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Analysis and Simulation of a Synergetic Environmental Control and Life Support System for Long Duration Spaceflight

A thesis submitted to
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and the University of Stuttgart
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by

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Índex

Nomenclature

Abbreviations

4BMS	4-Bed Molecular Sieve
ACRS	Advanced Carbon-formation Reactor System
AD	Anderson-Darling
AES	Air Evaporation Systems
ANN	Artificial Neural Networks
APC	Advanced Physico-Chemical
AR	Air Regulator
ASBR	Aerobic Slurry Bio-Reactor
BR	Bosch Reactor
BWP	Biological Water Processing
CDRA	Carbon Dioxide Removal Assembly
CFE	Components' Failure Estimation
CHX	Condensing Heat Exchanger
CNSA	China National Space Administration
CRD	Components Reliability Database
CRS	Carbon Dioxide Reduction System
dFTA	Dynamic FTA
DPP	Data Post-Processing
ECLSS	Environmental Control and Life Support System
EDC	Electrochemical Depolarized CO_2 Concentrator
ELISSA	Environment for Life-Support Systems Simulation and Analysis
EoM	End of Mission
ESA	European Space Agency
ESM	Equivalent System Mass

FDS	Failure Data Storage
FTA	Fault Tree Analysis
GUI	Graphical User Interface
HPP	Homogeneous Poisson Process
ICBTFB	Immobilized Cell Bioreactor and Trickling Filter Bio-reactor
IRS	Institute of Space Systems
ISS	International Space Station
KM	Kaplan-Meier
LEO	Low Earth Orbit
LoC	Loss of Crew
MDD	Mission Design Definition
MF	Multifiltration
MLE	Maximum Likelihood Estimation
MOOP	Multi-Objective Optimization Problem
MTBF	Mean Time Before Failure
NASA	National Aeronautics and Space Administration
OGA	Oxygen Generation Assembly
OGS	Oxygen Generation System
PBNR	Packed Bed Bioreactor with Nitrification Stage
PBR	Photobioreactor
PDF	Probability Density Function
PPS	Post-Processing Subsystem
PYRO	Pyrolysis
R-PEM	Reversible Polymer Electrolyte Membrane
R-SOFC	Reversible Solid Oxide Fuel Cell
RBD	Reliability Block Diagrams
RELISSA	Reliability ELISSA
RiAC	Reliability Information Analysis Center
RN	Random Number
RO	Reverse Osmosis
SAWD	Solid Amine Water Desorption
SDDS	Stochastic Dynamic Discrete-event Simulation

SFWE	Static Feed Water Electrolysis
SPWE	Solid Polymer Water Electrolysis
SR	Sabatier Reactor
SRE	System Reliability Estimation
SW	Solid Waste
SWIS	Solid Waste Incineration System
TCCS	Trace Contaminant Control System
TIMES	Thermoelectric Integrated Membrane Evaporator
TRL	Technology Readiness Level
UPC	Universitat Politècnica de Catalunya
VCCR	Variable Configuration Carbon Dioxide Removal
VCD	Vapor Compression Distillation
VPCAR	Vapor Phase Catalytic Ammonia Removal
WFRD	Wiped Film Rotating Disc
WRS	Water Recovery System

Latin Symbols

C_{eq}	Equivalency factor for the cooling infrastructure
CT_{eq}	Equivalency factor for the crew time
CT	Total crew time requirement
C	Maximum cooling requirement
D	Mission duration
F(t)	Cumulative density function
f(t)	Probability density function
f_M	Logarithmic mass function
f_R	Logarithmic reliability function
$L(\theta)$	Likelihood function
M	Total mass of the system
N_i	Number of parts of the i-th part type
n_i	Number of parts including spares for the i-th part type
N	Number of simulations
P_{eq}	Equivalency factor for the power generation infrastructure

P	Maximum power required
p	Pressure
Q	Heat production
R(t)	Reliability
r.h.	Relative humidity
R	Ideal gas constant
T	Temperature
V_{eq}	Equivalency factor for the volume
V	Total volume of the system

Greek Symbols

β	Weibull shape parameter
η	Weibull scale parameter
λ	Failure rate
$\Lambda(\theta)$	Log-likelihood function

Chemical Symbols

CH_4	Methane
CO_3^{2-}	Carbonate ion
CO_2	Carbon dioxide
CO	Carbon monoxide
C	Solid carbon
H_2O	Water
H_2	Hydrogen
KOH	Potassium hydroxide
Li_2CO_3	Lithium carbonate
LiOH	Lithium hydroxide
N_2O	Nitrogen dioxide
N_2	Nitrogen
O^{2-}	Oxygen ion
O_2	Oxygen
OH^-	Hydroxide ion

Abstract

Manned missions carried out in the last decades were either close to Earth or short missions. In contrast, Space Agencies future plans include manned exploration missions to asteroids, the Moon and finally Mars. The expected mission durations rise significantly and the greater distance from Earth makes a resupply or rescue mission almost impossible. These future plans make it necessary to develop a new Environmental Control and Life Support System (ECLSS), which ensures the survival of the astronauts for such missions. These frame conditions will impose a high degree of closure and a high reliability for the ECLSS.

In this thesis, firstly, the different ECLSS technology/component options are presented, and its suitability for a long duration human spaceflight is analyzed. From all technologies the most promising, regenerative systems for atmosphere, water and waste management are selected in order to examine them as part of a complete ECLSS.

Different approaches to evaluate the reliability of complex systems are analyzed. Since the failure of a component within the system does not necessarily lead a failure of the entire ECLSS, as the system is able to compensate for some failures, the Stochastic Dynamic Discrete Simulation (SDDS) method is selected. To carry out an SDDS, a robust and adaptable ECLSS model simulation is required. A new software is developed, based on the simulation tool *Environment for Life-Support Systems Simulation and Analysis* (ELISSA) from the Institute of Space Systems - University of Stuttgart. As a result of a stochastic simulation a list of failure times is obtained, which can be treated using the Maximum Likelihood Estimation (for parametric models) or the Kaplan-Meier method (for non-parametric models), to define the reliability of the system. The input data required to apply the SDDS are the reliabilities of each possible component of the ECLSS.

The reliability of each component is defined by the failure rate or its parts. It can be seen, that the use of redundancies (spare parts) is essential for long duration missions, as the reliability of the system without them after 60 days is lower than 50%. The analysis of all components, including their spare parts, is carried out with the Multi-Opbjective Optimization Problem to achieve a high reliability with the lowest possible mass.

Both methodologies, SDDS and MOOP have been implemented creating the user-friendly new software RELISSA. Finally, as an example, RELISSA is used to analyze a manned Mars mission. With this analysis, technologies currently in use (on board ISS) are compared with new technologies (currently under development), with the potential to reduce the system mass. The results clearly show that the new technologies can significantly reduce the mass of the system, for results of similar reliability. With these results, the need of development efforts of ECLSS technologies for manned missions beyond Low Earth Orbit is corroborated.

"We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard"

John F. Kennedy (1917 – 1963)

1

Introduction

The first manned space missions had a "short" duration (up to 12 days, for the Apollo missions to the Moon). Since then, the duration of space missions has increased to the point of having permanent human presence in space, currently with the International Space Station (ISS). However, these long duration missions have been "close to Earth" (up to 400 km above Earth surface). The next step in human spaceflight is to explore destinations beyond Low Earth Orbit (LEO). Space Agencies' plans include manned missions to the Moon, asteroids or Mars in the first half of the 21^{st} century.

The president of the United States of America (USA), Barack Obama, in his speech at Kennedy Space Center, in 2010, expressed the plans of the USA to carry out manned missions to an asteroid and Mars:

> "Early in the next decade, a set of crewed flights will test and prove the systems required for exploration beyond LEO. And by 2025, we expect new spacecraft designed for long journeys to allow us to begin the first-ever crewed missions beyond the Moon into deep space. So we'll start by sending astronauts to an asteroid for the first time in history. By the mid 2030s, I believe we can send humans to orbit Mars and return them safely to Earth. And a landing on Mars will follow. And I expect to be around to see it."
>
> *Barack Obama, 15th of April 2010*

President Obama's words were followed by the National Aeronautics and Space Administration (NASA) Strategic Plan [1], which sets as an objective to develop an integrated architecture and capabilities for safe crewed and cargo missions beyond LEO. NASA efforts focus on developing the required architectures for multiple destinations in the solar system, regarding, for example, technologies, partnerships, safety and risk. Among all challenges that such a mission poses, radiation exposure and health issues are specially being addressed.

The Russian space agency, Roscosmos, presented at the Moscow air and space show in August 2013 its strategy for human space exploration, which includes a deep-space manned spacecraft, a planetary orbital base and even a potential planetary base [2]. According to the head of strategic planning and target programs of Roscosmos, Yuri Makarov, a manned mission to the Moon could help us learn how to live and work on another celestial body, which would be necessary before flying to Mars [3].

The European Space Agency (ESA), within the frame of the Global Exploration Strategy: The Framework for Coordination, is focusing on new habitat designs (that should overcome the challenges of missions beyond LEO), the use of in-situ resources and the Environmental Control and Life Support System (ECLSS) [4].

Finally, China's National Space Administration (CNSA) is working on the Tiangong space station in LEO and in robotic missions to the Moon. According to the People's Daily, the official paper of the Communist Party of China, Chinese aerospace researchers are working on setting up a lunar base. [5]

Robotic missions have already been carried out to those destinations, but sending humans for such a long duration and to such a farther destination poses one more challenge: the Environmental Control and Life Support System design.

If the current existing systems are used, this increase of duration and distance will require an increase on supply of the consumables astronauts need, such as oxygen or water. In the space sector, an increase on mass implies a proportional increase on budget, as the cost of a launch is directly related with the amount of mass to be launched. For this reason, recycling will play an even more important role in future missions. Some recycling components are currently being used in the ISS, and many are under development for their future use.

Recycling components offer a new challenge, compared with the storage solution: it is necessary to ensure that the components will work under any possible given circumstances. Currently, in the ISS, the astronauts can come back to Earth quickly in case of an emergency, or it is possible to provide them more goods at a reasonable cost and time, if for example, the oxygen recycling system fails. These options cannot be considered for a long duration mission to a further destination, such as Mars. The long distance makes an emergency quick-return and an emergency resupply mission unfeasible.

Therefore, when designing and selecting an ECLSS for the planned future missions, reliability should be one of the primary parameters, together with system mass.

1.1 Objectives

The characteristics of long duration missions, regarding the ECLSS, differ from the systems used until today for “short” or “close to Earth” missions. The main objective of this thesis is to develop a methodology able to evaluate and analyze the reliability of the ECLSS and its components for long duration spaceflight, and to implement the methodology in a new software, in order to compare different technology options.

To fulfill the main objective, several secondary objectives are set:

- To evaluate the suitable ECLSS components, both currently in use and under development, for long duration missions, by analyzing the basic principles of the ECLSS system and the evaluation tools used up to date in the ECLSS sector.

- To define a methodology for ECLSS reliability estimation and to implement it in a new software, based, when possible, on the simulation tool *Environment for Life-Support Systems Simulation and Analysis* (ELISSA) from the Institute of Space Systems (IRS) - University of Stuttgart, by analyzing the different methods available to estimate the reliability of a complex system, such as the ECLSS.

- To identify the most suitable methodology to estimate the reliability of each ECLSS technology, considering that the technology components will need to be repaired during the mission. It is necessary to take into account that the system mass should be as low as possible. The methodology for component analysis should be implemented in the same software that analyzes the ECLSS as a whole.

- To test the methodologies proposed for a long duration mission, using the new developed tool. It will be necessary to define the main parameters of a long duration mission. Two different systems, one using ISS current components and another using technologies under development, will be analyzed and compared.

1.2 Document Structure

Basic concepts about ECLSS and the components studied in this thesis are explained in chapter 2. It includes the potential technology components for future long duration missions, as well as the currently used evaluation tools.

In chapter 3, the different options to evaluate the reliability of a complex system, such as the ECLSS, are analyzed. In this chapter, the selected methodology is presented, as well as the program developed to apply it, dubbed *Reliability ELISSA* (RELISSA). This new program includes the technology components discussed in the previous chapter, and the need arises to create a methodology to analyze each single technology component. Thus, chapter 4 analyzes how the reliability of each component can be estimated, and defines a methodology to evaluate each single component, considering that components will be repaired during the mission. It also explains how this component reliability analysis method has been implemented in RELISSA. The required data to apply this methodology to the technologies proposed in chapter 2 have been collected and included in a new database, and can be found in appendix A.

Chapter 5 provides a practical application of the methodology presented in the previous chapters. As an example, a manned Mars mission has been selected. The mission characteristics concerning the ECLSS have been identified and two different ECLSS configurations have been simulated with ELISSA in order to determine the nominal behavior of the system and properly size its tanks. Finally, a reliability analysis and the Equivalent System Mass (ESM) estimation have been carried out. Detailed information in the ESM calculation for the selected mission can be found in appendix B.

Finally, chapter 6 presents the conclusions and suggested future work of the presented methodology and its results of an ECLSS simulation for long duration spaceflight.

"The Environmental Control and Life Support System is a subsystem typical of crewed space vehicles which provides all the necessary conditions in order to make life in space possible"

Book *Space Stations: Systems and Utilization*,
Ernst Messerschmid & Reinhold Bertrand

2

The Environmental Control and Life Support System
Human Survival in Space

Human space exploration has an important characteristic that differs from the unmanned missions: the need to maintain the required conditions to allow astronauts survival in the spacecraft during the entire mission. Therefore, an additional subsystem is required: the Environmental Control and Life Support System.

This chapter explains basic ECLSS concepts, including the human requirements, such as water and oxygen (O_2) daily consumption, its main subsystems (atmosphere, water, food and waste management) and which technologies have been used up to date for short duration missions and in space stations. For each subsystem, potential new technologies are discussed, considering which ones would be more suitable for long duration missions. Finally, different evaluation tools, such as the Equivalent System Mass, Technology Readiness Level (TRL) or simulation tools are explained.

2.1 ECLSS Basic Concepts

The human requirements within a space vehicle, the main characteristics of an ECLSS and which technologies have been used up to date to fulfill these requirements are explained as followed.

2.1.1 Human Requirements

The first need to be covered to ensure survival in a space vehicle is to provide a breathable atmosphere. Table 2.1 shows the nominal atmosphere values and emergency levels.

The minimum partial pressure of O_2 is set to 19 kPa, the minimum pressure that allows proper respiration to occur. The maximum is set to a 30% in volume, as higher levels would increase risk of explosion. Nitrogen (N_2) is added to the atmosphere to obtain a total pressure (P) similar to Earth's atmosphere pressure. An emergency level of O_2 is set to 13.4 kPa, which could be hold up by the crew for two hours. [6]

High levels of carbon dioxide (CO_2) cause physiological effects on the crew, ranging from increased heart rate to headache and even unconsciousness. Therefore, the acceptable level for long duration missions is a partial pressure of 0.4 kPa. An emergency level for short periods is set to 3 kPa. [7]

Temperature (T) and relative humidity (r.h.) must be kept within the specified limits to ensure crew comfort in their daily life and at work, and avoid problems such as dry skin caused by low humidity or water condensation in the equipment due to high humidity.

Humans are an open system that exchanges matter and energy with their environment. O_2 is consumed and CO_2 produced (varying the atmosphere conditions). Moreover, for mission durations exceeding a few hours, water and food are also required. Table 2.2 shows the required input mass flows and the produced outputs, as well as the amount of heat produced per person per day.

The amount of O_2 inhaled and CO_2 exhaled per person depends on human activity and is not constant. However, when simulating long periods of time, a mean value can be considered. The food required is expressed as dehydrated food, therefore the water required for the food is included in "Drinking & Food" water. The quantity of hygiene and washing water provided will depend on the mission duration and the comfort level provided to the astronauts.

Table 2.1: Atmosphere Operational and Emergency Levels [6, 8]

Parameter	Operational	Emergency Levels
Temperature	18.3 - 26.7 °C	N/A
Relative Humidity	25 - 75 %	N/A
Total Pressure	99.9 - 102.7 kPa	N/A
pCO_2	0 - 0.4 kPa	max 3 kPa [7]
pO_2	19.5 - 23.1 kPa	min 13.4 kPa
Ventilation rate	0.08 - 0.2 m/s	N/A

Table 2.2: Human Needs and Products Mass Balance [9]

INPUTS	$kg/person-day$
Oxygen	0.84
Food	0.62
Water	
Drinking & Food	3.53
Hygiene	1.36-12.58
Washing	17.95

OUTPUTS	$kg/person-day$
Carbon Dioxide	1.00
Feces	0.12
Water	2.28
Urine	1.50
Hygiene Water	1.36-12.58
Wash Water	17.95

Heat Production	11.83 $MJ/person-day$

2.1.2 Subsystems

Traditionally, an ECLSS system is divided into five subsystems according to its main functions [10]:

- Atmosphere management: atmosphere composition control, temperature and humidity control, pressure control, atmosphere regeneration, contamination control, ventilation.
- Water management: provision of potable and hygiene water, recovery and processing of waste water.

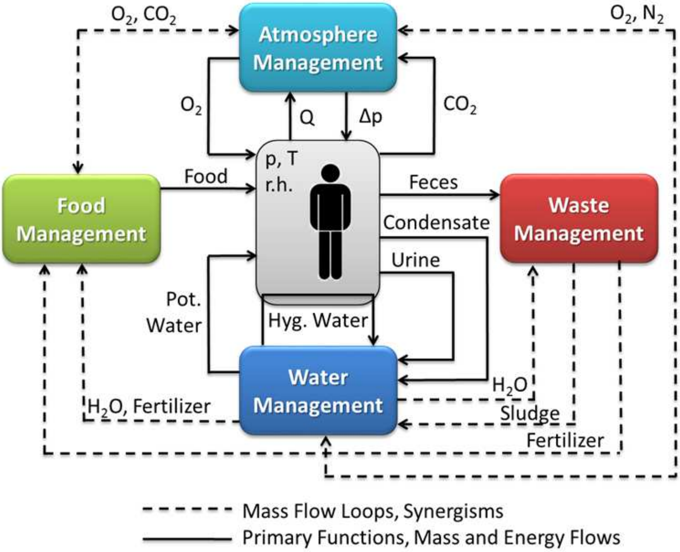


Figure 2.1: ECLSS Subsystems Division, adapted from [10]

- Food management: provision and production of food.
- Waste management: collection, storage and processing of human waste and trash.
- Crew safety: fire detection and suppression, radiation protection.

The first four subsystems are interconnected, as it can be seen in Figure 2.1. Crew safety is generally treated separately, as it does not interact directly with the others, and is not taken into account for this thesis.

2.1.3 Classification

There are different approaches to provide the astronauts the required consumables during the entire mission:

- Open system (non-regenerative): all consumables are directly provided from storage/stowage.
- Physico-chemical system: Physical and chemical processes are used to recycle. Water and O_2 cycles can be completely closed, but the carbon cycle stays open (food has to be provided).

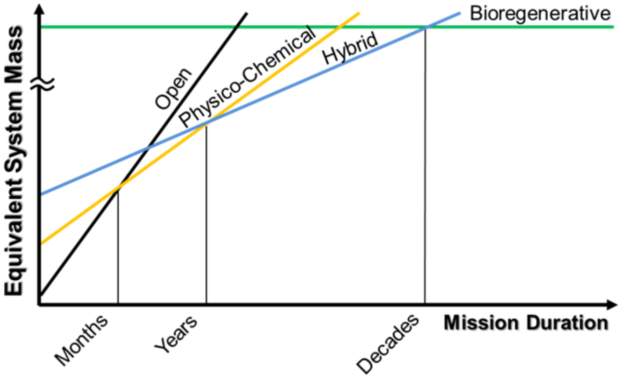


Figure 2.2: Mission Duration vs. Mass Breakeven, adapted from [6]

- Bioregenerative systems: based on biological processes. All cycles can be closed, obtaining theoretically a 100% closed system.
- Hybrid system: combination of physico-chemical and biological processes. Carbon cycle can be partially closed.

Depending on the duration of the mission, one of these types of system will be more suitable, as it can be seen in figure 2.2. For short missions (weeks - a couple of months), open systems are recommended. For missions longer than a couple of months, physico-chemical systems are more adequate. Hybrid systems, combining physico-chemical and biological processes, are mass-efficient for missions of a few years duration. Finally, for missions longer than a few years, bioregenerative systems are more suitable.

The type of mission considered in this thesis will range from one to several years. In this case, open and completely bioregenerative systems can be dismissed. The use of physico-chemical components, including in some cases biological components (thus, 100% physico-chemical or hybrid system) is advisable regarding system mass.

2.1.4 Current Technologies

Since Yuri Gagarin became the first man in space in 1961, different technologies have been used to ensure astronauts survival in space. They can be classified in two categories, those for short periods of time, such as Vostok capsules, the Apollo missions or the Space Shuttle missions, and space stations, such as Mir and the International Space Station (ISS). ECLSS information for these missions has been extracted from [6].

2.1.4.1 Short Duration Missions

The first human space missions lasted from minutes to a maximum of two weeks. These types of missions include the following space vehicles: Vostok, Voskhod, Mercury, Gemini and Apollo. The most recent or current short duration missions include the Space Shuttle and Soyuz capsule.

For all these missions, completely open systems have been used, where O_2, water and food were directly provided.

The Soviet Union missions (Vostok and Voskhod) were equipped with O_2 stored in chemical cartridges of potassium superoxide (KO_2), whereas in the American missions (Mercury, Gemini, Apollo and Space Shuttle), O_2 was stored in tanks. The Russian Soyuz uses a similar system than the previous Soviet Union missions.

CO_2 was extracted using non-regenerative systems. Lithium hydroxide (LiOH) systems were used in the American missions. In the Soviet missions, the by-product of O_2 production, potassium hydroxide (KOH), reacted with the CO_2, forming potassium carbonate (K_2CO_3) and water. The Russian Soyuz also uses this technology.

2.1.4.2 Space Stations

Since the beginning of human spaceflight, several space stations have been designed and used. Most of them have already been disposed: the soviet Salyut series (1971 - 1991) and Mir (1986 - 2001), the American Skylab (1973 - 1979) and the European SpaceLab (1981 - 1998). Currently, the ISS, a joint venture of USA, Russia, Japan, ESA and Canada, ensures permanent human presence in space [10]. Moreover, the Chinese Space Agency is currently working on the Tiangong Program. A first module, Tiangong-1, to be used as a testbed for a future modular space station, was launched at the end of 2011 and inhabited for two short periods in 2012 and 2013 [11].

Due to the longer duration of these missions, regenerative systems for CO_2 removal, O_2 production and water recycling are more suitable. However, in the first space station, Salyut, non-regenerative CO_2 removal and O_2 production systems from Soyuz were used. For the last two Salyut series stations, Salyut 6 and 7, a water regeneration system was added to reconvert condensate and wash water by filtration.

Spacelab used non-regenerative systems, like the ones used in the Space Shuttle.

The Mir ECLSS was similar to Salyut 7, but included a regenerative CO_2 removal system, Vozdukh, and O_2 was produced by water electrolysis using Elektron.

Skylab also used a regenerative CO_2 removal system, a molecular sieve.

In the ISS, CO_2 is removed using 4-Bed Molecular Sieves (4BMS), both in the American and Russian segments, Vozdukh and the Carbon Dioxide Removal Assembly (CDRA), respectively. O_2 is produced by water electrolysis using the American Oxygen Generation Assembly (OGA) and the Russian Elektron. Condensate and wash water is recycled using Multifiltration (MF) in the Russian segment. Moreover, the Water Recovery System (WRS) in the American segment is able to recycle not only condensate and wash water but also urine, using a distillation technique, Vapor Compression Distillation (VCD). Currently 15 - 20% of the waste water load is recovered. A Sabatier Reactor (SR) recovers 50% of the oxygen from the CO_2. [12]

No regenerative system has been used up to date to produce food, although some biological experiments producing eatable food have been carried out.

2.2 Near-Future Solutions

The future missions might include some of the technologies already used, but other technologies, more suitable for long duration missions, are currently being studied [6, 8, 10]. In figure 2.3, the studied tasks of the four ECLSS subsystems are shown, as well as the selected possible technologies that can fulfill the different tasks.

This thesis objective is to compare different ECLSS for long duration missions. Therefore, it will focus on the tasks where different technologies can fulfill the requirements. In this section, the analyzed technologies are briefly explained. Detailed information can be found in appendix A. The components information has been taken from [6, 8, 10].

2.2.1 Atmosphere Management

The atmosphere management tasks are to store the required gases, remove the CO_2 produced by the crew, provide/generate the required O_2 and N_2, remove trace contaminants, control the temperature and humidity, provide an adequate cabin ventilation and detect and suppress fire. CO_2 removal and O_2 generation technologies are explained below, as different potential options exist.

2.2.1.1 CO_2 Removal

For this study, three regenerative physico-chemical systems are considered: 4BMS, Electrochemical Depolarized CO_2 Concentrator (EDC) and Solid Amine Water

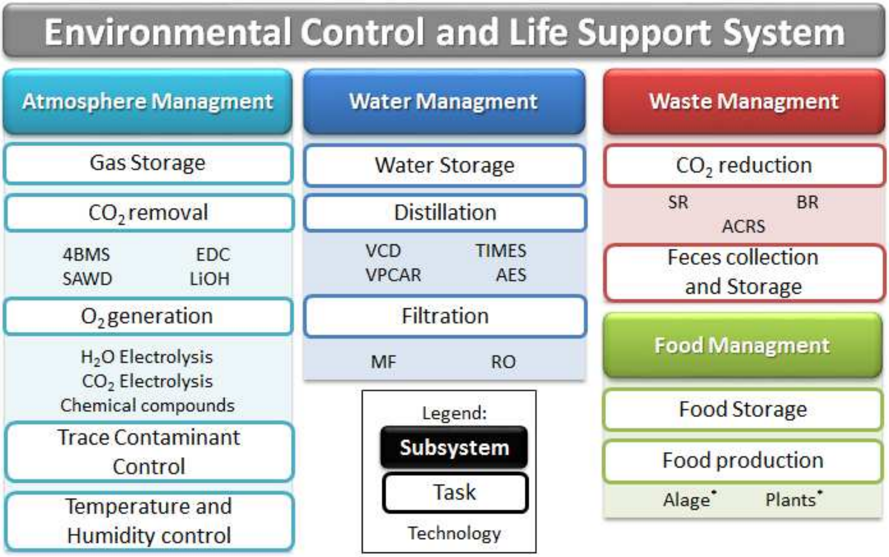


Figure 2.3: ECLSS Components - *Also remove CO_2 and produce O_2

Desorption (SAWD), as well as a non-regenerative system LiOH cartridges. Biological components such as algae and plants do also extract CO_2 from the atmosphere, but as they also fulfill other tasks, they are explained in section 2.2.3.

4BMS is a two cycle system, composed by two CO_2 sorbent beds (synthetic zeolite or alumino-silicate compounds) and two desiccant beds. At each cycle, the air goes through a desiccant bed, to extract the water vapor (to increase adsorption efficiency). After being accelerated and cooled, the air goes through one of the sorbent beds, where CO_2 is adsorbed. Water vapor is added again to the CO_2 free air flow, and it can be directly returned to the vehicle atmosphere. At the same time, the second sorbent bed, which is already full, is discharged by heating, and CO_2 is either vented to vacuum or stored for further processing. Currently, carbon molecular sieves, whose efficiency does not depend on air humidity, are being analyzed, in order to avoid the use of desiccant beds (obtaining a two-bed molecular sieve).

EDC is based on the principles of a fuel cell reaction, but including CO_2 in the reaction process. As shown in equation 2.1 four reactions take place. In the cathode, water is oxidized into hydroxide ions (OH^-) by taking electrons, and CO_2 reacts with OH^-, creating water and carbonate ions (CO_3^{2-}). In the anode, the CO_3^{2-} reacts with water, forming CO_2 and OH^-, and OH^- reacts with hydrogen (H_2), creating water and releasing electrons. As a result of these reactions, CO_2 is concentrated inside the anode's vapor space and separated from the O_2 stream.

$$\begin{aligned}\text{Cathode reactions: } & \frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^- \\ & CO_2 + 2OH^- \rightarrow H_2O + CO_3^{2-} \\ \text{Anode reactions: } & H_2O + CO_3^{2-} \rightarrow CO_2 + 2OH^- \\ & H_2 + 2OH^- \rightarrow H_2O + 2e^- \end{aligned} \tag{2.1}$$

SAWD is also composed by two adsorption beds, in this case of solid amine. At each cycle one of the beds is in adsorption mode, while the other is being discharged by a water vapor steam, that heats it up and hydrates it, as water is required in the adsorption process.

LiOH cartridge is a non-regenerative system. The LiOH reacts with the CO_2, producing lithium carbonate (Li_2CO_3) and water.

4BMS are currently in use in the ISS. However, technologies currently under development, such as EDC and SAWD, could considerably reduce the total mass of the system. LiOH cartridges have been used in short missions, and should be considered as a backup system.

2.2.1.2 O_2 Generation

To produce O_2, two different regenerative physico-chemical technologies can be considered: H_2O electrolysis and CO_2 electrolysis. O_2 candles, a non-regenerative technology is also considered. Biological components, explained in section 2.2.3 also produce O_2.

Water electrolysis enables separation of H_2 and O_2 from water molecules, using electric energy. Different types of water electrolysis exist, depending on the state of the electrolyte used, on the temperature level and on the current density inside the cell. In a Static Feed Water Electrolysis (SFWE), water is supplied through a water-permeable membrane, where it diffuses as vapor. This vapor goes through an aqueous KOH electrolyte, which is held inside the cell by gas- and water-permeable membranes, which are used as electrodes. Power is supplied to the electrode and as a result, O_2 is released at the anode, while H_2 at the cathode. Solid Polymer Water Electrolysis (SPWE) uses solid perfluorinated sulfonic acid polymer membranes, allowing only protons to diffuse. Catalyzed electrodes are placed in both sides of the membrane. In both cases, H_2 can be vented or used by other systems. It consumes power and produces heat. A water electrolysis system is currently in use in the ISS.

CO_2 electrolysis fulfills two tasks, CO_2 reduction and O_2 production. In the cathode, the CO_2 is decomposed in carbon monoxide (CO) and oxygen ion (O^{2^-}), which thanks to the ceramic electrolyte, travel to the anode, where it is converted into O_2. Power supply is required. With the amount of CO_2 produced by a crew member (1 kg/day), it is not possible to produce enough O_2 for human consumption. However, it is possible to combine CO_2 and water electrolysis to produce the required amount of O_2.

O_2 can be stored as a chemical compound in form of O_2 candles. Different compounds can be used, such as KO_2. This system is non-regenerative, and therefore, unfeasible for a long duration mission.

Currently in the ISS, O_2 is produced by water electrolysis. Another option for future missions could be the combination of CO_2 and water electrolysis, which would reduce the required amount of water by recovering O_2 from the CO_2 produced by the crew. The use of CO_2 electrolysis would be specially interesting in destinations where CO_2 is abundant, such as a Mars surface mission. O_2 candles should only be considered as a backup system.

2.2.2 Water Management

The first decision to be taken in the water management system is the full configuration of the water subsystem, the water recycling concept. Once it has been set, it is necessary to consider the differences between the two basic principles that can be used to recycle water: distillation and filtration. Distillation can treat all types of water, including urine, whereas filtration techniques can only process waste water. Urine contains different organic and inorganic substances that can not be treated by filtration methods.

2.2.2.1 Water Recycling Concept

In a centralized water recycling concept, all water is treated together. This implies having a single water recycling component, that should be able to recycle water (including urine) to a potable level (which is not required for all uses in the vehicle). On the other hand, a completely decentralized system, would recycle separately the water needed for each use (drinkable water, shower, dish washer, etc.). In this case, several recycling components are required, but for each use, water can be recycled to the quality level imposed by its use. Other intermediate options are also possible. For example, all water can be recycled to a hygiene water quality level, if potable water can be directly supplied. To select the most suitable concept for each mission, an analysis considering parameters such as system mass and redundancies is required.

2.2.2.2 Distillation

Technologies using distillation, i.e. phase separation, can recycle all types of waste water, including urine. Potential components to be used for long duration missions are the VCD, Thermoelectric Integrated Membrane Evaporator (TIMES), Vapor Phase Catalytic Ammonia Removal (VPCAR) and Air Evaporation System (AES).

In a VCD, waste water is introduced to a centrifuge at high temperatures, where it evaporates. This vapor is then compressed, which increases the saturation temperature making it re-condensate. The heat produced at re-condensation is used at the inlet to evaporate waste water. The system is currently used in the ISS to pretreate urine.

The TIMES technology uses a membrane evaporator for phase separation. Waste water circulates through a membrane tube, which only allows water molecules to pass through and evaporate. Waste water keeps circulating in the membrane tube, becoming more concentrated. The water vapor is liquified in a condenser, obtaining clean water. The latent heat produced at condensation is reused for evaporation, thanks to a thermoelectrical element.

A technology currently under development, the VPCAR, combines phase change and oxidation, obtaining a recovery efficiency of 98%. First, waste water is evaporated in a membrane evaporator, similar to the TIMES technology. The resulting vapor goes through two catalytic beds that oxidize the ammonia and hydrocarbons, producing nitrogen dioxide (N_2O), N_2, CO_2 and water. These gases go through a second bed, where N_2O is decomposed to N_2 and O_2, which can be used to compensate cabin leakage.

In the AES technology, waste water is pumped into a particulate filter to a wick package, by a pulse feed technique. A heated air stream evaporates pure water from waste water, leaving the waste solids in the wicks. Finally, a heat exchanger condensates the water from the air stream. The wick packages need to be replaced when they are full of waste solids.

Using VPCAR, compared to the other technologies, can provide the highest water quality. Both VPCAR and TIMES require a higher amount of heat per kilogram of purified water, about double as required by VCD. However, VCD is the only component with moving parts, as the entire system needs to rotate to be used in microgravity, which might disrupt the station microgravity environment. The AES system can be used to treat urine or brine, but it is necessary to consider the amount of wick packages required for the entire mission.

2.2.2.3 Filtration

There are two technologies currently used/being developed, based on filtration: MF and Reverse Osmosis (RO).

In MF, particulates are first removed by filtration, then an activated charcoal removes the suspended organic contaminants and finally inorganic salts are removed by cation and anion exchange resin beds. This system is relatively uncomplicated, but requires expendables (filters need to be changed). This technology is currently in use in the ISS.

In a standard osmosis process, water tends to move from a less concentrated compartment to a more concentrated through a semi-permeable membrane, driven by the osmotic pressure. In RO, this pressure is applied to the more concentrated compartment, obtaining more "clean" water on the less concentrated compartment. Most ions, larger organic compounds, suspended solids macromolecules and most low molecular weight salts are left in the high concentration compartment. Current membranes are incapable of removing small organics. This technology is currently used on Earth to purify running water. However, in order to use it for space applications, further research is required, and is dismissed for this study.

2.2.3 Food Management

When food is directly supplied for the entire mission, it can be stored, dehydrated, conserved in packages and cans, cooled or frozen.

In order to produce food, biological components are required. Biological systems can also be used to fulfill other ECLSS tasks, as they extract CO_2 from the atmosphere, produce O_2 and can recycle water. However, biological components are difficult to control, as some Earth base experiments have proved over the last decades [13, 14].

Plants, like they do on Earth, can provide the O_2 and food required for human survival. A surface of 3 - 5 m^2 per person is required to recycle water, 6 - 10 m^2 are necessary to also produce O_2, and finally 15 - 20 m^2 would be required if food also needs to be provided [6]. It would be necessary to chose the right combination of plants, that ensure a fast growth, a high harvest index, and the appropriate balance of CO_2 assimilation rate vs. human respiration rate.

Microalgae can also produce food and O_2, reducing the volume required, compared with plants. Algae can be used as part of the required daily food consumption. Algae could even be used as a sole nutrition source, however it would be necessary to ensure a well-balanced nourishment. Several algae species have been considered for space related applications, such as *Chlorella* or *Spirulina*. A volume of 0.1 - 0.5 m^3 per person would be required [6].

Only microalgae are considered for this study, as plants require a high volume, and should only be considered for even longer duration missions, such as a settlement on surfaces e.g. Moon or Mars.

2.2.4 Waste Management

The only task within the waste management considered for this study is CO_2 reduction. Several technologies to recycle solid waste produced by the crew (feces, packaging, etc.) such as incineration or Super Critical Waste Oxidation have been studied in the last decades. However, their development level is still too low, and they all present significant disadvantages. For the mission durations considered in this thesis, the amount of energy required or the high risk of such technologies do not compensate the amount of consumables that can be recovered. Therefore, the best option in this case is to properly store or unload the solid waste.

2.2.4.1 CO_2 Reduction

From the CO_2 produced by the crew, O_2 can be obtained by CO_2 electrolysis, explained in section 2.2.1.2, or in form of water by a Sabatier Reactor (SR) or a Bosch Reactor (BR).

In an SR, CO_2 and H_2 react under presence of a ruthenium catalyst, producing methane (CH_4) and water, equation 2.2. The operating temperatures range from 450 to 800 K. Heat only needs to be provided to start the reaction, as it is self-sustaining. Efficiencies over 99% can be achieved. The CH_4 produced can be used for the propulsion system, vented or treated through pyrolysis (PYRO) to recover the H_2.

$$4H_2 + CO_2 \rightarrow 2H_2O + CH_4 \tag{2.2}$$

The Advanced Carbon-formation Reactor System (ACRS) includes a SR and a carbon formation unit, which, through pyrolysis, recovers the H_2.

In a BR, the CO_2 also reacts with H_2, but in this case, water and solid carbon are obtained, equation 2.3. Activated steel wool, nickel, nickel/iron or ruthenium-iron alloys catalysts have been tested. Its efficiency is currently lower than in the SR, and the operating temperatures are higher, ranging from 700 to 1000 K.

$$2H_2 + CO_2 \rightarrow 2H_2O + C \tag{2.3}$$

An SR is currently in use in the ISS. The mass of the SR (and PYRO if H_2 is to be recovered) is higher than in the BR. However, the development and performance levels of the BR still need to increase before it can be considered a substitute of the SR.

2.3 Evaluation Tools

In order to compare different technologies or different system set-ups, evaluation tools are required. The ESM is a widely used parameter to compare launch cost for a component/system. The TRL is used to compare a technology development state. In order to fix some system characteristics, such as initial tank level or tank capacity, or to evaluate the behavior of the system over the course of the mission, ECLSS simulation tools are required, when dealing with complex systems.

2.3.1 Equivalent System Mass

The most critical parameter, when comparing different space systems, is the launch cost. The ESM is calculated as the sum of the system mass and appropriate fractions of supporting system masses (which includes required volume, power generation, cooling and crew time to maintain the system). This system is used, as the launch cost is about proportional to the mass of the payload, and avoids technical and political complications of using a specific currency. [15]

$$ESM = M + (V \cdot V_{eq}) + (P \cdot P_{eq}) + (C \cdot C_{eq}) + (CT \cdot D \cdot CT_{eq}) \tag{2.4}$$

M = the total mass of the system [kg]

V = the total volume of the system [m^3]

V_{eq} = equivalency factor for the volume [$\mathrm{kg/m}^3$]

P = the maximum power required [$\mathrm{kW_e}$]

P_{eq} = equivalency factor for the power generation infrastructure [$\mathrm{kg/kW_e}$]

C = the maximum cooling requirement [$\mathrm{kW_{th}}$]

C_{eq} = equivalency factor for the cooling infrastructure [$\mathrm{kg/kW_{th}}$]

CT = total crew time requirement [$\mathrm{CM-h/y}$]

D = duration of the mission [y]

CT_{eq} = equivalency factor for the crew time [$\mathrm{kg/CM-h}$]

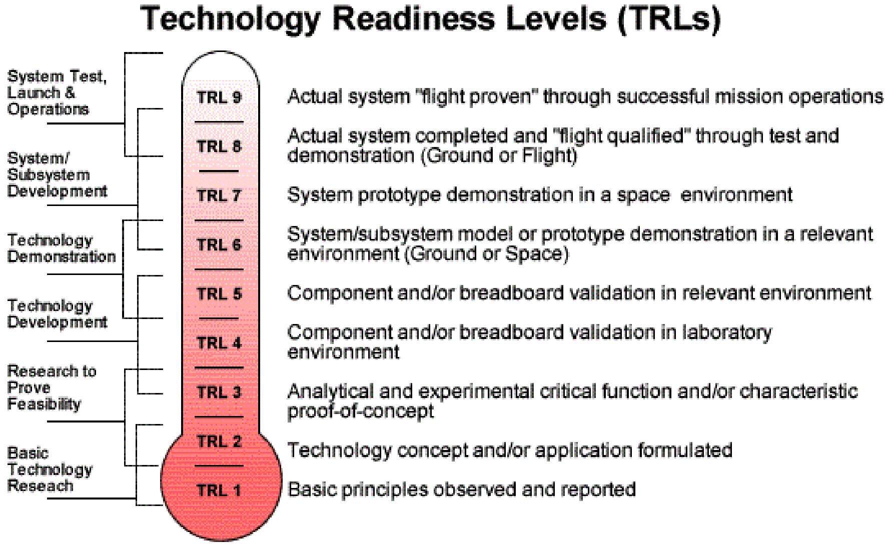


Figure 2.4: Technology Readiness Level Scale [17]

2.3.2 Technology Readiness Level

The TRL is used to define the maturity of a particular technology. As explained in figure 2.4, there are nine levels, ranging from an observed basic principal, TRL1, to a flight proven technology, TRL9. [16]

2.3.3 Simulation Tools

As explained in the beginning of this chapter, an ECLSS is a complex system, which components are connected in a complex manner. In order to analyze a system and its performances, a simulation tool is required. In the last decades, different tools have been used, including Fortran-based models, ASPEN-ACM, G-189A, SINDA85/FLUINT, CASE/A, TRASYS [18, 19].

The systems currently used by space agencies are BioSim (NASA) [20], and EcosimPro (ESA) [21]. As there is no free-access to these tools on its full version, research institutes have developed their own simulation tools, for example ELISSA from the IRS [22].

These tools can be used to evaluate the consumables required for a specific mission, as well as parameters such as power required or heat produced. These simulation tools are discussed in section 3.2.2.

2.3.4 Reliability Analysis

Some studies have been carried out to analyze the reliability of single components of an ECLSS, or to analyze the reliability of simple ECLSS.

Several papers from NASA have been published in the last years, regarding reliability of ECLSS. These papers include studies on the reliability of some ECLSS components, the effect of repairing the components during the mission and potential Life Support for Deep Space and Mars [23, 24, 25, 26]. The NASA simulation tool BioSim has been used to analyze the reliability of simple ECLSS, and comparing it with traditional methods [27, 28, 29]. In this case, the reliability of the components has been assumed by failures occurred on board of the ISS, or by the general behavior of the technologies used. Different distributions (linear, exponential, normal, Weibull) have been used, depending on the component estimated behavior.

2.4 Summary

An ECLSS can be classified as open, physico-chemical, bioregenerative or hybrid. For long duration missions, with durations of one to several years, open and 100% bioregenerative systems can be dismissed. Depending on the mission duration, 100% physico-chemical system or a combination of physico-chemical and biological components will be more suitable, regarding system mass.

Some physico-chemical technologies are currently being used in the ISS: 4BMS, SFWE, VCD, MF and SR. However, other technologies have been under development in the last decades, and might be able to reduce consumables, power or mass required, and thus, should be considered for a long duration mission. For CO_2 extraction, the EDC would be a mass-reducing option. For water recycling the VPCAR would be able to recycle all types of waste water, and avoid the re-supply required by MF. Other technologies such as the SR could be complemented by a PYRO, to recover the H_2 from the CH_4.

Non-regenerative technologies, used in previous space missions, such as O_2 candles or LiOH cartridges, should be considered as a backup system for long duration missions to increase system reliability.

The tools used to evaluate ECLSS include the ESM, simulation tools to evaluate the behavior of the component over time and the TRL. Some studies evaluating reliability of single components or of simple ECLSS structures have been carried out in the last decades.

"Reliability: ability of an item to perform a required function, under given environmental and operational conditions for a stated period of time"

ISO 8402

3

System Reliability Analysis Method RELISSA

Human Spaceflight long duration missions add more complexity to the space systems compared with those currently used either in short missions or in Earth proximity. Regenerative technologies will be required to keep the system mass as low as possible, but it will also be necessary to ensure the system does not fail during the entire mission. Thus, a tool to evaluate system reliability is required.

In this chapter, a methodology suited to analyze the reliability of an ECLSS is developed. The result of this chapter is a new software, able to evaluate system reliability using the selected methodology, *Reliability ELISSA*. In order to develop the methodology and RELISSA, the different options for analysis are discussed, whereby a Stochastic Dynamic Discrete-event Simulation (SDDS) method is selected. The currently existing ECLSS simulation tools are discussed, focusing on their advantages, disadvantages and adaptation for a reliability analysis. ELISSA, from IRS, is selected to be used as an ECLSS model tool for RELISSA. A modified version of ELISSA (2.0) has been created and is used as a subprogram by RELISSA. The requirements for the new methodology are described, and the development process and the decisions taken are explained in the last part of this chapter.

3.1 Analysis Approach

The structure of an ECLSS for long duration missions is generally established in conjunction with appropriate analysis methods. The two main ECLSS characteristics regarding reliability analysis are the complexity of the components connections and the relation component-failure/system-failure. For long duration missions, as explained in chapter 2, the ECLSS cannot be an open system. Recycling components, fully or partially closing the system, will be required. These recycling components are connected in a cross-linked configuration (non-series/parallel). Moreover, in this type of system, a failure of one of the components does not mean an immediate failure of the system. For example, if the O_2 production source fails, it will take some time (depending on the volume of the space vehicle and the crew O_2 consumption) to reach a critical O_2 level in the atmosphere.

Traditional reliability analysis methods can be divided into two types of approaches: analytical and simulation. Analytical approaches obtain a mathematical model to describe the reliability of the system that will depend on the reliabilities of its components. This approach is more suitable for simple system structures, and for exponential probability density functions (PDF). It is also possible to apply it with other PDFs or to more complex systems, but simplifications, assumptions and approximations might be required, risking of becoming unrealistic.

Simulation techniques estimate the reliability of the system, by simulating the process taking place with its random behavior in a computer model, creating a realistic lifetime scenario. It can be seen as a series of experiments (which are simulated in a computer, instead of a laboratory experiment). This approach is more suitable for complex systems, as no complex mathematical analysis is involved, but implies a high computing time, as the system needs to be simulated enough times to provide significant results [30].

Several papers propose alternative problem-solving techniques, such as neural networks [31, 32] or dynamic reliability analysis [30].

Different techniques from the analytical approach, simulation approach and alternative techniques are discussed in the following subsections.

3.1.1 Analytical Methods

Reliability Block Diagrams (RBD), Fault Tree Analysis (FTA) and Markov models are methods generally used to apply analytical techniques.

An RBD is a graphical representation of success logic of the system. Each block represents a component. Blocks are connected in series (when all the blocks need to work for the system to function), in parallel (when the failure of one block

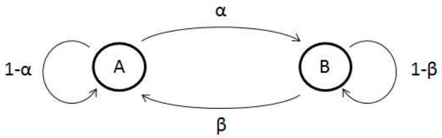


Figure 3.1: Markov Example

does not make the system fail, i.e. there is a redundancy), or M-out-of-N (when at least M of the N components should work to make the system function). A system is generally composed by a combination of these types of connections. The reliability of an RBD can be analytically obtained if the reliability of each block is known. The limitation of this method is that there is no possibility of considering different failure modes, external events or priority of events.

An FTA is a top-down approach identifying an undesirable event/accident (the top event) and the possible combinations of failure events leading to the top event. Each event is represented by a box. Logic gates connect events, defining the relationship of the events needed for the higher event to occur. The gates can be and-gates, or-gates, priority gates, etc. If the probability of each down-event occurring is known, the system reliability can be found. Using this method, any type of failure, including external events, can be represented and therefore taken into account in the analysis.

Markov chains are sequences of random variables in which the future state is only defined by its previous state, independent of what has happened before.

A Markov process is a stochastic process $\{X(t) \,|\, t \epsilon T\}$ if for any $t_0 < t_n < t_{n+1}$, $X(t_{n+1})$ only depends on $X(t_n)$.

The values $X(t_n)$ can assume "states". The group of all possible states are a "state space". The state space and time (t) can be discrete or continuous. The different states of the system are defined, and the probability of the system going from one state to the other needs to be known. Figure 3.1 shows a system with two possible states A and B (working, not working). α is the probability that the system fails, being $1-\alpha$ the probability of continued working. β is the probability of the system working again after a failure, being $1-\beta$ the probability of the system not recovering from the failure. If all possible states are defined and the probabilities of transition between states are known, the stochastic transition matrix can be found. This matrix allows to calculate the state of the system at different times and find the steady state, calculating the limit when t tends to infinite.

More information on these methods can be found at [30, 33].

3.1.2 Simulation Methods

Simulation methods can be divided into two main groups: deterministic and stochastic. A deterministic method simulates the system for a given set of inputs (when simulating the system many times, the same output will be obtained at each simulation). In a stochastic simulation, random values are introduced, and as a consequence, simulating the system many times will give different results. To analyze the output, multiple runs are required. To analyze the reliability, a stochastic method is required, as the system needs to be evaluated in different cases (the components in a system should fail according to its probability distribution).

Stochastic methods can be divided into static or dynamic, depending if time is a significant variable for the model. The Monte Carlo method is a stochastic static simulation. Stochastic dynamic simulations, in which the state is time-dependent, can be continuous or discrete-event. In a continuous simulation the system is defined by equational models, whereas the discrete-event simulation is defined by mathematical/logical models and the state of the system is calculated at precise points. [30]

3.1.3 Alternative Methods

To allow sequence-dependent failures or priority of failure events, a dynamic reliability analysis can be used. One of the most widely used is the dynamic FTA (dFTA). Besides the conventional static gates used in traditional FTA, dynamic gates are also used: priority-and, sequence enforcing, warm spare and functional dependency. Markov models or Monte Carlo Simulation are required to solve the dFTA (or the dynamic part of it) [30].

Another alternative method is Artificial Neural Networks (ANN). Inspired by biological neural networks, they consist of artificial neurons which interconnect the process information. ANNs consist of “neurons” (simple processing units), which perform a computation in their input to produce an output. The neurons inputs/outputs are connected, assigning each connection a specific weight. The network has the ability to change over time, according to its learning algorithm. More information on ANNs can be found in [34]. ANN can be used to predict reliability, by only using failure history as an input. Using a cascade-correlation learning algorithm with the failure history data, a neural network is built [32]. This method requires a wide failure history, in order to obtain a representative model.

3.1.4 Method Selection

As seen in chapter 2, in an ECLSS system for long duration missions, the components have many cross-connections. Thus, it is very difficult if not impossible, to reduce the system to a parallel/series configuration and to apply analytical methods. Moreover, the failure of a component does not necessarily mean an instant system failure and goods reserves are always considered for critical items. As a consequence, analytical methods cannot be used.

A simulation method is a possible solution. As previously explained, a stochastic dynamic simulation is required to analyze reliability. The state of an ECLSS changes with time, and the time between component failure and system failure will depend on the state of the system at component failure time, which makes it necessary to use a dynamic simulation model. It can be continuous or discrete, which will depend on how the system is modeled. In this case, the variables of the system are the state of the components (working/not working). These variables are governed by the failure probability distribution of each component.

A dynamic analysis, using dFTA, would be difficult to apply. For example, if the top event is Loss of Crew (LoC), a possible cause would be lack of water. Lack of water will occur when there is no water left in the tank and no recycling component is providing water. When no component is providing water, the crew will start using water from the tank, until it is empty. Thus, the two events are related, with a time delay between them. Defining this time delay is a complex task, as it will depend on the amount of water in the tank when the recycling component stops working. Moreover, there will generally be a primary water recycling component, but other components in charge of other tasks may also produce a small amount of water. The time where these secondary water production components fail, will also play an important role in defining the lack of water probability. As a consequence, defining the time dependence between different events is a complicated task, highly dependent on the definition of the ECLSS used and the behavior of the system over time.

ANNs are an interesting approach for reliability analysis. ANN is suitable for systems that have already generated a large failure history, which is generally not the case of space systems, as they are not produced in big series but are rather unique. ANNs cannot be used to analyze a long duration mission ECLSS, as it is still in an initial design phase and the suitable failure history data are not available.

As a consequence, a stochastic dynamic simulation method has been chosen. Depending on the ECLSS model selected, the simulation will be continuous (represented by differential equations) or discrete (the state of the system is calculated at specific times). In section 3.2, the requirements of the model as well as the currently existing simulation models are analyzed, in order to select the most suitable one.

3.2 ECLSS Model Simulation

The stochastic dynamic simulation approach requires an ECLSS model of the system to be simulated over mission time. The relations between the components need to be defined. Components are connected through mass-flows of O_2, CO_2, H_2O, H_2, power, etc. Models of the different ECLSS combinations for long duration mission can be created, or an ECLSS model simulation tool can be adapted to the stochastic dynamic simulation requirements. This section defines the requirements of the ECLSS models needed and reviews some ECLSS simulation tools.

3.2.1 Model Requirements

The goal of this thesis is analyzing ECLSS for long duration missions, thus the ECLSS model should include recycling components, as an open system is not an option for missions longer than weeks, and should be adaptable to the SDDS approach.

There are two possible options: using an existing ECLSS model simulation tool, adapting it to this thesis needs, or define the relations between the desired components in the new program. In both cases, the simulation tool should:

- Include a wide library of ECLSS components.
- Connect the components through their mass-flows/energy.
- Allow to modify/add new components.
- Be able to stop separately the components at a specific time.
- React realistically to components failures.

The goal of the proposed method is to provide reliability data in a fist design phase. As a consequence, the model does NOT require:

- A detailed model of the components (components can be a black box, with its inputs and outputs).
- A detailed design of the crew (i.e. average consumption rates can be assumed).

3.2.2 Existing ECLSS Simulation Tools

In the last decades, different tools have been used to analyze the behavior of ECLSS, both space industry's special programs, such as G189A [18], and general industry's common programs (Sinafluint, Fluent, ASPEN ACM, CFX) [19]. The systems currently used by space agencies are BioSim (NASA) and EcosimPro (ESA). As these tools are sometimes not fully accessible, or have a high license cost, research institutes have developed their own simulation tools, for example ELISSA, from IRS.

3.2.2.1 BioSim

This tool has specifically been designed to simulate an ECLSS, by NASA Johnson Space Center, Metrica Inc. and SKT Inc. It allows the simulation of a typical integrated advanced life support system in a typical mission scenario with malfunctions and perturbations. It supports stochastic processes that can be used to generate random events in the system, e.g. a fault in a subsystem or a crew member becoming sick.

The simulation includes models of the crew, air, water, biomass, power, food production and solid waste recycling. These models do not include a detailed model of each recycling component (at valve, pump, etc. level). Each module is a black box, including its production/consumption relationship, modeled according to systems or tests developed at NASA Johnson Space Center. The different modules do not interact directly, but are connected by its inputs/outputs.

- The crew module includes the astronauts that consume O_2, food and water and produce CO_2, dirty water and solid waste. As the resources consumed and produced depend on the astronauts activity, different levels are set during the day (sleep, maintenance, recreation, etc.). The crew is connected to the crew environment module, which defines the atmosphere inside the spacecraft.
- The air module extracts CO_2 and produces O_2. It consumes power, H_2, air, CO_2 and potable water and produces air (with less CO_2), O_2, H_2, CO_2 and potable water. Two different technologies are modeled regarding CO_2, the Variable Configuration Carbon Dioxide Removal (VCCR) system and the Carbon Dioxide Reduction System (CRS). The Oxygen Generation System (OGS), a water electrolysis component, adds O_2 to the system.
- The water module consumes power, greywater and dirty water and produces potable water. There are four systems that process the water: the Biological Water Processing (BWP), RO, the AES and the Post-Processing Subsystem (PPS).

- The biomass system produces air, biomass, dirty water, CO_2 and potable water, consuming power, potable water, greywater and air. It consists of a crop growing chamber producing O_2 and biomass, that can be turned into food.
- The food processing module is in charge of converting the biomass into food. It consumes power, biomass and crew time.
- The waste module consists of an incinerator consuming power, dry waste and O_2, producing CO_2.

There are two methods for user interaction with the simulation: the Graphical User Interface (GUI), easy to use, allowing the simulation of a system and the Application Programmers Interface, for advanced users, allowing to modify the code, and therefore simulation parameters. Further information can be found in [20].

3.2.2.2 EcosimPro

EcosimPro has been developed by Empresarios Agrupados Internacional S.A. under contract with ESA. It was originally designed to be a specific simulation tool for ECLSS. During its development, it was decided that it could also be used to simulate any physical system that could be represented by algebraic and differential equations. It uses its own language, called EL, but it is also possible to use functions from external libraries in FORTRAN, C and C++.

It offers different user levels, allowing advanced users to develop component libraries, and at the same time, it has a user-friendly interface for new users. ECLSS can be composed using the existing components from the libraries or new created components.

The ECLSS library provides a set of components to simulate the most typical process units, equipment and processes of the ECLSS. It includes cabin, crew, pumps, valves, sensors, etc. More information can be found in [21].

3.2.2.3 ELISSA

ELISSA was developed at IRS. It is based on the laboratory software LabVIEW, using a graphical programming language. This software includes models of air, water, food and waste management components. Each component is a subprogram, with its corresponding input and output mass flows. Components are not designed in detail, but as black boxes, which calculate the corresponding outputs, according to their inputs. The models have been created from specifications of existing technologies, prototypes, experimental data or physical and chemical fundamentals, according to the available information, and TRL.

The ELISSA components library includes:

- CO_2 removal: EDC, 4BMS, SAWD.
- O_2 generation: SFWE, Reversible Polymer Electrolyte Membrane (R-PEM), Reversible Solid Oxide Fuel Cell (R-SOFC), PhotobioReactor (PBR).
- Trace Contaminant Control System (TCCS) and Condensing Heat Exchanger (CHX).
- Water recycling (centralized or decentralized concept): MF, VPCAR, AES, TIMES, VCD, Immobilized Cell Bioreactor and Trickling Filter Bio-reactor (ICB+TFB), Packed Bed Bioreactor with Nitrification Stage (PBNR) .
- Food: dehydrated food, hydrated food, salad machine.
- CO_2 reduction: SR, BR.
- CH_4 reduction: ACRS, PYRO.
- Solid Waste: Solid Waste Incineration System (SWIS), Aerobic Slurry Bioreactor (ASBR).

The recycling components, as well as a crew module, a cabin module and a set of tanks are linked by its mass-flows. At each simulation step, the system calculates the corresponding outputs of each component, sending them to the following connected component.

It is possible to modify the program, adding new components, changing the components when more advanced information is available, or even change the relations/conditions between the different components. ELISSA provides a user-friendly interface: the user can select the mission scenario (with destinations like Mars, Moon and asteroids, and mission types such as orbital and surface stations) and the system design (recycling components and tanks). For each technology solution, the user can select how many components are to be used and the basic working parameters, within its limits. For the tanks, total capacity and initial storage level can be defined. Pressurized volume and nominal cabin atmosphere conditions can be selected. Operational and logistic issues, such as crew rotation or resupply capabilities can be set.

During the simulation, control and performance panels show the current state of the system (cabin atmosphere composition, resource storage levels, etc.) and allow the user to interact with the simulation, adjusting performance parameters, such as O_2 production level.

When required, mission specific environmental conditions are considered, for example eclipse intervals and distance from the Sun. For every simulation time step (i.e. 60 seconds), the state of the system is calculated and saved for further analysis.

More information of ELISSA can be found in [22, 35, 36, 37].

3.2.3 Simulation Tool Selection

According to the requirements, the relation between the components needs to be defined, but there is no need of a detailed design of the components or the crew. Therefore, EcosimPro offers a too detailed design. Moreover, only a demo version of the software is available for free, which means that an EcosimPro license would be necessary to run the new program. BioSim and ELISSA, provide the relation between components (the mass flows) without defining in detail the component structure. BioSim offers some of the components, and the possibility to create more. On the other hand, ELISSA already offers most of the components required for this thesis (the components explained in chapter 2), and also offers the possibility to modify or create new components. ELISSA belongs to the IRS, and is not available for the general public. The Universitat Politècnica de Catalunya (UPC) and the IRS have reached an agreement, and ELISSA is fully available at the UPC for the development of this thesis.

For its versatility and the components already modeled, ELISSA has been selected as an ECLSS simulation model of the new program. Modifications in ELISSA are required, in order to fulfill the requirements previously described, such as allowing to stop the components at a specific time automatically. The currently existing components library needs to be checked, and other components might be added. It is also necessary to analyze the reaction of the system when components fail, as the program was created to carry out failure-free simulations, and therefore problems resulting from component failures are to be tracked.

ELISSA carries out deterministic dynamic discrete-event simulations of an ECLSS. If ELISSA is to be used as an ECLSS model simulation tool, the stochastic dynamic simulation carried out will be discrete-event. Thus, the methodology proposed in this thesis is a Stochastic Dynamic Discrete-event Simulation.

3.3 Method of Application and Implementation - RELISSA

In the previous sections, the basic methodology process has been selected, the SDDS. In this section, the steps to implement this methodology are explained, and a proposed software solution is presented. The result is a new tool: RELISSA. It contains new subprograms, created specifically for this program, and a modified version of ELISSA. The requirements for this new tool, as well as how these requirements are fulfilled by the different subprograms, are explained in this section.

The first step in developing the new program RELISSA is identifying its requirements:

1. The number of simulations (N) has to be selected.
2. The mission design parameters (duration of the mission, ECLSS type to be used, etc.) have to be selected once.
3. The N estimated failure times for each used component need to be generated.
4. The ECLSS should be simulated N times, making the components fail in their estimated failure time. In the simulation, a failure of a component is represented as a non-working component (no inputs/outputs). The simulation should react as the real system would, when a component is not working. Each simulation should run until "system failure".
5. System failure times need to be saved for post-processing, as well as the cause of failure.
6. System failure times should be fitted to a distribution function to define the system reliability.
7. A reliability analysis should provide all relevant reliability information.
8. Simulation execution time should be reduced as much as possible.

The structure of the methodology is shown in figure 3.2. The numbers in the figure relate to the requirements previously defined. To fulfill requirements one to seven, new subprograms have been created. These subprograms work together in RELISSA. Requirement eight has been fulfilled, after analyzing how RELISSA works, adding changes in different subprograms.

3.3.1 RELISSA Core

The first step in the process is to introduce some basic information, such as the number of simulations to be done, and where all information created during the process should be saved. The next step is to enter the system main parameters, then the "loop", where the system will be simulated N times, and finally, the resulting information of the "loop" should be processed.

As a result, RELISSA is divided in four steps:

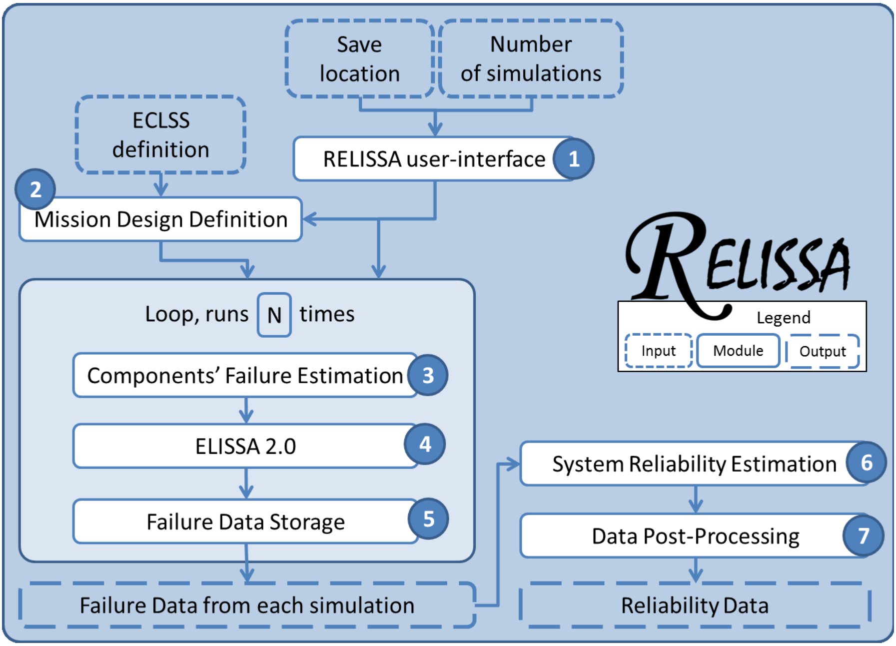


Figure 3.2: RELISSA Definition

- User Interface: asks the user to introduce two variables: number of simulations (N) and in which folder the information should be saved. It stays in this step, until the user presses "start".

- ECLSS Definition: it starts a subprogram, which asks for mission design parameters. It stays in this step, until the user presses "continue".

- The loop: a loop is started and runs N times (it contains all the processes involved, which need to be run N times). When the N simulations are completed, it automatically goes to the next step.

- Post-processing: once all simulations are done, the program analyzes the data, and saves the results in the previously defined folder.

The first step, which is mainly the RELISSA user-interface, is directly programmed in RELISSA. It creates two variables, `number of simulations` and `save location`, defined by the user, that are transferred through the entire program.

The other three steps are composed by different subprograms, explained in the following subsections.

3.3.2 Mission Design Definition

The next step, defining mission parameters, includes the provision of its destination, duration and crew composition (including rotations if necessary). The user also needs to define the ECLSS system to be used (which recycling components will compose the system, how many, at which load level they will work, which tanks are required, its size and initial level). ELISSA already includes a user-friendly interface allowing the user to select these parameters from all possible options ELISSA offers. The selected parameters are turned into variables, once the user starts one simulation, and are used by ELISSA during the entire simulation of the ECLSS. However, this tool is included inside ELISSA, and if ELISSA is to be run N times, the user would have to introduce such information N times. This would require the user to react when each simulation starts and manually introduce the data, which may lead to human mistakes.

All the simulations need to have the same mission design parameters, therefore, this part of the program has been taken out of ELISSA, creating a new subprogram Mission Design Definition (MDD), which is a modified version of the subprogram of ELISSA. MDD saves these parameters into variables, that are introduced directly in ELISSA the N times it is run inside RELISSA.

MDD introduces to the simulation tool the option of changing component performance during the mission. For long duration missions, for example to Mars or an asteroid, the crew inside the spacecraft may not be constant during the entire mission. Part of the crew may leave the vehicle to visit the surface. During periods with reduced crew, less resources will be required and some of the recycling components may reduce their performance, or even, if there are multiple components carrying out a specific task, some might be put in stand-by mode. Up to now, when ELISSA was used to analyze an ECLSS for long duration missions, only the nominal behavior of the system was taken into account, meaning the system was only simulated once, and the user had to change manually the performance of the components. As in RELISSA, the ECLSS will be analyzed multiple times, the user would have to change the load levels of the components manually at exactly the same simulation time for each run. Once again, that would take user-time and may lead to mistakes in the input parameters of the simulation. As the input data for each simulation come from the MDD, this information should also be directly sent from the MDD. Because of its nature, some of the components reduce their working level automatically. For example, when the crew is reduced, the CO_2 crew production is reduced. The CO_2 removal system works accordingly to the CO_2 input coming from the atmosphere and adjusts itself automatically when the crew is reduced or increased. On the other hand, when O_2 is produced from water electrolysis, the component will produce O_2, according to the performance selected by the user, independently of the crew size, as long as there is water available. Therefore, a reduction/increase in the crew does not directly affect the performance of this component in ELISSA. As a result, the space vehicle will accumulate unnecessary O_2 in the tanks at water expenses. The performance of all possible components of the ELISSA library has been analyzed. For those, where a change in the crew has no direct influence on the simulation, but should have, the MDD offers the possibility to define different performance levels for each change of crew. This information is saved as a new variable and is used in all simulation runs.

3.3.3 Component's Failure Estimation

The chosen methodology is based on a stochastic dynamic simulation, with system variables representing the state of the different components (working/failure). These states are governed by the reliability functions of the components, defining the probability that a component is working at a specific time. It is necessary to generate the failure times at which the components should stop working at each simulation (requirement three).

A uniformly distributed random number (RN), between zero and one, is generated, at each simulation for each component, by a standard random number generator using white noise. This RN is used as reliability at time t ($R(t)$). The time, at which the component should have this pre-set reliability can be found and will be used as the `estimated failure time`. This process can be repeated for each component, and for the N simulations.

How the `estimated failure time` is found depends on the reliability distribution of each component. As a first approach, an exponential distribution (which has a constant failure rate λ) has been assumed, equation 3.1. The estimated time can easily be found by equation 3.2. However, if repairs are to be planned for each component, a different equation for each component should be defined. Thus, in chapter 4 the method to analyze each single component and its implementation in RELISSA is explained.

$$R(t) = e^{-\lambda t} \tag{3.1}$$

$$\text{Estimated Failure Time} = -\frac{1}{\lambda}(\ln(RN)) \tag{3.2}$$

This process is carried out by the module Components' Failure Estimation (CFE). It includes the failure rates of all components defined in ELISSA. These failure rates are constant, as an exponential distribution has been assumed.

At each of the N loop runs, RELISSA generates a random number between zero and one for each component and estimates the failure times. These data are transferred to the next step, ELISSA 2.0, and is also saved in a text file.

3.3.4 ELISSA 2.0

As explained in previous sections, ELISSA was designed to simulate nominal-behavior ECLSS. Therefore, some characteristics required for reliability analysis need to be implemented. When components fail the simulation might react different as the system physically would. The simulation tool has been tested, by switching off the components independently. Physically unexpected reactions have been observed (e.g. relative humidity reaching values higher than 100%) and changes were applied to avoid them. Consequently, a new version 2.0 had to be created. ELISSA 2.0 cannot work alone, but is integrated as a subprogram in RELISSA.

In section 3.3.2, the first change has already been explained. The input-selection subprogram has been extracted of ELISSA, creating a new program MDD. Therefore, ELISSA 2.0, now starts with a set of variables the user has previously selected.

The main problems identified when using ELISSA for reliability analysis are:

- It needs to be able to switch off the components automatically (at failure time).
- It needs to detect when the ECLSS fails.
- In the original version of ELISSA, the system stops when the tanks are empty or full, allowing the user to add or subtract consumables, this is no longer required in RELISSA. In RELISSA, when a tank is full, the extra-generated resource will be vented, and when a tank is empty, this resource cannot be used anymore, which may lead to a system failure.
- In case of an emergency, backup technologies should be available and a reaction of the crew is to be expected (for example, a water consumption reduction).
- In case a component is not working in ELISSA, physically impossible responses occur (relative humidity reaches values over 100%, negative mass flows): these responses should be avoided.

3.3.4.1 Components Automatic Switch-off

In ELISSA, each component has a Boolean variable defining if it is working (`TRUE`) or not (`FALSE`). As explained before, the failure is simulated by switching off the components, i.e. setting its global variable to `FALSE`. A new subprogram has been created for each component (including its variable and its estimated failure time).

Each subprogram represents an automatic switch. When the component is working, at each step, it compares the current simulation time with the previously estimated failure time from CFE. When the failure time is reached, this subprogram switches-off the component by giving the value `FALSE` to its corresponding variable. When the component is not working, it keeps the variable to `FALSE`.

It is important to remark that all components are set to work when ELISSA is started, therefore their variable is set to `TRUE`. If a component is stopped, and ELISSA stops running and starts again (without rebooting), the value is still set to `FALSE`. In RELISSA, the program will be started several times without rebooting, and therefore it is necessary that, right before starting, it checks that all components are set to `TRUE`.

3.3.4.2 System Failure Definition

According to IEC60050, a failure is defined, as "the termination of the ability of an item to perform a required function" [38]. The ECLSS main task is to provide the necessary conditions to make survival in space possible. Therefore, system failure in this case means Loss of Crew (LoC). That would happen when the O_2 partial pressure is too low, the CO_2 partial pressure is too high, or the astronauts do not receive enough water or food for a specific duration of time. Table 3.1 shows the limit values and out-of-limit time selected for RELISSA. The program needs to identify when these limits are reached, and after the out-of-limit time, declare system failure and stop the simulation.

Table 3.1: Limit Values for LoC

	Limit value	Out-of-limit time
O_2 partial pressure [6, 10]	13.4 kPa	3 min
CO_2 partial pressure [7]	3 kPa	15 min
Water consumption [9]	$2.05\ \mathrm{kg/person-day}$	3 days
Food consumption [9]	$0.548\ \mathrm{kg/person-day}$	30 days

Two modules have been added to check these values are not exceeded. The first one is included in the atmosphere calculation at each step. It monitors the O_2 and CO_2 partial pressure in the atmosphere. Whenever the limit levels are reached, a timer starts counting the amount of time these values are out of limit. Once the out-of-limit time is reached, the system has failed, and the variable LoC becomes `TRUE`. In a similar way, a subprogram added right before the crew inputs, checks the amount of food and potable water they receive. When the amount is lower than the required value, a counter starts, allowing up to three days for potable water, and 30 days for food, out of limits. After this time, the system fails and the variable LoC becomes `TRUE`.

In ELISSA, the "Simulation Master Module" is in charge of making the simulation run. At the end of each step, it adds an extra step to the control variable, until the simulation reaches End of Mission (EoM). This module has been modified in ELISSA 2.0. In this new version each simulation runs until LoC.

3.3.4.3 Comfort Change

ELISSA originally has the option to manually change the comfort level of the crew. The comfort level defines the amount of water (for drink, food hydration, hygiene, laundry and dishes) and food that the astronauts receive. When analyzing nominal behavior of a system, it is not required to change the comfort during the mission. In a real mission, in case of a recycling system failure, the crew might reduce the amount of consumed water or food.

A comfort change module has been added. This module receives a signal from the automatic switch module when a water or food recycling component fails. In this case, the comfort level of the crew is reduced to emergency level. Both nominal and emergency levels were already defined in ELISSA and are listed in Table 3.2.

Table 3.2: ELISSA Defined Human Consumption in a Normal and Emergency Situation. In $kg/person - day$

	Normal	Emergency
Water (drink + food)	2.8137	2.05
Water (hygiene)	7.3649	1.05
Food (dry)	0.5604	0.548
Water (laundry)	12.5649	0
Water (dishes)	2.0649	0

3.3.4.4 Humidity Calculation

When the humidity control fails in ELISSA the relative humidity reaches levels over 100%. This is due to the fact that the system was not designed to simulate such failure, and the relative humidity calculation does not contemplate the possibility of obtaining such high levels. The module calculating the relative humidity has been modified. In the new version, when relative humidity reaches 100%, the water added to the atmosphere is counted as condensate water accumulated in the cabin.

3.3.4.5 Backup Models

Emergency backups are not required in nominal-behavior simulation, but play an important role in reliability analysis, as they increase the reliability of the system. For water and food, a specific amount for emergency supplies is generally brought on board. For O_2 generation, an extra amount can be brought on board, or other non-regenerative technologies can be used. For CO_2 removal, non-regenerative technologies are brought on board. For RELISSA, it has been decided to add LiOH cartridges for CO_2 extraction and $LiClO_4$ for O_2 generation, as they have already been used in space missions.

In MDD the user can select how many LiOH cartridges and O_2 candles are provided for the mission.

CO_2 Extraction Emergency System

LiOH cartridges are used to extract CO_2 when the recycling component fails. Eq. 3.3 shows the chemical equation. For each kilogram of LiOH, 0.92 kg CO_2 can be extracted. Each cartridge (including structure) weighs 7 kg and is able to extract 4 kg CO_2 [8]. Comparing the real ratio with the stoichiometric ratio, an efficiency of 62.1% is obtained.

$$2\mathrm{LiOH} + \mathrm{CO_2} \rightarrow \mathrm{Li_2CO_3} + \mathrm{H_2O} \tag{3.3}$$

A LiOH cartridge module has been added to ELISSA. Each cartridge can extract 4 kg/d CO_2, this amount is subtracted from the air atmosphere. The number of cartridges needed per day are calculated according to the size of the crew (each member produces 1 kg/d CO_2). For each kilogram of CO_2 absorbed, 0.41 kg water are produced. This water is added to the atmosphere condensate water.

O_2 Generation Emergency System

$LiClO_4$ O_2 candles are used for O_2 generation. The chemical equation, eq. 3.4, shows that 1 kg $LiClO_4$ delivers 0.6 kg O_2. Each candle weighs 2.2 kg, burns between 5 and 20 minutes and provides 600 liter of O_2 at an atmospheric pressure at 20 °C. The candle mass includes not only the $LiClO_4$, but also the equipment support. [10]

$$\mathrm{LiClO_4} \rightarrow \mathrm{LiCl} + 2\mathrm{O_2} \tag{3.4}$$

The amount of O_2 provided can be calculated using the ideal gas law, eq 3.5,

$$pV = nRT \tag{3.5}$$

where

p = 1 atm

V = 600 l

T = 293 K

R = 0.08205746 L · atm/K · mol

using this equation, 24.95 mols O_2 are obtained for each candle. The molar mass of O_2 is 32 g/mol. Thus, 0.8 kg of O_2 are obtained per candle. Dividing the O_2 obtained per candle, by the stoichiometric ratio (O_2 produced by 2.2 kg $LiClO_4$), an efficiency of 60% is obtained.

A module of $LiClO_4$ O_2 candles has been included in ELISSA 2.0. When an O_2 generation system failure occurs, an O_2 candle starts. A timer controls how long the candle burns. An average time of 12.5 minutes is used.

The module calculates how often O_2 candles need to be started to keep the O_2 level constant. The level of O_2 consumed depends on the number of crew (each member needs on average 0.84 kg/d), on the O_2 lost due to atmosphere leakage (which depends on the station volume and is automatically calculated by ELISSA) and on other O_2 recycling components consumption (e.g. the EDC). Adding these three terms, the amount of O_2 required per day is calculated. Dividing the 0.8 kg O_2 per candle by the O_2 required per day, the frequency of O_2 candles exchanges can be found.

3.3.5 Failure Data Storage

For the reliability analysis of the entire system, the failure times produced in each simulation should be saved. However, other information might be useful as well, in order to find weaknesses in the system and potential for improvement. The cause of the system failure (as it has been defined: lack of O_2, excess of CO_2 or lack of water or food) and the times each component has failed will show the user which subsystem is the weakest one.

A new program Failure Data Storage (FDS) has been created. It has two main tasks: save the failure data for each simulation (component's failure time, system failure time, and cause of system failure) and count how many times each event has occurred (how many times each component has failed, how many times the system has failed, and how many times for the same cause). These data are saved in variables and sent to the next module, once the N simulations are over.

3.3.6 System Reliability Estimation

Once the failure times of the system are found, it is necessary to define the reliability of the entire system. Two different approaches can be used: a parametric distribution analysis (including a fit-test to ensure that the data fit the proposed distribution) and a non-parametric analysis.

Parametric distribution analysis

For a parametric distribution analysis, a Weibull distribution has been suggested as it is the most versatile distribution, eq. 3.6 and 3.7.

$$f(t) = \begin{cases} \frac{\beta}{\eta^\beta} t^{\beta-1} \exp\left[-\left(\frac{t}{\eta}\right)^\beta\right] & \textit{for } t \geq 0 \\ 0 & \textit{for } t < 0 \end{cases} \tag{3.6}$$

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^\beta\right] \tag{3.7}$$

The two parameters defining a Weibull distribution are the shape parameter (β) and the scale parameter (η). To find them the Maximum Likelihood Estimation (MLE) method can be used. For a given set of data, and assuming a specific parametric distribution with unknown parameters θ, a likelihood function, eq. 3.8, expresses the probability of obtaining the data from the chosen parametric distribution.

$$L(\theta) = \prod_{i=1}^{n} f(t_i;\theta) \tag{3.8}$$

The parameters can be found by maximizing L. Since the maximization process is unchanged by a monotonic mathematical transformation, it is usually more convenient to use the log-likelihood function, eq. 3.9.

$$\Lambda(\theta) = ln(L(\theta)) = \sum_{i=1}^{n} f(t_i;\theta) \tag{3.9}$$

$$\frac{\mathrm{d}\Lambda(\theta)}{d\theta_m} = 0 \tag{3.10}$$

To avoid the use of an extra software (which might involve the obtainment of an extra license), the system reliability estimation has been included in RELISSA. A new subprogram, System Reliability Estimation (SRE), has been created. This program, based on the MLE, obtains the two parameters defining the Weibull distribution [39]. Two equations, 3.11 and 3.12, based on 3.10 and the two parameters of the Weibull distribution, can be found.

$$\frac{\partial lnL}{\partial \beta} = \frac{\eta}{\beta} + \sum ln(t_i) - \frac{1}{\eta}\sum (t_i)^{\beta} ln(t_i) = 0 \tag{3.11}$$

$$\frac{\partial lnL}{\partial \eta} = -\frac{n}{\eta} + \sum ln(t_i) - \frac{1}{\eta^2}\sum t_i = 0 \tag{3.12}$$

Combining both equations, eq. 3.13, the parameter η can be eliminated from the equation and the solution for β is found by using standard iterative procedures. Once β is found, η can be calculated using eq. 3.12.

$$\frac{\sum (t_i)^{\beta} ln(t_i)}{\sum (t_i)^{\beta}} - \frac{1}{\beta} - \frac{1}{n}\sum ln(t_i) = 0 \tag{3.13}$$

It is necessary to ensure whether the data follow the proposed distribution, by a goodness of fit test. The Anderson-Darling (AD) test is used. Two hypotheses are posed: H_o (the data follow a specific distribution, in this case, a Weibull) and the alternative hypothesis, H_a (the data do not follow the distribution); the goal is to validate one of them. The test statistic AD, which is a function of F (the cumulative distribution function) at each failure time and the number of samples, can be calculated using eq. 3.14.

$$AD = -n - \sum_{k=1}^{n} \frac{2k-1}{n}[lnF(X_k) + ln(1 - F(X_{n+1-k}))] \tag{3.14}$$

The AD has to be multiplied by a factor, that depends on the distribution function being tested and the number of samples, obtaining a modified AD (AD^*). For a Weibull distribution it is obtained using equation 3.15.

$$AD^* = AD(1 + 0.2\sqrt{n}) \tag{3.15}$$

Finally, the parameter $p - value$ can be calculated. This parameter should be compared with a $p - value_{limit}$, which is defined by a *confidence level*, eq. 3.16.

$$p - value_{limit} = 1 - \frac{confidence\ level}{100} \tag{3.16}$$

This $p - value$ depends on the distribution used and the value of AD^*. For the Weibull distribution, table 3.3 can be used. For AD^* between 0.474 and 1.038, the p-value can be found by interpolating the values presented on the table. For $AD^* < 0.474$ a p-value of 0.25 is assigned, and for values > 1.038, a p-value of 0.01 needs to be used.

More information on how to find the p-value for any distribution can be found in [40].

Table 3.3: p-values for the Weibull Distribution

p-value	0.25	0.10	0.05	0.025	0.01
AD^*	0.474	0.637	0.757	0.877	1.038

If $p - value > p - value_{limit}$, the alternative hypothesis H_a can be rejected. Therefore, H_o is accepted, i.e. the data follow the specified distribution. Otherwise, the hypothesis H_o is rejected.

SRE uses this process, and as a result, provides the two parameters β and η, if the hypothesis H_o can be accepted.

Non-Parametric Analysis

If the simulation results do not fit a Weibull distribution, a non-parametric data analysis is conducted. It avoids errors of assuming an incorrect distribution, but predictions outside the range of the observations are not possible. This presents not a problem, as the ECLSS system is designed and sized for a specific mission duration. Reliability previsions for times after the end of the mission are irrelevant, as the system would fail latest some days after the EoM, when the system runs out of consumables, which have been sized for the mission duration. Thus, the reliability data required for the mission analysis is the reliability at EoM.

Equation 3.17 defines the Kaplan-Meier KM estimator.

$$\hat{R}(t_i) = \prod_{j=1}^{i} \tfrac{n_j - r_j}{n_j} \quad i = 1, ..., m \tag{3.17}$$

where m is the total number of data points, n_i the number of survivors just prior to time t_i and r_j the number of failures at t_i.

The variance of the estimate $(V\{\hat{R}\})$ can be calculated using the Greenwood's formula [41], equation 3.18.

$$\hat{V}\{\hat{R}(t_i)\} = \hat{R}^2 \sum_{j=1}^{i} \frac{r_j}{n_j(n_j - r_j)} \quad i = 1, ..., m \tag{3.18}$$

The Kaplan-Meier estimate is asymptotically normally distributed. Thus, a confidence interval is defined by $\hat{R} \pm z_{1-\alpha/2}\hat{V}^{1/2}$, where (1-$\alpha$) is the coverage probability.

$\hat{R}(EoM)$ and its confidence intervals are calculated by RELISSA when the data do not fit the Weibull distribution.

3.3.7 Data Post-Processing

Finally, the last step of the process is to save all relevant information together in a comprehensive form for the user. As the goal of this process is to obtain the reliability of the system, the minimum required information consists of parameters defining the distribution function. However, during the entire process, other data are generated, which will help understand the behavior of the system and find ways for improvement. Questions such as "which is the most common failure cause for this system?" or "how much O_2 was still available when component X failed, and how long did it take until system failure?" can be answered with the information produced during the simulation.

To post-process the data, a new module Data Post-Processing (DPP) has been created. It saves simulation relevant data, coming directly from ELISSA 2.0, from FDS, and SRE. Using the SRE data, it calculates reliability at EoM, and reliability versus time.

As a result, four different types of file are saved by RELISSA:

- For each simulation, data on the state of the tanks, the atmosphere and the components versus time are saved (this option was already available in ELISSA, and has been kept, to allow the user to see the behavior of the system, when failures occur). This implies one folder per simulation, with several text files each.
- For each simulation, the times when components failures have occurred, as well as the total system failure time, and the cause of failure (lack of O_2, excess of CO_2 or lack of water or food) are saved. All information is saved in one text file, where each row represents one simulation.
- A system reliability summary. It includes the Weibull parameters (if the data fit the distribution), the R(EoM), the number of times each component has failed, and the causes of failure (both at EoM and n total). All information is saved in one text file.

- A graphical representation of reliability versus time.

The last two pieces of information define the system reliability, without entering in detail about what happened in the simulations. The first two types of data are meant to provide the user with more detailed information, to investigate in detail what happened when a specific component failed.

3.3.8 Simulation Time Optimization

The process completed and integrated in RELISSA, however, takes a considerable amount of simulation time. By testing, it has been observed that there are some options to reduce the simulation time and thus fulfilling requirement eight (simulation time should be reduced as much as possible). The main two changes are the use of failure-free simulation data and allowing the use of multiple computers for the simulations. With these changes, RELISSA structure has been modified, maintaining the core of the process seen in figure 3.2. The new structure can be seen in figure 3.3. Both changes are explained as follows.

Use of failure-free simulation data

When RELISSA was first programmed, each simulation started at time day 0, although the first component failure may have occurred some days later. Therefore, each of the N simulations had exactly the same results (tank levels, atmosphere composition) before the first component failed. To reduce the simulation time, it is possible to start each simulation one step before the first failure time, if the conditions at this point are known, i. e. failure-free simulation data are available.

Two options have been added to RELISSA in the user interface:

1. To void the failure module i.e. to allow the user to run a failure free simulation.
2. To use failure free simulation data i.e. the user is asked where these data are saved.

The first option, is a Boolean variable, the user sets when starting RELISSA. This Boolean variable has been added to all subprograms. When the variable is `TRUE` (failure mode is activated), all developed subprograms work normally, as it has been described. When the variable is `FALSE` (failure mode is deactivated), the program allows only one simulation of the system, the failure times at CFE are not calculated, the switches stopping the components working at ELISSA 2.0 are disabled, and FDS, SRE and DPP are not executed.

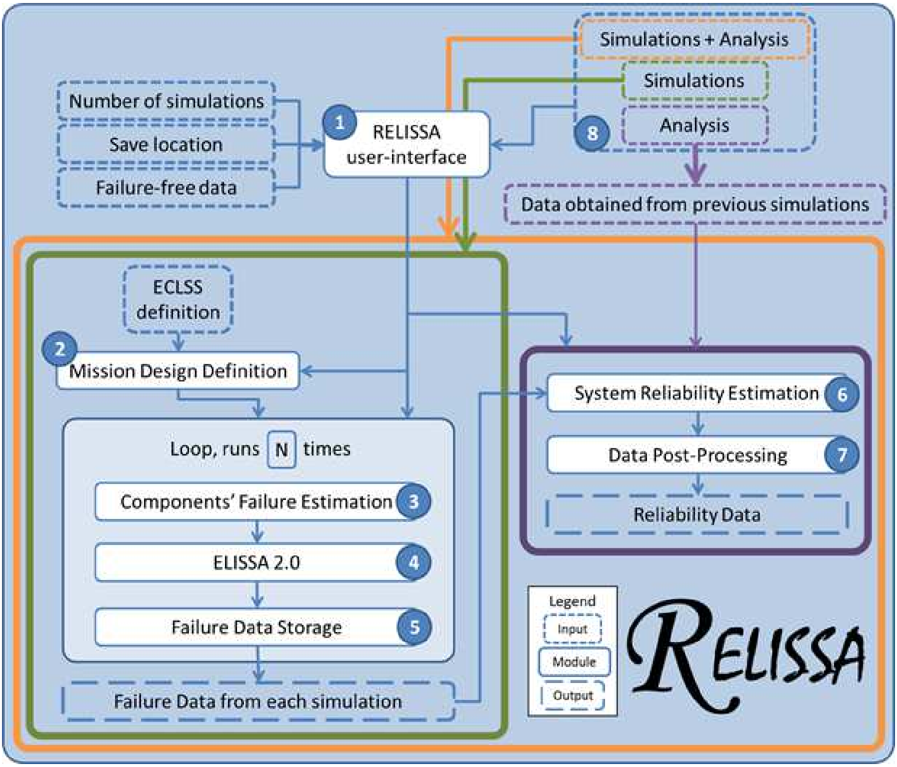


Figure 3.3: RELISSA 2.0

The second option, the use of failure free data, is only available if the failure mode is activated. It asks the user where to find the failure-free simulation data. After estimating the components failure times, and before starting each ECLSS simulation, a new subprogram searches the lowest component failure time, and looks in the failure-free simulation data for the step right before this simulation time. Right before starting ELISSA 2.0, when it receives its input information from MDD, a new subprogram (only active when failure free simulation data is on), provides the simulation starting time, the tank levels and the atmosphere composition to ELISSA 2.0. The simulation starts then at time "last step before first component failure time" ($T_{before\,1f}$).

This information is not enough to start the simulation at this time with exactly the same conditions. The problem is that some of the components, such as the SR, do not necessarily work continuously. The user can select that they start working only when the tank reaches a specific level, set by the user. The tank with the required input for the component has a valve which opens/closes depending on the level of the tank. As a consequence, the component will work until the tank is empty, and then wait again until the set tank level is reached again. It is possible that at time $T_{before\,1f}$ in the failure free simulation, the SR was working and thus, the CO_2 tank level was decreasing. When the new simulation starts, directly at time $T_{before\,1f}$, the CO_2 tank level will be below the set level to start the component and the CO_2 tank valve will be closed, the tank level will increase until the open-valve level is reached. This fact changes the characteristics of the simulation. Therefore, a new set of variables, saving the state of tank valves, has been created. Before starting a simulation at time $T_{before\,1f}$, these variables introduce the original state of the valves.

Allow Simulation on Multiple Computers

The reliability estimation approach is based on the random numbers entered into the system for the N simulations and used to estimate failure times. These random numbers are created from white noise. Therefore, simulating the system one time on N computers should provide statistically the same result as simulating the system N times on one computer. When simulating the same system on multiple computers, a new problem arises: the same MDD data need to be entered in all simulations.

An option to solve this problem could be to adapt the program to work by using a cluster of computers. RELISSA would then save the MDD data and the number of simulations to be done, and would split the number of simulations to the different computers connected to the cluster. For this thesis, different computers were available to carry out the simulation, but they where independent computers, i.e. not forming a cluster. Therefore, the solution used, has been to manually start the simulation on each computer (which can be done remotely from one computer).

Entering all the data manually each time in each computer would require a significant amount of time, risking human mistakes. This would make the resulting data useless, as the N simulation will not have the same input parameters. To avoid this problem, a new function has been added to MDD. When the user starts a new set of simulations on one computer, it saves in a text file all the inputs the user has selected. This text file can be copied to the next computer to run simulations. MDD now gives the option to use previous MDD data, and asks from which file the information should be taken. It reduces human time and avoids erroneous input. This approach requires some user-time to start the simulations in the different computers, but allows to use single computers, and even with different operating systems (LabVIEW, and therefore RELISSA, is able to run in Windows, in MAC and in Linux). A new problem arises: the reliability estimation and the data post-processing should not be done on each computer. Once the simulations are all run, the data should be post-processed, together.

A new option has been added to RELISSA, to allow the user to select among three options, where N is the total number of simulations required and N_x is a part of the N simulations, to be run in computer i:

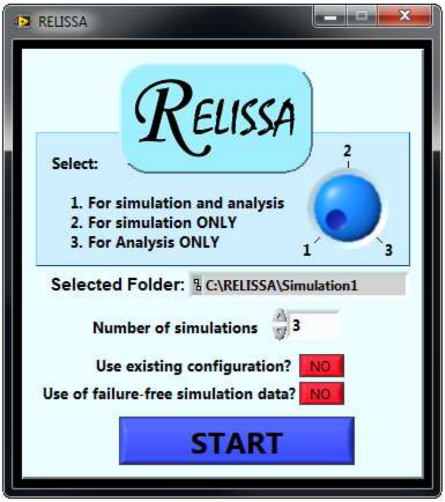
1. Run N simulations and obtain the final results from these N simulations.
2. Run N_x simulations (save only the results from each simulation).
3. Post-process the results from N simulations, which have been run in different computers.

These options are controlled by two Boolean variables: `run simulations` and `post processing`. These variables are implemented in RELISSA. When `run simulations` is set to `FALSE`, RELISSA disables MDD and the loop with the N simulations (CFE, ELISSA 2.0 and FDS). RELISSA takes the failure data from existing files (the user is asked where these files are) and post-process them. If `post processing` is set to `FALSE`, the SRE and DPP are disabled.

If the user selects option one, both variables are set to `TRUE` and RELISSA runs normally. This option is given in case the user wants to run all simulations in the same computer. If option two is selected, `run simulations` is set to `TRUE`, but `post processing` to `FALSE`. This option is necessary to simulate the system in different computers (without getting a post-analysis from each computer). If option three is selected, `run simulations` is set to `FALSE` and `post processing` to `TRUE`. This option should be chosen after running the simulations in different computers, in order to analyze all the data together in one computer. It is necessary to previously save the obtained simulation data in the computer that is going to be used for the post-processing. These three options are shown in figure 3.3, where the final structure of RELISSA, including time-optimization improvements, can be seen.

3.3.9 RELISSA Operation

Figure 3.4 shows the user-friendly interface. The user needs to select one of the three options: run the entire process, run only simulations or analyze data from previous simulations. Depending on the selection, the user will have to provide the folder where all information should be saved in, the number of simulations to be carried out, whether an existing system configuration should be used, whether failure-free simulation data should be used as data base, or where the data from other simulations are saved.



Select:

1. For simulation and analysis
2. For simulation ONLY
3. For Analysis ONLY

Selected Folder: C:\RELISSA\Simulation1

Number of simulations 3

Use existing configuration? NO

Use of failure-free simulation data? NO

Figure 3.4: RELISSA User Interface

Once “start” is pressed, the program asks, if necessary, the path for the required folders. In case the user chooses not to use an existing configuration, the MDD user interface, figure 3.5, opens, allowing the user to select the different parameters: mission scenario, crew, storage, logistics, energy and the components required for air, water, food and waste management.

Once the simulation has started, the user does no longer need to interact with the program. After the simulation, the user can access the results in the previously selected folder. Figure 3.6 shows an example of the summary text file and the reliability plot. The file provides the ECLSS reliability (defined by its two characteristic parameters), and the $R(EoM)$. Moreover, to help improve the design, the causes of system failure are given (if LoC was caused by lack of O_2, water or food, or excess of CO_2). It also provides the number of times each component has failed. The plot represents the reliability of the system over time.

The RELISSA manual [42] explains in detail how to use the program.

3.4 Summary

An SDDS needs to be used to evaluate the reliability of an ECLSS for long duration missions, as the components of the system are interconnected in a complex manner, and a failure of a component within the system does not mean a failure

MISSION START DATE MM/DD/YY
MISSION DURATION 0 d
MISSION SCENARIO
ORBIT
MOON
ORBIT PARAMETER
ECLIPSE CALC Worst Case
INCLINATION 0 deg
ALTITUDE 0 km

CO2 REMOVAL
EDC
UNITS 1
TRACE CONTAMINANT CONTROL
TCCS
UNITS 1

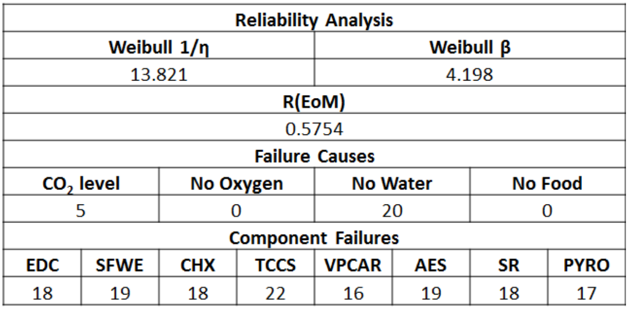
PC-REGENERATIVE O2 GENERATION
SWFE
UNITS 1
BIO-REGENERATIVE O2 GENERATION
NONE

UNIT 1 0 kg/d
SFWE O2 PL Crew 2
UNIT 1 0 kg/d
SFWE O2 PL Crew 3
UNIT 1 0 kg/d
SFWE O2 PL Crew 4
UNIT 1 0 kg/d

● **Use different O2 PL for different Crews?**

INITIAL ATMOSPHERE CONDTIONS
OXYGEN VOL % 21
TOTAL PRESSURE 101,12(kPa
PRESSUREZID VOLUME 500 m^3
TEMPERATURE 293 K
CIRCULATION RATE 0,0001 s^-1
REL. HUMIDITY 40
H2O VOL% 0,916
CO2 VOL% 0
TC VOL% 0
INTITIAL ATMOSPHERE CONDTIONS OUT

Figure 3.5: MDD User Interface



Reliability Analysis							
Weibull 1/η				**Weibull β**			
13.821				4.198			
R(EoM)							
0.5754							
Failure Causes							
CO_2 level		**No Oxygen**		**No Water**		**No Food**	
5		0		20		0	
Component Failures							
EDC	**SFWE**	**CHX**	**TCCS**	**VPCAR**	**AES**	**SR**	**PYRO**
18	19	18	22	16	19	18	17

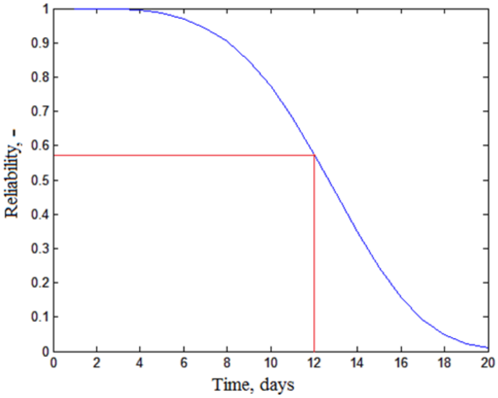


Figure 3.6: Reliability Text File and Plot Examples

of the system, i.e the remaining consumables in the tanks and the air present in the vehicle act as buffers.

To carry out an SDDS, an ECLSS model simulation is required, which defines the stage of the system over time. The simulation software from IRS, ELISSA, satisfies the requirements and can be used as a base to develop the new software.

The type of data obtained from this method is a list of system failure times. These data can be treated to define the reliability of the system, either by fitting the data in a parametric distribution or using a non-parametric method. For a parametric distribution, a Weibull has been selected, as it is the most versatile distribution. The two Weibull parameters, η and β, are found using the Maximum Likelihood Estimation, and the Anderson-Darling test is used to test whether the data follow the Weibull distribution. In case the data do not fit, a non-parametric method, the Kaplan-Meier estimator, is used. It provides $R(EOM)$.

A new software, *Reliability ELISSA*, has been developed to carry out the SDDS and the analysis of the data obtained. The ELISSA software has been modified to fulfill the SDDS requirements and integrated in the new software. The inputs required by the user are the number of simulations to carry out and the mission characteristics, such as mission duration, crew, components to be used and tank specifications.

As a first approach, it has been assumed that the components have an exponential failure rate. However, a deeper analysis needs to be carried out, as for such mission durations, repairs in the system will be required. The following chapter focuses on this task.

Component: entity able to carry out a specific task such as oxygen production or water recycling

Part: the smallest item that a component can be divided into, for example valves or heat exchangers

Spare: item (component or part), to be used to replace another item in case it fails

4

Component Reliability Analysis Method a Multi-Objective Optimization Problem

To use the system reliability analysis methodology developed in this thesis, it is necessary to drop one level down and estimate the reliability of the ECLSS components. In the last years, the backup components O_2 candles and LiOH cartridges have been widely used, and failure probabilities can be obtained. In contrast, for regenerative components failure data are scarcely or not available, as the components have been used discontinuously, shortly or not used at all in space.

In this chapter, a methodology able to estimate the reliability of the ECLSS components is developed. This methodology is implemented in RELISSA, completing the ECLSS reliability analysis tool. At the beginning of this chapter, the different analysis' approaches are presented and the "Handbook data" methodology is selected. To apply it, different sources are provided to obtain the required information, regarding components' structure and part failure rates, for the ECLSS components selected in this thesis for long duration missions. The methodology used is explained in the following, starting with a system without repairs, a system with redundancy and finally, the Multi-Objective Optimization Problem (MOOP), that arises when the number of repairs needs to be optimized regarding component mass and reliability. The last section of this chapter explains how this methodology is implemented in RELISSA, including the changes in the already existing programs and the newly developed ones.

4.1 Analysis Approach

In chapter 2, the possible components for a long duration mission have been selected, and in chapter 3, a methodology to estimate ECLSS reliability, based on the reliability of each of these components, has been developed. Thus, the reliability of each component needs to be defined.

Ideally, for each component, historical failure data from the components used in the actual working environment conditions would be used to define its reliability. This is only possible when several units of the component have been used for long periods. In other sectors, such as ground transportation, where a wide amount of historical data can be obtained, it is widely used. In the space sector, in general, components tend to be specific for a mission, which makes it difficult to obtain historical failure data.

Some of the components to be analyzed are already in use in the ISS. For example, the Russian O_2 generator system, Elektron, has been working since the end of the year 2000. According to the literature, it has failed in 4 occasions, on the 8th September 2004 [43], 1st January 2005 [44], June 2006 [45] and 21st April 2011 [46]. However, the station has currently different sources of O_2 supply, such as compressed gas delivery or expendable perchlorate candles. In fact, Elektron has been used intermittently in many occasions. As a consequence, its reliability cannot be obtained from the failures on-board the ISS or previous stations.

The backup components O_2 candles and LiOH cartridges have been used in space stations and space vehicles in the last years. Both components work for a short period of time and failure of the component is defined as the component not being able to start. As a consequence, the failure rate of the component is defined as the number of units failing divided by the number of units used. In the NASA Space Station On-Orbit Status [47], the expected failure rate for the O_2 candles is set to 20%.

For the required regenerative components, a direct estimation of the entire component's reliability is not possible. It is necessary to drop one level down: divide the component in parts (such as valves or heat exchangers) and identify the reliability of the different parts of the component. Most of the components still have a low TRL, i.e. they are in the development phase. Therefore, the reliability analysis methodology proposed in this thesis is aimed for a conceptual design phase.

Providing a component reliability without actually testing and measuring the product capabilities is defined as reliability prediction [48]. It assumes that:

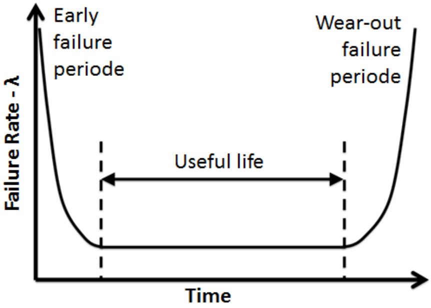


Figure 4.1: Failure Rate vs. Time

- Only random failures occur (the design is perfect, the stresses known, everything is within ratings at all times).
- The failure of every part will cause a component failure.
- The failure data used are valid.

These assumptions are not always valid, and therefore, the result obtained cannot be considered as an absolute figure for reliability, but as a mean to compare different systems.

For it is assumed that only random failures occur, the failure rate of the component will be constant. In other words, the component is assumed to be in its useful life. Most of the components present a time-dependent failure rate that forms a bathtub curve, see figure 4.1. At the start of the operating period, a higher failure rate can be observed, because of failures in manufacturing and material weaknesses. After the useful life, the failure rate generally increases due to wear-out, aging or fatigue. [48]

The four methods generally used to predict reliability for mechanical parts, depending on how the failure data are obtained, are part failure data analysis, empirical reliability techniques, stress strength interference analysis and handbook data [49]. These four methods are analyzed. Finally, the most suitable one for this thesis is selected, and future actions are proposed.

4.1.1 Part Failure Data Analysis

Ideally, the reliability of a part is predicted by historical data of this specific type of part used/tested in a suitable environment. This information might be provided by the manufacturer or be the result of a dedicated reliability test program. If historical failure data are available, a statistical data analysis should be carried out to identify the most suitable failure distribution.

This type of data is often not available. For new designs or parts never used in a specific environment, the historical data might not apply, and a high amount of testing is required. As it is not always possible to use part-specific failure data, other prediction techniques need to be used.

4.1.2 Empirical Reliability Techniques

Extensive testing campaigns can provide the empirical correlation between the different parameters, such as dimensions and materials, defining the part reliability. The data obtained can be used to define equations, tables or procedures to predict a new part reliability, given the different parameters.

This information can be found in handbooks, such as the NSWC-07 [50].

4.1.3 Stress-strength Interface Analysis

Stress-strength interface analysis consists of the characterization of statistical distributions for stresses applied in a part and its strength. The failure occurs when stress is greater than strength.

Stress distributions can be obtained from actual stress measurements or simulated by a finite element analysis. The strength distribution can be obtained from technical reports, such as the “Reliability Prediction - Mechanical Stress/Strength Interface” [51] or by test data.

4.1.4 Handbook Data

There are different handbook databases providing information on generic failure rate data. It is important to keep in mind that the failure rates provided are generic, and might not include some specific considerations of the specific design being analyzed.

4.1.5 Method Selection

The reliability of each component should be ideally defined by historical data of the component used in the suitable environment. As explained in the beginning of this chapter, this information can only be found for O_2 candles and LiOH cartridges. Both components are used for short periods of time, and the failures observed have occurred when starting the component. Therefore, failure is defined as the number of units failing to start, divided by the number of units used.

The regenerative components studied in this thesis have no historical failure data in a representative environment. Therefore, a different prediction technique needs to be used. These components are complex and cannot be analyzed as a single unit, but as a group of parts interconnected. The predicted reliability is obtained from the structure of the component and the reliability of the parts used.

Most of the components being analyzed are still in a development phase, thus the goal of this analysis, as explained in chapter 1, is to compare different systems in a preliminary design phase. At this point, a part failure analysis, an empirical reliability technique or a stress-strength interface analysis cannot be used, as the required information is not available at this point. Therefore, failure rates from handbook databases are used. As the development state of the components progresses, more accurate information could be applied to component reliability prediction. This option has been taken into account in the prediction process and how it is applied to RELISSA, to ensure new data can easily be implemented in the program.

In conclusion, historical failure data are used to estimate failure rate for the backup components, and handbook data, to predict the reliability of the regenerative components.

4.2 Required Data Sources

For each component, the reliability can be predicted by its parts failure rate obtained from handbooks. It is necessary for each component to identify:

- The different type of parts.
- The relative position of each part in the component.
- The generic failure rate of each type of part.

For all studied components, even the ones with a low TRL, the required structure has already been defined by development companies, research institutes or space agencies. Thus, the type of parts and how they are connected can be found in the component structure design. The failure rates of the parts are available in different studies or databases.

Table 4.1: Components Structure Information Source

Component	Structure provided by
CHX	Johnson Space Center, NASA [52]
TCCS	Marshall Space Flight Center, NASA [53]
EDC	Life Systems, Inc. (NASA Contractor) [54]
4BMS	Marshall Space Flight Center, NASA [53]
SAWD	McDonnell Douglas Space Systems Company (NASA Contractor) [55]
SFWE	Hamilton Standard (NASA Contractor) [56]
FC	Institute of Space Systems - University Stuttgart [57]
CO_2 electrolysis	Ames Research Center, NASA [23]
VCD	Marshall Space Flight Center, NASA - Ion Electronics [58]
TIMES	McDonnell Douglas Space Systems Company (NASA Contractor) [59]
VPCAR	Marshall Space Flight Center - Ames Research Center, NASA [60]
AES	McDonnell Douglas Space Systems Company (NASA Contractor) [55]
MF	Marshall Space Flight Center, NASA [61]
SR	Life Systems, Inc. (NASA Contractor) [62]
BR	Life Systems, Inc. (NASA Contractor) [62]
PYRO	Hamilton Standard and Johnson Space Center, NASA [63]
PBR	Institute of Space Systems - University Stuttgart [57]

4.2.1 Component Structure

The structure of each component has been found in a publication of the company, research institute or space agency developing or testing the technology. Table 4.1 shows the information source for each component.

As an example, figure 4.2 shows the structure of the Sabatier Reactor. Table 4.2 lists the parts seen in the structure, with the number of each used for this component.

This procedure has been repeated for each component. The results are shown in appendix A.

4.2.2 Reliability Characteristics

Reliability data for parts has been used in different fields in the last years. Two main sources have been identified:

1) Failure data used in space-related studies

Different papers/reports have analyzed, in the last decades, the reliability of components/parts of a space system. Although not much information is available in this field, two major sources have been found: Parametric Study of Manned

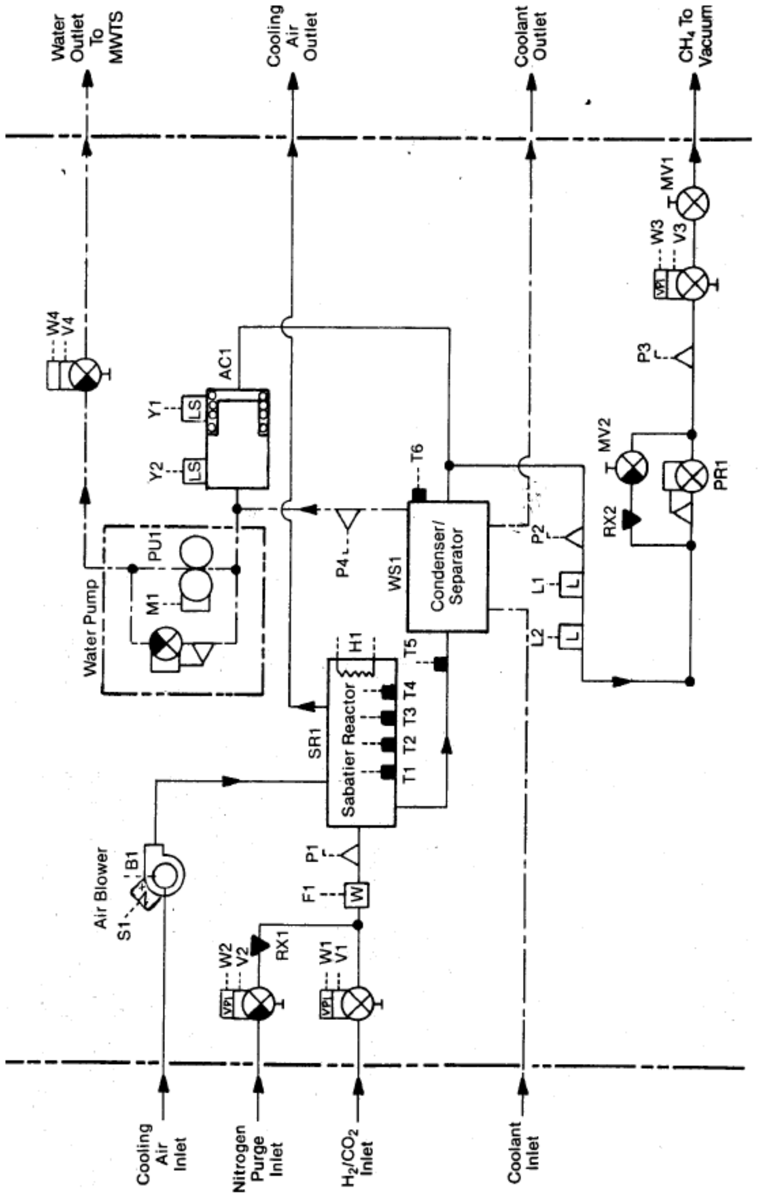


Figure 4.2: SR Structure [62]

Table 4.2: Sabatier Parts Information

Accumulator	1	AC
Blower	1	B
Blower Silencer	1	S
Condenser/Separator	1	WS
Flow Restrictor	2	RX
Flow Sensor	5	W,F
Heater	1	H
Level Sensor	2	Y
Liquid Trap	2	L
Pump	1	PU
Pressure Regulator	1	PR
Pressure Sensor	4	P
Sabatier Reactor	1	SR
Temperature Sensor	6	T
Valve (Electric)	4	V
Valve (Manual)	2	MV

Life Support Systems [64] and Advanced Life Support Values and Assumptions Document [52].

Yakut and Barker [64] identified different parts that can be used for atmosphere control, water supply and waste management subsystems. Mean Time Before Failure (MTBF) of these parts as well as their weight (scaled for different size of systems) is provided. Although this study is quite old (published in 1968), most of the data provided are still valuable, as mechanical components, such as valves or tanks, have not experienced a significant change regarding reliability.

In 2004, NASA published the Advanced Life Support Baseline Values and Assumptions Document [52], which includes a database of parameters, such as mass, volume or MTBF of different component parts. This database summarizes information of previous NASA Reports [65, 66].

NASA has also published in the last years several papers about reliability concepts for future missions, including the reliability analysis of different CO_2 reduction components, analyzing their structure and the reliability of its parts, using data from Yakut and Barker [23, 24, 25].

2) Generic failure rates (databases)

In the last decades, several databases with failure rate data have been published. Some organizations have created databases oriented to a specific component function. For example, OREDA is an organization sponsored by eight oil and gas companies. Its goal is to collect and exchange reliability data among the companies involved. It publishes a handbook "Offshore Reliability Data" (5th edition), which contains failure rates of parts used in the oil and gas sector. [67]

Regarding the space sector, the European Cooperation for Space Standardization has published in 2011 a guide of space product assurance, which discusses the currently existing reliability data sources. For electronic equipment multiple data handbooks are available for space applications: AT&T reliability manual, HRD5 from British Telecommunications plc, the IEEE Gold Book from the Institute of Electrical and Electronics Engineers, or Siemens SN29500 from Siemens AG. For mechanical parts, the ones to be analyzed in this thesis, only two databases are proposed: the NPRD-95 and NSWC-94/L07. [49]

NPRD, the Non-electronic Parts Reliability Data, has been developed by the Reliability Information Analysis Center (RiAC), which is part of the USA Department of Defense. The latest version, 2011, is available as a hard-copy or as an electronic database software. It provides failure rate data of different parts including mechanical, electromechanical and electronic assemblies. The database also includes quality level, application environments and data source information. The same organization also provides a widely used electronic parts database, the MIL-HDBK-217. [68]

NSWC stands for Naval Surface Warfare Center. Its handbook provides failure rate models for fundamental classes of mechanical components. Failure rate models include fractures (such as material, design characteristics or operating environment). In this case, the models require a significant amount of detailed input data. [50]

For this thesis, the NPRD database from RiAC is used. The other databases mentioned provide only information relative to electronic equipment, or need detailed specifications on the working environment or are specific for another field of application. Data from the previous space-related studies are also taken into consideration.

4.3 Method of Application

This section shows how the chosen component reliability methodology (section 4.1) is applied to one of the components, the EDC. First, as an example, the reliability of the component is estimated (the data required for the other components analysis can be found in Appendix A). As the reliability obtained is too low for long duration missions, the use of spares is considered. An example of using spare components and spare parts are analyzed.

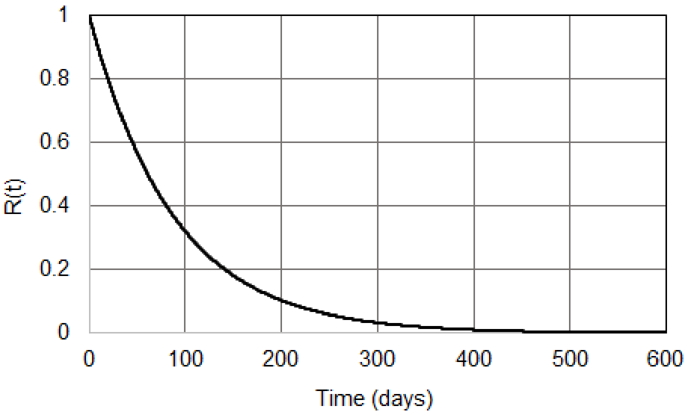


Figure 4.3: EDC Reliability

4.3.1 Reliability Estimation

The different parts of the component are listed in table 4.3, together with the number of units of each part in the component (N_i), the part failure rate and its source.

If any of the parts fail, the component fails. As a consequence, all parts are connected in series, regarding the system reliability. Therefore, the component failure rate (λ_c) can be calculated as:

$$\lambda_c = \sum_{i=1}^{k} (\lambda_i) N_i \tag{4.1}$$

where k is the number of different types of parts, λ_i is the failure rate of i-th part type and N_i is the number of units of each part type.

The failure rate obtained for the EDC is 4.74 for 10000 hours. The predicted reliability of the component follows an exponential distribution, which is represented in figure 4.3. The reliability rapidly decreases, reaching 50% before the first 60 days. For long duration missions, which will be much longer, this reliability level cannot be accepted. Two possible options are to be considered: a reliability growth due to technology improvements or due to the use of spares.

The parts to be used in the components are mainly mechanical parts, that have been used for years, and even if little improvements can be done, an acceptable reliability level for long missions (lasting more than a year) is unlikely to be achieved. As a consequence, it will be necessary to foresee spare parts.

Table 4.3: EDC Failure Rate Prediction

Part	Failure rate (per hour)	N_i
Accumulator	5.00E-07	1
Cell	3.00E-06	3
Combustible Gas Sensor	1.00E-05	1
Current Controller	1.00E-06	1
Current Sensor	2.14E-06	1
Filter	5.00E-06	6
Flow Sensor	1.00E-05	2
Flow Sensor Controller	1.00E-05	1
Heat Exchanger	6.00E-06	2
Humidity Sensor	1.00E-06	2
Pressure Controller	1.00E-05	1
Pressure Regulator	1.00E-05	1
Pressure Sensor	1.00E-05	2
Pump	1.50E-05	1
Temperature Sensor	1.00E-05	2
Valve (3-way)	1.00E-05	1
Valve (4-way)	1.00E-05	1
Valve (quick disconnect)	1.00E-05	7
Valve (selenoid liquid)	1.00E-05	1
Valve (electrical - 1)	1.00E-05	2
Valve (electrical - 2)	1.00E-05	1
Valve (relief)	1.00E-05	1
Voltage Sensor	2.33E-05	7
Total		4.74E-4

4.3.2 Reliability Estimation - Redundancy

The provision of one or more spare parts to be changed when the original part fails, is called cold stand-by redundancy. A first redundancy analysis is carried out, considering that for each part the same number of spares is taken.

The use of spare items can be mathematically considered as having an extra item in parallel, which is not working until the original one fails. In this case, the original item, from now on called item 1, is connected to the system and working until it fails at time t_1. When failure occurs, a switch changes the system, disabling item 1, and changing to the spare item, from now on called item 2. Until t_1, item 2 has not been working, and therefore is called a passive redundancy. The process of changing from item 1 to item 2 may not always be successful. A probability

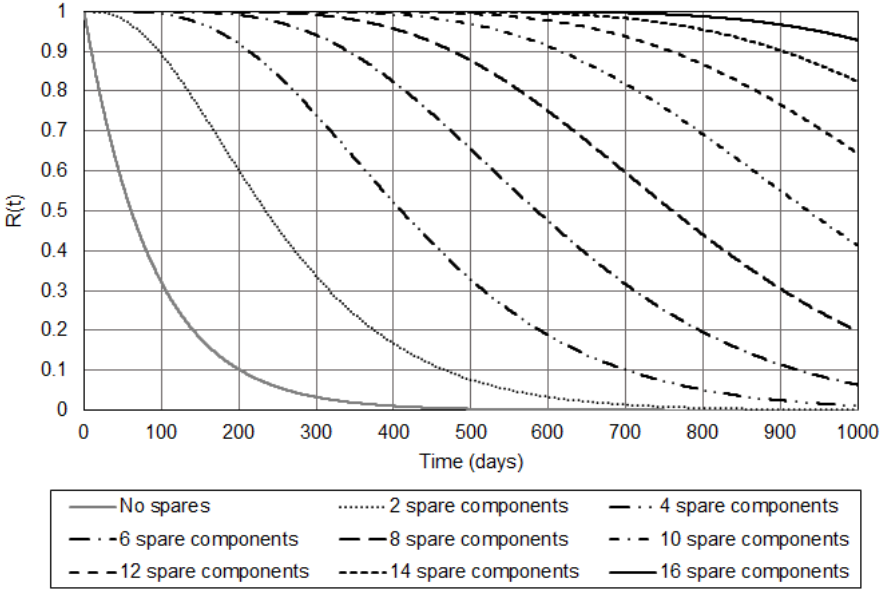


Figure 4.4: EDC Reliability Using Component Spares

of successful switching can be considered, if detailed information in the repair process can be provided. This process is known in the literature as "perfect repair or replacement as good as new". [38]

For n items (the original and $n-1$ spares), the system will fail when all spares have been used and have failed. If the item has a constant failure rate, the failure times T_1, T_2 ... T_n are independent and exponentially distributed, with a failure rate λ (characteristic of each item). This type of behavior model is called an Homogeneous Poisson Process (HPP). The survivor function of a part and its $n-1$ spare parts (with perfect switch), $R_{p+s}(t)$, is given by equation 4.2.

$$R_{p+s}(t) = \sum_{j=0}^{n-1} \frac{(\lambda t)^j}{j!} e^{-\lambda t} \tag{4.2}$$

A first option, that does not require a high expertise of the crew on the system, is to replace an entire component when it fails. The reliability of the system over time can be analyzed for different numbers of spare components. For the EDC, the reliability obtained can be seen in figure 4.4.

In the EDC example, to obtain a reliability over 90% in 1 000 days, 16 spare components would be required. Therefore, the total mass of the EDC system

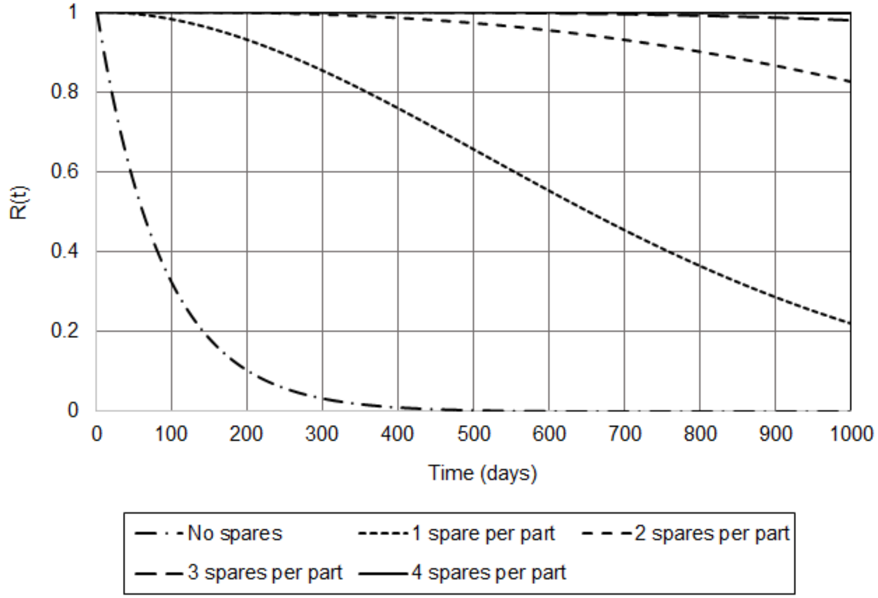


Figure 4.5: EDC Reliability Using Spare Parts

would be 17 times the mass of the component. This option would considerably increase the mass of the system, and as a consequence, the cost. Thus a different solution needs to be found.

Another option would be to take spare parts, to be replaced in the component. In the components analyzed in this thesis, the parts are connected in series, and as a consequence, the reliability of the entire component is the product of the reliability of each part and its spare parts, as shown in equation 4.3.

$$R_c(t) = \prod_{i=1}^{k} \sum_{j=0}^{n-1} \frac{(\lambda_i t)^j}{j!} e^{-\lambda_i t} \tag{4.3}$$

where the sub-index i identifies the different parts (being k the total number of different parts of the component).

The reliabilities of the EDC taking 1 - 4 spare units for each part have been calculated and can be seen in figure 4.5. It can be seen that taking one spare part ($n = 2$), the reliability of the component increases considerably, but at about 650 days, it has already reached 50% reliability. With four spare parts ($n = 5$), values close to one after 1000 days can be achieved.

This solution requires a better understanding of the components by the crew, and the knowledge and capabilities to identify the failure and successfully replace the failing part, which adds more complexity. However, the required mass is considerably reduced.

For example, the use of four spare parts of each part, provides a reliability of 99.78% after 1000 days, whereas using four spare components a reliability of 1.2% is obtained. Mass-wise, it is clear that taking four spare components would involve a total mass of five components. Using spare parts, the required mass would be maximum the mass of five components. This assumption is conservative, as the component itself is composed by the parts, but also by other support items, such as its container. As a first approximation, it will be considered that the parts represent an 80% of the component mass (not counting spare parts).

The number of spare parts required to obtain a satisfactory component reliability will depend on the duration of the mission. Thus, it is necessary, before starting a simulation of the entire system, to select the number of spare parts. For each simulation, it is necessary to estimate the reliability of the component using different levels of spare parts, and select which one is the most suitable. In other words, a minimum desirable reliability for the components needs to be set, and from this reliability, the number of spare parts can be set.

For this thesis, a level of 99% has been set for each component. It is important to remember that the reliability of the entire system will be higher than just multiplying the reliabilities of the components (as if they where connected in series) as the system does not fail when the component fails (it has a certain buffer, e.g. resources from the tanks can still be used).

Following the example of the EDC, for a 900 days mission, a spare level $n = 5$ would provide a reliability of 99.86%. A test of the entire system can be carried out. In case this value does not provide enough system reliability, a spare level $n = 6$ can be tested.

4.3.3 Reliability Estimation - Redundancy Optimization

For this first analysis, it has been considered that for every single part, the same amount of spare parts is taken. Some of the parts have a lower failure rate and a lower mass. Therefore, it makes more sense to take different amounts of spare parts for each part type. Thus, the reliability improvements should be compared together with the increase of mass of the spare parts. Each part type, which is included in the component N_i times, has a specific mass, m_i, and a specific number of spare parts to be taken, n_i. A vector $\vec{n}$ can be defined with the different values of n_i. The mass of the component, including spare parts, can be calculated using equation 4.4.

$$M_c(\vec{n}) = \sum_{i=0}^{k} n_i N_i m_i \tag{4.4}$$

A deep knowledge of the component, down to a level of the spare parts mass, is required in order to find the optimal combination of spare parts which maximizes reliability, minimizing mass.

The problem to solve is called the Multi-Objective Optimization Problem (MOOP). There are different combinations of spares to be taken for each part, which would be feasible solutions. As both criteria, maximum reliability and minimum mass, cannot be satisfied at the same time, multiple solutions will satisfy that they cannot be improved in one of the objectives, without degrading the other one. Each of this options is called a nondominated solution. The problem will have multiple nondominated solutions, therefore a decision maker will be required to select the most optimal one at each case.

In order to linearize the problem, the logarithm of equation 4.3 is used, as it satisfies that $max(R_c) = max(\ln(R_c))$.

$$f_R(\vec{n}) = \ln(R_c(\vec{n}, t)) = \sum_{i=1}^{k} N_i \ln(\sum_{j=0}^{n_i-1} \frac{(\lambda_i t)^j}{j!} e^{-\lambda_i t}) \tag{4.5}$$

To solve the MOOP, the matrix A, formed by the contribution (a_{il}) to f_R for a specific part and a specific value of $n_i = l$, is found, equation 4.6. Theoretically, l can be any integer value from one to infinite. However, for the higher the l, the higher the system mass. l can take, for this study case, values from one to eight.

$$a_{il} = ln(\sum_{j=0}^{l-1} \frac{(\lambda_i t)^j}{j!} e^{-\lambda_i t}) \tag{4.6}$$

To define each combination, it is necessary to select, for each part, which value of l is used. A binary matrix (X) can be used to define the selected value of l. Each row represents a part type, and the columns, the different values l can take.

$$x_{il} = \begin{cases} 1 & \text{if } n_i = l \quad i = 1, 2, ..., k \\ 0 & \text{otherwise} \quad i = 1, 2, ..., L \end{cases} \tag{4.7}$$

As only one number of spare parts should be selected for each part, the addition of each row must equal one. Using the parameters defined in equations 4.6 and 4.7, the logarithmic-reliability and the mass functions are defined as:

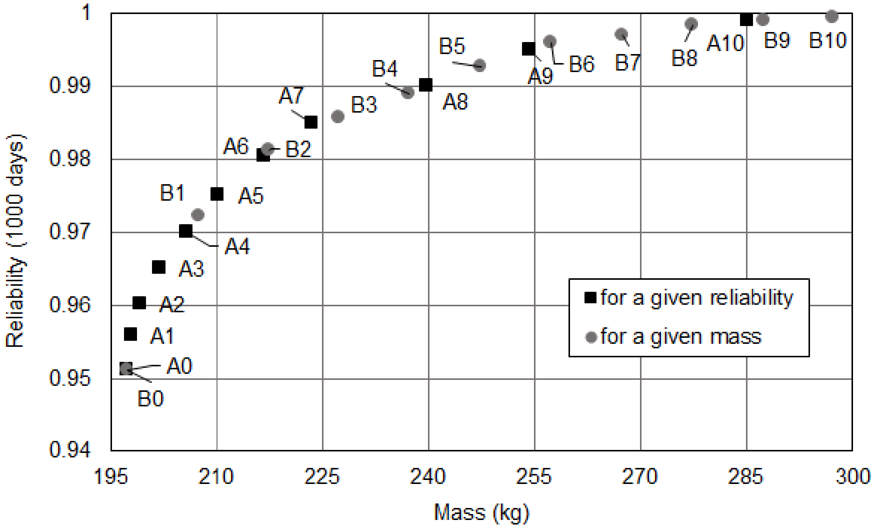


Figure 4.6: EDC Nondominated Solutions

$$f_R(X) = \sum_{i=1}^{k} \sum_{l=1}^{L} N_i a_{il} x_{il} \tag{4.8}$$

$$f_M(X) = \sum_{i=1}^{k} \sum_{l=1}^{L} N_i m_i x_{il} \tag{4.9}$$

The objective is to maximize f_R and minimize f_M. Both requirements cannot be satisfied, in absolute terms, at the same time. Two different type of solutions can be found, that provide:

- The minimum required mass, for a given reliability value.
- The maximum achievable reliability, for a given mass value.

Figure 4.6 shows the nondominated solutions for the EDC. For given reliabilities, starting from 0.95, with increments of 0.05, the minimum required mass is found. For the given mass criterion, the initial mass is the one obtained by a reliability of 0.95, with increments of about 15% of the system's mass. The results are found using the Excel solver.

This option should be considered when the characteristics of all parts of all components are known. Therefore, this option is implemented in RELISSA, to make sure that the program can include different number of spare parts for the different parts of the component.

To simulate the entire ECLSS, it is necessary to chose the number of spare parts for each component. As explained for redundant systems using the same number of spare parts of each type, a desired reliability of 99% is first set for each component.

4.4 Implementation in RELISSA

The methodology used to evaluate each component has been directly implemented in RELISSA. It was necessary to develop new programs and modify RELISSA itself. These changes are explained in this section.

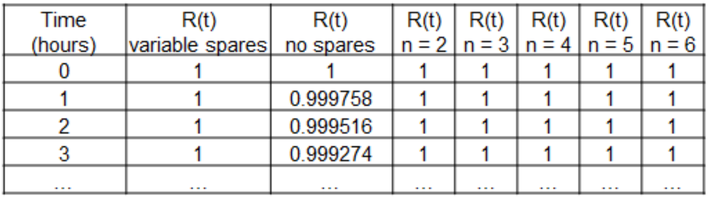
Due to the complexity in selecting the spare parts to be taken, the user is given three different options: RELISSA can automatically select the suitable level, the user can decide among different options or the user can manually select the "spare level" required for each part. The first two options consider the same amount of spare parts to be taken for each part, making it easier to estimate the required mass. The third option allows the user to select an optimal combination, but requires inputs such as parts' mass.

The default option is set to Automatic, but the user can change it in the Failure Mode panel in the Mission Design Definition described in section 3.3.2.

These three options allow the selection of the number of spare parts, which is required to define the reliability distribution. As seen in section 4.3, the component has a complex distribution, compared with the exponential distribution previously defined in RELISSA in chapter 3. As a consequence, the Component's Failure Estimation (CFE) module has been modified.

4.4.1 CFE Changes

The most significant change in RELISSA is the estimation of the components' failure time in the module CFE. As originally programmed, RELISSA would obtain the Failure Time from the $R(t)$, using the Monte Carlo method. The expression $R(t)$ for each component followed an exponential distribution, and thus, the t could easily be obtained. When spare parts are used, the expression $R(t)$ becomes more complex, which makes it difficult, if not impossible, to isolate the variable t of the equation.



Time (hours)	R(t) variable spares	R(t) no spares	R(t) n = 2	R(t) n = 3	R(t) n = 4	R(t) n = 5	R(t) n = 6
0	1	1	1	1	1	1	1
1	1	0.999758	1	1	1	1	1
2	1	0.999516	1	1	1	1	1
3	1	0.999274	1	1	1	1	1
...	...	...	...	...	...	...	...

Figure 4.7: Reliability Database Example

To obtain the failure times with spare parts, and to ensure that the same method can be used independently of the expression defining the component reliability, it has been decided to calculate the reliability of the component in one hour intervals, starting from $t = 0$ to 1 000 days, using 0, 1, 2, 3, 4 and 5 spare parts. This information is saved as a text file in RELISSA for each component, creating the Components Reliability Database (CRD).

Each text file in the database, figure 4.7, is divided into 8 columns, providing the reliability of the component using different spare levels. CFE receives the selected number of spare parts, and therefore knows which column is to be used for each component.

The module CFE continues generating a random number for each component, but instead of calculating the corresponding failure time, it searches it in the database. A loop looks for the random number in the specific column (defined by the number of spare parts) starting from $t =$ EoM, counting backwards until it is found. This time is saved as failure time of the component for the simulation and is used as it was originally programmed, by ELISSA 2.0.

4.4.2 Component Reliability Database Update

The CRD included in RELISSA might need updating. Reliability for longer mission durations or for higher spare parts levels could be required. Therefore, a new subprogram has been created to allow the user to recalculate these databases increasing time or spare parts level. For advanced users, familiar with LabView programming, it is also possible to modify the component set-up or the failure rate of its parts. The included databases can only be used if automatic and semi-automatic spare level selection are used. For manual selection, the reliability will need to be calculated, which can be carried out in the manual selection program.

This new subprogram includes the design data of each component (types of parts, and the required number of each type) as well as the failure rate of each part. Using equation 4.3, the reliability of each component can be found.

The user can select the maximum number of spare parts to be calculated. Once the program starts it calculates reliability from $t = 0$ to EoM, for the different number of spare parts selected. The data are updated in the text files of the database, starting in the 3rd column with no spare parts, and saving for one, two, etc. in the following columns.

4.4.3 Automatic "Spare Level" Selection

The default mode in RELISSA is the automatic selection of spare level. It does not require any action from the user. Once the mission duration has been set, this module looks at the $R(EoM)$ of the different options for each component (no spare parts used, or the same number of spare parts for all parts, from $n = 2$ to $n = 6$). The program looks at the different values from the database of the component, and selects the spare level which provides a reliability of at least 99% for the component.

For each component, the spare level is saved and used by CFE to find the estimated failure time in the database for each simulation. This information is also saved in a text file, to allow the user to check the spare levels used.

This new subprogram only is used if the Automatic level is selected.

4.4.4 Semi-Automatic "Spare Level" Selection

The automatic option preselects the spare level, which provides a reliability of at least 99% at EoM. However, it might be interesting to compare the results of this spare level, with a higher or lower spare level, to see how reliability of the entire system changes in relation to the system mass change. Therefore, a semi-automatic mode has been created, where the user can select manually the spare level (using the same spare parts for each part).

Once the mission design options have been selected, the user is asked to select for each component its spare level. The user interface shows the different options available in the database, together with the $R(EoM)$ for each option.

The user needs to define the spare level for each used component. Once selected, the user confirms the selection, and the values are saved and transferred to CFE.

The new module only asks the user when the semi-automatic option has been selected.

4.4.5 Manual "Spare Level" Selection

The manual mode allows to specify for some or all components, the number of spares to be taken. The user first needs to select for which components, more detailed information can be provided. For these components the user has to provide the number of spares parts to be taken for each part. An estimation of the mass is also required (either as a percentage of the component mass or in kilograms).

When all information has been provided, the program calculates the $R(t)$ of the component, saving it in the 2^{nd} column of the database (the one reserved for variable spare configuration). The spare level is set to variable.

At this point, the program is ready to work normally, as CFE will take the data information from the updated database.

This option is the most accurate. As explained in the previous section, not all the parts of the component are equal (neither in mass nor in failure rate). Therefore, for each specific case, a different combination will be the most suitable one. This option requires a better knowledge of the component itself, and the parts that form it. As the components studied in this thesis are still in its developing phase, all this information could not be provided. However, the aim of this thesis is to offer the required tools that will allow to introduce more updated information in the future.

4.4.6 Future Considerations

As explained in the previous subsection, the data used for this analysis might be updated when the components have a higher TRL. The program developed for this thesis has been programmed to easily be adapted with new data.

There are two possible ways of improvement:

1) Update data using the same methodology

Two possible changes can be made in the current methodology: changes in the component structure and changes in the parts failure rates.

The CRD update module allows to modify the reliability information of the component. The number of units of each type, or the failure rates of the components can easily be changed when more updated information is available. The user needs to enter the new information and the database will be updated.

2) Enter a component failure distribution

In RELISSA it is assumed that the components' parts have a constant failure rate. This approximation can be used in a preliminary design phase and provides a mean of comparison between different systems. However, to obtain a more accurate reliability prediction, that can be used as an absolute reliability measure, the reliability distribution of the component is required.

At this point, it is not possible to find such information for the regenerative components that would be used in a long duration mission. However, in the future, if these components have been widely used/tested, the historical failure data will allow to find the failure probabilistic distribution of the component. RELISSA has been reprogrammed, as explained in this chapter, to allow the use of any type of distribution. The required input is the CRD data, that can be produced with any program, as long as the structure (columns order) is kept and saved as a text file.

4.5 Summary

The reliability estimation of the regenerative components cannot be done by historical data, as there is not enough information available for the components currently working on the ISS nor for the components being developed. Therefore, a "Handbook Data" approach is used.

The information required for this analysis is the component structure and the failure rate of each part. For some components, specially for the ones currently in use or used in previous missions, the information is easily reachable, but for the components under development, it has been a complex task. The structure has been found in publications of the companies/agencies that have built or are developing the component, and the failure rates, from space-related publications or generic databases.

It has been proven that the reliability of a component is too low for a long mission duration. Therefore, it is necessary to consider that spare parts will be taken to repair the component when it fails. A first analysis has been carried out, considering the same number of spare parts for each part within the component. This option is not efficient, as each part has a different mass and failure rate, and it is possible to optimize the number of spare parts of each type to reduce mass and maximize reliability. A methodology to solve this optimization problem, the MOOP, has been applied. The results are nondominated solutions (they cannot be improved in one of the objectives, without degrading the other one). It will be necessary to chose for each specific mission, which nondominated solution fits better, either by fixing the maximum allowable mass or the minimum required component reliability.

This methodology has been implemented in RELISSA. The end-user of the program only needs to select a minimum $R(EoM)$, in order to see the effects on reliability in the entire system, and obtain the system mass, including the required spare parts. The changes in RELISSA allow to easily enter new data, when more detailed information can be provided.

"Mars is there, waiting to be reached"

Buzz Aldrin (1934 – present)

5

Practical Application A Long Duration Mission Analysis

In this chapter, RELISSA is applied to compare different ECLSS configurations for a long duration mission.

As explained in chapter 1, future human space flight plans have the Moon, asteroids or Mars as potential destinations. Thus, a mission to Mars has been selected to test and show the methodology developed in this thesis. The mission scenario is described and different ECLSS configurations are proposed and simulated using RELISSA. Finally, the results are shown and discussed.

5.1 Mission Scenario

Several parameters need to be defined in order to analyze the ECLSS for a long duration mission. The main parameters are given by the choice of the destination, as it defines the duration of the mission. Moreover, the size of the vehicle needs to be determined. This parameter depends on the crew size, and the volume required per crew member.

Destination: Mars

Considering long duration missions the planet Mars is seen as the ultimate and farthest destination. Therefore, a round trip mission to Mars, including a reasonable stay on the surface, has been selected to test the developed tool.

Mission Duration

The mission duration is imposed by the relative position of the Earth and Mars over time. Three different options can be considered according to the Reference Mission of the NASA Mars Exploration Study Team [69]: fast-transit, short-stay and long-stay. Table 5.1 provides the duration of the outbound, stay and return phases for these three options.

A short-stay mission, is dismissed for this analysis, as it implies that 95% of the mission duration is spent in the outbound and return phase. Moreover, this type of mission has high propulsion requirements, and usually requires a swing-by at Venus. A long-stay mission profile is the solution of minimum-energy for a given launch opportunity. In this case the time spent on the Mars surface represents almost 50% of the total mission time. Finally, a fast transit option would represent a stay of over 70% of the mission time. However, the energy requirements would be higher than for a long-stay mission. Therefore, for this analysis a long-stay profile is selected, and the total duration mission is set to 919 days.

Table 5.1: Mission Profile Options [69]

Mission type	Fast-transit	Short-stay	Long-stay
Outbound (days)	150	224	224
Stay (days)	619	30	458
Return (days)	110	291	237
TOTAL (days)	879	545	919

Vehicle Characteristics

This analysis only studies the transfer vehicle taking the entire crew to Mars during the outbound period, orbiting Mars with only part of the crew during the stay phase, where some of the astronauts would descend to the surface, and will finally bring the entire crew back to the Earth during the return phase.

For the ECLSS simulation two parameters are required: the total pressurized volume and the occupancy of the vehicle over time.

A minimum crew of six is recommended, according to literature, to ensure feasibility of surface activities [69, 70]. In this case, the occupancy during the outbound and return phase will be a crew of six, and during the stay phase, a crew of two, since four of the astronauts will descend to the surface.

The habitat volume should be, on the one hand, as small as possible, as it would reduce launch cost, and on the other hand, as big as possible, for crew comfort during the mission. Thus, a balance between launch cost and crew comfort needs to be found. The ISS has a pressurized volume of 916 m^3 and a habitable volume of 388 m^3 [71], and supports in normal operations a crew of 6. However, the maximum occupancy of the ISS has been a crew of 13 due to overlapping increment crews, reducing the pressurized volume per person from 152.6 to 70.5 m^3. For this study a volume of 500 m^3 has been selected, which offers more than 80 m^3 per person during outbound and return, and 250 m^3 per person during the Mars orbiting periode.

ESM Equivalency Factors

Reliability and Equivalent System Mass are the two parameters used to compare both systems. To evaluate reliability, the methodology developed for this thesis is used. As a result, the number of spare parts required for the entire mission is obtained and the mass and volume of the system, including tanks, components and spare parts, is calculated.

Moreover, power and cooling requirements are also provided in the simulation. To use these values to calculate the ESM, it is necessary to use the equivalent parameters for a Mars transit mission.

Table 5.2 shows the equivalency values used for volume, power and cooling. Crew time has not been considered in this study, as it is only a preliminary design and only a rough approximation could be used. The goal of this analysis is not to obtain absolute figures, but to compare the two proposed designs and thus to demonstrate the chosen methodology and tools developed here.

Table 5.2: ESM Equivalency Factor [52, 72]

Volume	Power	Cooling
9.16 kg/m^3	107 kg/kW	60 kg/kW

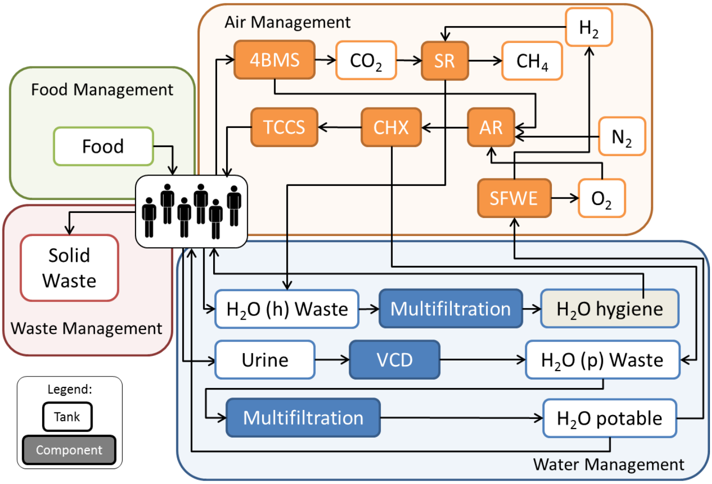


Figure 5.1: Design A

5.2 ECLSS Designs

Two different systems are analyzed for the defined mission, a system using ISS technologies and a system using some technologies under development, presenting significant reductions of mass and power needs over current technologies.

The different configurations are explained in the following. Each system has been first simulated with ELISSA (with no failures) in order to evaluate the initial tank levels.

5.2.1 Design A - ISS-like

The ISS-like design, figure 5.1, uses the same components as of the ISS. Currently, the ISS receives regularly resupply from Earth (about 7-8 launches per year) [73]. This resupply includes O_2, water, food, propellant and equipment. The goal of the design A is to use the same hardware, but close the system as much as possible. The consumables required for the entire mission should be brought on-board, as in a Mars round trip mission, resupply will not be an option or restricted to a costly cargo mission.

In the ISS, the CO_2 is extracted from the cabin air through a 4BMS. O_2 and N_2 are added to the CO_2-free air in an Air Regulator (AR), to ensure the desired atmosphere composition is kept. This air then goes through a CHX, to regulate temperature and humidity and through the TCCS, to remove contaminants before the air is returned to the cabin. O_2 is produced by SFWE, while the required N_2 for the entire mission needs to be stored in a tank.

The extracted CO_2 goes through an SR. It uses H_2 to convert the CO_2 in water and CH_4. The SFWE produces H_2, which can partially fulfill the SR requirements. However, extra H_2 is required.

Two levels of water quality are defined in this system: hygiene (h) water and potable (p) water. The two loops are independent. The components used in the ISS are MF and VCD.

The hygiene cycle includes the hygiene waste water and the water produced by the SR, which is treated as waste water. Hygiene waste water is recycled by a MF unit to a hygiene quality standard.

The potable water recycling system is formed by a VCD and a small MF unit. Urine produced by the crew goes through the VCD, and water is extracted and saved in a potable waste water tank, together with the water extracted from the atmosphere. Finally, potable waste water goes through a small MF unit. Potable water is used to obtain the O_2 in the electrolysis process.

For a crew of six, two units of 4BMS, SFWE, large MF and SR are required.

Figures 5.2, 5.3 and 5.4, show the evolution of tank levels over time, obtained simulating the system (with no failures). The values obtained can be used to set the required size of the tanks. The tank volume and mass are calculated together with the ESM in section 5.3.

In figure 5.2, the evolution of food, N_2, solid waste (SW), brine and CH_4 are shown. N_2 decreases at a constant rate, as it is used to replace the loss in the

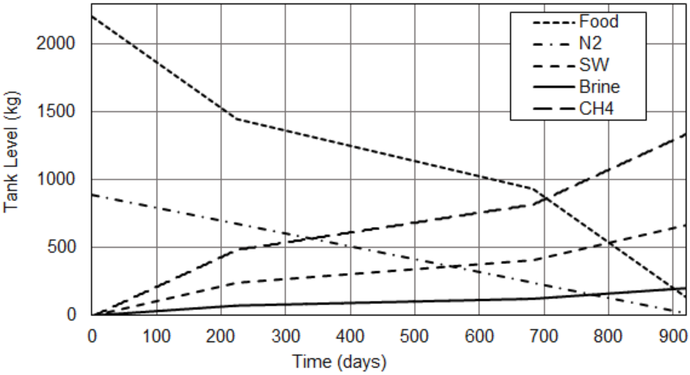


Figure 5.2: Design A - Tanks Level Evolution (1) - Food, N_2, solid waste, brine and CH_4

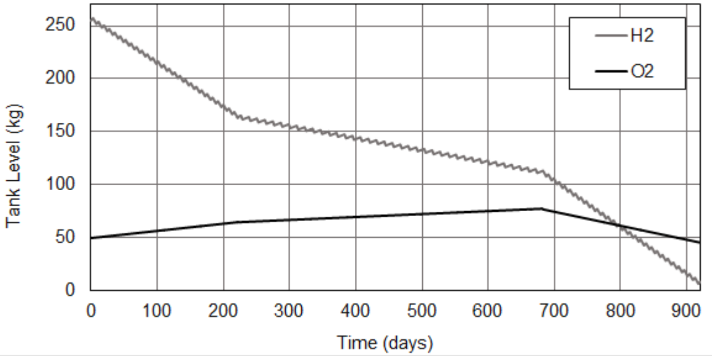


Figure 5.3: Design A - Tanks Level Evolution (2) - O_2 and H_2

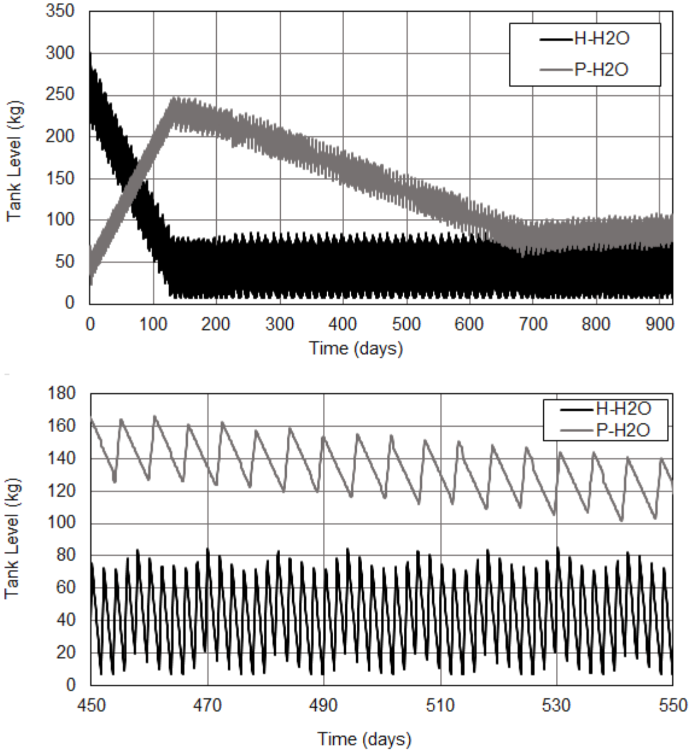


Figure 5.4: Design A - Tanks Level Evolution (3) - Hygiene and Potable Water

Table 5.3: ISS-like Tanks Configuration

	Initial level (kg)	Capacity (kg)
N_2	890	895
O_2	50	80
H_2	255	260
CO_2	0	25
CH_4	0	1500
P-H_2O	70	400
H-H_2O	300	310
P-Waste-H_2O	0	40
H-Waste-H_2O	0	70
Urine	0	15
Brine	0	250
Food	2200	2200
Solid Waste	0	700

cabin air due to leakage, and depends only on the size of the vehicle, which remains constant.

In the evolution of the other consumable tank levels, the three mission phases can be observed: outbound (day 0 - 224), stay (day 224 - 682) and return (day 682 - 919). The use of the consumables and the production of waste (solid waste and brine) is proportional to the crew size: the higher the number of crew members, the more food is required and the more waste is produced. However, for a preliminary design, it will only be necessary to identify the required size of these tanks and the required amount of consumables for the mission.

In figure 5.3, the three different phases can also be observed, for O_2 and H_2 tanks.

Finally, figure 5.4 shows the evolution of water over time. It is important to remark that the water recycling components do not work continuously. Waste water (both hygiene and potable) accumulates in the tanks until a minimum level is reached. At this point the tank valve opens, and waste water proceeds to the recycling components. Therefore, the evolution of water in the tanks presents a cyclic behavior. It can also be observed in the H_2 tank evolution, as the SR does not work continuously either.

The hygiene water level decreases rapidly within the first months, whereas the potable water increases. The system has been adjusted in order to optimize the amount of water required considering the total amount of water, both hygiene and potable water. To optimize the system, it should be considered that potable water can be used for hygiene purposes, if necessary. As a consequence, the

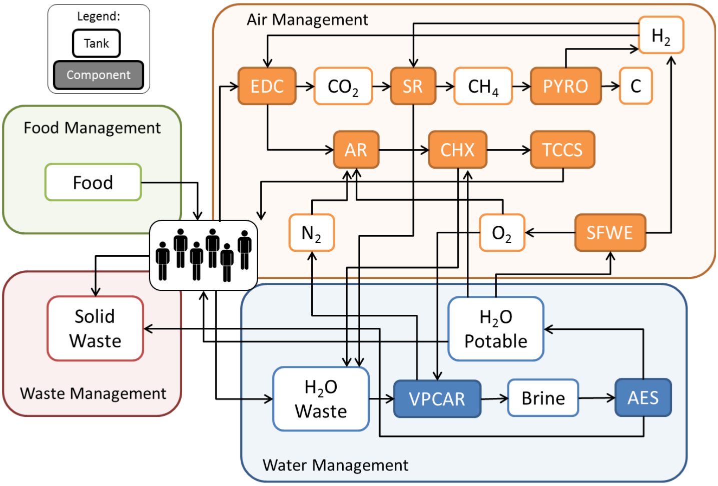


Figure 5.5: Design B

system will use as hygiene water, the recycled water from hygiene waste water and a small amount of potable water to compensate system losses.

In the ISS, no regenerative system is used to produce food or treat solid waste. In this design, food is provided in dehydrated form, thus, the water management system should take into account the water needed to re-hydrate food. Solid waste is properly stored in a tank. In consequence, to size the tank, it is necessary to estimate the amount of waste produced during the entire mission.

The initial tank levels and tank capacities can be seen in table 5.3.

5.2.2 Design B - Advanced Physico-Chemical

Figure 5.5 shows the proposed design of an Advanced Physico-Chemical (APC) system, using components that are still in a development phase, but with the potential to considerably reduce the ESM of the system.

In this case, an EDC is used to extract the CO_2 from the atmosphere. It requires H_2 to separate the CO_2 from the rest of the cabin air. The CO_2-free air follows then the same steps as in design A: it is sent to the AR, where O_2 and N_2 are added, through the CHX, to control temperature and humidity, and the TCCS, to control contaminants level. O_2, as in design A, is produced by water electrolysis, SFWE.

The CO_2 extracted by the EDC is converted into water and CH_4, as in design A, using the SR, which requires H_2. However, in design B, a PYRO is used to

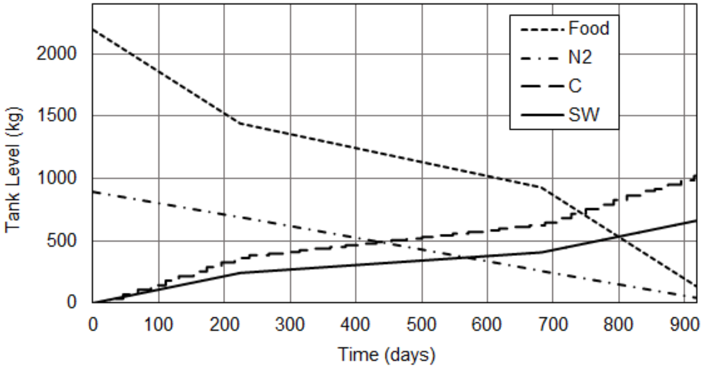


Figure 5.6: Design B - Tanks Level Evolution (1) - Food, N_2, carbon, solid waste

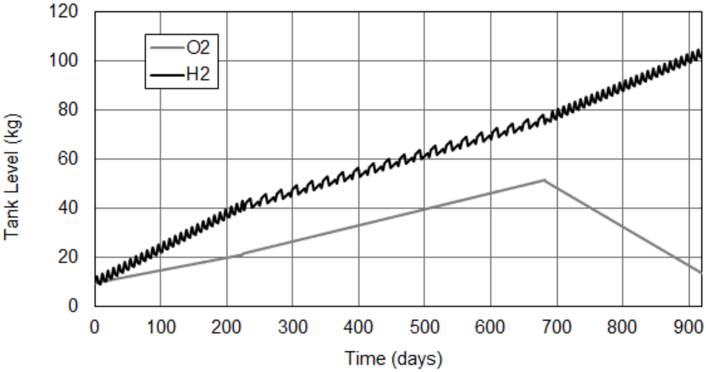


Figure 5.7: Design B - Tanks Level Evolution (2) - O_2 and H_2

separate CH_4 into solid carbon (C) and H_2. This H_2 can be used again in the SR, thus avoiding the need to bring extra H_2 for the mission.

The water recycling concept used is a centralized system: all types of water (including urine) are treated together and recycled to a potable standard. The component used is the VPCAR, which produces brine. To recover the maximum amount of water, this brine is treated in an AES.

As in design A, no regenerative technologies are used for food and solid waste management. Food is provided in a dehydrated form and solid waste is properly stored in a tank.

The system has been simulated with no failures to size the tanks and the required consumables. Figures 5.6, 5.7 and 5.8 show the results of the tanks evolution

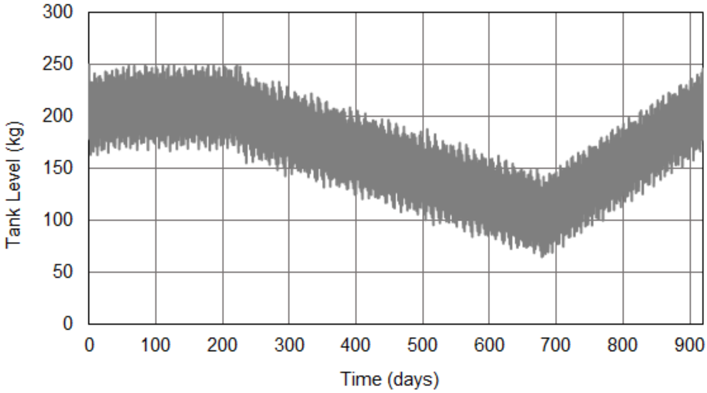


Figure 5.8: Design B - Tank Level Evolution (3) - Water

Table 5.4: APC Tanks Configuration

	Initial level (kg)	Capacity (kg)
N_2	890	895
O_2	10	60
H_2	10	110
CO_2	0	20
CH_4	0	10
H_2O	250	250
WW	0	70
Brine	0	10
Food	2200	2200
Solids	0	700
Carbon	0	10

over time, that have been used to define the tanks initial level and capacity, table 5.4. In figure 5.6, the evolution of food, N_2, solid carbon and solid waste can be seen. The evolution of food and N_2 is exactly the same as in design A. These consumables depend on the size of the crew and the vehicle, which are the same in both designs. In this case, CH_4 and brine are not plotted, since they are treated to obtain H_2 and solid carbon (using PYRO), and water (using AES). A small tank should be considered, as PYRO and AES do not work continuously, and a small amount should be stored, before both components start to work.

Figure 5.7, shows the evolution of O_2 and H_2. In this case, thanks to the PYRO, no H_2 should be provided. On the contrary, H_2 is produced and can be used by another vehicle subsystem, such as propulsion.

In figure 5.8, the evolution of water can be seen. In this case, as a centralized water concept is used, only one tank is required, which contains water for both potable and hygiene uses. The water tank level is linked both to the crew size and the O_2 production requiring water.

5.3 Simulations - Results and Interpretation

The reliability of the two proposed ECLSS designs is estimated using RELISSA. The only parameter that needs to be selected is the number of simulations to carry out, as the other system parameters have already been selected in the previous section.

Number of Simulations

According to the literature, for such type of simulation, to obtain representative results, a minimum of 300 runs are required [74]. The error in the process can be estimated, depending on the number of simulations carried out. The error, equation 5.1, is defined by the critical value of the normal distribution for a specific confidence level ($Z_{\alpha/2}$), the standard deviation of the output (σ^2) and the number of simulations (N).

$$Error = Z_{\alpha/2}\frac{\sigma^2}{\sqrt{N}} \tag{5.1}$$

In order to calculate the error, it is necessary to first run the simulations to calculate the standard deviation. As an example, 3000 random numbers between 0 and 1 uniformly distributed have been created, to evaluate the error, for different numbers of simulation. These random numbers would be used by RELISSA to identify the failure times, as it has been explained in chapter 4. For 300 simulations the error is 1%. For 3000 simulations the error has decreased to 0.3%.

For this analysis, the number of simulations has been set to 3000. Once the simulations have been carried out, the $R(EoM)$ of each component obtained in the simulations is compared with the previously set, to check whether the software is working properly.

Maximum Time for Loss of Crew

The ECLSS systems are designed for a specific mission duration, in this case, 919 days. Therefore, even when the components do not fail, the system will not be able to work indefinitely. The duration of the mission is set by the inbound and return phases (how long they are, and when can they take place). Theoretically, the only scenario where the mission duration could be increased, would be if once the mission has returned to Earth's proximity, a technical problem would prevent the crew returning to Earth's surface.

When the tanks are sized for a specific mission duration, a certain margin is given, and as a consequence the crew could survive longer than the defined mission duration.

For this study, the maximum time for LoC is found for each system, as failures after the maximum LoC do not need to be simulated.

Both systems have been simulated with no failure, to identify the LoC with no failure and its cause. The time for LoC is saved as the maximum failure time for a component, i.e. when the estimated failure time of a component exceeds the maximum time for LoC, it is considered that the component does not fail within the useful life-time of the system.

Both for designs A and B, the maximum LoC time is 983 days. At this point, even if all the components are working, the crew has run out of food, and has survived the estimated time humans can survive without food, 30 days. As the mission duration is set to 919 days, this does not pose a problem. Even if the mission duration should be increased, due to any technical problem, the crew would have enough food for 34 more days. This value has been only calculated to evaluate which is the critical consumable in the system, when no failure occurs. For a longer mission, a higher amount of food would be planned, postponing the LoC due to lack of food, to a higher value than the mission duration. These would increase the mass of consumables required, and should be studied for each specific mission.

5.3.1 Design A- ISS-like

The data obtained in the 3000 simulations are analyzed, comparing the theoretical component reliability with the obtained reliability in the simulations and analyzing the failure causes. The reliability of the system, as well as the system ESM, are then calculated.

Failures of Components

The desired component $R(EoM)$ has been previously fixed at a minimum of 99% for each component, using the theoretical reliability calculated with the methodology of chapter 4. For each component a different value is obtained, as

Table 5.5: Design A: Component Failures

Component	Set Reliability at 919 days	Failures at 919 days (Total)	Simulated $R(EoM)$
4BMS (x2)	0.9976	12 (19)	0.9980
SFWE (x2)	0.9957	19 (25)	0.9968
CHX	0.9987	2 (3)	0.9993
TCCS	0.9976	6 (6)	0.9980
MF (x3)	0.9979	24 (33)	0.9973
VCD	0.9956	15 (19)	0.9950
SR (x2)	0.9958	19 (32)	0.9968

the combinations of spare parts do not provide in any case a reliability of exactly 99%. The values range from 99.56% to 99.87%.

For this first study, it is checked whether these values have been correctly obtained in the simulations and whether the number of simulations is representative. Table 5.5 shows the set reliability at 919 days, the component's failures occurring until 919 days, as well as the total failures (including those after 919 days) for the 3000 simulations, and the reliability obtained from the simulation data. It can be seen that the simulated reliabilities differ by a maximum of 0.106% from the set values.

For some technologies, multiple units have been used (4BMS, SFWE, MF, SR). In this case the results shown in table 5.5 show the reliabilities obtained for each type of technology, not for each single unit used.

LoC Causes

Table 5.6 shows the causes of LoC for the 3000 simulations for design A at 919 days. As the simulation have run until LoC (independently of the mission duration), the values total LoC (including failures after 919 days) are also presented, in brackets. For this study, the most common LoC cause is lack of food after 983 days. Water and O_2 production and CO_2 extraction are not a problem after 983 days, if the recycling components work. As food is being carried on-board, not produced, the tank is empty after 953 days (as it has been designed), and the astronauts can survive approximately 30 days without food. As explained before, this does not pose a problem, since the astronauts should return safely to the Earth after 919 days.

The interesting failures for this analysis are those occurring before EoM. In this case, the 4BMS has failed in 12 occasions (seven times 4BMS1 and five 4BMS2).

Table 5.6: Design A: LoC Causes at 919 days - Values in brackets indicate total number of LoC

Excess of CO_2	Lack of water	Lack of O_2	Lack of food
12 (17)	12 (17)	28 (37)	0 (2929)

The time between component failure and system failure depends on the mission phase where the failure occurs. During the Mars orbiting phase, only two crew members are on-board, and therefore a failure of one 4BMS has no direct impact, as one 4BMS is enough for the CO_2 extraction in this phase. However, when six crew members are on-board, one 4BMS is not able to extract the produced amount of CO_2, and after 14 days, it reaches toxic levels in the atmosphere.

When the SFWE component fails, LoC due to lack of O_2 occurs. The time between component failure and system failure depends on the component failure time, as O_2 is kept in the tanks (the amount will depend on the mission elapsed time). Moreover, the O_2 present in the atmosphere starts decreasing when the tank of O_2 is empty, but it will require a certain amount of time, until it reaches the minimum O_2 partial pressure required for breathing. When only two crew members are on-board, one SFWE can produce enough O_2 for the crew, but the problem will arise, as soon as the remaining four astronauts join the transfer vehicle. In design A, times between component failure and system failure range from 20 to 50 days.

A failure in the hygiene-water MF system implies a lack of hygiene water, which has no direct impact in LoC. The only consequence will be that the crew has no hygiene water in the tank. As the amount of potable water is exceeding the requirements, part of the potable water can be used for the basic hygiene requirements.

When the VCD fails, urine cannot be treated. As a consequence, the astronauts will still get potable water (coming from the atmosphere condensate, through the potable-water MF). However, when the potable-water MF fails, the astronauts cannot get any potable water, as the water recovered in the VCD goes through the MF before becoming potable water. As a consequence, when the potable-water MF system fails, no potable water at all is produced, and LoC occurs due to lack of water. However, when the VCD fails, the astronauts are still getting some potable water, but the water produced is not enough to produce O_2, and LoC occurs due to lack of O_2. Lastly, the CHX failure poses two major problems: part of the system water is not recovered, and relative humidity will reach a value of 100% on the atmosphere and water will start to condensate in the vehicle, which could damage the electronic equipment. For this study, only the water loss in the system is considered. After a CHX failure, LoC will occur after 10 and 12 days, as the water recovered from urine is not enough to satisfy potable water

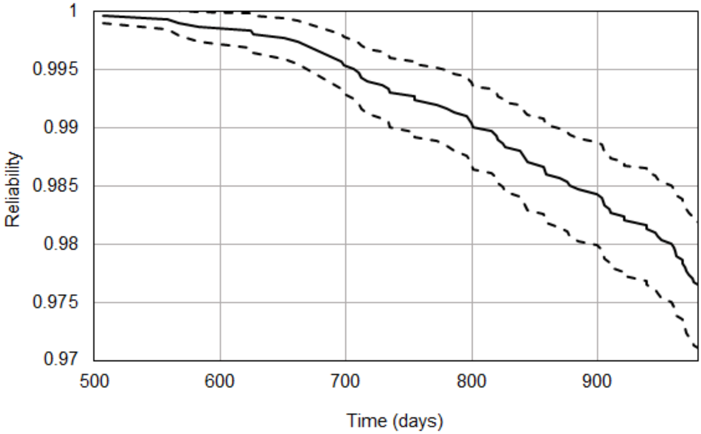


Figure 5.9: Design A - Reliability Estimation - Discontinuous lines show the 95% confidence interval

requirements.

Although the SR produces water, no problems have been experienced when the SR has failed in this simulations.

Finally, lack of food does never occur before EoM, as the food management system is non-regenerative, the required food is simply stored for the entire mission.

Reliability Analysis

The result of the multiple simulations is a list of LoC times that is post-processed in RELISSA. As explained in chapter 3, the first step is to check if the data fit a Weibull distribution. In this case, 2915 LoC times occur until day 983, the other 85 are distributed between days 506 and 983. In most of the simulation (2915), there has been no component failure. The system failure has occurred because the system has run out of consumables (in this case, food), after EoM. From a reliability point of view, this could be easily solved increasing the consumables in the tanks, which would delay these 2915 LoCs. However, as they happen after EoM, from a mission design point of view, adding more consumables is not a reasonable solution, as the astronauts would have already returned to Earth after 919 days.

The important parameter, for the mission design is the reliability at EoM. However, even if a mission duration longer than EoM is unlikely to happen, for a reliability analysis, it is also important to analyze the behavior of the system,

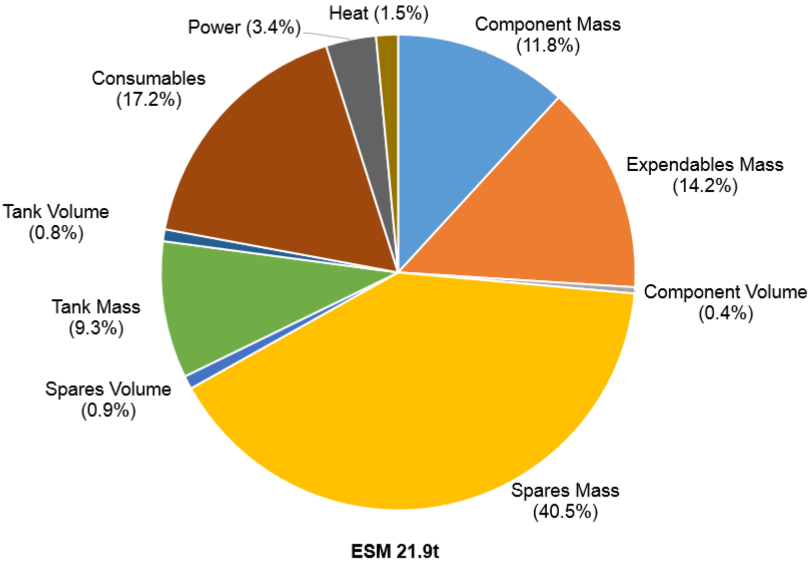


Figure 5.10: Design A - ESM Distribution

until system failure. The data do not fit a Weibull distribution, as the Anderson-Darling estimator is 1091.7.

The system failure due to lack of food occurs in 97% of the simulations. As the amount of food could theoretically be increased, the data obtained can be considered as right-censored. A test has been carried out using the statistical software MINITAB, considering the data as right-censured. The Anderson-Darling estimator is, in this case, even greater, and as a consequence, the censored-data do not follow a Weibull distribution.

Therefore, a non-parametric method, the Kaplan-Meier (KM) should be used. The results of the KM analysis, including a 95% confidence level, are shown in figure 5.9. The $R(EoM)$ for design A is 98.3%, with a confidence interval [97.7 to 98.7].

ESM Calculation

Finally, in order to compare the two systems, it is necessary to calculate the ESM. For this, the components, the required spare parts and the tanks mass and volume have been taken into account, as well as required consumables, the power required and the heat produced by the system. As result, the ESM obtained is

21.9 tons. Detailed information in the ESM calculation can be found in appendix B.

Figure 5.10 shows the distribution of the ESM. Spares (considering mass and volume) represent 41.4% of the total ESM. Both consumables (17.2%) and expendables (14.2%) represent an important part of the total ESM, followed by component mass (11.8%). The results regarding ESM distribution are discussed in section 5.3.3, together with the ESM results of design B.

5.3.2 Design B - Advanced PC

First, as done for design A, the components' failures and the LoC causes are analyzed. Finally, the reliability of the system is estimated and the ESM is calculated.

Failure of Components

Table 5.7 shows the number of failures of each component. In this case, it is also necessary to check if the simulations carried out are representative, and therefore the set reliabilities and the simulated are presented. In this case, the simulated reliabilities differ by a maximum of 0.19% from the theoretical values.

As in design A, for some technologies, multiple units have been used (EDC, SFWE, SR and PYRO). The results listed in table 5.7 show the reliabilities obtained for each type of technology (not for each single unit used).

LoC Causes

Table 5.8 shows the causes of LoC for the 3000 simulations for design B at 919 days. As in design A, the simulations have run until LoC, therefore the values of LoC after EoM are also shown. The critical LoC cause after EoM is food, as in design A, because food is not produced and the tank is empty after 953 days.

As explained in design A, the failures to be analyzed are those occurring before EoM. In design B, the EDC has failed in seven occasions, three times EDC1 and four times EDC2. As in design A, the time between component and system failure will depend on the mission phase where the failure occurs (if two or six crew members are on-board), as one EDC is enough to extract the CO_2 production of two astronauts, but not six. When the six crew members are on-board, LoC occurs after 11.5 days. In this case, the time between component and system failure is shorter than in design A, as the VPCAR adds CO_2 to the atmosphere, and as a consequence, the CO_2 accumulates faster in the atmosphere.

Table 5.7: Design B: Component Failures

Component	Set Reliability at 919 days	Failures at 919 days (Total)	Simulated $R(EoM)$
EDC (x2)	0.9985	7 (8)	0.9988
SFWE (x2)	0.9957	14 (27)	0.9976
CHX	0.9987	3 (4)	0.9990
TCCS	0.9976	10 (11)	0.9966
VPCAR	0.9956	12 (14)	0.9960
AES	0.9986	3 (3)	0.9990
SR (x2)	0.9958	21 (27)	0.9965
PYRO (x2)	0.9929	39 (55)	0.9935

Table 5.8: Design B: LoC Causes at 919 days - Values in brackets indicate total number of LoC

Excess of CO_2	Lack of water	Lack of O_2	Lack of food
7 (7)	18 (31)	11 (13)	0 (2949)

Lack of water can occur for several reasons, VPCAR, AES, SR or CHX failure, or lack of O_2 in the tanks. The VPCAR is the main water recycling component. When it fails, even if the crew consumption is reduced to an emergency level, the remaining water can only last between 5 and 18 days, depending on the tank level at VPCAR failure time and the crew members on-board. Moreover, lack of O_2 will make it impossible for the VPCAR to work. When only two members of the crew are on-board and the O_2 tank is empty (due to electrolysis failure), the water will be consumed before the O_2 in the atmosphere reaches a critical level. The SR also produces water, but in a much smaller amount. Therefore, its failure, even when it occurs as early as day 481, does not mean LoC before the mission ends. On the other hand, a failure in the AES, which also produces a small amount of water compared to the VPCAR, can mean LoC 357 days after AES failure, if it happens early in the mission (for example on day 470). Lastly, a CHX failure causes LoC after 25-40 days.

LoC due to lack of O_2 is produced when one of the electrolysis components fails. The time between component failure and system failure depends on the component failure time, as O_2 is kept in the tanks (the amount will depend on the current mission time). Moreover, the O_2 present in the atmosphere starts decreasing when the tank of O_2 is empty, but it will require a certain amount of time until it reaches the minimum O_2 partial pressure required for breathing. When failure occurs between day 400 and 600, the astronauts have enough O_2 for more than 100 days. However, when failure occurs approaching EoM, this

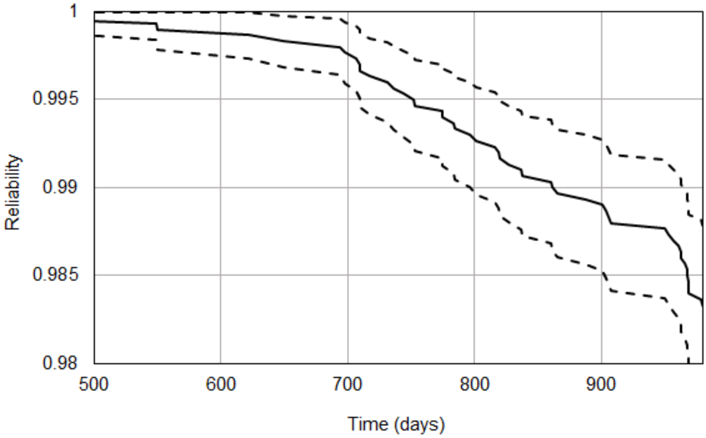


Figure 5.11: Design B - Reliability Estimation - Discontinuous lines show the 95% confidence interval

time is reduced to a maximum of 15 days. After EoM the time is reduced to less than 15 days, as the O_2 tank level decreases (the mission has been sized for EoM 919 days). As in design A, lack of food does never occur before EoM.

Reliability Analysis

In this case 2949 failure times occur at 983, 30 days after the crew runs out of food. The other 51 times are distributed between 419 and 981. As in the design A, most of LoC times are at day 983, and the data do not fit a Weibull distribution, as the Anderson-Darling estimator is 1111.180. Therefore, a non-parametric analysis has been carried out. Figure 5.11 shows the results of the KM reliability estimation, including a 95% confidence level. The $R(EoM)$ obtained is 98.8%, with a confidence interval [98.4 to 99.19].

As in design A, it is important to remark that the cause of the 2949 failure times occurring at day 983 is not a failure in the components, but because the tanks have been sized for the mission duration. The failure mode "lack of food", would actually never take place, as EoM is defined at 919 days.

ESM Calculation

The ESM is calculated for system B, in order to compare both reliability and ESM for both systems. As in design A, mass and volume of the components, the

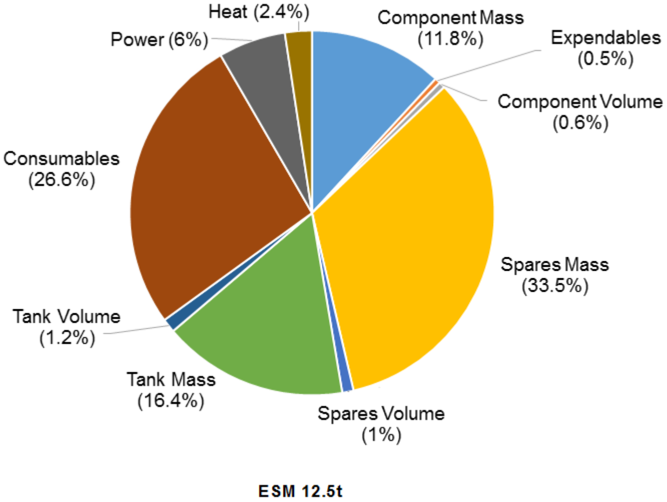


Figure 5.12: Design B - ESM Distribution

required spare parts and the tanks, consumables mass, power required and the heat produced by the system are taken into account. The ESM obtained is 12.5 tons. Detailed information in the ESM calculation can be found in appendix B.

Figure 5.12 shows the distribution of the ESM. In this case, the spares (including mass and volume) represent 34.5% of the ESM, being the major contributor, followed by consumables, tanks and components mass.

5.3.3 Comparison

As explained when selecting the two designs, design B should offer better characteristics regarding mass/power requirements. This can be proved, comparing the ESM contribution regarding mass and volume of components, spares and tanks, as well as the expendables, consumables, power and heat requirements, table 5.9.

A components mass reduction of about 40% for the design B can be observed. For tanks and consumables, the difference between both designs, compared with other parameters, is small. The highest difference between both systems is the mass of expendables (filters for MF) and spares mass and volume. To obtain similar reliabilities levels for the components, more spare parts are required for design A. Each design is composed of 12 components, but the required number of spares is higher for design B (27 vs 29). Moreover, the parts are heavier (as the mass of the components is almost double for design A). For design A, even with

Table 5.9: ESM Contributions for Designs A and B

Component	Design A (tons)	Design A (%)	Design B (tons)	Design B (%)
Components Mass	2.6	11.8	1.5	11.8
Expendables Mass	3.1	14.2	0.1	0.5
Components Volume	0.1	0.4	0.1	0.6
Spares Mass	8.9	40.5	4.2	33.4
Spares Volume	0.2	0.9	0.1	1.0
Tanks Mass	2.0	9.3	2.1	16.4
Tanks Volume	0.2	0.8	0.1	1.2
Consumables	3.8	17.2	3.3	26.7
Power	0.7	3.4	0.7	6
Heat	0.3	1.5	0.3	2.4
Total	21.9	100	12.5	100

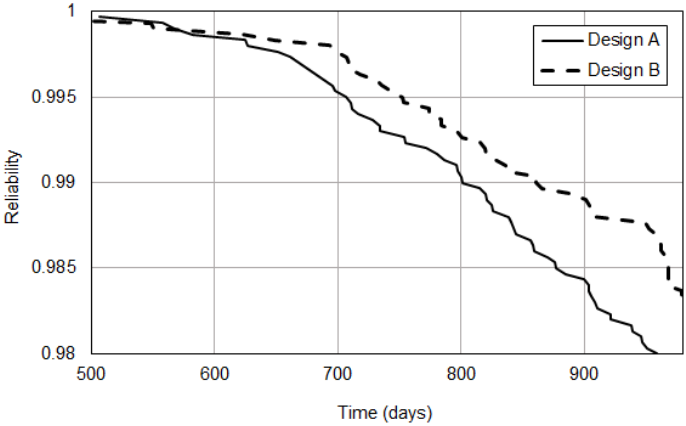


Figure 5.13: Designs A and B - Reliability Comparison

a higher mass of spares a lower reliability is obtained, figure 5.13. The reliabilities of the components has been fixed to a minimum of 99%. If this value is increased, a higher reliability can be obtained, but an increase on mass and spares volume would also be required.

Power and heat requirements are very similar in both cases.

5.4 Summary

The transfer vehicle for a round trip mission to Mars has been selected for a practical application of the proposed analysis methodology. According to the literature, a 919 days mission (224 days outbound, 458 days stay and 237 days return) and a crew of six have been chosen. Four astronauts will descend to the mass surface during the stay phase, while two remain in the transfer vehicle during the stay phase. The pressurized volume of the vehicle is set to 500 m^3.

The number of simulations has been set to 3 000, which ensures an error of 0.3% in component reliability simulation, with a 95% confidence interval.

Two different ECLSS are analyzed, one using ISS-like technology, and the other one using promising technologies but still under development. Both systems have been first analyzed with ELISSA, to size the consumables required and its tanks. The systems have been simulated 3000 times with RELISSA in order to set the required spares mass and evaluate $R(EoM)$. The data obtained have been analyzed using the non-parametric estimator KM. The reliabilities obtained are 98.3% and 98.8% for the ISS-like and the Advance Physico-Chemical (APC) system, respectively.

The ESM has been calculated for both systems, considering the mass and volume of the required spare parts. Results show that the spare represent an important part of the ESM, 41.4% and 34.5%, for the ISS-like and the APC system, respectively. Both systems require similar spare levels for its components, but since the components for the APC are lighter, the mass of the spare parts is lighter too.

The APC design offers a clear advantage regarding ESM (design A 21.9 tons and design B 12.5 tons), as the mass of the components including the required spare parts, expendables and consumables is smaller. However, some of the technologies used in the APC system have not been used in space yet, and therefore, full development and testing in a representative environment of these technologies are required.

During the simulation of both systems, the software has been validated, checking the program response, both statistically and to ECLSS simulation failures.

"In the end, everything will be ok. If it's not ok, it's not yet the end"

Fernando Sabino (1923 - 2004)

6

Conclusions and Future Work

The objective of this thesis is to develop a methodology to evaluate and analyze the reliability of the Environmental Control and Life Support System and its components (for atmosphere, water and waste management) for long duration spaceflight and implement it in a new software. The result is a new program dubbed *Reliability ELISSA*. The conclusions obtained in the process, as well as the next steps to follow, are explained in this chapter.

6.1 Conclusions

In chapter 2, the principles of an ECLSS have been analyzed, considering the human requirements, as well as the technologies available to fulfill these requirements. Some technologies are currently in use in the ISS: Water Electrolysis, 4-Bed Molecular Sieve, Multifiltration, Vapor Compression Distillation and Sabatier Reactor. However, in the past decades, promising technologies have been developed, allowing a reduction on system mass, power or consumables, and therefore might be considered for a long duration mission. The Equivalent System Mass has been widely used to evaluate ECLSS. The missions carried out up to date were either short duration missions or in Low Earth Orbit, making it possible to send the astronauts the required consumables or to bring the astronauts back to

Earth quickly, in case of a failure. For long duration missions and destinations far away, this will no longer be an option.

> *Conclusion 1: For long duration missions, physico-chemical or bioregenerative components (including those under development) are required. Non-regenerative technologies should be considered as a back-up solution. Different potential technologies have been analyzed. Only components with a TRL of at least 4, are considered for this thesis (14 regenerative components and 2 non-regenerative):*
>
> – Atmosphere Management: 4BMS, EDC, SAWD, SFWE, CO_2 electrolysis, LiOH Cartridges and O_2 Candles.
> – Water Management: VCD, TIMES, VPCAR, AES and MF.
> – Waste Management: SR, BR and PYRO.
> – Bio-regenerative: PBR.

> *Conclusion 2: Reliability will play an important role in long duration missions. As an increase on reliability will imply an increase of mass, reliability and the ESM, should be analyzed together for long duration missions.*

In chapter 3, the system reliability analysis method is selected. First, to evaluate the reliability, it is necessary to define the system failure. As the objective of the ECLSS is to keep the conditions for astronauts to survive within the space vehicle, system failure will occur at Loss of Crew.

> *Conclusion 3: The causes selected for system failure are lack of* O_2 *or excess of* CO_2 *in the atmosphere, lack of water or food, considering that humans can survive a specific amount of time out of the limits.*

The components within an ECLSS are complexly inter-connected, and a failure of a component does not mean an immediate LoC, e.g. if there is enough water in the tank to survive several days, a failure of the water recycling component will not imply LoC immediately. Therefore, a simulation of the ECLSS system is required.

> *Conclusion 4: A Stochastic Dynamic Discrete-event Simulation is the selected methodology, based on the ECLSS simulation tool ELISSA.*

> *Conclusion 5: The software RELISSA has been developed. It obtains the failure times after multiple simulations and provides the reliability of the system at EoM, either fitting the data in a Weibull distribution, when applicable, or using the non-parametric Kaplan-Meier estimator. It also provides the components' failure time at each simulation.*

To use the system reliability analysis method described and implemented as RELISSA, the reliability of each component needs to be previously set. Therefore, in chapter 4, a component reliability analysis method has been developed and implemented in RELISSA. For the majority of the potential components, failure historical data are not available, and the "handbook data" approach is used. The research of this information, especially for the components still under development, has been a major complex task.

> *Conclusion 6: A database has been created, which includes the structure of 15 regenerative components (obtained from previous studies) and the failure rates of its parts (obtained from space-related publications or generic databases). The components have 10 to 20 different types of parts.*
>
> *Conclusion 7: A Multiple-Objective Optimization Problem is chosen to evaluate the components reliability. As an increase of reliability implies an increase of mass (more spare parts are required to repair the component), an optimum value of spare parts is required. The problem faced is to maximize reliability while minimizing the mass. The result of the MOOP is a set of nondominated solutions (the ones that cannot be improved in one of the objectives, without degrading the other one). The user will then have to decide which nondominated solution fits better for a specific mission, either by selecting the maximum allowable mass or the minimum desired reliability.*
>
> *Conclusion 8: For some components, still under development, it is necessary to consider the same number of spare parts to be taken for each type of part. This is a first approximation, as the mass of each part is not available, thus the MOOP problem cannot be solved.*

In order to test and show the performance of the new software RELISSA, in chapter 5, a long duration mission analysis has been carried out. According to the literature, a Mars round-trip mission fits within the plans of space agencies and private companies for the coming decades. The mission analyzed is the transfer vehicle of a round-trip to Mars, which includes an outbound trip of 224 days, a stay of 458 days and a return of 237 days. The crew will be six for the outbound and return phases and two for the stay phase. It is assumed that four astronauts will descend with a surface vehicle, while two remain in the transfer vehicle orbiting Mars. Two different systems have been analyzed: one using currently used technologies (ISS-like system) and one using physico-chemical components still under development, the Advanced Physico-Chemical. First, the two systems have been simulated with ELISSA (without failures), to size the tanks and consumables required. Then, 3000 simulations have been carried out with RELISSA to evaluate its reliability. The ESM (including spare parts) and the reliability (using a KM estimator) have been estimated for both systems.

> *Conclusion 9: For a set reliability of at least 99% for each component, the reliabilities obtained are 98.3% for design A and 98.8% for design B. The spare levels required range from three to six, depending on the component. A high number of repairs will be required for each component.*

> *Conclusion 10: Spare parts represent, in mass and volume, 41.8% of the ESM for the ISS-like design, and 34.5% in the Advanced Physico-Chemical. Although the spare levels for the components are similar in both cases, the mass of the components for the Advanced Physico-Chemical system is much lower, and as a consequence, the spares mass is also lower. For surface missions, in-situ spares production should be considered.*

> *Conclusion 11: The Advanced Physico-Chemical design offers a mass reduction of more than 40% of the ESM compared to ISS-like (design A 21.9* tons *and design B 12.5* tons*) Although the technologies in the ISS-like design are more known, the reduction in mass (especially in the components, expendables and spares mass), represents a high advantage. Therefore, such technologies should be fully developed in the coming years, for a long duration mission to be feasible, regarding ECLSS.*

> *Conclusion 12: The software tool RELISSA has been validated. The number of required simulations to obtain a representative result has been analyzed, and the behavior of the program, both regarding the statistical approach and ECLSS simulation response to failures, has been checked.*

6.2 Future Work

The results obtained by using the methodologies developed in this thesis depend highly on the components' reliability data available. For this study a first approximation has been carried out, to obtain a preliminary reliability estimation. This methodology should only be used, at this point, to compare reliabilities of different systems, as the values obtained cannot be considered as an absolute reliability measure.

However, RELISSA has been programmed to allow an easy update of the reliability information. As a consequence, as mission design progresses, it will be possible to update the components information and obtain a more accurate reliability estimation.

Different approaches can be used to update RELISSA, depending on the type of information that can be provided:

- If a component can be fully tested in a representative environment, the reliability of the component can be directly estimated from the test data and implemented in RELISSA. However, the use of spare parts should already be considered during the test phase, as the designed MOOP solver cannot be used if the component is treated as an entire item.
- For some components, it was not possible to optimize the number of spare parts, as the mass of each part could not be found at this point. When detailed information of a component is available, it can be introduced in RELISSA, and the MOOP can be solved.
- If new information regarding component's structure, part's failure rate or part's mass can be provided, RELISSA Data Base should be updated.

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Zusammenfassung

Analyse und Simulation eines synergetischen Lebenserhaltungssystems für Langzeitmissionen

1. Einführung

Bemannte Missionen, die in den letzten Jahrzehnten durchgeführt wurden, waren meist entweder Kurzzeitmissionen (zwei Wochen bis sechs Monate) oder in Erdnähe (400 km). Die zukünftigen Pläne der Raumfahrtagenturen enthalten Missionen zu Asteroiden, dem Mond oder Mars. Mit solchen Missionen steigt die Missionsdauer auf ein bis 3 Jahre an und die Entfernung erhöht sich auf einige hundert Millionen Kilometer.

Mehrere Robotermissionen zu diesen Zielen wurden in den letzten Jahren schon erfolgreich durchgeführt. Allerdings stellen bemannte Missionen eine neue Herausforderung dar: dies gilt vor allem für das Lebenserhaltungssystem (ECLSS - *Environmental Control and Life Support System*).

Zukünftige Langzeitmissionen erfordern Recyclingsysteme, damit die Masse der Verbrauchsgüter der Mission und somit ein groSSer Teil der Kosten für eine Mission reduziert werden. Daneben gilt es, die Zuverlässigkeit speziell dieses Systems sicher zu stellen.

Das Hauptziel dieser Arbeit ist es, eine Vorgehensweise zu entwickeln, um die Zuverlässigkeit einer hochregenerativen ECLSS und dessen Komponenten zu analysieren. Die Vorgehensweise soll in eine neue Software implementiert werden, um ECLSS bewerten und vergleichen zu können.

2. Das Lebenserhaltungssystem

Das Lebenserhaltungssystem sorgt dafür, die notwendigen Randbedingungen für das Überleben der Astronauten im Inneren des Raumfahrzeugs aufrecht zu erhalten. Das System kann entsprechend dem Recycling-Niveau klassifiziert werden:

- Offene Systeme (ohne Recycling): geeignet für Missionen über Tage und Wochen.
- Physico-chemische Systeme (Recycling durch physikalische oder chemische Prozesse): Missionsdauer von Monaten bis Jahren.
- Biologische Systeme (Recycling durch Algen/Pflanzen): Missionen über Jahrzehnte.
- Hybridsysteme (Kombinationen von bisherigen Systemen).

Die Aufgaben des Systems können in vier Subsysteme unterteilt werden:

- Luftmanagement: Regelung der Luftzusammensetzung und des Luftdrucks, Temperatur- und Feuchtigkeitskontrolle und Luftfilterung.
- Wassermanagement: Wasserversorgung und -aufbereitung (nach den für Hygiene und Trinkwasser erforderlichen Standards).
- Nahrungsversorgung: Nahrungsproduktion und/oder -versorgung.
- Abfallmanagement: Abfallsammlung, -speicher und/oder -behandlung.

Jede dieser Aufgaben wird von einer Komponente erfüllt. Die möglichen Komponenten wurden untersucht, um die für eine Langzeitmission geeigneten zu identifizieren. Dabei werden Komponenten berücksichtigt, welche gegenwärtig in Betrieb sind sowie diejenigen, welche in der Entwicklungsphase und erfolgversprechend sind. Die ausgewählten Optionen, deren Zuverlässigkeit analysiert wurde, sind:

- Komponente für Luftmanagement:
  - Für die Filterung von Kohlendioxid (CO_2):
    - *4-Bed Molecular Sieve* (4BMS), wird derzeit auf der Internationalen Raumstation (ISS - *International Space Station*) verwendet.
    - *Electrochemical Depolarized* CO_2 *Concentrator* (EDC)
    - *Solid Amine Water Desorption* (SAWD)
  - Für Sauerstoff (O_2) Produktion:

    - Wasserelektrolyse, wird derzeit auf der ISS verwendet.
    - Elektrolyse von CO_2 (und dessen weitere Verwertung).

- Für die Wasseraufarbeitung gilt es, zwei Arten von Komponenten zu unterscheiden:
  - Destillation (kann Abwasser und Urin aufarbeiten):
    - *Vapor Compression Distillation* (VCD), wird derzeit auf der ISS verwendet.
    - *Thermoelectric Integrated Membrane Evaporator* (TIMES).
    - *Vapor Phase Catalytic Ammonia Removal* (VPCAR).
    - *Air Evaporation System* (AES).
  - Filtration (kann nur Abwasser aufarbeiten):
    - *Multifiltration* (MF), wird derzeit auf der ISS verwendet.

- Für Nahrungsmittelproduktion:
  - *Photobioreaktor* (PBR).

- Für Abfallbehandlung mit Berücksichtigung der CO_2-Reduzierung aus den folgenden Komponenten:
  - *Sabatier Reactor* (SR), derzeit auf der ISS verwendet.
  - *Advance Carbon Reduction System* (ACRS).
  - *Bosch Reactor* (BR).

Nicht-regenerative Systeme wie Sauerstoffkerzen oder LiOH-Kartuschen wurden bereits in mehreren Missionen verwendet. Für Langzeitmissionen könnten sie als Notreserve zur Erhöhung der Systemzuverlässigkeit verwendet werden.

Die zwei derzeit benutzten Methoden zur Bewertung eines ECLSS sind: die Äquivalente Systemmasse (ESM - *Equivalent System Mass*) und das technologische Entwicklungsniveau (TRL - *Technologie Readiness Level*). AuSSerdem sind Simulationsprogramme erforderlich, um komplexe Systeme analysieren zu können und die Entwicklung des Systems während der Mission zu beurteilen. In Bezug auf die Zuverlässigkeit wurden in den letzten Jahrzehnten entweder einzelne Komponenten oder einfache Systeme analysiert.

3. Vorgehensweise zur Analyse der Systemzuverlässigkeit

Der Ausfall eines ECLSS tritt auf, wenn das System nicht in der Lage ist, die für das Überleben der Astronauten notwendigen Bedingungen aufrecht zu erhalten. In der vorliegenden Arbeit werden vier Fehlerarten betrachtet: Kohlendioxidüberschuss, Sauerstoff-, Wasser- und Nahrungsmangel.

Das Lebenserhaltungssystem besteht aus verschiedenen Komponenten, die in Kapitel 2 genannt werden. Diese Komponenten sind in komplexer Weise miteinander verbunden und ein Ausfall einer Komponente führt nicht zwangsläufig zu einem unverzüglichen Ausfall des Systems. Deshalb ist es notwendig, ein dynamisches, stochastisches Simulationsverfahren zu verwenden, damit die Zuverlässigkeit eines ECLSS für Langzeitmissionen bewertet werden kann.

Um eine dynamische, stochastische Simulation durchzuführen, ist ein ECLSS Simulationsmodell erforderlich. Das Programm *Environment for Life-Support Systems Simulation and Analysis* (ELISSA), das seit Ende der 1990er Jahre am Institut für Raumfahrsysteme (IRS) der Universität Stuttgart entwickelt wird, wurde hierfür gewählt. Das neue Programm soll das ECLSS mehrmals simulieren, so dass die Komponenten semi-zufällig entsprechend ihrer Wahrscheinlichkeitsverteilung ausfallen. Diese Wahrscheinlichkeitsverteilung jeder Komponente ist komplex und wird aus der Fehlerrate jedes Komponententeils berechnet. Diese Vorgehensweise wird in Kapitel 4 beschrieben.

Zunächst wird die Zuverlässigkeit des Systems mit parametrischen Modellen (Weibull) bewertet, einmal durch die Methode maximale Wahrscheinlichkeit und zum andern mit nicht-parametrischen Modellen (Kaplan-Meier).

Diese Vorgehensweise wurde in einem neuen Programm *Reliability ELISSA* (RELISSA) eingeführt, das eine modifizierte Version von ELISSA sowie neue Unterprogramme enthält. Eine benutzerfreundliche Oberfläche ermöglich es dem Benutzer, die Anzahl der durchzuführenden Simulationen und die Eigenschaften des gewählten ECLSS (Komponenten, Tanks, etc.) und der Mission (Dauer, Crew, etc.) einzugeben. Als Ergebnis wird eine Datei mit Zuverlässigkeitsdaten erstellt, zum Beispiel Zuverlässigkeit am Ende der Mission, Ausfall-Zeiten der Komponenten und Ausfallursachen des Systems.

4. Vorgehensweise zur Analyse der Zuverlässigkeit der Komponenten

Um RELISSA verwenden zu können, müssen die Zuverlässigkeiten der in einem ECLSS verwendeten Komponenten definiert werden. Die Zuverlässigkeit der einzelnen Komponenten ist durch die Ausfallraten der Komponententeile (zum Beispiel Ventile, Wärmetauscher, etc.), welche aus Raumfahrtstudien und Datenbanken übernommen werden, definiert.

Das Problem einer Mehrzieloptimierung (MOOP - Multi-Objective Optimitzation Problem) wird für jede Komponente mit den zusätzlich erforderlichen Bauteilen vorgestellt. Ziel ist eine hohe Zuverlässigkeit mit der geringstmöglichen Masse zu erhalten. Es zeigt sich, dass die Verwendung von Redundanzen für eine Langzeitmission notwendig ist, angesichts der Zuverlässigkeit des Systems ohne Ersatzteile nach 60 Tagen von weniger als 50%.

Die Zuverlässigkeitsanalyse für alle in Kapitel 2 ausgewählten Komponenten wurde unter Berücksichtigung der Verwendung von Redundanzen in RELISSA angewendet.

5. Praktische Anwendung

Um die Vorgehensweise und das neue Programm RELISSA zu überprüfen, wurden zwei ECLSS-Entwürfe für eine Mars-Mission analysiert. Eine mit Technologien, die derzeit im Einsatz auf der ISS sind, und eine mit Komponenten in der Entwicklungsphase, aber mit dem Potenzial einer reduzierten Systemmasse.

- Entwurf A: ISS-Technologie (4BMS, Wasserelektrolyse, VCD, MF und SR)
- Entwurf B: mit physico-chemischen Komponenten in der Entwicklungsphase (EDC, Wasserelektrolyse, VPCAR, AES, SR und Pyrolyse).

Die Mission besteht aus Hinreise (224 Tage), Aufenthalt (458) und Rückreise (237) mit sechs Astronauten. Hierbei wurde ausschlieSSlich das Transfer-Fahrzeug analysiert. Während der Aufenthaltsphase wird das Fahrzeug mit zwei Astronauten den Mars umkreisen. Die restlichen vier werden auf der Oberfläche des Mars landen.

Die beiden Entwürfe wurden zuerst mit ELISSA simuliert, um das ECLSS zu dimensionieren (Betriebsniveau der Komponenten, TankgröSSen und notwendige Verbrauchsgüter). Zunächst wurde mit RELISSA analysiert, wie viele zusätzliche Bauteile erforderlich sind, damit eine hohe Zuverlässigkeit mit geringstmöglicher Masse möglich ist. Die Entwürfe wurden dann 3000 Mal mit RELISSA simuliert, und da die Daten keinem parametrischen-Modell folgten, wurde die Zuverlässigkeit des Systems durch die nicht-parametrische Kaplan-Meier-Schätzung ausgewertet.

Die erhaltene ESM und Zuverlässigkeit des Lebenserhaltungssystems am Ende der Mission (919 Tagen) sind 21.9 Tonnen und 98.3% für Entwurf A und 12.5 Tonnen und 98.8% für Entwurf B. Die Ersatzteile sind ein wesentlicher Teil der Masse des jeweiligen Systems (41.4% und 35.5%). Beide Systeme erfordern eine ähnliche

Anzahl von Ersatzteilen, aber da die Masse der Komponenten des Entwurfs A höher ist, ergibt sich auch eine höhere Ersatzteilmasse.

Entwurf B hat einen klaren Vorteil durch Massereduktion bei ähnlichem Zuverlässigkeitsniveau des Entwurfs A. Allerdings wurden die meisten der verwendeten Komponenten in Entwurf B noch nicht im Weltraum eingesetzt und erfordern weiterhin Entwicklung und Validierung, bevor sie für eine Mission eingesetzt werden können.

6. Fazit und Ausblick

In Kapitel 2 wurden die Grundlagen des Lebenserhaltungssystems analysiert und 14 regenerative physico-chemische und biologische Komponenten ausgewählt, welche sich für Langzeitmissionen eignen. Nicht-regenerative Lösungen sind ebenfalls in Betracht gezogen worden und sollten hauptsächlich als Notfallsysteme verwendet werden. Aus den Analyzen konnte geschlossen werden, dass die Zuverlässigkeit eine noch wichtigere Rolle bei den Langzeitmissionen spielen wird, da eine Rettungsmission nicht möglich sein wird. Infolge dessen sind die Parameter Masse und Zuverlässigkeit für Lebenserhaltungssysteme gleichermaSSen zu berücksichtigen.

Zwei Vorgehensweisen wurden entwickelt:

- Analyse der Zuverlässigkeit eines Lebenserhaltungssystems: Die Methode basiert auf der dynamischen, stochastischen Simulation. Diese Vorgehensweise ist mit dem Simulationsprogramm ELISSA realisiert. Typische Werte für geforderte Zuverlässigkeiten, Wahrscheinlichkeitsmodelle, sowohl parametrische als auch nicht-parametrische, wurden zur Schätzung der Zuverlässigkeit des Systems verwendet.
- Analyse der Zuverlässigkeit der Komponenten eines Lebenserhaltungssystems: Eine Datenbank mit Bauteile-Informationen (Masse und Ausfallrate) wurde erstellt. Um die Anzahl der jeweils benötigten Ersatzteile zu bestimmen (mit höchster Zuverlässigkeit und kleinster Masse), musste das Mehrzieloptimierungsproblem gelöst werden.

Ein neu entwickeltes Programm, RELISSA, wurde für zwei mögliche Anwendungen ausgelegt, zum einen für die Analyse der Zuverlässigkeit der Komponenten eines Lebenserhaltungssystems und zum anderen zur Analyse der 14 ausgewählten Komponenten. Mit RELISSA ist es möglich, unterschiedliche Kombinationen von Lebenserhaltungssystemen zu simulieren und zu analysieren.

SchlieSSlich wurden zwei ECLSS Entwurfsanalysen durchgeführt, um die vorgeschlagene Vorgehensweise zu überprüfen: die eine mit aktuellen Technologien und die andere mit viel versprechenden Technologien in der Entwicklungsphase. Es konnte gezeigt werden, dass die Anzahl von Simulationen repräsentativ ist und das Verhalten des Programms für Systemuntersuchungen und zur Systemoptimierung geeignet ist. Die Ergebnisse zeigen, dass die ausgewählten Komponenten in der Entwicklungsphase einen klaren Vorteil bei der Verringerung der Masse haben. Unbestritten ist, dass noch ein groSSer Aufwand für Entwicklung und Lebensdauertest notwendig ist, bevor an den Einsatz in zukünftigen bemannten Missionen gedacht werden kann.

Die Ergebnisse der Simulationen sind mit den Zuverlässigkeitsdaten der Komponenten stark gekoppelt. Für die vorliegende Arbeit mussten für einige der Komponenten Ansatzdaten benutzt werden, als in einigen Fällen genauere Daten nicht verfügbar sind. Das entwickelte Programm ist so gestaltet worden, dass der Benutzer bei vorhandenem Datensatz durch Änderungen spezifische Missionprofile simulieren kann.

Resum - Anàlisi i simulació d'un sistema sinergètic de control ambiental i de suport a la vida per a missions de llarga durada

1. Introducció

Les missions espacials tripulades realitzades en les últimes dècades han sigut missions de curta durada (de dues setmanes a sis mesos) o properes a la Terra (400 quilòmetres). Els futurs plans de les agències espacials i del sector privat inclouen viatges a asteroides, a la Lluna o a Mart. Amb aquestes missions, la durada s'incrementa d'un a tres anys i la distància a la Terra augmenta en centenars de milers de quilòmetres.

En els últims anys, ja s'han realitzat diverses missions robòtiques a aquestes destinacions. No obstant això, les missions tripulades impliquen un nou repte: el disseny del sistema de control ambiental i de suport a la vida (ECLSS - *Environmental Control and Life Support System*).

Per a les futures missions de llarga durada, serà necessari utilitzar sistemes de reciclatge per a reduir la massa del béns necessaris al llarg de la missió, i així una bona part dels costos de la missió. A més, per a aquest sistema en particular és important assegurar-ne la fiabilitat.

L'objectiu principal d'aquesta tesi és desenvolupar una metodologia per a avaluar i analitzar la fiabilitat d'ECLSS altament regeneratius i dels components que els poden formar. Aquesta metodologia s'ha d'implementar en un nou software, per tal de poder avaluar i comparar diferents ECLSS.

2. El sistema de control ambiental i de suport a la vida

El sistema de control ambiental i de suport a la vida és l'encarregat de mantenir les condicions necessàries per a la supervivència dels astronautes dins del vehicle espacial. L'ECLSS es pot classificar en funció del nivell de reciclatge del sistema:

- Sistema obert (sense reciclatge): apte per a missions de dies a setmanes.
- Sistema fisicoquímic (reciclatge a partir de processos físics o químics): per a missions de mesos a anys.
- Sistema biològic (reciclatge a partir d'algues/plantes): per a missions de dècades.
- Sistema híbrid (combinació dels sistemes anteriors).

Les tasques ha realitzar per l'ECLSS es poden agrupar en quatre subsistemes:

- Gestió de l'atmosfera: control de la composició i pressió de l'aire, de la temperatura i de la humitat i filtració.
- Gestió de l'aigua: abastament i reciclatge d'aigua (amb els estàndards necessàris per a higiene i aigua potable).
- Gestió de l'alimentació: producció i/o subministrament d'aliments.
- Gestió de residus: recollida, emmagatzematge i/o tractament dels residus.

Cada una d'aquestes tasques es realitza a partir d'un component. S'han estudiat els possibles components, per tal d'identificar aquells que es podrien emprar per a una missió de llarga durada. S'han tingut en compte components actualment en ús, així com aquells prometedors i en fase de desenvolupament. Les diferents opcions seleccionades, i que seran posteriorment analitzades en quant a la fiabilitat, són:

- Components per a la gestió de l'atmosfera:
  - Per a l'extracció de diòxid de carboni (CO_2):
    - *4-Bed Molecular Sieve* (4BMS), actualment en ús a l'Estació Espacial Internacional (ISS - *International Space Station*).
    - *Electrochemical Depolarized* CO_2 *Concentrator* (EDC)
    - *Solid Amine Water Desorption* (SAWD)
  - Per a la producció d'oxigen (O_2):
    - electròlisi d'aigua, actualment en ús a l'ISS.
    - electròlisi de CO_2 (permet alhora reutilitzar el CO_2 produit).
- Per al reciclatge de l'aigua, cal distingir dos tipus de components:
  - Reciclatge per destil·lació (pot tractar aigües residuals i orina):

        - *Vapor Compression Distillation* (VCD), actualment en ús a l'ISS.
        - *Thermoelectric Integrated Membrane Evaporator* (TIMES).
        - *Vapor Phase Catalytic Ammonia Removal* (VPCAR).
        - *Air Evaporation System* (AES).
    - Filtració (només pot tractar aigües residuals):
        - *Multifiltration* (MF), actualment en ús a l'ISS.

- Components per a la producció d'aliments:
    - *Photo-Bio-Reactor* (PBR).

- Per al tractament de residus s'ha considerat la reducció del CO_2, a partir de:
    - *Sabatier Reactor* (SR), actualment en ús a l'ISS.
    - *Advance Carbon Reduction System* (ACRS).
    - *Bosch Reactor* (BR).

Sistemes no-regeneratius com *Oxygen Candles* o *LiOH cartridges* s'han utilitzat en diverses missions. Per a les de llarga durada, poden utilitzar-se com a sistema d'emergència per a incrementar la fiabilitat del sistema.

Les dues eines utilitzades actualment per avaluar els ECLSS, són: la massa equivalent del sistema (ESM - *Equivalent System Mass*) i el nivell de desenvolupament tecnològic (TRL - *Technology Readiness Level*). A més, per poder dissenyar un ECLSS complex cal una eina de simulació per poder avaluar els béns consumibles necessaris i l'evolució del sistema al llarg de la missió. En quan a la fiabilitat del sistema, en les últimes dècades s'han realitzat únicament anàlisis de components aïllats o sistemes senzills.

3. Mètode d'anàlisi de la fiabilitat del sistema

La fallada d'un ECLSS es produeix quan el sistema és incapaç de mantenir les condicions necessàries per la supervivència dels astronautes. Per aquesta treball s'han considerat quatre possibilitats de fallada: excés de CO_2, falta d'O_2, d'aigua i d'alimentació.

L'ECLSS està format pels diversos components, explicats en el capítol 2. Aquests components estan connectats de forma complexa i la fallada d'un component no implica la fallada immediata del sistema. Per tant, per poder avaluar la fiabilitat d'un ECLSS per a missions de llarga durada, és necessari utilitzar un sistema estocàstic dinàmic de simulació.

Per a dur a terme una simulació dinàmica, estocàstica del sistema cal un model de simulació d'ECLSS. S'ha seleccionat el programa *Environment for Life-Support Systems Simulation and Analysis* (ELISSA), desenvolupat des de la dècada dels 90 a l'Insitut d'Estudis Espacials (IRS - *Institut für Raumfahrtsysteme*) de la Univeristat de Stuttgart. Aquest nou programa ha de simular l'ECLSS diverses vegades, fent fallar els components de forma aleatòria, a partir de la funció de distribució de cada component. La funció de distribució de cada component és complexa i es calcula a partir de la taxa de fallada de cada una de les parts que el componen. Aquest procés s'explica al capítol 4.

A continuació s'avalua la fiabilitat del sistema ECLSS, mitjançant models paramètrics (Weibull) pel mètode de mínims quadrats per dades censurades i de models no paramètrics (Kaplan-Meier).

Aquest procés s'ha implementat en un nou programa *Reliability ELISSA* (RELISSA), que conté una versió modificada d'ELISSA, així com nous subprogrames. Una senzilla interfície d'usuari permet a l'usuari triar el nombre de simulacions a realitzar i definir les propietats de l'ECLSS (components, tancs, etc.) i de la missió (durada, tripulació, etc.). Com a resultat, s'obté un fitxer amb dades relatives a la fiabilitat, per exemple la fiabilitat al final de la missió, dades de les fallades dels components i causes de la fallada.

4. Mètode d'anàlisi de fiabilitat dels components

Per a poder utilitzar RELISSA, cal definir prèviament les fiabilitats dels components a utilitzar en un ECLSS. La fiabilitat de cada component es defineix a partir de les taxes de fallada de les parts que el formen (per exemple vàlvules, intercanviadors de calor, etc.), que han estat extretes d'estudis de l'àmbit espacial i bases de dades.

S'ha plantejat el problema d'optimització d'objectius múltiples (MOOP - *Multi-Objective Optimization Problem*) per a cada component i les peces de recanvi requerides. L'objectiu és obtenir una alta fiabilitat amb la menor massa possible. S'ha observat que l'ús de sistemes redundants és necessari per a missions de llarga durada, ja que la fiabilitat dels components sense recanvis és inferior al 50% passats 60 dies.

S'ha implementat a RELISSA l'estimació de la fiabilitat per a tots els components seleccionats en el capítol 2, considerant l'ús de redundàncies.

5. Aplicació Pràctica

Per a validar la nova metodologia i el nou programa RELISSA, s'han analitzat dos dissenys d'ECLSS per a una missió a Mart. Un disseny amb tecnologies actualment en ús a la ISS i l'altre amb components en fase de desenvolupament, amb el potencial de reduir la massa del sistema.

- Disseny A: tecnologies de l'estació espacial internacional (4BMS, electròlisi d'aigua, VCD, MF i SR)
- Disseny B: components fisicoquímics en desenvolupament (EDC, electròlisi d'aigua, VPCAR, AES, SR i piròlisi).

La missió a Mart inclou un viatge d'anada (224 dies), estada (458) i retorn (237), amb sis astronautes. El vehicle analitzat és el de transferència. Durant l'estada dos astronautes romandran en el vehicle orbitant Mart. Els altres quatre realitzaran un descens a la superfície en un altre vehicle.

Els dos dissenys s'han simulat primer amb el software ELISSA, per a dimensionar l'ECLSS (seleccionar el nivell de funcionament dels components, tancs i béns necessaris). A continuació, s'ha utilitzat RELISSA per analitzar el nombre de peces de recanvi necessàries per maximitzar la fiabilitat i minimitzar la massa. S'han dut a terme 3000 simulacions de cada disseny i s'ha avaluat la fiabilitat dels ECLSS mitjançant l'estimador de Kaplan-Meier, ja que les dades no s'ajustaven a cap model probabilístic paramètric.

La massa equivalent del sistema i la fiabilitat al final de la missió (919 dies) obtingudes són de 21.9 tones i 98.3% per al disseny A i 12.5 tones i 98.8% per al disseny B. Les peces de recanvi representen una part important de la massa del sistema (41.4% i 35.5% respectivament). Els dos sistemes requereixen un nombre semblant de peces de recanvi, però degut a que la massa dels components del disseny A és més gran, la massa en recanvis també ho serà.

El disseny B ofereix un clar avantatge en quant a reducció de massa, per a nivells similars de fiabilitat. Tot i així, cal tenir en compte que la majoria dels components utilitzats en el disseny B encara no s'han fet servir a l'espai, i caldrà un esforç en desenvolupament i proves de vida abans no puguin ser utilitzats per a un missió.

6. Conclusions i treballs futurs

En el capítol 2, s'han analitzat els principis del sistema de control ambiental i de suport a la vida, i s'han seleccionat 14 possibles components regeneratius (fisicoquímics i biològics), aptes per a missions de llarga durada. S'han inclòs també components no regeneratius com a sistemes d'emergència. Finalment, es conclou que la fiabilitat jugarà un paper encara més important per a missions de llarga durada, ja que una missió de rescat no serà possible. Així, els dos paràmetres a considerar per l'anàlisi de l'ECLSS són la massa i la fiabilitat.

S'han elaborat dues metodologies, que s'han implementat en un nou programa, RELISSA:

- L'anàlisi de la fiabilitat d'un ECLSS. Es realitza a partir de la simulació estocàstica dinàmica del sistema. Aquest procés està basat en el programa de simulació ELISSA. S'han utilitzat models probabilístics propis de la fiabilitat, tant paramètrics com no-paramètrics, per estimar la fiabilitat del sistema.
- L'anàlisi de la fiabilitat dels components que poden formar un ECLSS. S'ha creat una base de dades de components que inclou les parts que el formen (la seva massa i la taxa de fallada). Per a obtenir el nombre de peces de recanvi necessàries en cada cas (maximitzant la fiabilitat i minimitzant la massa), s'ha resolt el problema d'optimització d'objectius múltiples.

S'ha creat un nou software, RELISSA, per implementar aquestes dues metodologies, per una banda l'anàlisi de fiabilitat d'un ECLSS i per altra, l'anàlisi de fiabilitat dels 14 components seleccionats. Com a resultat, RELISSA permet simular i analitzar la fiabilitat de diferents combinacions d'ECLSS.

Finalment, per posar a prova les metodologies desenvolupades i el nou programa RELISSA, s'han analitzat i comparat dos dissenys d'ECLSS: un amb tecnologies actuals i l'altre amb tecnologies molt més prometedores en fase de desenvolupament. S'ha comprovat que el nombre de simulacions realitzades és representatiu i que el comportament del programa per a l'estudi i optimització del sistema és l'adequat. Els resultats obtinguts mostren que els components en fase de desenvolupament ofereixen un clar avantatge en reducció de massa. No obstant, és recomanable un esforç, tant en desenvolupament com en proves de vida, per a que sigui factible utilitzar-los en les futures missions tripulades.

Els resultats obtinguts en les simulacions estan lligats a les dades de fiabilitat dels components. Per a aquest treball, per alguns components s'han utilitzat dades aproximades per tal d'obtenir una primera aproximació de la fiabilitat del sistema, ja que en alguns casos, les dades no estan actualment disponibles. El programa s'ha dissenyat de tal manera que l'usuari pugui modificar fàcilment aquestes dades, quan estiguin disponibles.

Appendices

A

ECLSS Components

In this appendix the components selected in this thesis for a long duration mission are analyzed. For each component, technical information, such as mass, volume and Technology Readiness Level, as well as a list of its parts, are provided. Failure rates for each parts and its source, can also be found for each component.

A.1 Air Management

The general components for air management are TCCS and CHX.

For CO_2 removal, three components are analyzed: 4BMS, EDC and SAWD.

Regarding O_2 generation, two possible options are provided: SFWE and CO_2 electrolysis.

CHX

Table A.1: CHX Technical Information - Adapted from [52, 75]

Mass	50 kg
Volume	0.4 m^3
Power Required	- kW
Heat Generated	2454 kJ/kg processed
TRL	8

Table A.2: CHX Reliability Data - Adapted from [52, 75]

Part	Number	MTBF (1/hour)	Mass (kg)	Source
Condensing Heat Exchanger	1	1.20E-06	49.71	[52]
Electronic Interface Box	2	4.25E-07	4.037	[52]
Fan Delta Pressure Sensor	1	8.00E-07	0.4535	[52]
Inlet ORU	1	3.00E-06	25.31	[52]
Liquid Sensor	2	8.80E-07	0.635	[52]
Pressure Transducer	1	8.00E-07	0.4762	[52]
Temperature Control Check Valve	2	3.04E-05	7.4526	[52]
Temperature Sensor	4	2.66E-08	0.263	[52]
Water Evaporator	2	7.65E-06	11.93	[52]

TCCS

Table A.3: TCCS Technical Information - Crew Size 6 - Adapted from [52, 75]

Mass	78 kg
Volume	0.27 m^3
Power Required	180 W
Heat Generated	N/D
TRL	8

Table A.4: TCCS Reliability Data - Adapted from [52, 53, 75]

Part	Number	MTBF (1/hour)	Mass (kg)	Source
Activated Charcoal Bed	1	4.65E-06	36.65	[52]
Blower	1	8.23E-07	2.94	[52]
Catalytic Oxidizer	1	1.12E-05	11.05	[52]
Electronic Interface Assembly	1	2.07E-06	3.42	[52]
Flowmeter	1	1.07E-06	1.09	[52]
LiOH Sorbent Bed	1	4.15E-06	4.11	[52]

4BMS

Table A.5: 4BMS Technical Information - Crew Size 4 - Adapted from [52, 75]

Mass	200 kg
Volume	0.39 m^3
Power Required	860 W
Heat Generated	860 W
TRL	8

Table A.6: 4BMS Reliability Data - Adapted from [52, 53, 75]

Part	Number	MTBF (1/hour)	Mass (kg)	Source
Blower	1	8.00E-06	2.30	[52, 75]
Desiccant bed	2	1.30E-05	17.30	[52, 75]
Heat exchanger	3	5.99E-06	3.30	[52, 75]
Humidity Sensor	1	1.00E-06	0.10	[52, 75]
Pre-cooler	1	5.99E-06	2.70	[52, 75]
Pressure Sensor	2	1.00E-05	0.20	[52, 75]
Pump	1	1.50E-05	9.50	[52, 75]
Sample Port	2	1.00E-05	0.10	[52, 75]
Sorbent Bed	2	1.30E-05	23.60	[52, 75]
Temperature Sensor	3	1.00E-05	0.10	[52, 75]
Valve (check)	2	6.00E-06	0.10	[52, 75]
Valve (3-way)	6	1.00E-05	2.00	[52, 75]

EDC

Table A.7: EDC Technical Information - Crew Size 4 - Adapted from [6]

Mass	44 kg
Volume	0.4 m^3
Power Required	42 W
Heat Generated	336 W
TRL	6

Table A.8: EDC Reliability Data - Adapted from [52, 54, 75, 76]

Part	Number	MTBF (1/hour)	Mass (kg)	Source
Accumulator	1	5.00E-07	0.91	[76]
Cell	3	3.00E-06	6.8	[76]
Combustible Gas Sensor	1	1.00E-05	0.2	[76]
Current Controller	1	1.00E-06	0.91	[76]
Current Sensor	1	2.14E-06	0.2	[76]
Filter	6	5.00E-06	2.09	[76]
Flow Sensor	2	1.00E-05	1	[76]
Flow Sensor Controller	1	1.00E-05	5.9	[76]
Heat Exchanger	2	6.00E-06	0.8	[76]
Humidity Sensor	2	1.00E-06	0.2	[76]
Pressure Controller	1	1.00E-05	0.6	[76]
Pressure Regulator	1	1.00E-05	1.36	[76]
Pressure Sensor	2	1.00E-05	0.2	[76]
Pump	1	1.50E-05	6.35	[76]
Temperature Sensor	2	1.00E-05	0.1	[76]
Valve (3-way)	1	1.00E-05	2.09	[76]
Valve (4-way)	1	1.00E-05	2	[76]
Valve (quick disconnect)	7	1.00E-05	0.23	[76]
Valve (selenoid liquid)	1	1.00E-05	0.45	[76]
Valve (electrical - 1)	2	1.00E-05	1.36	[76]
Valve (electrical - 2)	1	1.00E-05	0.91	[76]
Valve (relief)	1	1.00E-05	1.36	[76]
Voltage Sensor	7	2.33E-05	0.2	[76]

SAWD

Table A.9: SAWD Technical Information - Crew Size 3 - Adapted from [6]

Mass	51.3 kg
Volume	0.21 m^3
Power Required	454 W
Heat Generated	454 W
TRL	6

Table A.10: SAWD Reliability Data - Adapted from [55]

Part	Number	MTBF (1/hour)	Source
Amine Bed	2	1,30E-05	[64]
Blower	1	8,00E-06	[23]
Conductivity Sensor	1	4,67E-05	[68]
Heat Exchanger	2	5,99E-06	[64]
Pressure Sensor	3	1,00E-05	[23]
Pump	3	1,50E-05	[64]
Temperature Sensor	5	1,00E-05	[23]
Valve	3	1,00E-05	[64]
Valve (3-way)	2	1,00E-05	[64]
Valve (4-way)	1	1,00E-05	[64]
Valve (Check)	3	6,00E-06	[64]
Valve (Diverter)	2	1,00E-05	[64]
Valve (Electric)	2	1,00E-05	[64]

SFWE

Table A.11: SFWE Technical Information - Crew Size 4 - Adapted from [6, 75]

Mass	113 kg
Volume	0.14 m^3
Power Required	1470 kW
Heat Generated	39 kW
TRL	8

Table A.12: SFWE Reliability Data - Adapted from [56]

Part	Number	MTBF (1/hour)	Source
Accumulator	2	5.00E-07	[23]
Combustible Gas Sensor	4	1.00E-05	[23]
Condenser/Separator	2	1.70E-05	[23]
Conductivity Sensor	1	4.67E-05	[68]
Desiccant Bed	1	1.30E-05	[52]
Electrolysis Stack	1	3.00E-06	[64]
Flow Sensor	1	1.00E-05	[23]
Heat Exchanger	1	5.99E-06	[64]
Pressure Regulator	3	1.00E-05	[23]
Pressure Sensor	7	1.00E-05	[23]
Pump	1	1.50E-05	[64]
Sample Port	6	1.00E-05	[64]
Temperature Sensor	4	1.00E-05	[23]
Valve (3-way)	2	1.00E-05	[64]
Valve (Check)	5	6.00E-06	[23]
Valve (Diverter)	1	1.00E-05	[64]
Valve (Electric)	5	1.00E-05	[23]

CO_2 electrolysis

Table A.13: CO_2 Electrolysis Technical Information - Capacity to produce 36.8 kg/d [77]

Mass	356 kg
Volume	0.28 m^3
Power Required	13.3 kW
Heat Generated	3.5 kW
TRL	4

Table A.14: CO_2 Electrolysis Reliability Data - Adapted from [23]

Part	Number	MTBF (1/hour)	Source
Accumulator	1	5.00E-07	[23]
CO/H_2 reactor	2	2.00E-05	[23]
Combustible Gas Sensor	1	1.00E-05	[23]
Compressor	1	1.50E-05	[23]
Condenser/Separator	1	1.70E-05	[23]
Electrolysis Stack	1	3.00E-06	[23]
Flow Restrictor	2	1.00E-05	[23]
Flow sensor	9	1.00E-05	[23]
Heater	3	1.00E-05	[23]
Humidifier	1	1.00E-06	[23]
Level Sensor	2	1.00E-05	[23]
Pressure Regulator	1	1.00E-05	[23]
Pressure Sensor	4	1.00E-05	[23]
Pump	1	1.50E-05	[23]
Temperature Sensor	8	1.00E-05	[23]
Valve (Check)	2	6.00E-06	[23]
Valve (Electric)	9	1.00E-05	[23]
Valve (Manual)	3	5.99E-06	[23]

A.2 Water Management

Five different technologies are considered for water management: VCD, TIMES, VPCAR, AES and MF.

VCD

Table A.15: VCD Technical Information - Adapted from [52, 58]

Mass	128 kg
Volume	0.36 m^3
Power Required	397 W
Heat Generated	397 kW
TRL	8

Table A.16: VCD Reliability Data - Adapted from [75]

Part	Number	MTBF (1/hour)	Source
Condenser/separator	1	1.70E-05	[64]
conductivity sensor	1	4.67E-05	[68]
Distillation Assembly	1	7.02E-06	[52]
Level Sensor	1	1.00E-05	[64]
Pressure Regulator	1	1.00E-05	[64]
Pressure Sensor	11	1.00E-05	[64]
Pump	5	1.50E-05	[64]
Tank	1	1.00E-08	[68]
Temperature Sensor	2	1.00E-05	[64]
Valve (3-way)	1	1.00E-05	[64]
Valve (Check)	5	6.00E-06	[64]
Valve (Diverter)	2	1.00E-05	[64]
Valve (Electric)	3	1.00E-05	[64]
Valve (Manual)	4	5.99E-06	[64]

TIMES

Table A.17: TIMES Technical Information - based on a 20 kg/day model - [6]

Mass	68 kg
Volume	0.23 m^3
Power Required	170 W
Heat Generated	170 W
TRL	4-5

Table A.18: TIMES Reliability Data - Adapted from [59]

Part	Number	MTBF (1/hour)	Source
Blower	1	8.00E-6	[23]
Condenser/separator	1	1.70E-05	[23]
Conductivity Sensor	2	4.67E-05	[68]
Filter	3	5.00E-06	[64]
Heat Exchanger	4	5.99E-06	[64]
Microbial Check Valve	0	6.97E-06	[52]
Pressure Sensor	2	1.00E-05	[23]
Pump	2	1.50E-05	[64]
Sample Port	1	1.00E-05	[52]
Temperature Sensor	8	1.00E-05	[23]
Thermo Electric Device	2	N/D	N/D
Valve (3-way)	2	1.00E-05	[64]
Valve (Check)	1	6.00E-06	[23]
Valve (Diverter)	2	1.00E-05	[64]
Valve (Electric)	3	1.00E-05	[23]
Water Evaporator	3	7.65E-06	[52]

VPCAR

Table A.19: VPCAR Technical Information - Adapted from [6]

Mass	283 kg
Volume	1.57 m^3
Power Required	2232.4 kW
Heat Generated	2232.4 kW
TRL	6

Table A.20: VPCAR Reliability Data - Adapted from [60]

Part	Number	MTBF (1/hour)	Source
Conductivity Sensor	1	4.67E-05	[68]
Filter	2	5.00E-06	[64]
Heat Exchanger	4	5.99E-06	[64]
Heater	1	1.00E-05	[64]
Mass Flow Controller	1	1.07E-06	[52]
Oxidation Reactor	1	1.00E-05	[68]
Pressure Sensor	6	1.00E-05	[64]
Pump	4	1.50E-05	[64]
Temperature Sensor	15	1.00E-05	[64]
Vacuum Pump	1	1.75E-05	[64]
Valve (3-way)	3	1.00E-05	[64]
Valve (Check)	1	6.00E-06	[64]
Valve (Electric)	10	1.00E-05	[64]
Valve (Manual)	1	5.99E-06	[64]
Valve (Needle)	6	8.75E-06	[68]
WFRD	1	1.00E-05	[68]

AES

Table A.21: AES Technical Information - Adapted from [6, 77]

Mass	178 kg
Volume	0.05 m^3
Power Required	2270 W
Heat Generated	852 W
TRL	5

Table A.22: AES Reliability Data - Adapted from []Diamant1990

Part	Number	MTBF (1/hour)	Source
Blower	1	8.00E-06	[64]
Condenser/separator	1	1.70E-05	[64]
Delta p Sensor	1	1.00E-05	[64]
Heater	1	1.00E-05	[64]
Pressure Sensor	1	1.00E-05	[64]
Slurper	1	1.00E-05	[64]
Temperature Sensor	3	1.00E-05	[64]
Valve (Check)	5	6.00E-06	[64]
Valve (Electric)	1	1.00E-05	[64]
Wick Evaporator	1	1.00E-05	[64]

MF

Table A.23: MF Technical Information - Adapted from [6, 52, 75]

Mass	635 / 318 kg
Volume	2.36 / 1.18 m^3
Power Required	2042 / 1021 kW
Heat Generated	2042 / 1021 kW
Resupply	478 kg/year
TRL	8

Table A.24: MF Reliability Data - Adapted from [61, 52, 64]

Part	Number	MTBF (1/hour)	Source
Accumulator	1	5.00E-07	[64]
Conductivity Sensor	3	4.67E-05	[68]
Heat Exchanger	2	5.99E-06	[64]
Heater	4	1.00E-05	[64]
Ion Exchange Bed	1	3.37E-06	[52]
Multifiltration Bed	6	3.37E-06	[52]
Particulate Filter	1	1.39E-06	[52]
pH Adjuster	1	7.29E-06	[52]
Pressure Regulator	1	1.00E-05	[64]
Pressure Sensor	1	1.00E-05	[64]
Pump	1	1.50E-05	[64]
Temperature Sensor	8	1.00E-05	[64]
Valve (Electric)	2	1.00E-05	[64]

A.3 Waste Management

Regarding waste management, the only considered task is CO_2 reduction. Sabatier Reactor (SR) and Bosch Reactor (BR) are considered for this task. Moreover, a pyrolisis system has been analyzed to recover H_2 from CH_4.

SR

Table A.25: SR Technical Information - Adapted from (ELISSA)

Mass	43 kg
Volume	0.8 m^3
Power Required	50 W
Heat Generated	288 W
TRL	8

Table A.26: SR Reliability Data [62, 23]

Part	Number	MTBF (1/hour)	Source
Accumulator	1	5.00E-07	[23]
Blower	1	8.00E-06	[23]
Blower Silencer	1	5.00E-07	[23]
Condenser/Separator	1	1.70E-05	[23]
Flow Restrictor	2	1.00E-05	[23]
Flow Sensor	5	1.00E-05	[23]
Heater	1	1.00E-05	[23]
Level Sensor	2	1.00E-05	[23]
Liquid Trap	2	5.00E-07	[23]
Pressure Regulator	1	1.00E-05	[23]
Pressure Sensor	4	1.00E-05	[23]
Pump	1	1.50E-05	[23]
Sabatier Reactor	1	2.00E-05	[23]
Temperature Sensor	6	1.00E-05	[23]
Valve (Electric)	4	1.00E-05	[23]
Valve (Manual)	2	5.99E-06	[23]

BR

Table A.27: BR Technical Information - ELISSA

Mass	102 kg
Volume	0.3 m^3
Power Required	950 W
Heat Generated	313 W
TRL	6

Table A.28: BR Reliability Data - Adapted from [62, 23]

Part	Number	MTBF (1/hour)	Source
Accumulator	1	5.00E-07	[23]
Bosch Reactor	2	2.50E-05	[23]
Combustible Gas Sensor	2	1.00E-05	[23]
Compressor	1	1.50E-05	[23]
Condenser/Separator	1	1.70E-05	[23]
Electric Valve	9	1.00E-05	[23]
Flow Restrictor	2	1.00E-05	[23]
Flow Sensor 1	1	1.00E-05	[23]
Flow Sensor 2	9	1.00E-05	[23]
Heater	2	1.00E-05	[23]
Level Sensor	2	1.00E-05	[23]
Pressure Regulator	2	1.00E-05	[23]
Pressure Sensor	5	1.00E-05	[23]
Pump	1	1.50E-05	[23]
Temperature Sensor	6	1.00E-05	[23]
Valve (Electric)	9	1.00E-05	[23]
Valve (Manual)	2	5.99E-06	[23]

Pyrolisis

Table A.29: Pyrolisis Technical Information - Adapted from [6]

Mass	154 kg
Volume	0.8 m^3
Power Required	448.54 W
Heat Generated	98.44 W
TRL	-

Table A.30: Pyrolisis Reliability Data - Adapted from [63]

Part	Number	MTBF (1/hour)	Source
Blower	1	8.00E-06	[23]
Blower Silencer	1	5.00E-07	[23]
Carbon Formation Reactor	2	2.50E-05	[23]
Combustible Gas Sensor	1	1.00E-05	[23]
Flow Restrictor	6	1.00E-05	[23]
Flow Sensor	2	1.00E-05	[23]
Heater	2	1.00E-05	[23]
Pressure Sensor	3	1.00E-05	[23]
Temperature Sensor	6	1.00E-05	[23]
Valve (Check)	1	6.00E-06	[23]
Valve (Electric)	5	1.00E-05	[23]

A.4 Food Management

Regarding biological components, able to produce food, only algae are considered. Therefore, a PBR is analyzed.

PBR

Table A.31: PBR Technical Information - Crew of 0.3 - (ELISSA)

Mass	2.76 kg
Volume	0.046 m^3
Power Required	N/D
Heat Generated	N/D
TRL	5

Table A.32 shows the mechanical parts of the component. However, it is important to remark that the PBR has not only these mechanical parts, but also the algae itself. For each type of algae and design of the PBR chamber, a specific study will be required to evaluate the reliability contribution of the algae.

Table A.32: PBR Reliability Data - Adapted from [57]

Part	Number	MTBF (1/hour)	Source
Accumulator	4	5.00E-7	[64]
Compressor	1	1.50E-05	[64]
Cooling	1	N/D	N/D
Flow sensor	2	1.00E-05	[64]
Heat Exchanger	2	5.99E-06	[64]
pH Sensor	1	N/D	N/D
Photobioreactor Structure	1	N/D	N/D
Pump	3	1.50E-05	[64]
Temperature sensor	1	1.00E-05	[64]
Valve (Electric)	4	1.00E-05	[64]

B

Equivalent System Mass Calculation

In this appendix, the Equivalent System Mass for the two designs is calculated.

B.1 Design A

Table B.1 shows the mass and volume for each component, correspondingly, a mass and volume margin has been applied. According to [8], a margin of 2% should be added for known components with a mass lower than 500 kg and a 0.9% to the components with a mass between 500 and 2 500 kg, for known components in a preliminary design phase. As the components of this design are currently in use in the International Space Station (ISS), the TRL is 8, these margins can be used. The volume margin is set to 5%.

Table B.2 shows the expendables required (which are also calculated in ELISSA), as well as the spare parts. The spare level required is shown in the table, as well as spares mass and volume. As explained in chapter 5, it is considered that the parts represent an 80% of the components mass. Mass and volume margins from table B.1 have been used to calculate the total masses and volumes.

Table B.3 shows the tanks characteristics. For gas substances, two different types of tanks have been used: cryogenic (CR) and high pressure (HP). The required capacities and consumables have been obtained from the simulation without failures. Tank mass/capacity, density as well as mass and volume margins have been extracted from [77].

Finally, the power required for this system is 6987 W, and the heat produced 5464 kW.

The total ESM obtained is 21.9 tons.

Table B.1: Design A - Components Mass and Volume

	N	TRL	Component Mass (kg)	Mass Margin (%)	Component Volume (m^3)	Volume Margin (%)
4BMS	2	8	200	2	0.39	5
SFWE	2	8	113	2	0.14	5
CHX	1	8	50	2	0.40	5
TCCS	1	8	78	2	0.27	5
MF (h)	2	8	635	0.9	2.36	5
VCD	1	8	128	2	0.36	5
MF (p)	1	8	318	2	1.18	5
SR	2	8	43	2	0.80	5
Total	–	–	2593		10.1	

Table B.2: Design A - Expendables and Spares

	Expendables	Spares Level	Spares Mass (kg)	Spares Volume (m^3)
4BMS	0	3	480	0.59
SFWE	0	3	271	0.21
CHX	0	4	160	0.80
TCCS	61	2	125	0.27
MF (h)	1204	5	2540	5.89
VCD	0	4	410	0.72
MF (p)	602	5	1270	2.94
SR	0	3	103	1.20
Total	3104	–	8872	21.5

Table B.3: Design A - Tanks

	Type	Capacity (kg)	Tank Mass /capacity (kg/kg)	Tank Mass (kg)	Mass Margin (%)	Consumable Density (kg/m^3)	Tank Volume (m^3)	Volume Margin (%)	Consumables (kg)
N_2	CR	900	0.64	576	20	808.6	1.11	20	890
O_2	CR	80	0.25	20	20	1141	0.07	20	50
H_2	CR	260	0.1	26	20	70.97	3.66	20	255
CO_2	HP	20	0.5	10	20	750	0.03	20	0
CH_4	HP	20	2.3	46	20	187.2	0.11	20	0
H_2O- P	–	400	0.05	20	5	1000	0.40	15	70
WW - P	–	40	0.05	2	5	1000	0.04	15	0
H_2O- H	–	310	0.05	15.5	10	1000	0.31	15	300
WW - H	–	70	0.05	3.5	10	1000	0.07	15	0
Urine	–	15	0.08	1.2	10	1000	0.02	15	0
Brine	–	250	0.08	20	5	1000	0.25	15	0
Food	–	2000	0.5	1000	5	255	7.84	15	2200
Solids	–	700	0.15	105	5	255	2.75	15	0
Total	–	–	–	2040	–	–	19.40	–	3765

B.2 Design B

Table B.4 shows the mass and volume for each component, correspondingly a mass and volume margin has been applied. According to [8], for new designs in a preliminary design phase a margin of 25% should be added for known components with a small mass (lower than 50 kg), and 20% for components with a mass between 50 and 2 500 kg. For each component, the TRL is shown, as well as the margins applied.

Table B.6 shows the tanks characteristics.

Table B.4: Design B - Components Mass and Volume

	N	TRL	Component Mass (kg)	Mass Margin (%)	Component Volume (m^3)	Volume Margin (%)
EDC	2	6	44	25	0.40	20
SFWE	2	8	113	2	0.14	5
CHX	1	8	50	2	0.40	5
TCCS	1	8	78	2	0.27	5
VPCAR	1	5/6	283	20	1.57	20
AES	1	6	178	20	0.05	20
SR	2	8	43	2	0.80	5
PYRO	2	4	154	20	0.80	20
Total	–	–	1483		7.50	

Table B.5: Design B - Expendables and Spares

	Expendables	Spares Level	Spares Mass (kg)	Spares Volume (m^3)
EDC	0	4	142	0.80
SFWE	0	3	271	0.30
CHX	0	4	160	0.60
TCCS	61	2	120	0.27
VPCAR	0	4	906	3.14
AES	0	3	427	0.08
SR	0	3	103	1.20
PYRO	0	4	493	1.60
Total	62		4192	13.68

Table B.6: Design B - Tanks

	Type	Capacity (kg)	Tank Mass /capacity (kg/kg)	Tank Mass (kg)	Mass Margin (%)	Consumable Density (kg/m^3)	Tank Volume (m^3)	Volume Margin (%)	Consumables (kg)
N_2	CR	900	0.64	576	0.2	808.6	1.11	0.2	890
O_2	CR	60	0.25	15	0.2	1141	0.05	0.2	10
H_2	CR	110	0.1	11	0.2	70.97	1.55	0.2	10
CO_2	HP	20	0.5	10	0.2	750	0.03	0.2	0
CH_4	HP	10	2.3	23	0.2	187.2	0.05	0.2	0
H_2O	–	250	0.05	13	0.05	1000	0.25	0.15	250
WW	–	70	0.05	3.5	0.05	1000	0.07	0.15	0
Brine	–	10	0.08	0.8	0.05	1000	0.01	0.15	0
Food	–	2200	0.5	1100	0.05	255	8.63	0.15	2180
Solids	–	700	0.15	105	0.05	255	2.75	0.15	0
C	–	100	0.15	15	0.05	2260	0.04	0.15	0
Total	–	–	0	2061		–	16.86	–	3340

Finally, the power required for this system is 6946 W, and the heat produced 4920 W.

The total ESM obtained is 12.5 tons.