transfer of resources between habitat and rover in order to perform the vehicle's and the system's resupplies treating the vehicle like a moving system's module.

Housekeeping data and system functioning
This final group of functional exchanges regards the management of the health of the system itself. The habitat includes a logical component, called *Control and monitoring system*, which allows the crew to monitor the status of the system through dedicated inter-

faces, and to possibly generate commands. The responsibility for monitoring the health of the system does not lie only on the crew: in fact, the system itself is also capable of processing data from the various subsystems, and to detect faults. The *Housekeeping data* are collected from all the subsystems, and managed by the CDHS: the data, in general, are distributed, stored and elaborated by PUs, which can also elaborate commands (Figure 30). Hence, the system's status is reported to the crew by the Control and monitoring system, and transmitted to Earth through the *Communication System*: in this way, the ground operators and possibly contractors can monitor the system functioning, in order to provide necessary directions and commands, and to manage emergency remotely if needed. These commands and engineering supports reach the system, which distributes and elaborates the commands from GS.
As shown in Figure 30, the ability of the system to manage failures autonomously is highlighted by the explicitation of the logical component *Failure Management Unit*: this is essentially a Processing Unit (PU) dedicated to the management of failures, so, if a failure emerges from the elaboration of Housekeeping (HK) data, the system autonomously identifies, isolate and try to resolve failure. The failure – or in general anomalies – resolution can be obtained by the application of ground operators or crew's commands, or even by the elaboration of autonomous commands by the system, which can be able to resolve determined kinds of failures in autonomy[16]. When maintenance is required, guidelines can be supplied to the crew, who perform the necessary actions thanks to the accessibility of the system and to the equipment provided; also, the possibility of the presence of autonomous maintenance systems, part of the *Maintenance Support Unit*, enables the performance of specific maintenance operations, avoiding dangerous and complex EVAs, both on system and on docked exploration vehicles, if necessary.
The groups of functions seen in the previous Section during the description of LFBD and concerning the ability of the system to manage electrical power and the systems' thermal loads are pertinence of *Electrical Power System (EPS)* and *Thermal Control System (TCS)* logical components. From the EPS, by the use of components exchanges, the *electrical power* is distributed to all logical components and equipment interfaces that require it, as well as *heat* is exchanged between the various logical components and the TCS (Figure 32).

[16]The autonomy of the system in failure resolution must be carefully considered in relation with the priority of operators' and crew's commands and with the human supervision.

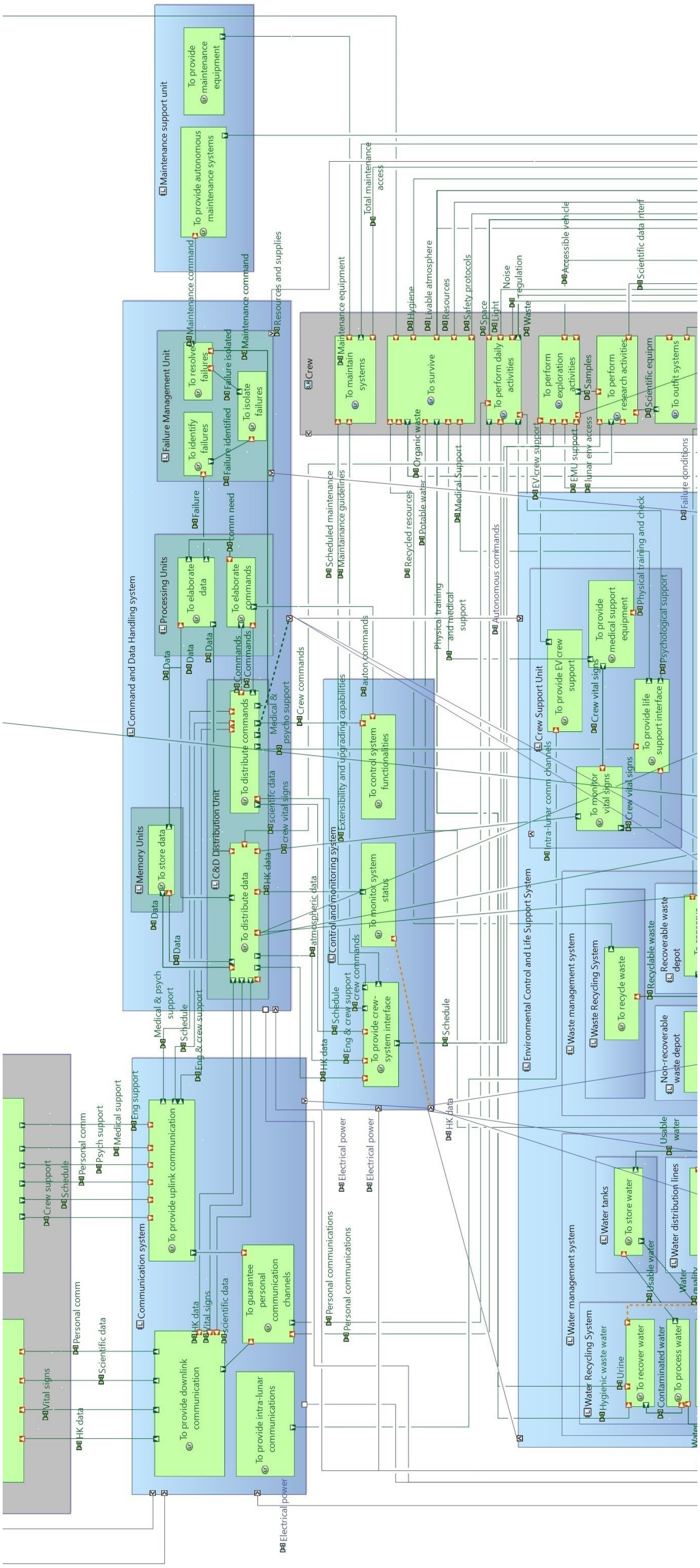


Figure 30: LAB fragment

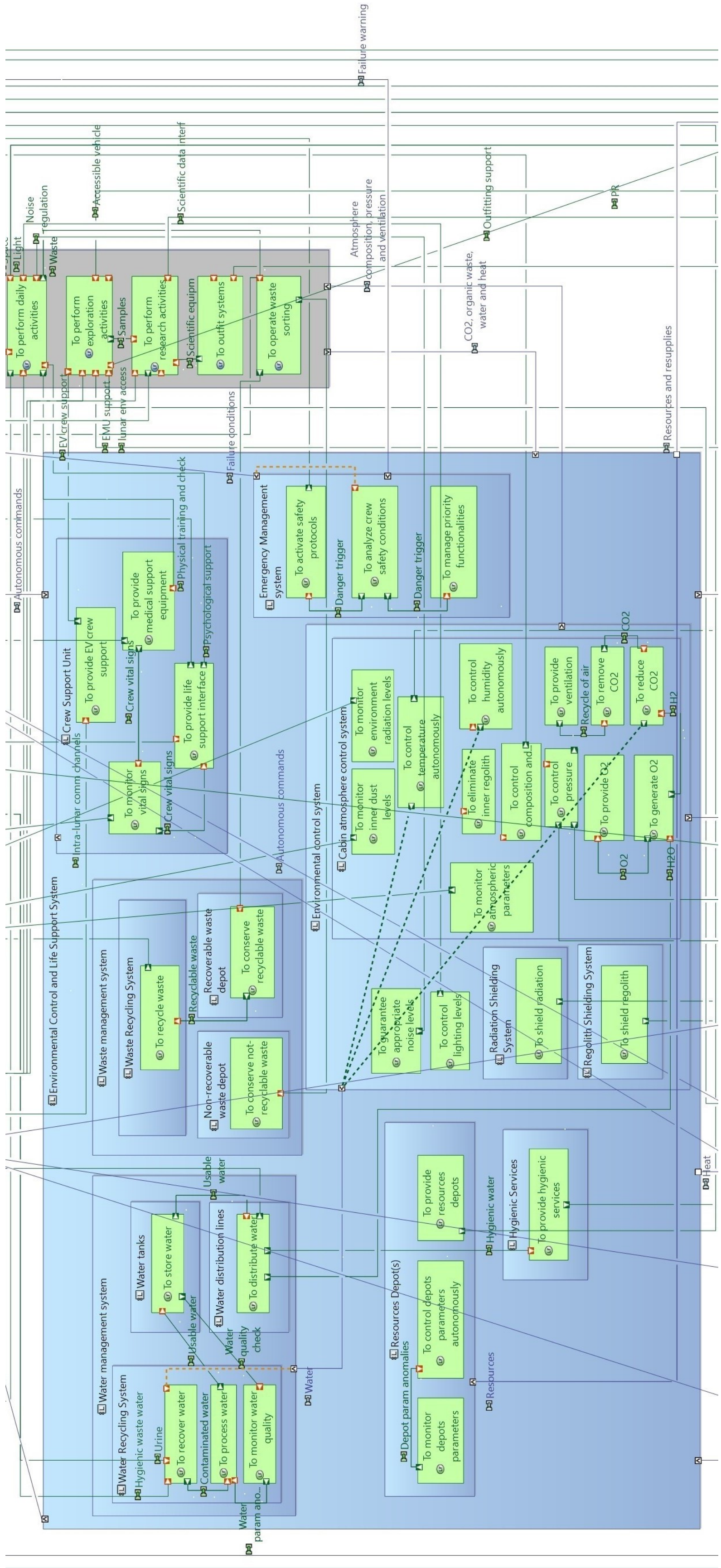


Figure 31: LAB fragment

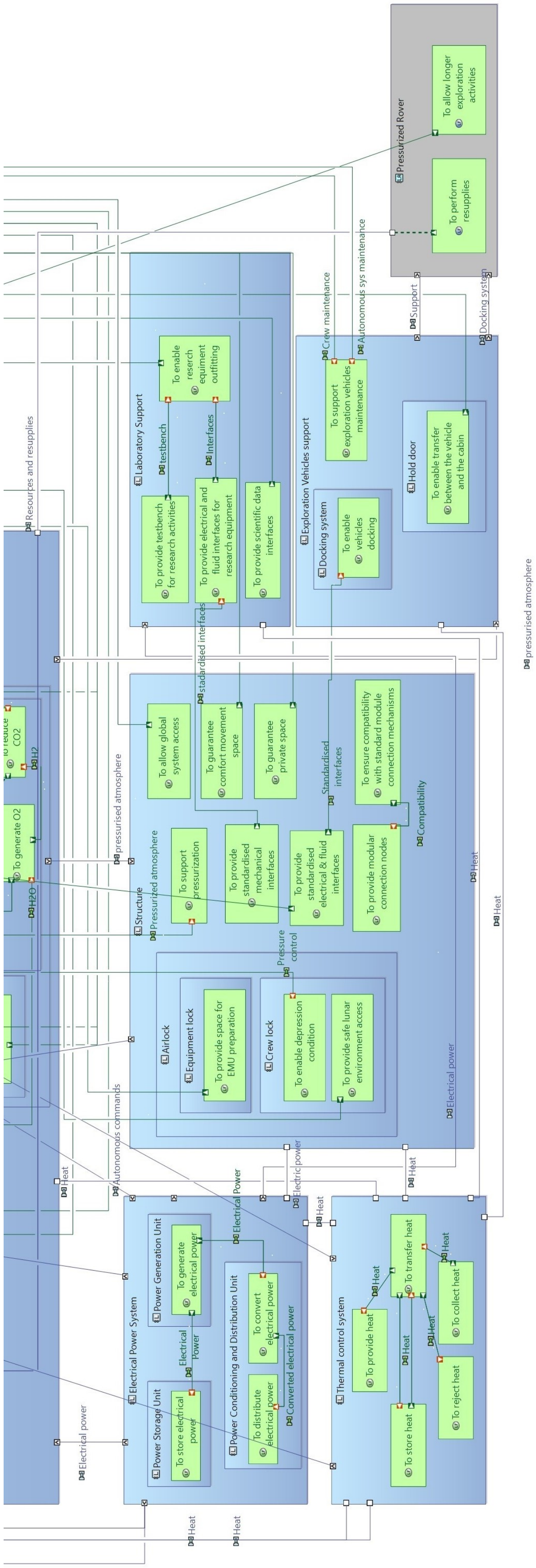


Figure 32: LAB fragment

5 Integration of Operative concepts

This section is dedicated to the elaboration of operational concepts, integrated into the design of the habitat discussed in the previous Section.

Although in this dissertation, for clarity of exposition, this integration is placed after the process of design, it is important to specify that it has to be intended in parallel to the system design process: in fact, the consideration of operational concepts in iterative way in these very early phases of design is essential to guarantee the achievement of a system compatible with operations. This characteristics of design can be fundamental for the effectiveness of the operations, allowing to save time and money, and to reach mission objectives pursuing more exploration and research activities.

This part of the work is being conducted with the support and supervision of ALTEC – Aerospace Logistics Technology Engineering Company (Turin, IT). Its heritage in provision of engineering and logistics services to support operations of space missions, including planetary exploration missions, allows to deepen these concepts and to improve the design process under an operational perspective. As an example – as will be presented in future sections – Pressurized Rover and Lunar Orbiter elements are implemented as their interactions with the system emerged during Operational considerations.

The Section is developed into two main subsections: the first one (5.1) is dedicated to the description of Concept of Operations (ConOps), discussing the main high level system's mission phases; the following subsection (5.2) provides an overview of the main system's Operative Modes (OMs) throughout the phases previously identified.

5.1 Concepts of Operations

In ARCADIA the integration of operational concepts is possible thanks to *Transverse Modeling*[17]: in fact, this is meant as transverse concepts modeling that directly influence the system design [52].

The leading diagrams developed in this analysis are the **Mode State Machines (MSMs)**: since Modes and states cannot cohabit in the same machine, MSMs can be Mode or State Machines.
A Mode or State Machine is a set of Modes or States linked to one other by transitions, and one or more machines can be associated with the characterization of the system, a component, an actor or an operational entity.

The first diagram analyzed in this Subsection is a *State Machine*. A State Machine includes the identification of **States**, which are defined as[18]

"a behavior undergone by the system, a component, an actor or an operational entity, in some conditions imposed by the environment" [52].

[17] *Transverse Modeling* is the nomenclature used in Capella to indicate Mode and States modeling.
[18] The definition of Modes follows in Subsection 5.2

In this case, the States indicate the high level phases covered by the system[19] since its Launch to its End Of Life (EOL), with explicit Transitions between each phase. As result, high level ConOps of the system are implemented in the model through this State Machine.

The **Transition** concept is proper of both State and Mode Machines, and is defined as

> *"a change from one mode to another mode or from one state to another state – respectively, called the transition source and transition target"* [52].

In Appendix E the State diagram shows the phases identified in their entirety; since this Figure does not provide a sufficient legibility due to its dimensions, this Subsection provides the description of each main block, allowing to visualize each phase.

Launch, Early Orbit and Transfer phases The first phase that the system faces is the Launch and Early Orbit Phase (LEOP), which in turn includes Launch, Early Orbit Operations and the Injection to the target transfer orbit (Figure 33).

During the launch phase the habitat system is contained in the fairing of the launcher, which protects it from the vibrations, thermal and other loads typical of this phase. After the stages separation procedures, the fairing separates too, leaving the system orbiting around Earth in a designed Earth Orbit. Even though this modeling process is not focused on a specific mission, can be interesting providing some examples of real employable systems: for the launch phase, to the author's best knowledge on information about the planning of NASA's Artemis missions [58], is reasonable to consider that this phase could be performed by an heavy-lift launch vehicle with the Space Launch System (SLS) rocket characteristics. Launch site facility would provide the support during this phase.

Once the system is officially separated from the launcher, Control Centers network[20] over the globe would follow the mission evolution: the system orbits around Earth supported by a large Cargo Lander [59], which provides the main support to the system during all the phases from LEOP to Commissioning on the lunar surface. Basing on the main capabilities of these kind of landers [54], the habitat in these phases would be supported in means of electrical power provision and communication system: the power is received by the lander and then distributed by the EPS of the habitat to system users, while the communication capability is provided entirely by the lander. In Early Orbit Operations, several checks are performed in order to demonstrate system and payloads' integrity after

[19] The phases identified in MSM, as well as the operative modes, are strictly focused on the habitat system. Additional phases and modes related to other mission elements could be deepened in other future iterations of this work. In addition, a State can also specify the imposed occurrence of a function (or activity in OA), or the occurrence of a functional exchange, especially at the moment of entry into this State, at the moment of exit or during the State (without other specification).

[20] Several Control and Support Centers all over the world would be interconnected and involved in the support of the mission: according to Love and Hill (NASA) [58] in Artemis context, *"while Mission Control Houston will provide flight control services for piloted American spacecraft at the Proving Ground, other elements, such as robotic cargo and service ships and partner-provided landers for human lunar surface sorties, will probably be operated from their own separate but interconnected control centers across the United States and around the world."*

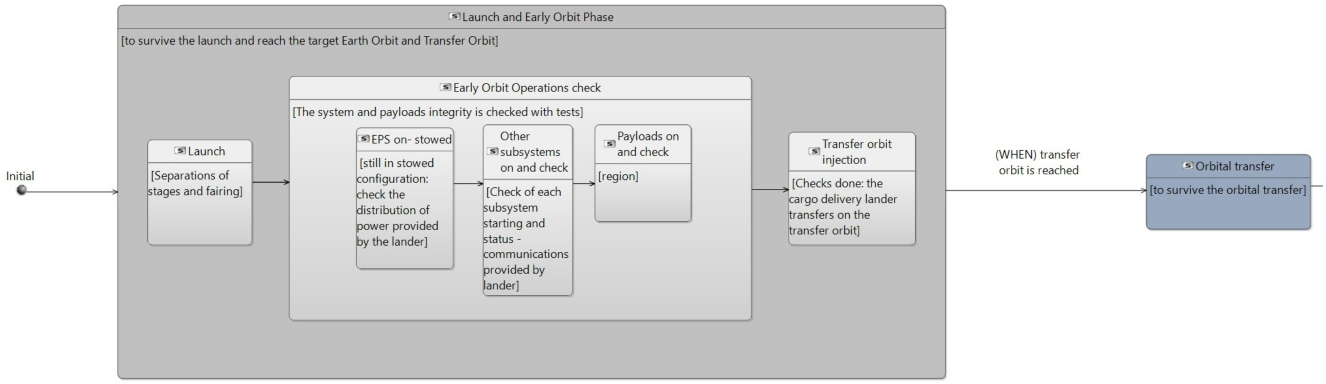


Figure 33: State Machine: Launch, Early Orbit and Transfer phases

the launch, and the first checks regard the EPS of the habitat in its power distribution function – the system is in stowed configuration, with solar arrays and antennas undeployed. Once the electrical power distribution capability has been verified, checks on the main subsystems and then on payloads are performed. Thus, the complex of habitat and lander performs the orbital injection in order to reach the designated translunar transfer orbit and start the transfer phase, which lasts around four days[21] [60].

NRHO Orbiting, Landing and Settlement phases Once the transfer has ended, the complex of habitat and lander starts to orbit around the Moon. In particular, the Lunar orbit selected for Artemis missions is the Near-Rectilinear Halo Orbit (NRHO): its characteristics meet several key needs for Lunar exploration, including the long-duration staging through minimal propellant demand for orbit maintenance, accessibility to the Lunar South Pole and other global access on a frequent and recurring basis, and consistent access for crew and cargo to and from Earth [59]. From this phase, the communication with Earth relies on a communication architecture consisting of both Lunar and Earth elements: in fact, the realistic scenario for a Lunar Habitat delivery, basing on the current space exploration purposes, includes an already evolved and consistent communication architecture that involves orbital communication elements around the Moon, in addition to the presence of a Lunar Gateway in an advanced state. Thus, these elements act as relays between Moon – orbit or surface – and Earth, where Deep Space Network (DSN), Near Space Network (NSN), ESA and Provider's and International sites can communicate with systems on the Moon with consistent availability, visibility, and high data rates [54].

From the NRHO orbit, the lander performs the landing on the Lunar surface (Figure 34), most likely on the Lunar South Pole, as mentioned before. Once landed in the target point, a new phase starts, during which the settlement of the Habitat on the surface occurs: the lander performs anchoring and settling modifications, until the required stability is achieved. In this case, it is supposed that the Habitat remains integrated with the lander [59], so an offloading phase is not expected.

[21]During the transfer, it is supposed that a terrestrial communication system is used.

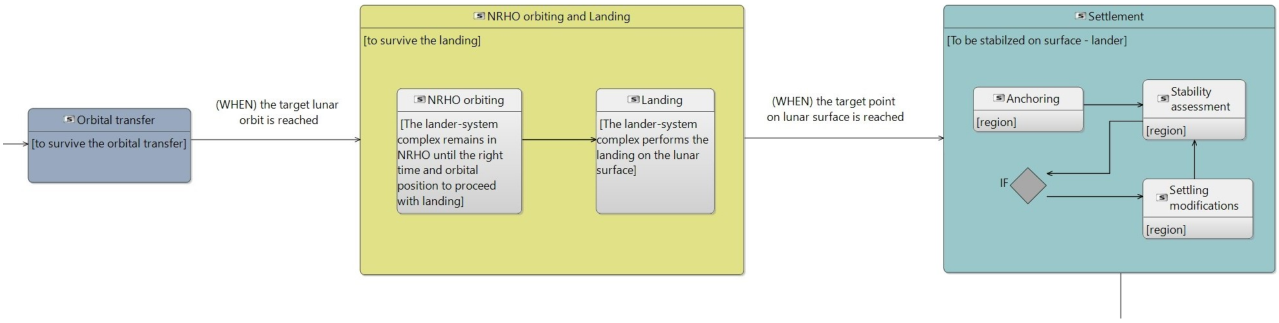


Figure 34: State Machine: NRHO Orbiting, Landing and Settlement phases

Commissioning phase With the lander and habitat definitely settled, during daylight, the Commissioning phase occurs: in this phase, the system performs the activation and testing activities that allow to obtain the habitat system finally operative. In Figure 35 the main high level phases of Commissioning are shown.

Firstly, the EPS must be entirely activated: up to this point, the only active function of EPS was the power distribution, while electrical power was generated and provided by the lander. In this phase, the habitat must become totally independent, hence the solar arrays are deployed in order to start to generate power. After EPS checks, the batteries and fuel cells onboard as energy storage are recharged, in order to face eclipse periods. At the end of this sub-phase, the habitat's EPS is commissioned and the energy storage charged.

After the capability of independent power management, the system must be able to communicate: deployable elements, such as antennas, are deployed and the communication link is established and tested. From this point, the habitat can communicate with elements in orbit around the Moon – such as Gateway, among all – and through these with Earth. At the end of ComSys commissioning, the habitat is independent from the lander: it remains integrated on it, but the lander is switched to Safe mode and disconnected [59].

Once the habitat has its basic functionalities active – power, communication, thermal and data management – it has to be made suitable for human stay. In resemblance with the current operations for the additional modules of ISS, it is supposed that the habitat is launched already pressurized[22]: so, at this phase, the cabin atmosphere's parameters are assessed and corrected, if necessary, with the commissioning of the Environmental Control System (ECS).

It the view of crew arrival, EVAs and logistic resupplies, it is fundamental that the Airlock of the habitat is correctly functioning: for this reason, the abilities of the airlock to be proper isolated, depressurized and accessible are tested.

Once it has been ensured that the crew can access and breath within the habitation

[22]In line with the concept of European Multi-Purpose Habitat (MPH), in this dissertation the habitat is supposed to consist into a rigid structure. In case of inflatable elements an additional sub-phase of atmosphere inflation would be included.

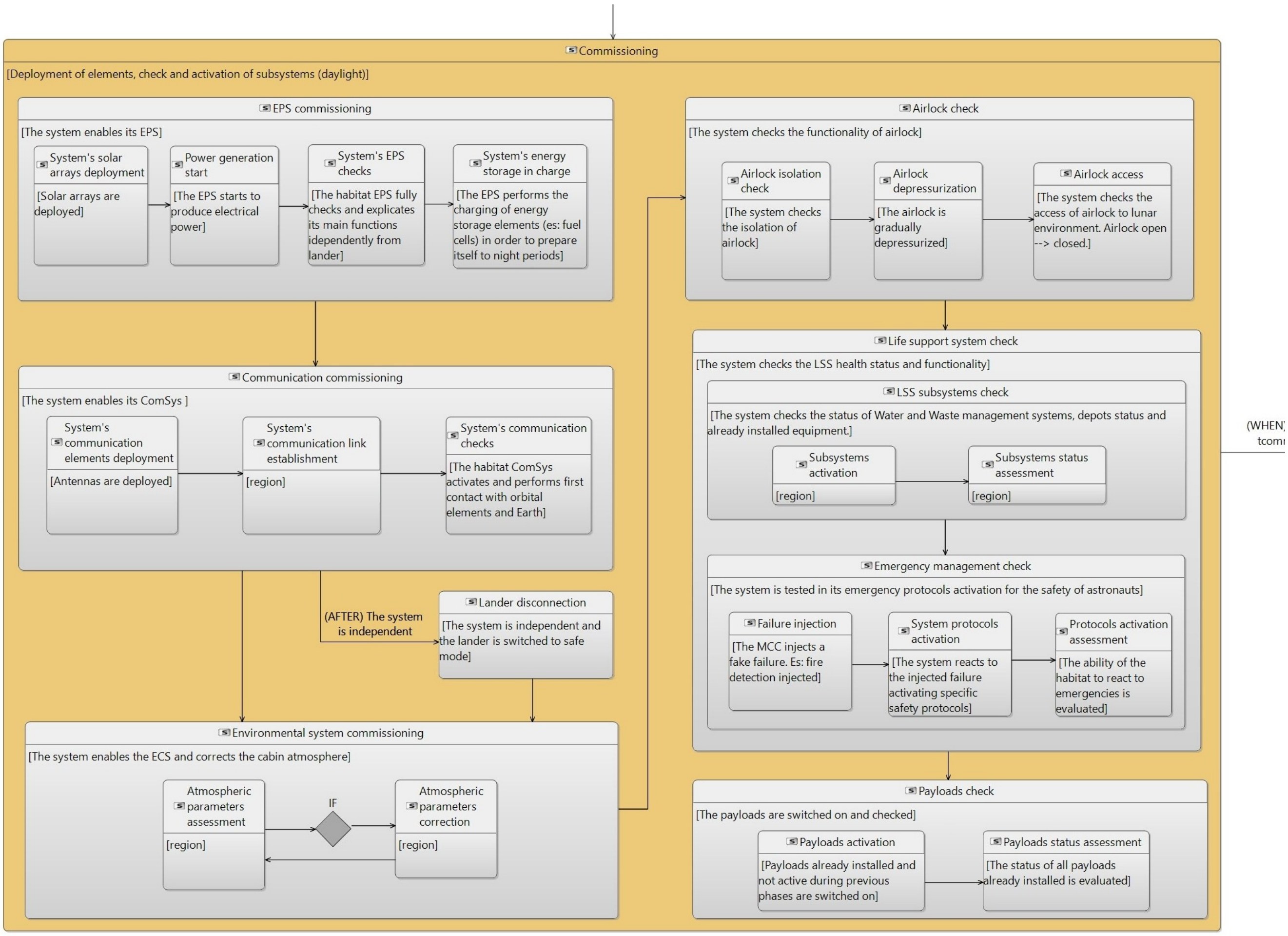


Figure 35: State Machine: Commissioning

system, in view of a long stay human mission, Control Centers must be certain that all the life support subsystems are properly functioning: thus, in this sub-phase checks of activation and status assessment of LSS subsystems occur. Another essential capability of the system that has to be tested is the emergency management: as described in the previous design Section, for the safety of crew and systems, the habitat is provided of specific emergency protocols, which are meant to be activated when a failure with high risks for crew health and systems survival occurs and requires an autonomous and rapid intervention. In order to ensure the proper activation and implementation of these protocols, a simulated failure detection could be injected in the system from Control Center, so the reaction of the habitat can be evaluated. Finally, check on payloads' activation and status are performed.

Operative phase(s) The end of commissioning enables the start of operative phase: in the state diagram (Figure 49) is possible to notice that two operative phases – represented in green – have been identified. These two phases are constituted by the same sub-phases, as will be described, but present different level of advancement of habitat capabilities: in fact, during crewed operative phases, several extension and upgrading activities are performed, and finally an extended version of the habitat will be achieved, allowing to host an incremented number of astronauts, for longer periods and with additional system capabilities. The identification of these two operative phases aligns to the current vision of future Artemis missions, which will involve a *Foundational Exploration* phase, during which an initial surface habitation with limited capabilities will be used, followed by a *Sustained Lunar Evolution* phase, with extended capabilities [59].

In Figure 36 the Initial operative phase is shown. In this phase the habitat is assumed to host two astronauts for a stay of 30 days [18]; essentially, the capabilities of the habitat in this phase are the ones derived in Section 4. After the commissioning, the system goes through a period of about one year of dormancy, during which it must survive the lunar environment and perform autonomous payloads research activities. So, the sub-phases identified are characterized by research activities performance and, if planned, quiescent phases with only system survival and telemetry communication activities. In addition to these two phases that can alternate during the year, a cargo lander with logistic resupply lands in the proximity of the habitat in order to provide resources and items required for the start of crewed phase. According to NASA [54], during this initial operative phase including two astronauts and 30 days stay durations, a logistic resupply must occur requiring between 1.5 and 2 tons of cargo, with annual cadence and an open loop ECLSS. The size of resupplies required for crewed phases strongly depends on the ECLSS architecture: in fact, designing an ECLSS with a limited level of closure since the initial operative phases, as the one described in Section 4, can substantially reduce the resupply needed. In particular, basing on the approximation made by Eckart [21], with the ECLSS functionalities described in Section 4 it is possible to reduce the resupply mass to a 15-10% compared to the 100% of an open loop.

The crewed phase begins with the arrival of the crew on the Lunar surface. According with Artemis' ConOps guideline [18], during this phase two astronauts are hosted by the habitation system, and other two astronauts perform exploration activities on Pressurized Rover (PR); these two crew teams trade places during the month through PR docking. In first place, once landed on the Lunar surface, two astronauts on Lunar Terrain Vehicle (LTV) reach and access the habitat: here, they start to arrange the cabin in order to prepare crew accommodation, to perform systems and payloads checks and to outfit equipment. At the same time, the other two astronauts on PR reach the cargo lander and bring the supplies to the habitat: rendezvous between PR and habitat and docking occur, allowing to transfer supplies from PR to habitat. Finally, the PR hosting half of the crew undocks and dedicates to exploration activities. Once the system is resupplied and properly arranged, nominal crewed operations can start. During these phases, crew daily performs activities aimed to mission objectives achievement, but also has periods of off duty activities and dedicated to rest. During the 30 days of stay, according to NASA's ConOps evaluations [18], the PR docks every 4-5 days to the habitat, in order to be resupplied and to perform crew swaps. In the end, the crew arranges and leaves the habitat, giving start to a new dormancy phase.

Crewed and dormancy phases continue to alternate during the operative life of the system in the same way just described also during the extended operative phase (Figure 37), if present. As mentioned above, this phase is composed by the same sub-phases than the initial one, but in this case the habitat can host a crew of four astronauts, for a stay

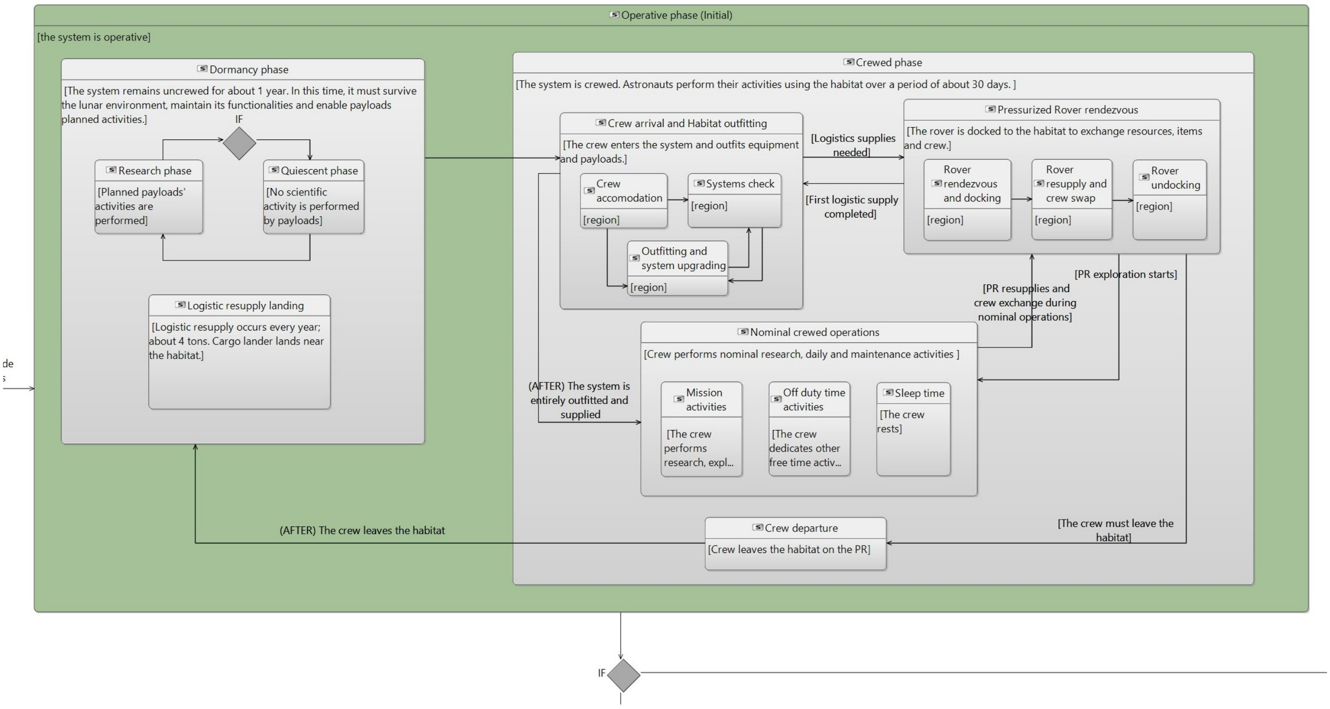


Figure 36: State Machine: Initial Operative phase

period of 60 days. Thus, the Extended operative phase involves an upgraded version of the habitat, also in terms of ECLSS loop closure: in this extended concept, the habitat could involve advanced capabilities for resource production and elimination of leakage, further reducing the mass of resupplies needed lower than 10% [21].

End of Life phase When the operative phase of the habitat ends – or in non nominal case if the system is irremediably not more usable in its operative activities – the End Of Life (EOL) phase occurs. In this phase[23], activities are performed both by the crew and via telecommands in order to safely decommission the system. In particular, as shown in Figure 38, during the first EOL sub-phase the crew recovers all the parts of the habitat that can be reused in other missions, payloads and organic remains. This logistic activity can be performed in more phases during the last part of the last operative crewed missions. After the last crewed phase, it is possible to proceed with the decommissioning of the system, managed in remote by Mission Control Center. First of all, the payloads left in the habitat are decommissioned, followed by the decommissioning of the ECLSS and then of TCS. In this way, at this point the habitat is only able to communicate telemetry and manage telecommands, continuing to generate power.

The power generation terminates with the refolding of solar arrays, restoring a stowed configuration of EPS. Since this moment, the system continues to communicate the telemetry to Earth in order to provide evidence of successful decommissioning, using stored energy. The last sub-phase, in fact, continues until all the stored energy is consumed: then,

[23] In this dissertation the nominal case is debated. In non nominal cases the system's EOL could be made of different phases depending on the non nominal situation.

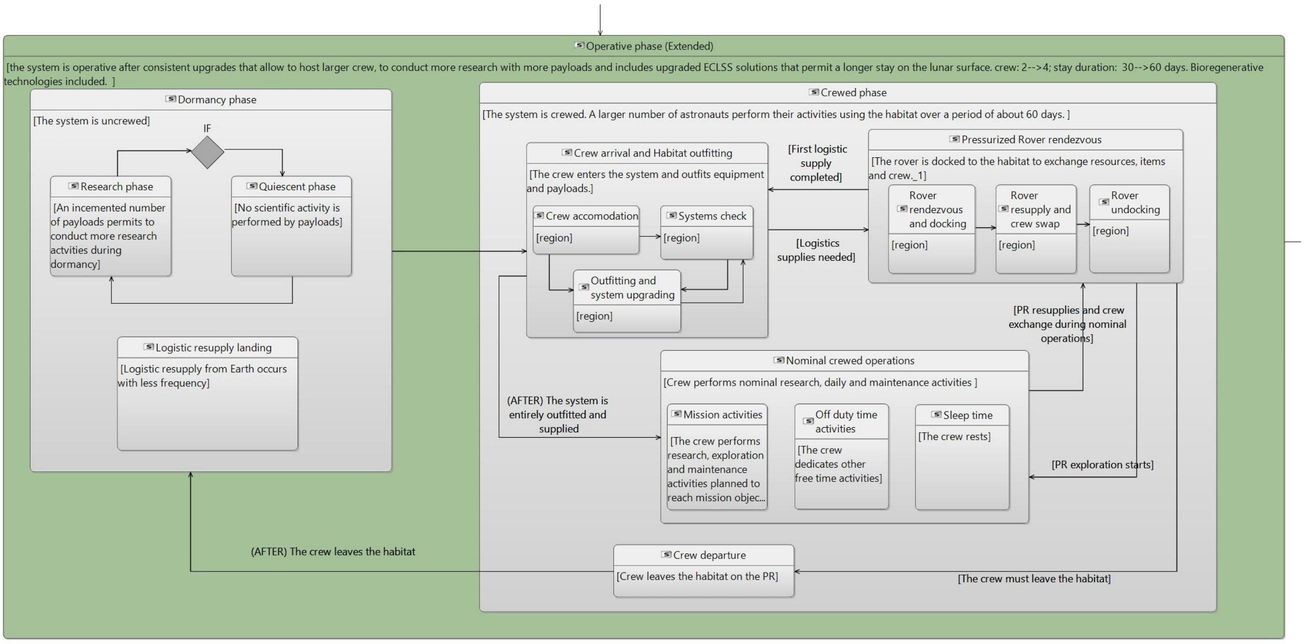


Figure 37: State Machine: Extended Operative phase

the system is completely devoid of energy, off and exposed to Lunar environment, hence sterilized.

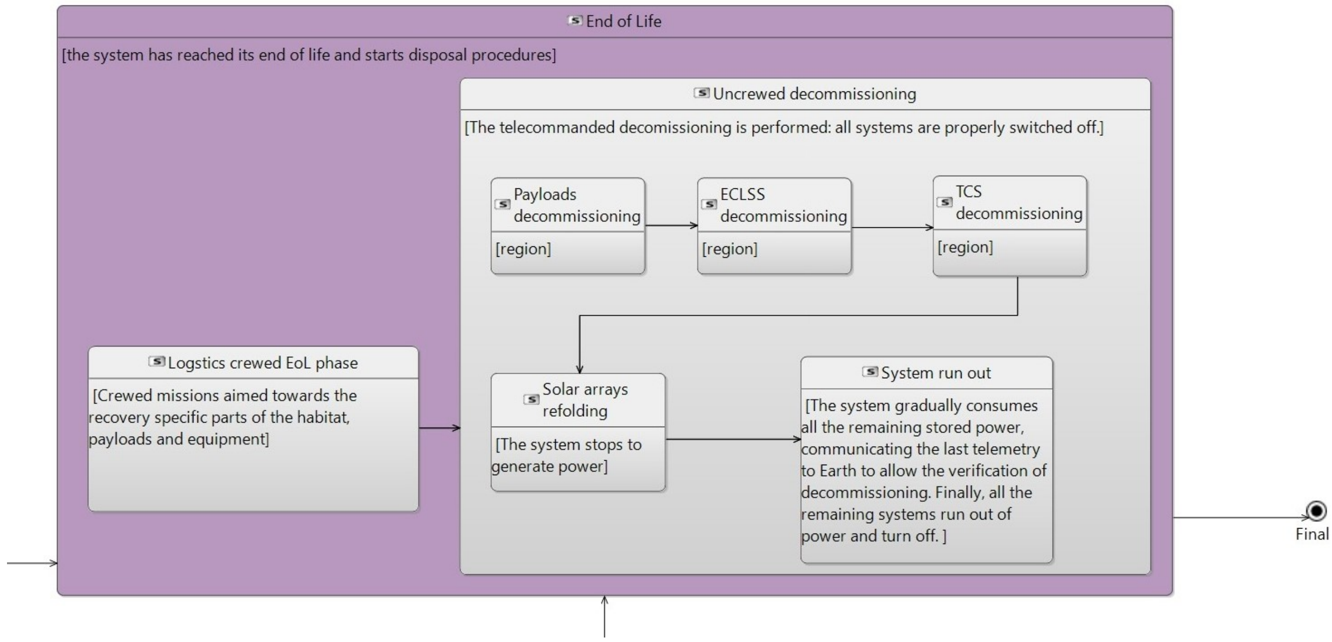


Figure 38: State Machine: End of Life phase

5.2 Operative Modes

As mentioned in Subsection 5.1, the States machine is not the only Mode State Machine integrated in the model: the second MSM is described in this Subsection is properly a Mode Machine.

A **Mode** is defined as

"a behavior expected of the system, a component or also an actor or operational entity, in some chosen conditions" [52].

In this diagram Modes represent the high level system's **Operative Modes (OMs)** during the phases discussed above[24]. With this set of defined Modes linked by Transitions, it is possible to integrate and explicit the Operative Modes of the system during its life, which can be further deepened in lower level analysis and associated to physical subsystems and components in future extensions of this Thesis.

Also in this case, due to the dimensions of the MSM, descriptions of each OM related to single parts of the Mode machine follow, in order to provide a better readability of the images. In Appendix F the Mode machine in its entirety is shown, providing a general visualization of the diagram. The colors in each following Figure remark the colors used for States identification in the previous Subsection.

Launch and Early Orbit phases modes During the initial LEOP phases the system involves two main operative modes (Figure 39): the *Launch* mode and the *Early Orbit*

[24]The Operative Modes in this dissertation are related to the initial system configuration analyzed in Section 4. Additional Operative Modes involved into an upgraded version of this system, possibly relative to an extended operational phase, could be included in further iterations of this work.

Phase check mode. In particular, the launch mode is the OM which the system adopts during the launch, and can include active payloads or be off: depending on the cases, the system could involve payloads that need to be launched already active. Hence, in these circumstances, the system would be launched with the functionality of power distribution to these users activated. In summary, the launch mode is strictly dependent from the specific case of payloads involved, so it is possible to generalize it as an OM that could involve a minimum power consumption due to specific payloads' requirements.

Once the system and lander complex reaches the target Earth orbit, Early Orbit Phase's checks begin: these checks, as anticipated, are performed in order to prepare the system to the Lunar transfer and to check the integrity of system and payloads after the launch. For this reason, the system is switched by Mission Control Center to the OM dedicated to these checks, which in turn includes three main sub-modes: during this phase, the system can operate the checks in communication with Earth when it is within the communication window, can carry on the telecommands autonomously out of the window, or can maintain a "freezed" mode waiting for further telecommands to perform. Thus, in the first case the system provides housekeeping data to the lander's ComSys to be transmitted to Earth, while in the last two cases the communication of these data is not provided. In addition, in the second case the system performs autonomously the check activity during the silent orbital phase, which can involve a subsystem or a payload, while in the third sub-mode the system only waits to be in communication with Earth to receive other telecommands or transmit data. The sequence of checks and activation in this phase includes first of all the check and activation of EPS's power distribution function, and commissioning of Command and Data Handling System (CDHS) and Thermal Control System (TCS). These are the basic functionalities that are involved in the nominal functioning of the system during the transfer, supported by the lander for power provision and communication capabilities.

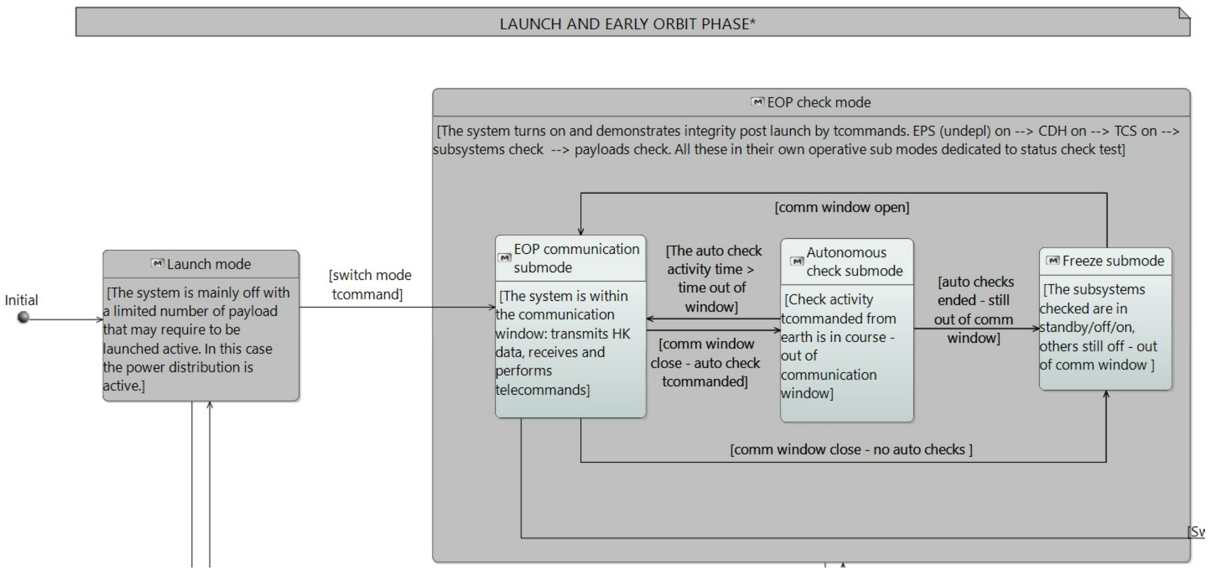


Figure 39: Mode Machine: Launch and Early Orbit phases modes

Standby mode Since the last part of LEOP, consisting into the injection to the transfer orbit, the system is switched to the Standby mode: the system keeps activated only the essential subsystems that allow the system's survival and the housekeeping data collection, hence EPS power distribution – it is reminded that the power is provided by the lander –, TCS for the management of transfer thermal loads and CDHS for the management of data and telecommands. All other subsystems, such as the ECLSS, are switched off after the EOP checks, as well as the payloads. A limited number of payloads could be kept activated for the performance of experiments during the transfer, if planned: in the case of specific mission definition, with specific payloads on board, more exact considerations on the status of payloads would be provided; in the most general case, in this dissertation, it is considered that the power consumption in this phases is reduced to minimum, thus, in general, all non necessary systems are off in order to save energy. As shown in Figure 40, the Standby mode includes in turn three sub-modes: if planned, the system can involve payloads' activity during transfer, so EPS' power distribution, TCS, CDHS and specific payloads are active; the other two modes consider the system in standby mode within and out the communication window with Earth, so if the system interfaces with the lander's communication system sending data and receiving telecommands from Earth or not.

This operative mode is maintained by the habitat for several phases, in particular from the transfer orbit injection, to the entire transfer, NRHO orbiting around the Moon, landing and settlement on Lunar surface. Basically, the habitat remains in standby until the lander provides its support during these phases: in fact, all these mission phases are managed by the lander.

Commissioning mode Once the lander has settled on the Lunar surface, the system shall become independent in order to start to operate nominally during the Operative phase. During the commissioning phase the system works with a dedicated Commissioning Operative Mode, which involves several sub-modes that together provide the system finally operative and independent from the lander. In Figure 41 the Commissioning OM and the sequence of its sub-modes are shown, retracing the Commissioning phases described previously. All the switches of modes that determine the proceeding of the Commissioning are managed and telecommanded from Earth.

First of all, the system is made independent from the lander. Since the lander supports the habitat with power generation and communication system, these are the first activities enabled during the commissioning. With the first sub-mode, the habitat deploys its solar arrays, in order to start to generate power; as visible, this is an *assisted* deployment, as the power required is still provided by the lander. Thus, in this OM, the system involves EPS' distribution and deployment mechanisms, TCS and CDHS activity. Once the solar arrays are properly deployed, the system can start to generate power: the Power Generation mode involves the commissioning of EPS, hence EPS, TCS and CDHS activities. In order to face future night periods, the system starts to recharge the energy storage items – fuel cells and batteries, for example – in Power Reserve mode.

Once the EPS is fully operative, the ComSys must be commissioned. This begins with the deployment of communication elements, like antennas, that in this case occurs with

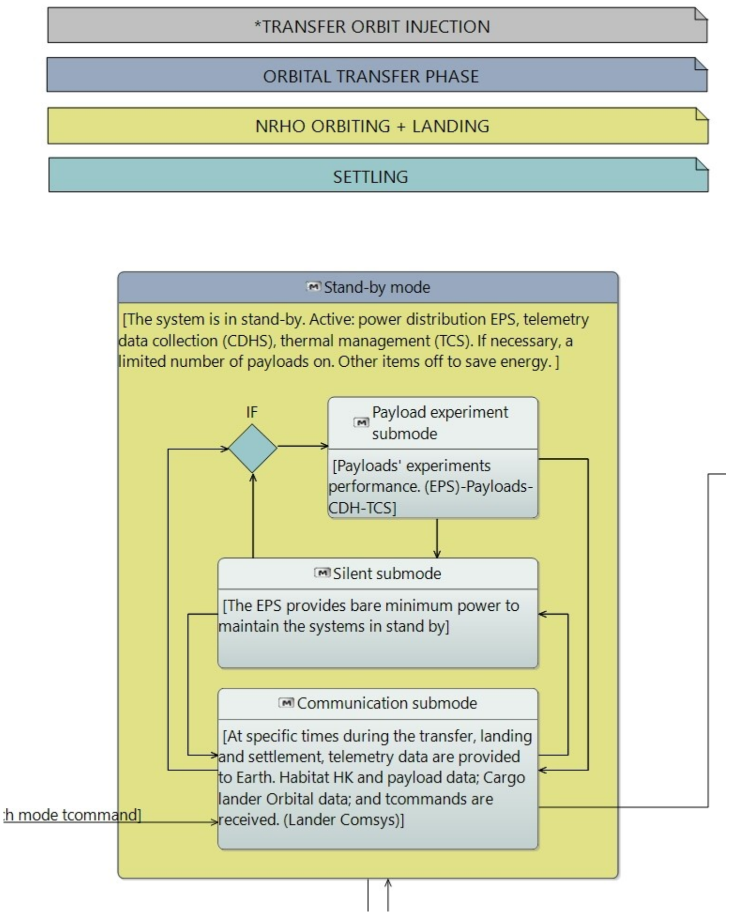


Figure 40: Mode Machine: Standby mode

power generated by the system's EPS. With the antennas deployed and the ComSys commissioned, the system can finally proceed with the rest of commissioning without lander's support: in this configuration, it works in Independency mode, which involves the basic functionalities of TCS, EPS, CDHS and ComSys.

As mentioned, the system is launched with inner cabin atmosphere: the Environmental Control System (ECS) is commissioned and the atmosphere is assessed and maintained with the activation of the Environmental mode, which involves the activity of TCS, CDHS, EPS, ComSys and ECS. From this OM, other sub-modes involving subsystems checks occur: the testing of Airlock's proper activity is performed with EVA Test mode, during which the Control Centers test the airlock's ability to isolate and depressurize sending telecommands and checking the system response. In this case, the same functionalities of Environmental mode are involved, but adding the activation of the airlock simulating an astronaut's access, as much as possible for remote testing. In addition to the Environmental control capability, the system must commission also Life Support System's functionalities, testing the activation and status of subsystems that will be essential to guarantee the survival of astronauts during crewed phases. In LSS subsystems test mode, the same subsystems of Environmental mode are involved with the addition of LSS in commissioning mode. In order to test the system's emergency response, at the injection of failure detection by the Mission Control Center, the system must demonstrate to be able to switch to Safe mode – shown later in this Section in Figure 44. In particular, the system must apply the emergency protocols defined in Safe's Emergency sub-mode autonomously and rapidly, in order to guarantee the safety of crew and systems in hypothetical real conditions of emergency. This point will be more visible later in the Section, when the Safe mode will be discussed.

Finally, the payloads can be commissioned: these are activated and checked, and most of them are kept on in order to perform research activities during the dormancy phase.

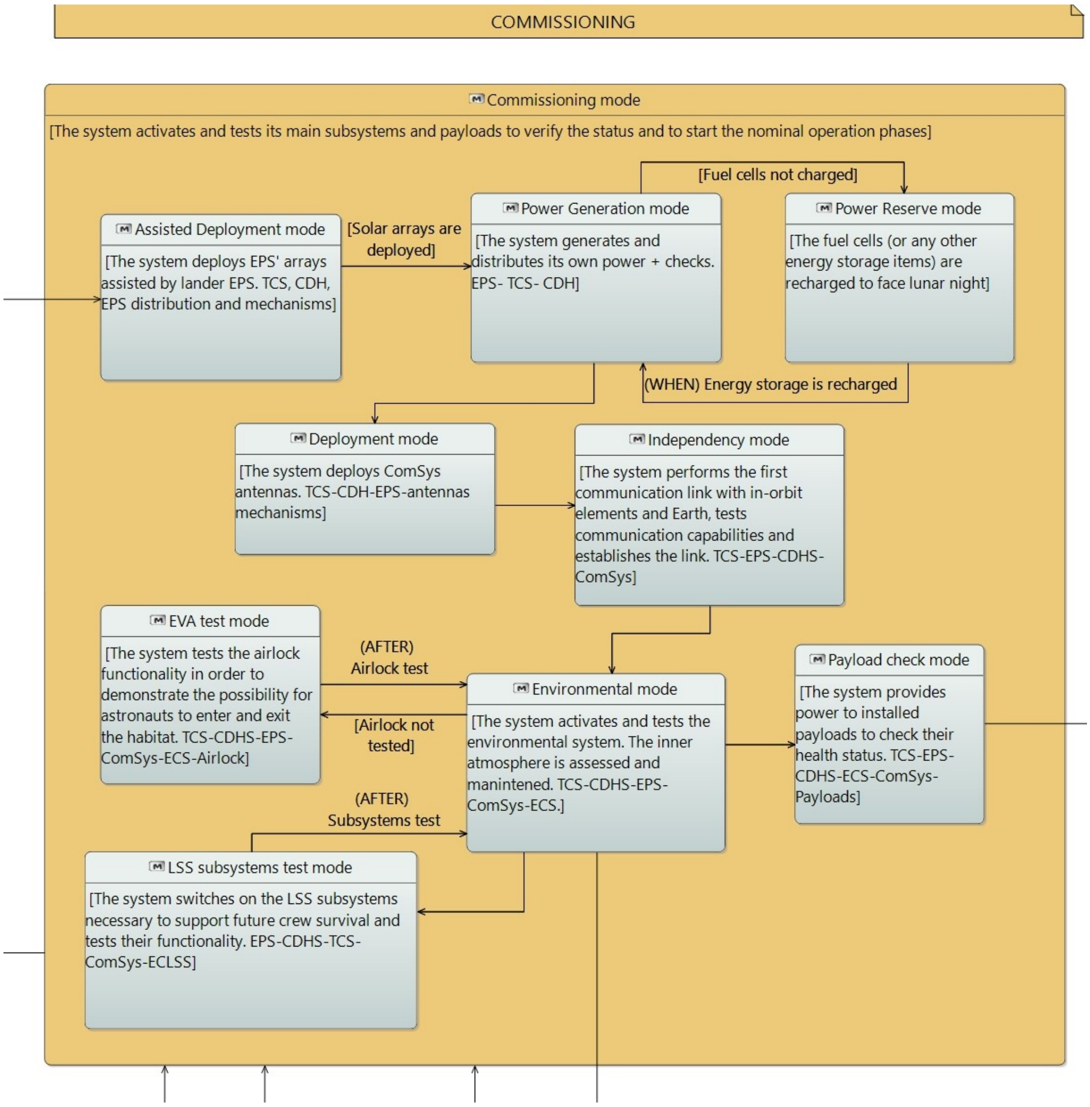


Figure 41: Mode Machine: Commissioning mode

Dormancy mode The habitat is finally commissioned, and the Mission Control Center upholds the beginning of Operative phase. As described earlier in this Section, the habitat first of all enters in a dormancy period of about one year [18]. During this phase, the system mainly safeguards itself from the Lunar environment and enables research activities of payloads: for this reason, the Dormancy mode related to dormancy period – shown in Figure 42 – includes a Basic sub-mode which involves the activity of TCS for the thermal management, CDHS for the data and commands management, EPS for the power management, ComSys for the communication of telemetry and receiving of telecommands, ECLSS for the management of cabin environment and of resources[25] [26] and Payloads for the performance of experiments.

The Basic sub-mode does not represent the only mode for the system to function during dormancy. If present onboard, autonomous robotic system can perform maintenance activities during uncrewed phases, telecommanded from ground operators, working in Autonomous Maintenance sub-mode. Thus, in addition to the Basic's functionalities, the system would involve the activity of this robotics too. The third operative mode is Eclipse, and is activated whenever an eclipse period occurs. The problem of energy availability during Lunar nights – besides the thermal management – is typical of Lunar long stay missions, specially if solar power systems are involved, and presents different durations depending on the Lunar base location: near the Lunar equator, the eclipse periods last about two weeks [21], while moving close to the Lunar Poles these night durations can considerably reduce. This is one of the main reasons for the selection of Lunar South Pole as the main region of interest for future exploration activities on the Moon: in this region could be possible to locate a solar power system such that it receives almost continuous solar radiation input, except for short periods of eclipse due to the slight tilt of the lunar rotational axis [21]. In particular, permanent sunlight could only occur at a sufficient height above ground level, such as on a mountain near the Poles: several regions illuminated for greater than 70% of lunar day in winter are optimal for energy availability; some of these regions can reach 98% of illumination, reducing the energy storage requirement to around zero [21]. Supposing that placing systems on high peaks for constant illumination could considerably increase the complexity of operations, in this dissertation it is considered the eclipse period as relevant in design of system and operations. NASA estimates Lunar nights with duration of 100+ hours [18]. For these reasons, the Eclipse mode permits to face eclipse periods, and so lack of power generation, taking advantage of stored energy and prioritizing the power consume, in order to limit it. This means that during the Lunar nights the system will be provided of limited energy which will be distributed to predefined subsystems – surely essential CDHS, ComSys, EPS and TCS in related eclipse sub-modes, for example considering that TCS would be even more involved due to the extreme low temperatures – and payloads in order to save energy.

Crewed mode With the arrival of the crew on the Lunar surface the habitat enters into a crewed utilization phase, and is switched to a Crewed mode. First of all, the access of the crew to the habitat occurs. Basing on NASA's ConOps evaluations, two astronauts head towards the habitat with an LTV in order to begin the arrangement of the habitat for crew stay. In this case, the system must guarantee the access of the crew from the lunar environment, so it works in EVA mode: this mode involves the isolation and

[25]It is supposed that the habitat is launched already with a limited amount of resources that could complicate operations for logistic transfer of resources from cargo lander to habitat, such as water.

[26]During Dormancy phase the ECLSS is active and includes both the atmosphere maintenance and the resources management, with crew support functionalities off. In particular, for the first dormancy period after commissioning, the habitat has not been resupplied yet and has no waste to manage, so the resources management would be limited to the management of water onboard for payloads utilization, for examples, and for its quality preservation.

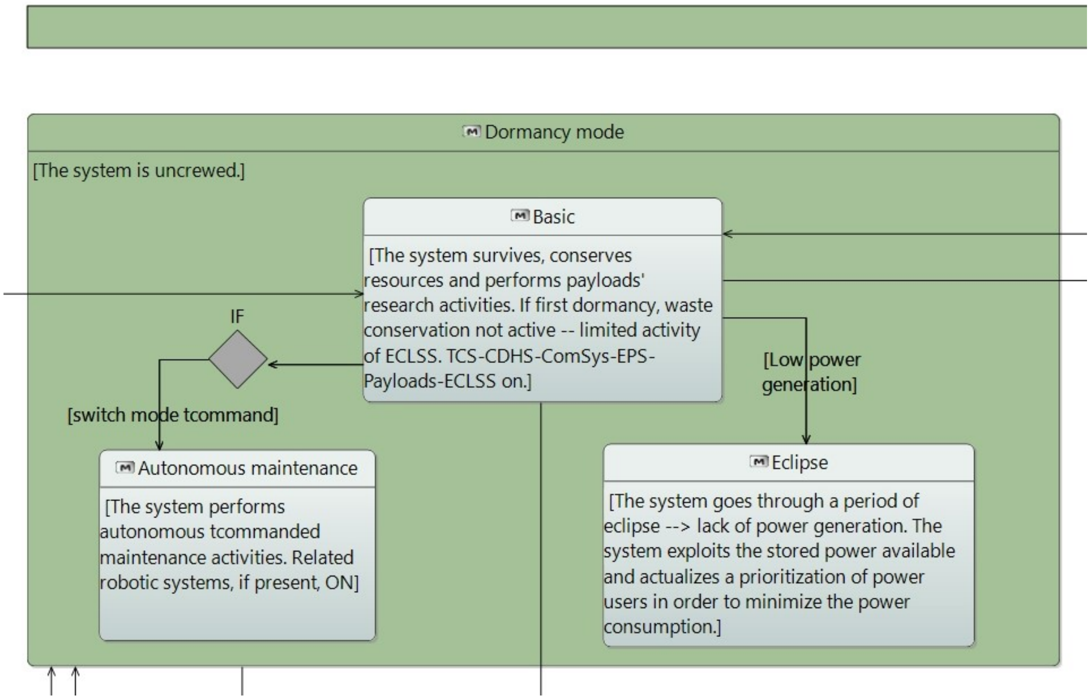


Figure 42: Mode Machine: Dormancy mode

depressurization of the airlock from the rest of the habitat, allowing the access of the crew with the opening of the hold door. As shown in Figure 43, the EVA mode is composed by two main sub-modes: the (De)Pressurization sub-mode is active whenever the airlock is being depressurized or pressurized. The EVA sub-mode, instead, is active during the EVA performance, so involves the airlock depressurized and the EVA's monitoring and support systems operational. In both cases, the airlock is isolated from the rest of the cabin environment. This mode is active whenever an EVA must be performed and when the crew must access the habitat from the lunar environment, at the end of en EVA or at the first access of the crewed phase.

As described during Operative phase overview, other two astronauts stay on the Pressurized Rover, at the beginning of the crewed phase for the resupply of the habitat and for the rest of the month of stay for exploration activities. In both these cases, whenever the PR shall approach the habitat, this works in a PR Docking mode. In particular, this involves an (Un)Docking sub-mode dedicated to the activation of the docking mechanisms in order to dock or undock the PR, and a Docked mode when the PR is docked and environmentally connected to the habitat. In this last mode, the crew can perform the same activities and has the availability of the same system's functionalities of the Basic mode, which will be described in a short while. In the context of the first part of the crewed phase, this OM allows the crew to transfer logistics from PR to the habitat, in order to complete its resupply and the outfitting and finally to start the core of the crewed phase.

The Basic mode is the OM which allow the astronauts to perform daily activities within the system, including scientific research and off duty activities. In this mode all the subsystems that ensure the survival of crew and system are activated as well as the required payloads to conduct the research activities, hence TCS, CDHS, ComSys, EPS, ECLSS and Payloads. In parallel to what already described for Dormancy mode, also in this case an Eclipse mode is included in order to face periods of lack of power generation. This OM differs from the analogue sub-mode in Dormancy for the different prioritization of the power distribution during these periods: in fact, if during dormancy the priority is given to the survival of the systems, during crewed phase the priority is to guarantee the health and habitability of the system for the astronauts. In these means, during the Eclipse mode the EPS manages differently the stored power giving priority to ECLSS and to TCS CDHS and ComSys.

The Rest mode is a sub-mode that allows the crew to rest in the most efficient way. When the crew activates this mode, the lightning, noise and temperature levels of the system adapt to specific comfort conditions, and it is considered the lower crew's awareness level in safety protocols and payloads activity, if necessary.

Finally, the Robotic Maintenance sub-mode is included if external autonomous robotic systems are present onboard. These could be necessary for the performance of specific maintenance activities that could require hazardous and complex EVAs, such as maintenance activities on items on the top of the habitat, as an example. If the robotic activity is in parallel to an EVA – for example in case the maintenance activity is an hybrid both human and robotic – the system combines the EVA and Robotic Maintenance modes in EVA Robotic Maintenance – airlock isolated and depressurized, EVA monitoring systems operative and robotic systems active.

All the transitions from Basic to other OMs would be mainly managed by the crew and by operators, if necessary. When the crew leaves the habitat, the system is switched again in Dormancy mode by operators and the Operative phase cycle continues.

Safe mode In every space system is essential to include into the design also OMs dedicated to situations out of nominal. Accurate evaluations about non nominal context are fundamental for the planning and conclusion of the mission, and would require a dedicated work. In this Thesis high level nominal considerations on the system and its operations have been conducted, so deeper analysis of non nominal behavior and operations could be carried in future extensions of this Thesis' work. In this model, a general high level Safe mode has been included (Figure 44), which enables the Mission Control Center to manage non nominal situations and brings the system in a safe configuration of functioning that limits possible further complications and waits directions from Earth or crew.

In particular, the Safe mode includes high level Safe sub-modes related to the phase of mission, hence to the system configuration. During the first phases, from launch to commissioning, the system is active but in a limited configuration supported by lander. In these cases, if necessary, the system switches to an Undeployed Safe mode, during which the system only provides telemetry and receives telecommands for safe resolution, but sustained by the lander for functions forementioned. Another specific Safe is the Independent Commissioned Safe: in this case, the system is in Commissioning phase, but is already independent from the lander, so EPS and ComSys are commissioned. During

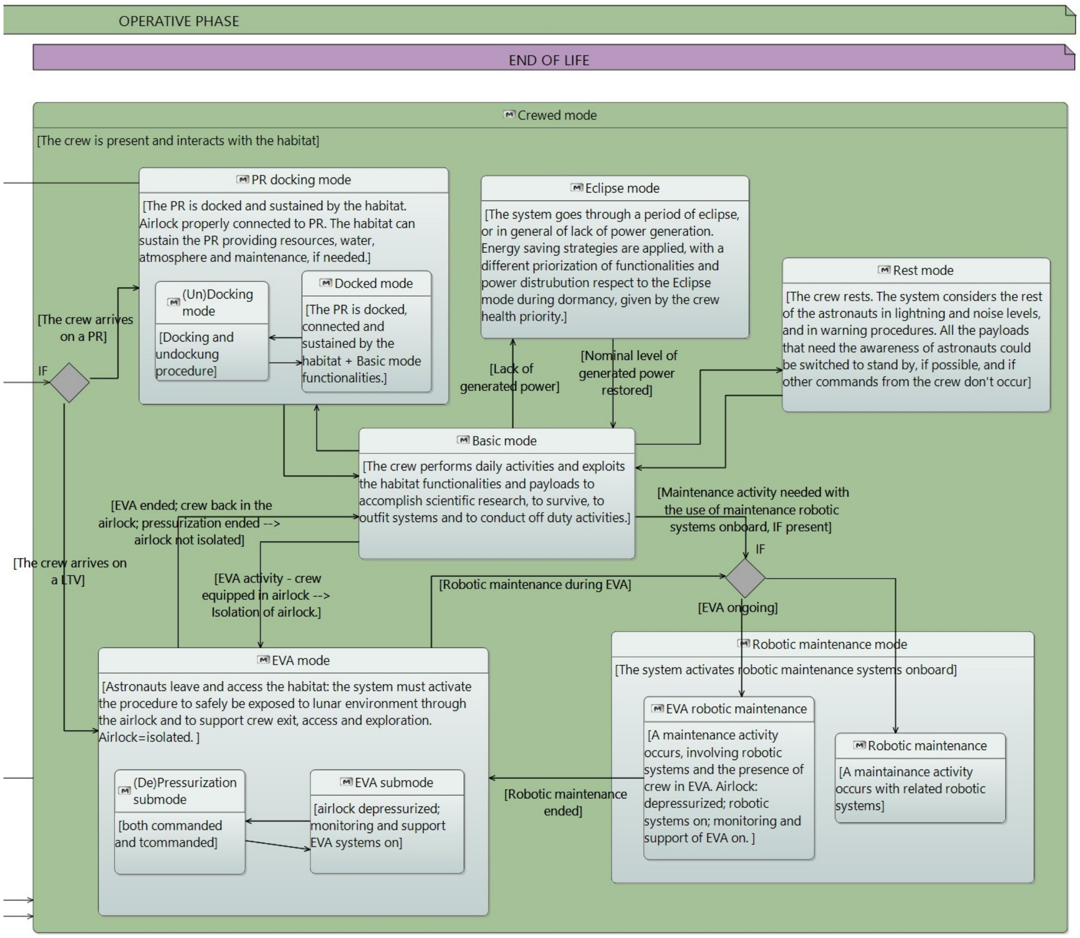


Figure 43: Mode Machine: Crewed mode

the Safe, the system suspends commissioning activities and waits for Mission Control Center's telecommands – this time without lander's support.

During the Commissioning, the system enters in Emergency mode following the failure detection injection already discussed. The Emergency mode is dedicated to emergency situations that require autonomous and rapid applications of emergency protocols, and includes Crewed and Uncrewed sub-modes: in the two cases the emergency identification changes due to the presence of astronauts, hence to the priority of safeguard their health. If the system is crewed, the first reaction to the emergency is to make the astronauts safe, in different ways basing on the specific case. When the crew is safe, then it is possible to manage the emergency for the recovery of the system.

The Safe Crew and Uncrewed modes are involved in case of non nominal condition that does not involve an emergency, that requires priority of intervention. The system in this case suspends all research and payloads activities and prioritizes telemetry communication and telecommands actualization. During crewed phase, this could occur with a critical failure involving one of the main subsystems not relevant for crew survival and safety.

When the Safe condition is resolved, the Mission Control Center's operators switch OM restoring the nominal condition.

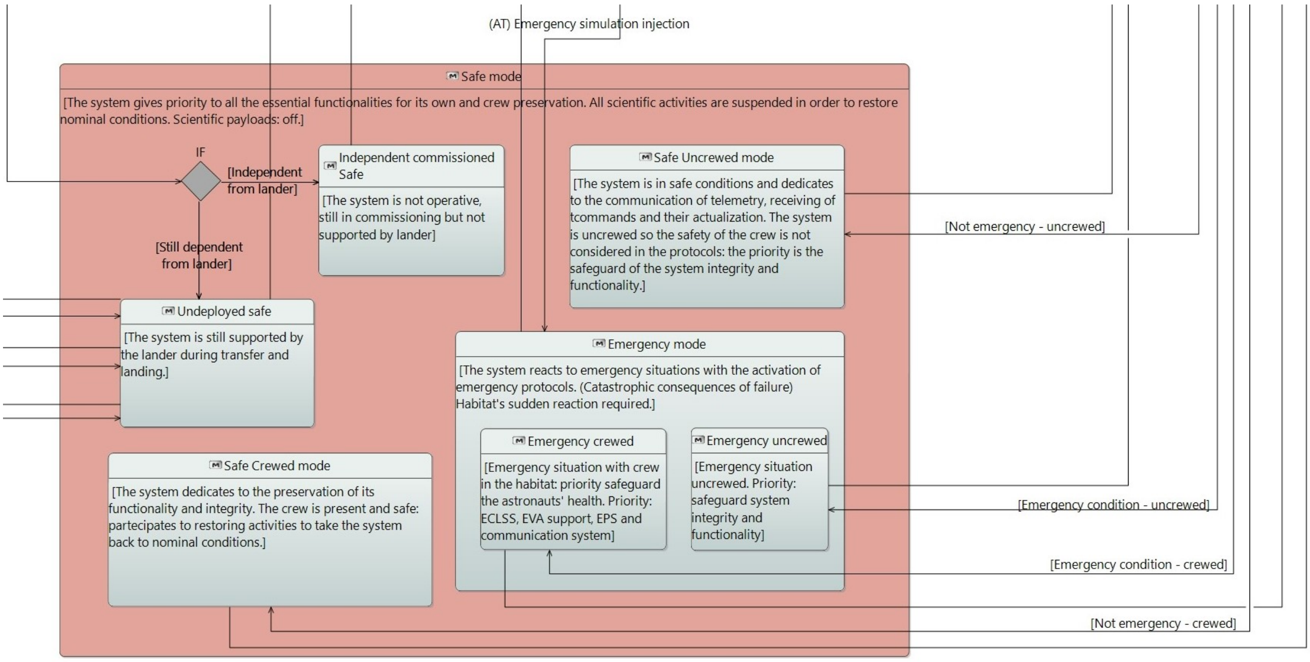


Figure 44: Mode Machine: Safe mode

End of Life mode The last Operative Mode is related to the End of Life phase, in particular to the Decommissioning performed after the last crewed phase. This OM is constituted by a sequence of sub-modes – shown in Figure 45 – that ensures the proper decommissioning of the system.

Firstly, the remaining payloads and Life and Crew Support subsystems are decommissioned; the related operative sub-mode is the Environmental mode, as it involves the activities of basic functionalities and of Environmental Control System. The following subsystem to be decommissioned is the ECS, and this is preceded by the depressurization of the habitat; in this way, the system is devoid of cabin atmosphere, exposing to the Lunar vacuum. The OM related to this depressurization is called Passive Decontamination mode, as the exposure of the cabin to Lunar environment entails a passive decontamination of the system[27]. After this, the ECS – and so the ECLSS – system is definitely decommissioned and the system works in Independency mode, recalling the Commissioning sub-mode: TCS, EPS, CDHS and ComSys are the remaining functionalities on.

The Decommissioning continues with the decommissioning of TCS.

With Undeployment mode, the system restores a stowed configuration of EPS, refolding solar arrays. The resulting OM at the end of refolding process is the Closure mode: the system in stowed configuration works with the remaining stored energy to provide the final telemetry to Earth, in order to demonstrate the correct decommissioning results. Thus, in this mode, the system involves power distribution and storage systems, ComSys

[27]The decontamination of the habitat could be relevant in case of organic and bacteria remains, in order to cancel any biologic trace on the site to prevent surface contamination and for ethical reasons. Active decontamination methods could be involved if necessary, but in this dissertation are not included for lack of supporting literature. Being the Lunar environment sterile, the exposure of the cabin to Lunar vacuum is supposed that could be sufficient in these regards.

and CDHS until the stored energy runs out. In this way, the EPS is decommissioned and passivated, with empty energy storage – particularly important in case of batteries, whose wrong maintenance and degradation could provoke explosions. At the depletion of stored energy the system is not more powered and turns off.

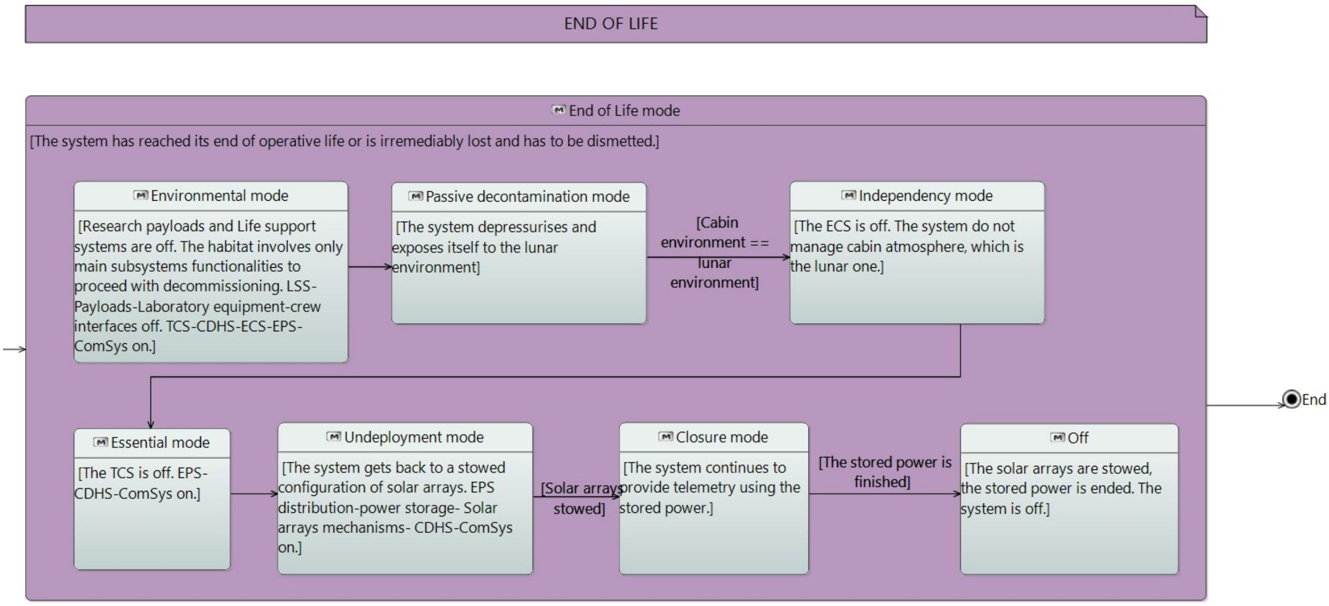


Figure 45: Mode Machine: End of Life mode

6 Conclusions

The purpose of this Thesis was to develop a functional model that captures the high-level capabilities required for a Lunar Habitat, ensuring alignment with mission objectives and stakeholder expectations. This goal was pursued through the application of Model Based System Engineering (MBSE), using the ARCADIA methodology to obtain an integrated representation of the system. In particular, the work focused on integrating operational aspects into the model, thereby enhancing its coherence with the envisioned mission concept.

The results of this study demonstrate that a comprehensive high-level functional model was successfully produced. The completeness of the derived capabilities is supported by the derivation process adopted throughout the work. Moreover, the integration of operational evaluations has proven essential for shaping the operability of the system: key contributions include, for example, the integration of the interface to the Pressurized Rover, the communication architecture considering relay assets, the operational elements necessary to support EVA activities, the definition of eclipse operating modes, and provisions to ensure maintainability and mission continuity through future upgrades.

Nevertheless, the outcomes of this work remain subject to several limitations inherent to high-level modeling. Such a model does not yet account for the critical considerations that would emerge at lower levels of definition, where subsystem-specific constraints and detailed physical interactions become central. Additionally, other perspectives could be integrated to further strengthen the completeness, robustness, and multidimensional coherence of the model: given the complexity of the system and of the mission itself, this work represents only an initial step that necessarily simplifies numerous aspects.

These limitations, however, constitute opportunities for future development. This model can be progressively refined by descending to lower levels of abstraction: the logical components identified here will be translated into physical subsystems and components, enabling subsequent sizing and performance assessments. Building upon the foundation established in this Thesis, the physical derivation of the architecture can follow, as well as the detailed definition of Operational Modes at subsystem level, essential for estimating resource consumption and supplying inputs for design calculations. Furthermore, all perspectives not fully addressed in this work, such as logistics strategies, safety considerations, and additional operational constraints, may be expanded. Many other evolutions are possible thanks to the high-level nature of the present study, maintaining the coherence and integration of future refinements with the existing model thanks to the traceability intrinsic to the ARCADIA methodology.

A Abbreviations

ALSEP Apollo Lunar Surface Experiments Package

ARCADIA ARchitecture Analysis and Design Integrated Approach

ASI Agenzia Spaziale Italiana

atm atmospheric

CDHS Command and Data Handling System

CIRA Centro Italiano Ricerche Aerospaziali

CNR Consiglio Nazionale delle Ricerche

ConOps Concept of Operations

CSM Command and Service Module

DNA DeoxyriboNucleic Acid

DSB Dipartimento di Scienze Biologiche

DSN Deep Space Network

EASEP Early Apollo Scientific Experiments Package

ECLSS Environmental Control and Life Support System

ECS Environmental Control System

EMU Extravehicular Mobility Unit

EO Earth Orbit

EOL End Of Life

EOP Early Orbit Phase

EPS Electrical Power System

ESA European Space Agency

EVA Extra Vehicular Activity

GCR Galactic Cosmic Rays

GS Ground Segment

HK Housekeeping

hr hour

IAEA International Atomic Energy Agency

INCOSE International Council on Systems Engineering

INFN Istituto Nazionale di Fisica Nucleare

ISRU In Situ Resource Utilization

ISS International Space Station

ITU International Telecommunication Union

LA Logical Analysis

LAB Logical Architecture Blank
LEO Low Earth Orbit
LEOP Launch and Early Orbit Phase
LFBD Logical Function Breakdown
LRV Lunar Roving Vehicle
LSII Lunar Science Innovation Institute
LTV Lunar Terrain Vehicle
MBSE Model Based System Engineering
MCB Mission Capabilities Blank
MCC Mission Control Center
MIT Massachusetts Institute of Technology
MLI Multi Layer Insulation
MPH Multi-Purpose Habitat
MSM Mode State Machine
MUR Ministero dell'Università e della Ricerca
NASA National Aeronautics and Space Administration
NEO Near Earth Orbit
NRHO Near-Rectilinear Halo Orbit
NSN Near Space Network
OA Operational Analysis
OAB Operational Architecture Blank
OC Operational Capability
OCB Operational Capabilities Blank
OEBD Operational Entities Breakdown Diagram
OM Operative Mode
OMG Object Management Group™
OOSEM Object-Oriented Systems Engineering Method
OPM Object-Process Methodology
PA Physical Analysis
POCC Payload Operations Control Center
PR Pressurized Rover
PU Processing Unit
QFD Quality Function Deployment
RTG Radioisotope Thermoelectric Generator
SA System Analysis

SAB	System Architecture Blank
SANS	Spaceflight Associated Neuro-Ocular Syndrome
SE	System Engineering
SFBD	System Function Breakdown
SH	Surface Habitat
SIU	Space It Up
SLS	Space Launch System
SMS	Space Motion Sickness
SOCC	Spacecraft Operations Control Center
SPE	Solar Particle Events
STG	Space Task Group
TBC	To Be Confirmed
TBD	To Be Defined
TCS	Thermal Control System
UNOOSA	United Nations Office for Outer Space Affairs
U.S.	United States
USSR	Union of Soviet Socialist Republics

B System Function Breakdown (SFBD)

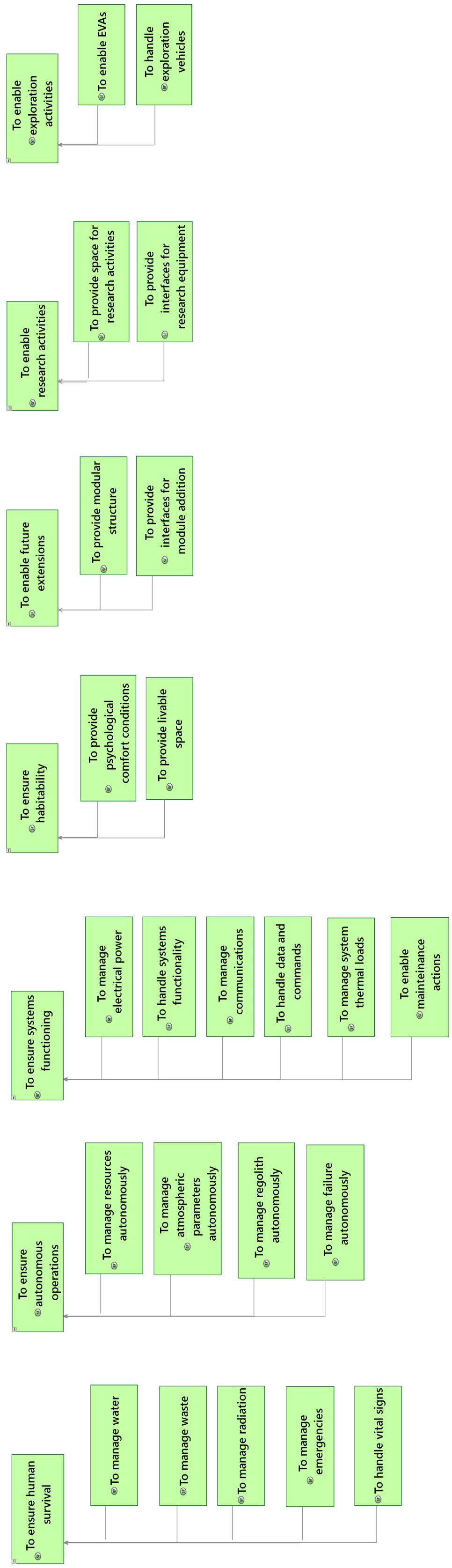


Figure 46: System Function Breakdown (SFBD)

C Logical Function Breakdown (LFBD)

Figure 47: Logical Function Breakdown (LFBD)

D Logical Architecture Blank (LAB)

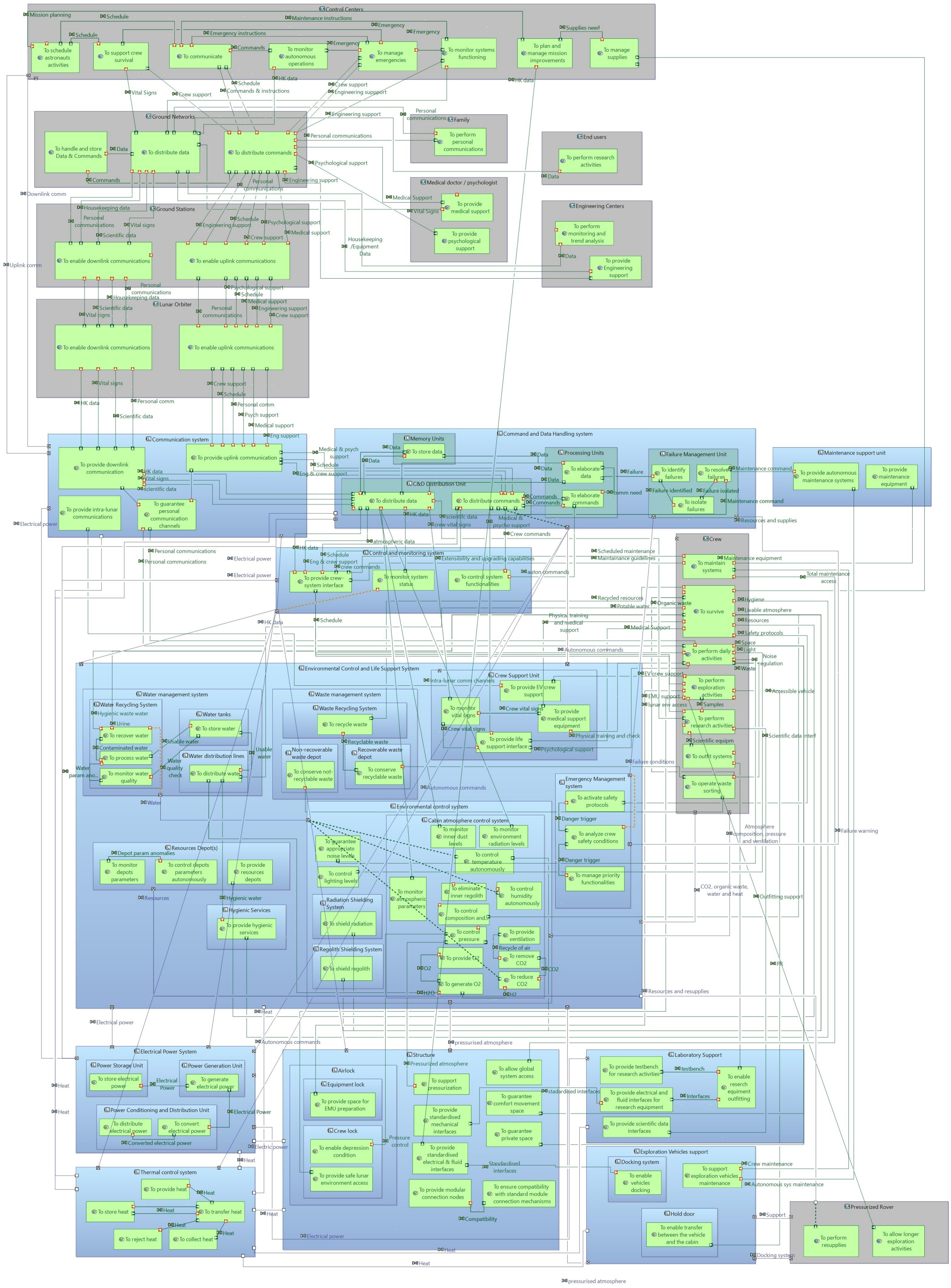


Figure 48: Logical Architecture Blank (LAB)

E State Machine

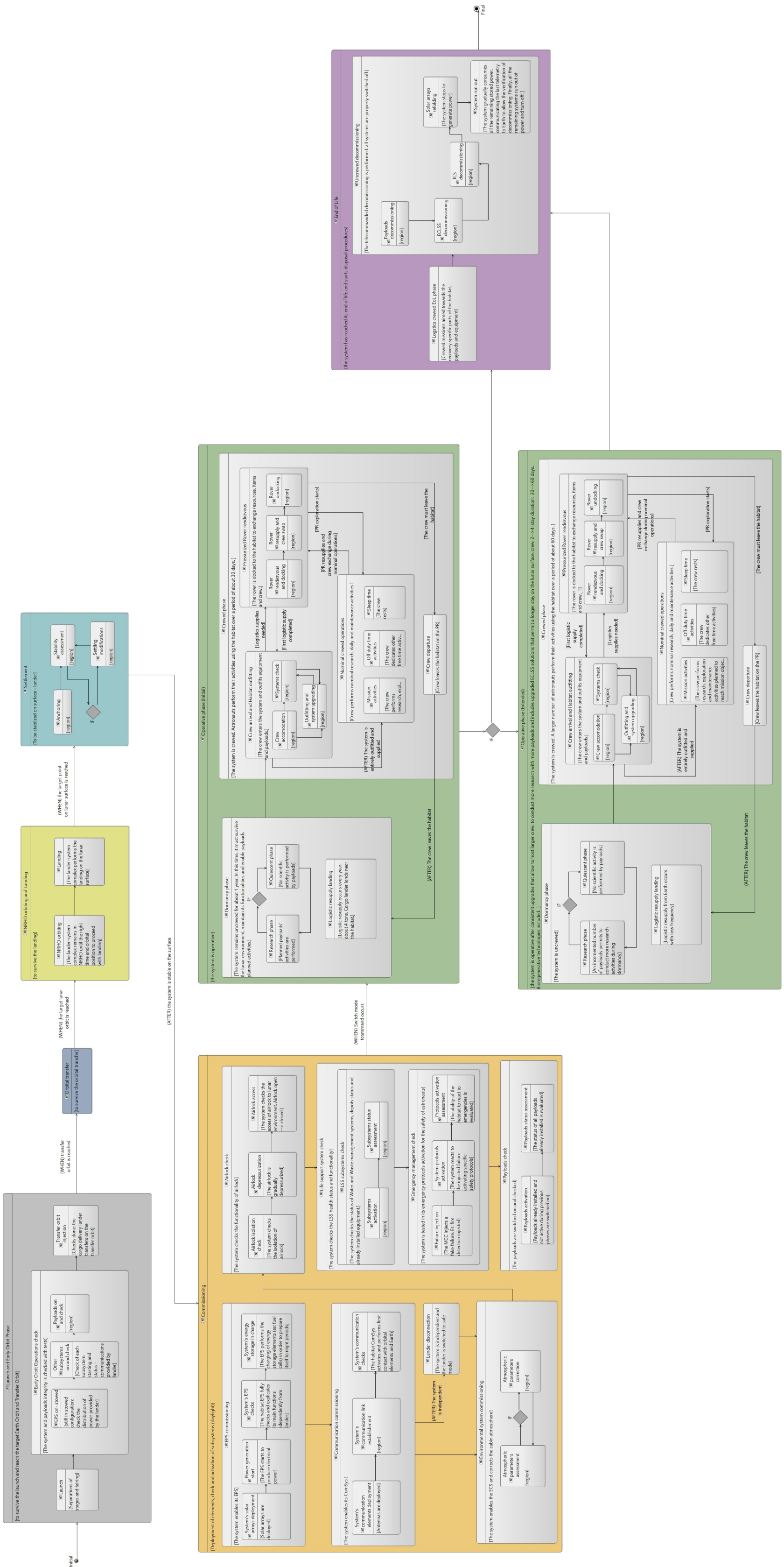


Figure 49: State Machine

F Mode Machine

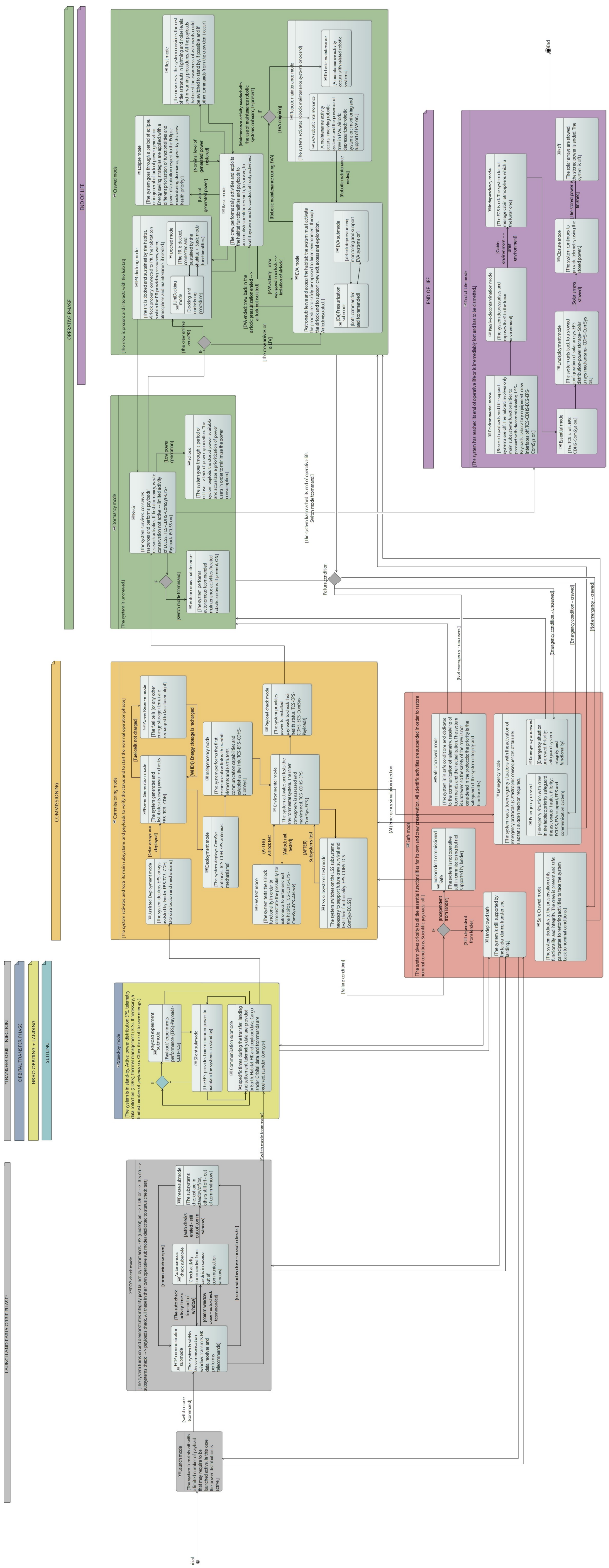


Figure 50: Mode Machine

References

[1] Space It Up! (SIU!). About Us, 2025. URL https://spaceitup.it/about-us/. Accessed on October 2025.

[2] European Space Agency (ESA). Report on the Space Economy 2025, 2025. Available online. URL: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://space-economy.esa.int/documents/tJMabTj61KkdGVOtF6SKw6wGSxicen6ajUWamCG3.pdf (accessed on October 2025).

[3] SpaceX. Mars Beyond: The Roas to Making the Humanity Multiplanetary. URL https://www.spacex.com/humanspaceflight/mars. Accessed: August 2025.

[4] H. Benaroya. Lunar habitats: A brief overview of issues and concepts. *REACH*, 7–8:14–33, December 2017. ISSN 2352-3093. doi: 10.1016/j.reach.2018.08.002.

[5] W. J. Larson and L. K. Pranke, editors. *Human spaceflight.* Space technology series. McGraw-Hill, New York, NY [u.a.], 5. dr. edition, 2007. ISBN 9780072368116. Literaturangaben.

[6] European Space Agency (ESA). Exploring the Lunar South Pole, 2025. URL https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Lunar_Lander/Exploring_the_lunar_South_Pole. Accessed: August 2025.

[7] National Aeronautics and Space Administration (NASA). NASA's Moon to Mars strategy and objectives development, . Available online. URL: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.nasa.gov/wp-content/uploads/2023/04/m2m_strategy_and_objectives_development.pdf?emrc=691da8ae824a8 (accessed on October 2025).

[8] P. Eckart. Lunar Base Parametric Model. *Journal of Aerospace Engineering*, 1997.

[9] CMSA. China reveals names of moon-landing spacesuit, manned lunar rover. Available online. URL: https://english.spacechina.com/n17212/c4265697/content.html (accessed on 28 Aug 2025).

[10] National Aeronautics and Space Administration (NASA). Artemis, . URL https://www.nasa.gov/feature/artemis/. Accessed: August 2025.

[11] G. Heiken, G. Heiken, D. T. Vaniman, and B. M. French, editors. *Lunar sourcebook.* Cambridge Univ. Pr., Cambridge [u.a.], 1. publ. edition, 1991. ISBN 0521334446. Includes bibliographical references (p. 655-715) and indexes.

[12] G. Mengali and A. A. Quarta. *Fondamenti di meccanica del volo spaziale.* 2013. ISBN 8867412108.

[13] National Aeronautics and Space Administration (NASA). Weather on the Moon, . URL https://science.nasa.gov/moon/weather-on-the-moon/. Accessed: September 2025.

[14] J. J. Zakrajsek, D. B. McKissock, J. M. Woytach, J. F. Zakrajsek, F. B. Oswald, K. J. McEntire, G. M. Hill, P. Abel, D. J.Eichenberg, and T. W. Goodnight. Exploration rover concepts and development challenges. Technical report, National Aeronautics and Space AdministrationJohn H. Glenn Research Center at Lewis Field Cleveland, Ohio, 2005.

[15] J. Feng and M. A. Siegler. Reconciling the Infrared and Microwave Observations of the Lunar South Pole: A Study on Subsurface Temperature and Regolith Density. *Journal of Geophysical Research: Planets*, 126(9), September 2021. ISSN 2169-9100. doi: 10.1029/2020je006623.

[16] NASA Manned Spacecraft Center. Apollo 11 Preliminary Science Report. Technical report, NASA, 1969.

[17] NASA Manned Spacecraft Center. Apollo 12 Preliminary Science Report. Technical report, NASA, 1970.

[18] P. Kessler, T. Prater, T. Nickens, and D. Harris. Artemis Deep Space Habitation: Enabling a Sustained Human Presence on the Moon and Beyond. In *2022 IEEE Aerospace Conference (AERO)*, pages 01–12. IEEE, March 2022. doi: 10.1109/aero53065.2022.9843393.

[19] National Aeronautics and Space Administration (NASA). Apollo 12 Mission image - View of the Surveyor III craft,which landed April 19,1967, 1967. URL https://images.nasa.gov/details/as12-48-7110. Accessed: September 2025.

[20] National Aeronautics and Space Administration (NASA). Space Faring: The Radiation Challenge. An Interdisciplinary Guide on Radiation and Human Space Flight, . URL chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.nasa.gov/wp-content/uploads/2017/04/radiationchallenge.pdf?emrc=ba69fb. Accessed: November 2025.

[21] P. Eckart and B. Aldrin, editors. *The lunar base handbook.* Space technology series. McGraw-Hill, New York, 1999. ISBN 0072401710.

[22] National Aeronautics and Space Administration (NASA). Design for Ionizing Radiation Protection. Technical report, Office of the Chief Health Medical Officer (OCHMO), 2022.

[23] National Aeronautics and Space Administration (NASA). Material Science, 2003. URL https://images.nasa.gov/details/0300231. Accessed: September 2025.

[24] Lisa C. Simonsen and John E. Nealy. Radiation protection for human missions to the moon and mars. Technical report, NASA, February 1991.

[25] European Space Agency (ESA). For astronaut radiation protection, just add water, . URL https://www.esa.int/Enabling_Support/Space_Engineering_Technology/For_astronaut_radiation_protection_just_add_water. Accessed: September 2025.

[26] F. Tripoli, L. Ridolfi, S. Scarsoglio, et al. Acute cardiovascular response to gravity changes: A multiscale mathematical model for microgravity and hypergravity applications. In *Proceedings of the International Astronautical Congress, IAC*, volume 2, pages 1106–1117. International Astronautical Federation, IAF, 2024.

[27] European Space Agency (ESA). Samantha running in space, 2015. URL https://www.esa.int/ESA_Multimedia/Images/2015/09/Samantha_running_in_space. Accessed: September 2025.

[28] National Aeronautics and Space Administration (NASA). The Moon's Atmosphere, . URL https://science.nasa.gov/moon/lunar-atmosphere/. Accessed: September 2025.

[29] J. S. Levine. Perturbing the Mass and Composition of the Lunar Atmosphere During the Artemis Surface Missions , 2011. URL `chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.lpi.usra.edu/announcements/artemis/whitepapers/2011.pdf`. Accessed: September 2025.

[30] Benaroya, Haym and Bernold, Leonhard. Engineering of Lunar Bases. *Acta Astronautica*, 62, February 2008. doi: 10.1016/j.actaastro.2007.05.001.

[31] National Aeronautics and Space Administration (NASA). 60 Years Ago: President Kennedy Proposes Moon Landing Goal in Speech to Congress, . URL `https://www.nasa.gov/history/60-years-ago-president-kennedy-proposes-moon-landing-goal-in-speech-to-congress/`. Accessed: August 2025.

[32] National Air and Space Museum. What Was the Space Race?, 2023. URL `https://airandspace.si.edu/stories/editorial/what-was-space-race`. Accessed: September 2025.

[33] National Aeronautics and Space Administration (NASA). The Apollo Program, . URL `https://www.nasa.gov/the-apollo-program/`. Accessed: August 2025.

[34] National Aeronautics and Space Administration (NASA). 50 Years Ago: After Apollo, What? Space Task Group Report to President Nixon, 2019. URL `https://www.nasa.gov/history/50-years-ago-after-apollo-what-space-task-group-report-to-president-nixon/`. Accessed: September 2025.

[35] A. W. Daga, M. A. Daga, and W. R. Wendel. Evolving concepts of lunar architecture: the potential of subselene development. 1992. URL `chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://ntrs.nasa.gov/api/citations/19930008258/downloads/19930008258.pdf`. Accessed: September 2025.

[36] Arthur D. Hall. *Methodology for Systems Engineering*. D. Van Nostrand Company. ISBN 9780442030469.

[37] Dennis M. Buede. *The Engineering Design of Systems: Models and Methods*. Wiley, May 2008. ISBN 9780470413791.

[38] INCOSE (International Council on Systems Engineering). Systems Engineering. URL `https://www.incose.org/about-systems-engineering/system-and-se-definitions/systems-engineering-definition`. Accessed: September 2025.

[39] International Council on Systems Engineering (INCOSE). Systems Engineering Vision 2035: Engineering Solutions for a Better World. Technical report, 2022.

[40] National Aeronautics and Space Administration (NASA). *NASA Systems Engineering Handbook*. Number NASA/SP-2007-6105 Rev1. National Aeronautics and Space Administration, Washington, DC, 2007. URL `https://ntrs.nasa.gov/citations/20080008301`.

[41] H. Sillitto, J. Martin, D. McKinney, R. Griego, D. Dori, D. Krob, P. Godfrey, E. Arnold, and S. Jackson. Systems engineering andsystem definitions,

2019. Available online. URL: https://www.incose.org/docs/default-source/default-document-library/final_-se-definition.pdf (accessed on 03 Nov 2025).

[42] International Council on Systems Engineering (INCOSE). Systems Engineering Vision 2020. Technical report, 2007.

[43] A. M. Madni, N. Augustine, M. Sievers, and C. F. Bolden, editors. *Handbook of model-based systems engineering*. Springer Nature reference. Springer, Cham, 2023. ISBN 9783030935818.

[44] Object Management Group® Standards Development Organization (OMG® SDO). UML® — Unified Modeling Language, . URL https://www.omg.org/spec/UML/. Accessed: November 2025.

[45] Object Management Group® Standards Development Organization (OMG® SDO). SysML® — OMG System Modeling Language, . URL https://www.omg.org/spec/SysML/. Accessed: November 2025.

[46] European Space Agency (ESA). Model-Based System Engineering, . URL https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Model-based_system_engineering. Accessed: September 2025.

[47] International Council on Systems Engineering (INCOSE). Object-Oriented SE Method Working Group. URL https://www.incose.org/communities/working-groups-initiatives/object-oriented-se-method. Accessed: November 2025.

[48] Jeff A. Estefan. Survey of Model-Based Systems Engineering (MBSE) Methodologies. Technical report, INCOSE, 2008. URL https://www.researchgate.net/publication/237302799_Survey_of_Model-Based_Systems_Engineering_MBSE_Methodologies.

[49] International Business Machines Corporation (IBM). The Harmony Process. URL https://www.ibm.com/docs/en/engineering-lifecycle-management-suite/design-rhapsody/10.0.0?topic=secsyscontroller-harmony-process. Accessed: November 2025.

[50] International Organization for Standardization (ISO). Automation systems and integration — Object-Process Methodology. URL https://www.iso.org/standard/62274.html. Accessed: November 2025.

[51] OPCAT Version 3.0 Getting Started Guide, 2009. URL chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://web.mit.edu/deweck/Public/opcat/OPCAT_Manual_3.0.pdf. Accessed: November 2025.

[52] Jean-Luc Voirin, editor. *Model-based system and architecture engineering with the arcadia method*. London, 2018. ISBN 0081017944. Includes bibliographical references and index. - Vendor-supplied metadata.

[53] National Aeronautics and Space Administration (NASA). Ground Data Systems and Mission Operations, 2024. URL https://www.nasa.gov/wp-content/uploads/2025/02/11-soa-ground-data-systems-2024.pdf. Accessed: September 2025.

[54] Exploration Systems Development Mission Directorate. Moon to Mars Architecture White Papers 2024 Architecture Concept Review. Technical report, NASA, 2024.

[55] National Aeronautics and Space Administration (NASA). Fault management handbook. Technical Report NASA-HDBK-1002, 2012. URL https://www.nasa.gov/wp-content/uploads/2015/04/636372main_NASA-HDBK-1002_Draft.pdf.

[56] J. Chambliss and D. Henninger. Exploration Architecture Options - ECLSS, TCS, EVA Implications. 2011.

[57] *Reference guide to the International Space Station.* National Aeronautics and Space Administration (NASA), Washington, DC, assembly complete ed., november 2010 edition, 2010. ISBN 9780160865176.

[58] Stanley G. Love and James J. Hill. Concept of Operations for a Prospective "Proving Ground" in the Lunar Vicinity. 2016.

[59] Exploration Systems Development Mission Directorate. Moon to Mars Architecture Definition Document(ESDMD-001) – Revision B.1. Technical report, NASA, April 2025.

[60] National Aeronautics and Space Administration (NASA). NASA's First Flight With Crew Important Step on Long-term Return to the Moon, Missions to Mars, 2025. Available online. URL: https://www.nasa.gov/missions/artemis/nasas-first-flight-with-crew-important-step-on-long-term-return-to-the-moon-missions-to-mars/(Accessed on October 2025).

[61] J. Holt and S. Perry. *SysML for Systems Engineering - A Model-Based Approach.* Institution of Engineering and Technology (The IET), 3rd edition, 2019. ISBN 978-1-78561-554-2. URL https://app.knovel.com/hotlink/toc/id:kpSMLSEA0L/sysml-systems-engineering/sysml-systems-engineering.

[62] T. Weilkiens. *Systems engineering with SysML/UML.* Morgan Kaufmann, Amsterdam, 2007. ISBN 9780123742742. doi: 10.1016/B978-0-12-374274-2.X0001-6.

[63] National Aeronautics and Space Administration (NASA). Artemis III: NASA's First Human Mission to Lunar South Pole, . URL https://www.nasa.gov/missions/artemis/artemis-iii/. Accessed: October 2025.

[64] Jenny R. Andrews, Monica A. Garcia, Patrick L. Mitchell, Sally K. N. Vail. ISS Safety Requirements Documents: International Space Station Program (Baseline), 2019.