Lehrstuhl für Raumfahrttechnik
Prof. Prof. h.c. Dr. Dr. h.c.
Ulrich Walter

Technische Universität München

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Advancement of a Trade-off Tool for Life Support Technologies and its Application in Proposing a Life Support Architecture for the Gateway

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Author:

Feigel, Andreas, B.Sc.

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Betreuer: Pütz, Daniel, M.Sc.
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Autor: Andreas Feigel

Matrikelnummer: 03637650

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Zusammenfassung

Aufgrund des Fortschritts in bemannter Raumfahrt in den letzten 60 Jahren und sich ändernden Missionsanforderungen gibt es heutzutage eine Vielzahl von Lebenserhaltungstechnologien. Die Auswahl der optimalen Lebenserhaltungsarchitektur wird von Trade-Off Programmen unterstützt, mit welchen man die überlegene Eignung einer Technologie über eine Alternative bestimmen kann. Der Zugang zu solchen Programmen ist jedoch durch ihren Mangel oder den limitierten Zugang zu ihnen eingeschränkt.

In einer vorherigen Arbeit wurde das Life Support Trade-off Tool (LiSTOT) erstellt, welches dazu gedacht ist, den Benutzer beim Selektieren von optimalen Technologien für vordefinierte Lebenserhaltungsunktionen zu unterstützen. Es kombiniert eine Multi-Criteria Analysis (MCA) mit der Equivalent System Mass (ESM) Metrik und einer vorläufigen dynamischen Simulation, um die Nachteile der statischen ESM Herangehensweise zu kompensieren. LiSTOT war bisher auf den Mars Transit Nutzungsfall eingeschränkt, weswegen das Programm innerhalb dieser Arbeit von neuem aufgesetzt wurde.

LiSTOT wurde durch das Hinzufügen eines Benutzerinterfaces und einer Benutzeranleitung anpassbarer und benutzerfreundlicher gestaltet. Zusätzliche Features wie das Crew Schedule Creation und Environmental Control and Life Support System (ECLSS) Composition Tool wurden implementiert, um detailliertere Trade-Offs zu ermöglichen. Biologische Systeme wurden der Datenbank an Lebenserhaltungstechnologien hinzugefügt, was die Betrachtung von hybriden ECLSS und Biological Life Support Systems erlaubt. Die Sensitivitätsanalyse ermöglicht es dem Benutzer nun, die Attributkritikalitäten der MCA als auch die Robustheit der MCA Resultate zu evaluieren. Ein Resupply Modelling Tool wurde implementiert, das die Möglichkeit eröffnet, die logistischen Anforderungen des ECLSS, welches mit LiSTOT designt worden war, zu modellieren.

LiSTOT wurde am Beispiel der Erstellung eines ECLSS für das Gateway, einer geplanten Raumstation in cislunarer Nähe, genutzt. 27 Lebenserhaltungstechnologien wurden untersucht um eine ultra-verlässliche Lebenserhaltungsarchitektur mit geringen ESM Kosten zu identifizieren, welche anschließend in einem zweiten Designzyklus optimiert wurde. Dadurch konnten fast 10 % der initialen System ESM gespart werden. Die Ergebnisse der Gateway Analyse zeigen, dass ein partiell geschlossenes ECLSS die optimale Lebenserhaltungsarchitektur für das Gateway darstellt, da seine ESM Kosten von 10,630 kg geringer waren, als die ESM eines offenen Systems mit 20,450 kg und die eines geschlossenen ECLSS mit 10,800 kg. Das vorgeschlagene ECLSS enthält sowohl gängige Technologien wie Multi Filtrationsbetten und einen Bosch Reaktor als auch Advanced Life Support Baugruppen wie die Solid Amine Water Desorption Technologie. Die Nützlichkeit des Resupply Modelling Tools wurde in der Analyse der logistischen Anforderungen eines Verbrauchsgüter getriebenen ECLSS gezeigt, wobei die Frachtverteilung ähnlich zu der von Versorgungsflügen zur International Space Station gehalten wurde. Basierend auf den Resultaten dieser Analyse wurde vorgeschlagen, die Anzahl an Missionen, die von einem einzelnen Versorgungsflug bedient werden, zu reduzieren, um die insgesamte Flugkritikalität zu senken. Es ist geplant, das vorgeschlagene Gateway ECLSS in einem Lebenserhaltungssimulationsprogramm zu verifizieren.

Abstract

Due to progression in human spaceflight over the last 60 years and changing mission requirements, a variety of life support technologies is nowadays available. Selecting the optimal life support architecture is supported by trade-off tools which determine the superior eligibility of a technology over an alternative for a given mission scenario. However, access to such tools is constrained by their lack or the restricted access to them.

In a previous work, the Life Support Trade-off Tool (LiSTOT) was created which is meant to assist the user in selecting the optimal technologies for predefined life support functions. It combines a Multi-Criteria Analysis (MCA) with the Equivalent System Mass (ESM) metric and a preliminary dynamic simulation to compensate for the shortcomings of the static ESM approach. LiSTOT was previously constrained to the Mars Transit use case, which is why the program was set up anew within this thesis.

LiSTOT was rendered more customizable and user-friendly by implementing a User Interface and a User’s Guide. Further features such as a Crew Schedule Creation and Environmental Control and Life Support System (ECLSS) Composition tool were implemented enabling more detailed trade-offs. Biological systems were added to the database of life support technologies allowing for the consideration of hybrid ECLSS and Biological Life Support Systems. The sensitivity analysis now allows the user to evaluate the attribute criticalities of the MCA as well as assessing the robustness of the MCA output. A Resupply Modelling tool was added which offers the capability of modelling the logistical demands of the ECLSS that has been designed with LiSTOT.

LiSTOT was used at the example of composing an ECLSS for the Gateway, a planned space station in cislunar vicinity. 27 life support technologies were examined in identifying an ultra-reliable, low ESM cost life support architecture which was then optimized and refined in a second design cycle saving almost 10 % of the initial system ESM. The results of the Gateway analysis show that a partially closed loop ECLSS represents the optimal life support architecture for the Gateway since its total ESM cost of 10,630 kg was lower than both the ESM of an open loop system with 20,450 kg and the ESM of a closed loop ECLSS with 10,800 kg. The proposed ECLSS incorporates established technologies such as Multi Filtration Beds and the Bosch reactor as well as Advanced Life Support assemblies such as the Solid Amine Water Desorption technology. The utility of the Resupply Modelling tool was shown in analysing the logistical demands of a consumable driven ECLSS, whereby the cargo distribution was held similar to that of the International Space Station. Based on the results of this analysis, it was proposed to limit the number of missions served by a single resupply flight to reduce the overall flight criticalities. It is planned to verify the suggested Gateway ECLSS in a life support simulation tool.

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Symbols and Formulas

a	-	Attribute value
a_{ij}	-	Performance factor
A	[kg/CM]	Constant clothing term
A_i	-	Alternative
$A_{maxscore}$	-	Maximal score
A_{score}	-	Score
b	-	Attribute value
B	[kg/(CM·d)]	Variable clothing term
c_{abs}	-	Absolute change
c_{rel}	[%]	Relative change
C	[kW]	Cooling
C_{eq}	[kg/kW]	Cooling equivalency factor
$C_{clothing}$	[m^3/(CM·d)]	Variable clothing term
C_i	-	Criterion
D	-	Dependency matrix
$D_{mission}$	[d]	Mission duration
D_{wt}	[m]	Water tank diameter
f_{CF}	-	Confidence factor
f_{ij}	-	Merit function value
f_{impr}	-	Improvement factor
f_{ORU}	-	ORU factor
f_R	-	Rescale factor
f_S	-	Scaling factor
F	-	Number of flights
FCI	-	Flight Criticality Index
K_l	[kg]	Mass term
L_{eq}	-	Location factor
$m_{backordered}$	[kg]	Mass backordered
$m_{carried-along}$	[kg]	Mass carried along
$m_{prepositioned}$	[kg]	Mass prepositioned
m_i	[kg]	Mass

m_{ij}	-	Mass matrix element
m_m	[g/mol]	Molar mass
m_{gas}	[kg]	Gas mass
m_{tank}	[kg]	Tank mass
M	[kg]	System mass
M_{matrix}	-	Mass matrix
$MTBF$	[h]	Mean Time Between Failures
$\dot{m}^{*}_{O2\ produced}$	[kg/d]	Oxygen mass produced daily by algal reaction
$\dot{m}_{O2\ produced}$	[kg/d]	Needed oxygen mass per day
$\dot{m}_{CO2\ absorbed}$	[kg/d]	Adsorbed carbon dioxide mass per day
$\dot{m}_{demand}$	[kg/d]	Demanded system mass throughput
$\dot{m}_{given}$	[kg/d]	Given system mass throughput
n_{crew}	-	Crew size
$n_{crew,desired}$	-	Desired crew size
$n_{crew,given}$	-	Given crew size
$n_{missions}$	-	Number of missions
n_{mole}	-	Mole number
N	-	Number of redundant systems
N_m^i	-	Number of missions served
p	[Pa]	Design pressure
p_{gas}	[Pa]	Gas partial pressure
p^{*}_{H2O}	[Pa]	Water equilibrium pressure
P	[kW]	Power
P_{eq}	[kg/kW]	Power equivalency factor
$P(k)$	[%]	Probability
$r_{algae\ required}$	[(L·d)/kg]	Ratio of algae required
r_w	-	Ratio of decision weights
R	-	reliability
R_{gas}	[J/(kg·K)]	Universal Gas Constant
S	[kg/cm^2]	Stress
t	[h]	Time period
t_{crew}	[CM·h/y]	Crew time
$t_{crew,eq}$	[kg/(CM·h)]	Crew time equivalency factor

t_b	[m]	Bladder thickness
t_s	[m]	Shell thickness
t_{wall}	[m]	Wall thickness
T	[K]	Temperature
T_{gas}	[K]	Gas temperature
$Tr(M_{matrix})$	[kg]	Trace of M_{matrix}
T_{FD}	[%]	Tank filling degree
V	[m^3]	Volume
V_{eq}	[kg/m^3]	Volume equivalency factor
V_{alg}	[L]	Total volume of algae
$V_{alg,CO2}$	[L]	Volume of algae required to process CO_2
$V_{alg,O2}$	[L]	Volume of algae required to generate O_2
V_{gas}	[m^3]	Gas volume
V_{tank}	[m^3]	Tank volume
w_i	-	Decision weight
w_i^*	-	New decision weight
x_{ij}	-	Matrix element

δ_{ij}	-	Dependency
λ	[1/h]	Failure rate
ρ	[kg/m^3]	Density
$\rho_{hardware}$	[kg/m^3]	Hardware density
ρ_b	[kg/m^3]	Bladder material density
ρ_{gas}	[kg/m^3]	Gas density
ρ_s	[kg/m^3]	Shell material density
ρ_{water}	[kg/m^3]	Water density
φ	[%]	Relative humidity

Abbreviations

4BMS	Four Bed Molecular Sieves
AAA	Avionics Air Assembly
ACRS	Advanced Carbon Reactor System
ACS	Atmosphere Control and Supply
AES	Air Evaporation System
AHP	Analytical Hierarchy Process
ALS	Advanced Life Support System
ALSSAT	Advanced Life Support Sizing Analysis Tool
ARM	Asteroid Redirect Mission
BAC	Bigelow Aerospace Corporation
BLSS	Biological Life Support System
BVAD	Baseline Values and Assumptions Document
CAMRAS	CO_2 And Moisture Removal Swing-bed
CASIS	Center for Advancement of Science in Space
CCAA	Common Cabin Air Assembly
CH_4	Methane
CHX	Condensing Heat Exchanger
CO_2	Carbon Dioxide
COE	Carbon Dioxide Electrolysis
CONOPS	Concept of Operations
CoS	Classes of Supply
CRS	Commercial Resupply Services
CS	Cryogenic Storage
CSA	Canadian Space Agency
DDT&E	Design Development Test and Evaluation
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DSG	Deep Space Gateway
ECLSS	Environmental Control and Life Support System
ELISSA	Environment for Life Support Systems Simulation and Analysis
EM	Exploration Mission
ESA	European Space Agency
ESM	Equivalent System Mass
ESPRIT	European System Providing Refuelling, Infrastructure and Telecommunications
EVA	Extravehicular Activity
FCI	Flight Criticality Index
FCP	Flight Criticality Path
FDA	Food and Drug Administration
FDS	Fire Detection System
H_2	Hydrogen
HEOMD	Human Exploration and Operations Mission Directorate
HEO	Human Exploration and Operations
HERACLES	Human-Enhanced Robotic Architecture and Capability for Lunar Exploration and Science

HEU	Human Equivalent Unit
HPS	High-Pressure Storage
IMV	Intermodular Ventilation Assembly
ISECG	International Space Exploration Coordination Group
ISRU	In Situ Resource Utilization
ISS	International Space Station
IVA	Intravehicular Activity
IWRS	Integrated Water Recovery System
L2	Earth-Moon Lagrange Point 2
LCC	Life Cycle and Cost
LCM	Logistics and Control Module
LIFE	Large Inflatable Fabric Environment
LiSTOT	Life Support Trade-off Tool
LLO	Low Lunar Orbit
LOP-G	Lunar Orbital Platform-Gateway
LV	Launch Vehicle
MCA	Multi-Criteria Analysis
MCDM	Multi-Criteria Decision Making
MF	Multi Filtration
MMC	Microbial Monitoring Control
MPEV	Manual Pressure Equalization Valve
MPLM	Multi-Purpose Logistics Module
MTBF	Mean Time Between Failures
N_2	Nitrogen
NASA	National Aeronautics and Space Administration
NextSTEP	Next Space Technologies for Exploration Partnerships
NIA	Nitrogen Interface Assembly
NRHO	Near-Rectilinear Halo Orbit
O_2	Oxygen
ORU	Orbital Replacement Unit
P/C	Physicochemical
PBR@LSR	Photobioreactor @ the Life Support Rack
PCA	Pressure Control Assembly
PPE	Power and Propulsion Element
SAWD	Solid Amine Water Desorption
SCALISS	Scaling of Life Support Systems
SEP	Solar Electric Propulsion
SFWE	Solid Feed Water Electrolysis
SLS	Space Launch System
SNC	Sierra Nevada Corporation
SPWE	Solid Polymer Water Electrolysis
TCCS	Trace Contaminant Control System
THC	Thermal and Humidity Control
TIMES	Thermoelectric Integrated Membrane Evaporation System
TRL	Technology Readiness Level

U.S.	United States
VBA	Visual Basic
VCD	Vapor Compression Distillation
V-HAB	Virtual Habitat
VPCAR	Vapor Phase Catalytic Ammonia Removal
WM	Waste Management
WRM	Water Recovery Management
WSM	Weighted Sum Model

1 Introduction

Ensuring the lives and well-being of the crew in an otherwise inhabitable environment is the primary premise for the feasibility of manned spaceflight. A system that is meant to fulfil this requirement is called an Environmental Control and Life Support System (ECLSS). By providing the demands of the human metabolism and by processing its loads, an ECLSS is a crucial part of any manned spacecraft. Since the beginning of human spaceflight in the 1950s, development efforts have been taken to design and advance life support technologies to meet the requirements of the various missions but also to create an ECLSS which ideally represents a low-cost and ultra-reliable system [1], [2]. Due to the extensive research in the field of life support technologies, various alternatives are nowadays available depending on the regarded ECLSS function. To determine the most eligible option for a given mission scenario, robust metrics are required for decision making. The most prevalent means in the life support community with which one assesses the superiority of an ECLSS technology over an alternative is the Equivalent System Mass (ESM) [3], [4]. This static approach allows to determine the cost of a technology by considering attributes including mass, volume, power, cooling and crew time. However, the reliability of a system which is arguably one of the most critical characteristics for human safety is omitted by this metric. To compensate for this shortcoming, conducting Multi-Criteria Analyses (MCA) that incorporate other, yet crucial life support attributes such as reliability and Technology Readiness Level (TRL) presents a viable alternative to the ESM [5], [6].

In composing an ECLSS for SpaceX's Starship, announced as the Interplanetary Transport System (ITS) in 2016, Schreck developed an Excel based tool to perform trade-offs between alternatives for a given life support function due to the lack of or restricted access to programs involving trade studies for ECLSS technologies [6]. The developed tool called Life Support Trade-off Tool (LiSTOT) is meant to be used to select technologies which are then combined and examined in a designated life support simulation tool such as the Virtual Habitat (V-HAB) code of the Technical University of Munich [7]. Since the creation of LiSTOT was not the goal of his thesis, Schreck programmed LiSTOT to be primarily focussed on the task of identifying life support technologies for the ITS, which is why LiSTOT ended up not being suitable for more individual trade studies. Furthermore, the tool was constrained by the limitations of using solely Excel spreadsheet calculation, which lead to the corruption of various links and references. Nevertheless, the utility of a trade-off tool for life support applications could be successfully demonstrated by Schreck within his work and therefore a thesis was issued by the Institute of Astronautics of the Technical University of Munich to set up LiSTOT anew. The research objectives of this work are provided in the following chapter.

1.1 Research objectives

1.1.1 Primary research objectives

- The primary objective of this thesis includes rendering LiSTOT applicable to any given spaceflight mission scenario, thus removing the limitation of the original version of LiSTOT to the ITS use case. In doing so, Schreck's proposed approach of conducting trade-offs between life support technologies for a given function by combining an MCA with the ESM metric shall be kept.
- In this programming effort, it is required to render LiSTOT user friendly by facilitating one's understanding of the tool so that the user is aware of how an analysis, being it the MCA, ESM or sensitivity analysis, can be adapted so that the user-specific requirements can be met.
- Since this thesis has been issued together with two other theses, it is necessary that LiSTOT is well documented so that future work with the tool is practicable. Moreover, interfaces shall be available with which one can connect the work done within the three theses.
- The procedure and capabilities of using LiSTOT shall be demonstrated by proposing a life support architecture for the Gateway, a space station in a lunar orbit proposed by the National Aeronautics and Space Administration (NASA) to return humans to the moon and to enable deep space exploration [8].

It is important to point out that this thesis is not meant to create an ECLSS simulation tool but focuses primarily on conducting trade-offs on technology as well as on system level. Even if ECLSS attributes such as subsystem power consumption or partial pressures are computed, one must understand those as estimations since their calculation is governed by several assumptions.

1.1.2 Secondary objective

By employing the simulation tool V-HAB, it is desired to verify that the ECLSS composed with LiSTOT represents a functional life support system. The realization of this verification depends on whether the technologies that have been identified using LiSTOT are implemented and available in V-HAB so that the ECLSS can be recreated.

1.1.3 Methodology

The steps necessary to fulfil the given tasks of this thesis are provided in the following:

- Acquiring an understanding of the functionality of Schreck's LiSTOT so that advantages and disadvantages of the tool can be identified.
- Translation of the spreadsheet-based tool into VBA code whilst incorporating the means needed to address the original tool's weaknesses and maintaining and leveraging its strengths.
- Performing frequent tests to ensure the correctness of the mathematical equations and models.
- Using the modified tool for composing an ECLSS for the Gateway and create a resupply model for the station.

1.2 Structure

This thesis is structured into nine chapters. Following the introduction, a description of the Gateway and its planned structure and usage as of April 2019 is provided. Recent developments in the field of life support systems, ECLSS trade-off and analysis tools, a brief historical background of life support systems for spaceflight applications and ECLSS requirements are given in the third chapter. In the fourth chapter, the structure of the tool and its functionality as well as usage possibilities are depicted. The trade study concerning life support technologies for the Gateway ECLSS is described in the following chapter. At this example, it is outlined how a user progresses efficiently through the tool. In a second design cycle, the composition of the previously identified and composed life support system is refined in detail to examine areas of potential mass savings in chapter seven. The required resupply of the designed ECLSS is modelled in the following chapter. Lastly, a discussion of the results of this thesis and future work is provided in chapters eight and nine.

2 The Gateway

On March 28th, 2017 the Human Exploration and Operations Missions Directorate (HEOMD) of NASA officially announced their decision to build a space station in a cislunar orbit as part of their Human Exploration and Operations (HEO) program [9]. Originally named Deep Space Gateway (DSG), this human outpost marks the beginning of the first phase of the HEO architecture succeeding the activities on the International Space Station (ISS) in Low Earth Orbit (LEO) in phase 0. Future program iterations ultimately aim at landing humans on Mars in the 2040s as displayed in Figure 2-1 [9].

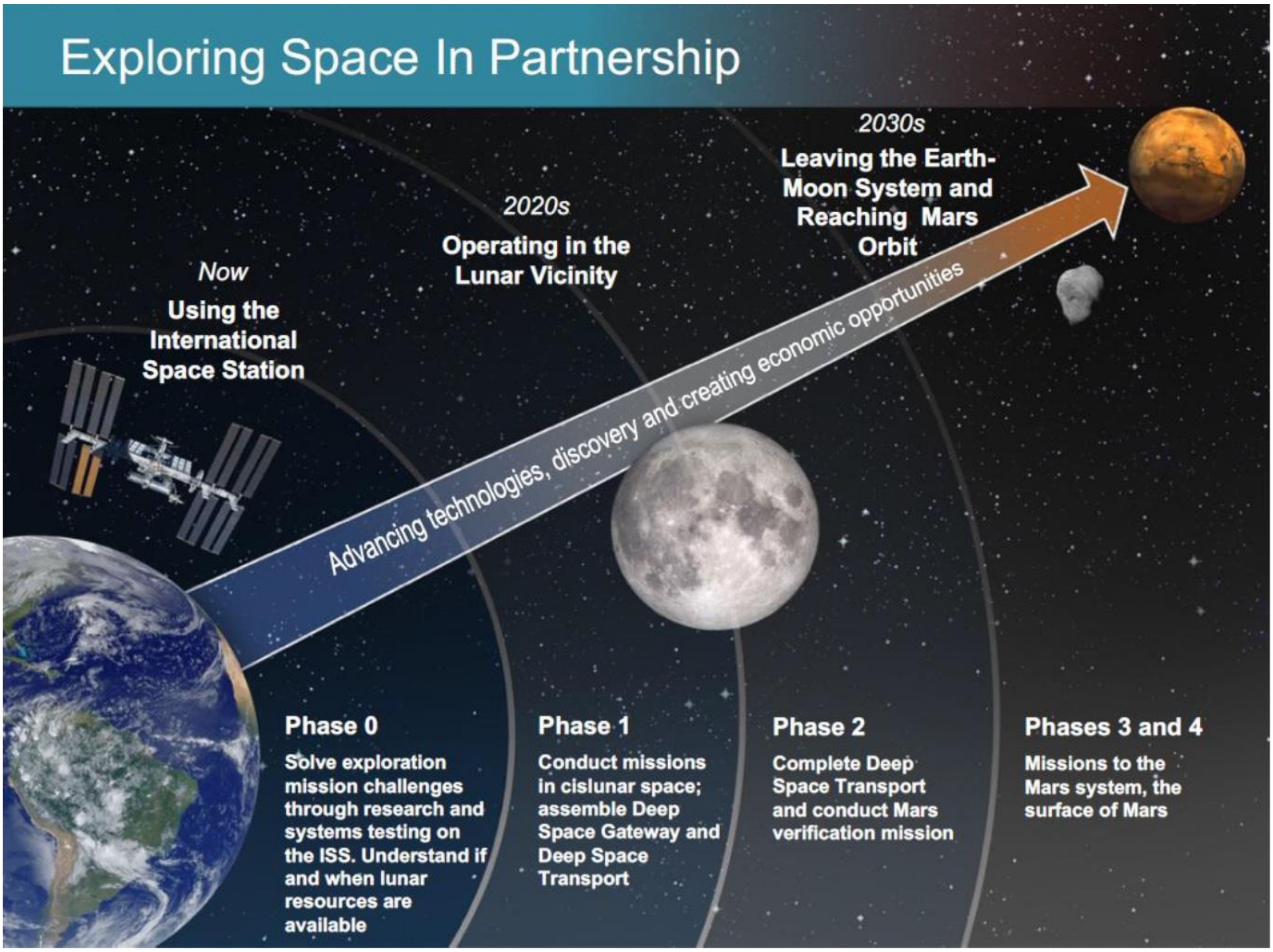
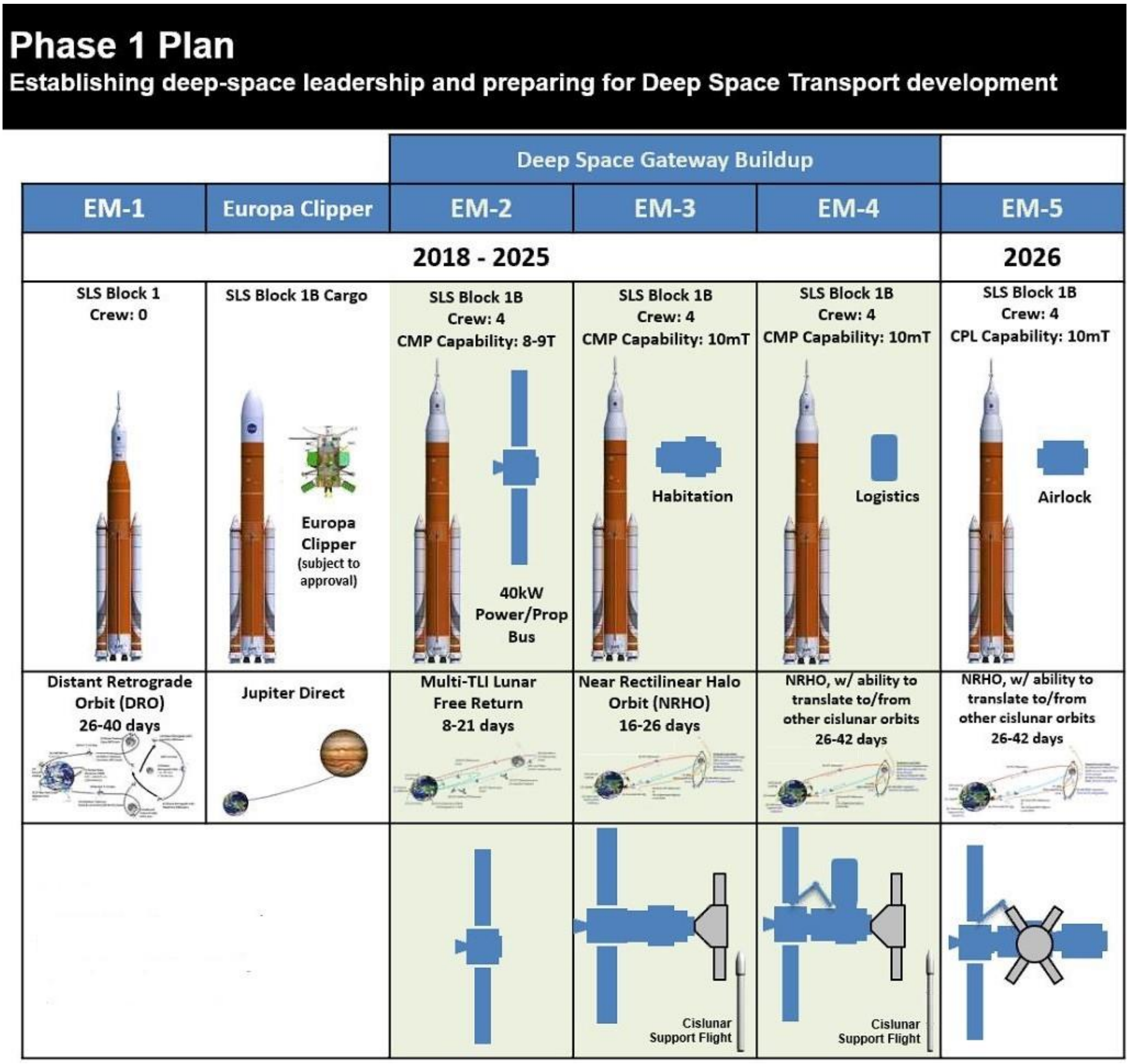


Figure 2-1: HEO phases [9]

In this respect, the DSG is intended to serve both as a stepping stone to extend human presence in the solar system by demonstrating and flight testing cislunar exploration systems as well as a basis to enable lunar exploration [9]. First intentions of establishing a space station in moon vicinity date back to the Apollo program era, when the US President’s Space Task Force proposed an integrated program plan for lunar exploration in 1969. These plans however were neglected in the following years in favour of Space Shuttle development [10], [11].

The decision to create a space station in a cislunar orbit can be seen as a response to NASA’s directive having changed under Trump administration to prioritize returning humans to the moon before targeting Mars and the cancellation of NASA’s Asteroid Redirect Mission (ARM) in 2017 [12]. The ARM, that had been under development for over four years with the goal of retrieving and redirecting a near-Earth asteroid to a lunar orbit where it could be examined by astronauts, was planned to be built up within the scope of NASA’s Exploration Missions (EM) using the Orion spacecraft and Space Launch System (SLS) [13]. Due to the shutdown of the ARM program, NASA can employ the SLS and Orion architecture for assembling the DSG as well as use technologies which have been developed for the ARM as displayed in Figure 2-2 [14].



Phase 1 Plan

Establishing deep-space leadership and preparing for Deep Space Transport development

		Deep Space Gateway Buildup			
EM-1	Europa Clipper	EM-2	EM-3	EM-4	EM-5
2018 - 2025					2026
SLS Block 1 Crew: 0	SLS Block 1B Cargo Europa Clipper (subject to approval)	SLS Block 1B Crew: 4 CMP Capability: 8-9T 40kW Power/Prop Bus	SLS Block 1B Crew: 4 CMP Capability: 10mT Habitation	SLS Block 1B Crew: 4 CMP Capability: 10mT Logistics	SLS Block 1B Crew: 4 CPL Capability: 10mT Airlock
Distant Retrograde Orbit (DRO) 26-40 days	Jupiter Direct	Multi-TLI Lunar Free Return 8-21 days	Near Rectilinear Halo Orbit (NRHO) 16-26 days	NRHO, w/ ability to translate to/from other cislunar orbits 26-42 days	NRHO, w/ ability to translate to/from other cislunar orbits 26-42 days
			Cislunar Support Flight	Cislunar Support Flight	

Figure 2-2: Gateway assembly [14]

Those include for example the ion thruster propulsion system and the Exploration Augmentation Module that was meant to bring humans to an Earth-lunar retrograde orbit and offer habitation for 30 to 60 days and extravehicular activity (EVA) capabilities [15].

NASA pointed out that the efforts needed to establish the Lunar Orbital Platform-Gateway (LOP-G) to which the DSG had been renamed by early 2018 required international cooperation and therefore announced its collaboration with the other 14 members of the International Space Exploration Coordination Group (ISECG) on this project [16]. ISECG had released a Global Exploration Roadmap in 2011 envisioning plans for manned space exploration after the support of the ISS had ended [17]. In both examined case scenarios regarding asteroid (AsteroidNext) or lunar explorations (MoonNext) the importance of a deep space gateway had been recognized. Thus far, NASA that intends to act as the overall lead gateway architect, operator and systems integrator has signed contracts with ROSCOSMOS, JAXA, the Canadian Space Agency (CSA) and the European Space Agency (ESA) [18], [19], [20], [21].

By October 2018, the LOP-G had been renamed to Gateway and its modular composition had been defined [8]. The location of the Gateway is currently the subject of trade studies. Possible lunar orbits include Near-Rectilinear Halo orbits (NRHO), a Distant Retrograde Orbit or an Earth-Moon Lagrange Point 2 (L2) halo orbit [14]. Despite NASA hosting workshops to seek utilization options for the Gateway, a clear concept of operations (CONOPS) for the space station has not been established yet. Contrary to the operation on the ISS however, NASA examines whether commercial usage of the Gateway is possible [22], [23].

This chapter is dedicated to depicting the Gateway’s planned architecture and usage, thereby outlining the parameters needed for designing an ECLSS for the station.

2.1 Gateway structure

Similar to the ISS, the lunar Gateway is planned to consist of several modules, each fulfilling a specific purpose [8]. The modular design approach allows for a step-by-step in orbit assembly and is necessary since launching a payload to a lunar orbit requires vastly more Δv than bringing an equivalent payload to LEO. Limiting payload mass and volume is not only crucial for cutting launch costs but also for choosing a launch vehicle (LV) that is capable of bringing a several ton payload to a cislunar orbit. For this purpose, NASA intends to use its SLS and Orion architecture which is supposed to have its maiden flight in the early 2020s. Other alternatives such as the Russian Angara A5M or Proton-M, the European Ariane 6 or commercial LVs like SpaceX's Falcon Heavy are also being considered [16]. The Orion capsule offers about 20 m^3 of pressurized volume and is connected with an ATV-based European Service Module that fulfils propulsion, attitude control, power and consumable provision tasks for the crew as well as storing unpressurized cargo [24].

As of October 2018, the Gateway consists of the following modules and components which are being described in this chapter [8]:

- Power and Propulsion Element (PPE)
- European System Providing Refuelling, Infrastructure and Telecommunications (ESPRIT)
- United States (U.S.) Habitat
- International Partner's Habitat
- U.S. Utilization
- Logistics
- Airlock or Multi-Purpose Module

It is worth noting that as of April 2019 the Gateway and its modules are still in early development phase, detailed information about their configuration has therefore not been released yet.

2.1.1 Power and Propulsion Element

The PPE module is meant to generate electricity for the station and provide solar electric propulsion (SEP) for attitude and orbit control. The PPE is provided by NASA which signed contracts with U.S. aerospace industry firms including Boeing, Lockheed Martin, Orbital ATK and Sierra Nevada Corporation (SNC) to conduct studies focused on possible configurations for a 40 kW SEP/PPE element [25]. These studies included an examination of PPE's operational usage and CONOPS, opportunities for commercial application and checking whether the proposed designs fulfilled NASA's requirements [26]. The contracts were signed under NASA's second Next Space Technologies for Exploration Partnerships (NextSTEP-2) program. NextSTEP-2 is a public-private partnership project initiated by NASA that expects to lower its mission costs by stimulating the commercial space industry as well as leveraging from its capabilities. Apart from development of a PPE, further areas of research supported by NextSTEP-2 include habitat systems, in-space manufacturing fabrication laboratory design, in situ resource utilization (ISRU), human landing systems and trash compaction and processing systems [27].

Independent from the progress made within the NextSTEP-2 commercial studies, NASA continues to work on a 40 kW PPE using a Xenon fuelled Hall thruster Advanced Electric Propulsion System that was originally developed for ARM. According to NASA, PPE is designed for a maximal lifetime of 15 years in a cislunar orbit and would be able to provide up to 24 kW of electric power to external hardware. PPE's initial storage capability of Xenon would be 2000 kg with the possibility of being refuelled. In 2022, PPE is intended to be the first piece of Gateway infrastructure to be launched [8], [28].

2.1.2 ESPRIT

The ESPRIT module is provided by ESA and built by its contractors including Thales Alenia Space, Airbus, RUAG Space and OHB amongst others. ESPRIT is meant to provide refuelling for PPE, permit telecommunications with radio assets on the lunar surface and is equipped with a science airlock for EVA experiments on the Gateway. Together with the U.S. Utilization module, ESPRIT is planned to be launched in 2023 with SLS [8], [29]. As of April 2019, no further information has been published.

2.1.3 U.S. Habitat

The U.S. Habitat consists of a pressurized volume allowing for crew operations and science. It is equipped with ECLSS components, a fire detection and suppression system and water storage and distribution capabilities. The U.S. Habitat is planned to be launched in 2025 with SLS [8]. Similar to PPE, competitive versions of the habitat are being developed by six US industry aerospace companies under the NextSTEP-2 program. The proposed habitat designs vary in size and used technology. For example, Lockheed Martin's concept involves a 64 m^3 module [30], [31], [32], [33], [34], [35], [36]. For more information on the suggested designs, one may refer to chapter C.

2.1.4 International Partner's Habitat

The International Partner's Habitat is the second habitat module on the Gateway. Its purpose and structure are similar to these of the U.S. Habitat enabling human presence and scientific research on the station. Little has been revealed about the International Partner's Habitat as of February 2019, however in 2017, JAXA hinted its involvement in a habitat of the DSG [37]. In an updated Gateway configuration concept released March 5, the collaboration of ESA and JAXA on the International Partner's Habitat was confirmed [38]. The International Partner's Habitat that is intended to be launched in 2024 with SLS [8].

2.1.5 U.S. Utilization

The U.S. Utilization module is provided by NASA and is meant to offer a small habitable volume, logistics for 15 days and crew ingress for the very first manned mission on the station. The module is planned to be launched together with ESPRIT in 2023 with SLS [8].

2.1.6 Logistics

Provided by NASA and CSA, the Logistics module's purpose is to allow for enhanced science operations by providing logistics and utilization payloads. Furthermore, it is intended to be equipped with a robotic arm that is currently developed by CSA and its contractors building up on their experience developing the Shuttle Remote Manipulator System and Mobile Servicing System on the ISS. The Logistics module and robotic arm are not expected to be delivered earlier than 2025 [8], [20].

2.1.7 Airlock or Multi-Purpose Module

According to the agreement about collaboration in space exploration signed by NASA and ROSCOSMOS in September 2017, the Russian space agency consented to provide an airlock module for the Gateway due to their experience in designing docking systems such as the Rassvet module on the ISS. The Airlock module on the Gateway will enable EVA capabilities and shall be built under NASA standards for power supply and User Interfaces (UI) and is planned to consist of two compartments with a total mass of about 4600 kg. In 2026, the module is intended to be the last Gateway element to be launched [8], [39].

2.2 Objectives and utilization

According to a NASA presentation held in March of 2018, the Gateway's initial scope involved crewed missions of up to four astronauts for 30-day missions offering a habitable volume of about 55 m^3 [40]. Since then the Gateway's conceptual architecture has evolved and been refined. Modules have been added to the design increasing the pressurized volume of the station to 125 m^3. By doing so, NASA hopes to expand the possible mission duration to up to 90 days of human presence on the Gateway [8]. The utilization of the station mainly comprises of scientific research and is according to NASA similar to that of the ISS. This suggests that the Gateway's primary usage next to educational activities and technology demonstration consists of conducting experiments in the fields of (human) biology, lunar and space science and physical and material science [41]. When unmanned, the Gateway is supposed to be utilized for technology demonstration and lunar exploration via its robotic system [42]. Thus, it can be stated that the power consumption of the Gateway's ECLSS must account for the power needs of other hardware installed on the station to prevent exceeding the power budget of 15 kW [8]. For more information on suggested Gateway missions, one may refer to chapter D.

3 State of the Art

3.1 ECLSS

An ECLSS is a subsystem of manned space flight vehicles that provides all the means and conditions necessary for enabling life in space. A human being can be seen as a “black box”, matter flows enter and leave the body, energy is exchanged with the surrounding environment which maintains its constant structure and balances the two flows ensuring the health of the person. This environment is referred to as a biosphere for terrestrial applications and is characterized by having a closed loop for matter flows and an open loop for the exchange of energy. In this respect, the design of ECLSS can be regarded as the general attempt of mimicking the natural biosphere of the Earth and adapt it to the needs of the crew and the mission whilst heeding additional boundary conditions such as system mass [43].

ECLSS can be divided into three principal types according to the life support system’s respective sustainability - an attribute that can be quantified in an isolated environment by the degree of resource loop closure that is achieved by the system. A completely unsustainable system which is referred to as open loop from this point on relies entirely on storing consumables that are metabolised or converted within the system into waste products which are then either stored or removed from the loop. This type of ECLSS can only operate until the initial consumables are depleted, which is why open loop systems depend heavily on frequent resupply to prevent running out of resources and consequently system failure. In contrast to this non-regenerable system, a fully sustainable or closed loop ECLSS can function indefinitely if no matter leaves the system borders. However, this advantage comes at the cost of high initial system masses as well as greater complexity compared to an open loop ECLSS. Partially closed loop life support systems are the third type of ECLSS. These allow a limited exchange of matter and energy with the surrounding environment, thereby sharing characteristics of both an open and closed loop system. Depending on the mission needs, partially closed loop systems typically consist of regenerable and non-regenerable subsystems [44].

ECLSS designs utilize technologies that operate based on physical, chemical or biological processes to fulfil a certain function. Life support technologies are therefore classified into two major groups: physicochemical (P/C) and biological technologies. Physicochemical technologies rely entirely on physical and/or chemical processes to convert resources. No living organisms such as plants or bacteria are actively employed for fulfilling the system’s function. On the contrary, biological technologies are based solely on biological processes thereby actively and intentionally using plants and/or bacteria to transform resources. If an ECLSS incorporates both physicochemical and biological technologies, it is referred to as a hybrid life support system [44]. An ECLSS is made up of several functional subsystems each fulfilling different purposes corresponding to biological and physiological factors. These principal life support functions include atmosphere, water and waste management as well as crew safety, food production and storage. Thereby, every primary function composes of various subfunctions. Table 3-1 depicts NASA’s definition of ECLSS primary and secondary functions [45].

Table 3-1: ECLSS primary and subfunctions [45]

Primary Functions	Subfunctions
Air Management	- Circulation - Conditioning - Emergency Services - Monitoring - Pressure Management
Water Management	- Potable Water Management - Wastewater Management - Water Quality Monitoring
Solid Waste Management	- Trash Management - Metabolic Waste Management - Logistical Waste Management

Addressing these subfunctions, NASA defines six different ECLSS subsystems [46]:

- **Atmosphere and Control (ACS):** The ACS subsystem's main function is to control the space habitat's atmospheric pressure and composition. In this regard, ACS regulates and monitors partial and total pressures of gases in the cabin atmosphere, which includes oxygen (O_2) and nitrogen (N_2) pressure control vent and relief, storage and distribution.
- **Air Revitalization (AR):** The AR subsystem's functions include carbon dioxide (CO_2) scrubbing, O_2 generation and removal of atmospheric trace contaminants. Thus, the system must monitor partial pressures and atmospheric concentrations of (potentially) hazardous gasses and airborne particles.
- **Temperature and Humidity Control (THC):** The THC subsystem is meant to monitor and control the space habitat's temperature and humidity, thus removing excess heat and human induced moisture. It also regulates the ventilation to ensure a comfortable atmosphere for the crew.
- **Water Recovery Management (WRM):** The WRM subsystem controls the water handling on the space station, which includes monitoring the quality of the water, storing water and processing wastewater and urine for recovery purposes.
- **Waste Management (WM):** The WM subsystem is meant to reduce, process and store gaseous, liquid and solid wastes.
- **Fire Detection & Suppression (FDS):** The FDS subsystem's function is to detect onboard fires and to suppress them in case they occur.

LiSTOT adapts this classification with the exception of FDS not being considered to be a standalone subsystem but part of THC. The ECLSS task of food provision is decoupled from these subsystems according to NASA. This chapter is meant to briefly depict developments in the field of ECLSS as well as to describe the overall boundary conditions and driving factors for ECLSS design. The technologies incorporated in LiSTOT for the various ECLSS subsystems are exemplified in chapter 4.3.

3.1.1 Background and modern developments

When examining the progress accomplished in the field of ECLSS technology during the last 60 years, it is necessary to comprehend in which context those developments have been made. An overview of the historical background of life support systems in space flight applications is provided in the following.

With the beginning of the space race and the crewed space flight era in the late 1950s, engineers faced the challenge of finding ways to ensure the well-being of the astronauts and cosmonauts in orbit. Early missions in both the U.S. and Soviet manned space flight programs were primarily meant for bringing humans to orbit and for testing of newly developed flight hardware. These objectives did not require long periods of time spent in space since it was desired to return the crew as fast as possible once the scheduled tasks had been completed. This was done to keep mission durations short and consequently complexity low. The average mission duration for the American Mercury program for example did not exceed 9 h whereas the cosmonauts of the Soviet Voskhod missions did not stay for more than 27 h in orbit. Figure 3-1 depicts the development of mission durations from the Mercury and Vostok to the ISS era[1].

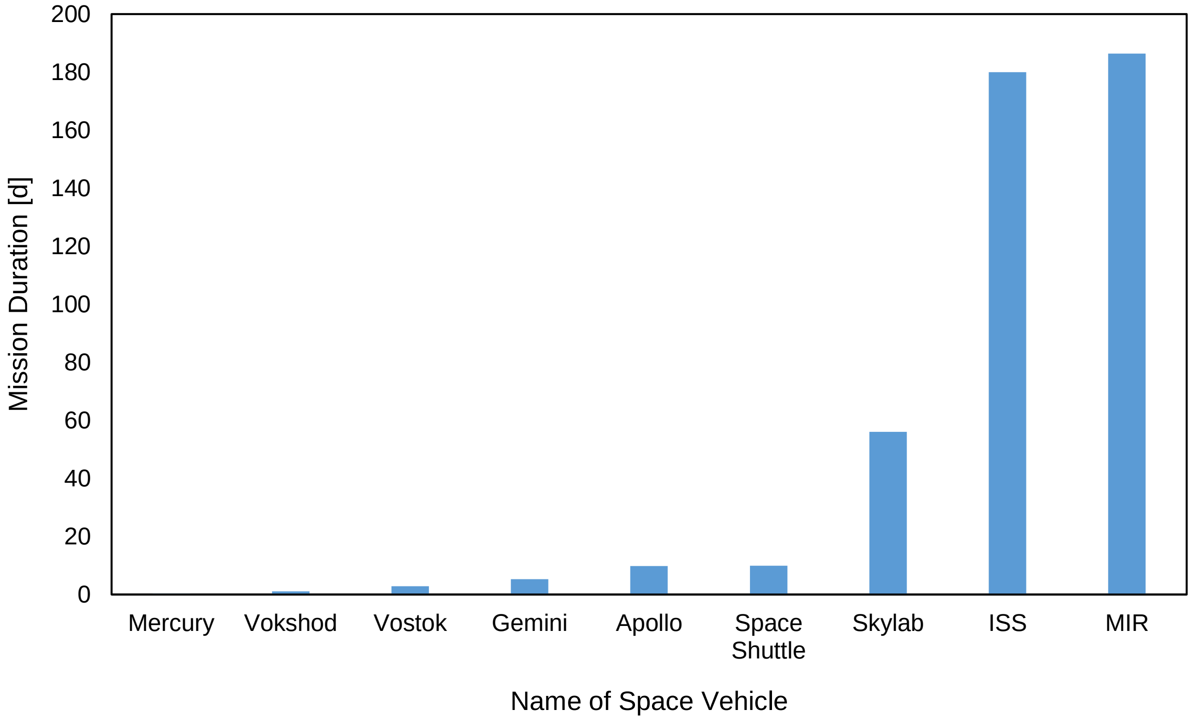


Figure 3-1: Development of mission durations

Expanding the time spent in space was to be achieved in later stages of the respective project or within succeeding programs when the agencies had gained enough confidence in their technologies to allow longer missions. With Gemini, NASA increased the time in orbit to roughly 126 h per flight preparing their astronauts for the goal of bringing humans to the moon during the Apollo program which required mission lengths of almost double that of Gemini. Until then, mission durations increased almost linearly. Both NASA and the Soviet Union relied entirely on expendable spacecraft - a

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[1] All mission information retrieved from [113]

philosophy that was also applied to the design of ECLSS during that period. ECLSS were non-regenerable, open loop systems intended to be light-weight and kept as simple as possible. CO_2 removal systems for U.S. space vehicles at that time consisted of using LiOH canisters, wastewater and urine were not recovered but vented or stored and potable water and O_2 were brought along in tanks for each mission [1]. Revaluating this design approach became inevitable when NASA and the Soviet Union decided to construct space stations that would allow human presence in orbit for considerably more time compared to previous manned space flight programs. In 1973, NASA launched Skylab which accommodated astronauts during three missions with an average duration of 1350 h (56.25 days). The Soviets built the Mir space station that had remained in orbit for 15 years until its decommission in 2001. Together with the ISS, stays on board Mir were scheduled to last about 6 months (4320 h). Those circumstances lead to the development of new technologies for ECLSS since trade-offs show that the consumables driven open loop ECLSS are outperformed in terms of ESM by life support systems with partially closed loops using regenerable technologies [47]. In this respect, the design of the ISS ECLSS dispensed with the non-regenerable LiOH and used Four Bed Molecular Sieves (4BMS) for CO_2 scrubbing instead. Despite this change, LiOH is still considered a state-of-the-art non-regenerable CO_2 removal technology [47]. Wastewater and urine were no longer removed from the loop but recovered via urine processing and wastewater filtration assemblies. Moreover, O_2 could be generated by water electrolysis [48]. Nonetheless, the degree of loop closure of the ISS ECLSS is still not equivalent to being fully sustainable (100 % loop closure), which is mainly prevented by limiting efficiencies of certain subsystems such as that of the water management, for example. Only 85 % of all wastewater can currently be recovered [49]. In addition to that, the food loop is not closed - a shortcoming that all P/C ECLSS have in common. Bioregenerative technologies utilizing plants, algal, bacteria in composters and bioreactors as well as leaching technology promise to cover life support tasks of air revitalization, water and other resource recovery and food and energy production. Yet, these technologies do not match the reliability and the TRL of P/C hardware since their functionality has thus far been primarily demonstrated in isolated and confined environments on Earth [44]. With the development of Advanced Life Support systems (ALS), hybrid ECLSS and Biological Life Support Systems (BLSS), NASA and other space agencies hope to further close the loop and achieve fully regenerable life support systems [50], [51], [52]. Those are of essential importance if goals that are severely restricted by the impracticability of resupply flights like the establishment of a base on the moon or even on Mars shall be accomplished. The recent developments in the field of ECLSS are strongly influenced by the lessons learned and experience gained whilst operating and designing the ISS ECLSS. Studies have shown that in order to advance life support technology, focus has to be placed on reducing ECLSS mass, volume and power needs, increasing reliability and redundancy of critical systems, easing maintenance and reducing overall system complexity. Proposed ways of achieving these points mainly include higher financial investments in the ECLSS design process, increasing development time, introducing commonality for spares and allowing on-orbit tests [53]. At Ames Research Center, NASA is currently developing ALS systems for water recovery, air revitalization and waste processing claiming to achieve improvements of lowering ESM of subsystems by a factor of up to five in comparison to conventional life support subsystems [54]. Furthermore, within its NextSTEP-1 program, NASA partnered with Dynetics Inc. for the demonstration of a CO_2 scrubbing system [55], with UTC Aerospace systems for developing larger, more modular ECLSS subsystems to reduce integration time and increase commonality [56] and with Orbital Technologies Corporation for the design of a hybrid life support system [56], [57]. Other development efforts for advancing life support system technology come from Russia, China, Europe and Japan [44].

3.1.2 Metabolic considerations

In designing an ECLSS, a human being can be treated as an individual subsystem and an active part of the life support system. The physiological and metabolic boundary conditions of the subsystem human define the performance requirements of the ECLSS design. This chapter is dedicated to depicting these conditions.

3.1.2.1 Physiological boundary conditions

Physiological boundary conditions are short-term requirements for ensuring the survival and well-being of the crew. They apply to the immediate environmental surrounding of the person and mainly concern atmospheric composition, humidity and temperature [58].

Atmospheric composition

The standard atmosphere on Earth mainly composes of N_2 and O_2 at a total pressure of 1013.25 hPa at sea level. According to the NASA Space Flight Human-System Standard document, total pressures for an artificial cabin can be within the range of 20.7 kPa and 103 kPa if the O_2 partial pressure is adjusted correspondingly and kept between 20.7 kPa and 50.6 kPa [59].

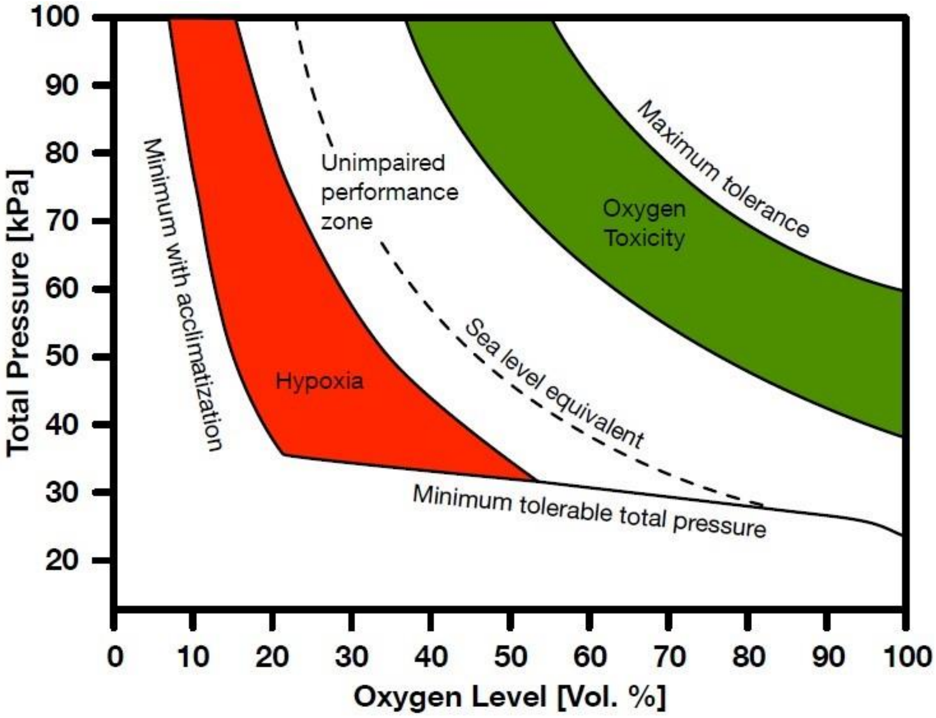

Figure 3-2: Human performance zone [62]

Recommendations by NASA's Explorations Atmospheres Working Group for cabin atmosphere pressure and composition vary depending on the mission type. For an EM architecture, it is advised to have a total pressure of 101.3 kPa and 21.3 kPa O_2 partial pressure whereas for missions with frequent EVAs, cabin pressure should be operable at 56.5 kPa with 34 % O_2. Design approaches for the Air Management ECLSS subsystem have been using 101.5 kPa total pressure with 21 % O_2 as guidelines [60], [61]. Figure 3-2 depicts the human performance zone and its borders depending on total and O_2 partial pressure [62].

The CO_2 concentration in the cabin atmosphere is detrimental for the performance and health of the crew. CO_2 removal systems have been designed based on the assumption that a CO_2 partial pressure of 0.72 kPa is tolerable for the human organism whilst still allowing the person to perform nominally [63]. However, recent studies have shown that especially for long-duration missions, the atmospheric content of CO_2 needs to be moved well below this level and closer to 0.26 kPa to ensure the well-being of a human [60], [64].

Apart from the CO_2 partial pressure, trace contaminants in the cabin atmosphere must be monitored as well since those can lead to symptoms of intoxication at far lower concentrations than that of CO_2. These substances are typically produced by metabolic or outgassing processes. NASA's Spacecraft Maximum Allowable Concentrations for Airborne Contaminants document defines limits for the atmospheric content of possible onboard contaminants depending on the mission duration [63].

Temperature and humidity

The cabin temperature has an influence on not only the physiological but also the psychological well-being of the crew and depends on the atmospheric humidity.

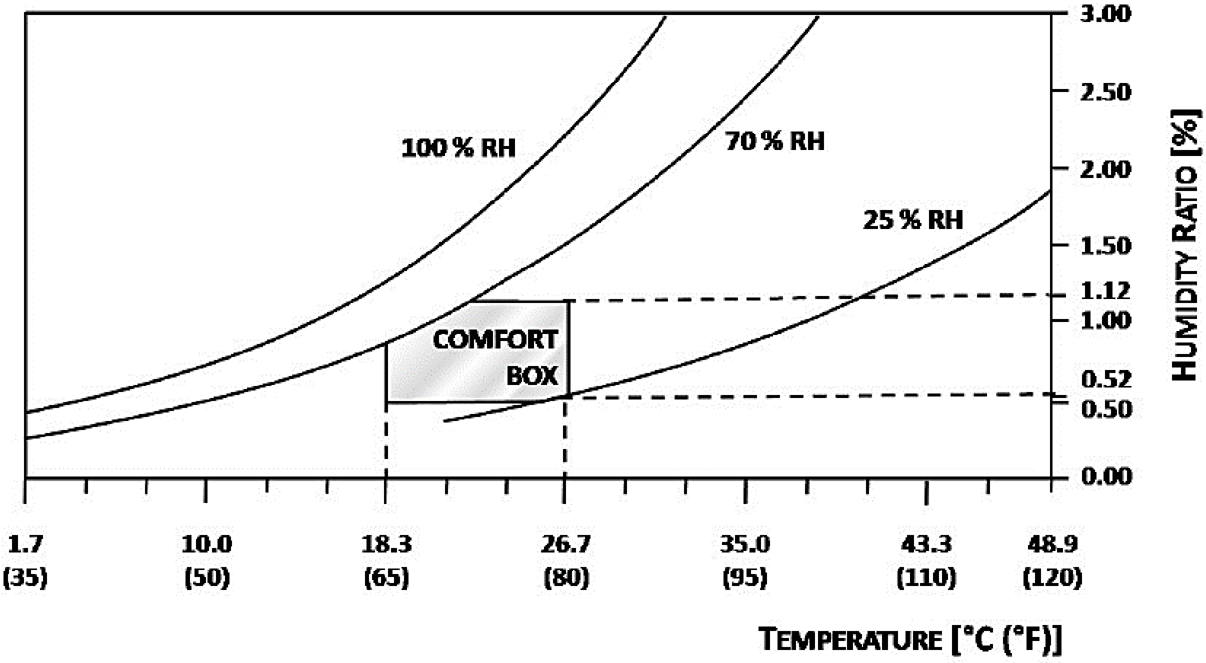

Figure 3-3: Human comfort box [62]

According to NASA, it is recommended to maintain the onboard temperature between 18 °C and 27 °C and a relative humidity within the range of 25 % and 75 % to prevent condensed water from entering electrical equipment [59], [60], [65]. However, if considered as a physiological factor, absolute humidity is more relevant than relative humidity. In this respect, it is advised to keep water vapor partial pressure at 1.3 kPa [60]. Figure 3-3 shows the “comfort box” that defines the optimal ranges of temperature and relative humidity for the well-being of a human [62].

3.1.2.2 Metabolic boundary conditions

Metabolic boundary conditions concern the matter flows entering and leaving the subsystem human. The human organism requires O_2, food and water as input and produces heat, CO_2, feces and water in the forms of urine and sweat. The daily metabolic in- and output loads depend heavily on the tasks that a person performs during a day. For instance, if one conducts physical exercises, vastly more O_2 and water are consumed and subsequently more heat, CO_2 and sweat are produced than in the case of recreational activities such as sleep. Thus, the design of any life support system must be sufficiently robust to be capable of handling varying metabolic loads and demands during a day [66].

3.1.2.3 Other boundary conditions

Additional boundary conditions affecting the crew’s health include the prevention of injuries by radiation protection, mitigation of noise and limitation of maximal acceleration. These conditions also incorporate the ensuring of maintaining a person’s psychological balance and subjective well-being, which is achieved by provision of enough personal and private space, colour and light design of the station and Earth viewing opportunities amongst other things. Despite their importance and influence on a mission’s success, these boundary conditions which are also known as human factors do not belong to ECLSS tasks. NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability and Environmental Health document provides explanations and guidelines for space habitat designs corresponding to the compliance with human factors [58].

3.2 Tools for ECLSS analysis

ECLSS are highly complex systems that require a lot of effort to be developed, built and tested. In particular modern ECLSS design for manned space flight applications is centred around finding a compromise between maximal performance and reliability whilst creating a low mass, volume and cost design. ECLSS are meant to allow human presence in an otherwise hostile environment and are therefore of vital importance for the health and well-being of a crew on board a space station. Since the 1990s, engineers have employed software tools for analysing and modelling ECLSS in order to ensure stability and reliability of the system. Early design tools were based on static approaches such as using worst-case scenario reference point design or the ESM method. Thereby, engineers relied on their experience and empirical equations for calculating the performance of the system [7]. More recent ECLSS modelling programs offer dynamic simulations since these portray an ECLSS more accurately during its operation than static design approaches [3], [7]. Dynamic tools allow the user to model the system's transient behaviour and the interaction between its subsystems facilitating the user's understanding of the ECLSS [3], [7].

Today, there are several ECLSS modelling tools of varying accuracy and purpose. This chapter is dedicated to providing a brief overview of established ECLSS modelling efforts and their use in life support studies. The tool developed within the scope of this thesis, LiSTOT, is described in chapter 4.

3.2.1 ALSSAT

Development of the Advanced Life Support Sizing and Analysis Tool (ALSSAT) was initiated by NASA JSC's Crew and Thermal Systems Division in 1997. ALSSAT is based on Microsoft Excel and was created to assist the user in conducting preliminary ECLSS design and trade studies as well as system optimization. The tool's medium-fidelity steady state models allow the user to define and scale the overall ECLSS structure and composition. Thereby, ALSSAT focuses on ALS, which suggests employing the program primarily when modelling regenerative ECLSS. The tool incorporates life support subsystems for air revitalization, water management, biomass, solid waste management, water management and thermal control which are connected via mass balance calculations. There are also interfaces for extravehicular activities and human accommodations available. ALSSAT has been used for several trade studies for a Mars Transit Vehicle evaluating open and closed loop ECLSS for mass, volume, power and ESM [67].

3.2.2 ELISSA

The Environment of Life-Support Simulation and Analysis (ELISSA) tool is under development at the Institute of Space Systems of the University Stuttgart since the mid-1990s. ELISSA is a time-discrete software program that is designed to analyse and validate ECLSS and to perform optimization studies. The tool contains a library for P/C and biological technologies for air, water, food and waste management emphasising long duration missions. This library is kept up to date with data and specifications of existing technologies received from experiments or literature. Components are modelled according to their TRL and reference data. Depending on the level of detail of the available information per component, ELISSA uses a dynamic or static calculation approach. The program incorporates a user-friendly interface and allows users to define mission specific parameters such as crew size, mission duration, initial consumables and tank sizes. Trades between different ECLSS designs can be performed on the basis of their respective ESM values. ELISSA consists of two separate tools: PrELISSA which is responsible for calculation of large numbers of component combinations for an early design selection and Reliability ELISSA enabling the evaluation of the ECLSS's reliability according to the chosen amount of spare parts [68].

3.2.3 EcosimPro

In corporation with ESA, Empresarios Agrupados A.I.E began developing EcosimPro in 1989 with the goal of simulating ECLSS for manned spacecraft. EcosimPro is a dynamic, continuous-discrete simulation tool for modelling zero- or one-dimensional multidisciplinary systems. By generating and solving linear or non-linear differential-algebraic or ordinary-differential equations and simulating discrete events, EcosimPro is capable of performing steady state, transient case and optimization studies. It uses a modular simulation approach. In this respect, EcosimPro incorporates a variety of libraries to be applied for mechanical, electrical, chemical and physical problems. Physical components are modelled based on EcosimPro's object-orientated programming language EL. Besides offering libraries for power and propulsion simulations for aerospace applications, EcosimPro incorporates an ECLSS library containing components for cabin, crew, fittings, pumps, tanks, fans and valves amongst other things. The simulations covered within this library include fluid flow, chemical and electrochemical reactions, thermal conduction and biological processes enabling high-fidelity modelling of ECLSS [69].

3.2.4 Virtual Habitat (V-HAB)

V-HAB is a dynamic, discrete-event ECLSS simulation tool that has been under development at the Technical University of Munich since 2006. The tool is based on MATLAB and allows the simulation of life support systems interacting with a human model and the habitat's environment using matter flow models. V-HAB consists of four modules: a crew module incorporating a dynamic, physiological model of a human body, modules for P/C and biological life support technologies and an infrastructure module that connects all modules with each other serving as the tool's backbone. V-HAB is meant to be used in early design phases to support the user analysing the modelled system. The tool has reached a high level of fidelity and maturity by simulating existing ECLSS such as the one of the ISS and validating V-HAB's results according to the actual performance of the respective life support system [7].

3.2.5 BioSim

The dynamic ALS simulation tool BioSim has been under development at Johnson Space Center since 2003. BioSim provides a habitat model which can be configured according to user needs and accessed via sensors and actors. Random or scheduled malfunctions of subsystems can be modelled as well as the inclusion of noise in the simulation if desired. The user can assign crew members to specific tasks such as EVA, repair, exercise, recreation and sleep and thereby indirectly define the metabolic loads induced by the inhabitants of the station. BioSim possesses a modular structure which roughly resembles the composition of subsystems of a habitat. The tool contains modules for environment, air, framework, water, power, water, food, waste and crew that are initialised using an eXtensible Markup Language. BioSim has been utilized for several trade studies, in particular regarding control schemes [70].

3.2.6 LiSTOT

The tools described above are or have been primarily developed for life support analysis but not for conducting trade studies between different ECLSS technologies. LiSTOT is meant to close this gap and is intended to be used to select life support hardware which is then implemented and examined in a designated ECLSS analysis tool such as V-HAB. The creation of a trade-off tool for life support systems became necessary when Schreck was faced with the task of choosing ECLSS technologies for a design of the life support system for SpaceX's ITS as it was announced in 2016. Schreck combined an MCA with the ESM metric and performed a sensitivity analysis in which the initial values of a technology are varied by +/- 10 % to assess the robustness of the results of the analyses. Furthermore, Schreck laid out an extensive database for ECLSS technologies ranging from established life support hardware to ALS equipment and calculated the reliabilities of these technologies. The tool was developed in Excel, whereby Schreck relied on spreadsheet calculations to determine the optimal ECLSS for the ITS. The analyses performed by Schreck were highly detailed, for example, he examined whether a dynamic or a static fan system would be the most eligible modular ventilation option. However, this level of detail lead to the trade-off tool being fitted for analysing ECLSS for a system whose boundary conditions such as crew size, mission duration and architecture are identical to that of the ITS. Moreover, the stiffness of spreadsheet calculation and its visual complexity contributed to not allowing LiSTOT to be used for general trade studies. Another shortcoming of spreadsheet calculation is its susceptibility to links becoming corrupted, which is even more likely to happen the more Excel files interact and are linked with each other [6].

3.3 Trade studies

During selection of ECLSS technologies, engineers carry out trade studies to identify a technology’s relative merit. The most commonly used metric in the ECLSS community is the ESM method. It is based on the approach to convert system specific parameters into an equivalent system mass, which directly correlates to launch costs. Despite its ease of application to life support system technology, the ESM metric is not capable of portraying crucial system attributes such as reliability, complexity or development costs in its results. For more information on the ESM method, one may refer to chapter 4.8. Within research efforts for a suitable, possibly more accurate alternative to the ESM technique, Jones examined whether the Life Cost Cycle (LCC) method which is more commonly used than the life support exclusive ESM approach would be advantageous when applied to ECLSS trade studies. He concluded that since LCC incorporates Design, Development, Test and Engineering (DDT&E) costs, employing LCC might lead to more accurate results than solely regarding the equivalent system mass. However, the author also emphasized that cost should not be the main design driver when evaluating ECLSS designs. Thus, a more technical approach might be more suitable for trade studies especially in preliminary design phases [4]. Since LiSTOT employs the ESM metric to decide between technology alternatives as well as different ECLSS architectures, this chapter summarizes two ECLSS trade studies, one on technology and one on ECLSS system level in the following.

3.3.1 Technology level - water processing trade study

Anderson compared the ISS water recovery technology to the Integrated Water Recovery System developed (IWRS) by NASA Johnson Space Center and to the Vapor Phase Catalytic Ammonia Removal (VPCAR) system. The ESM technique was used to perform the trade study. Due to their known specifications and performance, the established ISS ECLSS technologies are frequently used as a reference when evaluating ALS designs. However, since ISS technologies have reached a high level of optimization over years of operation, which cannot be matched by newly developed ALS systems, it is simplified that for the purpose of conducting this trade study some flight components of IWRS were substituted for commercial components to achieve a more equal comparison. Four mission scenarios were considered: 30-day and 90-day short-term surface stays for a crew of four, a 360-day transit mission and a 500-day surface stay both with six crewmembers respectively [71]. The results of the analysis as depicted in Figure 3-4 show that IWRS outperforms the ISS technology for long duration missions, whereas VPCAR has the lowest ESM in any of the regarded mission scenarios [71].

The author demonstrated that the ESM metric can be used to decide between different technologies for a given mission scenario. In doing so, the optimal alternative is the one with the lowest ESM, however the aspects of reliability and TRL are thereby neglected.

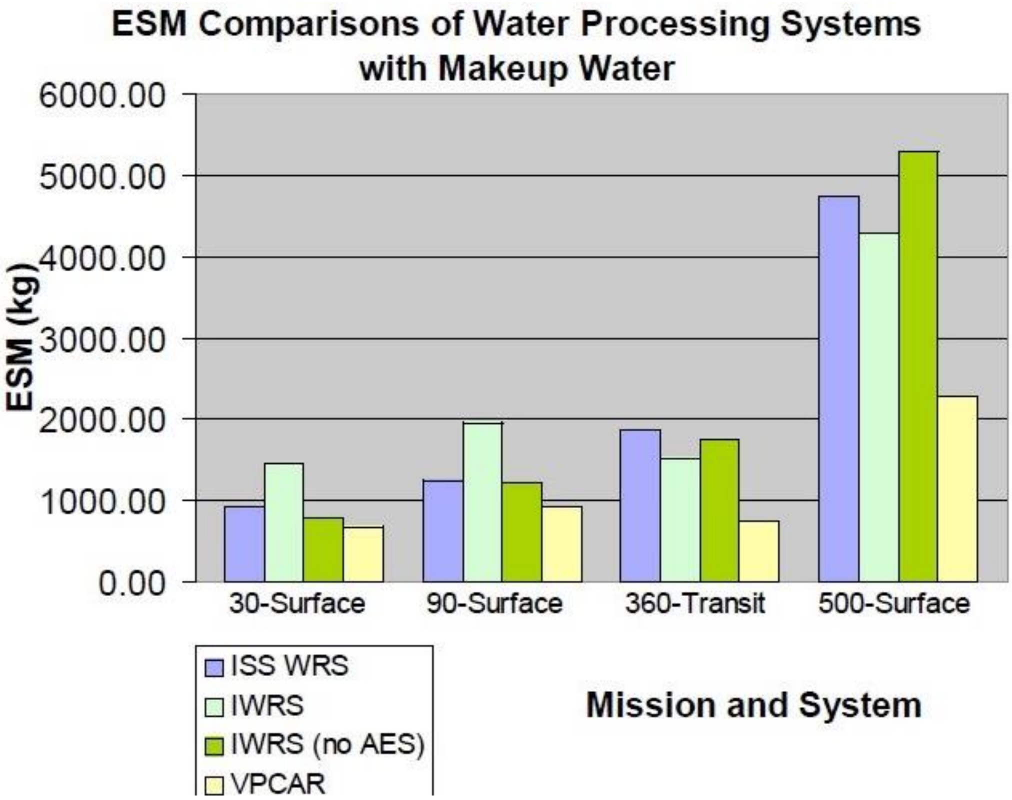

Figure 3-4: Results of water processing trade study [71]

3.3.2 ECLSS system level - design of a deep space life support system

Jones examined open loop, partially closed and closed loop ECLSS architectures to identify an optimal deep space life support system design which is characterized by providing the required performance whilst having maximal reliability and minimal equivalent system mass [47]. The author argued that the ultra-reliability needed for long-duration, nearly autonomous missions could only be achieved by storage type ECLSS. The reasoning for using regenerable instead of non-regenerable systems on board the ISS was according to Jones stemmed by their superior performance during long-term applications and the compensation of lower reliability by having frequent resupply missions in case of system failure or emergencies. Within the trade study, the author assumed to have 10 % spare parts for storage systems and multiple redundancies for regenerable system as means of increasing overall ECLSS reliability. Furthermore, it is worth noting that for ESM calculation of open loop systems only the mass of consumables was considered. Jones concluded that storage life support systems were the best option for mission durations of up to 240 days as shown in Figure 3-5 [47]. At that point they were outperformed by triple or higher multiple redundant regenerable systems.

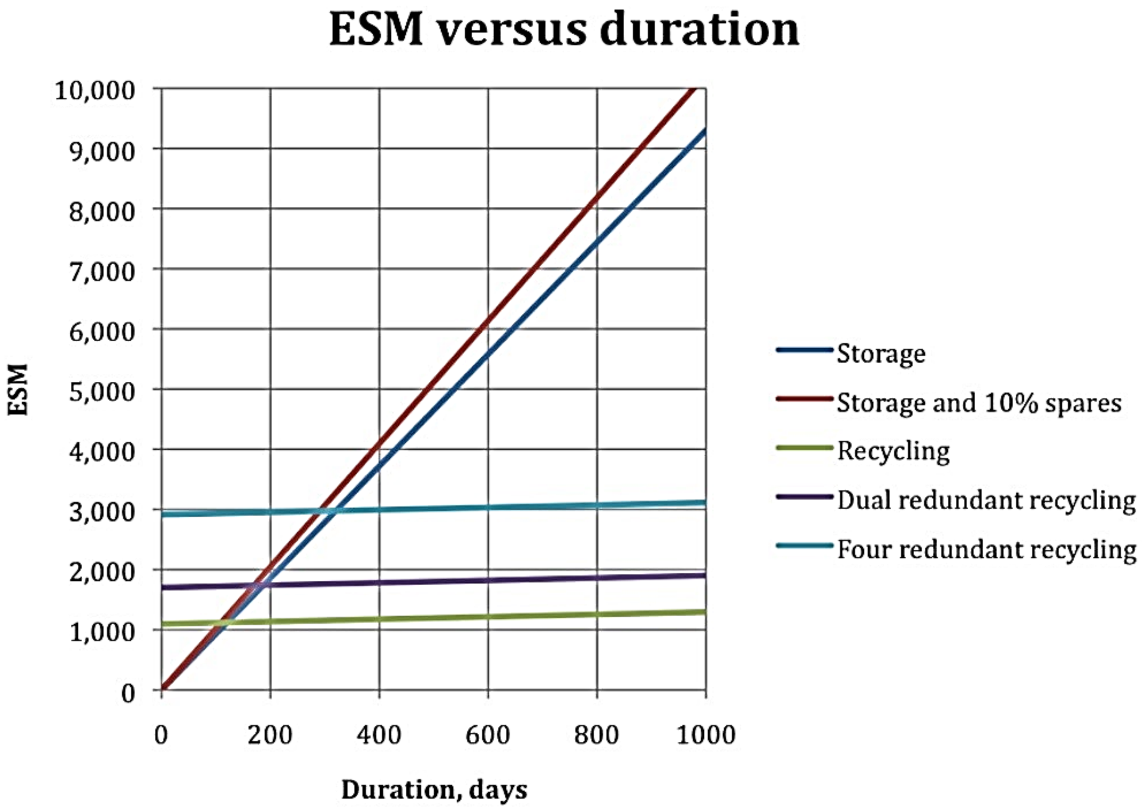

Figure 3-5: Results of open versus closed loop ECLSS trade study [47]

According to the author, the optimal deep space ECLSS design consisted of both storage and recycling technologies for water management since the amount of water necessary to ensure the survival of the crew is only approximately 25 % of the total water requirement. He proposed to use ultra-reliable storage for potable water and recycle the remaining 75 %. However, Jones pointed out that this partial approach should not be applied to O_2 provision or CO_2 removal because it could not guarantee crew survival [47].

Jones showed that when applied on ECLSS system level, the ESM metric can be used to provide breakeven points when different life support architectures are examined. By employing this approach, it is depicted until which point in time a specific ECLSS is more or less favourable than an alternative. This way of visualizing data deviates from the one used by Anderson and is arguably more beneficial since more information can be conveyed.

4 LiSTOT

4.1 Structure

LiSTOT has been developed to allow fast and yet detailed trade-offs for ECLSS technologies and architectures. LiSTOT incorporates the commonly used ESM metric for life support design on both subsystem and system level and combines it with an MCA to consider system characteristics that would otherwise be omitted by relying solely on the ESM methodology. Thereby, the tasks of an ECLSS are classified according to its subsystems into predefined functions. Depending on the selected ECLSS function, LiSTOT provides technologies which then become the subject of the MCA. In this regard, one is provided with alternatives for every ECLSS function that is of interest for the user. MCA is also meant to sort alternatives out that do not fulfil basic requirements such as having a high enough TRL for instance and is thus conducted prior to the ESM analysis. The mission, MCA and ESM parameters needed for initiating the analysis process are defined within the analysis initiation as the first step when using LiSTOT. Thereby, one outlines the mission scenario on which the proceeding steps of the tool are based. The mission parameters include mission duration and crew size as well as ECLSS architecture specifications such as type of life support system (open, partially closed or closed loop), total pressurized volume and number of modules.

The robustness of the results of the MCA and ESM analyses is examined in a sensitivity analysis. The procedure of conducting Multi-Criteria, ESM and sensitivity analyses can be regarded as a periodic process since in every cycle, alternatives for only one predefined ECLSS function can be examined. Once all the decisions on what life support technologies shall be used have been made, one can test the interactions between the selected technologies in the ECLSS composition tool and calculate the overall ESM of the entire finalized ECLSS design. As an optional final step, one can create resupply models for the ECLSS that was composed in the previous step. Figure 4-1 depicts the flow chart of LiSTOT's ECLSS design analysis process.

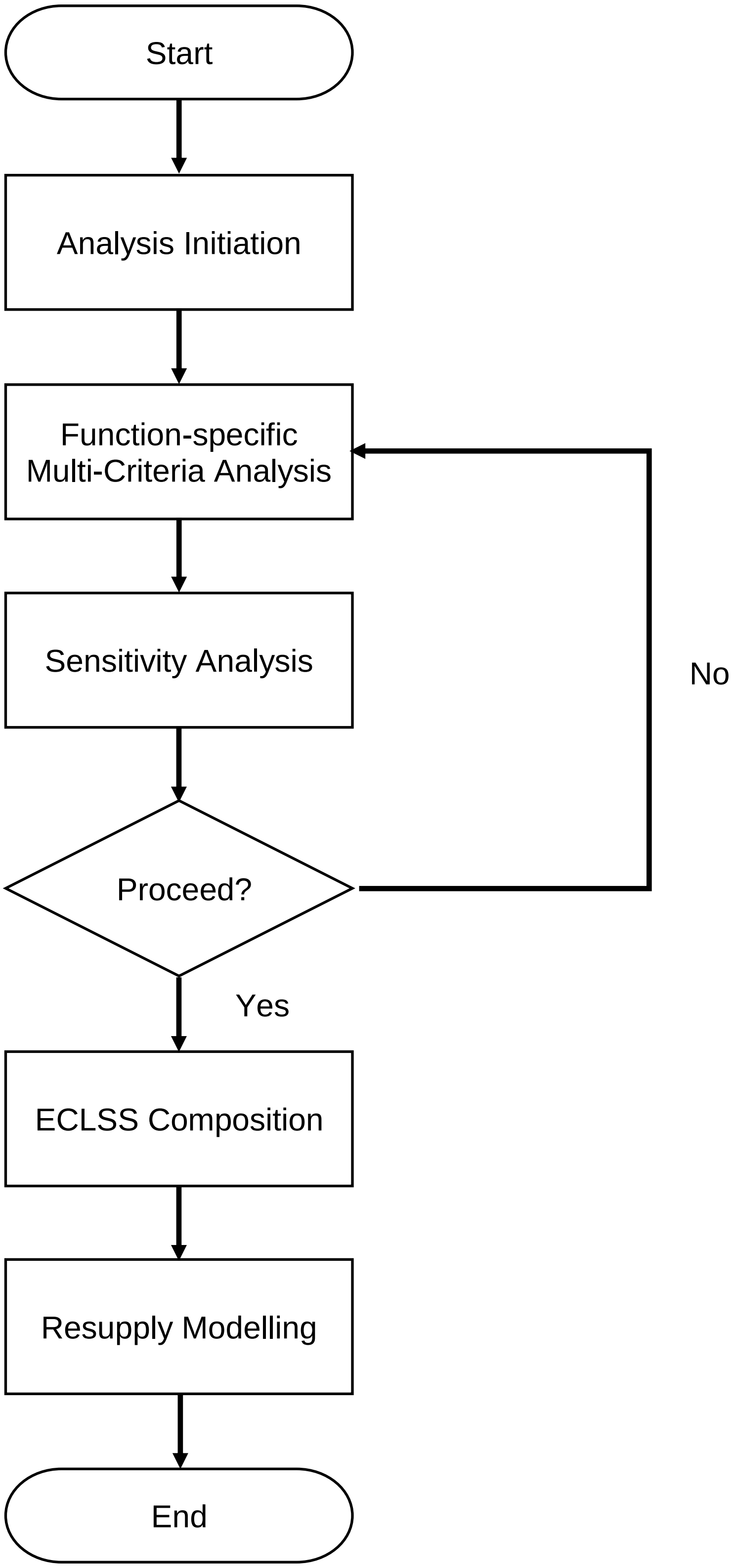

Figure 4-1: LiSTOT procedure

4.2 ECLSS functions

As described in chapter 4.1, the process of selecting and choosing technologies for which a Multi-Criteria, ESM and sensitivity analysis is performed, is dependent on given ECLSS functions. These functions have been identified by analytically decomposing an ECLSS and its tasks within development of the Scaling of Life Support Systems (SCALISS) software tool. The authors employ the defined functions to form an ECLSS functional architecture. Each architecture thereby demonstrates the interactions and relationships between the functions. It is worth noting that depending on the architecture, not every function needs to be considered. For example, the function of generating O_2 is not included in a non-regenerative ECLSS architecture. In selecting a certain function, the user is provided with all technologies that are included in LiSTOT's database and fulfil the specified function [72].

The user is not required to perform MCA analyses for each function but can proceed to the ECLSS composition once optimal technologies for functions that are of interest to the user have been determined. In the following table, all the currently implemented ECLSS functions, classified according to the corresponding life support subsystem, are listed.

The function "Process Wastewater" is subdivided into three subfunctions according to the type of wastewater that is meant to be processed:

- Process Wastewater a): It is permissible to process wastewater from humidity to recover potable or hygiene water.
- Process Wastewater b): It is permissible to process hygiene wastewater to recover potable or hygiene water.
- Process Wastewater c): It is permissible to process wastewater from urine to recover potable or hygiene water.

Table 4-1: ECLSS functions considered in LiSTOT

Function	Subsystem
Control Atmosphere Total Pressure	ACS
Detect Rapid Decompression	ACS
Recover from Rapid Decompression	ACS
Relieve Overpressure	ACS
Add Inert Gas to Atmosphere	ACS
Control Oxygen Partial Pressure	ACS
Add Oxygen to Atmosphere	ACS
Supply Inert Gas	ACS
Store Inert Gas	ACS
Store Oxygen	ACS
Control Atmospheric Composition	ACS
Control Atmospheric Temperature	THC
Remove or Add Sensible Heat	THC
Control Atmospheric Humidity	THC
Remove or Add Moisture	THC
Exchange Atmosphere between Modules	THC
Accept Thermal Energy	THC
Release Thermal Energy	THC
Reuse Thermal Energy	THC
Reject (Dispose of) Excess Thermal Energy	THC
Detect Fire	THC
Suppress Fire	THC
Remove Gaseous Atmospheric Contaminants	AR
Remove Carbon Dioxide	AR
Reduce Carbon Dioxide	AR
Control Airborne Particulates	AR
Remove Airborne Particulates	AR
Control Microbes	AR
Detect Hazardous Atmosphere	AR
Recover from Hazardous Atmosphere	AR
Regenerate Oxygen	AR
Process Gaseous Wastes	AR
Control Water Quality	WRM
Water System Decontamination	WRM
Supply Water	WRM
Store Water	WRM
Accept Wastewater	WRM
Store Wastewater	WRM
Process Wastewater (a-c)	WRM
Store Gaseous Wastes	WM
Accept Solid and Concentrated Liquid Wastes	WM
Store Solid and Concentrated Liquid Wastes	WM
Process Solid and Concentrated Liquid Wastes	WM

4.3 Technologies

LiSTOT incorporates an extensive database for life support technologies which is being kept up-to-date with data received from literature or experiments. This data bank provides information about system characteristics as well as operational and safety aspects of a specific technology. LiSTOT distinguishes between different hierarchic element levels which are listed in Table 4-2 [6].

Table 4-2: Element levels [6]

Level	Description	Examples
System	Group of subsystems	ECLSS
Subsystem	Part of a system	ACS, AR, THC, WRM
Assembly	Collection of related units in a subsystem	4BMS
Component	Functional unit within an assembly	Pump, amine bed

This bottom-up approach allows for more detailed calculations since one can consider every component and its specifications as well as attributes within an assembly.

4.3.1 Confidence factors

Dealing with uncertainties is a part of any design or trade study since rarely all the necessary data is available. Hence, not only the initial data may be inaccurate but also the processes and calculations relying on it may be affiliated with simplifications. To account for uncertainties in a trade analysis, Czupalla proposed to employ confidence factors f_{CF} which range from 0 to 1 depending on the reliability and certainty of information sources for data or processes [73]. In LiSTOT, confidence factors are used within the MCA. A more detailed description of their application is provided in chapter 4.7.

4.3.2 LiSTOT's technology database

The currently available life support technologies in LiSTOT's database are listed in this chapter in the context of corresponding life support subsystems. The initial values of the respective technology on which LiSTOT's scaling approach is based can be found in Table 9-1 in the annex [48], [74]. This is necessary since Schreck employed primarily life support design specifications related to Mars mission scenarios since it fitted the task of his thesis [6]. However, to a create a preferably general trade-off tool, efforts were taken to use design data that is not linked to any specific mission scenarios. Nonetheless, specifications for mission-dependent technologies are included in LiSTOT's database in case for a given mission scenario it is desired to employ more eligible data for system sizing. Schreck provides an in-depth description of every P/C technology that is incorporated in this chapter. One may refer to his work if additional information about certain systems is required [6]. The following tables depict which P/C assemblies are considered within LiSTOT for the ECLSS subsystems ACS, THC, AR, and WRM. Thereby, the assembly's functions and type (regenerable or non-regenerable) is provided.

It is also worth noting that certain assemblies may be depicted in more than one table if they fulfil functions of a different ECLSS subsystem, too. Furthermore, algal reactors have been added to LiSTOT's database and are discussed in chapter 4.3.3.

Table 4-3: Assemblies for ACS

Assembly	Function	Type
High-pressure storage (HPS)	Store Oxygen Store Inert Gas Store Gaseous Wastes Recover from Rapid Decompression	Non-regenerable
Cryogenic storage (CS)	Store Oxygen Store Inert Gas Store Gaseous Wastes Recover from Rapid Decompression	Non-regenerable
Oxygen Candles ($LiClO_4$)	Store Oxygen	Non-regenerable
Hydrogen Peroxide	Store Oxygen	Non-regenerable
Hydrazine	Store Inert Gas	Non-regenerable

Table 4-4: Assemblies for THC

Assembly	Function	Type
Carbon Dioxide and Moisture Removal Anime Swing-Bed System (CAMRAS)	Remove or Add Moisture Remove Gaseous Atmospheric Contaminants Remove Carbon Dioxide Control Atmospheric Humidity	Non-regenerable
Common Cabin Air Assembly (CCAA)	Remove or Add Moisture Control Atmospheric Temperature Remove or Add Sensible Heat Control Atmospheric Humidity	Regenerable
Water Vapor Electrolysis	Regenerate Oxygen Control Atmospheric Humidity Remove or Add Moisture	Regenerable
Fire Detection and Handling System	Detect Fire Suppress Fire	Non-regenerable

Table 4-5: Assemblies for AR

Assembly	**Function**	**Type**
Lithium Hydroxide	Process Gaseous Wastes Remove Gaseous Atmospheric Contaminants Remove Carbon Dioxide	Non-regenerable
Metal Oxides (METOX)	Remove Gaseous Atmospheric Contaminants Remove Carbon Dioxide	Regenerable
Sodasorb	Remove Gaseous Atmospheric Contaminants Remove Carbon Dioxide	Non-regenerable
Superoxides	Regenerate Oxygen Process Gaseous Wastes Remove Gaseous Atmospheric Contaminants Remove Carbon Dioxide	Non-regenerable
Two Bed Molecular Sieves (2BMS)	Remove Gaseous Atmospheric Contaminants Remove Carbon Dioxide	Regenerable
Four Bed Molecular Sieves (4BMS)	Remove Gaseous Atmospheric Contaminants Remove Carbon Dioxide	Regenerable
Solid Amine Water Desorption (SAWD)	Remove Gaseous Atmospheric Contaminants Remove Carbon Dioxide	Regenerable
Solid Amine Vacuum Desorption (SAVD)	Remove Gaseous Atmospheric Contaminants Remove Carbon Dioxide	Regenerable
Electrochemical Depolarization Concentration (EDC)	Remove Gaseous Atmospheric Contaminants Remove Carbon Dioxide	Regenerable
Air Polarized Concentrator (APC)	Remove Gaseous Atmospheric Contaminants Remove Carbon Dioxide	Regenerable

Carbon Dioxide and Moisture Removal Anime Swing-Bed System (CAMRAS)	Remove or Add Moisture Remove Gaseous Atmospheric Contaminants Remove Carbon Dioxide Control Atmospheric Humidity	Non-regenerable
Sabatier Reactor	Remove Gaseous Atmospheric Contaminants Reduce Carbon Dioxide Process Gaseous Wastes	Regenerable
Bosch Reactor	Remove Gaseous Atmospheric Contaminants Reduce Carbon Dioxide Process Gaseous Wastes	Regenerable
Advanced Carbon Reactor System (ACRS)	Process Gaseous Wastes Regenerate Oxygen Reduce Oxygen	Regenerable
Carbon Dioxide Electrolysis (COE)	Process Gaseous Wastes Regenerate Oxygen Reduce Oxygen	Regenerable
Solid Polymer Water Electrolysis (SPWE)	Regenerate Oxygen	Regenerable
Solid Feed Water Electrolysis (SFWE)	Regenerate Oxygen	Regenerable
Water Vapor Electrolysis	Regenerate Oxygen Control Atmospheric Humidity Remove or Add Moisture	Regenerable
Solid Electrolyte Oxygen System (SEOS)	Regenerate Oxygen	Regenerable
High-Pressure Electrolysis (HPE)	Regenerate Oxygen	Regenerable
Trace Contaminant Control System (TCCS)	Remove Gaseous Atmospheric Contaminants	Non-regenerable

Table 4-6: Assemblies for WRM

Assembly	**Function**	**Type**
Multifiltration (MF)	Water System Decontamination Process Wastewater a) Process Wastewater b)	Non-regenerable
Reverse Osmosis (RO)	Water System Decontamination Process Wastewater a) Process Wastewater b)	Regenerable
Electrodialysis (EDI)	Process Wastewater a) Process Wastewater b) Process Wastewater c)	Regenerable
Vapor Compression Distillation (VCD)	Water System Decontamination Process Wastewater a) Process Wastewater b) Process Wastewater c)	Regenerable
Thermoelectric Integrated Membrane Evaporation (TIMES)	Water System Decontamination Process Wastewater a) Process Wastewater b) Process Wastewater c)	Regenerable
Air Evaporation System (AES)	Water System Decontamination Process Wastewater a) Process Wastewater b) Process Wastewater c)	Non-regenerable
Vapor Phase Catalytic Ammonia Removal (VPCAR)	Water System Decontamination Process Wastewater a) Process Wastewater b) Process Wastewater c)	Regenerable
Water Quality Monitoring	Control Water Quality	Non-regenerable
Bladder tank (storage)	Store Water Store Wastewater	Non-regenerable

4.3.3 Algal Photobioreactors

Algal photobioreactors are multifunctional by their very nature. They are capable of air revitalization, processing wastewater, providing food and could also offer radiation shielding and thermal control. Algae metabolically process water, CO_2 and produce O_2 and biomass in the photosynthetic reaction which can be simplified as:

$$6\,CO_2 + 6\,H_2O \xrightarrow{yields} C_6H_{12}O_6 + 6\,O_2 \tag{4.1}$$

whereby all biomass that is produced is assumed to be glucose ($C_6H_{12}O_6$). As all photosynthetic systems, algae respond to changes in the environment concerning temperature, illumination, CO_2 and O_2 content and pH in real-time. This dynamic reaction capability may be useful to achieve a high level of autonomy of algal photobioreactors. Moreover, due to the reduction of moving parts, algal systems may surpass reliability values of established P/C systems [75]. The following chapters discuss the use of algal reactors for air revitalization, wastewater (urine) processing and food supply since those relate to immediate ECLSS tasks.

4.3.3.1 Air Revitalization

As shown in equation (4.1), algae consume CO_2 and water and produce biomass and O_2. Furthermore, nitrate and phosphate are required to sustain the mass of algae. The CO_2 turnover capability of the photobioreactor is based on the type of algal used. Chlorella Vulgaris is utilized in the given example of an algal reactor. Table 4-7 depicts the daily amount of nitrate and phosphate required and biomass produced per litre of Chlorella Vulgaris for CO_2 removal and O_2 generation [75].

Table 4-7: Loads and demands of Chlorella Vulgaris [75]

Parameter	**Value**
Nitrate [g/(L·d)]	0.26
Phosphate [g/(L·d)]	0.74
Biomass [g/(L·d)]	1.5

One could consider adding these nutrients using the urine of the crew. Despite several studies having been conducted on this topic however, the required amount of nitrate and phosphate is typically provided as consumables [76].

The volume of algae required to support a crew of six is shown in Table 4-8. Thereby, the authors assumed an O_2 consumption of 0.815 kg/(CM·d) and CO_2 production of 1.04 kg/(CM·d) [75].

Table 4-8: Volume of algae required to support crew of six [75]

Parameter	**Amount of algae required [L]**	**Absorbed/Produced [kg/d]**
Carbon dioxide removal	1,300	6.24
Oxygen generation	1,200	4.89

Using this information, one can compute the volume of algal necessary to support a certain CO_2 production per crew member by calculating the ratio $r_{algae\ required}$ of algae required $V_{alg,CO2}$ to the corresponding mass of CO_2 absorbed $\dot{m}_{CO2\ absorbed}$:

$$r_{algae\ required} = \frac{V_{alg,CO2}}{\dot{m}_{CO2\ absorbed}} \qquad (4.2)$$

Thereby, with $V_{alg,CO2}$ being 1,300 L and $m_{CO2\ absorbed}$ 6.24 kg/d, one obtains a $r_{algae\ required}$ of 208.3 L·d/kg. Multiplying this ratio with the specified daily amount of CO_2 produced per crew member provides the volume of algal per crew member. Considering the volume specifications of Table 4-8, it is evident that more volume of Chlorella Vulgaris is necessary to fulfil the CO_2 requirement than what is needed to satisfy the daily O_2 needs of the crew. This means, that if the amount of algal medium is high enough to meet the CO_2 absorption function, the task of O_2 generation is automatically achieved. In this respect, the CO_2 removal requirement dictates the amount of algae V_{alg}, which consequently implies that the O_2 content produced by the photobioreactor depends on the volume of algae necessary for CO_2 consumption. Thus, the amount of O_2 $\dot{m}^*_{O2\ produced}$ produced by the reaction overall can be calculated as:

$$\dot{m}^*_{O2\ produced} = \frac{\dot{m}_{O2\ produced}}{V_{alg,O2}} \cdot V_{alg} \qquad (4.3)$$

with $\dot{m}_{O2\ produced}$ being the given amount of O_2 as 4.89 kg/d and $V_{alg,O2}$ the volume of Chlorella Vulgaris required to produce this O_2 content which is specified as 1,200 L. The functionality of an algal photobioreactor is provided in the following.

Cabin air with a CO_2 concentration high enough (approximately 5 %) to support algal cultures is fed to a gas membrane. The O_2 that is produced is then removed by a gas removal membrane and can be reintroduced to the cabin. If the cabin air within the membrane has a CO_2 concentration of more than 0.5 %, the gas stream is recirculated through the membrane [75]. Figure 4-2 depicts how an algal photobioreactor may be integrated in an ECLSS [75].

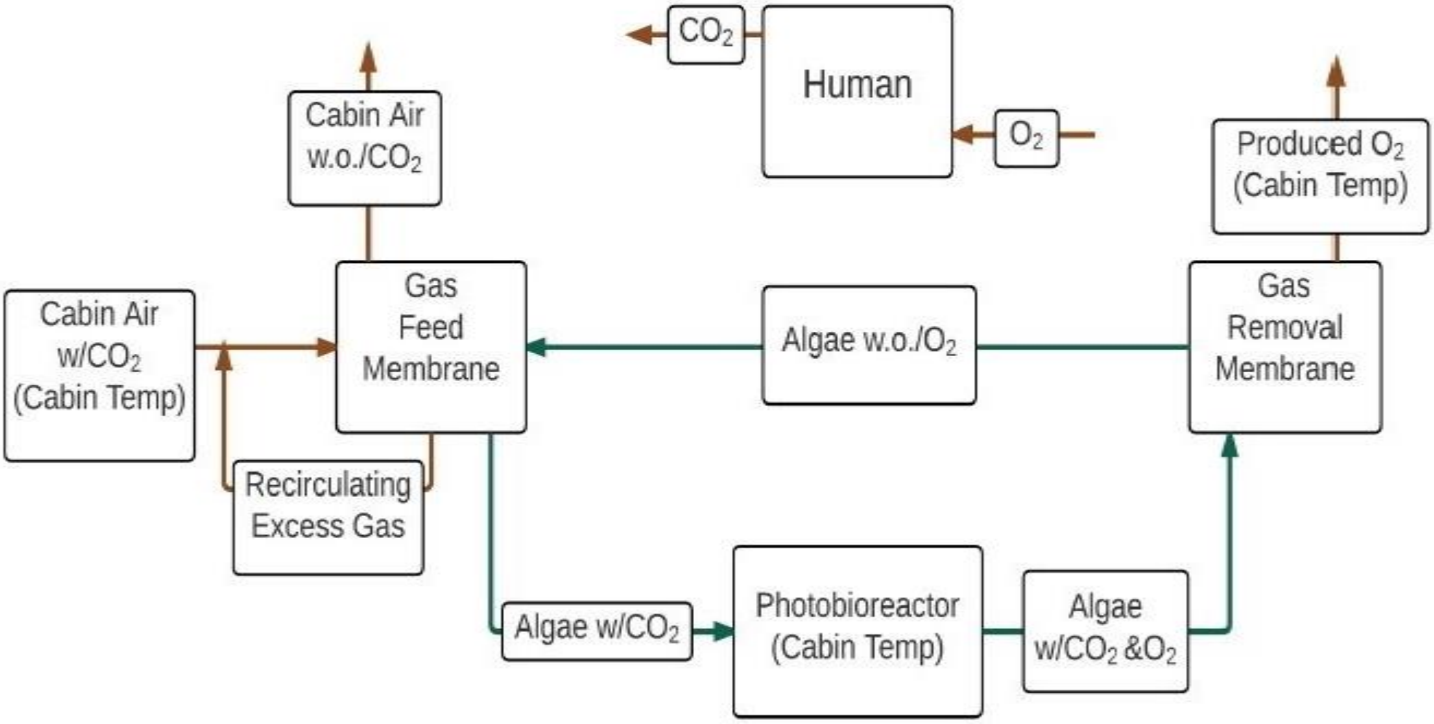

Figure 4-2: Scheme of an algal photobioreactor for AR [75]

The specifications of a Chlorella Vulgaris photobioreactor supporting a crew of six is given in Table 4-9 [75].

Table 4-9: Specifications of algal photobioreactor [75]

Parameter	**Value**
Mass [kg]	1,700
Volume [m^3]	1.66
Power [kW]	4.08

No cooling requirement could be found and is thus assumed to be equivalent to the given power need of the system. Furthermore, the authors did not state any crew time requirements for the algal reactor. However, since biomass needs to be processed, crew time needs may likely exceed those for comparable P/C technologies. To compensate for this critical, yet missing piece of information, a crew time half of what is needed for handling crops is assumed since crops necessitate crew activities that are not shared by processing algal biomass. The crew time needs of a crop system are given by NASA's Baseline Values and Assumptions Document (BVAD) as 13.1 CM·h/(m^2·y) [66].

The required area for fulfilling the air revitalization functions of an algal reactor, absorbing CO_2 and providing O_2, by growing crops, can be estimated to be 10 m^2. This leads to a crew time of the crop system of 0.36 CM·h/d and a crew time of 0.18 CM·h/d for the algal photobioreactor.

In addition, it is important to note that the reactor inlet gas stream must provide a CO_2 concentration of about 5 %, which is significantly higher than the nominal CO_2 concentration of the cabin air. In this regard, a CO_2 removal device must be present to increase the CO_2 content of the air flow. Since the authors compared the algal photobioreactor specified in Table 4-9 with the summed-up mass, volume and power characteristics of the CO_2 removal, reduction and water electrolysis assemblies of the ISS, it is assumed that a CO_2 removal device is incorporated in the given data.

Due to the lack of testing on the ISS, a TRL of 4 is applied. Furthermore, since the data primarily relies on one paper, a $f_{certainty}$ of 0.5 is used. The Institute of the University of Stuttgart, the German Center for Aerospace (DLR) and Airbus Defence & Space developed an algal reactor experiment called Photobioreactor @ the Life Support Rack (PBR@LSR) that uses Chlorella Vulgaris and is meant to be tested on board the ISS in 2019 [77], [78]. One may adjust the TRL of algal photobioreactors for CO_2 removal after the results of this test have been published.

4.3.3.2 Wastewater Processing

As stated in chapter 4.3.3.1, algae require nitrate and phosphate to support cellular growth. Since urine contains these compounds, studies have been conducted to examine the feasibility of using algal photobioreactors for processing wastewater. The content of nitrate and phosphate in urine is outlined in Table 4-10 [75].

Table 4-10: Nitrate and phosphate content in urine [75]

Compound content	Amount per CM [g/(CM·d)]
Nitrate	11
Phosphate	1

Thereby, urine is usually diluted ranging from 1:2 to 1:2000. Similar to the CO_2 turnover capability of the air revitalization reactors, the efficiency and characteristics of wastewater processing photobioreactors depend on the type of algae used. The difference between Chlorella Vulgaris and Chlorella Sorokiniana for wastewater processing is depicted in Table 4-11 [75].

Table 4-11: Wastewater processing characteristics for Chlorella Vulgaris and Chlorella Sorokiniana [75]

	Parameter	**Value for Chlorella Vulgaris**	**Value for Chlorella Sorokiniana**
Inputs	Carbon dioxide concentration in gas stream [%]	0.03	10
	Nitrogen (post dilution) [g/L]	0.173	1.77
	Phosphorus (post dilution) [kg/L]	0.014	0.130
	Dilution ratio	1:25	1:3
Outputs	Nitrogen reduction [%]	40	45
	Phosphorus reduction [%]	35	70
	Turnover time [d]	21	200
	Biomass productivity [g/(L·d)]	0.06	15

Accounting for the values listed in Table 4-11, it is obvious that the choice of algae imposes a detrimental effect on the characteristics of the wastewater processing photobioreactor. For instance, Chlorella Vulgaris requires a urine dilution ratio of 1:25, which means that assuming one considers processing all daily produced urine by one crew member (1.6 kg/(CM·d)), 40 kg/(CM·d) of water is necessary. However, even if the entire daily load of wastewater per crew member (estimated 8 kg/(CM·d) including sweat and wastewater from hygiene activities), the required amount of water to dilute the urine vastly exceeds the water content available on the station. This consequently implies that additional water is needed on the station to achieve urine processing. Furthermore, the reduction capabilities of Chlorella Vulgaris are inferior to those of Chlorella Sorokiniana. Assuming one uses Chlorella Sorokiniana, significantly less water is needed to dilute the urine (4.8 kg/(CM·d)), yet the turnover time is increased roughly by a factor of ten in comparison to Chlorella Vulgaris, which limits the practicability of utilizing Chlorella Sorokiniana. In addition, the biomass productivity is 250 times higher than that of Chlorella Vulgaris, which leads to vastly increased loads on the station’s waste management as well as the required crew time necessary to handle the biomass. The amount of algae required to process the nitrate and phosphate compounds outlined in Table 4-10 are listed in the following table [75].

Table 4-12: Amount of algal medium required to process urine [75]

Parameter	**Chlorella Vulgaris**	**Chlorella Sorokiniana**
Algal medium required to reduce all nitrogen [L]	19,600	16,200
Algal medium required to reduce all phosphor [L]	26,500	13,800

In the case of Chlorella Vulgaris, the requirement of processing all N_2 is incorporated in reducing all phosphor. For Chlorella Sorokiniana, this circumstance is inverted. It is critical to state that if one takes the CO_2 consumption values of Chlorella Vulgaris as provided in chapter 4.3.3.1 into account, it is evident that the CO_2 that is produced by the crew is not enough to sustain the amount of algal needed for wastewater processing. Additional “fuel” for the photosynthetic reaction would thus be required.

The specifications of an algal photobioreactor using Chlorella Vulgaris for urine processing supporting a crew of six are outlined in Table 4-13 [75].

Table 4-13: Specifications of an algal reactor for urine processing [75]

Parameter	**Value for algal photobioreactor**	**Value for UPA+WPA**
Mass [kg]	24,050	1,200
Volume [m^3]	21	3.14
Power [kW]	85.7	0.56

Comparing these specifications with the Urine Processing Assembly (UPA) and Wastewater Processing Assembly (WPA) of the ISS, given in Table 4-13, it is striking that the algal photobioreactor performs considerably worse in any given parameter. The mass is 20 times higher, the volume seven times and the power requirement over 150 times higher than the ISS technologies. Taking these infrastructural demands into account and considering the issues concerning urine dilution, turnover time and compound reduction capabilities as described above, the feasibility of using algal reactors for urine and wastewater processing is highly questionable.

A TRL of 4 is assumed due to the lack of testing this algal photobioreactor in a relevant environment. Furthermore, since the data primarily relies on one paper, a $f_{certainty}$ of 0.5 is used.

4.3.3.3 Food provision

Due to their high biomass production rates and high nutrient content, the usage of algae for food provision is currently an area of research. The U.S. Food and Drug Administration (FDA) advises that daily consumption rates of algae for a person (70 kg male) shall not exceed 16.8 g/(CM·d) [79]. Hence, algae can contribute to the food provision system onboard a space station but cannot be the only food source. When using Chlorella Vulgaris, 1.5 g/(L·d) of dry biomass is produced, which defines the amount of algae necessary to fulfil the food requirement of the FDA to 11.2 L/CM. Comparing this volume with what is needed for air revitalization or wastewater processing as shown in chapters 4.3.3.1 and 4.3.3.2, the task of food provision is completely covered by both algal photobioreactors. This suggests that part (16.8 g/(CM·d)) of the biomass that is produced during air filtering or wastewater processing is used as food, whereas the remaining part is transferred to the Waste Management system [75].

Additional aspects need to be considered if it is desired to employ Chlorella Vulgaris as a food source [75]:

- Cells of Chlorella Vulgaris contain a thick cellulose wall, which makes them hard to digest in larger quantities for humans. Post-harvest processing such as grinding the biomass to powder may facilitate digestion.
- Biomass of Chlorella Vulgaris is characterized by a fishy taste, which is unpleasant if consumed in larger quantities.

4.4 System scaling

Performance data for life support systems is usually specified depending on a fixed crew size and mission scenario for which the respective system was designed. In this respect, it is likely that one may obtain several specifications for one particular system. For example, Eckart provides design data for an EDC CO_2 removal device for a crew of eight [80], whereas Jones specifies an EDC system for a 400-day Mars mission with four crew members [81]. Furthermore, raw data received from researchers may come from a laboratory prototype which was built for technology demonstration purposes and not for supporting a human being. The design specifications of such systems are commonly based on performance characteristics that were achieved by that assembly [3].

Robust sizing mechanisms are required if it is intended to scale a system according to a specific crew size. To address this sizing issue, various scaling approaches have been proposed depending on the available information about a system and the required accuracy of an analysis. Hardware is usually scaled according to a characteristic parameter such as system through-, in- and/or output values. A common way of sizing a CO_2 removal device for example consists of multiplying the amount of crew members by the average CO_2 production per individual [3]. Thereby, it is important to decide whether the system is meant to be scaled according to nominal or emergency operation, which dictates the system's residual margins. Since this method relies on the metabolic loads and demands of a human, it is referred to as a metabolic scaling approach from this point on. Its advantages lie in its simplicity and ease of application for life support systems. However, these benefits come at the cost of low-fidelity, which is caused by the fact that system masses usually do not scale linearly with crew size due to components that scale independently with crew size. Thus, the linear scaling approach can be considered a conservative sizing methodology. Additional linear or non-linear scaling or component-specific factors may be required to obtain more accurate results [3]. In sizing life support technologies for ALSSAT for instance, Yeh et al. employed scaling factors used by the chemical industry [67]. Another shortcoming of the metabolic scaling approach is the lack of consideration of hardware components that are independent of crew size [3].

A more accurate but also vastly more extensive way of scaling life support technology consists of evaluating every component of an assembly separately to assess its respective influence on system sizing. In this regard, one may exclude hardware that only has a minor effect from system scaling to save analysis efforts. It is thereby crucial that the entirety of the system is examined to prevent any non-intuitive, yet significant elements from being omitted. During trade studies for water processing systems, Anderson used a 40/60 sizing approach in which 40 % of the system mass is kept constant, while the remaining 60 % scale linearly with the mass flow [71].

Depending on the demanded fidelity of the system sizing, scaling efforts can range from steady-state to dynamic conditions. A steady-state approach is typically simple but also less accurate than a high-fidelity, more costly transient sizing method that requires the use of dynamic simulation tools. Such a dynamic software for automated scaling of life support systems called SCALISS has been developed by ESA in corporation with DLR and Thales Alenia Space [72].

4.4.1 LiSTOT's system sizing approach

LiSTOT uses a steady-state metabolic scaling approach that can be individually adapted for every assembly that scales proportionally with crew size. This method was chosen since reliable and accurate data which is required for high-accuracy, component-specific or transient sizing efforts of certain life support technologies especially those of ALS is hard to come by. The sizing is realized via a rescale factor f_R that is calculated as the quotient of a given crew size $n_{crew,given}$ to a desired crew size $n_{crew,desired}$:

$$f_R = \frac{n_{crew,given}}{n_{crew,desired}} \tag{4.4}$$

in case a crew size specification is provided. Thereby, crew size is dealt with as a sum of individual human equivalent units (HEU) - an approach that was also used for sizing ISS O_2 generation and CO_2 removal systems [48]. A HEU is characterized by its daily metabolic loads and demands. In LiSTOT, these requirements are defined by selecting or composing a desired schedule (see chapter 4.5). In this regard, one can choose according to which operational case (nominal or user defined) an assembly is sized.

If no design crew size is provided, the system is scaled according to its through-, in- or output. In doing so, the rescale factor is obtained by computing the ratio of a given through-, in- or output $\dot{m}_{given}$ which may be specified in kg/d to the corresponding demand of one HEU $\dot{m}_{demand}$ in kg/d and multiplying this quotient with $n_{crew,desired}$:

$$f_R = \frac{\dot{m}_{given}}{\dot{m}_{demand}} \cdot n_{crew,desired} \tag{4.5}$$

To compensate for inaccuracies resulting from non-linear system sizing behaviour, an additional system dependent scaling factor f_s can be defined and assigned to each assembly. By default, this factor is set to 1, 0.9 or 0.8 depending on the crew size because certain components such as tubes typically do not scale with a factor of one, which would mean double the mass for double the crew size. The relation between the number of crew members and the scaling factor is given as follows:

$1 < n_{crew,desired} < 7$: $f_s = 1$

$7 \leq n_{crew,desired} < 10$: $f_s = 0.9$

$n_{crew,desired} > 10$: $f_s = 0.8$

This classification was made under the assumption that since most ISS systems have been designed for a crew size of up to six, the scaling approach in LiSTOT should return values that are equivalent to those of ISS life support hardware if the specified number of crew members is within the design range of ISS life support equipment. It is assumed that for crew sizes exceeding ten crew members, the scaling behaviour remains constant with a f_s of 0.8. The classification stated above is not mandatory, because the system specific scaling factors can be individually adapted to user needs.

Summarizing the sizing aspects described above, a system attribute a may be scaled as follows:

$$a = f_R \cdot f_S \tag{4.6}$$

LiSTOT’s sizing approach applies to the system characteristics of mass, volume, power and cooling. One can decide for each characteristic whether a scaling factor is assigned or not. It is assumed that the crew time and reliability are not affected by system sizing.

To further address uncertainties in system scaling, contingency values for mass and power are added within LiSTOT’s system scaling effort to factor in uncertainties depending on the system’s TRL. TRL is a metric to classify technologies according to their level of maturity. TRL values are within the range of 1 to 9, whereby a TRL of one stands for the lowest possible state a technology can be in with only basic principles about it having been observed. A TRL of 9 however means that the respective technology is flight proven throughout several mission operations. Figure 4-3 depicts NASA’s TRL classification metric [82].

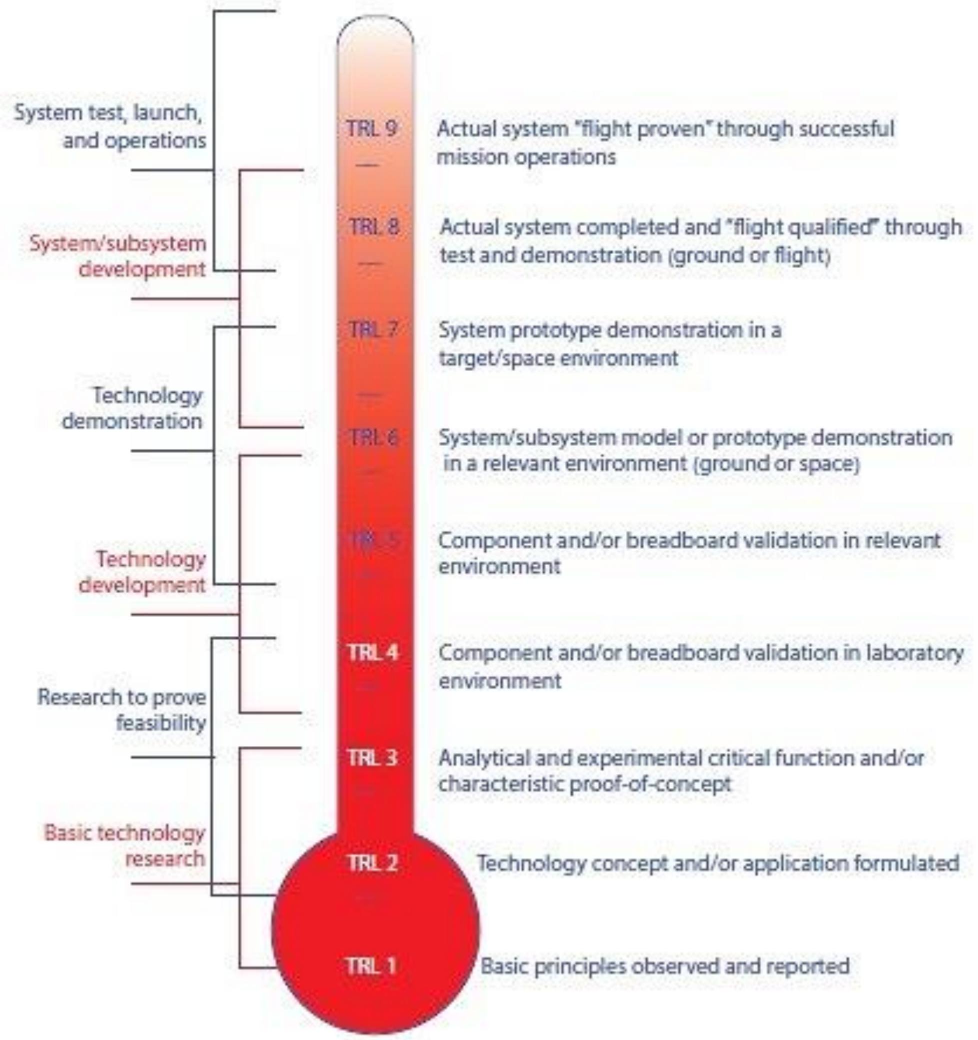

Figure 4-3: NASA TRL classification [82]

The contingency values employed in LiSTOT's sizing approach to improve the accuracy of the analysis results are listed in Table 4-14 [6], [83]. It is evident that the higher a system's TRL, the lower the required contingency mass and power.

Table 4-14: Contingency values for mass and power [6], [83]

		Increase %		
System mass	**Characteristic**	**TRL 1-3**	**TRL 4-7**	**TRL 8-9**
0-50 kg	Mass	35	25	3
	Power	75	25	12
50-500 kg	Mass	30	20	3
	Power	65	22	12
500-2500 kg	Mass	25	15	1
	Power	60	20	12
>2500 kg	Mass	22	12	0.8
	Power	35	20	11

Assemblies that scale independently or disproportionally with the amount of crew members are more difficult to size. Scaling approaches for these systems vary and may be based on characteristics of the station architecture like the number of modules or the total pressurized volume. If a default sizing method for a specific assembly is not satisfactory, LiSTOT allows the user to select the amount of such an assembly to be installed or carried along for a mission.

4.5 Schedule design

As described before, the metabolic loads and demands of the crew as outlined in chapter 3.1.2 are heavily dependent on the performed tasks which therefore dictate the operational and performance requirements of an ECLSS. The more physical exercises one performs the more O_2 and potable water are required and consequently more heat, CO_2 and sweat are produced. To obtain the daily metabolic consumption and production values of the crew, the schedule which determines the choice and succession of tasks must be examined. Schedules for use on space stations usually consist of six different basic types of tasks that include sleep, meals, work, exercise, personal hygiene and recreation [66]. Thereby, some of these activities are divided into subtasks since certain activities require preparation or post-task activities before a crew member can proceed to the next scheduled task. The activity-dependent metabolic loads and demands for each of these activities according to NASA's BVAD can be found in Table 4-15 [66].

Table 4-15: Activity-dependent metabolic loads and demands [66]

Task	**Subtask**	**Oxygen [kg/(CM·h)]**	**Carbon Dioxide [kg/(CM·h)]**	**Sweat [kg/(CM·h)]**	**Heat [kJ/(CM·h)]**
Sleep	Pre-Sleep	0.034	0.043	0.071	500
	Sleep	0.022	0.027	0.038	317
	Post-Sleep	0.034	0.043	0.071	500
Meals	Breakfast	0.034	0.043	0.071	500
	Lunch	0.034	0.043	0.071	500
	Dinner	0.034	0.043	0.071	500
Work	Work	0.034	0.043	0.071	500
	Planning/Preparation	0.034	0.043	0.071	500
Exercise	Exercise	0.236	0.299	0.629	2,090
	Post-Exercise	0.034	0.043	0.281	1,175
Personal Hygiene	Personal Hygiene	0.034	0.043	0.071	500
Recreation	Recreation	0.034	0.043	0.071	500
Homekeeping	Homekeeping	0.034	0.043	0.071	500

The daily food, potable and hygiene water needs as well as the production of wastewater, urine and feces are not directly task-dependent since one cannot predict when a crew member uses the toilet or consumes water, for example. The distribution of these metabolic loads and demands in the schedules provided by LiSTOT and the corresponding assumptions are depicted in chapter 4.5.1.

The average daily metabolic consumption and production values as provided by NASA's BVAD are depicted in Table 4-16 [66].

Table 4-16: Average daily metabolic consumption and production values [66]

	Metabolic in- or output	Value
Air	Oxygen [kg/(CM·d)]	0.816
	Carbon Dioxide [kg/(CM·d)]	1.04
Water	(Potable) Water [kg/(CM·d)]	2.5
	(Water) Food [kg/(CM·d)]	0.7
	Metabolic Water [kg/(CM·d)]	0.4
	Urine [kg/(CM·d)]	1.6
	Fecal Water [kg/(CM·d)]	0.1
	Sweat [kg/(CM·d)]	1.9
Heat	Heat load [MJ/(CM·d)]	12
Food	(Solid) Food [kg/(CM·d)]	0.81
	Energy Content of Food [MJ/(CM·d)]	12.59
Waste	Solid Urine Wastes [kg/(CM·d)]	0.059
	Solid Fecal Wastes [kg/(CM·d)]	0.032
	Solid Sweat Wastes [kg/(CM·d)]	0.018

Langston proposed generic schedules for application on the ISS. In doing so, he distinguished between variable and invariable tasks [66], [84]:

- Invariable tasks concern every activity that is applied to each crew member at the same time and is therefore fixed in a schedule and cannot be shifted or rescheduled. They include sleep, exercise, hygiene and recreation.
- Variable tasks fill the time gaps in between invariant activities and can be variably scheduled. They include work and meals.

The amount of time per task depends on various factors:

Type of life support system: Crew time for P/C life support systems is limited to monitoring, maintaining or replacing equipment. However, in case of a bioregenerative ECLSS, a substantial amount of the crew's time would be consumed by working on the biomass food production.

Mission objective: Crew times must be adapted and balanced to allow both maintenance work and mission specific tasks such as performing EVAs or conducting experiments.

Type of day: Astronauts typically have a similar workweek to that of people on Earth. From Monday to Friday, daily schedules are dominated by working activities, whereas time during the weekend can be primarily spent on recreation or housekeeping. Therefore, the respective type of day must be taken into account when scheduling tasks.

Operation case: In case of an onboard failure, an emergency schedule must be available to save resources and ensure the health of the crew.

Human factors: Certain task times cannot be shortened or even omitted. For example, NASA demands every astronaut to perform at least 1.5 h of physical exercise per day (including post-exercise tasks) to compensate for bone resorption processes that are induced by the 0 g environment.

Depending on the day type, Table 4-17 depicts exemplary time allocations for an ISS schedule [66], [84].

Table 4-17: ISS time allocations [66], [84]

Tasks	**Weekday**	**Weekend Day**	
Daily Planning Conferences [h]	0.5	0	Variably-Scheduled Time
Daily Plan Review / Report Preparation [h]	1	0	
Work Preparation [h]	0.5	0	
Scheduled Assembly, Systems and Utilization Operations [h]	6.5	0.5	
Meals [h]	3	3	
Housekeeping and Laundry [h]	0	2	
Post-Sleep [h]	0.5	0.5	Invariantly-Scheduled Time
Exercise, Hygiene, Setup/Stow [h]	2.5	2.5	
Recreation [h]	0	6	
Pre-Sleep [h]	1	1	
Sleep [h]	8.5	8.5	
Total	24	24	

4.5.1 LiSTOT schedules

LiSTOT provides several ways of composing or selecting a schedule which then forms the basis of all the metabolic dependent calculations within the tool. The schedules in LiSTOT are subdivided into intervals of half an hour. Depending on the given or selected task and the number of crew members performing it, metabolic loads and demands are induced for this interval. The sum of these consumption and production values dictates the daily performance requirements and therefore the design boundary conditions of the life support system. In defining a desired schedule, crew members can be individually assigned to tasks. Similar to Langston's schedule creation efforts, LiSTOT distinguishes between variable and non-variable activities. However, some changes and assumptions have been made for the nominal operation case.

- The exercise and recreation tasks are no longer considered to be invariable. This was done to enable the user to decide for each inhabitant of the station when or for how long an exercise is performed or when the respective crew member recreates. For example, by increasing exercise times and therefore CO_2 output, this approach allows the examination of the stability and robustness of the life support system's CO_2 removal device. The exercise task is defined as a block activity lasting 1.5 h in total since for every half an hour of physical exercise, one hour of post-exercise is demanded to let the crew member recover from the physical strains. Opposing to the other variable tasks that do not necessarily need to be implemented in a schedule, one exercise block per day is required.
- The daily meals task consists of 0.5 h of breakfast and 1 h of lunch and dinner respectively. These subtasks are dealt with as invariant because it is assumed that the entire crew comes together during meals.

In a nominal operation case, the amount of variable tasks per schedule is 11.5 h and 12.5 h for invariant activities. Every available task in LiSTOT is listed in Table 4-18.

Further assumptions include:

- All the used metabolic loads and demands are taken from NASA's BVAD [66].
- Feces (0.132 kg/(CM·d)) are accumulated during post-sleep. Feces include fecal water (0.1 kg/(CM·d)) and fecal solid wastes (0.032 kg/(CM·d)).
- Fecal water is considered blackwater and is therefore not recovered but directed to the WM subsystem.
- Food (1.51 kg/(CM·d)) is only consumed during meals. Food comprises of water (0.7 kg/(CM·d)) and solid food (0.81 kg/(CM·d)). Furthermore, metabolic water (0.4 kg/(CM·d)) is produced by oxidation of the food within the human organism. To fully hydrate food, additional water is needed which is included in the crew's potable water consumption rate.
- Potable water is consumed during meals and post-exercise activities. For nominal operations, 2.5 kg/(CM·d) are considered. The more physical exercise is performed, the more potable water is consumed. To ensure the balance of the water flows entering and leaving the body, the urine production is related to the amount of potable water consumed and thus adjusted accordingly to changes of the consumption of potable water.

- Hygiene water is required during personal hygiene, post-exercise, lunch and dinner. For nominal operations, 6.8 kg/(CM·d) are considered. The hygiene water needs for a shower once a week is incorporated in this value.
- Urine is produced during post- and pre-sleep. For nominal operations, 1.6 kg/(CM·d) are considered. Solid urine wastes (0.059 kg/(CM·d)) are consequently accumulated during urination.

These steady-state assumptions were made based on real-life empirical and expectation values since one cannot predict the occurrence of certain events. However, by choosing this simplified, yet realistic approach, the balance of the daily mass flows is ensured. The remaining metabolic loads and demands are accumulated continuously throughout the day depending on the respective tasks.

4.5.2 Default schedule

The default schedule is a generic schedule that resembles the workday routine onboard the ISS. Made under the simplification that every crew member performs the same task at the same time, which leads to distinct peaks in the gradient of the metabolic loads and demands, the default schedule represents a worst-case scenario reference point design. In this respect, every task in the default schedule can be considered invariable because tasks cannot be selected or rescheduled.

This simplification is unrealistic since space stations for instance do not have enough space or equipment like treadmills to allow the crew to physically exercise all at the same time. Yet, the default schedule provides a robust option for early life support design. Refinements in later stages of the analysis process can be made by employing a user defined schedule.

4.5.3 User defined schedule

If one wants to create a more individual crew schedule, the user defined schedule option can be employed. Thereby, the user can assign each crew member to a specific variable task. Invariable tasks as stated before are predefined and cannot be changed or shifted. LiSTOT provides several approaches for schedule composition.

4.5.3.1 Default task scheduling

Default task scheduling allows the user to choose between a “Weekday” and a “Weekend Day”. For each of these types of day, there is a fixed time allocation available which is similar to the ones depicted in Table 4-17. Thereby, the difference to selecting the default schedule is the fact that variable tasks can now be distributed among the individual crew members as desired if the time limits and requirements of each task are met. The task times for both day types in LiSTOT are depicted in Table 4-18.

Table 4-18: Time allocations for “Weekday” and “Weekend Day”

Tasks	**Weekday**	**Weekend Day**
Sleep [h]	8	8
Pre-Sleep [h]	1	1
Post-Sleep [h]	0.5	0.5
Breakfast [h]	0.5	0.5
Lunch [h]	1	1
Dinner [h]	1	1
Personal Hygiene [h]	0.5	0.5
Work [h]	6.5	0.5
Planning/Preparation [h]	2	0
Exercise [h]	1	1
Post-Exercise [h]	2	2
Recreation [h]	0	5.5
Homekeeping [h]	0	2.5
Total	24	24

4.5.3.2 Individual task scheduling

If the user intends to compose a schedule that is independent from day types, the individual task scheduling option can be selected. In doing so, one can choose any available variable task, define task dependent time allocations for every crew member and select when which activity shall be performed. Using this scheduling option, two boundary conditions must be considered:

- Total duration of all chosen variable tasks must not exceed 11.5 h. This is due to the remaining 12.5 h per day being occupied by invariant activities.
- At least one block of exercise per crew member must be included in the schedules to ensure the health and well-being of every station inhabitant.

4.6 Reliability

Reliability is one of the most critical factors for any system. Especially the life support infrastructure on board a spacecraft or station must be ultra-reliable to ensure the most important factor of human space exploration, which is guaranteeing the survival of the crew. Designing a robust life support system therefore includes accurate reliability prediction which involves considering random component failures, maintenance and contingency planning and mostly the buffering capability of the system [85].

Reliability analysis efforts thus far have been heavily reliant on historical operational data, the opinions of experts, assumptions and data retrieved from experiments. NASA, for example, uses a database called ISS Risk Management Application which allows the prediction of the probability that a certain event occurs and the possible consequences that go along with it. Furthermore, based on the failure modes of the Space Shuttle, NASA has developed a Probabilistic Risk Assessment tool, which includes the failure modes that have been determined by any personnel working on or with the Space Shuttle. Other prevalent reliability analysis tools like the Failure Modes and Effects Analysis program employ approaches such as a Fault Tree Analysis, What-If Analysis or a Hazard and Operability Method [85]. The published results of reliability analyses for life support equipment that have been conducted using the tools stated above are the basis of LiSTOT's reliability calculations. Depending on the system level, there are two types of reliability calculations in LiSTOT:

A component's reliability is determined by employing the Poisson distribution on a given Mean Time Between Failure (MTBF) rate and mission duration. MTBF values for ISS ECLSS equipment are retrieved from NASA's BVAD [66].

$$R(t) = e^{-\lambda t} \tag{4.7}$$

with λ being the components failure rate and t the observation period. The failure rate is computed as follows:

$$\lambda = \frac{1}{MTBF} \tag{4.8}$$

The total reliability for an assembly $R(t)_{series,total}$ is calculated as the product of component reliabilities $R(t)$ that are contained within the regarded system. Thereby, it is assumed that all n components are connected in series.

$$R(t)_{series,total} = \prod_{i=1}^{n} R(t)_i \tag{4.9}$$

Even though LiSTOT is not designed to conduct reliability analyses, the technology parameter reliability plays a major role in several parts of LiSTOT's design analysis process.

4.6.1 Multi-Criteria Analysis

Reliability is one of seven technology characteristics that are being considered and evaluated during LiSTOT's MCA. If desired, a user defined minimal reliability value will sort out any alternative that does not fulfil the given requirement. For further information about MCA, one may refer to chapter 4.7.

4.6.2 Contingency planning

To prevent a loss of crew in case of a failure, the crew of a space vehicle must be capable of repairing or replacing any life support system that has ceased working. Hence, as part of any maintenance or contingency strategy for spacecraft or space stations, the amount of available onboard spares is crucial since in case of an emergency, resupply is impracticable even for the ISS in LEO. The total number of spares for a system depends on the demanded reliability for the regarded piece of hardware. The chosen approach for the ISS to address this issue, involves using orbital replacement units (ORU) which consist of a set amount of spare parts depending on the equipment that must be replaced. Typically, one or two spares of each ORU are on board at any time [86]. The primary advantage of this maintenance strategy is to substantially cut repair times since the replacement of a failed assembly requires considerably less time than what it would take to identify the cause of a failure, to acquire the needed spare part and then to fix the fault. Time is an invaluable factor in any emergency case. The disadvantage of employing ORUs on the other hand is that most spares on board may never be used or needed. For example, one may assume that an ORU has a 97 % chance of working throughout its life time. Yet, if the demanded overall reliability is higher than 97 %, a second ORU is required to meet the given requirement. This however indicates that with a probability of 97 %, the second ORU will never be used but only serves insurance purposes. One must also keep in mind that two ORUs may be sufficient for LEO applications, whereas for lunar or Mars missions three or more replacement units may be necessary, which would further increase the mass of spares.

To account for this circumstance, Jones proposed a different approach to handle onboard maintenance for post-ISS missions. He suggested to determine the number of spares needed per component to achieve a reliability that in case of a failure, the chance of not having a spare part available was lower than 0.001 [86]. The author used the Poisson distribution:

$$P(k)_\lambda = \sum_{k=0}^{n} \frac{\lambda^k}{k!} e^{-\lambda} \tag{4.10}$$

with k being the number of events occurring for these calculations since the approach of determining the failure probability of N redundant systems as:

$$P = (\lambda \cdot t)^N \tag{4.11}$$

would only be adequate for operating "hot" masses since otherwise, the numbers of "cold" storage spares would be inaccurately high. Jones based his analysis on reliability data of ISS life support assemblies and components and concluded that depending on the mission duration the mass savings per assembly could be up to five or even seven times that of using an ORU [86]. However, the author did not state how much the estimated repair time would increase by dispensing with ORUs, which is arguably the most significant disadvantage of this maintenance strategy. It is also important to note that this method which is referred to as the 0.001 approach in the following is heavily reliant on the disposability of data concerning the structural composition of an assembly and the reliability or MTBF values for all its components.

Independent from those maintenance strategies, LiSTOT is capable of accounting for any life support system that exceeds its life expectancy within a given mission duration in which case an additional ORU is added to the overall ECLSS mass.

4.6.3 LiSTOT's maintenance strategy

Derived from the two contingency plans depicted above, LiSTOT allows the user to decide between an ORU or the 0.001 approach when deciding on the ECLSS maintenance strategy.

4.6.3.1 Orbital Replacement Units

Using the ORU approach, one can specify how many ORUs per life support assembly are brought along. Determining the ORU mass of ECLSS assemblies that have not been used on the ISS is not trivial since their ORU designs have not been conceptualized yet. This concerns all ALS equipment, for example. To address this issue, an ORU factor f_{ORU} is calculated as the ratio between the given ORU mass for a specific ISS system and the corresponding ISS system mass depending on its function and the availability of specifications. The computed ORU factors are listed in Table 4-19.

Table 4-19: ORU factors[2]

Function	$\boldsymbol{f_{ORU}}$
Oxygen Generation	0.59
Remove Carbon Dioxide	0.8
Reduce Carbon Dioxide	0.67
Urine Processing	0.49
Wastewater Processing	0.55
Other	0.62

The ORU factor for "Other" ECLSS functions including monitoring and control tasks for instance, is determined as the average value of the ORU factors listed in Table 4-20. Multiplication of f_{ORU} with the mass of an assembly with the respective function returns the estimated ORU mass of this system. To incorporate the consideration of the volume required to store the ORUs, a hardware density $\rho_{hardware}$ depending on the function of the regarded assembly is computed. $\rho_{hardware}$ is obtained by calculating the mass to volume ratio of a given technology.

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[2] [48] was used to calculate ORU factors and hardware densities

This approach is necessary since no information about the stowage requirements of non-ISS ORUs have been published so far. The function dependent hardware densities are provided in Table 4-20 [48], [74].

Table 4-20: Hardware densities [48], [74]

Function	$\rho_{hardware}$	Unit
Oxygen Generation	244.7	kg/m^3
Remove Carbon Dioxide	301.1	kg/m^3
Reduce Carbon Dioxide	302.3	kg/m^3
Urine Processing	323.7	kg/m^3
Wastewater Processing	216.4	kg/m^3
Other	277.6	kg/m^3

Similar to the calculation of f_{ORU}, $\rho_{hardware}$ for "Other" ECLSS functions is determined as the average value of the densities listed in the table above. The volume of an ORU is obtained by dividing the ORU mass by the corresponding hardware density. Since f_{ORU} is applied to systems after the sizing process, the scaling of the ORU masses according to a given crew size and mission duration is incorporated in this approach. However, it must be noted that the methodologies stated above are vast simplifications because they neglect the fact that despite fulfilling the same function, systems may be structured entirely different and thus require different spares. Therefore, the ORU approach that is currently implemented serves as a placeholder until more accurate ORU data has been published or is available to be used instead.

It is also important to point out that for consumable driven technologies such as LiOH or O_2 candles, the ORU consists of extra cartridges or candles respectively which amount in mass and volume to 10 % of the initial system attributes. If one used f_{ORU} and $\rho_{hardware}$ instead, the ESM cost for these technologies would increase inappropriately high as it has been shown during the trade analysis in chapter 5.2.5.2.

4.6.3.2 0.001 approach

The 0.001 approach is similar to that proposed by Jones. In LiSTOT, an improvement factor f_{impr} was introduced in the calculation to take improvements in the field of ALS for instance into account. By default, this factor is set to one. Due to the lack of information concerning the reliability and composition of life support assemblies, this method of determining the needed number of spares has only been applied to the 4BMS CO_2 removal device so far to demonstrate its functionality. For a crew of three during a 40-day mission, the ORU mass of this system amounts to 108.27 kg, whereas the mass of spare parts required to achieve the 0.001 failure probability adds up to only 67.7 kg. Thus, almost 38 % of the ORU mass could be saved by solely using spares. The code necessary to conduct these calculations is implemented and can be used once the needed reliability data for the various life support technologies and their components is specified.

4.7 Multi-Criteria Analysis

As depicted in chapter 1, one of the main disadvantages of the ESM metric is its inability to account for crucial system parameters such as TRL or reliability. To compensate for this shortcoming, LiSTOT incorporates an MCA, which allows the consideration of the following system attributes and their respective merits [6]:

- Mass
- Volume
- Power
- Cooling
- Crew Time
- Reliability
- TRL

Multi-Criteria Decision Making (MCDM) is one of the most relevant branches of decision making. MCDM can be subdivided into two categories, one containing models that assume continuous solution spaces called Multi-Objective Decision Making and one that concentrates on problems with a finite or discrete decision space. The latter is referred to as Multi-Attribute Decision Making, however the more general term MCDM is often used instead because both mean the same class of models [87]. Since LiSTOT deals with a finite solution space, the MCDM approach is of relevance for this thesis.

The following vocabulary is useful when discussing MCDM related topics [87]:

Alternative

Alternatives represent the (finite) range of different decision choices available to the decision maker. In LiSTOT, the term alternative applies to all the assemblies and components that are compared with each other.

Attribute

The attributes or decision criteria of a system are the characteristics according to which the systems are compared. The attributes considered in LiSTOT are listed above. No sub-criteria are incorporated. The term attribute value is used to refer to the performance of an alternative under a specific criterion. The mass of a certain assembly is an example for an attribute value.

Incommensurable Units

Typically, different attributes are associated with different units, which complicates the decision-making process. For example, apart from power and cooling, every attribute considered in LiSTOT is characterized by a different unit or lack thereof such as TRL. In the following chapter, the method implemented in LiSTOT to deal with the issue of incommensurable units is explained.

Decision Weight

Decision weights w are either objective or subjective weights that can be assigned to criteria to emphasize their respective degree of importance. In LiSTOT, subjective decision weights ranging from 0 to 1 can be individually applied to each attribute according to user needs. Thereby, a decision weight of 0 leads to the omittance of an attribute, whereas a weight of 1 means that the regarded attribute has maximal importance in an analysis. If all the attributes share the same weight factor, then they are equally represented in the analysis.

Decision Matrix

A $(m\,x\,n)$ matrix in which a MCDM problem is expressed is referred to as a decision matrix, whereby each row corresponds to an alternative and each column to an attribute. Thus, a matrix element x_{ij} (for $i = 1,2,3 \ldots m$ and $j = 1,2,3 \ldots n$) for m alternatives and n attributes represents the performance of an alternative A_i corresponding to a criterion C_j as outlined in Table 4-21 [87].

Table 4-21: Decision matrix [87]

	Criteria				
	$\boldsymbol{C_1}$	$\boldsymbol{C_2}$	$\boldsymbol{C_3}$	$\cdots$	$\boldsymbol{C_n}$
Alts.	$(w_1$	w_2	w_3	$\cdots$	$w_n)$
$\boldsymbol{A_1}$	x_{11}	x_{12}	x_{13}	$\cdots$	x_{1n}
$\boldsymbol{A_2}$	x_{21}	x_{22}	x_{23}	$\cdots$	x_{2n}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$\boldsymbol{A_m}$	x_{m1}	x_{m2}	x_{m3}	$\cdots$	x_{mn}

When performing an MCA, one must carefully decide what MCDM method should be used. Prevalent decision methods include the weighted sum model (WSM), weighted product model (WPM) and the analytic hierarchy process (AHP) amongst others. For instance, AHP was used by Richardson during a trade study for CO_2 management systems [88]. The following focuses on the WSM method since this approach is used within LiSTOT.

4.7.1 Weighted Sum Model

WSM is one of the most commonly used MCDM methods, especially for single-dimensional applications. Assuming there are m alternatives and n attributes, then the optimal or best alternative $A_{maxscore,i}$ is the one that achieves the maximal score which is calculated as [87]:

$$A_{maxscore,i} = \max_{i} A_{score,i} \tag{4.12}$$

(for $i = 1,2,3 \ldots m$ and $j = 1,2,3 \ldots n$). The individual scores $A_{score,i}$ are obtained as:

$$A_{score,i} = \frac{\sum_{j=1}^{n} w_j a_{ij}}{n} \tag{4.13}$$

with the decision weight w_j and an individual performance factor a_{ij}. The resulting scores are normalized by dividing them with the total number of decision criteria. The individual performance factors of an alternative are based on the product of a confidence factor $f_{CF,ij}$ and the dimensionless value of a merit function f_{ij} that calculates the performance of an alternative within a specific criterion relative to the best and worst performing options:

$$a_{ij} = f_{CF,ij} f_{ij} \tag{4.14}$$

Confidence factors are introduced in LiSTOT to take uncertainties concerning system values and characteristics into account. They can range from 0 to 1 in steps of 0.25 and depend on the amount, reliability and certainty of information sources or data acquisition [73]:

0	value based on an “educated guess”
0.25	value based on assumptions
0.5	value based on references with questionable assumptions
0.75	value from reliable reference or based on reasonable assumptions
1	value confirmed by multiple independent references

By using merit functions which return dimensionless values, a multi-dimensional problem is turned into a single-dimensional one, which is essential for the applicability of the WSM method. This is because the WSM model is governed by the additive utility assumption that postulates that the total value of each alternative must be equal to the sum value given in (4.13). In other words, this assumption can only be fulfilled in one-dimensional cases, where there are no incommensurable units. Another reason for employing merit functions is the circumstance that the attributes considered within LiSTOT’s MCA can be distinguished into two types:

For the mass, volume, power, cooling and crew time criteria it is desired to have a low respective value, which means that a system is optimal if its mass, volume, power, cooling and crew time needs are preferably small when compared to other alternatives. The opposite is the case for reliability and TRL, where the respective values should be ideally high. To account for these type-specific traits, LiSTOT incorporates two merit functions. Both are quadratic since the available information and data are limited in which case quadratic functions depict differences more accurately than linear functions as shown in Figure 4-4 where the quadratic function for attributes a as described in the following is compared to the dotted line of a linear function [6]. The shape of the quadratic function plot differs if the function for attributes b is regarded.

The merit function for attributes a including mass, volume, power, cooling and crew time is given as [6]:

$$f(a) = \frac{a^2 - 2aa_{max} + a_{max}^2}{(a_{max} - a_{min})^2} \tag{4.15}$$

The higher the individual performance of the regarded system, the higher the score that is returned by the function.

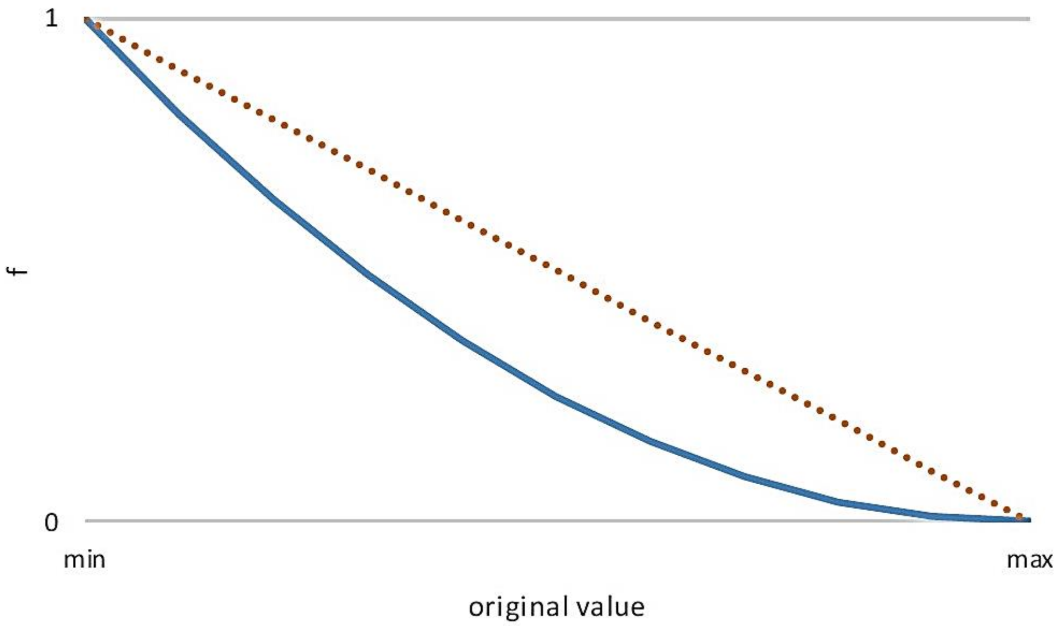


Figure 4-4: Quadratic vs. Linear merit function [6]

The merit function for attributes b including reliability and TRL is given as [6]:

$$f(b) = \frac{b^2 - bb_{min}}{b_{max}^2 - b_{max}b_{min}} \tag{4.16}$$

The lower the individual performance of the regarded system, the higher the score that is returned by the function.

In LiSTOT, the number of alternatives per MCA depends on the available technologies for the ECLSS function selected by the user. This means that the overall MCDM process within LiSTOT consists of various individual Multi-Criteria Analyses. Thereby, one can decide how many or for which ECLSS function an MCA shall be performed. LiSTOT's MCDM procedure can be divided into two successive steps which are described in the following.

4.7.2 Absolute step

The absolute step is the first step in the MCA. It is meant to sort out alternatives that do not fulfil the basic requirements of being safe and having a high enough TRL. The intention behind the absolute step is to reduce the number of alternatives early before in a proceeding step more information and data about a system is required.

4.7.2.1 Safety

Safety is the very fundamental requirement that every considered life support technology must fulfil. Thus, any materials, systems or procedures that may harm or be a threat to the crew must be excluded. For example, substances such as hydrazine or high operating pressures and temperatures exceeding 1,500 K resulting in questionable reliability are considered to be unsafe.

4.7.2.2 Technology Readiness Level

The TRL classification is employed to assess a system's level of maturity which is directly related to its reliability and cost. In LiSTOT, a user can define a minimum TRL, which means that every technology with a TRL lower than the given one is being sorted out. When choosing assemblies for ECLSS composition however, it is advised to not use a TRL lower than five since any components with a TRL beneath that are characterized by lacking validation in a relevant environment, which severely limits their reliability for real-life applications.

4.7.3 Decision step

The decision step is the second step in the MCA and focuses on those assemblies and components that have passed the absolute step. Within the decision step the systems are compared to each other based on the WSM approach stated above and ranked according to their respective performance. It is worth noting that TRL is incorporated in this step as well in order to allow to conduct trade-offs that consider different levels of maturity.

4.7.4 Conclusion

By taking into account critical system attributes such as reliability and TRL, the Multi-Criteria approach used in LiSTOT allows to compensate for the "stiffness" of the ESM metric. Moreover, the possibility of applying subjective weighting factors to the individual attributes enables the user to adapt the analysis according to the respective needs and requirements. However, the disadvantages of LiSTOT's MCDM method must be considered when performing an MCA:

- A total cost attribute including development time and efforts is not included in the analysis since this kind of information is hard to obtain.
- Weighting factors are purely subjective and depend on the user's knowledge about a system or the emphasis put on certain criteria by the user. Decision weights strongly influence the outcome of an analysis and should thus be employed carefully.
- The results of the MCA are reliant on the accuracy of the available values for the various attributes. In this regard, a low-fidelity scaling approach or other uncertainties heavily affect the outcome of an analysis.
- The chosen WSM approach does not portray the advantages and disadvantages of a certain system when it is interacting with other life support subsystems or assemblies. For example, if one chooses CAMRAS as the ECLSS CO_2 scrubbing device, no CO_2 reduction system will be consecutively selectable since the all of the CO_2 adsorbed by CAMRAS is being removed from the loop. To address this issue of non-observance, LiSTOT incorporates an ECLSS composition tool which depicts the influence of an assembly choice on the structure of the life support system. This tool is described in chapter 4.10.

4.8 Equivalent System Mass

Over the years, the ESM methodology has become the prevalent means with which one may determinate the superiority of a life support technology over an alternative [4]. This technique can also be used on ECLSS system level, in which one is provided with a rough prediction of what degree of life support loop closure is optimal for a specific mission scenario. The ESM metric is based on the approach to convert and sum up system performance parameters including mass, volume, power, cooling and crew time needs that are required to support the technology in space into an equivalent system mass. This is achieved by multiplying each of these characteristics with a parameter specific equivalency factor before summation. Equivalency factors are obtained by calculating the quotient of infrastructure required per unit of resource. The resulting mass value represents the total launch mass which is needed to provide the system function and thereby correlates directly to launch cost that is primarily mass driven [3].

4.8.1 ESM Calculation

The following simplified equation is used to for ESM calculation [3].

$$\begin{aligned} ESM = L_{eq} \cdot \big[M + (V \cdot V_{eq}) + (P \cdot P_{eq}) + (C \cdot C_{eq}) \\ + (t_{crew} \cdot D_{mission} \cdot t_{crew,eq})\big] \end{aligned} \tag{4.17}$$

With:

ESM	[kg]:	ESM value of the ECLSS
L_{eq}	[kg/kg]:	Location factor
M	[kg]:	Total mass of the ECLSS
V	[m^3]:	Total volume of the ECLSS
V_{eq}	[kg/m^3]:	Volume equivalency factor
P	[kW]:	Total power needs of the ECLSS
P_{eq}	[kg/kW]:	Power equivalency factor
C	[kW]:	Total cooling needs of the ECLSS
C_{eq}	[kg/kW]:	Cooling equivalency factor
t_{crew}	[CM·h/y]:	Total crew time needs of the ECLSS
$D_{mission}$	[d]:	Duration of mission segment
$t_{crew,eq}$	[kg/(CM·h)]:	Crew time equivalency factor

Thereby, the total mass includes life support hardware components and working gasses and masses inside the pressurized space habitat. It is worth noting the personal space of the crew is not included in the volume term of the ESM equation since it is not considered to be a part of an ECLSS. Concerning the crew time factor, only scheduled maintenance should be included because unscheduled repair activities apply solely to non-nominal operation cases. Reliable data for crew time needs of certain assemblies or components is hard to come by, in this regard it may be advisable to use the non-crew time ESM (ESM NCT) values which are also being provided by LiSTOT when conducting trade studies.

To incorporate the consideration of different locations (e.g. LEO, moon, Mars), Fisher proposed to define location factors which would be applied to the ESM equation [3]. This would allow to take into account, that depending on the mass, bringing a payload to a specific location may require different amounts of fuel. Thereby, a location factor represents the additional mass necessary to transport a payload from a starting point (typically LEO) to a desired destination. Employing location factors is particularly useful if one compares systems with deviating transportation histories, which applies to missions with multiple segments where one payload may remain entirely on board throughout the mission, whereas the other payload may jettison some of its mass at some point [3]. For example, lunar missions with different architectures for surface lander concepts are affected by location factors. LiSTOT's ESM equation therefore incorporates a location factor that is applied to the overall ESM term. Since this factor depends on critical information such as propellant needs for a certain mission which are currently not available, the location factor is set to 1 kg/kg by default. A thesis conducted parallel to this work is meant to examine how much payload one could bring to the Gateway in different lunar orbits. Once this data is published, the location factor in LiSTOT can be adjusted accordingly.

The mass term in the ESM equation is associated with masses of hardware and infrastructure as well as with masses of resupply and logistical goods and equipment. This was done to account equally for life support systems with high initial mass, low resupply needs and systems with low initial mass but high logistical demands. During early development phases of LiSTOT, it was examined whether a logistics term should be introduced in the ESM equation that would solely apply to masses of resupply and consumables. Thereby, the corresponding equivalency factor would be defined similarly to a location factor by incorporating information about how many resources may be needed to transport cargo to the desired destination. The intention behind it was to emphasize the effect of frequent logistic needs in the ESM equation. However, since this approach does not give equal importance to different types of loop closure, it was dispensed with including a logistics term and decided for a location factor that applies to all characteristics of an ECLSS considered in the ESM equation.

When discussing resupply and logistical goods in LiSTOT, one can distinguish between two types of resupply materials:

- **Technical resupply materials:** Technical resupply materials may include technology dependent parts that need to be exchanged after a certain amount of time. For example, sorbent or amine beds of CO_2 scrubbing systems belong to this type of resupply material.
- **Non-technical resupply materials:** Non-technical resupply materials refer to consumable substances such as O_2 or water. The consumables considered in LiSTOT include:
  - Oxygen
  - Nitrogen
  - Water
  - Food
  - LiOH
  - LiClO4

The technical resupply needs of the various life support assemblies and technologies come from the industry and respective manufacturers as well as from other trade study and ECLSS analysis efforts. It is assumed that the masses of non-technical resupply materials are represented under the logistics instead of the mass term in the ESM equation, whereas their needed infrastructure such as tanks or packaging for instance may contribute to the mass, volume, power, cooling and crew time terms. This infrastructure is designed to store or accommodate the respective consumable mass that is required for the specified mission scenario. If one wants to analyse resupply efforts for a user defined ECLSS in detail, LiSTOT's Resupply Modelling tool which is described in chapter 4.11 is meant to be used. It is also important to note that the resupply is incorporated in LiSTOT's scaling approach.

4.8.2 Equivalency factors

As stated before, equivalency factors are derived by calculating the ratio of infrastructure required per unit of resource and therefore heavily based on the architecture of a spacecraft. For example, the volume equivalency factor depends on the pressure loads, radiation protection and thermal shielding, etc of the infrastructure. Therefore, an exact determination of ESM factors is only possible once the structure and composition of the spacecraft or space station that is to be examined has been established. For preliminary analyses, NASA provides various equivalency factors within their Baseline Assumptions and Values document for several habitat design options for lunar and Mars missions [66].

4.8.3 MCA vs. ESM

Since two metrics are used within LiSTOT to assess an alternative's superiority over that of another, the question which metric one should refer to if the outcomes of the metrics differ must be asked. In other words, if the MCA postulates that an alternative A has the rank one and an alternative B the rank two, whereas the ESM analysis comes to the exact opposite result, it is not evident how one decides which alternative is more eligible. One may argue that since the purpose of the MCA within LiSTOT is to preliminarily sort out alternatives, one should rely on the final analysis, which is the ESM metric. Yet, if one values reliability and TRL higher than the attributes considered in the ESM metric, one may prefer the ranking of the MCA. Thus, it can be stated that the question asked above cannot be generally answered. Instead, the user must choose the optimal alternative according to the individual preferences. It is worth mentioning that since the MCA incorporates all attributes that are included in the ESM analysis, the occurrence of different analysis outcomes is not expected to happen frequently.

4.9 Sensitivity analysis

Sensitivity analyses are primarily meant to test the robustness and stability of a system or model including the results thereof and to convey the relationship between in- and output values to the user. In this respect, a sensitivity analysis may be employed to facilitate one's understanding of a system or model and to determine critical criteria within the regarded object. Despite considerable research efforts on using sensitivity analyses for management or operations science over the last decades, research on the topic of applying sensitivity analyses to MCDM models has been limited thus far [89]. Different approaches have been proposed for this purpose including stochastic Bayesian models, or entropy and distance minimization procedures like the least-squares methodology to identify alternatives to an optimal solution. One of the major MCDM related sensitivity analysis problems is associated with the determination of the respective criticality of given attributes in a deterministic Multi-Criteria model. This chapter describes how LiSTOT's sensitivity analysis addresses this issue.

Similar to the human metabolism when designing life support systems, an MCDM model can be regarded as a "black-box". A user is aware of the in- and output values of the system but maybe does not know how and to what extent these parameters interact with each other. Figure 4-5 depicts the in- and output values of LiSTOT's MCA**.**

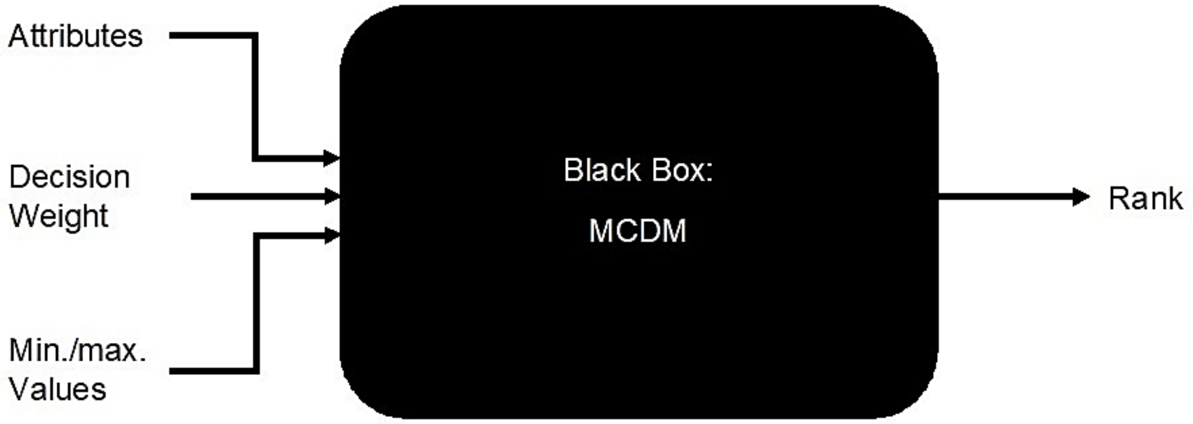


Figure 4-5: Sensitivity analysis „black-box"

A sensitivity analysis allows the evaluation of the attributes' respective criticality, which provides the user with information about what criterion needs to be adapted to achieve a different result such as a change in the ranking of the alternatives with a minimum amount of variation of the initial attribute's value. Thereby, the term criticality may be misleading since it does not necessarily correspond to the criterion with the highest weighting factor. Instead, within this thesis the most critical attribute is defined as the one that results in a different outcome of the MCA with the smallest change of the respective criterion value. This minimum change can be calculated in either absolute or relative terms.

The absolute smallest change $c_{abs,i}$ for a weighting factor w_i is given by [89]:

$$c_{abs,i} = |w_i^* - w_i| \tag{4.18}$$

where w_i^* stands for the weighting factor for criterion i when a change in its rank occurs. The smallest relative change $c_{rel,i}$ in % is calculated as [89]:

$$c_{rel,i} = \frac{|w_i^* - w_i|}{w_i} \cdot 100\% \tag{4.19}$$

The relative term is generally considered to be more meaningful since it puts the change into perspective to the original value. For instance, the significance of a change of 0.05 is very different for an initial criterion value of 0.9 or 0.09. Since the attributes within LiSTOT's MCDM model can be in the order of several hundred kilograms of mass and down to less than one cubic meter of volume, it is crucial to choose the relative change approach over the absolute one to ensure a fair representation in the sensitivity analysis.

4.9.1 LiSTOT's sensitivity analysis

LiSTOT's sensitivity analysis aims at determining the criticality of the various attributes for a given MCA and at testing the robustness of the MCDM results. The sensitivity analysis is therefore divided into two successive parts which are described in the following.

4.9.1.1 Step 1: Determine criticality of attributes (LiSTOT's Attribute Criticality tool)

Before examining the robustness of the outcome of the MCA, the user can identify the most critical attributes so that during the second step of the sensitivity analysis these attribute values can be varied to test the stability of the ranking results. However, it is worth noting that this first step is not mandatory, which means that both steps can be performed independently from one another. Depending on the selected ECLSS function for the Multi-Criteria and ESM analyses and the specified decision weights, the number of alternatives and consequently the attribute values in the decision matrix may vary. Thus, despite using the same MCDM model, almost every MCA is unique and therefore characterized by a different distribution of criticality among its attributes. Assessing the most critical criterion for each MCA may be necessary if it is intended to choose the most significant attributes in the second step of the sensitivity analysis.

To obtain the average overall criticality values for the entire regarded MCDM model, the individual criticality values for each alternative are calculated via equation (4.19), summed up and then normalized with the number of alternatives. Thereby, the program iterates in steps of 5 % until a change in the overall ranking occurs. Since the average overall criticality values are of interest for this step, it is irrelevant which alternatives change their ranks.

4.9.1.2 Step 2: Test robustness of MCDM results

The result of LiSTOT's MCA is a ranking of the alternatives in which their individual performance is represented whereby rank number one corresponds to the optimal alternative. LiSTOT provides the user with a manual or iterative approach to test the robustness and stability of an alternative's rank. Thereby, the user can select for which of the available alternatives the sensitivity analysis shall be performed, which attributes shall be varied and whether a specific attribute value shall be in- or decreased for this purpose. The difference between the manual and iterative approach is that in case of a manual sensitivity analysis, the user specifies by how much the default attribute values shall be changed. In an iterative sensitivity analysis, the user can provide the width of the iteration step. The sensitivity analysis tool will then vary iteratively the chosen attribute value(s) until the rank of the regarded alternative has changed and inform the user at which iteration step the change occurred.

4.10 ECLSS Composition

The ECLSS Composition tool was introduced to allow the evaluation of interactions between various life support technologies that were chosen during the MCDM process by combining them in the context of an ECLSS. The user can thereby identify advantages or disadvantages of using a certain technology that could not be accounted for in the MCA. The tool distinguishes between open, partially closed, closed loop, hybrid and biological ECLSS types and predefines a set of technologies per life support subsystem depending on the selected type. In other words, non-regenerable assemblies are only available in the open, partially closed loop and hybrid ECLSS schemes, whereas regenerable technologies can be selected in the partially closed, closed loop and hybrid schemes. Thereby, the hybrid scheme is dealt with as a form of a partially closed loop system, which allows the usage of both regenerable and non-regenerable technologies whilst offering the possibility of utilizing bioregenerative hardware. It is important to note that the closed loop scheme does not represent a fully closed life support system since this cannot be achieved in a P/C ECLSS due to the inability of closing the food loop. It merely stands for a system that incorporates solely regenerable technologies apart from three exceptions as stated in chapters 4.10.1.4 and 4.10.2.1. The amount of technologies available in the ECLSS Composition tool is smaller than what is included in LiSTOT’s database since only those assemblies have been implemented that do not lack any information about their critical attributes and possess a TRL of at least five. Other technologies can be included once the missing data has been provided and the system has reached a TRL of five. The procedure of using the ECLSS composition tool is subdivided into three successive steps which are described in the following chapters. The biological ECLSS scheme is excluded from this iterative approach and is described in chapter 4.10.4.

4.10.1 Step 1: Composition of subsystems

The overall subsystems that are being regarded within the first step of the ECLSS composition are depicted in Table 4-22.

Table 4-22: ECLSS subsystems considered in the first step

System	Open Loop	Partially Closed Loop	Closed Loop	Hybrid
Carbon Dioxide Removal	X	X	X	X
Carbon Dioxide Reduction		X	X	
Urine Processing	X	X	X	X
Wastewater Filtration	X	X	X	X
Water Electrolysis		X	X	
Oxygen Provision	X	X		
Water Provision	X	X		X

As shown in Table 4-22, depending on the choice of ECLSS type, not every one of these subsystems may be available to be specified. For example, no CO_2 Reduction or Water Electrolysis subsystem is included in the ECLSS scheme if one examines an open loop life support system. One may notice that critical ECLSS functions such as microbes or temperature control are not covered by the subsystems listed above. This is because the systems in the first step of the ECLSS Composition tool are characterized by processing the human induced metabolic loads and providing the metabolic demands of a person, whereby the subsystems interact with each other by transferring mass flows. Hence, these subsystem scale directly with crew size, which is not necessarily the case for other life support systems that are therefore specified and sized in the second step of the ECLSS composition tool.

The tool calculates the daily mass flows induced by one crew member and checks whether the composed ECLSS is capable of maintaining the balance of in- and output flows of a human. Based on the chemical processes which are employed by a technology to fulfil its function, the masses of educts and products of a reaction are computed to determine the mass portions of reactants needed to achieve a certain goal. The following equation is used for this purpose:

$$m_i = \frac{n_{mole,i} \cdot m_{m,i}}{n_{mole,j} \cdot m_{m,j}} \cdot m_j \qquad (4.20)$$

With m_i in kg/(CM·d) being the mass of the reactant which is meant to be calculated, m_j the given mass of a reactant in kg/(CM·d), n_{mole} the respective number of moles in the reaction and m_m the respective molar masses of the reactants in g/mol. The metabolic loads and demands of a human are retrieved from the chosen schedule. The ECLSS composition tool considers the following types of mass flows:

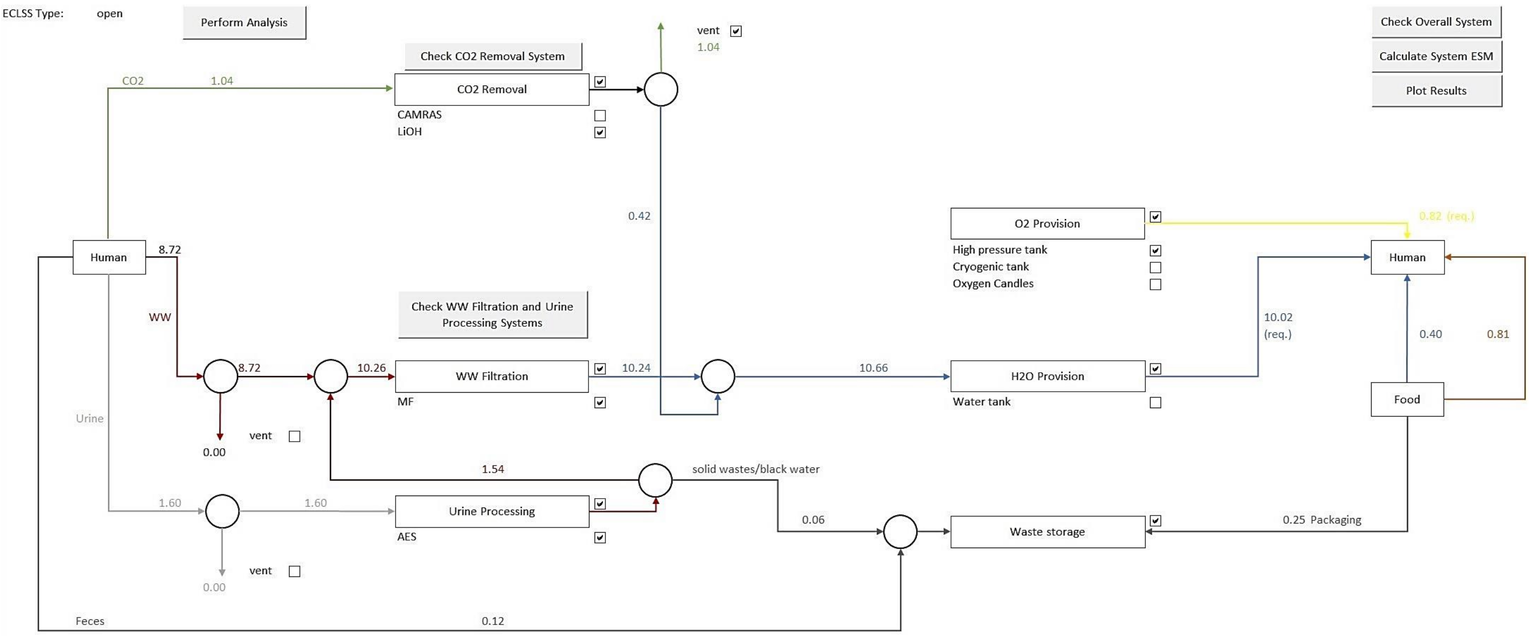
- Carbon dioxide
- Oxygen
- Hydrogen
- Methane
- Water
- Wastewater
- Urine
- Food
- Feces
- Waste

Thereby, it is assumed that the direct wastewater output of a human comprises of the sum of sweat/vapor and wastewater from personal hygiene. Furthermore, water is considered to consist of both potable and hygiene water. In this respect, the tool does not distinguish between potable and hygiene water. It is furthermore simplified that no losses occur within the chemical reactions for CO_2 removal and reduction and O_2 generation. Thus, the entire input of a system is fully transformed into a specific output. Losses are only incorporated in urine processing and wastewater filtration. Additional, more subsystem specific simplifications are described in chapters 4.10.1.2 to 4.10.1.7.

The metabolic loads of a human are wastewater, CO_2, urine and feces, whereas the demands include O_2, water and food. Thereby, the person’s daily water consumption also incorporates water included in food (0.7 kg/(CM·d)) and metabolic water (0.4 kg/(CM·d)) which is produced by the oxidation of food in the human organism. The other mass flows result from chemical processes or waste management.

4.10.1.1 User Interface

The tool’s UI is held similar to that of a flow chart to show the user the course of mass flows which can be distinguished by distinct, individual colours within the composed ECLSS. Each mass flow is portrayed as an arrow which resembles the transportation of a mass from one subsystem to another. Thus, depending on the in- and output requirements of a selected life support technology, the visibility of respective arrows is dis- or enabled to portray the interaction of the system with its surrounding. In addition to selecting life support technologies, the user can also decide to remove certain masses from the loop. For instance, one can elect to vent a desired amount of CO_2 after it has been scrubbed. Thereby, the term vent is generally used for eliminating a gas or fluid from the loop. It is assumed that fluids do not need to be vaporized for being vented. An exemplary ECLSS Composition UI for an open loop ECLSS is provided in Figure 4-6.



ECLSS Type: open

CO2 Removal ☑
CAMRAS ☐
LiOH ☑
vent ☑

O2 Provision ☑
High pressure tank ☑
Cryogenic tank ☐
Oxygen Candles ☐

WW Filtration ☑
MF ☑
vent ☐

H2O Provision ☑
Water tank ☐

Urine Processing ☑
AES ☑
vent ☐

Waste storage ☑

Figure 4-6: Exemplary UI of ECLSS Composition tool

The procedure during the first step of the ECLSS composition tool for P/C and hybrid systems is predefined. After having selected the desired ECLSS type, the user is guided from one subsystem to the next until all values necessary for overall system evaluation have been computed. This approach was chosen to take into account that certain subsystems may have an effect on the initial, human induced mass flows. For example, if one decides to utilize CO_2 reduction via a Sabatier process, additional wastewater is produced and added to the human wastewater mass flow. Hence, the examination of wastewater filtration options is conducted after having decided on CO_2 reduction. Nonetheless, it is worth mentioning that the user can generally change technology selections in previous steps. In this case however, one must progress through all successive steps to ensure that the changed values are adopted by the subsystems that are affected by the changes. Once all the necessary data has been specified, one can evaluate the composed ECLSS and check whether it is capable of balancing the given human in- and output mass flows. In the following chapters, the subsystems of the ECLSS composition tool and the incorporated life support technologies are exemplified.

4.10.1.2 Carbon Dioxide Removal

As described above, the Carbon Dioxide Removal subsystem is the first step in composing the desired ECLSS. The CO_2 scrubbing technologies and the respective in- and output flows are listed in Table 4-23.

Table 4-23: Carbon Dioxide Removal assemblies

Assembly	**Open Loop**	**Partially Closed Loop**	**Closed Loop**	**Hybrid**
LiOH	X			
CAMRAS	X	X		
4BMS		X	X	
SAWD		X	X	
EDC			X	
Algal photobioreactor				X

The chemical reaction for LiOH is given as:

$$CO_2 + 2\ LiOH \xrightarrow{yields} Li_2CO_3 + H_2O \qquad (4.21)$$

whereby it can be seen that using LiOH produces lithium carbonate and water. CAMRAS removes not only CO_2 but also water vapor and eliminates both substances from the loop. Therefore, CAMRAS cannot be used if one intends to reduce CO_2 in a partially closed loop ECLSS. The circumstance that CAMRAS handles humidity control tasks within a life support system is taken into consideration when discussing THC systems in chapter 4.10.2.2. It is assumed that LiOH is only available for open loop ECLSS. Furthermore, in an open loop system, all the removed CO_2 is vented by default since no reduction subsystem is available. EDC requires hydrogen (H_2) and O_2 for CO_2 removal and produces gaseous water, which necessitates the usage of a condensing heat exchanger (CHX) in order to make use of the generated water. SAWD also uses water and produces gaseous water, which is why, similar to EDC, a CHX is needed and added to the design. In a partially closed and closed loop ECLSS scheme, the user can specify what percentage of CO_2 shall be reduced in the next step. The remaining amount of CO_2 will be vented. If one decides that no CO_2 shall be reduced by venting all CO_2 for example, the entire Carbon Dioxide Reduction subsystem will be eliminated from the ECLSS scheme.

In a hybrid life support scheme, the algal photobioreactor is the only currently available choice for CO_2 removal. Since this technology fulfils the functions of CO_2 removal and reduction, O_2 generation and partial food provision, the Carbon Dioxide Reduction, Water Electrolysis and Oxygen Provision subsystem are removed from the scheme and substituted by the algal photobioreactor. It is also important to point out that the amount of nitrate and phosphate needed to sustain the algal medium is provided as a consumable and not extracted from urine. Thus, the potential wastewater cleansing function of the algal reactor is not considered and therefore water must be provided depending on the CO_2 content to produce biomass and O_2 as given in equation (4.1).

4.10.1.3 Carbon Dioxide Reduction

In case of having decided to reduce CO_2 in a partially closed or closed loop ECLSS, the Carbon Dioxide Reduction subsystem is the second step in the composition procedure. Otherwise, the wastewater filtration and urine processing subsystems would take its place. All currently available CO_2 reduction technologies are listed in Table 4-24.

Table 4-24: Carbon Dioxide Reduction assemblies

Assembly	**Open Loop**	**Partially Closed Loop**	**Closed Loop**	**Hybrid**
Bosch		X	X	
Sabatier		X	X	
Carbon Dioxide Electrolysis (COE)		X		

The chemical reactions for Bosch, Sabatier and COE are provided in the following equations.

Bosch:

$$CO_2 + 2\,H_2 \xrightarrow{yields} C + 2\,H_2O \tag{4.22}$$

Sabatier:

$$CO_2 + 4\,H_2 \xrightarrow{yields} CH_4 + 2\,H_2O \tag{4.23}$$

COE:

$$CO_2 \xrightarrow{yields} C + O_2 \tag{4.24}$$

Bosch and Sabatier require H_2 as input and produce carbon or methane (CH_4), respectively. COE decomposes CO_2 into the elements carbon and O_2.

The assumptions that have been made within the Carbon Dioxide Reduction subsystem are the following:

- H_2 cannot be stored but must be produced via water electrolysis.
- CH_4 cannot be utilized and must thus be vented.

Both the Bosch and Sabatier process require H_2 as input and are therefore relying on the production capacity of the Water Electrolysis system. Due to this reason, the Water Electrolysis subsystem is included in this step and scaled according to the amount of CO_2 that shall be reduced. Since one may want to generate additional O_2, the user can specify whether and how much more O_2 shall be produced via water electrolysis. Additionally generated H_2 will be automatically vented since it cannot be used or stored. CH_4, the by-product of the Sabatier process, will be removed from the loop as well. COE is only included in the partially closed loop ECLSS since it lacks reliability information and just barely fits the TRL requirement.

4.10.1.4 Wastewater Filtration and Urine Processing

Depending on whether a CO_2 reduction assembly has been chosen, selecting wastewater filtration and urine processing technologies is the third step in composing the ECLSS. In choosing desired assemblies, one starts with the urine processing subsystem. The corresponding technologies are depicted in Table 4-25.

Table 4-25: Urine Processing assemblies

Assembly	Open Loop	Partially Closed Loop	Closed Loop	Hybrid
AES	X	X		X
TIMES		X	X	X
VPCAR		X	X	X
VCD		X	X	X

The output mass flow of this system is divided into a wastewater stream which then joins the human induced wastewater flow and a blackwater stream. Blackwater cannot be reprocessed and must thus be transferred to the Waste Management system together with the solid contaminants that have been extracted from the urine. The relative portions of waste- and blackwater depend on the efficiency of the selected urine processing assembly. For example, a technology that is 80 % efficient can recover 80 % of the urine as wastewater. The remaining 20 % consist of blackwater and solid contaminants. In this respect, the tern efficiency is applied to the mass flow balance entering and leaving the assembly, which must be accounted for if efficiency values are changed. An efficiency of 100 % is therefore not possible since there are always substances that are removed during wastewater and urine processing. The values for the amount of solid wastes in the daily urine production of one crew member are taken from NASA's BVAD [66].

After having chosen a urine processing system, one can elect a wastewater filtration technology. There are currently two alternatives implemented:

Table 4-26: Wastewater Filtration assemblies

Assembly	**Open Loop**	**Partially Closed Loop**	**Closed Loop**	**Hybrid**
MF	X	X	X	X
VPCAR		X	X	X

It is important to note that VPCAR is not only capable of processing urine but also of filtrating wastewater. Thus, VPCAR is automatically enabled for wastewater filtration if it has been selected as the urine processing assembly. Furthermore, MF is considered for every type of loop closure including a closed loop system despite MF being classified as a non-regenerable technology. This was done since the amount of established wastewater filtration systems is relatively small when compared to CO_2 removal devices, for example. Including MF for closed loop systems means that one can examine various urine processing assemblies because the only other available wastewater filtration system, VPCAR, can only be used if VPCAR has been chosen for urine processing.

The wastewater flow entering the filtration system may come from various sources including direct human output, a CO_2 reduction system and the Urine Processing subsystem. The output of the filtration system is water which can be used for hygiene or drinking purposes. Since the efficiency of established filtration systems has come close to 100 %, it is assumed that no blackwater is generated. Nonetheless, the mass of contaminants that have been extracted during the filtration process is accounted for in the output mass flow of the system.

The user can elect to vent all wastewater and/or urine in an open loop ECLSS if desired. In that case, the wastewater filtration and urine processing subsystems will be eliminated from the ECLSS scheme.

The hybrid scheme does not provide any bioregenerative technologies for urine and wastewater processing but uses P/C hardware instead. This is because the drawbacks of an algal reactor for urine treatment including low TRL, questionable practicability and substantial mass, volume and power demands prohibit the usage of such technology. For further information, one may refer to chapter 4.3.3.

To meet the requirement of water quality control, the water quality monitoring assembly of the ISS is used and incorporated in the ESM of the WRM subsystem.

4.10.1.5 Water Electrolysis

Water Electrolysis is only available as a stand-alone subsystem if one has dispensed with CO_2 reduction in which it would otherwise be incorporated for partially closed or closed loop ECLSS. The currently available options for water electrolysis are listed in Table 4-27.

Table 4-27: Water Electrolysis assemblies

Assembly	Open Loop	Partially Closed Loop	Closed Loop	Hybrid
SPWE		X	X	
SFWE		X	X	

The SPWE and SFWE electrolyze water into H_2 and O_2 as it is given in the following equation:

$$2\ H_2O \xrightarrow{yields} 2\ H_2 + O_2 \tag{4.25}$$

In adjusting the Water Electrolysis system, the user can specify how much O_2 shall be generated. The produced H_2 will be automatically vented.

4.10.1.6 Oxygen Provision

The Oxygen Provision subsystem provides non-regenerable options for O_2 storage as depicted in Table 4-28. Thus, those are only available in open or partially closed loop ECLSS.

Table 4-28: Oxygen Provision assemblies

Assembly	Open Loop	Partially Closed Loop	Closed Loop	Hybrid
$LiClO_4$ (Oxygen Candles)	X			
HPS	X	X		
CS	X	X		

In order to generate O_2, lithium perchlorate is decomposed into O_2 and lithium chloride as shown in the following equation:

$$LiClO_4 \xrightarrow{yields} LiCl + 2\ O_2 \tag{4.26}$$

It is assumed that O_2 candles can only be used in an open loop ECLSS.

The masses of high-pressure and cryogenic tanks are computed using mass increase coefficients depending on the gas that is meant to be stored. These coefficients as outlined in Table 4-29 are given in kg/kg, which means that for 1 kg of O_2, 0.364 kg of high-pressure tank mass is needed, for example.

Table 4-29: Mass increase coefficients [6]

	Oxygen	**Nitrogen**
HPS	0.364	0.556
CS	0.429	0.524

The volume of such tanks V_{tank} which are assumed to be spherical is calculated using equation (4.27) [6]:

$$V_{tank} = \left(\sqrt[3]{\frac{m_{gas}}{\rho_{gas}} \frac{3}{4\pi}} + t_{wall} \right)^3 \frac{4}{3} \pi \frac{1}{T_{FD}} + 0.064 \tag{4.27}$$

with m_{gas} being the gas mass in kg, ρ_{gas} the gas density in kg/m^3, t_{wall} the wall thickness in m, T_{FD} the tank filling degree in % and a volume term of 0.064 m^3 that incorporates the volume of additional tank equipment. For HPS, a tank pressure of 34.5 MPa is assumed, which results in an O_2 density of 451.12 kg/m^3. The wall thickness including insulation is 0.01 m. In case of CS, one can expect temperatures of 73.15 K and a tank pressure of also 34.5 MPa, which gives an O_2 density of 1268.76 kg/m^3. To account for additional insulation material in case of a cryogenic tank, a t_{wall} 0.02 m is assumed. For both HPS and CS, a tank filling degree of 95 % is used [6]. Independently of the type of storage, a pump and a valve are added to the tank design. It is worth noting that this tank sizing has been overtaken from Schreck and is provided in this chapter to facilitate one’s understanding when discussing the results of the trade study in chapter 5.

4.10.1.7 Water Provision

The Water Provision subsystem allows the user to choose to store water in bladder tanks in an open, partially closed loop or hybrid ECLSS. Calculating the tank mass for water storage deviates from the approach of computing tank masses for O_2 or N_2 storage. The mass of a bladder water tank is not determined via mass increase coefficients but using equation (4.28) [6]:

$$m_{tank} = \pi {D_{wt}}^2 \rho_s t_s + \pi {D_{wt}}^2 \rho_b t_b + K_l \tag{4.28}$$

with D_{wt} being the tank diameter in m, ρ_s the density of the shell material (aluminium with a density of 2,710 kg/m^3), t_s the shell thickness in m which is minimum 0.5 mm, ρ_b the density of the bladder material that is set to 1,500 kg/m^3, t_b the thickness of the bladder material is assumed to be 0.5 mm and a fixed mass term K_l to account for mounting brackets, etc that is given as 2.3 kg [6].

The volume of such bladder tank is computed as follows:

$$V_{tank} = \frac{m_{water}}{\rho_{water}} \frac{1}{T_{FD}} \tag{4.29}$$

whereby m_{water} stands for the water mass in kg, ρ_{water} for the density of water which is 997 kg/m^3 and a tank filling degree that is assumed to be 91 % since 4 % of the water volume inside the tank cannot be removed [6]. Using V_{tank}, one can calculate the required tank diameter as:

$$D_{wt} = 2\left(\sqrt[3]{\frac{3}{4}\frac{V_{tank}}{\pi}}\right) \tag{4.30}$$

The shell thickness can be calculated using the following equation [6]:

$$t_s = \frac{p \cdot D_{wt}}{4 \cdot S} \tag{4.31}$$

with p being the design tank pressure, which is given as 3.5 kg/cm^2 and S the design stress that is assumed to be 700 kg/cm^2. Similar to the tank design of HPS and CS, this sizing approach has been overtaken from Schreck.

4.10.1.8 System evaluation

A system evaluation script becomes available to run once all the necessary data from the ECLSS subsystems has been specified. The program checks whether the amount of O_2 and water provided by the ECLSS design is sufficient to satisfy the daily needs of a crew member. If this is not the case, the user is informed about the shortcomings and how they could be addressed. Table 4-30 shows how one may consequently adjust the ECLSS design depending on the ECLSS type.

Table 4-30: System evaluation

Shortcoming	**Open Loop**	**Partially Closed Loop**	**Closed Loop**	**Hybrid**
Oxygen provision insufficient	Select Oxygen Provision assembly	Select Oxygen Provision assembly Adjust Water Electrolysis	Adjust Water Electrolysis	
Water provision insufficient	Select Water Provision assembly	Select Water Provision assembly Adjust Water Electrolysis Adjust Urine Processing	Adjust Water Electrolysis Adjust Urine Processing	Adjust Urine Processing

If an ECLSS design provides more O_2 than required, the user can specify whether the excess O_2 shall be used for repressuring and leakage handling purposes, whereby 0.2 kg/d of leakage are assumed. Remaining O_2 is vented as it is the case if one dispenses with using the surplus of O_2 altogether. The user can proceed to the second step in the ECLSS Composition tool if the designed ECLSS meets the requirements.

4.10.2 Step 2: Calculation of ESM and other characteristics of the designed ECLSS

The second step in using the ECLSS Composition tool is dedicated to specifying life support subsystems and technologies that have not been covered within the previous step and to calculating the overall ESM of the designed ECLSS. In addition, other ECLSS characteristics are determined which include CO_2 and O_2 partial pressures, relative humidity and average power needs of the various life support subsystems amongst other things. Thereby, the technologies are structured in respect of their function under the life support subsystems ACS, AR and THC. It is assumed that all WRM functions are fulfilled by the respective systems in step one.

For each technology, the tool offers a default scaling approach that may be based on the total pressurized volume of the station or the number of modules. These sizing efforts differ from those that have been employed for scaling the technologies included in step one since no longer is a system sized according to a HEU and a given throughput. Instead, the system scaling is based on assemblies and components that have been used on the ISS and on determining how many of such an assembly may be necessary for a given space station architecture. The default scaling approach is intentionally kept conservative since the basic design data of the ECLSS specified during mission definition (total pressurized volume and number of modules) is too general to allow for a more detailed sizing. Hence, the default scaling approach is meant to be used for early ECLSS design phases. In refining the composition of the ECLSS, one can dispense with the default system sizing option and individually specify the number of the various assemblies that shall be installed on the space station. The following chapters provide an overview of the technologies and their scaling approaches incorporated in the second step of the ECLSS Calculation tool as well as the calculations of additional ECLSS characteristics.

4.10.2.1 ACS

Function: Control atmospheric pressure and composition

As stated in chapter 3.1, the main function of the ACS subsystem is to control the space habitat's atmospheric pressure and composition. In case of a rapid decompression, the ACS subsystem must be capable of repressuring the entire habitat. The amount of O_2 and N_2 required for this task can be computed using the ideal gas equation:

$$m_{gas} = \frac{p_{gas} \cdot V}{R_{gas} \cdot T} \tag{4.32}$$

with m_{gas} being the mass of the respective gas in kg, p_{gas} the nominal respective partial pressure in Pa, R_{gas} the specific gas constant in J/(kg·K), V the total pressurized volume of the habitat in m^3 and T the nominal cabin temperature in K. The required parameters for the calculation are specified in Table 4-31.

Table 4-31: Gas parameters for oxygen and nitrogen

Parameter	**Value**	
	Oxygen	**Nitrogen**
Nominal partial pressure [kPa]	21.3	79.76
Nominal temperature [K]	293.15	293.15
Specific gas constant [J/(kg·K)]	259.84	296.80
Total pressurized volume [m^3]	Specified by user	Specified by user

Providing O_2 and N_2 via storage is ACS's method of achieving its task. Hydrogen peroxide and hydrazine analysis is not considered for this purpose due to both technologies being characterized by unsafe operation such as high temperatures or hazardous substances and low TRL. One could consider storing O_2 in the form of water and generate the required O_2 via electrolysis within a regenerative life support system. However, in case of an emergency such as a rapid decompression event for example, the ACS subsystem must be capable of repressuring the space habitat within 5 h [90]. Figure 4-7 depicts the water mass necessary for producing the needed O_2 depending on the pressurized volume of a space habitat.

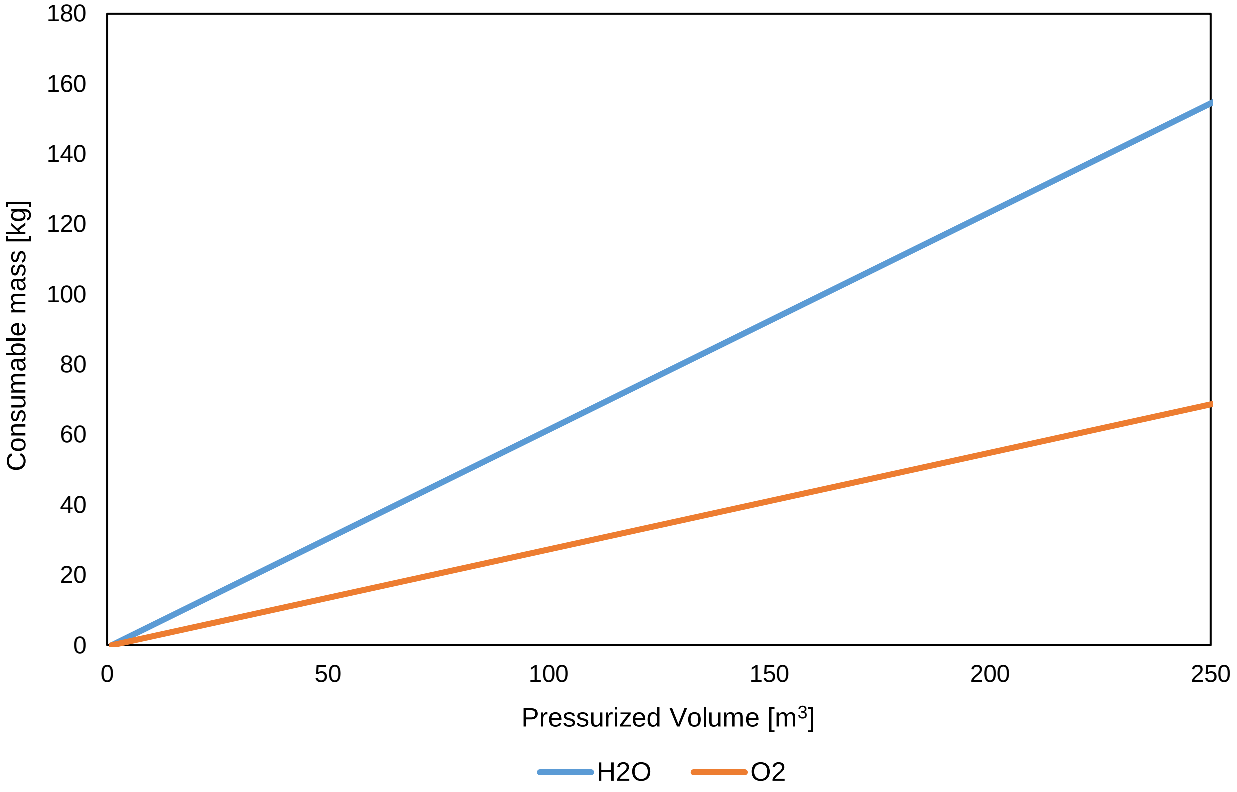


Figure 4-7: Water mass needed for electrolysis

It is evident that the consumable mass required for repressuring the cabin atmosphere via electrolysis exceeds that of an O_2 storage option. Furthermore, it is uncertain whether the by-product of the electrolysis, H_2, could be completely or even partially used, which further limits the efficiency of generating O_2 for atmosphere recovery purposes. In addition, the electrolysis device on board must be redesigned and adapted, if it is decided to generate O_2 for repressuring the habitat. In such case, the performance requirements and capabilities of the electrolysis system would be roughly ten times higher than using electrolysis solely for human consumption rates assuming a crew of three and a pressurized habitat volume of 100 m^3. This circumstance would be directly reflected in the system's ESM using LiSTOT's linear scaling approach. Moreover, one must take into account that the respond time of a tank system, where basically just a valve needs to be opened, is considerably faster than generating O_2 by electrolysis. Considering the points stated above, it was concluded to dismiss the idea of employing water electrolysis for atmosphere recovery since a storage option presents a more practicable alternative and is better suited as an emergency system. Thus, independent of the chosen ECLSS type in the ECLSS Composition tool, tanks are used for storing O_2 and N_2.

Another reason that contributed to the fact that even for a closed loop system, storage tanks for repressurization are used is the circumstance that no regenerable N_2 generation devices could be identified that would fit the requirements of being safe and having a high TRL.

By default, cryogenic storage tanks have been selected since even though the ESM performances of cryogenic and high-pressure storage tanks in repressuring the habitat are almost identical, the cryogenic option shows a slight advantage at higher pressurized cabin volumes and consequently higher O_2 masses as shown in Figure 4-8. The mass increase coefficient for N_2 is given in Table 4-29, furthermore the density of N_2 amounts to 883.42 kg/m^3 considering the storage characteristics of cryogenic tanks (chapter 4.10.1.6). It must be pointed out the plot below neglects the boil-off of the cryogenic fluids since Schreck showed that the boil-off rate for O_2 and N_2 using Multi-Layer Insulation (MLI) amounts to around 5 % [6]. Therefore, he concluded that active cooling is not necessary which would otherwise likely result in a vastly higher ESM of the CS tanks compared to HPS [6].

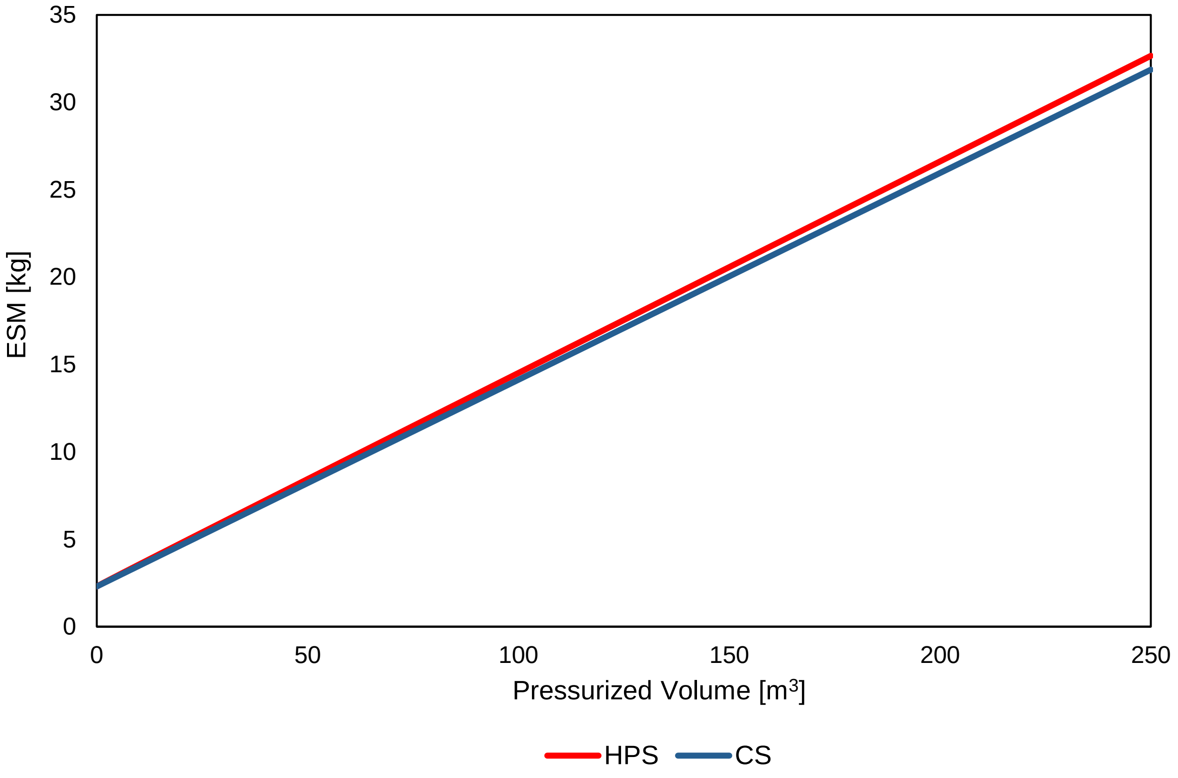


Figure 4-8: HPS vs. CS

Since the difference between HPS and CS can be considered insignificant, the choice of selecting either of those may be influenced by other boundary conditions. For example, if one chooses to use HPS for O_2 provision for the crew, it may be advisable to employ only one type of tankage, thereby accepting the slightly worse performance of the HPS system compared to cryogenic tanks for the given life support function.

In addition to repressuring the habitat, ACS must handle atmospheric leakage which is assumed to be 0.2 kg/d. This value was adapted from the leakage values of the ISS which also include losses due to EVA. One could conceivably put the leakage of a station in relation to its pressurized volume, however since the extent of losses caused by EVA is unknown, this approach was dismissed. Furthermore, leakage handling only has a minor influence on the O_2 household of the station when compared to the O_2 demands of the crew and affects primarily the N_2 storage. For example, for a 40-day mission with a crew of four, the O_2 leakage losses amount to 1.68 kg, whereas the metabolic O_2 demand is 130 kg. The only currently implemented assembly for actively controlling the atmospheric pressure is the Pressure Control Assembly (PCA) of the ISS. The default scaling approach for this system comprises of having one PCA per module. In addition, three Nitrogen Interface Assemblies (NIA) per PCA and eight Manual Pressure Equalization Valves (MPEV) per PCA are selected by default [48].

4.10.2.2 THC

Function: Temperature and humidity control

The temperature and humidity control function involves monitoring and removing heat and humidity from the air and circulating the air masses inside the habitat to ensure a comfortable atmosphere for the crew and to prevent the condensation of water vapor on sensitive electrical equipment. In this regard, THC's main function can be divided into three subfunctions:

- Remove atmospheric humidity
- Control temperature
- Enable cabin ventilation

CAMRAS and CCAA are considered within LiSTOT to fulfil the temperature and humidity control function:

Common Cabin Air Assembly (CCAA):

The CCAA which is used on the ISS consists of various subassemblies (outlined in Table 4-32) to be capable of addressing the control of temperature and humidity.

Table 4-32: CCAA composition [48]

Component	Quantity
Inlet ORU	1
Condensing Heat Exchanger	1
Water Separator	1
Temperature Control and Check Valve TCCV)	2
Electrical Interface Box	1
Temperature Sensor	1
Liquid Sensor	1
Pressure Sensor	1

Sizing such a multifunctional system is not trivial since it is not evident according to which characteristic the system should be scaled. Previous CCAA scaling approaches for LiSTOT were based on calculating the number of CCAA needed for a given pressurized volume using a ratio that was derived from the number of CCAA installed on the ISS divided by the total pressurized volume of the ISS. Since this approach is very general and would thus likely lead to inaccurate results, it was decided to size the CCAA according to its capability of removing excess atmospheric moisture under the assumption that the components required to fulfil the temperature control subfunction scales proportionally with humidity removal. Five CCAA are currently installed on the ISS that can process up to 1.45 kg of humidity per hour in total which would then be transferred to the WRM subsystem [48]. This means that one CCAA is capable of removing 6.96 kg of moisture per day. Hence, the rescale factor for the CCAA system is obtained by dividing the daily sweat production of the crew by the given humidity removal capability of one CCAA.

CAMRAS:

CAMRAS is incorporated in the first step of the ECLSS Composition tool since it can scrub CO_2 from the cabin atmosphere. In this respect, the system is scaled according to its capability of removing the daily human induced CO_2. Thereby, it is assumed that the sizing of CAMRAS's excess moisture removal function is included in this scaling effort. In other words, if CAMRAS can scrub the daily produced CO_2 over a day, the system is also capable of removing all daily human induced excess atmospheric humidity. However, as a standalone system, CAMRAS cannot fulfil the subfunction of temperature control. To compensate for this shortcoming and to enable trade-offs with the CCAA, an assembly comprising of temperature control equipment is added to the CAMRAS design. The composition of this assembly is kept similar to that of the CCAA and includes the following components (Table 4-33):

Table 4-33: CAMRAS temperature control assembly

Component	Quantity
Inlet ORU	1
Heat Exchanger	1
Temperature Control and Check Valve (TCCV)	2
Electrical Interface Box	1
Temperature Sensor	1
Pressure Sensor	1

It is important to note that in contrast to the CCAA, a non-condensing heat exchanger is utilized in this assembly since CAMRAS removes humidity (and CO_2) via adsorption instead of condensation processes. The Inlet ORU consisting of a fan assembly provides an air flow which is regulated by the TCCV depending on the deviation of the actual cabin temperature to the desired cabin temperature. The air flow is then directed to the heat exchanger.

In analysing an open or partially closed loop ECLSS that employs CAMRAS as its CO_2 removal device, the CCAA is substituted by CAMRAS and the temperature control assembly defined above. In case a different CO_2 scrubbing system has been chosen, the CCAA is selected by default and cannot be replaced by CAMRAS in the second step of the ECLSS Composition tool.

The Intermodular Ventilation (IMV) assembly, each consisting of a fan and two valves used on the ISS is employed for ensuring intermodular cabin ventilation. Its default scaling approach involves assuming one IMV per two modules. The Avionics Air

Assembly (AAA) of the ISS is meant to provide air cooling. By default, one AAA per module is assumed. Both assemblies are used independently of whether CCAA or CAMRAS has been chosen.

Function: Fire detection and handling

As stated in chapter 3.1, in LiSTOT, FDS is included in the THC subsystem. The fire detection and handling system comprises of Fire Detection Assemblies (FDA) and fire extinguishers (FE). The default scaling for this system assumes one FDA per module and one FE per two FDA's.

4.10.2.3 AR

Function: Monitor airborne microbes and bacteria

The user can choose from two technologies that fulfil the function of monitoring airborne microbes and bacteria. These include the Major Constituent Analyser and the Microbial Monitoring and Control (MMC) assembly. The default sizing for both technologies consists of installing one technology per module.

Function: Remove trace contaminants

Apart from CO_2, other atmospheric contaminants (outlined in chapter 3.1.2) need to be monitored and removed. The only currently implemented option for this purpose is the TCCS of the ISS. Its scaling approach involves using the ratio given by the amount of TCCS's installed on the ISS divided by the total pressurized volume of the ISS.

4.10.2.4 WM

Recent development efforts of waste recycling assemblies to gain useable resources from waste products involve technologies of wet oxidation and dry incineration. However, their TRL is below 5, which is why none of these technologies are included in the ECLSS Composition tool. Instead, all gaseous, liquid and solid wastes are stored or vented. The amount of produced waste depends on the composed life support system. Examples of waste considered within LiSTOT are provided in Table 4-34.

Table 4-34: Examples of waste considered within LiSTOT

	Types of Waste
Solid Wastes	- Used LiOH cartridges - Food packaging - Solids in urine and wastewater - Biomass - Clothing
Liquid Wastes	Blackwater including fecal water
Gaseous Wastes	Methane

4.10.2.5 Food

Food possesses the largest logistical load on long-duration missions and has therefore a significant impact on loop closure and life support cost [44]. Due to this reason, the food provision is considered within the second step of ECLSS composition even if food as a subsystem is historically omitted from life support analysis. Food can be provided using a bioregenerative or resupply approach.

In a P/C ECLSS, the food loop cannot be closed, which is why food needs to be (re-) supplied for each mission. Thereby, one can distinguish between prepacked food and bulk packaging. Schreck provided an in-depth comparison between both food provision approaches and concluded that despite bulk packaging offering some advantages such as a higher nutrient density, combination variety and overall positive psychological effect over prepacked food, it is still less eligible due to its extensive requirements of mass, volume, waste production and crew time for food preparation [6]. Due to these reasons, Schreck decided to use the ISS "pantry-style" of food provision which is outlined in Table 4-35 and used in LiSTOT by default.

Table 4-35: ISS food system

Parameter	**Value**
Food mass [kg/(CM·d)]	1.26
Individual meal package mass [kg/(CM·d)]	0.25
Volume of packaged food [m^3/(CM·d)]	0.00472
"Pantry-style" storage mass [kg/(CM·d)]	0.35

One may notice that to process prepacked food, additional infrastructure is required which includes a refrigerator, microwave and assembly to rehydrate water if it is supplied in a dehydrated form. In this respect, one refrigerator as it is currently used on the ISS as well as a rehydration apparatus and conduction oven of the Space Shuttle is considered. By default, it is assumed that all prepacked food comes in a partially dehydrated form, whereby dry food amounts to 0.81 kg/(CM·d) and the water content to 0.7 kg/(CM·d). To achieve the required rehydration, additional water is required which is incorporated in the daily consumed potable water [66]. Reducing the degree of hydration of the food means that the logistical costs decrease. However, food is typically more tasteful the higher the water content. Plus, the need of rehydration puts stress on the water management system of the station, which may affect reliability of the ECLSS. Due to these reasons, a trade-off can be performed in which one can select whether food is provided in a de- or hydrated form. Figure 4-9 depicts the mass difference between the two approaches and shows by how much water a station's WRM can be relived if the food is supplied in completely hydrated form. The influence of dehydrated food is particularly high on a P/C closed loop system, which by the definition stated in chapter 4.10 cannot use water tanks for storage. Hence, certain life support technology combinations are no longer practicable. For instance, reducing all daily produced CO_2 via the Sabatier process is not feasible anymore since the amount of water required to generate the H_2 necessary for the reaction exceeds together with the water demand for rehydration the water budget of the life support system. It is worth mentioning that the user can decide whether food as a subsystem shall be considered in the ESM calculation.

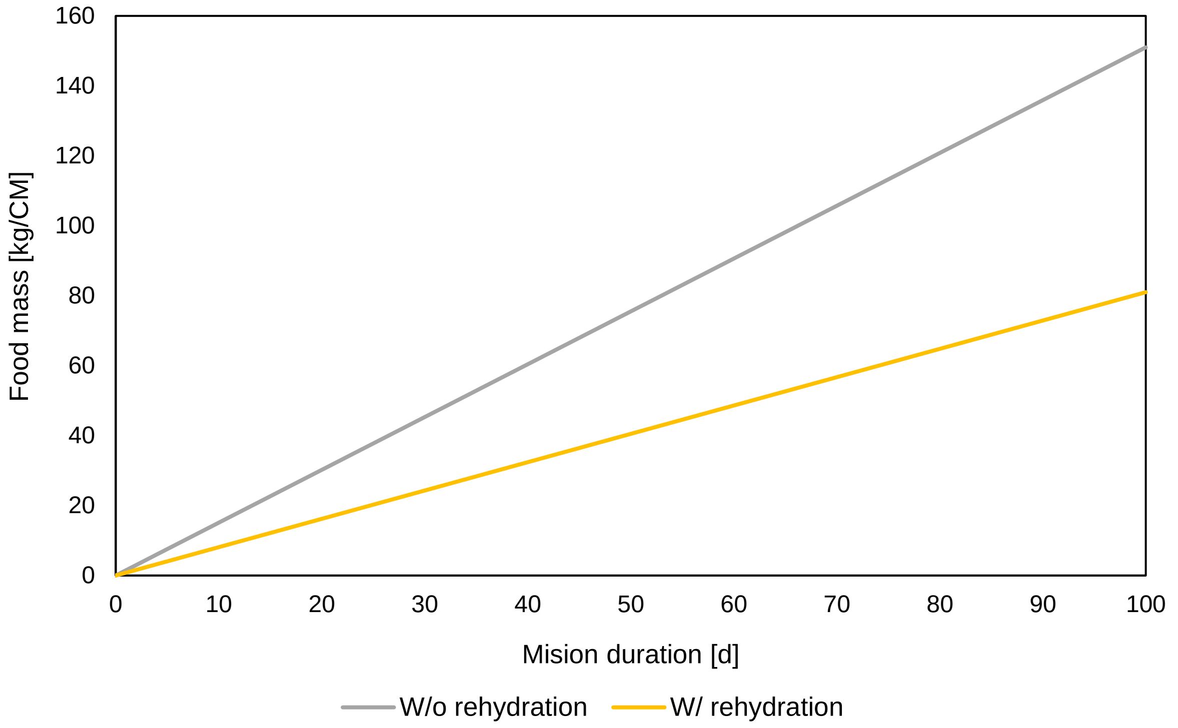


Figure 4-9: Dehydrated vs. Hydrated food

Contrary to P/C systems, a BLSS or a hybrid ECLSS does not necessitate food resupply but can provide food by growing plants or algae. Growing crops offers a great diversity in the daily meals due to high customizability whilst providing a nutrient density that surpasses that of prepacked food and bulk packaging. This variety of meals has a positive psychological effect. Furthermore, the natural moisture in the crops neglects the need to rehydrate the food. NASA's BVAD lists typical types of crops and their growth characteristics and nutrient contents. The disadvantages of growing crops include high initial infrastructural demands, increased crew time needs for crop harvesting and processing as well as a low TRL amongst others. For more information about BLSS, one may refer to chapter 4.10.4. Algae can contribute to the daily meals but are not capable of satisfying the entire food demand of the crew. As stated in chapter 4.3.3.3, the acceptable consume of algae per day is according to the FDA 16.8 g/CM. Additional aspects that need to be considered concern the digestibility and taste of algae if eaten in larger quantities, which may have a negative psychological effect for the crew. In LiSTOT's ECLSS Composition tool, 16.8 g/(CM·d) of algal biomass are separated from the daily produced biomass and transferred to the food provision subsystem. Consequently, the demand of solid food that is consumed daily by a crew member is reduced by this mass of algae. The remaining content of biomass is directed to the Waste Management system. Figure 4-10 shows the extent of food mass that can be saved by utilizing algae to supplement daily meals.

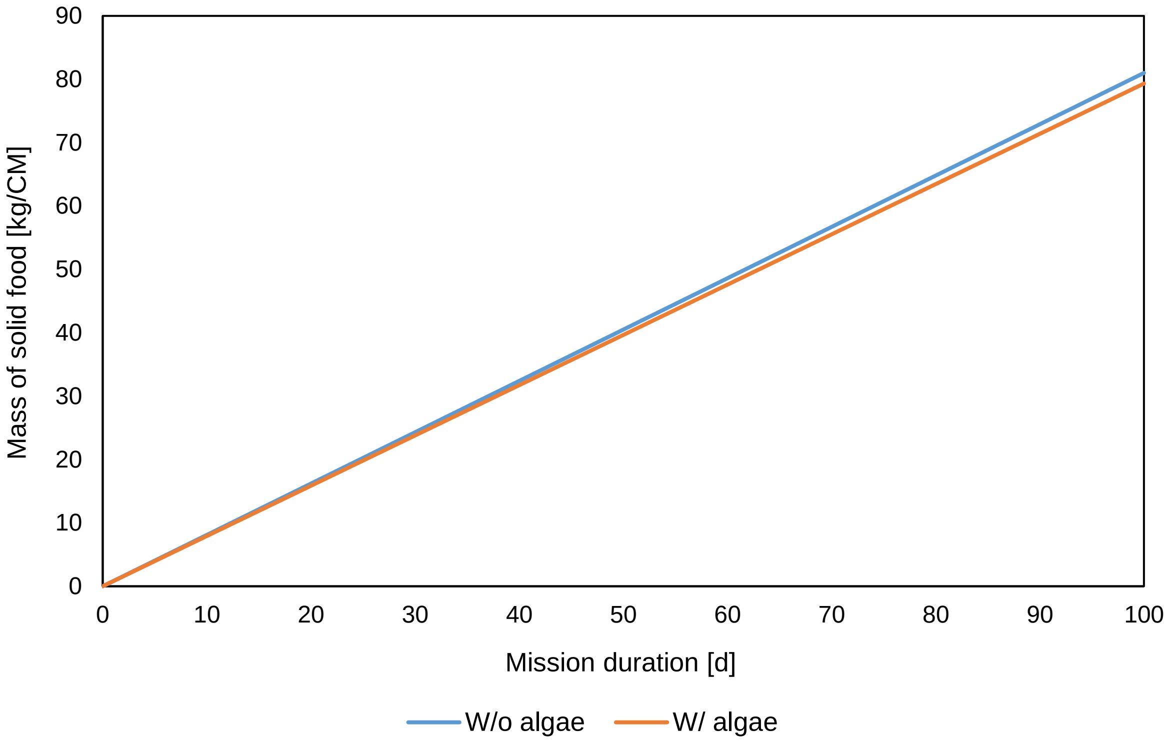


Figure 4-10: Use of algae for food provision

It is evident the mass savings can be considered negligible since the amount of 16.8 g/(CM·d) represents only about 2 % of the daily needed (solid) food (0.81 kg/(CM·d)).

4.10.2.6 Clothing

Similar to food provision, clothing is usually not included in life support analysis. However, if not recovered, clothing has the second largest resupply needs after food for long-duration missions and is therefore considered in the second step of ECLSS composition [44]. The clothing quantities and change frequency are dependent on personal preferences and mission constraints. For example, the clothing must provide comfort for the crew over a wide range of conditions including station temperature, humidity and the tasks meant to be performed by the crew. At the same time, the extent of clothing is detrimental to waste production and stowage requirements and must thus be selected carefully. Two types of clothing can be distinguished.

Disposable clothes

As its name suggests, disposable clothes are meant to be disposed after having been worn. This type of clothing has been used on the ISS, which allows to estimate the required quantities of clothes and their change frequency. NASA’s Human Integration Design Handbook and Joint Crew Provisioning Catalog provide information about these two parameters [65].

The mass of disposable clothing can be calculated using the following equations [6], [65]:

$$m_{clothing} = (A + B \cdot t_{mission}) \cdot n_{crew} \tag{4.33}$$

whereby the overall mass consists of a constant term A of 4.99 kg/CM and a variable term B of 0.3323 kg/(CM·d). The parameter $t_{mission}$ stands for the mission duration in days and n_{crew} for the crew size.

The volume of disposable clothing is computed as [6], [65]:

$$v_{clothing} = C \cdot t_{mission} \cdot n_{crew} \tag{4.34}$$

with C being a variable clothing parameter of 0.0013 m^3/(CM·d). A disposable clothing system presents a simple storage approach that however leads to raised waste production and stowage requirement, which increase linearly with crew size and mission duration. Especially for long-term missions, a reusable clothing system may be more viable.

Reusable clothing

A reusable clothing system is characterized by recovering worn clothes by washing and drying. Thereby, the cost of this type of clothing is driven by a constant clothing mass per crew member of 4.99 kg and the demands of the laundry system. Development of laundry systems for spaceflight applications is currently an area of research which is focused on reducing the cost of clothing for long-duration missions. Laundry systems can be classified according to water-use and sanitation laundry. A water-based laundry option that was designed for use on ISS is specified in [91]. Recent developments lean towards smaller and simpler designs including a Smaller Microgravity Laundry as outlined in Table 4-36 and an Advanced Micro-G Compatible Integrated Laundry System.

Table 4-36: Smaller Microgravity Laundry specifications [91]

Parameter	Value
Mass [kg]	14
Volume [m^3]	0.136
Power [W]	90
Clothing capacity [kg/load]	1.5

Water-based laundry systems have a strong impact on the stations WRM subsystem since they not only demand water as input (up to 51 kg/load) but produce wastewater and water vapor, which must be accounted for in the station's ECLSS design. To compensate for this issue, waterless, nontoxic sanitation laundry systems are under development which rely on ozone, steam, vacuum and ultraviolet sanitation methods [91]. No specifications for these systems have been published as of March 2019. It is important to note that no laundry system has been flight tested on board the ISS, which is why a TRL lower than five must be assumed. Due to this reason, disposable clothing is used independently from the selected ECLSS type.

4.10.2.7 Calculation of additional ECLSS characteristics

Apart from the ESM of the designed ECLSS, the calculation of various other ECLSS characteristics is incorporated in the second step of the ECLSS Composition tool. These characteristics include:

- CO_2 and O_2 partial pressures
- Relative atmospheric humidity
- Power needs of the systems included in the composed ECLSS

It is worth mentioning that all the following calculation efforts in this chapter represent estimations for ECLSS characteristics to show what performance one may expect from the designed ECLSS. It is advisable to employ dynamic analysis tools such as V-HAB for instance for more elaborate and detailed computations.

<u>Calculation of partial pressures:</u>

LiSTOT incorporates a rough estimation of the partial pressures of CO_2 and O_2 in the cabin atmosphere based on the human induced metabolic loads and demands and the performance of the CO_2 removal and O_2 provision systems throughout the day. This is necessary since thus far, mass flows have only been balanced over a day in total.

For example, a CO_2 removal system is scaled and designed to be capable of scrubbing the amount of CO_2 produced by the crew within a day. However, this approach neglects the fact that CO_2 is not accumulated continuously throughout the day but depends on the tasks conducted by the crew in a certain time interval (see chapter 4.5). In this regard, due to physical exercise being performed by the crew for instance, the CO_2 removal device may be incapable of scrubbing the CO_2 that was produced during that period, which would then lead to an increase in its partial pressure.

Ultimately, the well-being of the crew depends on the partial pressures of CO_2 and O_2 in the cabin atmosphere not on the extent of how much of a specific gas is added or removed. In this respect, the following equation is used to determine partial pressures p_{gas} in Pa based on a mass flow that is given by the chosen or composed LiSTOT schedule:

$$p_{gas} = \frac{m_{gas} \cdot R_{gas} \cdot T}{V} \tag{4.35}$$

whereby m_{gas} stands for the mass of the respective gas in the cabin atmosphere in kg, R_{gas} for the specific gas constant in J/(kg·K) (R_{gas} for CO_2 is 188.92 J/(kg·K)), T for the nominal cabin temperature in K and V for the total pressurized volume in m^3. A parameter was introduced to express the nominal performance of a system within a time interval of 0.5 h. This parameter is also being used for estimating the relative humidity and the power loads of the various systems.

In computing partial pressures, several assumptions have been made:

- The overall volume and temperature remain constant.
- No dynamic processes such as start-up transients or varying system efficiencies at different pressure levels are considered.
- CO_2 and O_2 are uniformly distributed within the atmosphere.

To ensure that the average CO_2 partial pressure remains within its limit, which can be specified by the user (maximal allowable CO_2 partial pressure is 0.7 kPa by default), one approach of handling CO_2 partial pressures has been implemented. It consists of assuming that the CO_2 scrubbing device operates continuously throughout the day, whereby the assembly removes a constant amount of CO_2 which is defined by its nominal system performance parameter. According to the calculated average CO_2 partial pressure, one can decide on the quantity of CO_2 removal devices used in the ECLSS, thereby adding the same CO_2 scrubbing system to the composition if desired.

In the case of regulating the O_2 partial pressure, one method is currently included which is similar to the CO_2 controlling approach. In this regard, O_2 is constantly added to the cabin atmosphere throughout the day. Using this method, the O_2 partial pressure would remain within its limits, even for worst-case scenario reference point designs of the schedule (see chapter 4.5.2).

Calculation of relative humidity:

The relative humidity φ of the cabin atmosphere is calculated as the ratio of water vapor partial pressure p_{H2O} and the equilibrium vapor pressure of water p_{H2O}^* at a given temperature:

$$\varphi = \frac{p_{H2O}}{p_{H2O}^*} \tag{4.36}$$

For a cabin temperature of 293.15 K, the equilibrium pressure of water amounts to 2.37 kPa. The water vapor partial pressure is obtained using equation (4.36). It is important to note that the same assumptions that have been made for computing the CO_2 and O_2 partial pressures also apply to the calculation of the relative humidity. Moreover, the same static approach that was used for regulating the O_2 partial pressure is employed in determining the relative humidity.

Calculation of power needs:

For every system chosen within the first step of the ECLSS Composition tool, the power demands over the course of a day are determined by calculating the deviation of the nominal system performance in a time interval to the actual system performance during that period. In doing so, one obtains a ratio with which the nominal power of the regarded system is multiplied to receive the power needed to achieve the required performance. Normalized over a day, the total power demand does not change using this approach, yet the user gets an understanding of how much power may be needed by the various systems during a day. For the remaining life support systems, a constant power demand throughout the day is assumed.

4.10.2.8 Calculation of ECLSS ESM

Based on the chosen life support systems in steps one and two of the ECLSS Composition tool, the ESM of the entire ECLSS is calculated. Thereby, the following assumptions have been made:

- No tubing is considered. This was done since the extent of tubing required for an ECLSS is heavily dependent on precise information about the architecture of the station. LiSTOT's input data concerning station structure including the number of modules and total pressurized volume however is too general to allow for detailed calculations of tubing.
- Additional tanks for CO_2 and water storage have been added. They are designed to store the amount of CO_2 produced or water required per day. These tanks have been included for contingency purposes if one intends to reduce CO_2 or to electrolyze water for O_2 generation, compensating for possible fluctuations and shortcomings in the daily CO_2 and water processing rates. If it is dispensed with CO_2 reduction and/or water electrolysis, these tanks are not included in the ECLSS.
- The mass of food and its packaging is included (see chapter 4.10.2.5).

Before the total ESM of the ECLSS is calculated, technologies are rescaled, which is necessary since the ESM value of an assembly is by default sized according to one HEU and the overall crew size as described in chapter 4.4.1. However, in composing a partially closed loop ECLSS for example, one may decide to reduce only 50 % of the available CO_2. Thus, the default ESM value is no longer appropriate because the CO_2 reduction technology must now support only half a HEU. In this respect, the rescaling is required to prevent over- or undersizing in case the defined assembly must provide higher quantities of a substance than what is required by one HEU. This rescaling effort in LiSTOT's ECLSS Composition tool employs the same metabolic system sizing approach as it is outlined in chapter 4.4.1. Furthermore, it is worth noting that the user can choose to consider the masses of ORU's and spares in the ESM calculation if desired.

4.10.3 Step 3: Plotting of the results of the analysis

As the final step in the ECLSS Composition tool, the user can plot the results of the analysis. The currently available plots include:

- Plot of ESM composition (food is incorporated in this plot as a separate subsystem)
- Plot of ESM increase over mission duration
- Plot of daily CO_2 production
- Plot of daily O_2 consumption
- Plot of daily potable and hygiene water needs
- Plot of daily wastewater and urine production
- Plot of daily power needs of the WRM subsystem
- Plot of CO_2 partial pressure over three days
- Plot of O_2 partial pressure over three days

4.10.4 Biological ECLSS

BLSS are capable of fully closing the life support loop since they can provide food. They consume CO_2 and water and produce biomass and O_2, which is portrayed in the simplified equation of photosynthetic reaction as outlined in chapter 4.3.3. Plants can also process wastewater if the contamination levels are not too high and offer a positive psychological effect on the crew. Due to these advantages, BLSS have been researched and under development for over a decade. Examples for prevalent research efforts in that field include NASA's Controlled Ecological Life Support System (CELSS) program, ESA's Micro-Ecological Life Support System Alternative (MELiSSA) project, JAXA's Closed Ecology Experiment Facility (CEEF) and the bioregenerative life support program Controllo Ambiente Biorigenerativo (CAB) of the Italian Space agency. Additional studies of BLSS are currently being conducted in Canada, Russia and China [44], [51], [92], [93].

In assessing the feasibility of BLSS, one must account for the shortcomings of this type of life support system [66]:

- The stability and robustness of BLSS are susceptible to changes in the environment which include amongst other things temperature, humidity, illumination and atmospheric composition. Especially the liability of crops to even low levels of ethylene may pose a problem. These factors lead to BLSS being difficult to control.
- NASA considers the big unknowns of growing plants in space as the major drawback of BLSS. Despite years of research, the behaviour of plants in space environment cannot confidently be predicted since the influence of microgravity and radiation on crops is not fully understood, yet.
- The initial infrastructural demands of a BLSS concerning mass, volume, power and crew time are high and may only be exceeded by P/C systems for long-duration missions such as Mars surface stays. In particular, the crew time needed to harvest and process crops is likely to limit other crew tasks and activities. These cost factors are discussed in chapter 4.10.4.1.
- The reliability as well as the low TRL of a BLSS are a matter of concern and require further testing before such a life support system is used for supporting a crew. One may also consider that P/C backup systems are needed to compensate for low reliability and predictability [44].

4.10.4.1 Cost factors of BLSS

In order to compare a BLSS to a P/C or hybrid ECLSS, the ESM metric is used. However, the approach of determining the attribute values of BLSS which are then applied to the ESM's equivalency factors differ from that which is used for an ECLSS. Cost factors for BLSS are derived on a square-meter basis. These factors are then multiplied with the growth area of the plant growth chamber. NASA's BVAD provides cost factors for BLSS as outlined in Table 4-37 [66].

Table 4-37: Cost factors for BLSS [66]

Cost factor	**Value**
Mass [kg/m^2]	101.5
Volume [m^3/m^2]	1.03
Power [kW/m^2]	2.6
Cooling [kW/m^2]	2.6
Crew time [CM·h/(m^2·y)]	13.1
Logistics [kg/(m^2·y)]	3.81

These factors include the consideration of the following infrastructural components that contribute to the overall BLSS design [66]:

- Crops
- Shoot zone
- Root zone, water and nutrients
- Lamps
- Ballasts
- Mechanization systems
- Secondary structure

The resupply needs concern primarily the illumination of the plants and the ballasts [66]. The growth area of a BLSS required to sustain the crew depends on the type of crop and the requirements that the life support system must meet [94]. For example, if the BLSS is meant to process all accumulated wastewater on the station, a growth area of approximately 5 m^2/(CM·d) is needed in case of higher plants. This value doubles if the BLSS shall also revitalize the cabin air. If a BLSS with a fully closed food loop is desired, the necessary crop growth area increases to 15-20 m^2/(CM·d) [94]. However, it is critical to state that even in the case of 20 m^2/(CM·d), no additional, yet important aspects such as crop growth, yield and buffer capacities are incorporated. If those are considered, an area of an estimated 100 m^2/(CM·d) is required [94]. One must also note that the CO_2 provided by the crew is insufficient to support the plant growth for food provision. Using the photosynthetic equation (4.1) and assuming a crew member produces 1.04 kg per day, 0.71 kg/(CM·d) of glucose can be generated. About 50 % of this biomass is estimated to be edible, which reduces the amount of food to 0.355 kg/(CM·d). With a calorific value of glucose of 15.7 kJ/g, the overall energy content that is contained within this amount of food amounts to 5.57 MJ/(CM·d).

Yet, this energy is only half as much as what is required (see Table 4-16). In this regard, additional CO_2 sources are therefore necessitated.

4.10.4.2 BLSS analysis

The biological ECLSS scheme included in LiSTOT's ECLSS Composition tool is meant to demonstrate the estimated cost of a fully closed bioregenerative system via comparison with P/C or hybrid life support systems. The approach that was thereby used for BLSS analysis is vastly simplified:

The user selects the crop growth area of the life support system. Since a BLSS with a fully closed food loop is regarded, one can choose between 20 $m^2/(CM \cdot d)$ and 100 $m^2/(CM \cdot d)$. Hence, the user decides whether contingency and safety aspects as outlined in the previous chapter are considered in the analysis of the BLSS. Depending on this specification and the mission parameters crew size and mission duration, the total ESM of the entire life support system is calculated. The second step in the ECLSS Composition tool that accounts in particular for monitoring and control tasks is neglected for BLSS since the overall ESM content of these life support components and assemblies would only represent about 2 % of the total ESM of the BLSS even for a crop growth area of 20 $m^2/(CM \cdot d)$.[3] In the scheme of the tool, the BLSS is portrayed as a crop growth chamber which accepts human metabolic output (CO_2, wastewater, urine and feces), processes these loads and returns O_2, water and food that are transferred to the crew as metabolic input. The processing and exchange of matter and energy within the crop growth chamber is not considered and thus treated as a black box. The results of this BLSS analysis can be plotted to enable comparison with other types of life support systems. It is however worth noting that the plots for CO_2 and O_2 partial pressures as well as the plot for WRM power needs are not available. This is because the approach of determining these characteristics as described in chapter 4.10.2.7 does not necessarily apply for a bioregenerative life support system.

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[3] Calculation made under the assumptions of a crew of three, mission duration of 40 days and a total pressurized volume of 50 m^3.

4.11 Resupply Modelling

The possibility and practicability of providing resupply to a space station is not only critical for its mission campaigns but also decisive for its ECLSS architecture. As stated in chapter 3.1, the feasibility of an open loop life support system that is heavily reliant on frequent resupply flights becomes increasingly limited the more impracticable resupply missions become. Two factors play a major role in assessing the viability of logistics for space stations:

Cost:

As in any space flight application, the cost of bringing a payload to orbit is high. Within its Commercial Resupply Services 1 (CRS-1) program for the ISS, NASA awarded SpaceX and Orbital ATK with contracts worth $3.5 billion in total for twenty resupply flights conducted between 2008 and 2010 [95]. After 2020, the average price of a transportation mission to the ISS is expected to amount up to $220 million [96]. According to NASA, the contracts for CRS-2 which is meant to supply the ISS from 2019 to 2024 are worth $14 billion [97]. Furthermore, one can expect that the costs of crewed flights to the ISS may likely exceed those of merely cargo transportation missions due to vastly increased safety concerns. For example, ROSCOSMOS charges $81 million per seat in the Soyuz spacecraft [98]. In trying to cut resupply masses and therefore the logistical costs of supplying the ISS, NASA introduced the Logistics Reduction and Repurposing (LRR) project. To achieve its objective, LRR builds on lessons learned from the Space Shuttle Program, the ISS and Skylab, whereby it addresses issues of stowage, packaging, commonality and maintenance amongst others [99].

Distance:

The second factor determining the practicability of resupply is the distance of a space station to Earth. Generally, the farther away the target is, the more Δv is required to transport a specific payload mass to its destination. For instance, a Δv of 9.1-9.5 km/s is needed to launch a cargo to LEO. Additional 4.04 km/s of Δv is required if this payload is meant to be brought from LEO to a Low Lunar Orbit (LLO) [100]. The increase in Δv is directly reflected in higher propellant needs of the spacecraft, which reduces cargo mass since the transportation capability of space vehicles is limited.

Taking these factors into account, one must carefully plan the logistical resupply of a space station and how it may influence the station's ECLSS architecture. In this respect, LiSTOT's Resupply Modelling tool fulfils three functions:

- The tool serves as an interface to following works that determine the cargo transportation capability depending on the destination of the space station and on the type of spacecraft.
- The tool can be included in the decision-making process on ECLSS system level to evaluate the extent of resupply required by the respective type of loop closure. The aspect of logistical needs that are induced by a specific ECLSS architecture has been considered within the ESM analysis (see chapter 4.8), however the Resupply Modelling tool allows to account for trade-offs and limitations that cannot be covered by the ESM metric. For example, the tool is capable of portraying how much additional non-ECLSS related cargo can be brought to the station depending on the type of life support system.

- The tool's main function is to allow the user to plan the resupply of a space station during a mission campaign, which involves defining the number of resupply flights, the initial consumables available on the station and the amount and types of cargo brought to the station per flight based on the mission parameters and cargo transportation capability. Thereby, one can choose to preposition, carry-along or backorder cargo and identify the respective criticality of each resupply flight.

This modelling approach is based on the ECLSS that has been designed by the user during ECLSS composition (see chapter 4.10) since it accounts for the amount of consumables that cannot be provided by the ECLSS and must thus be resupplied or brought along for each mission. These consumables include non-technical as well as technical materials for every life support subsystem incorporated in the first step of the ECLSS Composition tool as shown in Table 4-38.

Table 4-38: Consumables considered during resupply modelling

Consumable	Type
Oxygen Provision	Non-technical
Nitrogen	Non-technical
Water	Non-technical
Food	Non-technical
Carbon Dioxide Removal	Non-technical/Technical
Carbon Dioxide Reduction	Technical
Wastewater Filtration	Technical
Urine Processing	Technical
Water Electrolysis	Technical

Thereby, the consumable for Oxygen Provision can either be O_2 or $LiClO_4$ if O_2 Candles are used. The consumable for CO_2 removal can be non-technical in case one uses LiOH or technical if a different CO_2 scrubbing device is employed. Apart from these consumables, the mass of the crew that is transported to the station is considered by default. The nominal mass of a male crew member which is 82 kg according to NASA is used for this purpose [66]. In case of a mere cargo resupply flight, the crew mass term can be nullified.

The procedure of using LiSTOT's Resupply Modelling tool can be subdivided into three parts which are described in the following chapters.

4.11.1 Step 1: Define mission campaign

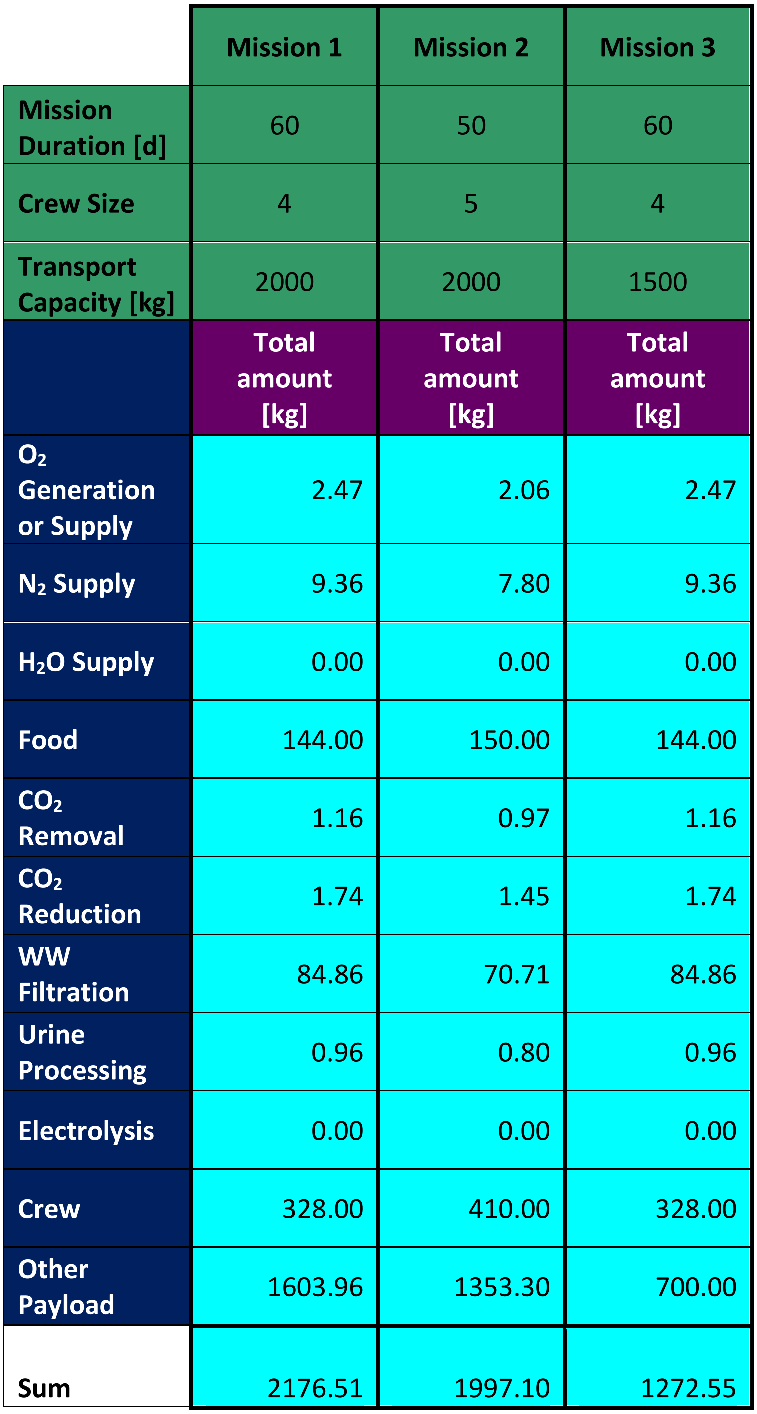
During the first step of employing the Resupply Modelling tool, the overall campaign consisting of a desired number of missions and flights is defined, which involves the following successive aspects:

1. The user selects the number of missions included in the regarded campaign.
2. For every mission after the first mission of the campaign, defining parameters need to be specified which comprise of the mission duration and crew size. By default, these parameters for the first mission are identical to those that have been defined under Mission Definition in LiSTOT's UI. The required consumables as listed in Table 4-38 for each mission are calculated based on the mission specifications. In addition, the cargo transportation capability must be defined for every mission under the assumption that there is one resupply flight per mission.
3. For each mission the user can specify whether for a specific consumable, initial incidentals are available on the station. If this is the case, the amount of consumables that are required to be carried along for the following missions is reduced by the amount of initial incidentals.
4. Non-ECLSS related payloads can be added after having defined the consumable management of the space station during the campaign. There are no internationally accepted standards for Classes of Supply (CoS), however ten functional CoS that have been previously specified and are used in LiSTOT's Resupply Modelling tool [101]:

    - Propellants and Fuels
    - Crew Provisions
    - Crew Operations
    - Maintenance and Upkeep
    - Stowage and Restraint
    - Exploration and Research
    - Waste and Disposal
    - Habitation and Infrastructure
    - Transportation and Carriers
    - Miscellaneous

    These specified payload masses are added up and classified under “Other Payloads” in the Resupply Modelling tool's UI. It is worth mentioning that NASA distinguishes between Science Investigations, Crew Supplies, Vehicle Hardware, Spacewalk Equipment and Computer Resources in discussing resupply classifications [102].
5. The user defines the number of flights to be conducted during the campaign. By default, one flight per mission is assumed as stated before. If the total mass of payloads including the mass of consumables for a specific mission exceeds the mission's cargo transportation capability, one flight is added. Independently from this approach, the user can individually specify the number of flights. For each additional flight, one must specify the respective cargo transportation capability.

Having defined the overall campaign, the Resupply Modelling tool's UI for a campaign with three individual missions may look as displayed in Figure 4-11.



	Mission 1	**Mission 2**	**Mission 3**
Mission Duration [d]	60	50	60
Crew Size	4	5	4
Transport Capacity [kg]	2000	2000	1500
	Total amount [kg]	**Total amount [kg]**	**Total amount [kg]**
O_2 Generation or Supply	2.47	2.06	2.47
N_2 Supply	9.36	7.80	9.36
H_2O Supply	0.00	0.00	0.00
Food	144.00	150.00	144.00
CO_2 Removal	1.16	0.97	1.16
CO_2 Reduction	1.74	1.45	1.74
WW Filtration	84.86	70.71	84.86
Urine Processing	0.96	0.80	0.96
Electrolysis	0.00	0.00	0.00
Crew	328.00	410.00	328.00
Other Payload	1603.96	1353.30	700.00
Sum	2176.51	1997.10	1272.55

Figure 4-11: Exemplary Resupply Modelling tool UI

4.11.2 Step 2: Matrix modelling

The modelling approach for the flight manifest established in the previous step is based on a mass matrix M_{matrix} which contains the missions as columns j and flights as rows i, whereby the entries of the matrix portray the cargo mass that is consumed over various time periods. Thus, the matrix element m_{ij} corresponds to the cargo mass supplied by flight i for mission j. This matrix with F total missions and flights is displayed below [103].

$$M_{matrix} = \begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1F} \\ m_{21} & \ddots & & m_{2F} \\ \vdots & & m_{ij} & \vdots \\ m_{F1} & m_{F2} & \cdots & m_{FF} \end{bmatrix} \tag{4.37}$$

The ith row sum is therefore equivalent to the total cargo brought by flight i, whereas the jth column sum corresponds to the total cargo required by mission j.

It is assumed that the consumption times (missions) start once the respective flights have arrived. In doing so, the overall modelling complexity is reduced since certain information such as the factor of time are implicitly included in the formulation of the matrix. For a matrix element m_{ij}, one can distinguish between cargo carried-along ($i = j$), prepositioned ($i < j$) and backordered ($i > j$). Due to this classification, the properties of the campaign are resembled in the form of the matrix. For example, in case no backordered cargo is intended for a campaign, all matrix elements, where $i > j$ should be 0, which leads to an upper triangular matrix M as shown in equation (4.38) [103].

$$M_{matrix} = \begin{bmatrix} m_{11} & \cdots & & m_{1F} \\ 0 & \ddots & & \vdots \\ \vdots & 0 & m_{ij} & \\ 0 & 0 & \cdots & m_{FF} \end{bmatrix} \tag{4.38}$$

If all the cargo is carried-along for a campaign, so that there is no prepositioned or backordered cargo, the matrix M will be of diagonal form as displayed in equation (4.39) [103].

$$M_{matrix} = \begin{bmatrix} m_{11} & \cdots & & 0 \\ & \ddots & 0 & \vdots \\ \vdots & 0 & m_{ij} & \\ 0 & & \cdots & m_{FF} \end{bmatrix} \tag{4.39}$$

In this case, the sum of diagonal elements (trace) of M corresponds to the total amount of cargo carried-along for the campaign [103].

$$Tr(M_{matrix}) = \sum_{i=1}^{F} m_{ii} = m_{carried-along} \tag{4.40}$$

The total mass of prepositioned and backordered cargo is calculated as [103]:

$$\sum_{i=1}^{F-1} \sum_{j=i+1}^{F} m_{ij} = m_{prepositioned} \tag{4.41}$$

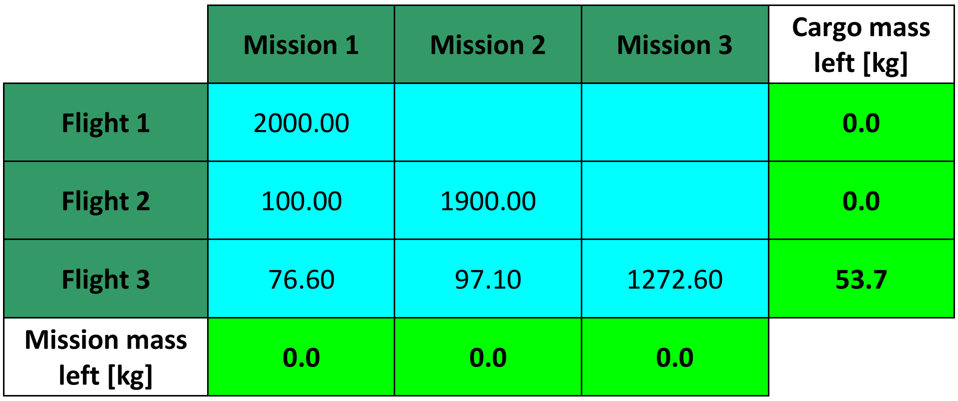
$$\sum_{i=2}^{F} \sum_{j=1}^{i-1} m_{ij} = m_{backordered} \tag{4.42}$$

It is important to note that these matrix attributes only apply to square matrices, where the number of missions is equal to the number of flights. However, this is not necessarily the case for every campaign and situation since one may want to have more or less flights than missions in a certain campaign, which would lead to a rectangular matrix M_{matrix}. In such a matrix, it is no longer possible to classify the types of cargo positioning into carried-along, prepositioned and backordered [103].

In LiSTOT's Resupply Modelling tool, the matrix modelling approach described above is utilized to allow the user to distribute the chunks of cargo according to the respective needs. Thereby, the total cargo requirements for every mission and the total cargo transportation capability for each flight, that have been overtaken from the overall campaign definition, are listed. According to these specifications, the user can assign cargo masses to missions and flights. In doing so, two boundary conditions need to be met which include:

- The cargo transportation capability for a flight must not be exceeded.
- The cargo mass for each mission must be provided.

The UI after having distributed all required cargo is exemplarily displayed in Figure 4-12.



	Mission 1	**Mission 2**	**Mission 3**	**Cargo mass left [kg]**
Flight 1	2000.00			**0.0**
Flight 2	100.00	1900.00		**0.0**
Flight 3	76.60	97.10	1272.60	**53.7**
Mission mass left [kg]	**0.0**	**0.0**	**0.0**	

Figure 4-12: Exemplary resupply matrix

4.11.3 Step 3: Identify flight criticalities

The criticality of a flight is determined by the number of missions depending on it and the degree of dependency. In this regard, a factor δ_{ij} describes the dependency of a mission j on a flight i

$$\delta_{ij} = \frac{m_{ij}}{\sum_{i=1}^{F} m_{ij}} \tag{4.43}$$

by computing the ratio of mass brought by flight i to the total cargo mass required by mission j which is brought by all flights F [103]. For a mission with purely carried-along flights, δ_{ij} is characterized as follows:

$i = j$: $\delta_{ij} = 1$

$i \neq j$: $\delta_{ij} = 0$

For a mission with purely prepositioned cargo, δ_{ij} is characterized as follows:

$i = j$: $\delta_{ij} = 0$

$i < j$: $\delta_{ij} \geq 0$

The dependency factors for a campaign can be entered into a dependency matrix D which is identical in its formulation to the mass matrix m, however the mass entries are substituted by the respective dependency factors [103]:

$$D = \begin{bmatrix} \delta_{11} & \delta_{12} & \cdots & \delta_{1F} \\ \delta_{21} & \ddots & & \delta_{2F} \\ \vdots & & \delta_{ij} & \vdots \\ \delta_{F1} & \delta_{F2} & \cdots & \delta_{FF} \end{bmatrix} \tag{4.44}$$

To obtain the flight criticality path (FCP) for the entire campaign, one must plot

$$\sum_{j=1}^{F} \delta_{ij} \tag{4.45}$$

over the total number of missions served by each flight within the campaign. A mission is considered to be served by a flight if $\delta_{ij} > 0$ [103]. The total number of missions N_m^i served by a flight i is computed as

$$N_m^i = \sum_{j=1}^{F} \delta_{ij} \tag{4.46}$$

whereby $n_{ij} = 1$ if $\delta_{ij} > 0$ or $n_{ij} = 0$ if $\delta_{ij} = 0$ [103]. A flight i carries along all cargo for $n_{missions}$ missions if

$$\sum_{j=1}^{F} \delta_{ij} = n_{missions} \tag{4.47}$$

and all $\delta_{ij} = 1$. In an FCP plot, this flight would appear in position (n, n) as shown in Figure 4-13 [103].

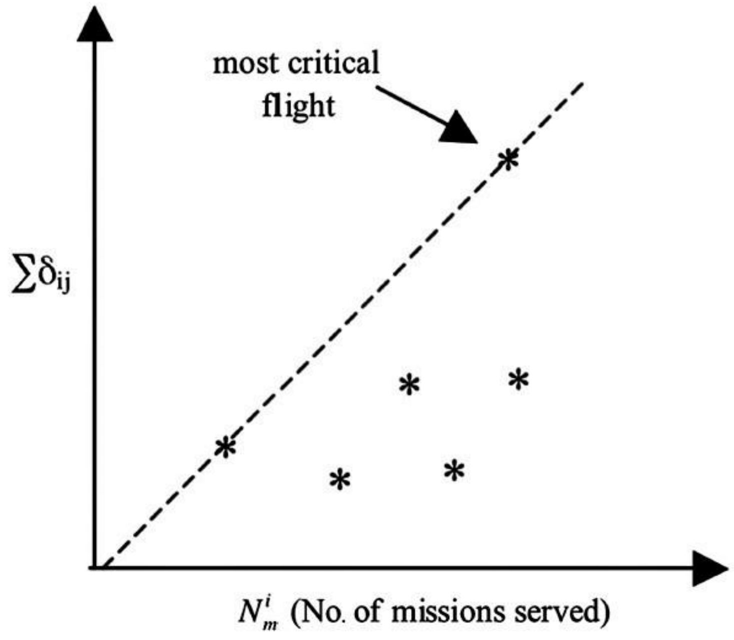


Figure 4-13: Flight Criticality Plot [103]

Thus, the 45° line can be seen as a reference indicating the criticality of a flight within a campaign by demonstrating the amount of cargo that is provided by each flight. Thereby, the most critical flight would be the one that is located the farthest away from the diagram's origin whilst being on the reference line. Another way of determining the criticality of a flight within a campaign is calculating the Euclidian distance between the origin and the point in the plot associated with flight i. In doing so, one obtains a scalar flight criticality index (FCI) which can be used to rank flights according to their criticality [103]:

$$FCI_i = \sqrt{\left(\sum_{j=1}^{F} \delta_{ij}\right)^2 + \left(N_m^i\right)^2} \tag{4.48}$$

This definition of FCI weights the overall dependency of missions on flight i given in (4.43) equally to the number of missions served by this flight as stated in (4.46).

In LiSTOT's Resupplying Modelling tool, the dependency matrix D_{matrix} and the various FCI are calculated as well as an FCP plot is generated based on the cargo allocations specified in the mass matrix M during the second step. Thus, the user is provided with several means of evaluating the importance of specific resupply flights within a campaign. An FCP plot may look like as depicted in Figure 4-14.

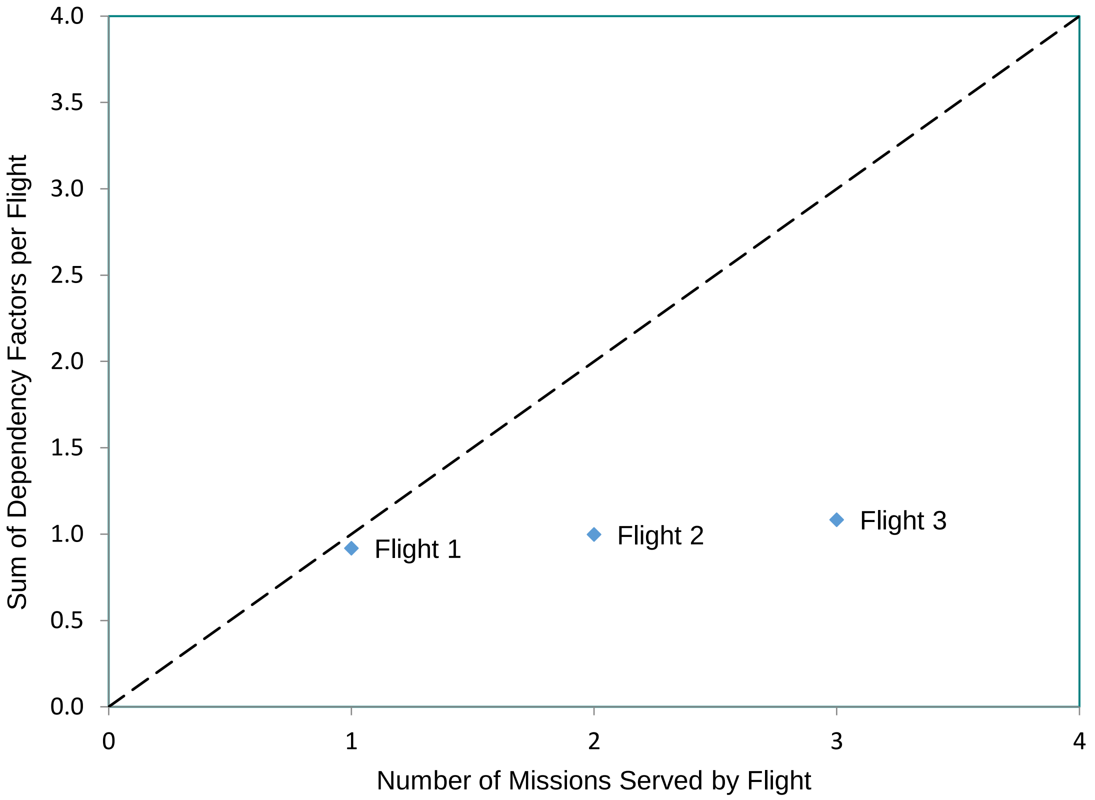
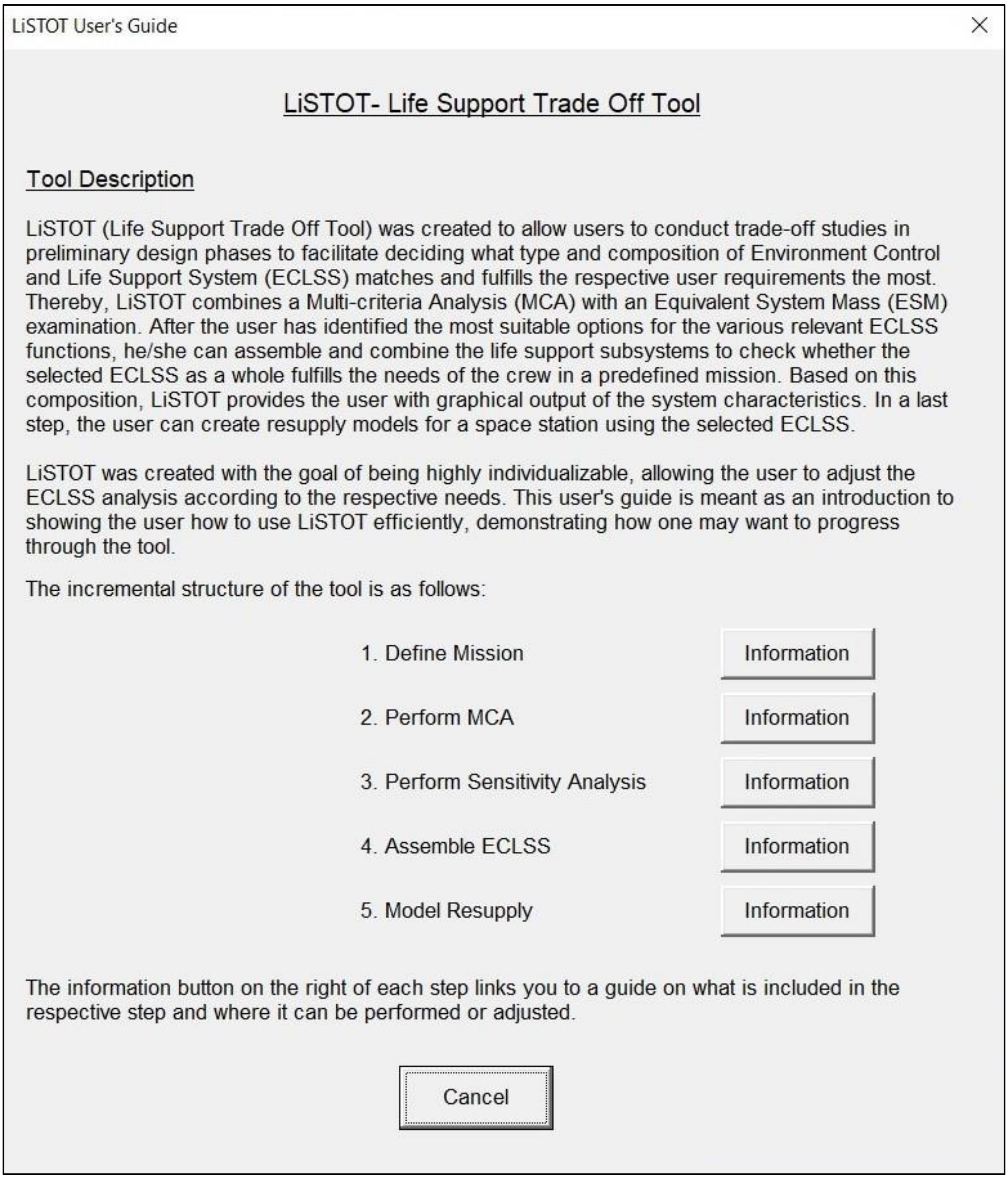


Figure 4-14: Exemplary Flight Criticality Plot

4.12 User’s guide

LiSTOT is equipped with a User’s Guide and instruction manuals that are meant to facilitate one’s introduction to the tool. These aids are focused on explaining how one uses the different interfaces efficiently, which is achieved by describing the various input parameters and how they affect the analyses conducted within LiSTOT. Detailed mathematical information and equations are not provided within the User’s Guide. One may refer to this thesis for that kind of data. The User’s Guide is structured according to how one ideally proceeds through the tool and is therefore subdivided into several successive parts. The UI of the User’s Guide is outlined in Figure 4-15.



LiSTOT- Life Support Trade Off Tool

Tool Description

LiSTOT (Life Support Trade Off Tool) was created to allow users to conduct trade-off studies in preliminary design phases to facilitate deciding what type and composition of Environment Control and Life Support System (ECLSS) matches and fulfills the respective user requirements the most. Thereby, LiSTOT combines a Multi-criteria Analysis (MCA) with an Equivalent System Mass (ESM) examination. After the user has identified the most suitable options for the various relevant ECLSS functions, he/she can assemble and combine the life support subsystems to check whether the selected ECLSS as a whole fulfills the needs of the crew in a predefined mission. Based on this composition, LiSTOT provides the user with graphical output of the system characteristics. In a last step, the user can create resupply models for a space station using the selected ECLSS.

LiSTOT was created with the goal of being highly individualizable, allowing the user to adjust the ECLSS analysis according to the respective needs. This user's guide is meant as an introduction to showing the user how to use LiSTOT efficiently, demonstrating how one may want to progress through the tool.

The incremental structure of the tool is as follows:

1. Define Mission
2. Perform MCA
3. Perform Sensitivity Analysis
4. Assemble ECLSS
5. Model Resupply

The information button on the right of each step links you to a guide on what is included in the respective step and where it can be performed or adjusted.

Figure 4-15: LiSTOT User’s Guide

4.13 Assumptions and simplifications

When creating a model or tool, the assumptions and simplifications that have been made throughout the design process must be stated to demonstrate the limitations of a model and possible inaccuracies that go along accordingly. The reasons for having to simplify certain processes within LiSTOT mainly include the lack of information and data. This chapter is dedicated to depicting the assumptions that have been made in creating LiSTOT. It is worth noting that the list of simplifications provided in the following does not incorporate rationales or explanations of the effects of a certain assumption on the analysis. For more detailed information about the specified simplifications, links to the respective chapters are given to describe those in a relevant context.

4.13.1 Algal photobioreactors related assumptions

- The design of the algal photobioreactor incorporates a CO_2 removal device. See chapter 4.3.3.1.
- Furthermore, it is simplified that the reactor's cooling requirement is equivalent to its power needs, whereas the crew time is assumed to be half as that of a crop growth chamber. See chapter 4.3.3.1.

4.13.2 Scaling related assumptions

- LiSTOT employs a metabolic steady-state sizing approach, in which each crew member is dealt with as a human equivalent unit, whereby it is not distinguished between men and women. Hence, the daily metabolic loads and demands are the same for every inhabitant of the station. See chapter 4.4.1.
- A scaling factor f_s is introduced for considering hardware components that do not scale linearly with crew size. In addition to this factor, contingency values for mass and power depending on a technology's TRL are included in system sizing. See chapter 4.4.1.
- LiSTOT's technology sizing does apply to every system attribute apart from reliability, crew time and TRL. See chapter 4.4.1.

4.13.3 Schedule related assumptions

- The daily metabolic consumption and production values for a HEU depend on the tasks to be performed which are defined in a crew schedule. Thereby, it is assumed that the chosen schedule applies to every day during the entire mission duration. However, different types of schedules as well as a schedule composition tool are available to adjust the crew schedule to user needs. See chapter 4.5.1.
- The daily metabolic consumption and production values are taken from NASA's BVAD [66]. See chapter 4.5.1.
- In composing a schedule, it is distinguished between variable and invariable tasks, whereby the user can only assign variable tasks to the crew since invariable tasks are predefined. See chapter 4.5.

- Based on the selected activities, it is distinguished between metabolic loads and demands that are produced and required continuously throughout the day and ones that are accumulated only during specific activities. The first mentioned class includes O_2, CO_2, sweat and heat. The latter involves potable and hygiene water and food and production of urine, feces and wastewater from hygiene tasks. See chapter 4.5.1.
- Fecal water is considered blackwater and is thus not recovered. See chapter 4.5.1.
- Wastewater from humidity, sweat, hygiene tasks and urine can be recovered, whereby the extracted solid contaminants are directed to the Waste Management system. See chapter 4.5.1.

4.13.4 Reliability and maintenance strategy related assumptions

- The reliability of an assembly is calculated as the sum-product of reliabilities of components that are incorporated in the assembly and are assumed to be connected in series. See chapter 4.6.
- LiSTOT's maintenance strategy consists of an ORU or 0.001 approach (spares). The mass and volume of an ORU are computed using an ORU factor for mass and a hardware density that are derived from ISS hardware depending on the function of the regarded technology. In case of the 0.001 approach, no increase of crew time for repairs is considered. See chapter 4.6.3.
- An improvement factor f_{impr} is included to consider reliability enhancements for ALS technologies. f_{impr} is set to one by default. See chapter 4.6.3.2.

4.13.5 Multi-Criteria related assumptions

- LiSTOT's MCA incorporates confidence factors to account for the confidence with which one can rely on a source of information. See chapter 4.7.1.
- Merit functions are utilized to calculate a dimensionless score of an alternative. See chapter 4.7.1.

4.13.6 Equivalent system mass related assumptions

- A location factor L_{eq} is introduced that is set to one by default. See chapter 4.8.2.
- The user of LiSTOT should be aware of ESM metric inherent simplifications such as the non-observance of certain system attributes. See chapter 4.8.

4.13.7 ECLSS Composition tool related assumptions

- The technologies considered in the ECLSS Composition tool must have a TRL of at least five and must not lack any crucial data concerning their attributes. See chapter 4.10.
- Within LiSTOT's ECLSS Composition tool it is distinguished between open, partially closed and closed loop as well as hybrid ECLSS. Furthermore, a scheme of a BLSS is provided. In this classification, a closed loop life support system does not refer to a completely regenerative ECLSS but for a system that is entirely composed of regenerable technologies with the exception of ACS

atmosphere repressuring tanks, the use of disposable clothing and the MF assembly. See chapter 4.10.

- The hybrid ECLSS scheme incorporates an algal reactor that substitutes the CO_2 removal and reduction as well as the O_2 generation (water electrolysis) systems. P/C technologies are used for the WRM subsystem. See chapter 4.10.1.
- It is simplified that for CO_2 removal and reduction as well as for O_2 generation reactions no losses occur. See chapter 4.10.1.
- It is generally assumed that H_2 cannot be stored and must thus be generated if it is necessary for CO_2 reduction. Furthermore, CH_4, if produced, cannot be used and is therefore vented. See chapter 4.10.1.3.
- CAMRAS is outfitted with a temperature control assembly to allow trade-offs with the CCAA. See chapter 4.10.2.2.
- Technologies that cannot be scaled using steady-state metabolic approach are sized according to total pressurized volume or number of modules. See chapter 4.10.2.
- Food is provided in prepacked form for P/C and hybrid systems. A hybrid system provides algal biomass in an allowable extent of 16.8 g/(CM·d). See chapter 4.10.2.5.
- Independent from the analysed type of ECLSS or BLSS, disposable clothing is used. See chapter 4.10.2.6.
- In calculating partial pressures of CO_2 and O_2 and the relative humidity of the cabin atmosphere, a constant volume and temperature are assumed. Furthermore, efficiencies of CO_2 removal devices that are based on the atmospheric concentration of CO_2 are not considered. See chapter 4.10.2.7.
- The calculation of the ESM of the entire life support system for any non-BLSS is based on adding the individual ESM of the assemblies and components that are contained in the system. Thereby, it is assumed that no tubing is considered, however, additional storage tanks for water and CO_2[4] are accounted for. Food is by default included in the ESM calculation but can be computed separately. See chapter 4.10.2.8.
- The ESM of the BLSS is computed via cost factors related to crop growth chambers, whereby the growth area is sized to be capable of fulfilling every task of a life support system. It is assumed that 20 m^2 per crew member and day are sufficient if no additional conditions such as yield, growth time and buffer capacity are accounted for. If one intends to include those considerations, 100 m^2/(CM·d) must be selected. Due to their insignificance in the overall ESM of the BLSS, it is simplified that additional life support technologies such as controlling or monitoring hardware are not considered for BLSS. See chapter 4.10.4.

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[4] Water tanks only for water electrolysis systems to compensate for fluctuations in the daily water production.
CO_2 tanks only for CO_2 reduction systems to compensate for fluctuations in the daily CO_2 removal capacity.

5 Trade-off analysis

The performance and capabilities of LiSTOT are meant to be demonstrated at the example of identifying and analysing an optimal overall ECLSS for the Gateway, in which the term optimal is characterized by an ideally low total ESM value. It is critical to note that during trade-offs on technology level, an assembly may be chosen due to its performance in the MCA instead of its ESM.

Open, partially closed and closed loop ECLSS are examined, which means that for each of these types of life support system, an ideal ECLSS is designed on the basis of the total manned mission campaign duration of the Gateway. By comparing the overall ESM performance of the respective type-dependent optimal life support systems, the overall most eligible ECLSS is identified. Hybrid and bioregenerative life support systems do not represent viable options due to their general shortcomings in terms of low TRL (< 5) and the thereof resulting reliability concerns. However, both serve as references to depict what kind of ESM performance one may expect once those types of life support systems reach acceptable levels of technology readiness and reliability. The procedure of using LiSTOT is held equivalent to that outlined in chapter 4.1. The life support technologies that are included in this trade study are those which are incorporated in the ECLSS Composition tool so that one can only decide on hardware with which an ECLSS can currently be designed in LiSTOT. In this respect, one may refer to chapter 4.10 for detailed information about what life support hardware is available for the respective type of ECLSS.

In this trade study, the sensitivity and ESM analyses are applied to the two most viable alternatives for a given function, which necessitates that inferior options are excluded from the analysis process after having performed the MCA. By considering the two best performing technologies, possible instabilities of the outcome of the MCA can be compensated for. Analogous to the work of Schreck, an MCA ranking is declared instable if a change of less than 10 % of the initial value of any attribute leads to a different rank of the regarded alternative [6]. One could conceivably investigate each alternative of an MCA in a sensitivity analysis, however this would exceed the time schedule of this thesis. The sensitivity analysis is conducted using an iterative approach using an iteration step width of 5 % to examine by how much an initial attribute value needs to be changed for the worse to achieve a different rank for the best performing alternative. In doing so, only one attribute is analysed at a time. Equivalently, one could evaluate by how much the initial characteristics of a second-best alternative need to be improved to achieve rank number one. It is important to note that on technology level, only assemblies that perform best in either the Multi-Criteria or ESM analyses are chosen. Other considerations the choice of technology such as employing solely one type of tankage on a station may be stated but the final selection is based on the actual results of the analyses.

The life support technologies that have been selected during Multi-Criteria, sensitivity and ESM analyses are integrated in the corresponding life support scheme of the ECLSS Composition tool. By default, food and clothing are included in the total ESM of the composed life support system. Furthermore, the effect of ORU mass and volume on the total ESM is investigated. The composition of the optimal ECLSS is divided into two cycles. During the first iteration, the conservative, default scaling approach for technologies incorporated in the second step of the ECLSS Composition tool is used (see chapter 4.10.2). In the final iteration, the life support system design is refined by examining more appropriate sizing values for the respective technologies to save ESM and lower infrastructural demands in chapter 6. A second trade-off is conducted using LiSTOT's Resupply Modelling tool examining the feasibility of a consumable driven ECLSS for each individual mission. This approach aims at assessing the amount of any extra non-ECLSS related cargo that can be carried along for each flight and is depicted in chapter 7. This trade-off was conducted using LiSTOT version 1.4.7.

5.1 Initiate analysis

The initiation of the analysis involves the overall mission definition, the adjustment of the MCA and ESM parameters and factors, as well as defining a schedule and choosing a maintenance strategy. These steps are described in the following chapters.

5.1.1 Mission definition

The Gateway architecture as planned in October 2018 is described in chapter 2. It involves a total life time of 15 years, a pressurized volume of 125 m^3, a crew of four and mission durations ranging from 30 to 90 days. For this analysis, one mission per year with an average mission duration of 60 days is assumed. Thus, the overall length of the Gateway manned mission campaign amounts to 900 days assuming one mission per year. Seven modules have been proposed thus far, however it is unknown whether each of these will be pressurized and thus require atmospheric control and monitoring equipment. A user defined schedule is employed which is outlined in chapter 5.1.4. The parameters of the Gateway mission scenario are listed in Table 5-1.

Table 5-1: Mission definition parameters

Parameter	Value
Crew size	4
Mission duration [d]	900
Number of modules	7
Total pressurized volume [m^3]	125
Schedule type	User defined

5.1.2 Adjustment of MCA parameters

The adjustment of MCA parameters involves the definition of decision weights and minimal or maximal (boundary) values for the system attributes that are considered within the MCA. For this analysis, all decision weights are set to one to put equal importance on each attribute. In order to address the fact that in other applications one would most certainly adapt the decision weights to value TRL and reliability higher than mass or crew time for instance, an exemplary analysis of the impact of decision weights on the outcome of the MCA is provided in chapter 5.4.2.2.

Furthermore, the only boundary value is assigned to TRL to exclude any technology with a TRL lower than 5.

5.1.3 Adjustment of ESM equivalency factors

The following Table 5-2 depicts the ESM factors used for the Gateway's trade study.

Table 5-2: Gateway equivalency factors

Equivalency Factor	Value
Volume [kg/m^3]	35.9
Power [kg/kW]	60
Cooling [kg/kW]	55.4
Crew time [kg/(CM·h)]	0.8

These values have been calculated by Ewert within the research on trash disposal options and their reusability for the Gateway and a Mars Transfer Vehicle [14]. A location factor which is set to one is used for this analysis.

5.1.4 Schedule composition

As stated in 5.1.1, a user defined schedule is employed, whereby the individual scheduling option has been selected. The daily task allocations for each crew member consist of the following tasks and respective times.

Table 5-3: Time allocations for trade-off

Tasks	Day
Sleep [h]	8
Pre-Sleep [h]	1
Post-Sleep [h]	0.5
Breakfast [h]	0.5
Lunch [h]	1
Dinner [h]	1
Personal Hygiene [h]	0.5
Work [h]	7
Planning/Preparation [h]	1.5
Exercise [h]	0.5
Post-Exercise [h]	1
Recreation [h]	0.5
Homekeeping [h]	1
Total	24

The time allocations in Table 5-3 share characteristics of both a weekday and a weekend day by incorporating work as well as recreation and homekeeping tasks. The entire crew schedule as defined in LiSTOT is displayed in Figure 5-1.

The exercise activities are assigned at different times in the schedule for each crew member since only one crew member can perform physical exercise at a time. Furthermore, in doing so, the CO_2 level is not increasing as drastically throughout the day as it would be if the entire crew exercised at the same time. The metabolic loads and demands that are induced per crew member based on this schedule are outlined in Table 5-4.

Table 5-4: Metabolic loads and demands

Metabolic load/demand	**Value**
Oxygen [kg/(CM·d)]	0.82
Carbon dioxide [kg/(CM·d)]	1.04
Potable water [kg/(CM·d)]	2.52
Hygiene water [kg/(CM·d)]	6.8
Urine [kg/(CM·d)]	1.6
Hygiene wastewater [kg/(CM·d)]	6.8
Sweat [kg/(CM·d)]	1.92
Feces [kg/(CM·d)]	0.12
Food[5] [kg/(CM·d)]	1.51
Heat [MJ/(CM·d)]	12

5.1.5 Maintenance Strategy

The chosen maintenance strategy includes having one ORU per assembly on board. This amount may seem low when compared to the number of ORU per assembly on the ISS, especially if one accounts for the vastly enlarged distance to the Gateway. However, since the overall Gateway mission comprises of various individual missions with considerably shorter durations than those of the ISS, it is assumed that one ORU is enough to fulfil the contingency requirement of an individual mission. In case of a system failure and the usage of an ORU, an additional ORU can be brought along for the next individual mission to maintain the demanded contingency. It is furthermore simplified for this analysis, that during the mission campaign no system fails, which would necessitate more than one ORU per technology over the course of the entire mission.

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[5] Includes 0.7 kg/(CM·d) of water

User defined time	Crew Member 1 task	Crew Member 2 task	Crew Member 3 task	Crew Member 4 task
00:00	Sleep	Sleep	Sleep	Sleep
00:30	Sleep	Sleep	Sleep	Sleep
01:00	Sleep	Sleep	Sleep	Sleep
01:30	Sleep	Sleep	Sleep	Sleep
02:00	Sleep	Sleep	Sleep	Sleep
02:30	Sleep	Sleep	Sleep	Sleep
03:00	Sleep	Sleep	Sleep	Sleep
03:30	Sleep	Sleep	Sleep	Sleep
04:00	Sleep	Sleep	Sleep	Sleep
04:30	Sleep	Sleep	Sleep	Sleep
05:00	Post-Sleep	Post-Sleep	Post-Sleep	Post-Sleep
05:30	Breakfast	Breakfast	Breakfast	Breakfast
06:00	Personal Hygiene	Personal Hygiene	Personal Hygiene	Personal Hygiene
06:30	Exercise	Planning/Prep.	Planning/Prep.	Planning/Prep.
07:00	Post Exercise	Planning/Prep.	Planning/Prep.	Planning/Prep.
07:30	Post Exercise	Planning/Prep.	Planning/Prep.	Planning/Prep.
08:00	Planning/Prep.	Exercise	Work	Work
08:30	Planning/Prep.	Post Exercise	Work	Work
09:00	Planning/Prep.	Post Exercise	Work	Work
09:30	Work	Recreation	Exercise	Work
10:00	Work	Work	Post Exercise	Work
10:30	Work	Work	Post Exercise	Work
11:00	Lunch	Lunch	Lunch	Lunch
11:30	Lunch	Lunch	Lunch	Lunch
12:00	Work	Work	Recreation	Exercise
12:30	Work	Work	Work	Post Exercise
13:00	Work	Work	Work	Post Exercise
13:30	Work	Work	Work	Recreation
14:00	Work	Work	Work	Work
14:30	Work	Work	Work	Work
15:00	Work	Work	Work	Work
15:30	Work	Work	Work	Work
16:00	Work	Work	Work	Work
16:30	Work	Work	Work	Work
17:00	Dinner	Dinner	Dinner	Dinner
17:30	Dinner	Dinner	Dinner	Dinner
18:00	Homekeeping	Work	Homekeeping	Homekeeping
18:30	Homekeeping	Work	Homekeeping	Homekeeping
19:00	Work	Homekeeping	Work	Work
19:30	Recreation	Homekeeping	Work	Work
20:00	Pre-Sleep	Pre-Sleep	Pre-Sleep	Pre-Sleep
20:30	Pre-Sleep	Pre-Sleep	Pre-Sleep	Pre-Sleep
21:00	Sleep	Sleep	Sleep	Sleep
21:30	Sleep	Sleep	Sleep	Sleep
22:00	Sleep	Sleep	Sleep	Sleep
22:30	Sleep	Sleep	Sleep	Sleep
23:00	Sleep	Sleep	Sleep	Sleep
23:30	Sleep	Sleep	Sleep	Sleep

Figure 5-1: LiSTOT schedule for trade-off

5.1.6 Conclusion

Having initiated the analysis according to the parameters described in the chapters before, LiSTOT's UI may look as depicted in Figure 5-2.

1. Mission Definition

Mission Parameters (required)

Crew Size: 4
Mission Duration: 900 [days]
Schedule Number: 2
ECLSS Type: open
Pressurized Volume: 150 [m^3]
Amount of Modules: 7
Date: (not required)

2. Multi-criteria Analysis

Weighting Coefficients (optional)

Mass: 1.00 [0 to 1]
Volume: 1.00 [0 to 1]
Power: 1.00 [0 to 1]
Cooling: 1.00 [0 to 1]
Maintenance: 1.00 [0 to 1]
Reliability: 1.00 [0 to 1]
TRL: 1.00 [0 to 1]

Minimum Value (optional)

Reliability: [0 to 1]
TRL: 5

Maximum Value (optional)

Mass: [kg]
Volume: [m^3]
Power: [W]
Cooling: [W]
Maintenance: [h]

ECLSS System Function (required)

Recover from Rapid Decompression

Descriptions of all currently available functions can be found here

3. ESM Analysis

ESM Factors (required)

Location Factor: 1.00 [kg/kg]
Volume: 35.90 [kg/m^3]
Power: 60.00 [kg/kW]
Cooling: 55.40 [kg/kW]
Crew Time: 0.80 [kg/CM*h]

Additional Filter and MCA Options

Filter by System Level: component
Mass Margin: 0 [0 to 1]
Exclude Alternatives with partially missing Information from MCA? Yes
Allow MCA in between different System Levels? No
Reliability Calculation Approach: A. of ORUs
Number of ORUs: 1 [1 to 5]
Exclude Alternatives not fitting to selected ECLSS type? Yes

Metabolic Considerations

Metabolic factors can be adjusted in the "Schedule and Metabolic" Worksheet

Figure 5-2: LiSTOT Mission initiation UI

5.2 Trade study for open loop ECLSS

The results below depict the outcome of the Multi-Criteria, sensitivity and ESM analyses applied to the subsystem functions outlined in chapter 4.2. Since an open loop ECLSS is analysed, only non-regenerable technologies are considered. The selected life support technologies are then examined in the ECLSS composition tool to determine the overall ESM of the ECLSS. It also important to note that when discussing the O_2 and N_2 CS option, one may refer to chapter 4.10.2.1 for more information.

5.2.1 Atmosphere Control and Supply

5.2.1.1 Multi-Criteria Analysis

The alternatives and their MCA rank for providing O_2 for consumption by the crew in an open loop ECLSS are outlined in Table 5-5. Other technologies such as hydrogen peroxide have been sorted out due to reasons stated in chapter 4.10. As it can be seen, a high-pressure storage option achieves the highest rank, followed by cryogenic storage. O_2 candles have the lowest MCA score and therefore rank and are thus excluded from this trade study.

Table 5-5: Oxygen provision technologies for open loop systems

Alternative	**Mass [kg]**	**Volume [m³]**	**Power [W]**	**Cooling [W]**	**Crew time [h]**	**Relia-bility**	**TRL**	**MCA Score**	**Rank**
CS	4,215	1.92	9	0	0	0.988	9	0.30	2
HPS	4,022	5.94	9	0	0	0.997	9	0.37	1
Oxygen Candles	6,066	8.02	0	0	0	0.990	8	0.13	3

The score gap between high-pressure and cryogenic storage is with 0.07 comparably small. Cryogenic tanks offer a significant saving in terms of volume, which is however compensated by slightly higher mass demands and lower reliability in comparison to high-pressure tanks.

Storing inert gas can be achieved by the alternatives listed in Table 5-6. The mass of N_2 required for the given mission campaign amounts to 278 kg. It is important to note that storing inert gas includes the N_2 requirements for repressuring and leakage handling. Cryogenic storage outperforms high-pressure storage. Thus, one can conclude that the volume savings of cryogenic tanks outweigh the advantages of high-pressure tanks for the given ACS function.

Table 5-6: Inert gas provision technologies

Alternative	Mass [kg]	Volume [m^3]	Power [W]	Cooling [W]	Crew time [h]	Relia-bility	TRL	MCA Score	Rank
CS	426	0.28	9	0	0	0.988	9	0.21	1
HPS	440	0.72	9	0	0	0.997	9	0.11	2

Two alternatives are available for storing O_2 for repressuring and leakage handling as outlined in Table 5-7. 80 kg of O_2 are needed to fulfil this ACS function for the regarded campaign. Other means of generating O_2 via O_2 candles or water electrolysis for example are excluded due to their deficiency as an emergency system as described in chapter 4.10.2.1. As it can be seen, cryogenic storage poses the optimal solution for the specified mission scenario due to the same reasons that are stated in discussing alternatives for inert gas storage.

Table 5-7: Oxygen provision technologies for repressuring and leakage handling

Alternative	Mass [kg]	Volume [m^3]	Power [W]	Cooling [W]	Crew time [h]	Relia-bility	TRL	MCA Score	Rank
CS	60	0.10	9	0	0	0.988	9	0.21	1
HPS	57	0.15	9	0	0	0.997	9	0.11	2

It is striking that considering the Multi-Criteria Analyses examined before, the ranking of cryogenic and high-pressure storage systems varies strongly over different O_2 and N_2 demands. This raises the question of how stable these results are. Thus, the robustness of the MCA outcome is evaluated in the following chapter, when the sensitivity analysis is discussed. Furthermore, one may notice that within the ECLSS Composition tool, cryogenic tanks are used by default for repressuring and leakage handling.

5.2.1.2 Sensitivity analysis

The amount by which an initial system attribute needs to be varied to receive a different best performing alternative other than high-pressure storage for providing O_2 for crew consumption is shown in Table 5-8. Since the performance of the two best performing options differ only in regard to mass, volume and reliability, those characteristics are being considered within this sensitivity analysis. As it can be seen, if the mass of the high-pressure tank is increased by 20 % or the reliability is decreased by 5 %, the ranking of the alternatives changes and the cryogenic tank becomes the optimal option. Moreover, one may notice that interestingly, the volume attribute on its own has no influence on the outcome of the sensitivity analysis. However, if coupled with an increase in mass of 15 % for instance, a 10 % volume increase leads to a change in rank of the high-pressure storage system. Thus, the criticality of the volume attribute is not insignificant but vastly less substantial than the criticality of reliability or even mass.

Table 5-8: Sensitivity analysis for oxygen provision for crew consumption

Mass	Volume	Reliability
20 %	-	5 %

The results of the sensitivity analysis for inert gas storage technologies are displayed in Table 5-9. Since the only viable options include high-pressure and cryogenic storage, mass, volume and reliability are examined. However, in contrast to the previous analysis, the cryogenic tanks pose the optimal alternative.

Table 5-9: Sensitivity analysis for inert gas provision

Mass	Volume	Reliability
5 %	150 %	-

It is evident that the mass attribute is the most critical characteristic since an increase of 5 % leads to a change of rank, whereas 150 % are necessary for volume. This circumstance emphasizes the comparably low criticality of volume, which has been identified in the previous sensitivity analysis. A deterioration of reliability for cryogenic tanks has no influence on the ranking, which can be explained by considering the corresponding merit function (4.16) which determines the performance of an alternative regarding a certain characteristic. This particular merit function returns the value of 0 if the system attribute value is equivalent to the lowest attribute value in the analysis. Due to the function value being 0, the MCA score of an alternative is not improved at all if the alternative is characterized by performing worse than other options. This is consequential but also implies that the case of an even further performance decrease is not resembled in the MCA score of the regarded alternative since the outcome of the corresponding merit function remains 0. It is however important to state that other options and their MCA scores are affected since now, their performance is evaluated according to a new boundary value. This effect can only be experienced if more than two alternatives are examined in the sensitivity analysis.

The results of the sensitivity analysis for high-pressure and cryogenic tanks that provide O_2 for repressuring and leakage handling are outlined in Table 5-10. As it can be seen, an increase of 5 % in mass or of 150 % in volume leads to the cryogenic storage alternative being the optimal solution. The reliability attribute has no effect on the MCA scores due to the same reason as explained before.

Table 5-10: Sensitivity analysis for oxygen gas provision for repressuring and leakage handling

Mass	Volume	Reliability
5 %	150 %	-

By comparing the results of the sensitivity analysis applied to high-pressure and cryogenic storage systems, it is evident that the results of the MCA are not robust since a change of 5 % in mass or reliability can already lead to a different outcome.

Therefore, one can conclude that the differences concerning the attributes that are considered within the MCA between the high-pressure and cryogenic tanks are minor.

5.2.1.3 ESM analysis

The alternatives providing O_2 for crew consumption and their ESM ranks are outlined in Table 5-11. It is evident that the outcome of the ESM analysis is equivalent to that of the corresponding MCA, whereby the high-pressure storage system achieves the highest rank. The ESM performance of the O_2 Candles is not shown since they have been excluded after the MCA.

Table 5-11: ESM for oxygen provision for crew consumption

Alternative	**ESM [kg]**	**Rank**
Cryogenic Storage	4,284	2
High-pressure Storage	4,237	1

The results of the ESM analysis for high-pressure and cryogenic tanks for storing N_2 to repressure the specified habitat and handle leakage are listed in Table 5-12. The cryogenic system is characterized by a lower ESM value than the high-pressure storage option, which is equivalent to the ranking of the MCA.

Table 5-12: ESM of inert gas provision for repressurization and leakage handling

Alternative	**ESM [kg]**	**Rank**
Cryogenic Storage	437.0	1
High-pressure Storage	466.0	2

The results of the ESM analysis for high-pressure and cryogenic tanks for storing O_2 to repressure the specified habitat and handle leakage are listed in Table 5-13. Similar to the outcome of the MCA, the high-pressure tank system has the highest rank although the difference in ESM is only 0.6 kg.

Table 5-13: ESM for oxygen provision for repressuring and leakage handling

Alternative	**ESM [kg]**	**Rank**
Cryogenic Storage	64.0	2
High-pressure Storage	63.4	1

5.2.1.4 Conclusion

Taking the results of the Multi-Criteria, sensitivity and ESM analyses described in the previous chapters into account, the technology choices for the ACS functions are as shown in Table 5-14. No trade-off analysis is conducted for the pressure control assembly due to the lack of alternatives. Moreover, it is important to note that part of the ACS subsystem designed within the previous chapters is identical for an open, partially closed and closed loop ECLSS since even life support systems incorporating regenerable technologies do meet the requirements of habitat repressurization and leakage handling via means of storing O_2 and N_2. For additional information on this topic, one may refer to chapter 4.10. As one can see, both HPS and CS have been chosen due to their performances in the Multi-Criteria and ESM analyses. It is worth noting that it may be useful to rely only on one type of tankage, however as stated in chapter 5, the final selection is solely affected by the results of the previous analyses even if the difference in performance may be insignificant.

Table 5-14. Technologies for ACS functions

Function	Technology
Recover from Rapid Decompression	Cryogenic storage
Store Oxygen	High-pressure storage
Store Inert Gas	Cryogenic storage
Control Atmosphere Total Pressure	Pressure Control Assembly

5.2.2 Atmosphere Revitalization

5.2.2.1 Multi-Criteria Analysis

The alternatives for CO_2 removal include LiOH and CAMRAS. Their performance in the MCA is depicted in Table 5-15. It is striking that CAMRAS is vastly outperforming LiOH, especially regarding system mass, which is due to LiOH being a consumable driven system. However, critical characteristics of these technologies are not represented in this ranking. For example, CAMRAS removes in addition to CO_2 excess atmospheric humidity, which means that less wastewater is available to be recovered. In contrast to this, LiOH produces 0.43 kg/(CM·d) of water if 1.04 kg/(CM·d) of CO_2 are removed. To account for these traits, LiOH is not excluded despite its worse performance in the MCA but analysed in the ECLSS Composition.

Table 5-15: Carbon dioxide removal technologies for open loop system

Alternative	Mass [kg]	Volume [m^3]	Power [W]	Cooling [W]	Crew time [h]	Relia-bility	TRL	MCA Score	Rank
CAMRAS	320	1.20	53.76	0	0	0.990	9	0.21	1
LiOH	6022	2.08	53.76	0	293.4	0.999	9	0.04	2

5.2.2.2 Sensitivity analysis

Considering the gap between the MCA score of CAMRAS and LiOH, it is expected that the ranking is robust. The results of the sensitivity analysis for both technologies are provided in Table 5-16, whereby mass, volume, power and reliability have been examined. As it can be seen, changing solely one attribute at a time does not affect the ranking.

Table 5-16: Sensitivity analysis for carbon dioxide removal devices

Mass	**Volume**	**Power**	**Reliability**
-	-	-	-

To receive a different outcome, the mass, volume and power values of CAMRAS need to be increased by 80 %, for example. Thus, it can be concluded that the expectation stated above is met.

5.2.2.3 ESM analysis

The ESM performance of CAMRAS and LiOH are shown in Table 5-17. As suggested by the MCA, CAMRAS vastly outperforms LiOH.

Table 5-17: ESM analysis for carbon dioxide removal devices

Alternative	**ESM [kg]**	**Rank**
CAMRAS	366.3	1
LiOH	6335.2	2

5.2.2.4 Conclusion

The Multi-Criteria and ESM analyses demonstrated that CAMRAS is superior to LiOH for the given mission scenario. Nonetheless, both technologies (as outlined in Table 5-18) are examined in the ECLSS Composition tool due to their different, yet equally significant impact on the WRM subsystem of the station. Because of the lack of alternatives, the Multibed TCCS is used to remove trace contaminants other than CO_2 and the Microbial Monitoring and Control assembly is employed for controlling airborne microbes and particles.

Table 5-18: Technologies for AR functions

Function	Technology
Remove Gaseous Atmospheric Contaminants	TCCS/CAMRAS/LiOH
Remove Carbon Dioxide	CAMRAS/LiOH
Control Microbes	Microbial Monitoring and Control
Control Airborne Particles	Microbial Monitoring and Control
Remove Airborne Particles	Microbial Monitoring and Control

5.2.3 Temperature and Humidity Control

5.2.3.1 Multi-Criteria Analysis

The alternatives for controlling atmospheric temperature and humidity include CAMRAS and CCAA, whereby CAMRAS can only be selected if it has been used for CO_2 removal. For more information on that topic, see chapter 4.10.2.2. The performance of both systems in the MCA is outlined in Table 5-19. When discussing the results of this analysis, one must keep in mind that CAMRAS is capable of removing CO_2 and excess moisture, whereas CCAA can control cabin temperature and remove atmospheric humidity. Hence, both technologies offer different functionalities, which makes comparisons based on one shared function (humidity control) difficult. A more detailed trade-off for these systems is conducted in the ECLSS composition by evaluating the performance of the combination of LiOH and CCAA with that of CAMRAS and a temperature control assembly. In doing so, no function is omitted from the analysis. The attribute values listed in the table below neglect the temperature control assembly for CAMRAS and the CO_2 removal device for CCAA. Nonetheless, the power and cooling needs of CCAA are striking when compared to CAMRAS. Due to the significantly lower mass and volume however, CCAA is considered to be the optimal solution despite its worse performance in terms of power, cooling and reliability.

Table 5-19: Humidity control technologies for an open loop system

Alternative	Mass [kg]	Volume [m^3]	Power [W]	Cooling [W]	Crew time [h]	Relia-bility	TRL	MCA Score	Rank
CAMRAS	320	1.20	53.76	0	0	0.990	9	0.20	2
CCAA	127	0.44	579.02	512.98	0	0.959	9	0.30	1

5.2.3.2 Sensitivity analysis

The attributes of mass and volume are considered within the sensitivity analysis whose results are given in Table 5-20. Power, cooling and reliability are not regarded since CCAA's corresponding performance is inferior to that of CAMRAS. A further deterioration will therefore have no influence on the score (see chapter 5.2.1.2). As one can see, mass or volume of CCAA would need to be increased by roughly 160 % to achieve a different outcome of the MCA.

Table 5-20: Sensitivity analysis for temperature and humidity control technologies

Mass	**Volume**
155 %	175 %

5.2.3.3 ESM analysis

The ESM performance of CAMRAS and CCAA is displayed in Table 5-21. CCAA offers the lower ESM, even though its power and cooling needs considerably exceed those of CAMRAS.

Table 5-21: ESM analysis for temperature and humidity control technologies

Alternative	**ESM [kg]**	**Rank**
CAMRAS	366.3	2
CCAA	206.7	1

5.2.3.4 Conclusion

Due to the reasons stated in chapter 5.2.3.1, CAMRAS and CCAA are examined in the ECLSS Composition although the Multi-Criteria and ESM analyses demonstrated that CCAA outperforms CAMRAS. IMV is used for air circulation, AAA for air cooling and FDH for fire detection and handling because of a lack of alternatives concerning those functions (see Table 5-22).

Table 5-22: Technologies for THC functions

Function	Technology
Control Atmospheric Temperature	CAMRAS/CCAA
Control Atmospheric Humidity	CAMRAS/CCAA
Remove or Add Moisture	CAMRAS/CCAA
Exchange Atmosphere between Modules	IMV
Accept Thermal Energy	AAA
Release Thermal Energy	AAA
Detect Fire	FDHS
Suppress Fire	FDHS

5.2.4 Water Recovery Management

In an open loop system, one can decide to process urine and wastewater to recover water or to store all the necessary water for the mission in tanks. As stated in chapter 4.10.1.4, only one urine processing assembly, AES, is considered for open loop life support systems. Since the trade-off between water recovery and storage applies to different functions (Process Wastewater (a-c) and Store Water), an MCA cannot be performed. Instead, the ECLSS Composition tool would have to be used to conduct this trade study. Thereby, the water storage option can be selected by removing all urine and/or wastewater from the loop. Another way of evaluating the difference between water recovery and storage involves employing the ESM analysis. Table 5-23 depicts the performance of AES compared to water tanks providing an ESM score. It is evident that the water tank option has significantly higher mass and volume requirements than AES, which leads to an ESM gap of more than 20,000 kg. the reason for this being the consumable driven characteristic of water storage whose infrastructural demands increase linearly with crew size and mission duration. Considering the results of the ESM analysis, it is decided to employ AES for water management. Furthermore, the water quality monitoring assembly used on the ISS is used to meet the water quality control requirement.

Table 5-23: ESM analysis of AES and water tank

Alternative	Mass [kg]	Volume [m³]	Power [W]	Cooling [W]	Crew time [h]	Relia-bility	TRL	ESM [kg]	Rank
AES	218	0.28	1,279	1,064	165.6	0.953	9	496.2	1
Water tank	24,574	26.98	0	0	0	0.985	9	25,543	2

5.2.5 ECLSS Composition

One trade-off concerning the choice of CO_2 removal device is conducted using the ECLSS Composition tool which is described in the following chapters.

5.2.5.1 CAMRAS

To perform the trade-off discussed in chapter 5.2.3.1, the first ECLSS composition includes CAMRAS for CO_2 and excess humidity removal as well as temperature control. Figure 5-3 displays the ESM performance of the life support system over the mission duration with and without food and clothing.

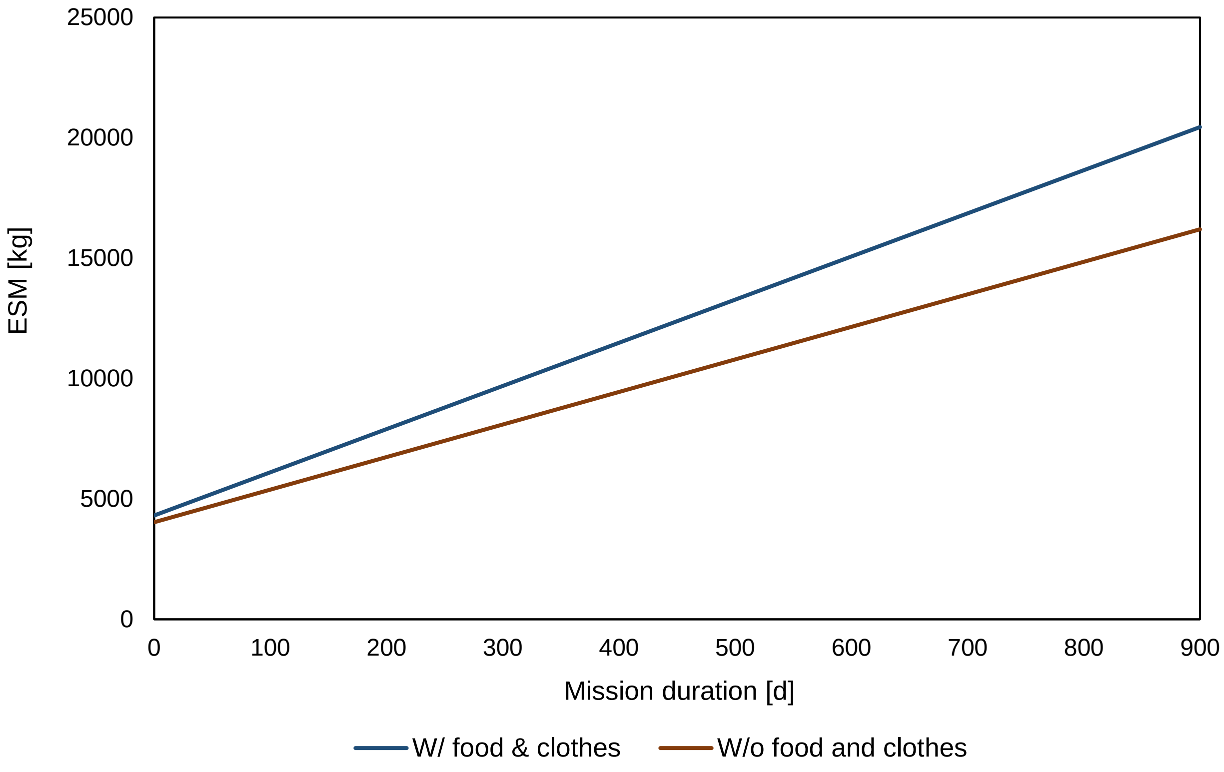

Figure 5-3: CAMRAS based ECLSS with and without food and clothing

For the given mission campaign, the ESM of food and clothes amounts to 4,246 kg, whereby the total ESM including food and clothing is 20,448 kg. The ESM cost of the various subsystems is displayed in Figure 5-4. It is evident that the total ESM is primarily driven by consumables including food, disposable clothing and water and the repressuring tanks containing O_2 and N_2. Due to the selection of CAMRAS, not enough wastewater is available for water recovery. 1.70 kg/(CM·d) of water is missing, which thus needs to be provided in tanks for the campaign as displayed in Figure 5-5.

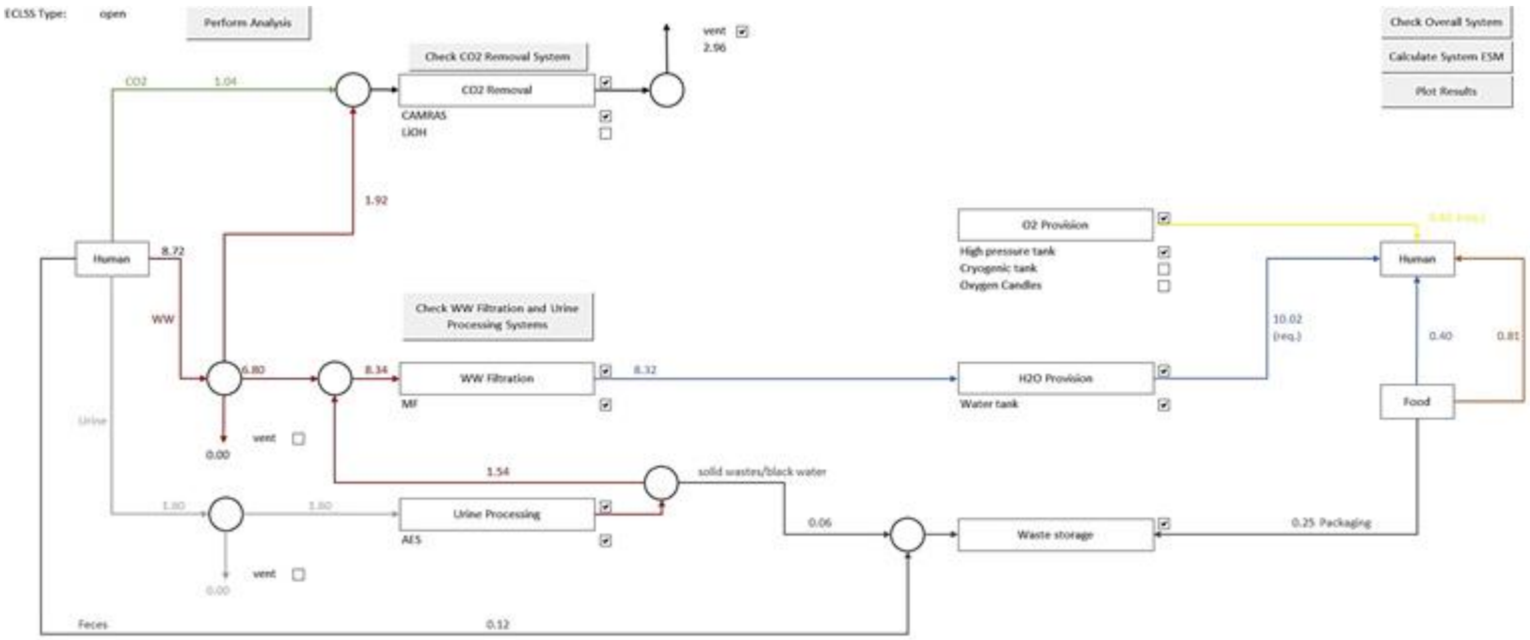

Figure 5-5: CAMRAS based ECLSS scheme

The ESM cost of these tanks including the mass and volume of the required water is 6,550 kg. In contrast to this, the ESM of MF and AES combined adds up to merely 2,276 kg, whereby MF is the main driver with 1,726 kg due to its significant resupply needs of 978 kg for the given mission. Thus, WRM is the subsystem with the highest costs (44 % of the total ESM). On the other hand, with only 5 % of the total ESM, the AR and THC subsystems have the smallest impact followed by ACS with 26 %. The ESM cost of the maintenance strategy as outlined in chapter 5.1.5 amounts to 1,078 kg.

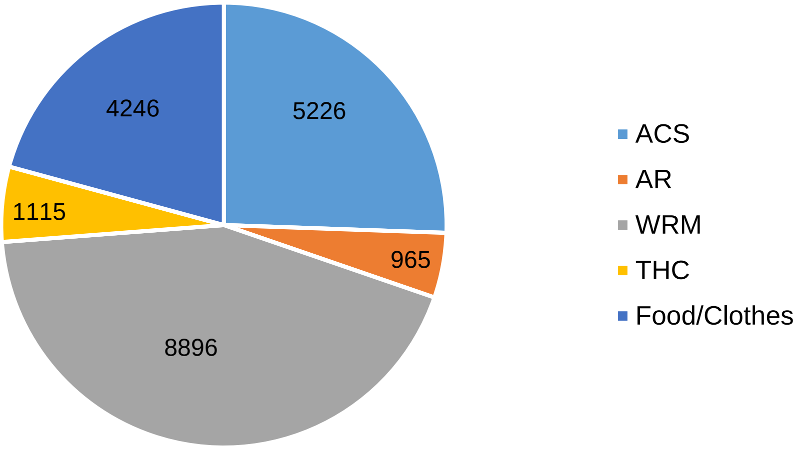

Figure 5-4: CAMRAS (open) ECLSS subsystems ESM costs

5.2.5.2 LiOH

The second ECLSS composition involves LiOH for CO_2 removal and CCAA for humidity and temperature control. The total ESM of the life support system including food and clothing over the campaign duration amounts to 25,609 kg. The individual contribution of the life support subsystems to the total ECLSS ESM is shown in Figure 5-6.

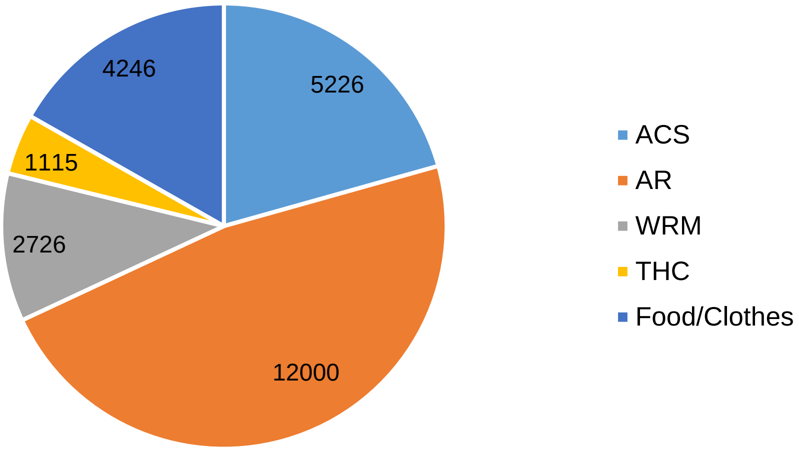

Figure 5-6: LiOH ECLSS subsystems ESM costs

It is striking that the AR subsystem is now the main cost driver with 12,000 kg, almost 50 % of the total ESM, which is due to the infrastructural demands of the consumable LiOH. Yet, no additional water tanks are required since the usage of LiOH allows to provide enough water (and wastewater) for the daily needs of the crew. Consequently, the WRM subsystem makes for only 11 % of the total ESM. It is worth pointing out however, that due to the increased amount of wastewater which must be filtered, the ESM cost of MF is rescaled and reaches 2,105 kg, thus exceeding that if CAMRAS had been employed instead of LiOH. The second most influential subsystem is ACS with 21 % of the total ESM which is closely followed by food and clothing that require 17 %.

The ESM cost of ORUs reaches 6,510 kg since the ORU factor of CO_2 removal is applied to the entire LiOH system including the mass and volume of the consumable LiOH. The reason behind this lies in the assumption that spares and replacement units for a LiOH system consist of extra cartridges. One could rightfully argue that this simplification leads to inappropriately high contingency masses since the LiOH system is characterized by having a high reliability of 0.999. In examining the feasibility of employing LiOH for CO_2 removal, Jones calculated with an ESM cost of the spares amounting to 10 % of the overall LiOH system ESM [47]. Figure 5-7 depicts the impact of defining the ORU mass and volume of LiOH to 10 % of its initial corresponding attributes

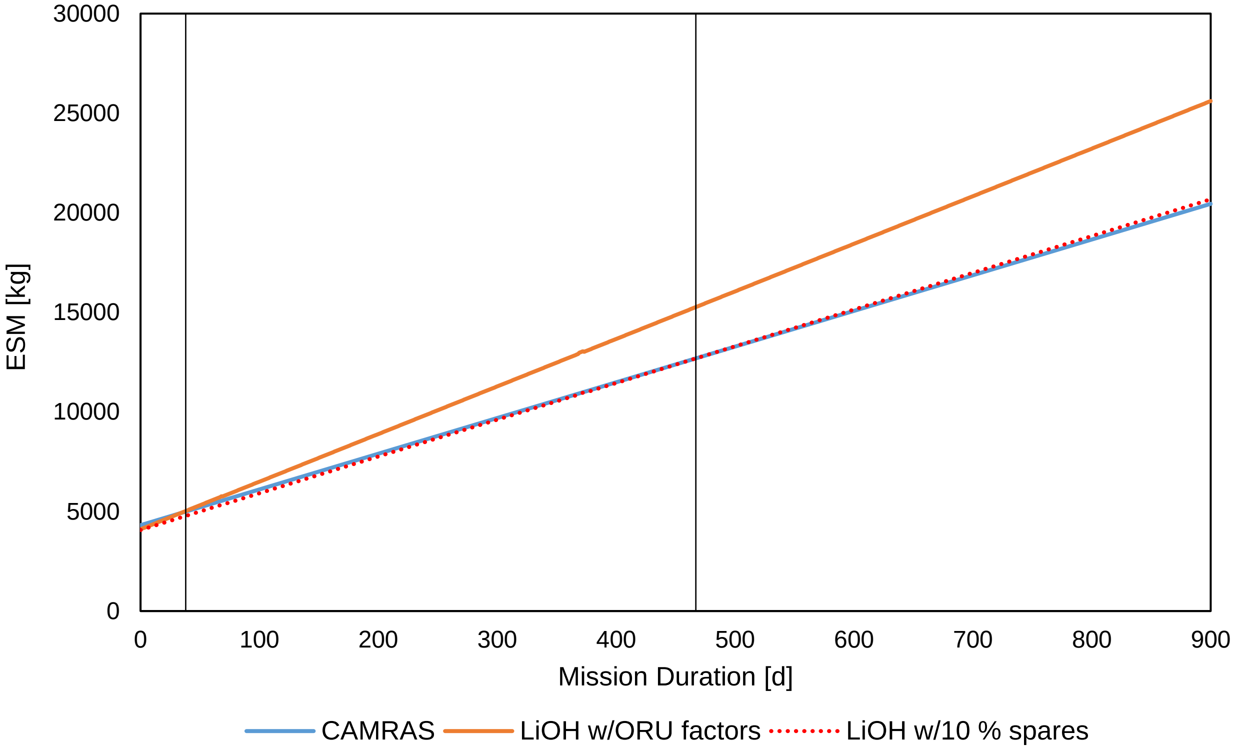

Figure 5-7: ESM costs of CAMRAS vs LiOH based on ORU approach

By using 10 % spares, the total ESM cost of the LiOH system can be reduced by 4,934 kg. Using ORU factors for mass and volume leads expectedly to a higher ESM than employing the 10 % approach. Nonetheless, the LiOH system with ORU factors has a lower ESM than the CAMRAS based ECLSS until the breakeven point of 38 days. Furthermore, until 467 days into the mission, the 10 % LiOH based ECLSS outperforms the CAMRAS option. At the total scale of the mission campaign however, utilizing CAMRAS instead of LiOH poses the most eligible CO_2 removal solution, independently from the choice of the ORU costs of the LiOH system even though the difference to a LiOH with 10 % spares is almost negligible. The outcome of this analysis lead to the adjustment of the ORU factors outlined in chapter 4.6.3.1 for the consumable driven LiOH and O_2 candles.

5.2.5.3 Conclusion

As shown in Figure 5-7, using CAMRAS instead of LiOH is the more viable option for the given mission scenario. Up to 227 kg of ESM can be saved by avoiding the consumable driven LiOH[6]. Thus, one can conclude that the infrastructural requirements of LiOH exceed those of the added water tanks in case of using CAMRAS. The ECLSS design described in chapter 5.2.5.1 represents the optimal open loop life support system.

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[6] 227 kg for 10 % spares, 4,908 kg if ORU factors for LiOH were used

5.3 Trade study for partially closed loop ECLSS

The results below depict the outcome of the Multi-Criteria, sensitivity and ESM analyses applied to the subsystem functions outlined in chapter 4.2. Since a partially closed loop ECLSS is examined, both regenerable and non-regenerable technologies are considered. The selected life support technologies are then examined in the ECLSS composition tool to determine the overall ESM of the ECLSS.

5.3.1 Atmosphere Control and Supply

As mentioned in chapter 5.2.1.4, the ACS subsystem for repressuring and leakage handling outlined for an open loop ECLSS is also used for any partially closed loop life support system.

5.3.2 Atmosphere Revitalization

5.3.2.1 Multi-Criteria Analysis

The alternatives for CO_2 removal and their MCA performance in a partially closed ECLSS are outlined in Table 5-24. Despite having a substantial mass and volume, CAMRAS achieves the highest rank due to its high reliability and low power and cooling demands. The score difference between 4BMS and SAWD is with 0.02 very small, which suggests that their ranking is instable. In a direct comparison between 4BMS and SAWD, the latter is the more eligible alternative in any attribute but TRL.

Table 5-24: Carbon dioxide removal technologies for a partially closed loop ECLSS

Alternative	**Mass [kg]**	**Volume $[m^3]$**	**Power [W]**	**Cooling [W]**	**Crew time [h]**	**Relia-bility**	**TRL**	**MCA Score**	**Rank**
CAMRAS	320.0	1.2	53.8	0	0	0.990	9	0.36	1
4BMS	255.4	0.46	829.0	740.1	4.47	0.934	9	0.27	3
SAWD	190.8	0.29	533.0	475.9	0	0.945	8	0.29	2

Depending on the choice of CO_2 removal technology, CO_2 can be reduced to generate wastewater if 4BMS or SAWD are selected. Because of this reason and the close score gap between the two CO_2 removal devices, neither of them is excluded after the MCA. Instead, based on their respective ESM performance, an optimal technology is identified.

The alternatives for CO_2 reduction are listed in Table 5-25, whereby the attribute values are given for the case that all CO_2 produced by the crew is reduced. It is evident that Sabatier outperforms Bosch in any attribute but reliability, which explains why Bosch's MCA score is 0. Due to this circumstance, it is expected that the ranking is very robust. One must however note that Sabatier requires double the amount of H_2 to reduce the same amount of CO_2.[7] In other words, Bosch can completely retain H_2, whereas Sabatier is reliant on H_2 resupply in the form of water. Since this characteristic is not

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[7] See equations (4.22) and (4.23)

represented in the MCA scores, yet critical for the design of the water electrolysis technology providing O_2 and H_2 as well as for the design of water provision system, a trade-off between the two CO_2 reduction assemblies will be conducted using the ECLSS Composition tool.

Table 5-25: Carbon dioxide reduction technologies for partially closed loop ECLSS

Alternative	Mass [kg]	Volume [m³]	Power [W]	Cooling [W]	Crew time [h]	Relia-bility	TRL	MCA Score	Rank
Bosch	268.7	0.31	1,182.8	324.8	24.0	0.990	6	0	2
Sabatier	125.0	0.15	46.5	240.0	0	0.990	9	0.57	1

The alternatives for O_2 generation via water electrolysis as depicted in Table 5-26 are scaled according to the requirement of producing the amount of O_2 that is demanded daily by the crew. The scaling of these technologies within the ECLSS Composition tool comprises of providing the amount of H_2 required by the CO_2 reduction systems. Thus, the ESM performance of the water electrolysis systems may strongly deviate from the values given in Table 5-32. As one can see, SPWE outperforms SFWE mainly due to the higher reliability and vastly lower power and cooling needs.

Table 5-26: Water electrolysis systems for partially closed loop ECLSS

Alternative	Mass [kg]	Volume [m³]	Power [W]	Cooling [W]	Crew time [h]	Relia-bility	TRL	MCA Score	Rank
SPWE	328.4	1.05	716.7	16.4	0	0.873	9	0.36	1
SFWE	116.4	0.14	1,646.4	39.0	0	0.873	8	0.21	2

One could also consider using water electrolysis solely for O_2 generation and vent the by-product H_2. For example, this possibility is available if CAMRAS has been chosen so that no CO_2 can be reduced. In this case, a trade-off must be conducted between O_2 generation via water electrolysis and O_2 storage. Since two different life support functions are compared in this particular study however, the ESM metric needs to be used prior to ECLSS composition.

5.3.2.2 Sensitivity analysis

The attributes that need to be regarded within the sensitivity analysis for CO_2 removal technologies include mass, volume, power, reliability and TRL. Cooling and maintenance are excluded since the values for those characteristics are 0 in the case of CAMRAS. The results of sensitivity analysis are given in Table 5-27. As it can be seen, a decrease in reliability of only 5 % already leads to a change in rank. The TRL attribute is similarly critical, whereby a TRL of 8 would lead to a different ranking. Yet, it can be rightfully argued that a worsening in TRL represents a purely theoretical event since TRL can realistically only improve. Volume on its own does not affect the outcome of the MCA, power can also be considered insignificant.

Table 5-27: Sensitivity analysis for carbon dioxide removal devices

Mass	Volume	Power	Reliability	TRL
190 %	-	800 %	5 %	-1

Mass, volume, power, cooling, reliability and TRL are examined in the sensitivity analysis for CO_2 reduction technologies. Maintenance is not regarded since Sabatier's crew time requirement is 0 h. The outcome of the sensitivity analysis are provided in Table 5-28. It is evident that varying one attribute value at a time does not affect the ranking, which proves the expectation of a robust ranking between Bosch and Sabatier. Mass, volume, power and cooling all would have to be worsened by 115 % so that Bosch becomes rank one, for instance.

Table 5-28: Sensitivity analysis for carbon dioxide reduction devices

Mass	Volume	Power	Cooling	Reliability	TRL
-	-	-	-	-	-

The results of the sensitivity analysis for water electrolysis are provided in Table 5-29, whereby the attributes of power, cooling, reliability and TRL are considered. Mass and volume are not regarded since SPWE is performing worse in these characteristics than SFWE. As it can be seen, power and cooling are roughly equally critical with about 135 % of variation necessary to change the ranking. Reliability as a standalone characteristic has no influence on the MCA ranks, whereas the TRL of SPWE would have to be decreased to 7 to render SFWE the optimal alternative.

Table 5-29: Sensitivity analysis for water electrolysis technologies

Power	Cooling	Reliability	TRL
130 %	140 %	-	-2

5.3.2.3 ESM analysis

The ESM performance of the carbon removal devices for a partially closed loop ECLSS are given in Table 5-30. The ranking of the alternatives almost reversed in comparison to MCA. CAMRAS which was identified as the optimal alternative in the MCA has the highest ESM cost. SAWD outperforms both CAMRAS and 4BMS whose ESM values are almost identical by more than 25 %.

Table 5-30: ESM analysis for carbon dioxide removal devices

Alternative	**ESM [kg]**	**Rank**
CAMRAS	366.3	3
4BMS	366.2	2
SAWD	259.6	1

The outcome of the ESM analysis for CO_2 reduction technologies is given in Table 5-31. Since Sabatier excels in every attribute that affects system ESM, its ESM cost is only about 38 % of that of Bosch.

Table 5-31: ESM analysis for carbon dioxide reduction technologies

Alternative	**ESM [kg]**	**Rank**
Bosch	388.0	2
Sabatier	146.5	1

The ESM ranking of the water electrolysis options SPWE and SFWE is outlined in Table 5-32. Opposing to the MCA ranking, SFWE offers an ESM value that is about half of that of SPWE. This due to the savings in mass and volume if using SFWE, the advantages of SPWE in terms of lower power and cooling requirements cannot compensate for SPWE's shortcomings.

Table 5-32: ESM analysis for water electrolysis technologies

Alternative	**ESM [kg]**	**Rank**
SPWE	410.0	2
SFWE	222.4	1

If one intends to use water electrolysis primarily for O_2 generation, a comparison between the ESM values of SPWE/SFWE and O_2 storage is required. As shown in chapter 5.2.1, high-pressure tanks are the most eligible option in terms of O_2 storage. Their ESM cost for meeting the daily crew needs amounts to 4,237 kg which is more than ten times the ESM of SPWE and almost 20 times that of SFWE. Yet, one must take into account that 0.92 kg/(CM·d) of water are required to generate the amount of O_2 necessary for crew consumption[8], which significantly stresses the WRM subsystem. Assuming CAMRAS is used for CO_2 removal, the amount of wastewater input of the

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[8] Value calculated for O_2 consumption of 0.82 kg/(CM·d)

filtration assembly does not offer the contingencies needed for water electrolysis. Thus, all the water required for O_2 generation must be taken along. In case of the given mission campaign, 3,312 kg of water are needed, which results in an ESM of the corresponding water tank of 3,546 kg. Surprisingly, one can see that the ESM cost of carrying water along for generating O_2 is lower than the ESM of using O_2 storage tank. The reason for this lies in the different types of tanks for O_2 and water respectively. A high-pressure tank is an all-metal pressure vessel that must sustain a considerably higher pressure than a bladder tank containing water. The increased loads on the tank structure are represented in a significantly higher mass. For example, using the mass increase coefficient for O_2 in an HPS as outlined in Table 4-29, 0.364 kg of tank mass are required to store 1 kg of O_2. On the other hand, if one stores 1 kg of water in a bladder tank, merely 0.026 kg of tank mass is necessary.[9]

Figure 5-8 displays the ESM of two ECLSS, which only differentiate in terms of O_2 provision. As it can be seen, the ESM performances of both life support systems are almost identical. The usage of water electrolysis results in a higher initial ESM due to the additionally required hardware which is SFWE in this case. The breakeven point of this trade-off is at about 358 days. After this point in time, the ECLSS employing HPS is performing worse because of the increased structural demands of storing O_2.

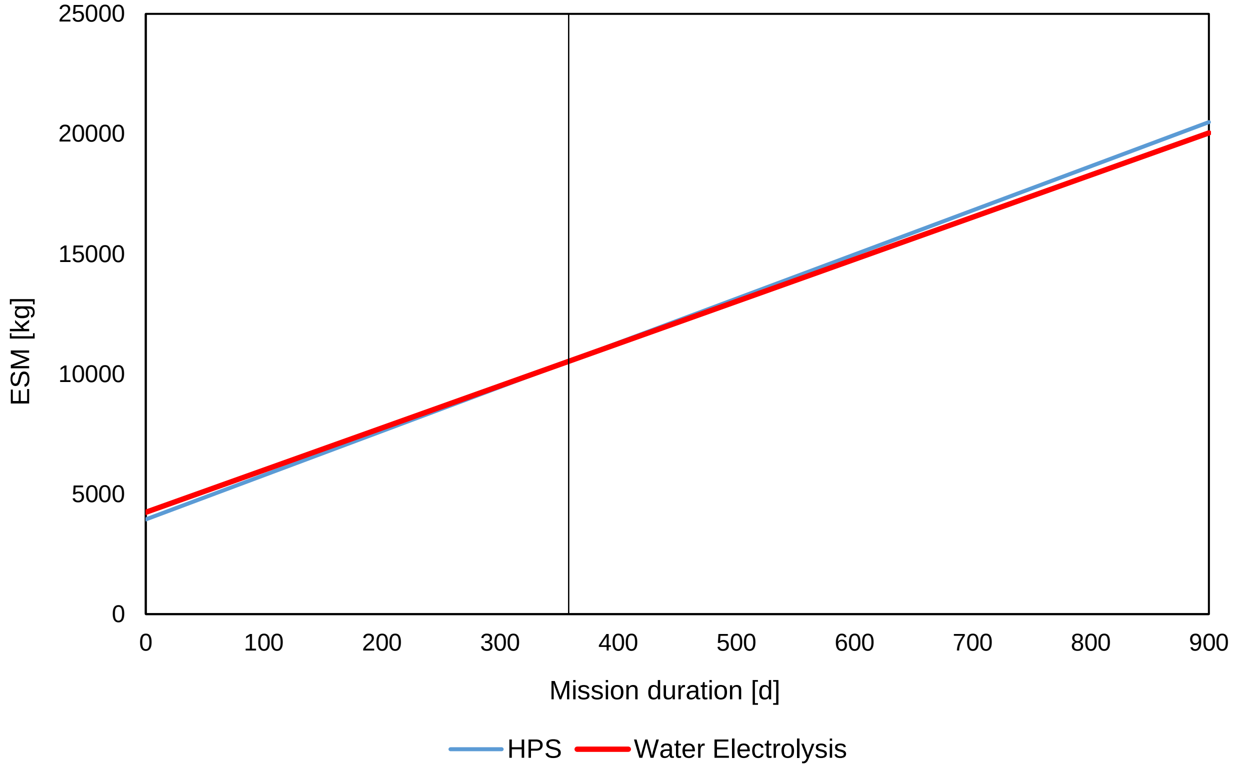

Figure 5-8: HPS vs. SFWE

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[9] Calculated using equation (4.27) for 1 kg/(CM·d) and a mission duration of 900 days and a crew size of four

Before comparing the performance difference between usage of CAMRAS and SAWD, a second trade-off will be conducted which assesses the optimal CO_2 content that is reduced in an SAWD life support system. This is necessary since the water demands of generating the amount of H_2 required by the Sabatier process substantially exceed those of only producing O_2 for crew consumption.

5.3.2.4 Conclusion

The MCA identified CAMRAS as the optimal CO_2 removal technology. However, the corresponding ESM analysis demonstrates that SAWD has by far the lowest ESM. To consider the different outcomes of the analyses and the fact that CAMRAS does not allow for CO_2 reduction, whereas SAWD does, a trade-off will be conducted between both alternatives employing the ECLSS Composition tool. An additional trade-off will be performed to examine how O_2 is provided for the crew. In doing so, it is assessed what O_2 content should be generated and/or stored to achieve an ideally low ESM cost ECLSS design. For this very reason, the Store Oxygen function is included in the table below even though it is classified as belonging to the ACS subsystem. A third trade-off will be performed to investigate whether Bosch's more efficient water production capability in comparison to Sabatier can compensate for its shortcomings as portrayed in the Multi-Criteria and ESM analyses. SFWE is chosen to be the water electrolysis system since its ESM is substantially lower than that of SPWE. The SFWE main disadvantage of lower TRL should be kept in mind nonetheless. Addressing the remaining AR functions, the same technologies as outlined in chapter 5.2.2.4 are used. Table 5-33 lists the hardware choices for the AR subsystem in a partially closed ECLSS.

Table 5-33: AR technologies for a partially closed loop ECLSS

Function	Technology
Remove Gaseous Atmospheric Contaminants	TCCS/CAMRAS/SAWD
Remove Carbon Dioxide	CAMRAS/SAWD
Reduce Carbon Dioxide	Bosch/Sabatier
Regenerate Oxygen	SFWE
Store Oxygen	High-pressure storage
Control Microbes	Microbial Monitoring and Control
Control Airborne Particles	Microbial Monitoring and Control
Remove Airborne Particles	Microbial Monitoring and Control

5.3.3 Temperature and Humidity Control

The alternatives for temperature and humidity control include CAMRAS and CCAA. Similar to the trade-off between both options conducted for an open loop system, CAMRAS is used for THC if it has been chosen for CO_2 removal, whereas CCAA is employed in case any other CO_2 scrubbing device has been selected. The impact of CAMRAS not only on the THC but also on the WRM subsystem is analysed in a trade-off as stated in the previous chapter. The technologies fulfilling the remaining THC functions are the same as for an open loop life support system. Table 5-34 outlines the THC hardware for partially closed ECLSS.

Table 5-34: THC technologies for partially closed loop ECLSS

Function	Technology
Control Atmospheric Temperature	CAMRAS/CCAA
Control Atmospheric Humidity	CAMRAS/CCAA
Remove or Add Moisture	CAMRAS/CCAA
Exchange Atmosphere between Modules	IMV
Accept Thermal Energy	AAA
Release Thermal Energy	AAA
Detect Fire	FDHS
Suppress Fire	FDHS

5.3.4 Water Recovery Management

5.3.4.1 Multi-Criteria Analysis

The alternatives for processing urine in a partially closed loop ECLSS and their performance in the MCA are provided in Table 5-35. It is worth pointing out that VPCAR is not included in this list due to lacking reliability and crew time information concerning this technology. As one can see, TIMES poses the optimal alternative according to the MCA due to significantly lower mass, volume, power and cooling requirements than the other options. The reason why the score difference to the second most viable alternative, VCD, is with 0.13 relatively small considering the low infrastructural demands of TIMES, lies in its low TRL which is 6. AES can be excluded due to it performing worse than VCD, especially in terms of TRL.

Table 5-35: Urine processing technologies for partially closed loop ECLSS

Alternative	Mass [kg]	Volume [m^3]	Power [W]	Cooling [W]	Crew time [h]	Relia-bility	TRL	MCA Score	Rank
AES	218.1	0.28	1279.0	1064.0	165.60	0.953	5	0.16	3
TIMES	41.6	0.07	66.3	54.4	28.80	0.935	6	0.37	1
VCD	1004.1	0.89	1609.8	431.5	10.48	0.932	9	0.24	2

The only available option for filtrating wastewater includes MF. VPCAR could also fulfil this function and could be considered once the missing reliability and crew time data is provided. Table 5-36 depicts the performance of VPCAR, whereby it is important to note the system is scaled according to the input of both wastewater and urine and therefore deviates from the sizing approach of AES, TIMES, VCD, as well as MF since these technologies only process either urine or wastewater and not both.

Table 5-36: Characteristics of VPCAR

Alternative	Mass [kg]	Volume [m^3]	Power [W]	Cooling [W]	Crew time [h]	Relia-bility	TRL
VPCAR	283.1	1.04	1759.6	1571.1	N/A	N/A	6

5.3.4.2 Sensitivity analysis

The outcome of the sensitivity analysis for urine processing technologies is outlined in Table 5-37, whereby all attributes are considered. It is evident that the rank of TIMES is very stable since no attribute variation alone can change the ranking. The attribute values for mass, volume, power and cooling would have to deteriorate by 740 % to achieve a different outcome of the analysis.

Table 5-37: Sensitivity analysis for urine processing technologies

Mass	Volume	Power	Cooling	Maintenance	Reliability	TRL
-	-	-	-	-	-	-

5.3.4.3 ESM analysis

The ESM performance of TIMES and VCD is depicted in Table 5-38. The respective value of AES is not shown since it has been sorted out after the MCA. VCD has significantly higher infrastructural demands than TIMES, which is the reason why the ESM cost of TIMES is about 16 times lower than of that of VCD.

Table 5-38: ESM analysis for urine processing technologies

Alternative	ESM [kg]	Rank
TIMES	74.2	1
VCD	1,164.7	2

The ESM of VPCAR amounts to 512.9 kg. In comparison to that, the ESM cost of MF reaches 1,514.8 kg, demonstrating the potential of VPCAR.

5.3.4.4 Conclusion

Based on the Multi-Criteria, sensitivity and ESM analyses, TIMES is chosen as the urine processing assembly and MF for wastewater filtration. It is also worth mentioning that in case the amount of recovered water does not fulfil the consumption requirements of the crew, tanks for storing the additionally needed water are used. In terms of water storage, there is no trade-off being conducted since the only available option for water storage are bladder tanks. For more information, one may concern chapter 4.10.1.7. Table 5-39 depicts the technology choices for the WRM subsystem. Due to the lack of alternatives, the water quality monitoring assembly of the ISS is used for water quality control.

Table 5-39: WRM technologies for a partially closed loop ECLSS

Function	Technology
Process Wastewater a, b	MF
Process Wastewater c	TIMES
Water System Decontamination	MF/TIMES
Store Water	Bladder tank
Store Wastewater	Bladder tank
Control Water Quality	Water Quality Monitoring

5.3.5 ECLSS Composition

Two trade-offs which are described in this chapter are performed using the ECLSS Composition tool. One trade-off involves evaluating the choice of CO_2 removal device (CAMRAS vs. SAWD) and the second trade-off consists of analysing the water electrolysis system.

5.3.5.1 CAMRAS

Employing CAMRAS for CO_2 removal means that no carbon reduction is available to be reduced. Since the composed ECLSS cannot fulfil the daily water consumption needs of the crew, water tanks providing the remaining water are used. As the trade-off between SFWE and high-pressure O_2 storage demonstrated, using water electrolysis for O_2 provision is more cost efficient than utilizing O_2 tanks. The ESM performance of this ECLSS over the mission duration reaches 20,041 kg. Figure 5-9 shows the ESM distribution over the life support subsystems. One can see that WRM represents the major contributor with 62 % of the total ESM, which is to be expected due to the vastly increased water needs as described in chapter 5.3.2.3. The second most influential subsystem is food and clothing with 21 %. The remaining ESM portions are equally distributed among the subsystems of ACS, THC and AR. The total ESM of the all the ORUs on board the station amounts to 1,175 kg.

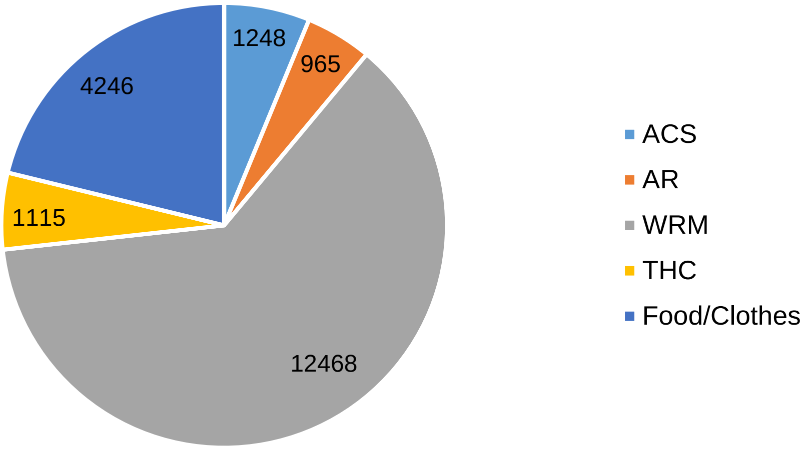

Figure 5-9: CAMRAS (partial) ECLSS subsystems ESM costs

5.3.5.2 SAWD

This ECLSS composition involves utilizing SAWD for CO_2 removal. Since the selection of SAWD allows for CO_2 reduction, the second and third trade-offs are performed in this chapter.

Trade-off concerning ideal carbon dioxide reduction content

The second trade-off addressing the assessment of the optimal O_2 content that is generated by water electrolysis is performed in the following. Within LiSTOT's ECLSS Composition tool, the water electrolysis system is coupled with CO_2 reduction and scaled according to the amount of CO_2 that is meant to be processed. Hence, by varying the CO_2 input of the corresponding reduction system, one can conduct the regarded trade-off. This particular trade study only applies to ECLSS utilizing Sabatier, which is due to the different H_2 demands of Bosch and Sabatier. For example, if one considers reducing all available CO_2 with the Sabatier technology, 1.51 kg/(CM·d) of O_2 are produced by electrolysing the amount of water that is needed to provide enough H_2 for the CO_2 reduction. This O_2 content however is almost double that of the daily crew consumption requirement and thus can only partially be used. Even more detrimental is the fact that 0.85 kg/(CM·d) of water are irreversibly consumed in the reaction, which puts a lot of stress on the WRM subsystem[10]. Hence, the necessity of a trade-off evaluating the optimal amount of water that should be processed for both O_2 and H_2 provision.

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[10] 1.70 kg/(CM·d) are consumed in total, whereby 0.85 kg/(CM·d) can be recovered by using CO_2 reduction. Therefore, the remaining 0.85 kg/(CM·d) are irreversibly lost.

In case one intends to reduce all CO_2 using Bosch, merely 0.75 kg/(CM·d) of O_2 are generated, which means that roughly 0.07 kg/(CM·d) of additional O_2 must be produced to fulfil the daily O_2 consumption needs. Therefore, the trade-off outlined for a Sabatier system does not apply anymore since the optimal design point utilizing Bosch involves the reduction of all available CO_2 and generating the remaining amount of O_2.

Three main cases can be distinguished in the trade study involving the usage of Sabatier:

1. Reducing no CO_2. If no CO_2 is reduced, all necessary O_2 is generated via water electrolysis since the trade-off conducted in chapter 5.3.2.3 demonstrated its superiority over high-pressure O_2 storage for the given mission scenario.
2. Producing enough O_2 to meet the crew consumption requirement and use all the generated H_2 in the Sabatier process. In that case 0.10 kg/(CM·d) of H_2 is generated with which 0.56 kg/(CM·d) of CO_2 can be reduced for the given mission scenario. This content of CO_2 equates to 55 % of the daily produced CO_2.
3. Reducing all daily produced CO_2. In doing so, more O_2 will be generated than what is needed.

LiSTOT allows to utilize excess O_2 for leakage handling, which would consequently reduce the mass of O_2 provided by the ACS by the amount that is required to compensate for leakage. Based on the atmospheric composition of 78 % N_2 and 21 % O_2, 0.042 kg/d of O_2 are necessary to handle leakage. One could conceivably consider to also use excess O_2 for refilling the repressuring tanks. However, in this trade study, no decompression event is included, which means that refilling the storage tanks apart from the losses due to leakage is not necessary. Hence, the amount of O_2 exceeding 0.042 kg/d are vented due to a lack of usage. In order to prevent disregarding the fact that the optimal amount of CO_2 being reduced may lie in between the three cases stated above, the CO_2 input of the reduction system is varied ranging from 0 % to 100 % in steps of 5 %. It is expected that case number two results in the overall lowest system ESM since it yields the highest chemical efficiency because neither excess H_2 nor O_2 is generated that would have to be vented, which thus grants the most efficient usage of water.

Figure 5-10 depicts the ESM of the ECLSS depending on the content of CO_2 that is reduced. The graph shows that the ideal CO_2 content lies at 55 %, which corresponds to case number two and confirms the expectation stated above. From 0 % to 55 %, the ESM decreases linearly, whereas within the range of 55 % to 100 %, a linear increase can be seen. The reason for this behaviour of the total ESM lies in the usage of water or how much additional water needs to be supplied in tanks depending on the reduced CO_2 content to fulfil the water consumption requirement. It is worth pointing out that the amount of O_2 needed for leakage handling is included if 55 % of the daily produced CO_2 is reduced.

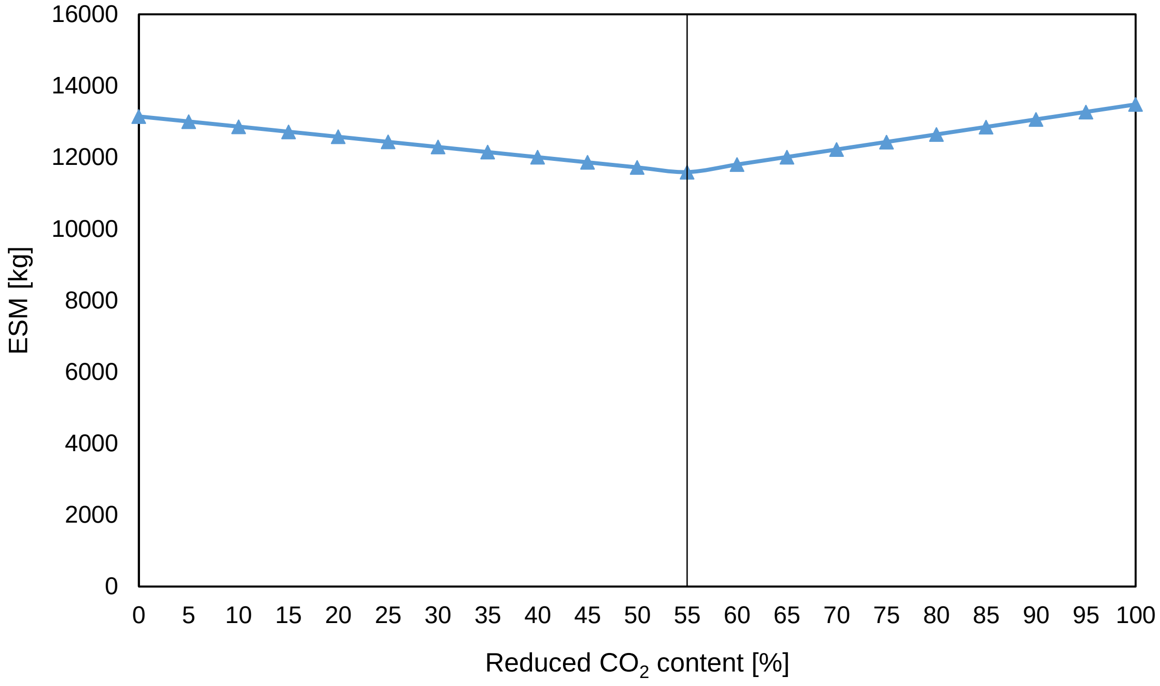

Figure 5-10: ESM demand based on reduced CO_2 content

Figure 5-11 demonstrates that the least amount of additional water (0.39 kg/(CM·d)) is required in case 55 % of the available CO_2 is reduced. The highest additional water mass (0.85 kg/(CM·d)) is demanded if no CO_2 is reduced, which is consequential since no water can be recovered by the CO_2 reduction process of Sabatier.

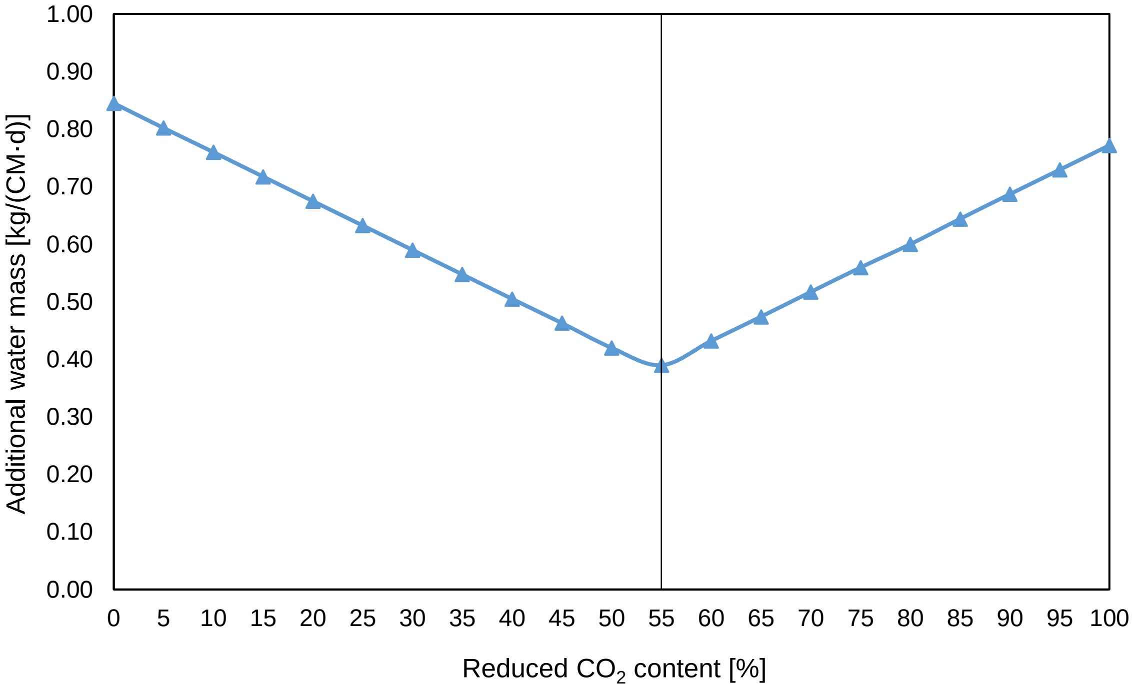

Figure 5-11: Additional water demand based on reduced CO_2 content

The ESM performances of the three cases outlined above are provided in Figure 5-12. It is evident that the case involving not reducing any CO_2 presents the lowest ESM until the breakeven point of 84 days after which case number two becomes the most eligible option. One can also see that reducing all CO_2 poses the highest ESM cost design throughout the given mission scenario. Yet, it is worth noting that the slopes of cases one and three suggests that reducing all CO_2 would outperform no CO_2 reduction at 2,345 days.

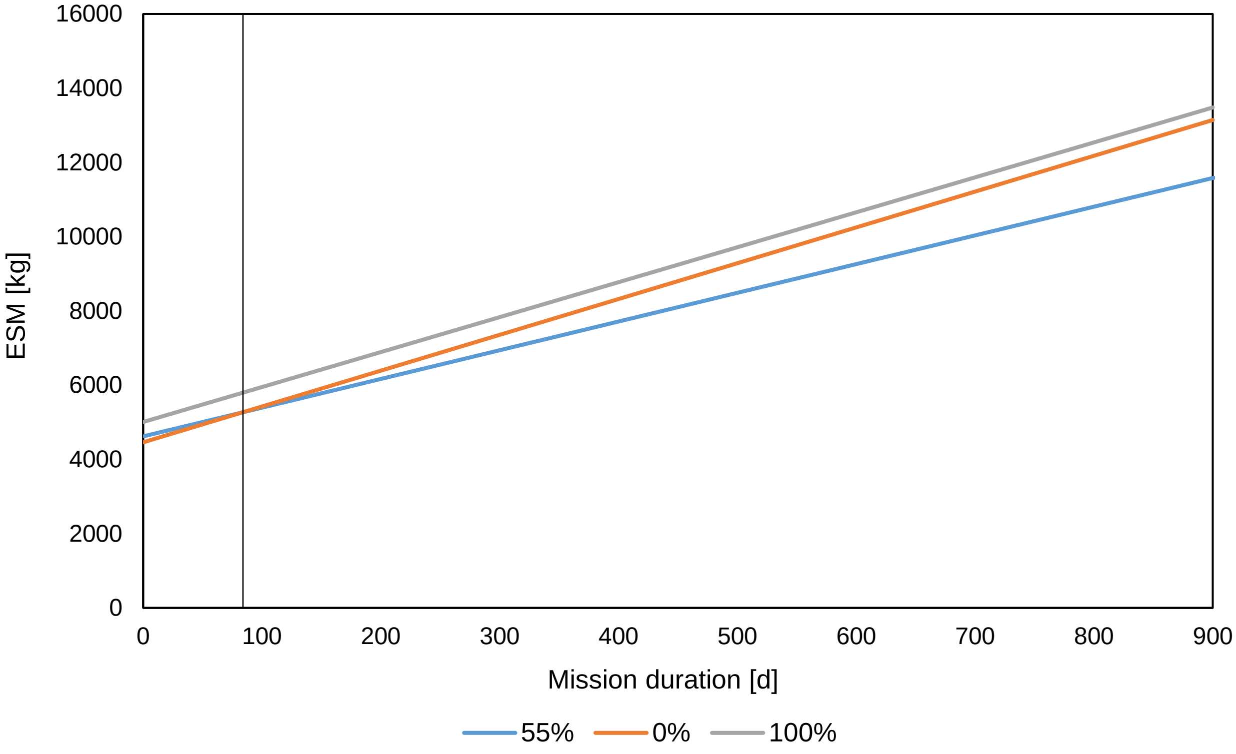

Figure 5-12: ESM of Sabatier systems based on reduced CO_2 content

Considering the outcome of this trade-off, the optimal ECLSS using SAWD and Sabatier involves reducing the amount of CO_2 necessary to generate the O_2 needed to fulfil the daily O_2 crew consumption requirement. Yet, one must note that for this particular ECLSS design 0.39 kg/(CM·d) of water must be provided in storage tanks to meet the daily water consumption requirements. The ESM of the maintenance approach amounts to 1,224 kg.

Trade-off between Bosch and Sabatier

In the previous trade-off, the optimal design points of both Sabatier and Bosch have been determined:

Sabatier is designed to reduce roughly 55 % of all available CO_2, whereas Bosch processes the entire CO_2 content, which necessitates the generation of 0.065 kg/(CM·d) of additional O_2 for which 0.073 kg/(CM·d) of water is required. Figure 5-13 depicts the comparison of the respective ESM costs over the given mission duration.

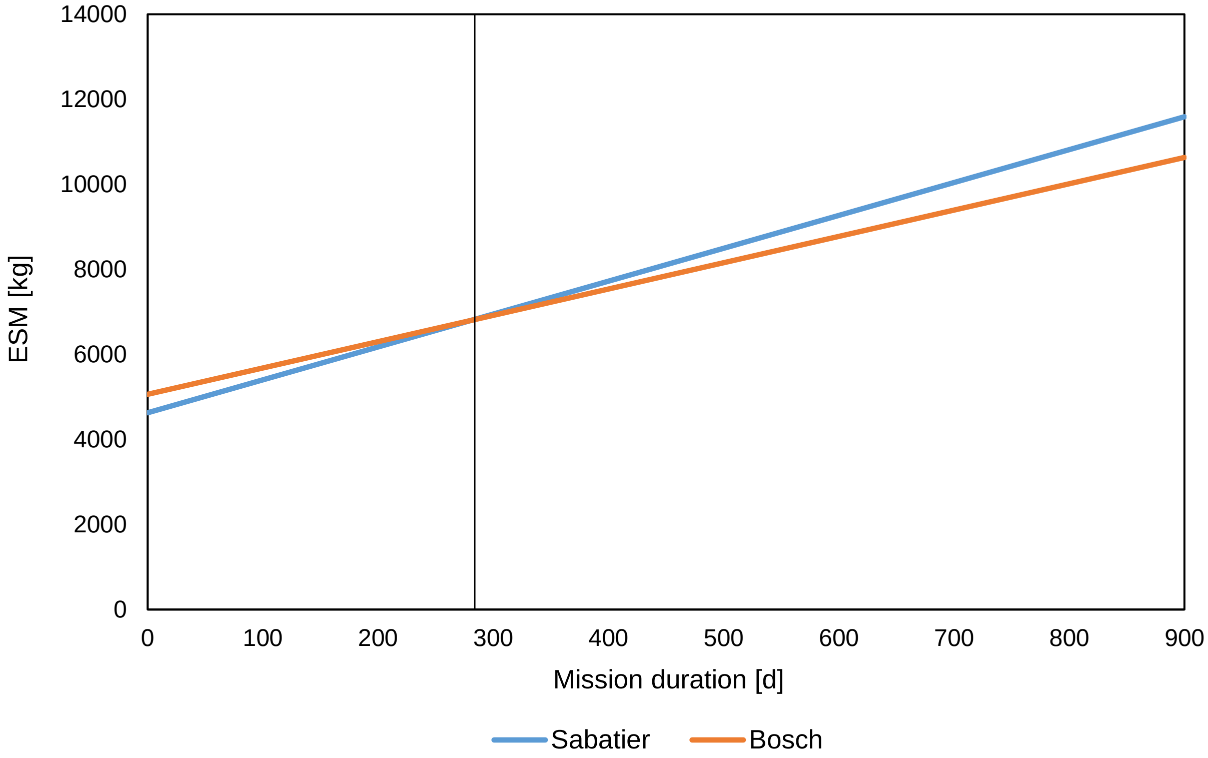

Figure 5-13: ESM performances of Sabatier and Bosch

It is evident that with a total ESM of 10,632 kg, Bosch poses an option with which one can save up to 957 kg of ESM compared to the usage of Sabatier. Despite having the higher initial infrastructural demands, Bosch outperforms Sabatier starting at 284 days into the mission. The higher water needs can no longer be compensated for by the lower mass, volume, power and cooling requirements of the Sabatier system. Thus, it can be concluded that the ECLSS utilizing Bosch presents the more eligible life support system design for the given mission campaign. The ESM cost of all the ORUs and spares amounts to 1,368 kg, which is 144 kg heavier than the Sabatier based ECLSS because of the higher mass and volume of the Bosch system.

5.3.5.3 Conclusion

Comparing the ESM cost of the CAMRAS design described in chapter 5.3.5.1 with that of the SAWD based ECLSS using Bosch for CO_2 reduction, the latter life support system design presents the more eligible option. Figure 5-14 depicts that employing CAMRAS is only superior until both ECLSS break even at 74 days. Due to its higher degree of water loop closure, the SAWD life support system outperforms the CAMRAS based design after this point in time.

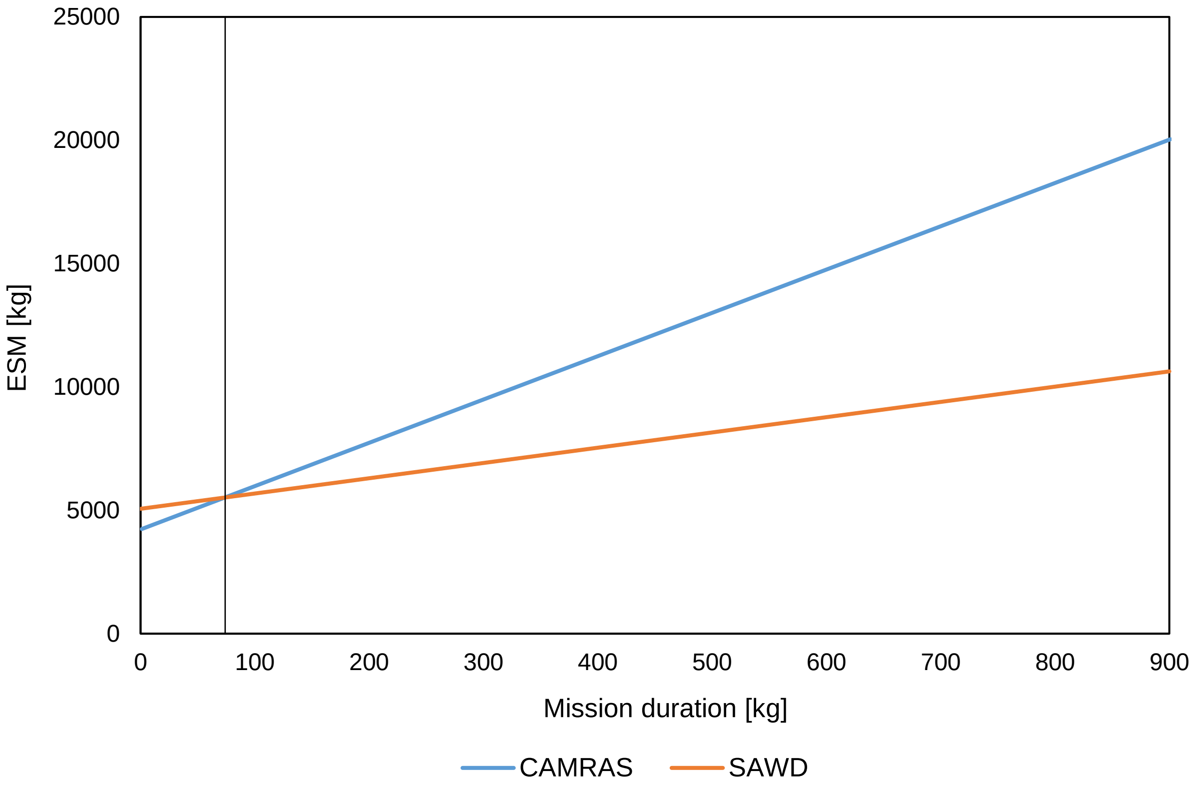

Figure 5-14: ESM performances of CAMRAS and SAWD based ECLSS

Its ESM composition is provided in Figure 5-15. One can see that in contrast to the life support systems analysed before, the majority of 41 % of the ESM is contributed by food and clothing. Moreover, the portion that is induced by the AR subsystem represents with 13 % the third highest ESM cost after WRM with 23 %. The increase in ESM of the AR subsystem can be attributed to the inclusion of CO_2 reduction hardware. ACS and THC perform about equally with 12 % and 11 % of the total ESM, respectively.

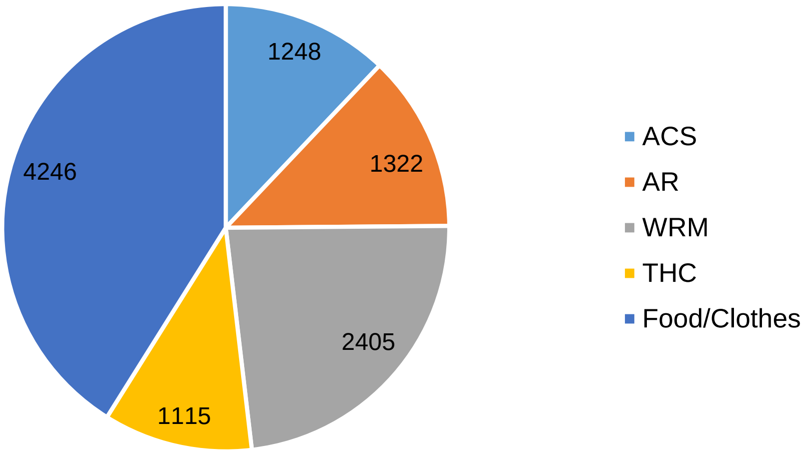

Figure 5-15: SAWD (partial) ECLSS subsystems ESM cost

5.4 Trade study for closed loop ECLSS

The results below depict the outcome of the Multi-Criteria, sensitivity and ESM analyses applied to the subsystem functions outlined in chapter 4.2. Since a closed loop ECLSS is analysed, regenerable technologies are considered. Thus, storage tanks for consumables such as O_2 or water are excluded from the analysis, for example. The selected life support technologies are then examined in the ECLSS composition tool to determine the overall ESM of the ECLSS.

5.4.1 Atmosphere Control and Supply

As mentioned in chapter 5.2.1.4, the ACS subsystem for repressuring and leakage handling outlined for an open loop ECLSS is also used for any closed loop life support system.

5.4.2 Atmosphere Revitalization

5.4.2.1 Multi-Criteria Analysis

The alternatives that fulfil the CO_2 removal function for a closed loop ECLSS are provided in Table 5-40. CAMRAS is no longer considered due to it being a non-regenerable technology. EDC achieves the highest rank in the MCA because of its superior performance in terms of mass, volume, power and cooling in comparison to the other alternatives. However, EDC's reliability is roughly 14 % worse than that of 4BMS and SAWD. Furthermore, the TRL of EDC just barely matches the respective exclusion criterion. Since the decision weights are defined to put equal importance on all attributes, the low reliability and TRL are compensated for by the remaining characteristics. In order to receive a different ranking of the MCA, the decision weights of mass, volume, power and cooling would have to be half of those of reliability and TRL. EDC requires O_2 and H_2 as input to remove CO_2 and produces water as an additional output to the scrubbed CO_2. This water can then be reintroduced to the water loop of the ECLSS, which therefore means that ideally (neglecting any water losses), no additional water needs to be brought along if EDC is used. Thus, EDC only impacts the scaling of the water electrolysis system due to increased loads. This circumstance is not represented in the MCA but must be kept in mind.

Table 5-40: Carbon dioxide removal technologies for closed loop ECLSS

Alternative	Mass [kg]	Volume [m³]	Power [W]	Cooling [W]	Crew time [h]	Relia-bility	TRL	MCA Score	Rank
EDC	154.1	0.07	54.5	348.6	0	0.812	6	0.46	1
4BMS	255.4	0.46	829.0	740.1	4.47	0.934	9	0.24	3
SAWD	190.8	0.29	533.0	475.9	0	0.945	8	0.30	2

The trade-off between Sabatier and Bosch in chapter 5.3.5.2 showed that no matter the CO_2 content that is being reduced, Sabatier requires additional water that must be stored in tanks. Due to the restrictions of the closed loop ECLSS, Sabatier can therefore be sorted out. Bosch requires 0.073 kg/(CM·d) of water to generate the remaining amount of O_2 to meet the daily O_2 consumption requirement. However, this amount of water is incorporated in the margin of the ECLSS's water balance. This margin amounts to 0.077 kg/(CM·d)[11] and is obtained by subtracting the total amount of water required by a crew member (10.02 kg/(CM·d)) from the amount of water that can be provided/recovered by the WRM subsystem (10.09 kg/(CM·d)). Water losses including fecal water, blackwater and the losses due to wastewater filtration are thereby accounted for. Considering that the difference between the water margin and the water demand of Bosch equates to only 4 g/(CM·d), the usage of Bosch just barely avoids having to rely on water storage, which would contradict the given restrictions. Thus, Bosch fulfils the requirements of a closed loop ECLSS, however it must be pointed out that any additional water losses will result in an imbalance of the water flows. For example, if the efficiency of TIMES is reduced from 91 % to merely 90 %, the available water margin is already exceeded. Despite the lack of contingency, Bosch is selected for CO_2 reduction since the other alternative is even less suitable.

The alternatives for water electrolysis are identical to those discussed for partially closed ECLSS. Hence, SFWE is employed for water electrolysis.

5.4.2.2 Sensitivity analysis

Since the MCA score gap between EDC and SAWD is with 0.16 relatively high when compared to the difference in score between 4BMS and SAWD, it is expected that the ranking of the MCA is robust. As depicted in Table 5-41, the sensitivity analysis shows that the rank of EDC is stable. Each attribute except for crew time, reliability and TRL have been considered in the analysis. Only mass and volume as standalone characteristics have an influence on the outcome, whereby EDC's mass would have to be increased by 60 % and EDC's volume value by 415 % to achieve a lower rank for the technology. Consequently, one can conclude that the outcome of the MCA is robust.

Table 5-41: Sensitivity analysis for carbon dioxide removal devices

Mass	Volume	Power	Cooling
60 %	415 %	-	-

Considering the fact that EDC achieves the highest rank despite its significantly lower reliability and TRL compared to the other alternatives, it is interesting to examine how the ratio r_w of decision weights concerning mass, volume, power, cooling and crew time summarized as $w_{m,v,p,c,ct}$ to the decision weights of reliability and TRL summarized as $w_{r,TRL}$ would have to be adjusted to receive a different MCA ranking. In performing this analysis, $w_{r,TRL}$ is kept at the value of 1, whereas $w_{m,v,p,c,ct}$ is lowered from 1 to 0 in steps of 0.05.

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[11] Margin computed under the assumption that TIMES and MF are used.

With this assumption, r_w is simplified as:

$$r_w = \frac{w_{m,v,p,c,ct}}{w_{r,TRL}} \tag{5.1}$$

The resulting MCA scores of EDC, 4BMS and SAWD over the described decision weight variation are given in Figure 5-16.

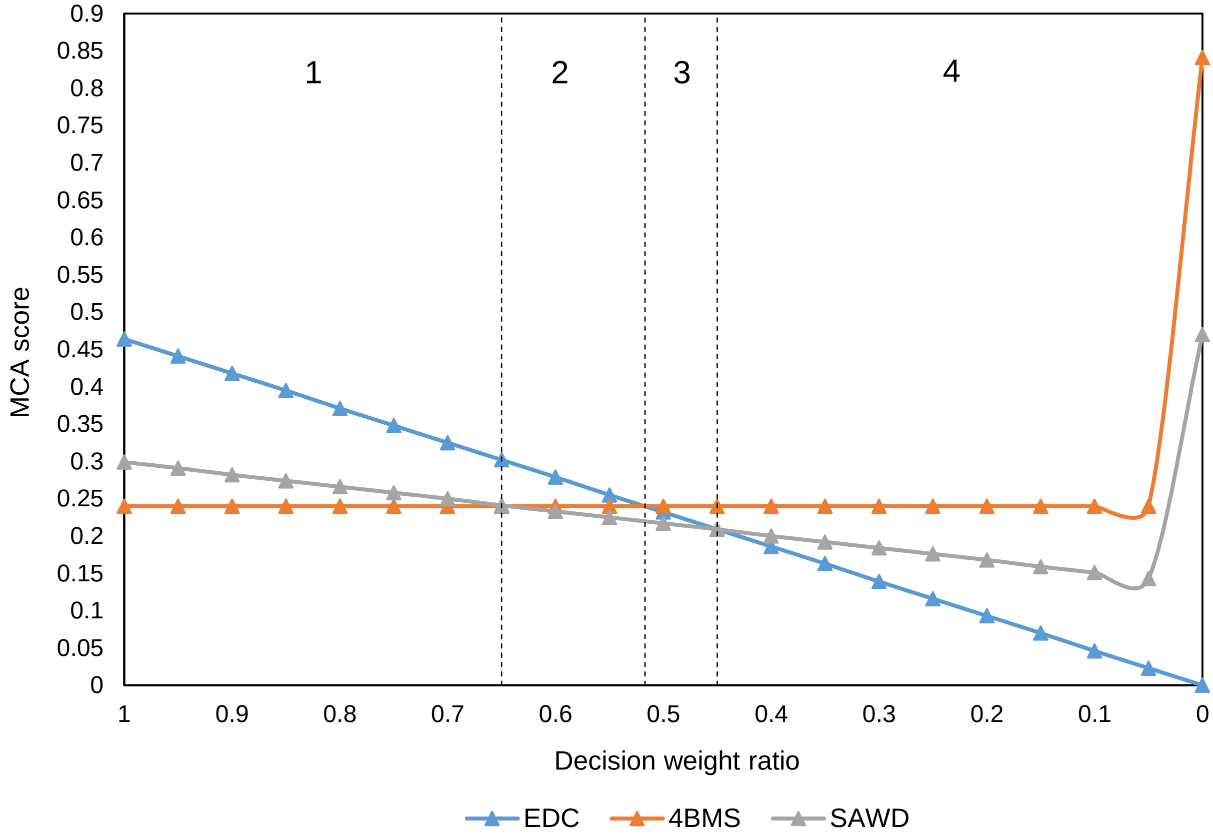

Figure 5-16: MCA scores over decision weight variation

The EDC slope shows the steepest decline of MCA score, which is to be expected since the attributes in which EDC outperforms the other alternatives are continuously lowered in weighting. 4BMS demonstrates a score that is independent from the variation of decision. This can be explained by considering the merit functions outlined in chapter 4.7.1 and the fact that 4BMS has the highest mass, volume, power, cooling and crew time demands of all systems regarded in this analysis. Therefore, the individual scores for mass, volume, power, cooling and crew time are and remain 0 and are thus not affected by the changes of the decision weights. Similar to the EDC slope, the SAWD gradient also displays a linear decrease which is however not as steep as the one of EDC. The reason for this behaviour lies in the circumstance that SAWD achieves in contrast to EDC a constant score for both reliability and TRL throughout the analysis. As it can be seen, the diagram is subdivided into four sections demonstrating the changing ranks of the alternatives over the variation of decision weights, which are displayed in Table 5-42 along with r_w at which the change occurs.

Table 5-42: Ranking over variation of decision weights

	Rank 1	Rank 3	Rank 3	r_w
Section 1	EDC	SAWD	4BMS	-
Section 2	EDC	4BMS	SAWD	0.65
Section 3	4BMS	EDC	SAWD	0.52
Section 4	4BMS	SAWD	EDC	0.45

The first change in rank happens at a r_w of 0.65, which means that if the attributes of reliability and TRL are valued 65 % higher than the other characteristics, a different outcome of the MCA is generated. One may wonder why the 4BMS's score is more favourable than that of SAWD and EDC in the sections 3 and 4 considering that 4BMS only offers the highest TRL and a high reliability but is severely outperformed in the remaining attributes. This characteristic is induced by the varying criticality of the attributes. In the given MCA, TRL is the overall most critical attribute, which can be shown by using LiSTOT's Check Attribute Criticality tool[12]. Figure 5-17 demonstrates that TRL has with a relative change of 26 % a several times higher criticality then mass, volume, power, cooling and crew time since the lower the relative change, the more critical the regarded attribute is. Only reliability possesses a comparable criticality with a relative change of 31 %. Due to the high criticalities of TRL and reliability, the shortcomings of 4BMS are compensated for once the decision weights of mass, volume, power, cooling and crew time have been lowered to 0.52.

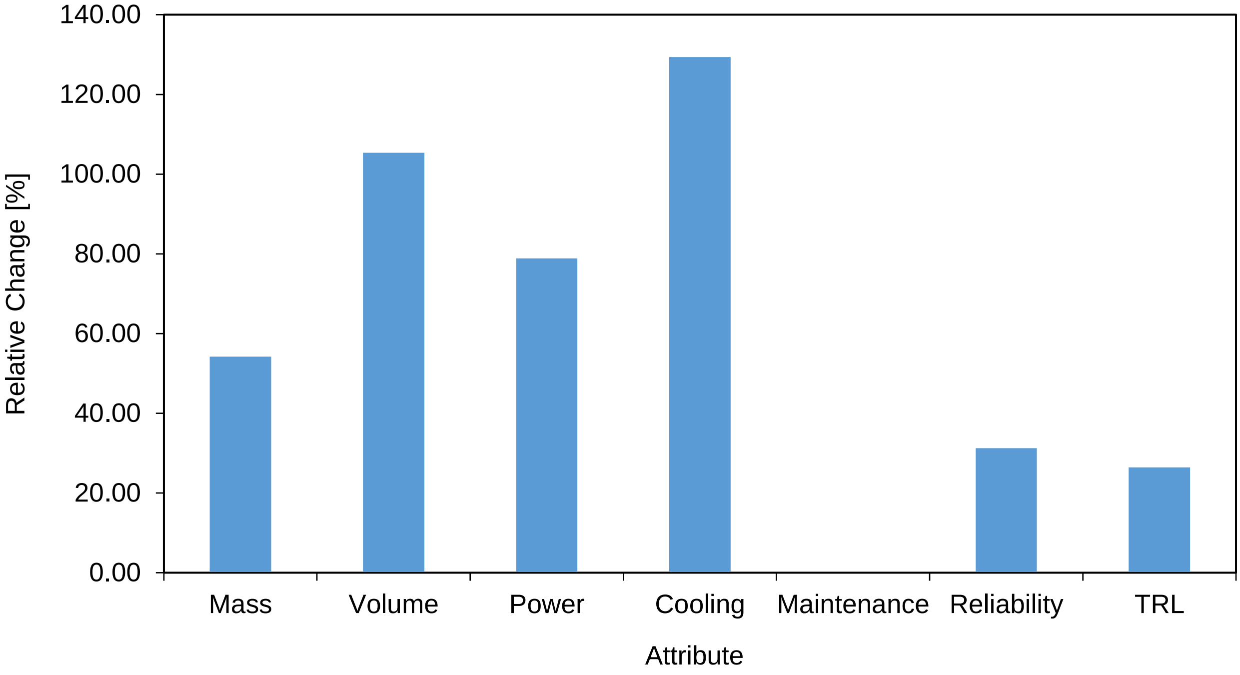

Figure 5-17: Attribute criticalities

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[12] Attribute criticalities have been calculated for all decision weights set to 1 for the entire given MCA and not for EDC specifically. For information about LiSTOT's Attribute Criticality tool, one may refer to chapter 4.9.1.1.

One must also keep in mind that the confidence factors which are meant to account for uncertainties in the design data of technologies as described in chapter have a considerable impact on the criticality of attributes and MCA scores. The confidence factors of 4BMS and SAWD concerning TRL and reliability are given in Table 5-43.

Table 5-43: Confidence factors of 4BMS and SAWD

	4BMS	**SAWD**
$f_{CF,rel}$	0.75	0.5
$f_{CF,TRL}$	1	0.75

As it can be seen, the confidence factors of 4BMS are higher than those of SAWD, which leads to relatively higher scores.

The arguably most distinct characteristic of Figure 5-16 are the jumps in MCA scores of 4BMS and SAWD occurring when $w_{m,v,p,c,ct}$ is set to 0. This behaviour is caused by the fact that the overall MCA scores of an alternative are normalized by the number of attributes considered within the analysis as mentioned in chapter 4.7.1. Once all the decision weights for mass, volume, power, cooling and crew time are 0, the number of attributes decreases from seven to two, which leads to the drastic increase of the overall MCA scores as shown in Figure 5-16.

5.4.2.3 ESM analysis

Since EDC outperforms any of the other alternatives in every attribute affecting the ESM, one can expect that EDC also achieves the highest rank in the ESM analysis. This expectation is met, which can be seen in Table 5-44.

Table 5-44: ESM analysis for carbon reduction technologies

Alternative	**ESM [kg]**	**Rank**
EDC	179.3	1
4BMS	366.2	3
SAWD	259.6	2

5.4.2.4 Conclusion

Both the MCA and ESM analysis identified EDC as the optimal CO_2 removal technology. Due to its vastly superior performance to the second-best alternative, no other CO_2 removal device is considered. The assemblies that fulfil the remaining AR functions are the same as for the partially closed loop ECLSS and are listed in Table 5-45.

Table 5-45: AR technologies for a closed loop ECLSS

Function	Technology
Remove Gaseous Atmospheric Contaminants	TCCS/EDC
Remove Carbon Dioxide	EDC
Reduce Carbon Dioxide	Bosch
Regenerate Oxygen	SFWE
Control Microbes	Microbial Monitoring and Control
Control Airborne Particles	Microbial Monitoring and Control
Remove Airborne Particles	Microbial Monitoring and Control

5.4.3 Temperature and Humidity Control

CCAA is employed for temperature and humidity control since CAMRAS cannot be selected in an open loop ECLSS. The other THC technologies are identical to those for open and partially closed loop life support systems as shown in Table 5-46.

Table 5-46: THC technologies for closed loop ECLSS

Function	Technology
Control Atmospheric Temperature	CCAA
Control Atmospheric Humidity	CCAA
Remove or Add Moisture	CCAA
Exchange Atmosphere between Modules	IMV
Accept Thermal Energy	AAA
Release Thermal Energy	AAA
Detect Fire	FDHS
Suppress Fire	FDHS

5.4.4 Water Recovery Management

5.4.4.1 Multi-Criteria Analysis

The alternatives for urine processing in a closed loop ECLSS and their MCA performance are provided in Table 5-47. As one can see, in comparison to partially closed loop life support systems, AES has been sorted out since it is classified as being non-regenerable. The other alternatives remain the same. Thus, TIMES and VCD are still available options, whereby TIMES poses the vastly more eligible technology. The only attributes in which VCD outperforms TIMES include crew time and TRL.

Table 5-47: Urine processing technologies for closed loop ECLSS

Alternative	Mass [kg]	Volume [m^3]	Power [W]	Cooling [W]	Crew time [h]	Relia-bility	TRL	MCA Score	Rank
TIMES	41.6	0.07	66.3	54.4	28.80	0.935	6	0.37	1
VCD	1004.1	0.89	1609.8	431.5	10.48	0.932	9	0.24	2

5.4.4.2 Conclusion

Since TIMES and VCD have been examined in the sensitivity and ESM analysis for a partially closed ECLSS (see chapter 5.3.4), it can be concluded that TIMES is the optimal technology for urine processing. Especially its lower infrastructural demands result in a vastly decreased ESM compared to VCD. The other WRM technologies are identical to those in a partially closed loop ECLSS, which can be seen in Table 5-48.

Table 5-48: WRM technologies for closed loop ECLSS

Function	Technology
Process Wastewater a, b	MF
Process Wastewater c	TIMES
Water System Decontamination	MF/TIMES
Store Wastewater	Bladder tank
Control Water Quality	Water Quality Monitoring

5.4.5 ECLSS Composition

No technology-based trade-off is conducted for closed loop systems since the respective trade studies have already been performed in the background of a partially closed ECLSS. It is evident that apart from the chosen CO_2 removal device, its structure is similar to that of the best performing partially closed loop system. The ECLSS's ESM performance reaches 10,799 kg for the given mission duration.

The total system ESM is distributed among the ECLSS subsystems as depicted in Figure 5-18. As one would expect, the contributions to the overall ESM of the ECLSS are identical to those which have been examined for the corresponding partially closed loop life support system. The only difference between the two ECLSS is manifested in the ESM of AR and food and clothes being 1 % lower and consequently the ESM of ACS being 2 % higher in comparison to the life support system outlined in chapter 5.3.5.2. The ESM of the maintenance amounts to 1,412 kg.

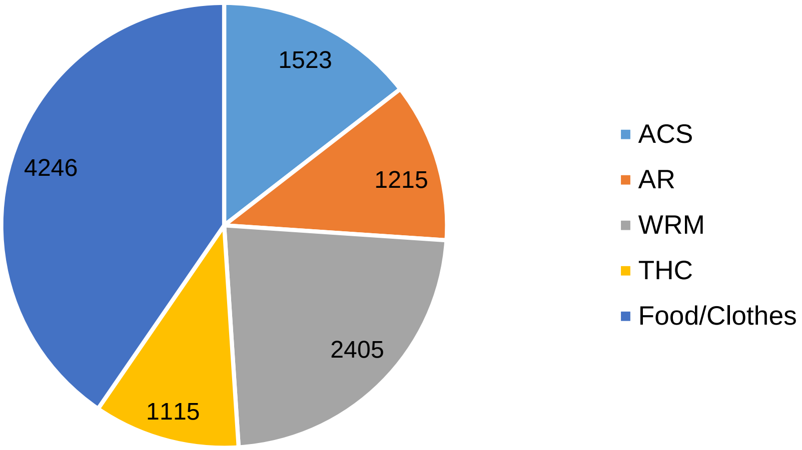

Figure 5-18: EDC ECLSS subsystems ESM cost

5.5 Open vs. Partially closed vs. Closed loop ECLSS

The ESM performances of the best performing open, partially closed and closed loop ECLSS are displayed in Figure 5-19. One can see that the entirely non-regenerable consumable driven life support system possesses the lowest ESM cost until its ESM exceeds that of the partially closed loop ECLSS at 64 days. At 79 days, the open loop life support system is outperformed by the closed loop ECLSS. One would expect that the closed loop life support system presented the most eligible option for the given mission scenario considering the outcome of the MCA determining the superiority of EDC over SAWD. Yet, it can be seen the partially closed loop has an ESM that is by 168 kg lower in comparison to the closed loop ECLSS at 900 days. This deviation in ESM is caused by the H_2 and O_2 demand of the EDC device – a demand that necessitates a rescaling of the water electrolysis system. Using EDC, SFWE must process almost double the amount of water that is electrolyzed if SAWD is employed, which means that the HEU of the water electrolysis assembly rises from four to eight for the closed loop ECLSS. The consequence thereof is an increase in ESM of SFWE of 275 kg which compensates for the infrastructural advantages of utilizing EDC and renders the SAWD based ECLSS design the optimal life support system for the set mission campaign. It also worth noting that due to the different resupply needs[13] of the CO_2 removal technologies, the gradients of the EDC and SAWD based life support systems suggest an intersection at 25,218 days after which the closed loop ECLSS is more eligible.

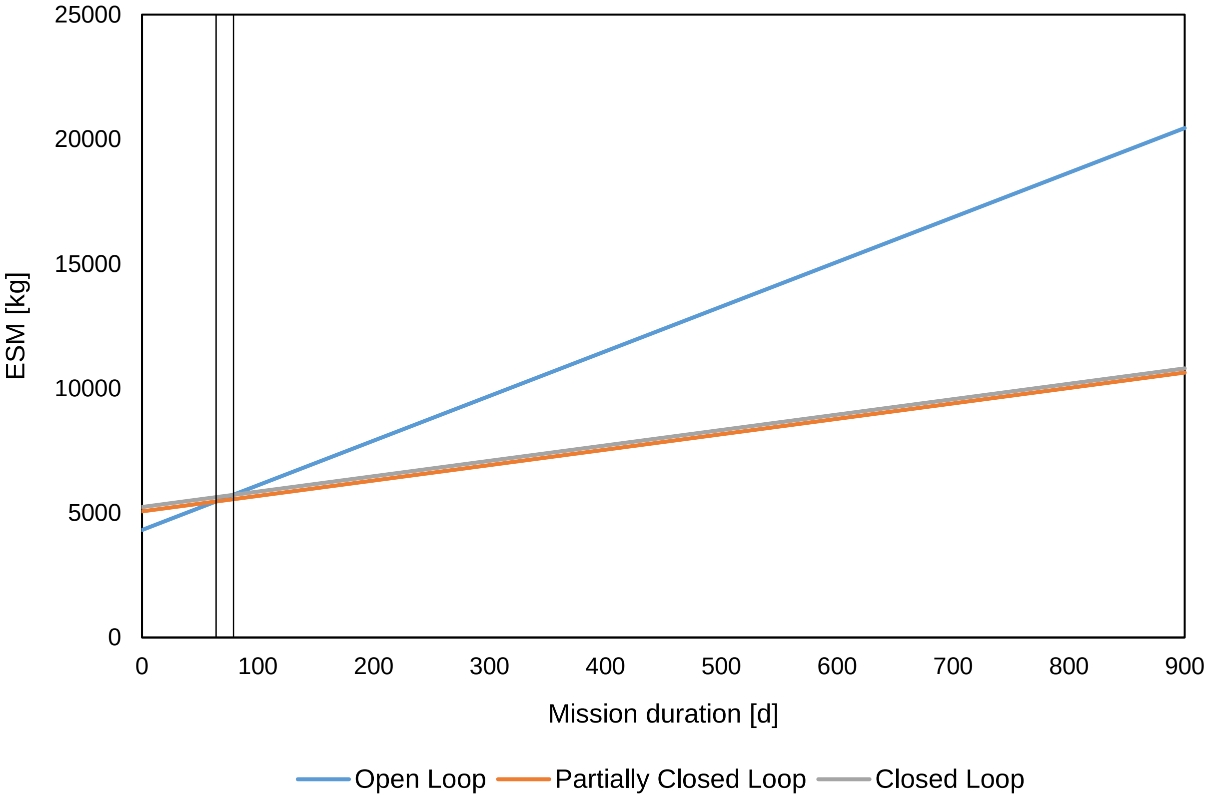

Figure 5-19: Open vs. Partially closed vs. Closed loop ECLSS

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[13] Resupply of EDC amounts to 0.012 kg/d, resupply of SAWD amounts to 0.019 kg/d

5.6 Performance of hybrid ECLSS and BLSS

The ESM performances of a hybrid ECLSS and BLSS are provided in Figure 5-20 and are compared to the partially closed loop life support system designed in chapter 5.3.5.2. The hybrid ECLSS employs and an algal photobioreactor for air revitalization which involves the functions of CO_2 removal and reduction as well as O_2 generation. It is furthermore important to note that TIMES is utilized for urine processing. The ESM performance of the BLSS is given under the assumption that 20 m^2 of growth area per crew member are enough to close the food loop of the life support system. For the given mission duration, the ESM cost of the hybrid ECLSS amounts to 17,936 kg, whereas the BLSS has an ESM of 37,900 kg and therefore more than twice the ESM cost of the hybrid life support system. Nonetheless, since the hybrid life support system requires additional water and nutrients and is thus consumable driven, the breakeven point of hybrid ECLSS and BLSS lies at 2,845 days. One can conclude that for the given mission campaign, neither the hybrid life support system nor the BLSS outperform the partially closed ECLSS. It is worth mentioning that at 9,821 days, the BLSS becomes the most eligible option.

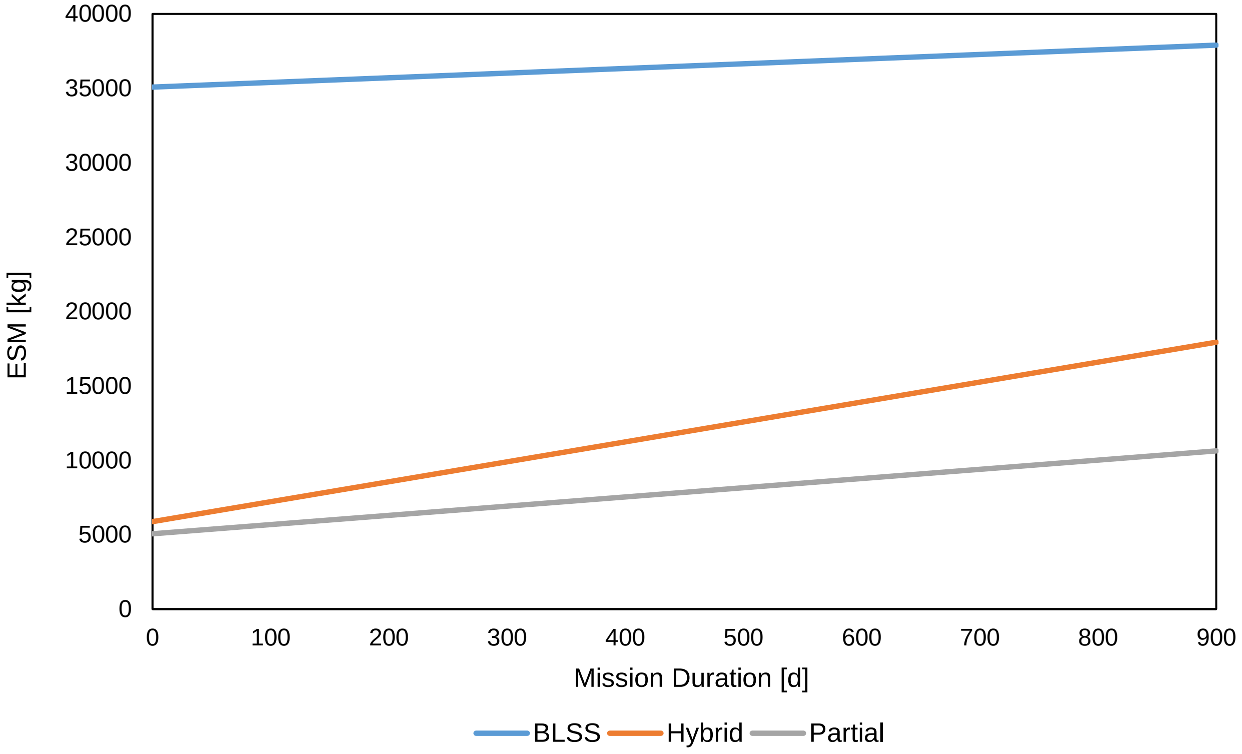

Figure 5-20: ESM performance of hybrid ECLSS and BLSS

6 Final design of the ECLSS of the Gateway

The final design of the ECLSS of the Gateway is depicted in this chapter. One may note that the ESM specifications of the technologies described in the following may deviate from the values provided in chapter 5.3.5.2. The reason for this lies in the consideration of the resupply and spare part masses and volumes which are included in the following ESM costs of the respective technology.

6.1.1 Final design of the ACS subsystem

The general layout of the ACS subsystem is similar to that of the ISS. Due to safety concerns and stowage considerations, it is advised to mount the O_2 and N_2 tanks for repressurization and leakage handling outside the pressurized compartments. The ACS technologies have been identified throughout the trade study conducted in chapter 5.2.1 and listed in Table 6-1.

Table 6-1: Final ACS technologies

	Dry mass [kg]	**Spares and resupply [kg]**	**Volume [m^3]**	**Power [W]**	**Cooling [W]**	**ESM [kg]**
PCA	27.10	16.80	0.05	113	0	54.73
NIA	7.50	4.65	0.01	5.50	0	13.52
MPEV	1.20	1.20	0.001	0	0	2.60
Oxygen Tank	34.21	80.75	0.12	9	9	120.97
Nitrogen Tank	145.61	278.88	0.28	9	9	435.17

The specifications of PCA, NIA and MPEV are given for a single assembly or component, whereas for the given station architecture, one PCA per module is assumed by default. Therefore, seven PCA are installed on the Gateway. A high number since three PCA are equipped on the ISS. The number of PCA is thus reduced to one because the pressurized volume of 125 m^3 is lower by a factor of six than that of the ISS. Consequently, the amount of MPEV is decreased to eight and the that of the NIA to three under the assumption stated in chapter 4.10.2.1.

The resupply and spares of the tankage includes the mass of O_2 and N_2 respectively as well as one spare valve per tank since the valve represents the component with the lowest reliability in a tank assembly.

6.1.2 Final design of the THC subsystem

The final design of the THC subsystem incorporates CCAA for temperature and humidity control since it could be shown that CAMRAS is inferior to SAWD due to its higher water demands. CCAA is operated similarly to how it is employed on the ISS. The CHX removes excess humidity and moisture from the cabin air and directs it to the WRM subsystem where it is filtered before usage. For more details on the CCAA, one may refer to chapter 4.10.2.2. The AAA provides air cooling and the air flow required by the FDS in the racks. The IMV exchanges atmosphere between the modules to ensure the even distribution of O_2 and the removal of CO_2 and other trace contaminants from modules that may not be equipped with a CO_2 removal system. The default scaling approach that has been used for AAA is the same as for PCA, which is why a redesign of the THC subsystem is appropriate. Six AAA are installed on the ISS, therefore one AAA is used for the Gateway due to the same reasoning which was used in rescaling the PCA. The final THC technologies are given in Table 6-2, whereby it must be noted that the specifications are provided for one assembly respectively. Using the default scaling approach, five IMV are installed in between the modules. Moreover, the FDS of the Gateway consists of seven FDA and four FE.

Table 6-2: Final THC technologies

	System mass [kg]	**Spares and resupply [kg]**	**Volume [m³]**	**Power [W]**	**Cooling [W]**	**ESM [kg]**
CCAA	127.43	79.01	0.44	579	517	295.90
AAA	12.52	7.76	0.03	175	175	42.56
IMV	14.30	8.87	0.019	61	0	28.67
FDS	8.30	0.93	0.04	1.48	1.48	11.07

6.1.3 Final design of the AR subsystem

The final AR subsystem design includes SAWD coupled with a CHX for CO_2 removal which is then directed to the Bosch reactor that reduces the CO_2 into carbon and water. The H_2 required for CO_2 reduction as well as all the O_2 needed to meet the daily crew consumption requirement is produced via the SFWE system by electrolyzing water. Furthermore, TCCS is used to remove other trace contaminants and MMC for controlling microbes.

SAWD, Bosch and SFWE are rescaled automatically by using the ECLSS Composition tool as described in chapter 4.10.2.8. The default scaling approach for TCCS is appropriate, therefore one TCCS assembly is installed on the Gateway. However, in case of MMC, the default scaling leads to seven control units being built in the ECLSS, which exceeds the amount of the corresponding system on the ISS despite a considerably smaller pressurized volume. Thus, the number of MMC assemblies is adapted to that of the ISS and set to two units. The final AR systems are provided in Table 6-3.

Table 6-3: Final AR technologies

	System mass [kg]	**Spares and resupply [kg]**	**Volume [m^3]**	**Power [W]**	**Cooling [W]**	**ESM [kg]**
SAWD	173.41	156.13	0.29	533	476	414.88
CHX	49.71	5.40	0.39	0	682	63.73
Bosch	242.58	188.68	0.31	1183	325	569.88
SFWE	116.31	68.62	0.14	1645	39	300.89
TCCS	79.83	108.92	0.27	180	130	228.67
MMC	50.00	31.00	0.27	25	25	92.75

The total daily CO_2 production is given in Figure 6-1. The peaks are allocated at the times at which a crew member physically exercises, which is why four peaks can be identified over the course of a day. The CO_2 production remains otherwise constant throughout the workday and, at a lower level, at night.

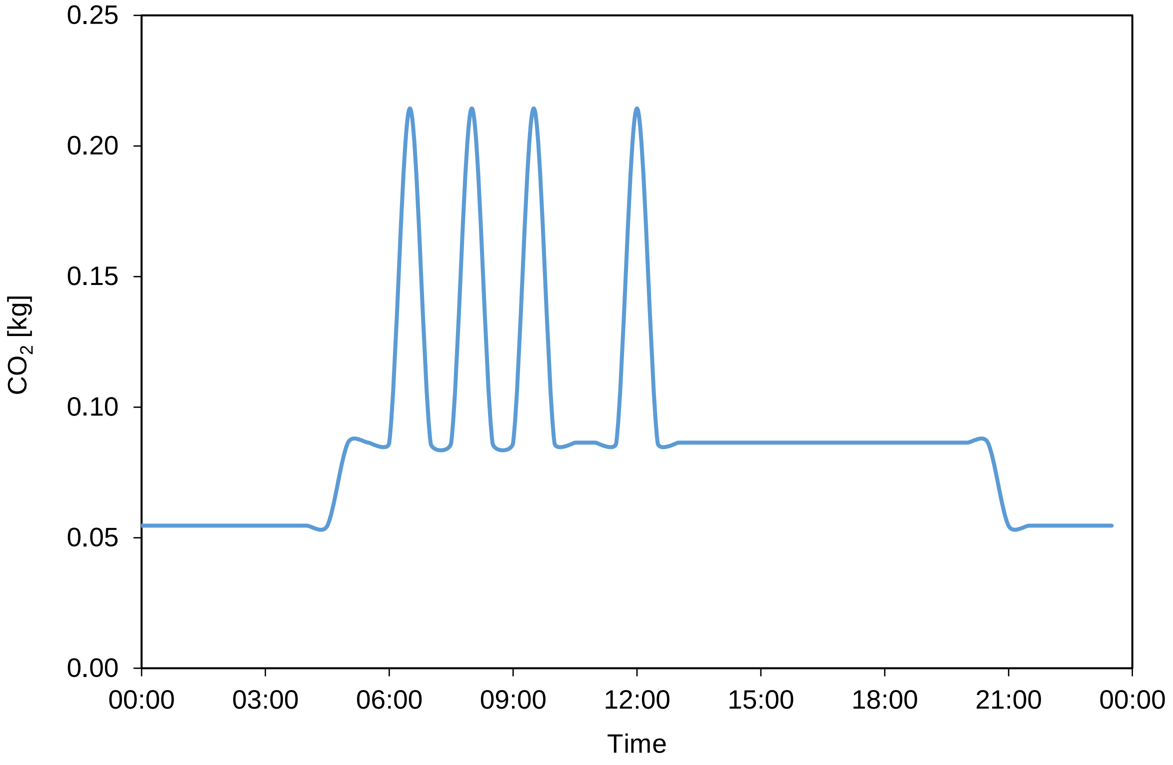

Figure 6-1: CO_2 production over the course of a day

The corresponding, estimated CO_2 partial pressure is displayed in Figure 6-2 at a three days scale. Under the assumptions stated in chapter 4.10.2.7, an average CO_2 partial pressure of 720-730 Pa is determined which is in accordance to previous allowable CO_2 concentration limits as described in chapter 3.1.2.1. However, according to more recent studies, the estimated average CO_2 partial pressure is too high and would therefore necessitate a second CO_2 removal assembly.

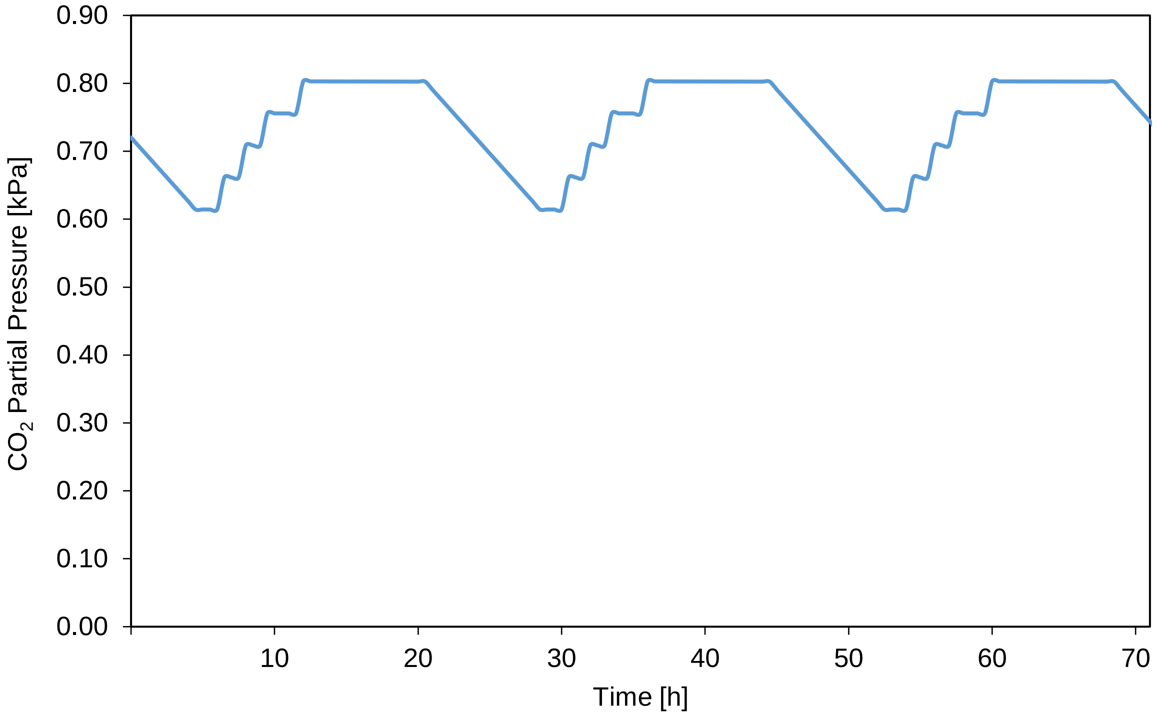

Figure 6-2: CO_2 partial pressure estimation

In Figure 6-3 the daily O_2 consumption rate is provided. As it can be seen, the peaks in O_2 demand are identical to those of CO_2 production and occur at the points in time physical exercise is performed. Similar to the CO_2 loads, the O_2 consumption is constant throughout the workday and during the night, albeit at a lower level.

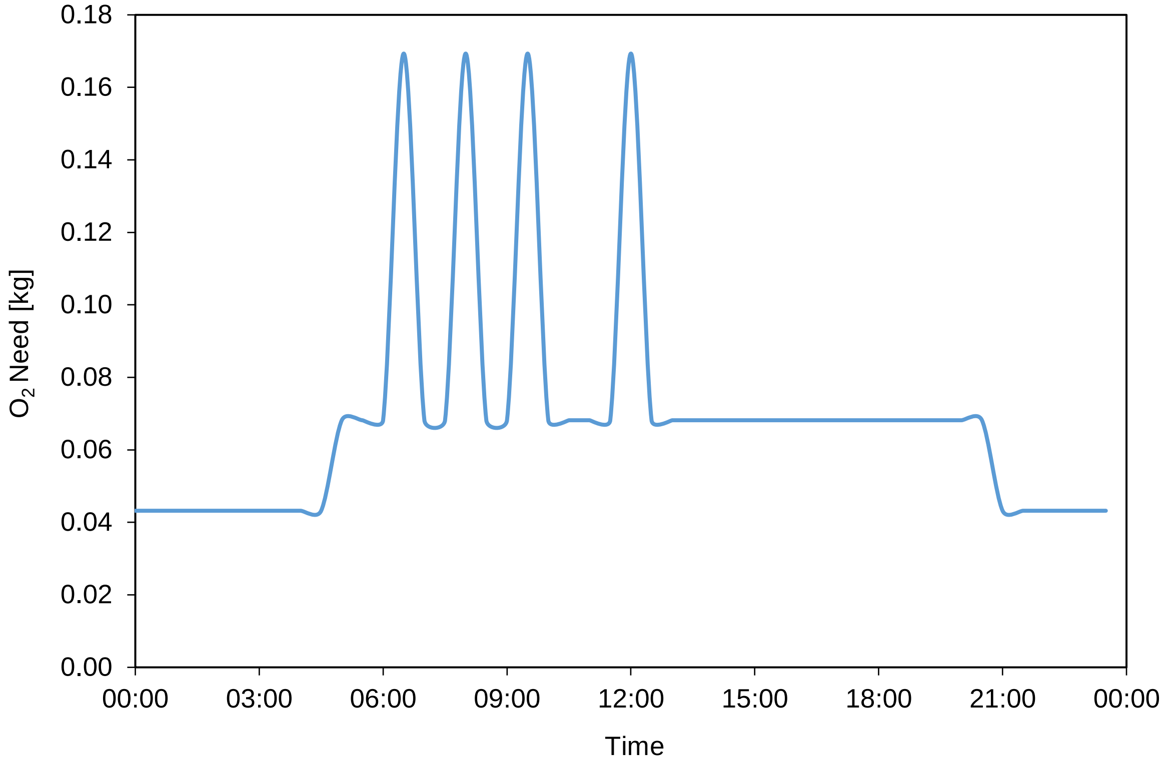

Figure 6-3: O_2 consumption

The estimated O_2 partial pressure is given in Figure 6-4 at a three days scale. An average O_2 partial pressure of 21 kPa is achieved which is within the allowable range as described in chapter3.1.2.1.

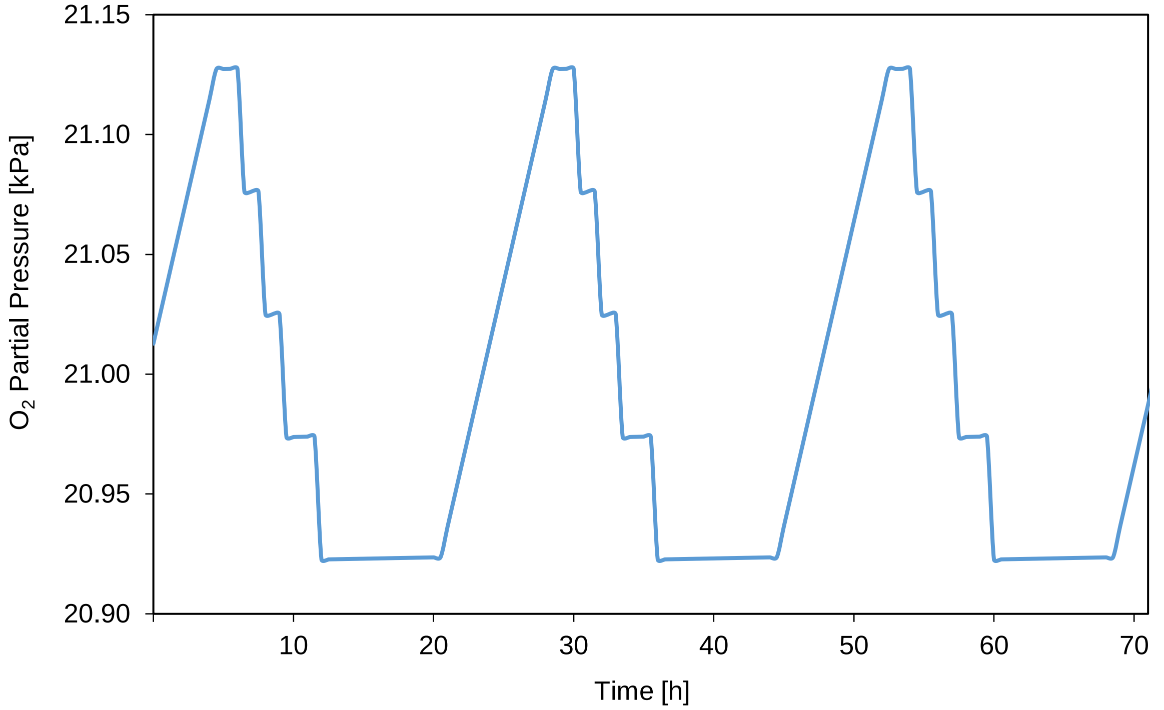

Figure 6-4: O_2 partial pressure estimation

6.1.4 Final design of the WRM subsystem

In the final design of the WRM subsystem, MF is used for filtrating the wastewater which consist of hygiene wastewater, brine that comes from the CCAA and wastewater from urine processing which employs TIMES. The quality of the water is monitored by the WQM. In Table 6-4, the final WRM technologies are listed.

Table 6-4: Final WRM technologies

	System mass [kg]	**Spares and resupply [kg]**	**Volume [m^3]**	**Power [W]**	**Cooling [W]**	**ESM [kg]**
MF	434.44	1511.79	1.95	986	880	2245.58
TIMES	27.17	27.70	0.07	66	54	89.00
WQM	38.00	23.56	0.051	30	30	69.90

The daily water demands of the crew are provided in Figure 6-5. As laid out in the crew schedule, potable water is consumed during meals and post-exercise, whereas hygiene water is also required for personal hygiene.

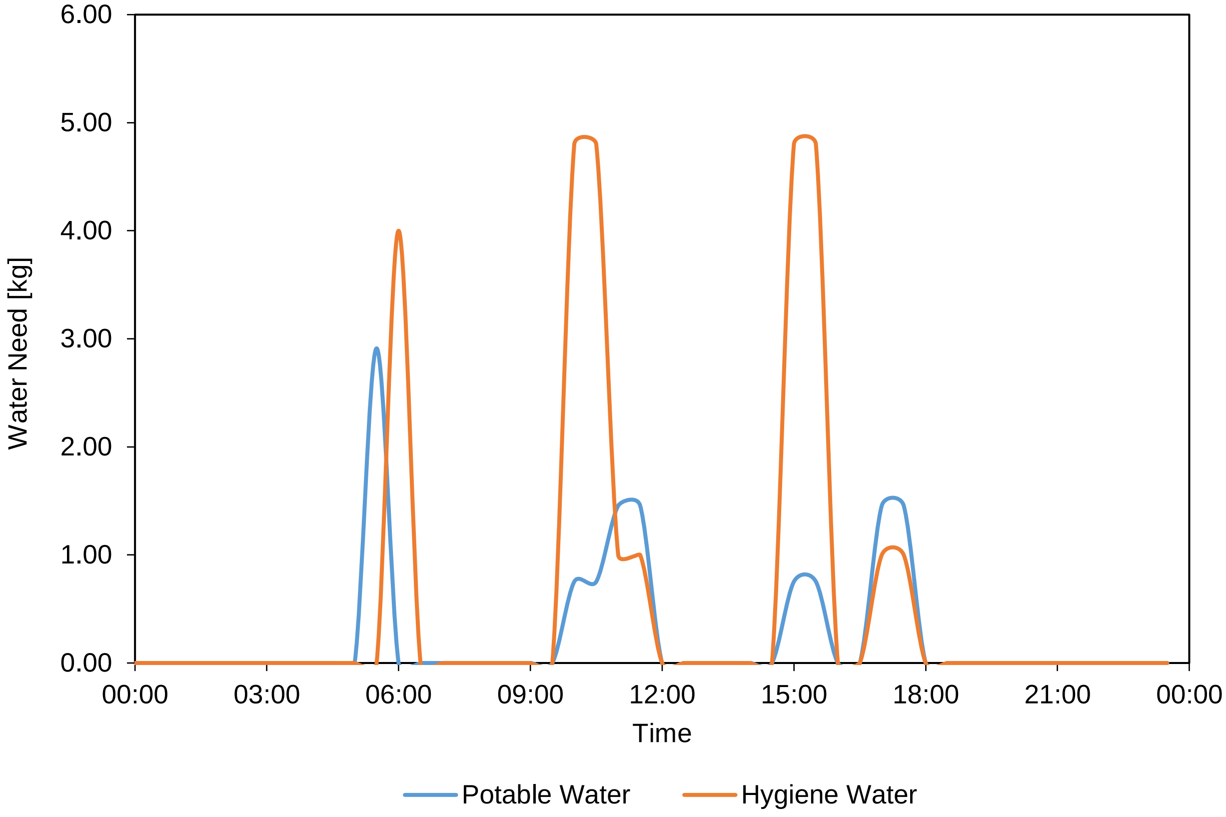

Figure 6-5: Hygiene and potable water consumption

Hygiene wastewater is allocated whenever hygiene activities are performed. Urine is produced during post- and pre-sleep and sweat continuously throughout the day depending on the tasks, which explains the peaks in sweat production at the times physical exercise is performed. The daily wastewater and urine production is depicted in Figure 6-6.

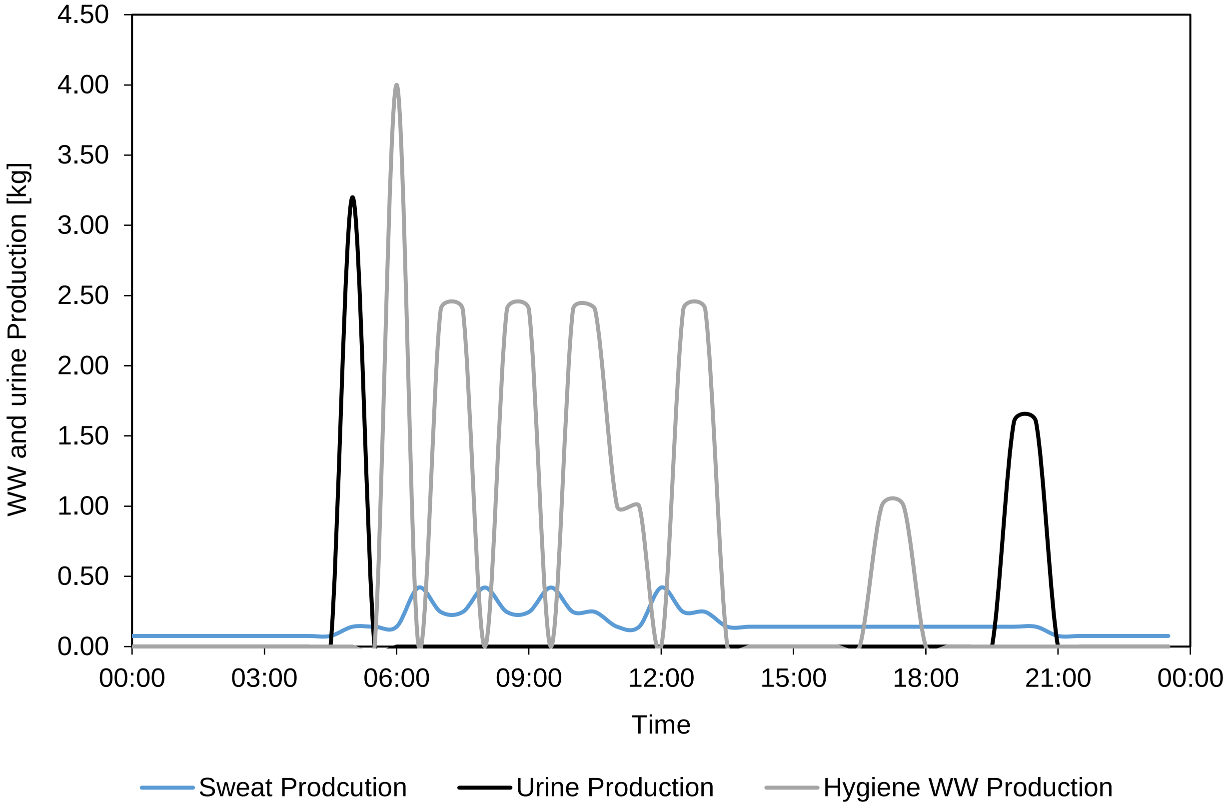

Figure 6-6: Sweat, urine and hygiene wastewater production

6.1.5 Conclusion

The intention behind refining the life support system identified in chapter 5.5 was to save infrastructural demands by dispensing with the default scaling approach outlined in chapter 4.10.2 and by using real-life (ISS) points of reference instead. In particular the number of PCA, AAA and MMC installed in the proposed Gateway ECLSS was adapted. Figure 6-7 compares the ESM performance of the old life support system with that of the refined ECLSS. As it can be seen, the newly designed life support system is characterized by an ESM which is 1,003 kg lower than that of the old version. Under the assumptions made for system power consumption described in chapter 4.13.7, a peak power demand of 6 kW for all life support technologies is required which occurs at 6 am when the hygiene wastewater needs to be processed. Given that the Gateway's PPE provides 15 kW of electrical power, 9 kW could be used for scientific experiments or orbit control. Thus, the proposed ECLSS does not exceed the power budget of the station.

As stated in chapter 1.1, this thesis's secondary objective is to examine if the ECLSS designed and composed with LiSTOT represents a functional life support system by implementing and verifying the ECLSS in the institute's life support analysis code V-HAB. The realization of this goal depends on whether the technologies selected with LiSTOT are available in V-HAB since otherwise the respective models would need to be implemented before the ECLSS could be assembled, which requires a modelling effort that would exceed the time schedule of this thesis. In this regard, it was dispensed with the verification of the refined life support system design because the current version of V-HAB does not incorporate models for all the ALS technologies as well as lacks a Bosch model, for instance.

The ECLSS Composition tool scheme of the life support system designed within this trade study is displayed in Figure 6-8.

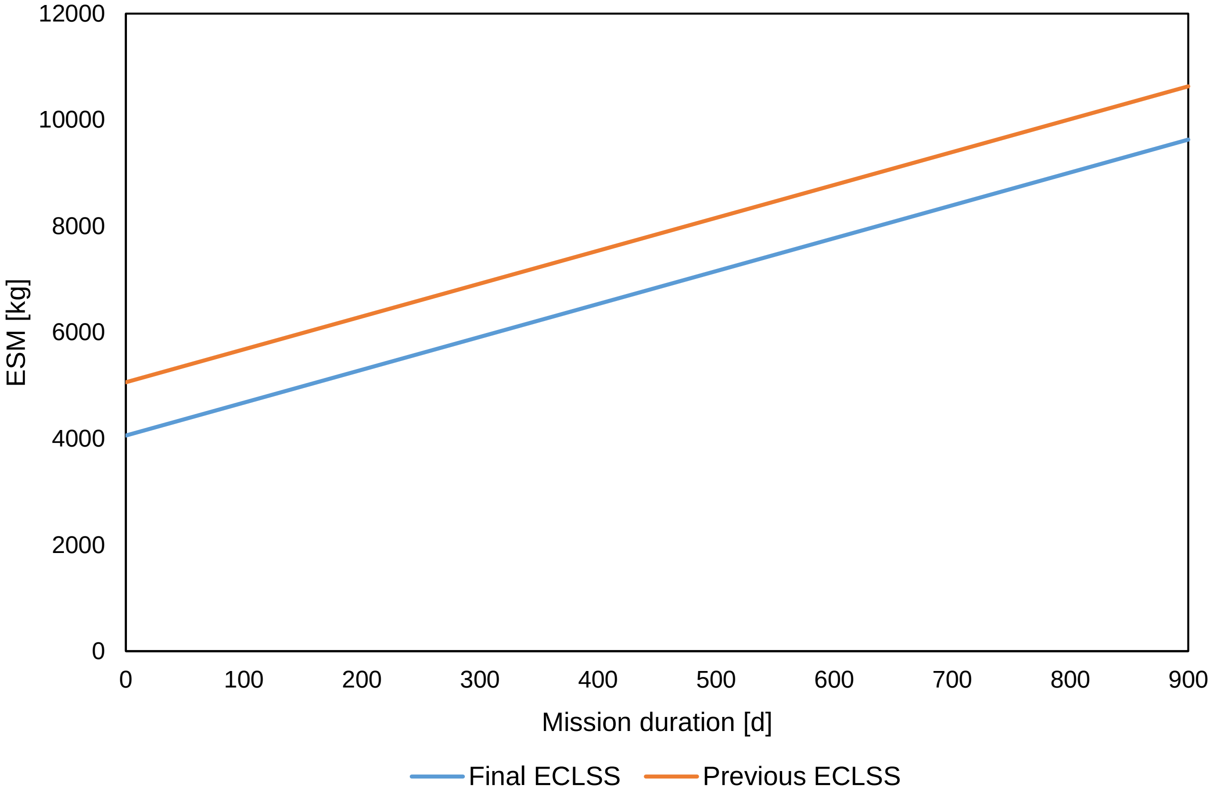

Figure 6-7: Comparison between old and new ECLSS design

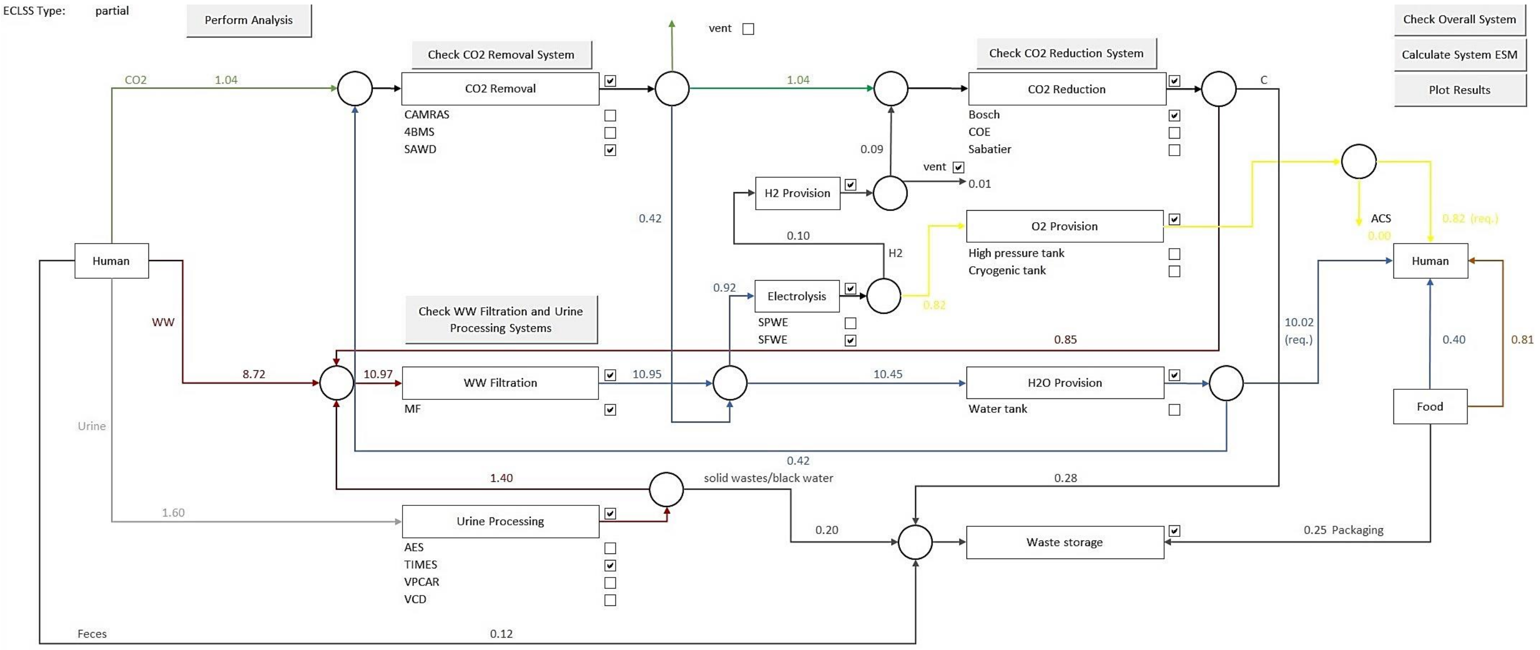

Figure 6-8: ECLSS scheme

7 Trade study employing the Resupply Modelling tool

The previous trade-off analysis identified a partially closed loop life support system as the most eligible option for the overall manned mission campaign of 900 days. Instead of regarding the total duration of the campaign, one could also examine an optimal ECLSS for each individual mission with an assumed length of 60 days. The other mission initiation parameters as defined in chapter 5.1 remain unchanged, whereby 15 individual missions during the campaign are assumed. Figure 5-19 showed that an open loop life support system presents the ECLSS with the lowest ESM cost until 64 days into the campaign. Since within the previous trade study, the ideal open loop life support system has been determined under the boundary condition of 900 days, a thorough re-evaluation of the most eligible ECLSS for a mission duration of 60 days is necessary. In chapter 5.2.5.2, it was shown that a LiOH based ECLSS with 10 % spares outperforms a life support system using CAMRAS until the breakeven point of 467 days, which is why LiOH is utilized for CO_2 removal for this trade study. Three additional ECLSS design variations are considered:

- Option 1: with urine processing and wastewater filtration
- Option 2: with wastewater filtration and without urine processing
- Option 3: without urine processing and wastewater filtration

The impact of each of these WRM subsystem attitudes on the total ECLSS ESM is displayed in Figure 7-1.

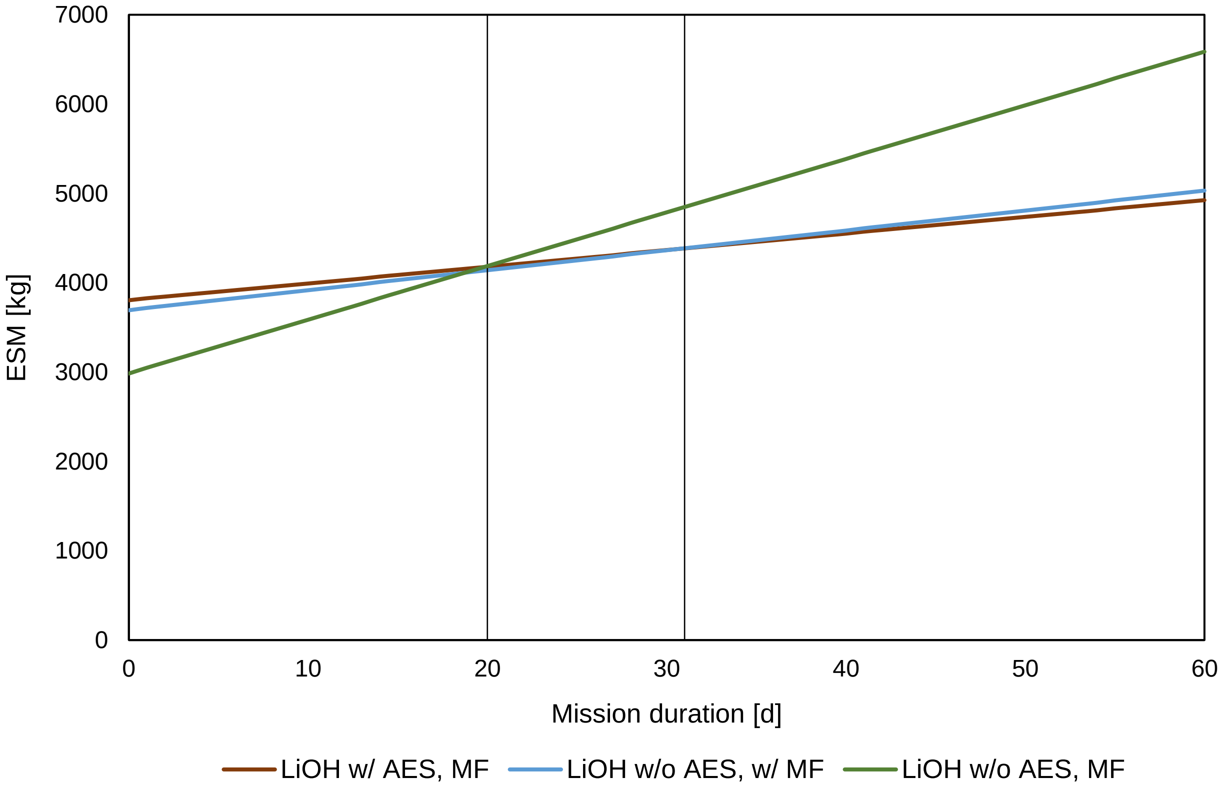

Figure 7-1: ESM depending on wastewater filtration and urine processing choice

Dispensing with both urine processing and wastewater filtration altogether results in the lowest ESM until 20 days into the mission. After this point in time, the other two alternatives are superior life support designs due to the extensive water needs of option 3. The breakeven point of options 1 and 2 lies at 31 days; for missions exceeding this duration, processing urine and filtrating wastewater poses the optimal ECLSS design. The remaining life support technologies are identical to those outlined in chapter 5.2. Based on this ECLSS composition, the resupply of the station is modelled.

This trade study is divided into two parts, whereby LiSTOT's Resupply Modelling tool is utilized both times. In the first part, it is examined how the choice of life support architecture affects the logistics of a space station. A comparison of the resupply demands for a 60-day mission is provided between the open loop ECLSS described above and the partially closed life support system that has been identified in chapter 5.5 as the optimal solution in case the duration of the entire mission campaign is regarded. In the second part of this trade study, the resupply of a space station with the open loop LiOH system is modelled in the background of the Gateway's mission parameters and campaign. The results of this trade study and analyses are depicted in the following chapters.

7.1 Trade study part 1: Consumables

By using the Resupply Modelling tool, the first part of the trade study does not focus on the ESM metric to determine the feasibility of the LiOH but assesses the amount of any non-ECLSS related cargo which can be taken along in a resupply flight. Thus, only technical and non-technical resupply materials are considered, while additional payloads as classified in chapter 4.11.1 are not specified for this analysis. One must also note that in regard to non-technical materials, merely the mass of the respective consumable is calculated since with the exception of food provision, it is not given how or in what tank or container a consumable is supplied. Hence, additionally required hardware masses for transportation must be kept in mind. The results of this trade study are described in this chapter.

The masses of consumables that consist of both technical and non-technical resupply materials as defined in chapter 4.8.1 required for the given mission scenario are listed in Table 7-1. It is important to mention that the O_2 and N_2 needs for atmosphere repressurization are not included within the values depicted below, whereas the demands for leakage handling are considered. This is because repressuring the cabin does not correlate with crew size or mission duration. If an emergency occurred and the repressurization tanks are to be replenished, the respective O_2 and N_2 masses can be added via the Add Payload Mass UI.

Table 7-1: Technical and non-technical resupply requirements of open loop ECLSS

ECLSS Subsystem related Supply	**Total amount [kg]**
Oxygen Generation or Supply	199.14
Nitrogen Supply	9.36
Water Supply	0.00
Food	144.00
Carbon dioxide Removal	271.02
Carbon dioxide Reduction	0.00
Wastewater Filtration	79.36
Urine Processing	7.86
Electrolysis	0.00
Total	710.74

Oxygen Generation or Supply: No technical resupply is needed since pure O_2 for crew consumption (196.6 kg) and for leakage handling (2.5 kg) is provided.

Nitrogen Supply: No technical resupply needed since pure N_2 is provided solely for leakage handling.

Water Supply: No additional water is required since the designed ECLSS can close the water loop.

Food: The mass of packaging and pantries are considered within the specified food mass.

Carbon dioxide Removal: The consumable mass of LiOH amounts to 271.02 kg. The entire system mass of hardware including cartridges reaches 492.92 kg.

Carbon dioxide Reduction: No resupply is needed for CO_2 reduction since the designed ECLSS dispenses with such assembly.

Wastewater Filtration: The resupply for wastewater filtration is classified as technical and induced by the MF technology.

Urine Processing: The resupply for urine processing is classified as technical and induced by the AES technology.

Electrolysis: No resupply is needed for water electrolysis since the designed ECLSS dispenses with such assembly.

The consumables outlined above are calculated by default for the given ECLSS design but can be adjusted using the Initial Consumables UI if desired. The total mass of resupply materials amounts to 710.74 kg (932.64 kg if LiOH hardware is considered) for the specified ECLSS.

In comparison to this, the resupply needed for an individual 60-day mission by the optimal life support system identified in chapter 5.5 equates to just 244.60 kg.

Thereby, food is the main resupply driver followed by wastewater filtration as shown in Table 7-2. The technical resupply required by MF deviates from that determined for the open loop ECLSS above despite using the same technology, which is due to the fact in LiSTOT, resupply is scaled accordingly with mass, volume, power and cooling as described in chapter 4.8.1. Apart from food, the only non-technical resupply materials are the O_2 and N_2 demand for leakage handling. The remaining logistical needs of the other ECLSS subsystems are hardware specific technical resupply. Comparing the two life support systems, it can be concluded that by employing the partially closed loop ECLSS 466.14 kg of cargo mass can be saved per flight. One must note however that this advantage comes at the cost of having more or higher payload mass flights to establish the life support infrastructure prior to any manned mission.

Table 7-2: Technical and non-technical resupply requirements of partially closed loop ECLSS

ECLSS Subsystem related Supply	**Total amount [kg]**
Oxygen Generation or Supply	2.52
Nitrogen Supply	9.36
Water Supply	0.00
Food	144.00
Carbon dioxide Removal	1.16
Carbon dioxide Reduction	1.74
Wastewater Filtration	84.86
Urine Processing	0.96
Electrolysis	0.00
Total	244.60

7.2 Trade study part 2: Resupply modelling

In order to model the resupply of the Gateway, the parameter of cargo transportation capability of the spacecraft supplying the station is required. This attribute depends on various factors such as the lunar destination orbit of the Gateway and the launch system that is used. Thus far, the only consent was made on employing Orion connected with the European Service Module for resupply and build-up flights. As of April 2019, however, it remains uncertain which carrier rocket system shall launch the Orion capsule. NASA favours its own SLS, yet it is doubtable whether SLS will be flight ready in time to meet the goal of performing Exploration Mission 1 in 2020. According to the NASA Administrator, SpaceX's Falcon Heavy is currently the only operational rocket capable of bringing Orion to a polar lunar orbit. Nonetheless, he pointed out that a vast amount of modifications of both the rocket system as well as the launch infrastructure are needed to support the Orion spacecraft. These redesign efforts and the unknowns that go along with them necessitate time and financial means that may exceed those required for rendering SLS operational [104]. Hence, as of April 2019, determining the cargo transportation capability of Orion to the Gateway is difficult due to the lack of reliable data. A symbolic value for the pressurized and unpressurized cargo transportation capability of 2 t is assumed which corresponds to the standard payload capacity of the Cygnus spacecraft that offers with 18 m^3 a similar pressurized volume to that of the Orion capsule [105], [24].

An additional assumption must be made in composing the non-ECLSS related cargo since a resupply payload composition typically deviates from mission to mission depending on the respective mission requirements. Since the Cygnus spacecraft is used as a point of reference in this modelling effort, five exemplary CRS flights[14] with Cygnus have been analysed to determine the cargo distribution among the CoS defined by NASA as described in chapter 4.11.1. The results of this examination are depicted in Figure 7-2. Vehicle Hardware demands with 33 % the majority of the total resupply masses followed by food provision (usually under Crew Supplies) with 28 % and Science Investigations with 25 %. The other Crew Supplies goods, Computer Resources and Spacewalk Equipment make up the remaining 16 %.

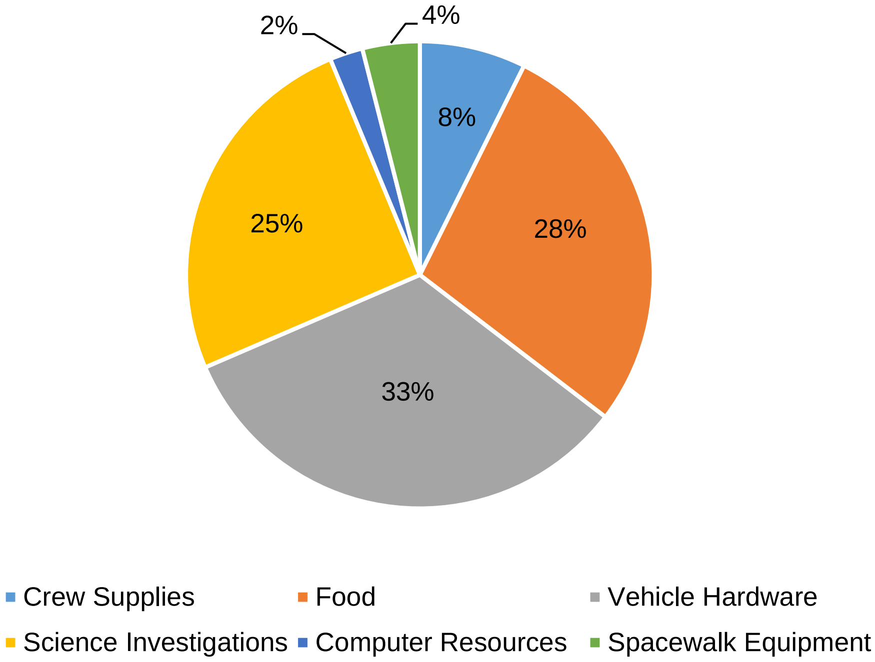

Figure 7-2: Distribution of total supply

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[14] Orb-2 [114], Orb-3 [115], OA-4 [116], OA-5 [117] and OA-6 [118]

It is furthermore assumed that 70 % of the resupply masses belonging to Vehicle Hardware and all the food provided are ECLSS related consumables that are therefore covered by the technical and non-technical resupply materials listed in Table 7-1. This percentage has been estimated by calculating the ratio of yearly needed resupply of the U.S. ECLSS on board the ISS (2,170.1 kg/y) with the amount of Vehicle Hardware brought to the station in one year [48]. Under the assumption that only resupply flights conducted by the U.S. support the U.S. ECLSS, it has been focused on four CRS flights[15] which were performed during 2015. Employing the Vehicle Hardware factor of 33 % computed above and the given payload masses of all flights, a total Vehicle Hardware mass of 3,027 kg is estimated to have been brought to the ISS in 2015 by the U.S., which leads to a life support-related cargo factor of roughly 70 %. Given the simplification stated before, it is likely that this percentage is too high since Russian resupply flights may also carry U.S. cargo. However, due to the lack of information concerning the composition of resupply cargo, this approach is justifiable. It is thus estimated that food and life support related Vehicle Hardware make up 50 % of the total logistical payload brought to a space station. Considering the additional hardware of the LiOH system, the amount of non-ECLSS related cargo amounts to 932.64 kg, which brings the total cargo mass per resupply flight to 1,865 kg. Opposing to the ISS, the attitude control and orbit transfers of the Gateway is not performed by the resupply spacecraft but by the PPE of the station which requires Xenon for its thrusters. Since no data is available predicting the fuel consumption and needs of the propulsion module, the resupply of Xenon is neglected in this analysis.

One flight per individual mission is assumed, which necessitates the consideration of the mass of the crew that is transported to the Gateway. The mass of one crew member is 82 kg plus the mass of 10 kg per space suit.[16] This brings the total payload mass to 2,233 kg that must be brought to the Gateway for each individual mission. One must also note that the flights needed to establish the Gateway architecture are not considered within this resupply modelling effort. Hence, all life support assemblies except for the CO_2 removal and O_2 provision systems have already been installed so that solely the technical and non-technical resupply materials for the mounted life support hardware must be carried along.

Summarizing the payload specifications stated above, 2,233 kg per mission must be supplied, which amounts to 33,495 kg for the entire campaign. Yet, under the assumption that one flight serves one individual mission only 30,000 kg can be delivered, which is why at least two resupply additional flights are required. Thus, 17 flights are incorporated in the mission campaign.

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[15] SpaceX CRS-5 [119], SpaceX CRS-6 [120], SpaceX CRS-7 [121], OA-4 [116]

[16] Mass of space suit derived from Sokol Intravehicular Activity (IVA) space suit [122]

7.2.1 Resupply matrix

As described in chapter 4.11.2, the assignment of cargo masses to flights is only constrained by two aspects:

- The cargo transportation capability of any flight must not be exceeded.
- The payload demand of any mission must be fulfilled.

Thus, one may distribute the chunks of cargo among the flights and missions as desired as long as the restrictions mentioned above are met. Three assumptions have been made for this analysis:

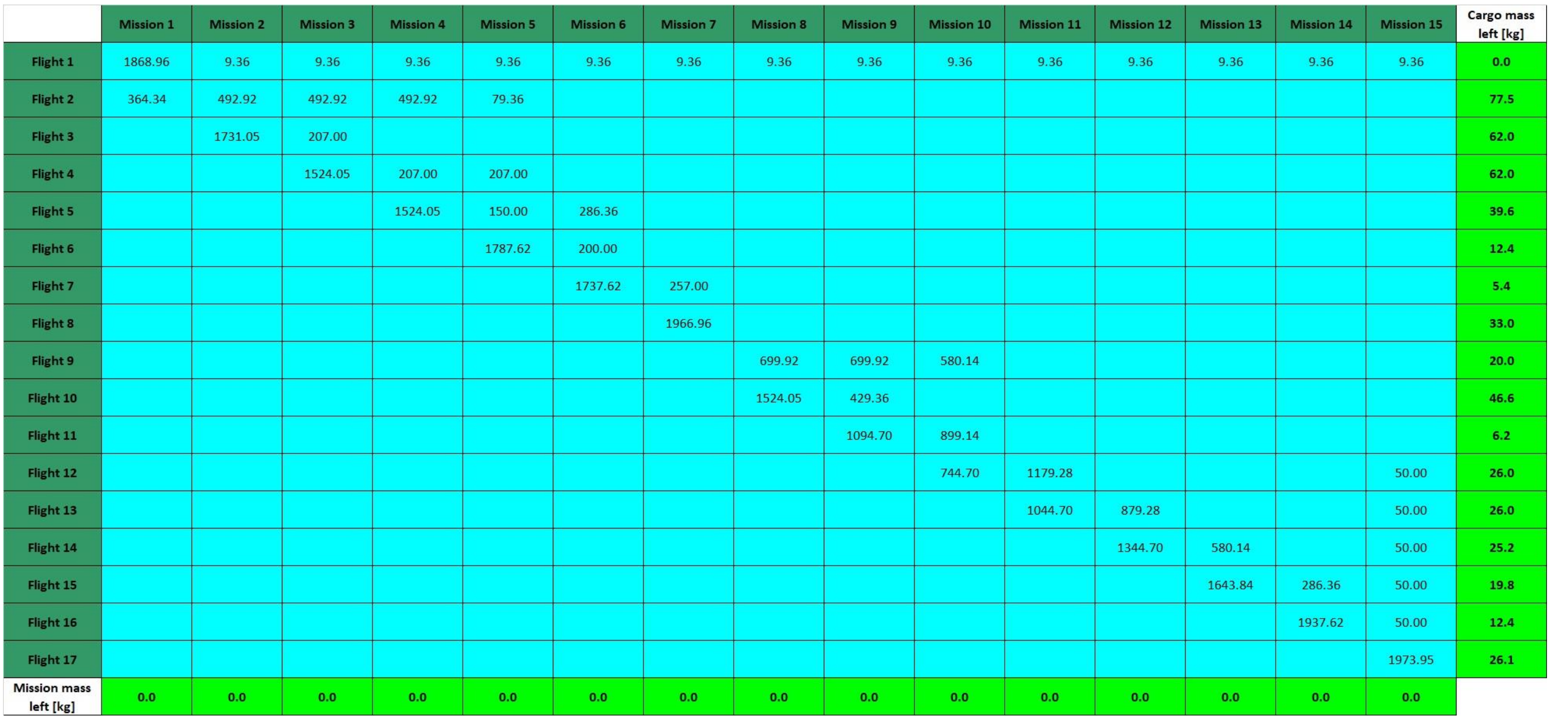
ECLSS related cargo is more important than any non-life support related hardware. Therefore, the process of assigning payloads prioritizes the prepositioning of life support equipment over non-ECLSS related resupply. Moreover, it is assumed that food cannot be prepositioned but is carried along in case of a manned flight to the Gateway to ensure the food quality. Life support resupply materials cannot be split up. In other words, the CO_2 removal hardware of one mission is not allowed to be transported via two or more different flights but must be supplied by one flight. The only type of cargo that can be brought to the station via more than one flight is non-ECLSS related Vehicle Hardware, whereby the smallest allowed chunk of cargo is 50 kg. It is worth mentioning that in the following, the term Vehicle Hardware is exclusively applied to any non-life support related equipment. The cargo distribution among the 17 flights of the mission campaign is described in Table 7-3.

Table 7-3: Cargo distribution among flights

Flight	**Description**
Flight 1	The first flight is manned and carries along all life support equipment needed for the first mission as well as the entire N_2 demand of the campaign. Furthermore, 608.32 kg of Vehicle Hardware are taken along. The remaining 364.34 kg of cargo are supplied by the second flight.
Flight 2	The second flight is unmanned and designated to preposition cargo for upcoming missions and to bring the remaining Vehicle Hardware payload for the first mission. It takes place during the first mission so that the crew can process and stow the cargo delivery. Flight 2 prepositions all the required CO_2 removal hardware for missions 2, 3 and 4, which sums up to 1,843.1 kg in total. In addition, the wastewater filtration resupply materials for mission 5 are supplied.
Flight 3	The third flight carries along the crew, food, O_2 and all Vehicle Hardware for the second mission as well as the O_2 and urine processing resupply materials for the following mission.
Flight 4	The fourth flight delivers all the crew, food and all Vehicle Hardware for the third mission, plus the O_2 and urine processing resupply material for the fourth and fifth mission.
Flight 5	Flight 5 brings the crew, food, wastewater filtration resupply and all Vehicle Hardware needed by the fourth mission. Furthermore, 150 kg of Vehicle Hardware of mission 5 is prepositioned together with the O_2 and resupply of wastewater filtration and urine processing of the sixth mission.

Flight 6	The sixth flight brings the crew, CO_2 removal hardware, food and the remaining 782.69 kg of Vehicle Hardware for mission 6 as well as 200 kg of non-ECLSS related Vehicle Hardware for mission 6.
Flight 7	Flight 7 transports the crew, food, CO_2 removal hardware and the remaining 732.6 kg of Vehicle Hardware for the sixth mission. The O_2 and urine processing resupply materials of mission 7 as well as 50 kg of Vehicle Hardware of mission 7 are also carried along.
Flight 8	The eighth flight brings the crew, CO_2 removal hardware, food, wastewater filtration resupply and the remaining 882.64 kg of Vehicle Hardware for the seventh mission.
Flight 9	Flight 9 is an unmanned resupply flight conducted during the seventh mission and prepositions the carbon removal hardware, urine processing resupply and O_2 for missions 8 and 9 as well as the CO_2 removal hardware, wastewater filtration and urine processing resupply for the tenth mission.
Flight 10	Flight 10 carries along the crew, food, wastewater filtration resupply and all Vehicle Hardware of the eighth mission, plus the wastewater filtration and 350 kg of Vehicle Hardware for mission 9.
Flight 11	The eleventh flight brings the crew, food and the remaining 582.64 kg of non-life support related Vehicle Hardware for the ninth mission. In addition, the O_2 and 700 kg of Vehicle Hardware are prepositioned for mission 10.
Flight 12	Flight 12 carries along the crew, food and the remaining 232.64 kg of Vehicle Hardware. Furthermore, the CO_2 removal hardware, O_2, wastewater filtration and urine processing resupply and 400 kg of Vehicle Hardware are brought along for mission 11. 50 kg of Vehicle Hardware is prepositioned for mission 15.
Flight 13	Flight 13 transports the crew, food and 532.7 kg of Vehicle Hardware for the eleventh mission. The CO_2 removal hardware, O_2, wastewater filtration and urine processing resupply and 100 kg of Vehicle Hardware of mission 12 are prepositioned. 50 kg of Vehicle Hardware is prepositioned for mission 15.
Flight 14	The fourteenth flight brings the crew, food and 832.64 kg of Vehicle Hardware for mission 12. Moreover, the CO_2 removal hardware and wastewater filtration and urine processing resupply of the thirteenth mission are carried along. 50 kg of Vehicle Hardware is prepositioned for mission 15.
Flight 15	Flight 15 carries the crew, food, O_2 and all Vehicle Hardware for mission 13 along. In addition, the O_2, wastewater filtration and urine processing resupply of the fourteenth mission is prepositioned. 50 kg of Vehicle Hardware is prepositioned for mission 15.
Flight 16	The sixteenth flight brings the crew, food, CO_2 removal hardware and all Vehicle Hardware for the fourteenth mission. 50 kg of Vehicle Hardware is prepositioned for mission 15.
Flight 17	Flight 17 carries along all remaining crew and cargo for the final mission.

The resupply matrix is displayed in Figure 7-3. As one can see the total cargo transportation capability of 2,000 kg of all flights are not maxed out due to the assumption that life support related resupply cannot be split up.



	Mission 1	Mission 2	Mission 3	Mission 4	Mission 5	Mission 6	Mission 7	Mission 8	Mission 9	Mission 10	Mission 11	Mission 12	Mission 13	Mission 14	Mission 15	Cargo mass left [kg]
Flight 1	1868.96	9.36	9.36	9.36	9.36	9.36	9.36	9.36	9.36	9.36	9.36	9.36	9.36	9.36	9.36	**0.0**
Flight 2	364.34	492.92	492.92	492.92	79.36											**77.5**
Flight 3		1731.05	207.00													**62.0**
Flight 4			1524.05	207.00	207.00											**62.0**
Flight 5				1524.05	150.00	286.36										**39.6**
Flight 6					1787.62	200.00										**12.4**
Flight 7						1737.62	257.00									**5.4**
Flight 8							1966.96									**33.0**
Flight 9								699.92	699.92	580.14						**20.0**
Flight 10								1524.05	429.36							**46.6**
Flight 11									1094.70	899.14						**6.2**
Flight 12										744.70	1179.28				50.00	**26.0**
Flight 13											1044.70	879.28			50.00	**26.0**
Flight 14												1344.70	580.14		50.00	**25.2**
Flight 15													1643.84	286.36	50.00	**19.8**
Flight 16														1937.62	50.00	**12.4**
Flight 17															1973.95	**26.1**
Mission mass left [kg]	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	

Figure 7-3: Resupply Matrix

7.2.2 Flight criticalities

To determine the respective criticality of each flight, the FCI is used which is described in chapter 4.11.3 since several flights have identical dependency factors and number of missions served because the individual missions including the transportation capabilities are the same for the entire campaign. Therefore, the FC plot is not a suitable means of assessing the flight criticalities as flights are hard to distinguish in the plot. The FC ranking and indices are provided in Table 7-4. The first flight of the campaign is the most critical since it serves all individual missions by supplying the N_2 demand of the entire campaign. Five missions receive cargo from the flight number 2 which is thus the second most critical flight. Seven flights (4, 5, 9, 12, 13, 14, 15) achieve a similar FCI of roughly 3.13 by serving three missions each. The small differences between those flights can be explained by the slightly varying degree of cargo transportation capacity of the flights. For example, flight 9 is more critical than flight 4 because it carries 42 kg more cargo as can be seen in Table 7-4. Six flights (3, 6, 7, 10, 11, 16) are characterized by an FCI of 2.18, which is attributed to the fact that they serve two flights each. The flights that provide the cargo for solely one mission (flights 8 and 17) achieve an FCI of roughly 1.33.

The results of this modelling effort show that apart from the first flight, the FCI differ only by about +/- 2 at the maximum. Thus, one may want to reduce the criticality of flight 1 to lower the extent of damage to the campaign in case of a failure of flight 1.

The criticality of flight 1 can be lowered in two ways: one can either assign part of the N_2 cargo chunks to other flights or the total amount of cargo brought by the first flight can be reduced. Electing to use the second approach however leads to the transportation capacity of the regarded flight not being utilized to its fullest potential.

One could argue that in order to achieve the lowest criticalities, each flight should only serve one mission. Yet, to max out the cargo transportation capabilities of flights, it may be advisable to preposition payloads for following missions. In doing so, the need of having additional resupply flights can be mitigated and therefore financial funds can be saved. It may also be possible that the payload of one mission exceeds the transportation capability of the corresponding flight, which necessitates the preposition of cargo or the addition of another resupply flight.

Thus, one must carefully decide what level of flight criticality in a campaign is allowable to both efficiently utilize the cargo transportation capacities as well as ensuring that the success of the entire campaign is not at stake in case of one particular flight having failed. As shown in this chapter, LiSTOT's Resupply Modelling tool can be employed in not only modelling the logistics of a space station but also in identifying critical flights in a campaign.

Table 7-4: Flight criticalities

Flight Number	**FC Ranking**	FCI
1	1	15.0267
2	2	5.0736
3	15	2.1802
4	9	3.1230
5	8	3.1258
6	12	2.1891
7	10	2.1904
8	17	1.3326
9	4	3.1283
10	14	2.1829
11	11	2.1902
12	6	3.1275
13	6	3.1275
14	5	3.1276
15	3	3.1283
16	12	2.1891
17	16	1.3346

8 Final Discussion

8.1 Summary

The main objective of this thesis was to translate the Excel spreadsheet based LiSTOT code created by Schreck into a VBA tool to render LiSTOT applicable to a wider range of mission scenarios and making it more user friendly. In doing so, the approach outlined by Schreck of combining Multi-Criteria with ESM and sensitivity analyses was kept. It was furthermore leveraged from the extensive database that had been put together for the original version of LiSTOT. Apart from these points, LiSTOT was entirely built anew. The changes which were made are described in the following.

8.1.1 Multi-Criteria, ESM and sensitivity analyses

The MCA including the usage of decision weights, merit functions and confidence factors was kept the same. However, additional min/max criteria and filter options were added to make the MCA more customizable and to provide one with more means to specify the analysis according to the user's needs. The sensitivity analysis was entirely redesigned to not only examine the effect of a parameter variation of +/- 10 % but to allow the user to assess the criticalities of attributes and to specify the sensitivity analysis depending on the respective requirements. A location factor was added to the ESM equation to account for different locations of a space station.

8.1.2 Schedule composition

A tool was created that allows to compose crew schedules by assigning predefined tasks to crew members. If the user does not intend to create a mission specific schedule, a robust default schedule is available which resembles that of an exemplary ISS schedule. The choice of schedule impacts system scaling as well as the calculation of ECLSS characteristics such as CO_2 and O_2 partial pressures.

8.1.3 Technologies

Apart from the P/C technologies that had already been available in the original version of LiSTOT, biological assemblies were added to the tool's database which enable the design of both hybrid ECLSS as well as BLSS. In doing so, trade-offs between the various types of life support systems are possible.

8.1.4 ECLSS Composition tool

The ECLSS Composition tool was added since the original LiSTOT version did not incorporate a tool with which one could examine the interactions and consequences of combining life support technologies. This tool can be seen as LiSTOT's backbone in assembling an ECLSS out of the selected life support technologies. Trade-offs can be performed efficiently since most of the relevant ECLSS hardware (TRL>5 and all MCA related attributes are specified) is already implemented. The tool automatically rescales the chosen technologies and informs the user whether the composed life support systems is capable of balancing the in- and output mass flows of the human metabolism. Default scaling and individual sizing options are available for all life support hardware components that scale independently of crew size. Furthermore, the tool provides a graphical output in the form of plots depicting critical attributes of the designed ECLSS including ESM composition and performance over the mission duration amongst others.

8.1.5 Maintenance strategy

The maintenance strategy was reworked by allowing the user to select whether an ORU or 0.001 spares approach should be used. It must be noted however that even though the 0.001 approach is implemented, it can only be used for technologies for which detailed reliability information is available.

8.1.6 Resupply Modelling tool

The Resupply Modelling tool was added to LiSTOT to allow the user to assess the amount of resupply that would be needed by the composed life support system. The tool also provides the means with which one can model the logistics of a mission campaign by assigning cargo to resupply flights. Based on this modelling effort, the criticalities of each individual flight can be examined. The tool is also meant to serve as an interface for following works and theses which provide information such as the extent of cargo transport capability one could expect.

8.1.7 User Interface and User’s Guide

LiSTOT’s UI was designed to guide the user efficiently through the tool by providing instructions and a User’s Guide to depict how the various input parameters affect the respective analysis. The User’s Guide is divided into the various iterative steps one progresses through in using LiSTOT and incorporates detailed descriptions of each analysis included in the tool. Furthermore, LiSTOT is outfitted with an error handling system that informs the user about missing or false input as well as restricts one from writing or accidently changing the tool’s setup.

8.2 Conclusion

The tool was used in composing an ECLSS for the Gateway under the assumptions stated in chapter 5 demonstrating how one may use LiSTOT in a trade-off analysis. Open, partially closed and closed life support systems were examined in identifying an optimal overall ECLSS for the given Gateway mission campaign. The first design iteration used a conservative sizing approach which was followed by a more precise scaling effort in the second design cycle allowing to save about 1,000 kg of ESM.

The trade-off for an open loop ECLSS primarily focused on comparing storage options for both O_2 and N_2 and on identifying the optimal non-regenerable CO_2 removal technology. It was concluded that HPS presents the most eligible technology for providing the O_2 for crew consumption, whereas CS should be used for storing the gases for leakage handling. Furthermore, it could be shown that the overall ESM of the ECLSS employing CAMRAS or LiOH with 10 % spares is almost identical. Within the trade study for a partially closed loop life support system, the CO_2 reduction assemblies Sabatier and Bosch were examined. In doing so, it was demonstrated that the optimal CO_2 content processed in a Sabatier reactor resulting in the lowest overall ECLSS ESM is 55 %. This corresponds to producing all the O_2 necessary to meet the crew and leakage handling demands. However, when compared to the Bosch reactor, it could be shown that the Sabatier process does not present the most eligible technology. Moreover, SAWD was identified as the most favourable CO_2 removal assembly, TIMES as the most favourable urine processing technology and SFWE as the best option for water electrolysis, which turned out to result in a lower total system ESM than using HPS for O_2 provision. In evaluating life support technologies for a closed loop P/C ECLSS, EDC was found to be superior to SAWD. In addition, a thorough sensitivity analysis of decision weight variation was performed depicting the impact of decision weight variation on the MCA results. Comparing the three ECLSS architectures with each other and with a hybrid ECLSS and BLSS, it was concluded that the partially closed loop life support system represents the optimal overall design with an ESM of 10,630 kg since the resupply needs of the EDC assembly lead to a higher total ESM of the closed loop ECLSS which amounted to 10,800 kg. The open loop system performed considerably worse with a total ESM of 20,450 kg.

Plots of the metabolic loads and demands of the crew and power needs of the WRM subsystem over a day were provided within the second design cycle which focused on technologies that scale independently with crew size. It could be shown that the peak power consumption of the ECLSS amounted to 6 kW, which is within the Gateway's power budget of 15 kW. Due to the reasons provided in chapter 6.1.5, a verification of the composed ECLSS with V-HAB was not possible, which is why the life support system designed within this work must be regarded as a mere proposal until it has been verified using an ECLSS simulation tool.

The Gateway's resupply was exemplarily modelled for a life support system optimized for individual mission lengths of 60 days. The cargo distribution was thereby kept similar to CRS flights to the ISS conducted in 2015 and the transportation capability similar to that of the Cygnus spacecraft. The chosen cargo assignments lead to almost even flight criticalities of all 17 resupply flights with the exception of the first flight that carried along all the inert gas for leakage handling for the entire campaign. Thus, its criticality was substantially higher than that of the remaining flights.

9 Future work

Keeping LiSTOT up to date in terms of adding new life support technologies as well as adapting system attributes such as TRL or reliability of ALS hardware can be seen as a continuous process that must be considered to ensure that the trade-offs conducted using LiSTOT are based on appropriate data. Especially the inclusion of more detailed reliability values is essential if one intends to dispense with the chosen ORU calculations and favours the 0.001 approach. The ORU masses and volumes were computed using ORU factors and hardware densities that were derived from ISS technologies, which is why the adaption of those parameters to ALS standards is necessary to receive more accurate results. Inserting missing data and the improvement of a technology's TRL to a value of at least 5 allows the addition of new life support hardware to LiSTOT's ECLSS Composition tool, which is needed to widen the range of assemblies with which the user can design an ECLSS. The current BLSS model is very simplistic since it is merely based on respective equivalency factors provided by [66]. More elaborate calculations especially regarding the interaction of BLSS subsystems are required to equally contrast biological with P/C life support systems once BLSS technologies have reached a comparable level of technology readiness and reliability.

Moreover, the Gateway ECLSS design proposed in chapter 6 must be verified to ensure that LiSTOT's output represents a functional life support system and that the corresponding assumptions which were made in creating the tool are justifiable. Lastly, a future thesis is needed to connect the works done within the three theses that have been issued by the Institute of Astronautics of the Technical University of Munich and DLR on the topic of analysing the Gateway.

A List of References

[1] P. O. Wieland, *Designing For Human Presence in Space: An Introduction to Environmental Control and Life Support Systems (ECLSS),* NASA Marshall Space Flight Center, Huntsville, Alabama, U.S., Alabama, 2005.

[2] E. W. Hodgson, M. H. Kliss and H. W. Jones, *Life Support for Deep Space and Mars,* presented at 44th International Conference on Environmental Systems, 13-17 July 2014, Tucson, Arizona, U.S..

[3] J. W. Fisher, J. A. Levri, A. E. Drysdale, M. K. Ewert, A. J. Hanford, J. A. Hogan, J. A. Joshi, D. A. Vaccari and H. W. Jones, *Advanced Life Support Equivalent System Mass Guidelines Document,* NASA Ames Research Center, Moffett Field, California, U.S., 2003.

[4] H. W. Jones, *Equivalent Mass versus Life Cycle Cost for Life Support Technology Selection,* NASA Ames Research Center, Moffett Field, California, U.S., 2003.

[5] T. J. Richardson and D. Jan, *A Trade-off Study of the Spacecraft Carbon Dioxide Management System using the Analytical Hierachy Process,* presented at 48th International Conference on Environment Systems, 8-12 July 2018, Albuquerque, New Mexico, U.S..

[6] B. Schreck, *Feasibility Analysis of a Life Support Architecture for an Interplanetary Transport Ship,* Technical University of Munich: Master Thesis, 2017.

[7] C. Olthoff, D. Pütz and J. Schnaitmann, *Dynamic Life Support System Simulation With V-HAB,* presented at Deutscher Luft- und Raumfahrtkongress, 2015, Rostock, Germany.

[8] W. Gerstenmaier and J. Crusan, *Cislunar and Gateway Overview,* Presentation, 2018.

[9] J. Free, *Architecture Status,* Presentation: NASA, HEOMD, 2017.

[10] S. T. Force, *The Post-Apollo Space Program: Directions for the Future,* NASA, September 1969.

[11] R. W. Farquhar, *A Halo-Orbit Lunar Station,* NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S., 1972.

[12] W. Harwood, “Spaceflight Now,” 16 March 2017. [Online]. Available: https://spaceflightnow.com/2017/03/16/trump-budget-blueprint-focuses-on-deep-space-exploration-commercial-partnerships/. [Accessed 20 November 2018].

[13] M. L. McGuire, N. J. Strange, L. M. Burke, S. L. McCarty, G. B. Lantoine, M. Qu, H. Shen, D. A. Smith and M. A. Vavrina, *Overview of the Mission Design*

Reference Trajectory for NASA's Asteroid Redirect Robotic Mission, NASA, 2017.

[14] M. Ewert, J. Broyan, K. Goodliff, M. Clowdsley and R. Singleterry, *Comparing Trash Disposal and Reuse Options for Deep Space Gateway and Mars Missions,* NASA Johnson Space Center and Langley Research Center, 2018.

[15] “Tech Port,” 15 November 2018. [Online]. Available: https://techport.nasa.gov/view/14651. [Accessed 5 December 2018].

[16] NASA, *Gateway Memorandum for the Record,* 2018.

[17] ISECG, *The Global Exploration Roadmap,* 2011.

[18] J. NASA, *NASA-JAXA Joint Statement on Collaboration Efforts for Lunar Exploration and Beyond,* 2018.

[19] “ROSCOSMOS,” 27 September 2017. [Online]. Available: https://www.roscosmos.ru/24136/. [Accessed 5 December 2018].

[20] P. Rakobowchuk, “Global News,” 29 September 2017. [Online]. Available: https://globalnews.ca/news/3775926/canadian-space-agency-robotic-arms/. [Accessed 5 December 2018].

[21] “ESA,” 11 March 2019. [Online]. Available: https://m.esa.int/Our_Activities/Human_and_Robotic_Exploration/Gateway_to_the_Moon. [Accessed 1 April 2019].

[22] J. A. Robinson, *Update on Gateway with Science and Technology (Utilization) Discussion,* NASA Johnson Space Center, presented at Aeronautics and Space Engineering Board, 162nd Meeting, Irvine, California, 2018.

[23] E. Mahoney, “NASA,” 19 June 2018. [Online]. Available: https://www.nasa.gov/feature/nasa-seeks-ideas-for-commercial-uses-of-gateway. [Accessed 11 November 2018].

[24] NASA, *Orioin - Quick Facts,* NASA Johnson Space Center, Houston, Texas, U.S..

[25] T. Gill, *NASA's Lunar Orbital Platform-Gateway,* presented at 45th Space Congress, Cape Canaveral, Florida, U.S., 2018.

[26] *Next Space Technologies for Exploration Partnerships-2 (NextSTEP-2) Omnibus Broad Agency Announcement (BAA),* Washington, D.C.: NASA, 2017.

[27] “NASA,” 27 April 2019. [Online]. Available: https://www.nasa.gov/nextstep. [Accessed 27 April 2019].

[28] *Deep Space Gateway (DSG) Concept Power and Propulsion Element (PPE) Request for Information,* NASA, 2017.

[29] “OHB,” 28 September 2018. [Online]. Available: https://www.ohb.de/de/news/ohb-an-esprit-modul-fuer-kuenftiges-gateway-im-mond-orbit-beteiligt/. [Accessed 27 April 2019].

[30] N. T. Redd, “Space,” 8 September 2018. [Online]. Available: https://www.space.com/41764-nasa-lunar-gateway-lockheed-martin-habitat-module.html. [Accessed 13 November 2018].

[31] “Northrup Grumman,” 31 July 2018. [Online]. Available: https://news.northropgrumman.com/news/features/from-space-station-cargo-delivery-to-deep-space-crew-habitats-northrop-grummans-versatile-cygnus-spacecraft. [Accessed 13 November 2018].

[32] „SpaceRef,“ 18 August 2015. [Online]. Available: http://spaceref.biz/company/bigelow-aerospace-and-nasa-execute-nextstep-contract-to-study-b330-utilization.html. [Zugriff am 14 November 2018].

[33] G. Scarano, “Geek,” 5 April 2019. [Online]. Available: https://www.geek.com/news/nasa-starts-testing-habitat-designs-for-its-lunar-gateway-space-station-1781682/. [Accessed 27 April 2019].

[34] J. Crusan and R. Gatens, *Cislunar Habitation & Environmental Control & Life Support Systems,* NASA AES, 2017.

[35] J. Valania, *Progress and Plans for Sierra Nevada Corporation's NextSTEP-2 Deep Space Habitat,* presented at AIAA SPACE and Astronautics Forum and Exposition, 14-17 September 2017, Orlando, Florida, U.S..

[36] “StarPosts,” 12 June 2017. [Online]. Available: https://www.starposts.space/blog/2018/4/6/new-chapter-opens-for-commercial-space-nanoracks-and-nasa-sign-nextstep-contract-for-commercial-habitat-concept-study. [Accessed 27 April 2019].

[37] M. Miyake, *Global Partnership for Space Exploration,* presented at High Level Forum, November 7, 2017.

[38] C. Webb, „NASA,“ 17 March 2019. [Online]. Available: https://www.nasa.gov/feature/multilateral-coordination-board-joint-statement. [Zugriff am 15 May 2019].

[39] “CSEF,” 22 October 2017. [Online]. Available: http://csef.ru/en/politica-i-geopolitica/223/roskosmosu-doverili-stroitelstvo-shlyuzovogo-modulya-na-mezhdunarodnoj-lunnoj-orbitalnoj-stanczii-8050. [Accessed 2 February 2019].

[40] J. Crusan, *Future Human Exploration Planning: Lunar Orbital Platform-Gateway and Science Workshop Findings,* NASA AES, 2018.

[41] R. Jones, *International Space Station Overview Research and On-Orbit Facilities Non-Partner Participation,* NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S., 2011.

[42] T. Fong, *Autonomy and the Gateway - Human-Robotic Systems and Operations,* NASA, 2018.

[43] P. Eckart, in *Spaceflight Life Support and Biospherics*, Torrance, Calif., Dordrecht, Boston: Microcosm Press, Kluwer Academic, 1996, pp. 79-81.

[44] M. Miller Shaw, *An Analysis of Hybrid Life Support Systems for Sustainable Habitats,* Massachusetts Institute of Technology: Master Thesis, 2014.

[45] J. Metcalf, R. Carrasquillo, L. Peterson, B. Bagdigian and D. Westheimer, *Environmental Control and Life Support (ECLS) Integrated Roadmap Development,* Houston, Texas: Tech. Rep., NASA, 2011.

[46] P. Guirgis, W. West, M. Heldmann und D. Samplatsky, *Beyond LEO: Life Support Requirements and Technology Development Strategy,* presented at 44th International Conference on Environmental Systems, 13-17 July 2014, Tucson, Arizona, U.S..

[47] H. W. Jones, *Design and Analysis of a Flexible, Reliable Deep Space Life Support System,* Ames Research Center, Moffet Field, California, U.S., 2012.

[48] P. O. Wieland, *Living Together in Space: The Design and Operation of the Life Support Systems on the International Space Station,* NASA Marshall Space Flight Center, Huntsville, Alabama, U.S., 1998.

[49] L. Carter, J. Wiliamson, A. Brown, J. Bazley, D. Gazda, R. Schaezler und F. Thomas, „Status of ISS Water Management and Recovery," in *48th International Conference on Environmental Systems*, Albuquerque, New Mexico, U.S., 8-12 July 2018.

[50] B. Frages, L. Poughon, C. Creuly, J.-F. Cornet, C.-G. Dussap and C. Lasseur, *Dynamic Aspects and Controllability of the MELiSSA Project: A Bioregenerative System to Provide Life Support in Space,* Humana Press, 2008.

[51] R. D. MacElroy and D. T. Smernoff, *Controlled Ecological Life Support System,* presented at XXVI COSPAR meeting, Toulouse, France, 1986.

[52] D. Barta, *Advanced Life Support Systems,* NASA, Johnson Space Center, Houston, Texas, U.S., 2004.

[53] H. W. Jones, E. W. Hodgson, G. J. Gentry and M. H. Kliss, *How Do Lessons Learned on the International Space Station (ISS) Help Plan Life Support for Mars?,* presented at 46th International Conference on Environmental Systems, 10-14 July 2016, Vienna, Austria.

[54] J. Dino and B. Dunbar, “NASA,” 29 March 2008. [Online]. Available: https://www.nasa.gov/centers/ames/research/technology-onepagers/advanced-life-support.html. [Accessed 28 April 2019].

[55] “Dynetics,” 2 January 2018. [Online]. Available: https://www.dynetics.com/newsroom/news/2018/dynetics-to-build-carbon-dioxide-scrubbers-for-space. [Accessed 14 November 2018].

[56] J. Crusan, *HEOMD's Advanced Exploration Systems - Status Update,* NASA HEOMD, 2015.

[57] R. C. Richter, *Orbital Technologies Corporation (ORBITEC) - Implementation Partner.*

[58] E. Messerschmid and R. Bertrand, in *Space Stations - Systems and Utilization*, Stuttgart, Springer-Verlag Berlin Heidelberg GmbH, 1999, pp. 109-113.

[59] NASA, *NASA Space Flight Human-System Standard - Volume 2: Human Factors, Habitability, and Environmental Health,* Washington, D.C., U.S., 2015.

[60] J. L. Perry, M. J. Sargusingh and N. Toomarian, *Guiding Requirements for Designing Life Support System Architectures for Crewed Exploration Missions beyond Low-Earth Orbit,* presented at AIAA SPACE 2016, 2016.

[61] N. E. A. W. Group, *Recommendations for Exploration Spacecraft Internal Atmospheres: The Final Report of the NASA Exploration Atmospheres Working Group,* 2016.

[62] C. Olthoff, *Lebenserhaltungssysteme Teil 1: Physikalisch-Chemische Systeme,* presented at Technical University of Munich, 2016.

[63] NASA, *Spacecraft Maximum Allowable Concentrations for Airborne Contaminants,* NASA Johnson Space Center, Houston, Texas, U.S., 2008.

[64] J. T. James and S. M. Zalesak, *Surprising Effects of CO2 Exposure on Decision Making,* presented at AIAA 43rd International Conference on Environmental Systems, Vail, Colorado, U.S., 2013.

[65] NASA, *Human Integration Design Handbook (HDIH),* NASA, Washington, D.C., US, 2010.

[66] M. Anderson, M. K. Ewert, J. F. Keener und S. A. Wagner, *Life Support Baseline Values and Assumptions Document,* NASA Johnson Space Center, Houston, Texas, U.S., 2015.

[67] H. Y. Yeh, C. B. Brown, F. F. Jeng, C. H. Lin and M. K. Ewert, *ALSSAT Development Status and its Application in Trade Studies,* Lockheed Martin Space Operations Company, NASA Johnsons Space Center, Houston, Texas, U.S., 2004.

[68] G. Detrell and S. Belz, *ELISSA - a comprehensive software package for ECLSS technology selection, modelling and simulation for human spaceflight missions,* presented at 47th International Conference on Environmental Systems, Charleston, South Carolina, U.S., 16-20 July 2017.

[69] E. Agrupados, *Installation & Getting Started Guide, Version 4.8,* 2010.

[70] D. Kortenkamp and S. Bell, *BioSim: An Integrated Simulation of an Advanced Life Support System for Intelligent Control Research,* presented at International Symposium on Artificial Intelligence, Robotics and Automation in Space, Nara, Japan, 2003.

[71] M. Anderson, *Summary of Water Processing Trade Studies and Analysis of JSC Integrated Water Recovery System,* NASA Johnson Space Center, Houston, Texas, U.S., 2004.

[72] G. Boscheri, V. Guarmieri, S. Chirico, P. Zabel and C. Lasseur, *SCALISS: A Eurpean tool for automated SCaling of LIfe Support Systems,* presented at 47th International Conference on Environmental Systems, 16-20 July 2017, Charleston, South Carolina, U.S..

[73] M. Czupalla, V. Aponte, S. Chappell and D. Klaus, *Analysis of a spacecraft life support system for a Mars mission,* University of Applied Sciences, Aachen, Germany and University of Colorado, Boulder, Colorado, U.S., 2003.

[74] T. Binder, E. Nathanson, S. Belz and S. Fasoulas, *Efficient Evaluation Method of System Concepts for Preliminary ECLSS Design Studies,* presented at 44th International Conference on Environmental Systems, 13-17 July 2014, Tucson, Arizona, U.S..

[75] E. E. Matula and J. A. Nabity, *Feasibility of Photobioreactor Systems for use in Multifunctional Environmental Control and Life Support System for Spacecraft and Habitat Environments,* presented at 46th International Conference on Environmental Systems, 10-14 July 2016, Vienna, Austria.

[76] S. Jaatinen, A. Lakaiemi and J. Rintala, *Use of diluted urine for cultivation of Chlorella vulgaris,* Environmental Technology, 2015.

[77] J. Keppler, S. Belz, G. Detrell, H. Helisch, J. Martin, N. Henn, S. Fasoulas, R. Ewald, O. Angerer and H. Hartstein, *The final configuration of the algae-based ISS experiment PBR@LSR,* presented at 48th International Conference on Environmental Systems, 8-12 July, Albuquerque, New Mexico, US.

[78] N. Henn, “DLR,” [Online]. Available: https://www.dlr.de/rd/desktopdefault.aspx/tabid-2277/3405_read-45348/. [Accessed 21 March 2019].

[79] S. Carlson, *GRAS Excemption Claim for Chlorella Vulgaris as an Ingredient in Foods.*

[80] P. Eckart, in *Spaceflight Life Support and Biospherics*, Torrance, California, Dordrecht, Boston: Microcosm Press, Kluwer Academic, 1996, pp. 188-189.

[81] H. W. Jones, J. W. Fisher, L. D. Delzeit, M. T. Flynn and M. H. Kliss, *Developing the Water Supply System for Travel to Mars,* presented at 46th International Conference on Environmental Systems, 10-14 July 2016, Vienna, Austria.

[82] S. R. Hirshorn, *NASA Systems Enigneering Handbook, Rev2,* Washington, D.C., U.S., 2016.

[83] W. J. Larson and L. K. Pranke, Human Spaceflight: Mission Analysis and Design, New York: McGraw-Hill, 200.

[84] L. Langston, *Generic Groundrules, Requirements, and Constraints Part 1: Strategic and Tactical Planning,* NASA Lyndon B. Johnson Space Center, Houston, Texas, U.S., 2012.

[85] H. Jiang, L. F. Rodríguez, S. Bell, D. Kortenkamp and F. Capristan, “Predicition of Reliability and Cost for Environmental Control and Life Support Systems,” *Journal of Spacecraft and Rockets, vol 48,* pp. 336-345, March 2011.

[86] H. W. Jones, *Would Current International Space Station (ISS) Recycling Life Support Systems Save Mass on a Mars Transit?,* presented at 47th International Conference on Environmental Systems, 16-20 July 2017, Charleston, South Carolina, U.S..

[87] E. Triantaphyllou, in *Mulit-Criteria Decision Making Methods: A Comparative Study*, Dordrecht, Springer Science+Business Media, 200, pp. 1-3.

[88] T. J. Richardson and D. Jan, *A Trade-off Study of the Spacecraft Carbon Dioxide Management System using the Analytical Hierachy Process,* presented at 48th International Conference on Environmental Systems, 8-12 July 2018, Albuquerque, New Mexico, U.S..

[89] E. Triantaphyllou and A. Sánchez, “A Sensitivity Analysis Approach for Some Deterministic Multi-Criteria Decision Making Methods,” *Decision Sciences, vol. 28,* pp. 151-194, Winter 1997.

[90] NASA, „Trade-off Study and Conceptual Designs of Regenerative Advanced Integrated Life Support Systems (AILSS),“ Tech Library, NM, Washingtion, D.C., U.S., 1970.

[91] M. K. Ewert and F. F. Jeng, *Will Astronauts Wash Clothes on the Way to Mars?,* presented at 45th International Conference on Environmental Systems, 12-16 July 2015, Bellevue, Washington, U.S..

[92] M. Sakurai, M. Oguchi, S. Yoshihara and M. Ohnishi, *Water Electrolysis Cells that are Free Liquid-Gas Separation System for Microgravity Conditions in order to Establish Circulated Life Support System,* JAXA, Chofu, Tokyo, Japan.

[93] C. Lobascio, M. Lamantea, V. Cotronei, B. Negri, S. De Pascale, A. Maggio, M. Foti and S. Palumberi, “Plant bioregenerative life supports: The Italian CAB Project,” *Journal of Plant Interactions,* pp. 125-134, 2007.

[94] C. Norberg, in *Human Spaceflight and Exploration*, Heidelberg New York Dordrecht London, Springer Verlag, 2013, p. 195.

[95] J. Rhian, “SpaceFlligh Iinsider,” 27 September 2014. [Online]. Available: https://www.spaceflightinsider.com/missions/commercial/nasa-continues-commercial-push-crs-extension/. [Accessed 12 March 2019].

[96] S. Dent, “Engadget,” 27 April 2018. [Online]. Available: https://www.engadget.com/2018/04/27/spacex-price-hikes-iss-resupply-costs/?guccounter=1&guce_referrer_us=aHR0cHM6Ly93d3cuZ29vZ2xl%E2%80%A6. [Accessed 12 March 2019].

[97] C. Warner, S. Schierholz and D. Huot, “NASA,” 7 August 2017. [Online]. Available: https://www.nasa.gov/press-release/nasa-awards-international-space-station-cargo-transport-contracts. [Accessed 13 March 2019].

[98] NASA, *Commercial Crew Transportation.*

[99] J. L. Broyan, A. Chu and M. K. Ewert, *Logistics Reduction and Repurposing Technology for Long-Duration Space Missions,* presented at 44th International Conference on Environmental Systems, 13-17 July 2014, Tuscon, Arizona, U.S..

[100] H. Thronson, *Human Exploration Beyond LEO by the End of the Decade: Designs for Long-Duration "Gateway" Habitats,* presented at FISO Telecon Colloquium, 15 December 2010.

[101] S. Shull, E. Gralla, O. de Weck, A. Siddiq and R. Shishko, *The Future of Asset Management for Human Space Exploration,* Cambridge, Massachusetts, US, 2006.

[102] NASA, *Orbital-2 Mission to the International Space Station - Media Press Kit,* 2014.

[103] A. Siddiqi, O. de Weck, G. Y. Lee and S. A. Shull, “Matrix Modelling Methods for Spaceflight Campaign Logistics Analysis,” *Journal of Spacecraft and Rockets, vol. 46, no. 5,* pp. 1037-1048, September-October 2009.

[104] NASA, „Official NASA YouTube Channel,“ 1 April 2019. [Online]. Available: https://www.youtube.com/watch?v=o2gz2E-Wrws&t=2123s. [Zugriff am 1 April 2019].

[105] C. Walz, *Cygnus Beyond Low-Earth Orbit – Logistics and Habitation in Cis-Lunar Space,* Northrop Grumman presentation.

[106] W. Carvey, Y. Karouji, T. Haltigin, G. Osinski, U. Mall, K. Hashizume, M. Landgraf and H. Hiesinger, *HERACLES: An ESA-JAXA-CSA Joint Study on Returning to the Moon,* presented at 50th Lunar and Planetary Science Conference 2019, 2019.

[107] M. Landgraf, *HERACLES - Preparing Human Exploration by Integrated Certification of Crew and Hardware for Lunar Surface Operations,* ESA/ESTEC, 2016.

[108] “Lockheed Martin,” 3 October 2018. [Online]. Available: https://news.lockheedmartin.com/2018-10-03-Lockheed-Martin-Reveals-New-Human-Lunar-Lander-Concept. [Accessed 12 February 2019].

[109] *Next Space Technologies for Exploration Partnerships-2 (NextSTEP-2) Appendix E: Human Landing System Studies, Risk Reduction, Development and Demonstration,* Washington, D.C., U.S.: NASA AES, 2019.

[110] J. Wattles, “CNN,” 5 August 2018. [Online]. Available: https://money.cnn.com/2018/08/05/news/companies/goodyear-delta-faucet/index.html. [Accessed 27 April 2019].

[111] “NASA,” 15 February 2019. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/fy_2019_agency_fact_sheet.pdf. [Accessed 27 April 2019].

[112] *Gateway Commercial Opportunities - Request for Information,* NASA, 2018.

[113] “NSSDC,” [Online]. Available: https://nssdc.gsfc.nasa.gov. [Accessed 3 March 2019].

[114] NASA, *Orbital-2 Mission to the Internation Space Station - Media Press Kit, Version 1,* 2014.

[115] NASA, *Orbital CRS-3 Mission to the Internation Space Station - Media Press Kit, Version 1,* 2014.

[116] NASA, *Orbital ATK CRS-4 Mission Overview.*

[117] NASA, *Orbital ATK CRS-5 Mission Overview.*

[118] NASA, *Orbital ATK CRS-6 Mission Overview.*

[119] SpaceX, *SpaceX CRS-5 Mission Cargo Resupply Services - Press Kit,* 2015.

[120] SpaceX, *SpaceX CRS-6 Mission Cargo Resupply Services Mission - Press Kit,* 2015.

[121] SpaceX, *SpaceX CRS-7 Mission Cargo Resupply Services Mission - Press Kit,* 2015.

[122] I. Abramov and I. Skoog, Russian Spacesuits, Chichester, UK: Praxis Publishing Ltd., 2003.

B Initial scaling reference points of life support technologies

Table 9-1: Initial scaling reference points [48], [74]

Technology	**Mass [kg]**	**Volume [m^3]**	**Power [W]**	**Cooling [W]**	**Resupply [kg/d]**	**Scaling Reference Point**
2BMS	48.1	0.26	230	230	0.02	Data given for HEU of 3
4BMS	87.9	0.33	535	535	0.024	Data given for CO_2 input of 4 kg/d
CAMRAS	7.26	0.3	12	0	0	Data given for HEU of 1
EDC	44.4	0.07	42	336	0.012	Data given for CO_2 input of 4 kg/d
SAWD	51.3	0.21	344	344	0.014	Data given for CO_2 input of 3 kg/d
ACRS	180	0.3	400	150	0	Data given for HEU of 3
Bosch	102.1	0.3	950	313	0.028	Data given for CO_2 input of 4 kg/d
COE	356	0.28	13,300	3,500	0	Data given for CO_2 input of 36.8 kg/d
Sabatier	43	0.18	50	289	0.012	Data given for CO_2 input of 5 kg/d
CCAA	112	0.4	468	468	0	Scaled according to 0.29 kg/h condensate processing rate of one CCAA
MF	489.1	2.26	1,021	1,021	1.64	Data given for wastewater input of 50.9 kg/d
AES	45.3	0.15	578	577	0.071	Data given for urine input of 7.64 kg/d
TIMES	68	0.23	170	170	0.05	Data given for wastewater output of 22 kg/d
VCD	245.7	0.88	1,429	429	0.828	Data given for wastewater output of 9.09 kg/d
VPCAR	412	1.57	2,380	2,380	0.005	Data given for wastewater output of 50.9 kg/d
SFWE	113	0.14	1,470	39	0	Data given for HEU of 4
SPWE	416	1.7	1,035	26.5	0.114	Data given for O_2 output of 5.3 kg/d

C Gateway: U.S. Habitat

C.1 Lockheed Martin

Lockheed Martin’s design approach is focused on using the Donatello Multi-Purpose Logistics Module (MPLM) as test equipment. MPLM was initially built to bring cargo to and from the ISS. Lockheed Martin’s engineering model is planned to be completed in January 2019 with ground tests being conducted shortly afterwards. According to Lockheed Martin, the size of their habitat is 4.6 m wide and 6.7 m long resulting in a total pressurized volume of 64 m^3 which is designed to support human presence for 90 days [30].

C.2 Northrop Grumman

Northrup Grumman designs a habitat based on their commercial human rated Cygnus spacecraft from which they intend to reuse hardware and technology. Apart from the known dimensions and payload capabilities of Cygnus to LEO, no additional information about the design has been published as of April 2018 [31].

C.3 Bigelow Aerospace Corporation

Bigelow Aerospace Corporation (BAC) was founded with the goal of advancing space commercialization by constructing small near-Earth orbital space stations that could then be leased by potential users such as governmental or commercial organizations and companies. A 16 m^3 inflatable module called Bigelow Expandable Activity Module was successfully tested on the ISS in 2016. In addition, NASA was investigating whether B330, another expandable module of BAC with a pressurized volume of 330 m^3, could be used as a depot in a lunar orbit under the first NextSTEP program in 2015. Despite no final information about this investigation having been released yet, it can be assumed that the results thereof will influence BAC’s design of the U.S. Habitat. Ground tests of this habitat are expected to be performed in April 2019 [32], [33], [34].

C.4 Boeing

Boeing’s design concept is based on using existing technology and the company’s experience gained whilst serving as NASA’s prime contractor for building ISS assets as well as constructing GEO satellite busses for the aerospace industry. In addition, Boeing leverages NASA workforce by receiving support from various NASA centers such as Jet Propulsion Laboratory, Johnson Space Center, Marshall Space Flight Center and the University of Southern California. According to NASA, Boeing’s concept involves an innovative modular approach for subsystem integration. First ground tests are planned to be conducted at Marshall Space Flight Center in 2018, however no information whether this timeline could be met or any further details about potential test results have been published as of January 2019 [34].

C.5 Sierra Nevada Corporation

In August 2018, SNC completed its design study for a potential PPE configuration called Solar Electric Propulsion Module within NASA’s NextSTEP-2 program. Under a separate NextSTEP-2 contract, SNC builds a prototype on a scale of 1:3 of a deep space habitat in partnerships with Aerojet Rocketdyne and ILC Dover. This prototype consists of a Large Inflatable Fabric Environment (LIFE) which provides the living and experiment processing area for the crew and a Logistics and Control Module (LCM) that serves as an assembly node and houses the life support components. The design of LIFE is based on ILC Dover's commercial Resilient Tunnel Plug and TransHab technology whereas the LCM is derived from the Commercial Resupply Services (CRS2) cargo module. SNC's habitat design approach also leverages technologies developed for Dream Chaser, a reusable lifting body spaceplane designed within NASA's Commercial Crew Development and CRS2 programs to resupply the ISS with both unpressurized and pressurized cargo and to enable human transportation of up to eight crew into LEO. In particular the vehicle's ECLSS is adapted and modified in order to fulfil the life support requirements of a deep space habitat [34], [35].

C.6 NanoRacks

Separate from the companies that design and develop a habitat prototype, NanoRacks examined the feasibility of converting a rocket upper stage into a habitat (“wet lab”) called Ixion under NASA's NextSTEP-2 program. In this respect, NanoRacks pursues NASA's design approach for the Skylab space station which was built out of a second stage of a Saturn IB rocket (AS-212). Contrary to NASA that outfitted the stage on earth and launched it with a Saturn V rocket in 1973, NanoRacks intends to modify a Centaur upper stage of the ATLAS V rocket in orbit solely using robotics. In doing so, NanoRacks partners with Space Systems Loral and United Launch Alliance. After having successfully completed the initial study in 2017, NanoRacks received a new NASA contract for a study of a commercial habitat which was renamed from Ixion to Independence-1 in 2018. NASA and NanoRacks hope to lower development and manufacturing costs significantly by repurposing in-space hardware. It is also desired to investigate whether this habitat design approach can be applied to any upper stage including that of the SLS [34], [36].

D Gateway: Mission scenarios and further usage

One potential robotic mission employing the Gateway is the Human-Enhanced Robotic Architecture and Capability for Lunar Exploration and Science (HERACLES) project initiated and developed by ESA and JAXA [106]. With HERACLES, the European and Japanese space agencies aim at exploring lunar terrain prior to the arrival of astronauts and return samples back to Earth to investigate the feasibility of ISRU. Furthermore, HERACLES is meant to demonstrate and achieve human rating of crucial technologies such as the lander's engines as well as an autonomous Guidance, Navigation and Control system for descent, landing, ascent and rendezvous for future manned lunar missions. The planned architecture consists of multiple stages: a reusable ascent element, a descent element and a rover. The ascent element returns frequently to the Gateway where it would be captured by the robotic arm and transfers samples to the Orion spacecraft for transportation back to Earth. These samples have been collected by the rover that had been dispatched by the descent element on the lunar surface. The first lunar lander with a total mass of 11 t is intended to be launched with an Ariane 64 during the late 2020s [107].

Lockheed Martin proposed a concept for a single stage reusable lunar landing system that would be able to carry a crew of four and approximately 900 kg of additional payload to the lunar surface [108]. The current design leverages technologies used by the Orion spacecraft and offers stays of up to 14 days on the surface before returning to the Gateway where it is meant to be refuelled. According to Lockheed Martin, this lander could also be utilized to transport commercial or scientific cargo or for establishing a lunar base. The lander's design is Lockheed Martin's response to NASA asking the U.S. industry to provide new approaches for advancing the goal defined by the U.S. space policy directive-1 of returning humans to the moon. In January 2019, NASA officially included the appendix Human Landing System Studies, Risk Reduction, Development and Demonstration to their NextSTEP-2 program. NASA's HLS architecture comprises of descent, ascent, refuelling and surface suit elements as well as a transfer vehicle. Within the scope of the NextSTEP-2 project, NASA expects to receive proposals for design, cost, schedule and maturation of the descent, refuelling and transfer vehicle elements [109].

Commercial usage of the ISS currently includes research and technology development activities via the Center of Advancement of Science in Space (CASIS) for example - a non-profit organization managing and selecting the experiments meant to be conducted in the ISS United States Laboratory.

As of August 2018, more than 50 percent of all payloads brought to the ISS by CASIS came from the private sector [110]. Space agencies involved in the ISS project seek opportunities to further advance commercialization to compensate for budget cuts or to lower their operational costs. The U.S. federal budget request of 2019 shows a stop of funding of the ISS in 2025 but demands $ 150 million to develop LEO privatization capabilities to be employed by companies or NASA [111]. In contrast to the ISS, commercial utilization of the Gateway is planned to play a major role in future operation of the station. NASA has recognized that in order to allow for the Gateway's long-term sustainability, potential stakeholders need to be involved in the project as early as possible. Therefore, Gateway capabilities shall not only support scientific research but also correspond to the respective needs of stakeholders. NASA incorporates the U.S. industry in identifying commercial applications of the station via a Request for

Information on topics concerning resupply of the Gateway such as flight frequency and crew and cargo transportation, resource requirements and hindrances for commercialization [112].