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Development of the Atmosphere Management System of the EDEN Next Gen greenhouse module for long-term space missions

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Zum

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DIPLOMINGENIEUR

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Thema: Entwicklung eines Atmosphärenmanagememtsystems des EDEN Next Generation Greenhouses für zukünftige Raumfahrtmissionen

Subject: Development of the Atmosphere Management System of the EDEN Next Generation greenhouse for future long-term space missions

Motivation:

Due to the increasing interest in missions to Moon and Mars new challenges concerning life support systems arise. For such manned, long-term missions it needs innovative concepts to provide food for the crew. This is only possible by using local resources or by producing commodities in-situ. The second option can be realized by using a greenhouse which comes along with several benefits. In this thesis the focus will be on the Atmosphere Management System (AMS) of such a greenhouse. The AMS regulates the temperature, the humidity, the ventilation and the CO_2 level inside the greenhouse. Main objective is to transfer the knowledge and the lessons-learned from laboratory conditions to space environment conditions. The aim is to develop and dimension an AMS for the EDEN Next Generation greenhouse. EDEN Next Generation greenhouse is the next step towards a space-based greenhouse module to supply a crew of six astronauts.

Aufgaben:

- Literature research on AMS and its components with respect to the present state of the art at space applications
- Transfer the gathered knowledge from literature research into functional and technical requirements for the AMS of the greenhouse module
- Generate a functional diagram and define the system boundaries of the AMS
- Create a system model and defining its input and output parameters quantitatively in order to the established general parameters
- Determine the individual necessary performances to regulate the temperature, the humidity, the ventilation and the CO2 level inside the greenhouse
- Execute a technology trade-off for AMS components followed by designing and sizing the different components with respect to their necessary performance
- Design of suitable interfaces to other sub-systems of the greenhouse and to AMS of the habitat

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Ausgabe: 01.10.2020
Abgabe: 28.02.2021

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Ich bestätige hiermit, dass ich die Aufgabenstellung sowie die rechtlichen Bestimmungen und die Studien- und Prüfungsordnung gelesen und verstanden habe.

Prof. Dr. Martin Tajmar	Betreuer	Prof. Dr. Martin Tajmar	Studierende(r)
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Declaration of authorship

I declare that the final thesis "Development of the Atmosphere Management System of the EDEN Next Gen greenhouse module for long-term space missions" presented to the Institute of Aerospace Engineering of the Faculty of Mechanical Science and Engineering is my own unaided work. All direct or indirect sources used are acknowledged as references. This thesis was not previously presented to another examination board.

Selbstständigkeitserklärung

Hiermit erkläre ich, dass ich die von mir dem Institut für Luft- und Raumfahrttechnik der Fakultät Maschinenwesen eingereichte Diplomarbeit zum Thema „Entwicklung eines Atmosphärenmanagememtsystems des EDEN Next Generation Greenhouses für zukünftige Raumfahrtmissionen“ selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt sowie Zitate kenntlich gemacht habe.

Bremen, 26.02.2021 J. Schroth

Julius Schroth place, date, signature

Declaration of authorship

Lists of abbreviations

Abbreviation	Meaning
2BMS	two-bed molecular sieve
4BMS	four-bed molecular sieve
A	assumption
ACC	air composition control
aH	absolute humidity
AM	ante meridiem
AMS	atmosphere management systems
AQM	air quality monitor
AS	Arescosmo
AR	air revitalization
ARS	atmosphere revitalization system
CAD	computer-aided design
CASEO	cabin air separator for EVA oxygen
CCAA	common cabin air assembly
CDHS	control and data handling system
CEA	controlled environment agriculture
CEF	concurrent engineering facility
CFD	computational fluid dynamics
CFU	carbon formation unit
CHIPS	charcoal HEPA integrated particle scrubbers
CHX	condensing heat exchanger
C.R.O.P.	combined regenerative organic food production
ctrl	control
D	depth
DC	direct current
DLR	Deutsches Zentrum für Luft- und Raumfahrttechnik (German aerospace center)
DP	dew point
EDC	electrochemical depolarized CO_2 concentration
EDEN	evolution and design of environmentally-closed nutrition-sources
EN	europäische Norm (European standard)
ESA	European space agency
EVA	extra-vehicular activity
FEG	future exploration greenhouse
FR	functional requirement
GC-DMS	gas chromatograph - differential mobility spectrometer
Gen	generation
GHM	greenhouse module
H	height
HEPA	high efficiency particulate arrestance
ILS	illumination system
ISECG	international space exploration and coordination group
ISO	International organization for standardization
ISPR	international standard payload rack

Lists of abbreviations

Abbreviation	Meaning
ISS	international space station
JEM	Japanese experiment module
L	length
LED	light-emitting diode
LEO	low earth orbit
LL	lesson learned
LSS	life support systems
LSG	Liquifer Systems Group
MCA	major constituent analyzer
MLGH	mars-lunar greenhouse
MLI	multilayer insulation
MTF	mobile test facility
NASA	national aeronautics and space administration
NDS	nutrient delivery system
NM III	Neumayer station III
ORBITEC	orbital technologies corporation
ORU	orbital replacement unit
PALACE	permanent astrobase life-support artificial closed ecosystem
PAR	photosynthetic active radiation
PBR	PhotoBioReaktor
PCDS	power control and distribution system
PM	post meridiem
ppb	parts per billion
ppm	parts per million
rH	relative humidity
SAWD	solid amine water desorption
SFOG	solid fuel oxygen generator
SI	support infrastructure
SLS	space launch system
SMAC	spacecraft maximum allowable concentration
tbd	to be determined
TCCS	trace contaminant control subassembly
TCS	thermal control system
THC	temperature and humidity control
TRL	technology readiness level
US	United States
USOS	United States on-orbit segment
UV	ultraviolet
UV-C	ultraviolet C
VAC	voltage alternating current
Veggie	vegetable production system
VOA	volatile organic compounds
VOC	volatile organic compound
VRV	vent and relieve valve
W	width
WRM	water recovery and management

List of formula symbols and constants

Symbol	Unit	Description
aH; aH_{input}; aH_{output}	$\frac{g}{kg}$	absolute humidity; absolute humidity at cultivation area input; absolute humidity at cultivation area output
A; A_c; $A_{distribution}$; $A_{ducts\ total}$; $A_{main\ ducts}$; $A_{membrane}$; A_{rigid}; A_t; A_{total}	m^2	area/cross-section area; cultivation area; cross-section area of air distribution ducts; total cross-section area of ducts; cross-section area of main ducts; area of membrane; area of outer wall of rigid sections; tray area; total area of outer wall
C	---	carbon
C_c; C_r	---	conduction constant; radiation constant
$c_{p\ air}$	$\frac{kJ}{kg\ K}$	specific heat at constant pressure of air
CH_4	---	methane
CO_2	---	carbon dioxide
d; $d_{deployable\ part}$; d_{rigid}	m	diameter; diameter of the deployable part; diameter of the rigid part
E_{therm}	J	thermal energy
g_M	$\frac{m}{s^2}$	gravity acceleration on the Moon
H_2	---	hydrogen
H_2O	---	water
H_2S	---	hydrogen sulfide
ΔH_{water}	$\frac{kJ}{kg}$; $\frac{Wh}{kg}$	enthalpy of vaporization/condensation of water
K	---	potassium
$KMnO_4$	---	potassium permanganate
l; $l_{deployable\ part}$; l_{rigid}	m	length; length of deployable part; length of the rigid part
$LiClO_4$	---	lithium perchlorate
Li_2CO_3	---	lithium carbonate
LiOH	---	lithium hydroxide

Symbol	Unit	Description
$\dot{m}$; $\dot{m}_{air}$; $\dot{m}_{condensation}$; $\dot{m}_{CO_2}$; $\dot{m}_{ethylene}$; $\dot{m}_{H_2O\ transpiration}$; $\dot{m}_{O_2}$; $\dot{m}_{O_2 production}$; $\dot{m}_{O_2 resupply}$	$\frac{kg}{h}$; $\frac{kg}{day}$; $\frac{g}{day}$; $\frac{l}{day}$	mass flow rate; air mass flow rate; mass flow rate of condensation; carbon dioxide mass flow rate; ethylene mass flow rate; transpiration mass flow rate; oxygen mass flow rate; oxygen production mass flow rate; oxygen resupply mass flow rate
Δm_{water}	$\frac{g}{kg}$	water content increase within the cultivation area
n	---	number of facing pairs of low-emittance surfaces within the MLI
N	$\frac{layers}{cm}$	MLI layer density
N_2	---	nitrogen
NO_x	---	mono-nitrogen oxides
O_2	---	oxygen
p; p_p; $p_{p_{CO2}}$	Pa	pressure; partial pressure; CO_2 partial pressure
P	---	phosphorus
Δp; Δp_x	Pa	pressure difference; pressure loss at component x
q; q_{warm}; q_{cold}	$\frac{W}{m^2}$	heat flux; heat flux at warm phase; heat flux at cold phase
Q; Q_{latent}; $Q_{sensible}$	J	heat; latent heat; sensible heat
$\dot{Q}$; $\dot{Q}_{CHX}$; $\dot{Q}_{extern\ (cold)}$; $\dot{Q}_{extern\ (warm)}$; $\dot{Q}_{heater}$; $\dot{Q}_{max}$; $\dot{Q}_{subsystems\ day}$; $\dot{Q}_{subsystems\ night}$	W	heat flow rate; thermal capability of CHX; heat flow rate via the outside walls at cold phase; heat flow rate via the outside walls at warm phase; thermal capability of the heater; maximum thermal load; heat flow rate of the subsystems at daytime; heat flow rate of the subsystems at nighttime
rH; rH_{input}; rH_{output}	%	relative humidity; relative humidity at cultivation area input; relative humidity at cultivation area output
S	---	sulfur
SO_2	---	sulfur dioxide
t_R	m	thickness regolith layer
t	h	time
t_w	$\frac{h}{week}$	working hours

List of formula symbols and constants

Symbol	Unit	Description
T; T_a; T_{DP}; T_{input}; T_{inside}; T_{mean}; T_{output}; $T_{outside}$	K; °C	temperature; ambient temperature; dew point temperature; temperature at cultivation area input; inside temperature; mean temperature; temperature at cultivation area output; outside temperature
ΔT; ΔT_{ca}	K	temperature difference; thermal rise within the cultivation area
v; v_{air}; v_{plant}	$\frac{m}{s}$	velocity; air flow velocity; air flow speed at plant
V; V_{GHM}; $V_{deploy\ overhead}$; $V_{deploy\ underfloor}$; $V_{rigid\ overhead\ AMS}$; $V_{rigid\ overhead\ total}$; $V_{rigid\ underfloor\ AMS}$; $V_{rigid\ underfloor\ total}$	m^3	volume; volume of the greenhouse module; overhead volume of the deployable part; underfloor volume of the deployable part; overhead volume of the rigid part foreseen for the AMS; overhead volume of the rigid part; underfloor volume of the rigid part foreseen for the AMS; underfloor volume of the rigid part
$\dot{V}$; $\dot{V}_{air}$	$\frac{m^3}{h}$	air volume flow rate
$\dot{V}_{injection}$	$\frac{m^3}{h\ m}$	air injection rate (per duct meter)
$\emptyset$; $\emptyset_{distribution}$; $\emptyset_{main\ ducts}$	m	diameter; diameter air distribution ducts; diameter main ducts
ε	---	MLI shield layer emissivity
ζ_x	---	discharge coefficient of component x
κ	ppm	carbon dioxide concentration
ρ; ρ_{air}; ρ_{water}	$\frac{kg}{m^3}$	density; density of air; density of water
ϕ	%	oxygen concentration
ψ	ppb	maximum VOC-level

1 Introduction

The interest in missions to Moon and Mars is increasing. Plans of space agencies from countries all over the world and from private companies are getting more and more precise. The international space exploration and coordination group (ISECG) regularly publishes the global exploration roadmap to summarize the activities and the planned projects of all important space players. In 2018 their last roadmap was released with a main focus on exploring Moon and Mars [1]. Even more ambition is added by the 2020 lunar surface exploration scenario update [2]. Gateway, the proposed lunar orbital platform, is an international cooperation project which will pave the way for future crewed missions to Moon and Mars. The American program Artemis and the European program Moon Village focus more specifically on human exploration on the surface of the Moon. Plans to explore Mars also exist but are a little less concrete at present. For more information see documents [1] and [2] of the ISECG. Figure 1.1 shows a basic global roadmap of exploring orbits and the surface of Moon and Mars.

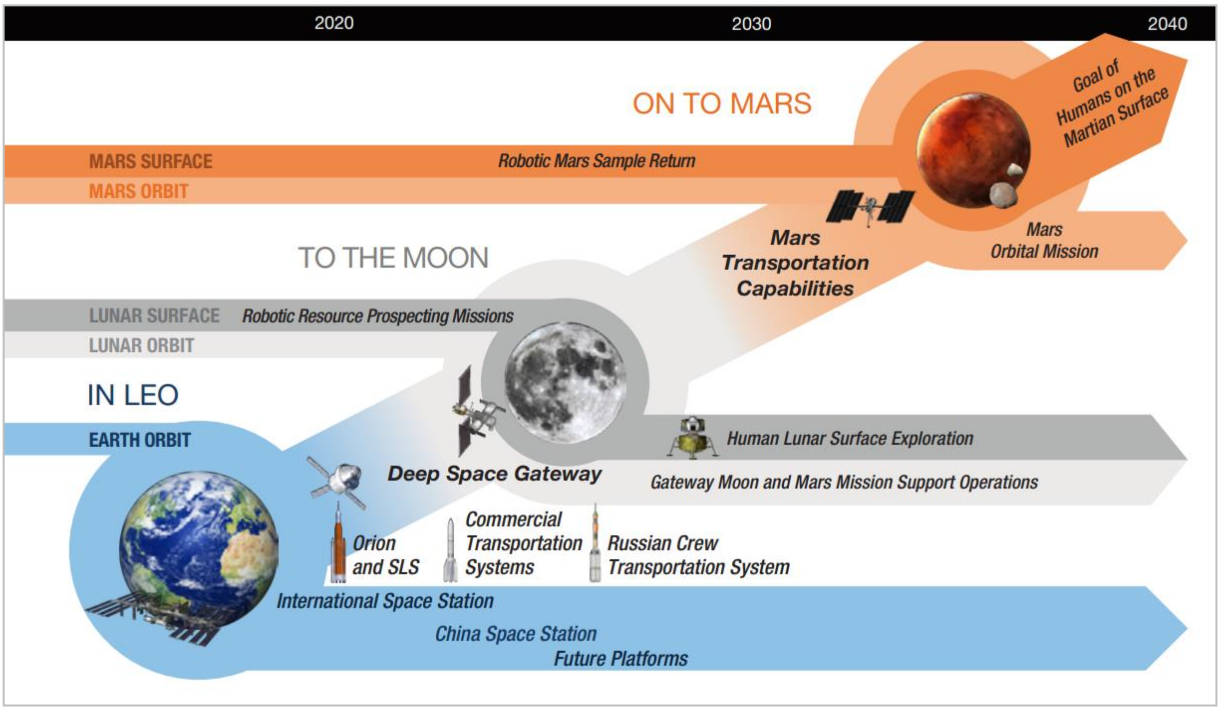


Figure 1.1: Global exploration roadmap of ISECG [1]

The ISECG also identifies critical technologies for the realization of the mentioned projects. These are technologies which need to be improved and developed further or require novel designs and breakthroughs. Life support systems (LSS) are one category of those critical technologies. In particular, the development of the reliability of LSS, closed loop life support and in-flight environmental monitoring have to be pushed forward. Innovative concepts are needed to meet the requirements of crewed long-duration missions. [1]
One such concept is to integrate a greenhouse module into the LSS for a long-duration crewed mission. Such a greenhouse module allows plant cultivation by using controlled environment agriculture (CEA). By using food production as an integral part of a closed loop life support

system some major advantages arise. Beneficial is for example that besides food production also oxygen (O_2) production and carbon dioxide (CO_2) reduction is happening. In addition, waste water recycling and general waste management can be covered by the greenhouse module too. Also advantageous are positive psychological well-being effects. More details about advantages and challenges of biological LSS are presented in chapter 2.3.1.
A lot of effort has been put into researching advanced LSS and greenhouses in space. The German Aerospace Center has investigated these research areas at the Institute for Space Systems in Bremen since 2011 within the EDEN (evolution and design of environmentally-closed nutrition-sources) initiative. Their focus is on biological LSS and the connected topic of plant cultivation in space. The main activity of the last years was to design, manufacture, test and optimize a semi-closed-loop greenhouse prototype at a space analog test site in the Antarctic. This prototype is called the EDEN ISS Mobile Test Facility (MTF) and was funded by the European Union within the Horizon 2020 program. Detailed information about the EDEN ISS MTF can be found in chapter 3.1 and in references [3] and [4]. After successfully completing the set objectives of the EDEN ISS MTF a next phase was heralded. The next step is to design, test and qualify a space ready greenhouse module. Therefore, a concurrent design session was held in 2019 and a preliminary design of the so-called EDEN Next Gen greenhouse module was developed. It is meant to provide supplemental fresh food for a crew of six astronauts. For more details about the EDEN Next Gen greenhouse see chapter 3.2 or [5] and [6].

In this thesis the focus will be on developing a first design of the atmosphere management system (AMS) of the EDEN Next Gen greenhouse module. The AMS regulates the temperature, the humidity, the air ventilation, the atmospheric composition and the air quality inside the greenhouse module. Being one of the key subsystems the AMS plays a major role in the development process of the greenhouse module. It has a large influence on the internal configuration and also on the capability and performance of the entire greenhouse module. The main objective of this thesis is to elaborate the preliminary design of the EDEN Next Gen AMS. To accomplish this, the existing design of the EDEN ISS MTF AMS will be reviewed and the knowledge and lessons-learned from the operations in Antarctica will be applied to improve the system performance. Additionally, the key requirements and constraints of space missions will be taken into account during the design process for the first step towards a space-rated design of the EDEN Next Gen AMS. Main gain of insight will be the information about feasibility concerning required space of the components of the AMS in comparison to the available space in the greenhouse module.
The thesis is structured as follows: After summarizing the results of a detailed literature research on LSS in general and the state of the art of physicochemical and biological LSS (chapter 2), the initial situation concerning previous work within the EDEN group is presented in chapter 3. Subsequently, requirements and assumptions are defined and technology trade-offs are performed in chapter 4. Furthermore, a model of the greenhouse module is built up and fed with numerical data. Afterwards, in chapter 5, the single components of the AMS are sized and ideas for redundancies and operation modes are introduced. To conclude, a critical review of the thesis and an outlook on further development steps and some design ideas are given.

The study logic in Figure 1.2 summarizes the proceeding of this thesis and gives additional information on the interconnections between the different subchapters. The single chapters on the right and the performed steps on the left are in corresponding colors to each other.

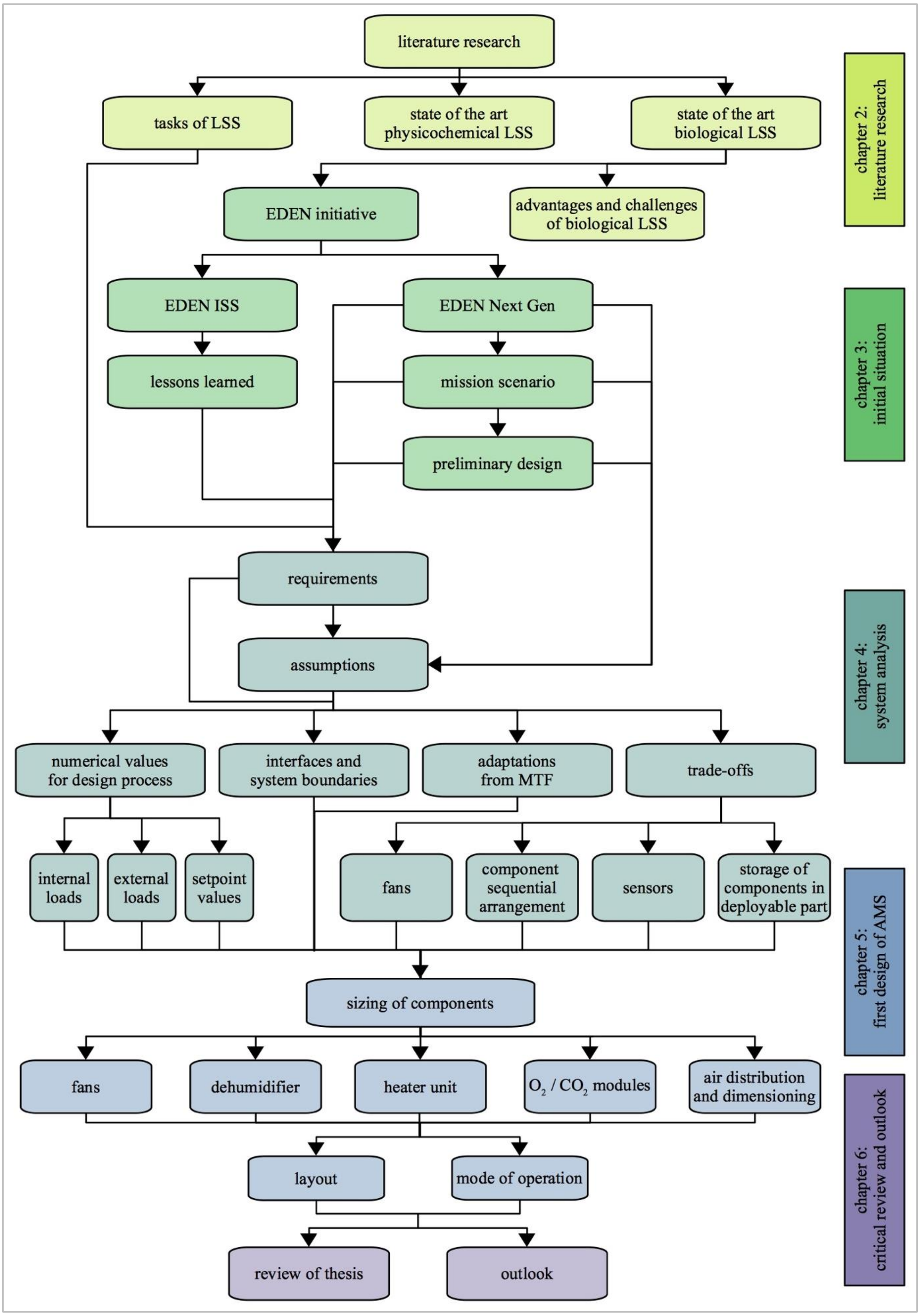


Figure 1.2: Study logic of the thesis

2 Literature research on Life Support Systems

This chapter gives an overview of LSS. After a brief summary on the classification of LSS the focus will be on the tasks of LSS for space applications (chapter 2.1). In particular the tasks of an AMS are defined. Subsequently the two basic approaches to fulfil those tasks are examined in detail. They are classified depending on the applied techniques. First physicochemical LSS and its various possible components are explained in chapter 2.2. This profound state of the art shows the functionality of the currently used LSS. Afterwards, biological LSS and their concepts are characterized in chapter 2.3. Different elements are explained and their advantages and current challenges are listed and discussed. So far biological systems are exclusively found at test stands and prototypes.

Life support systems for space applications have been under investigation since manned space flights started [7]. This was with Vostok at the Soviet/Russian space program and Mercury at the US American space program [7]. Since then a lot of research went on and LSS these days look quite different to the first ones from the early sixties.
The mentioned two basic approaches of LSS, physicochemical and biological, can both be more or less open or closed. The more closed a system is, the more regenerative processes take place in it. The aim is to close more and more loops because this is expected to result in mass savings. Although a fully closed system is likely to be heavier than an open system there will be cost savings over the entire mission lifetime due to lower amounts of needed resupply. This makes closed-loop systems especially important to long-term missions. Figure 2.1 shows steps for closing different loops and the resulting resupply mass savings.

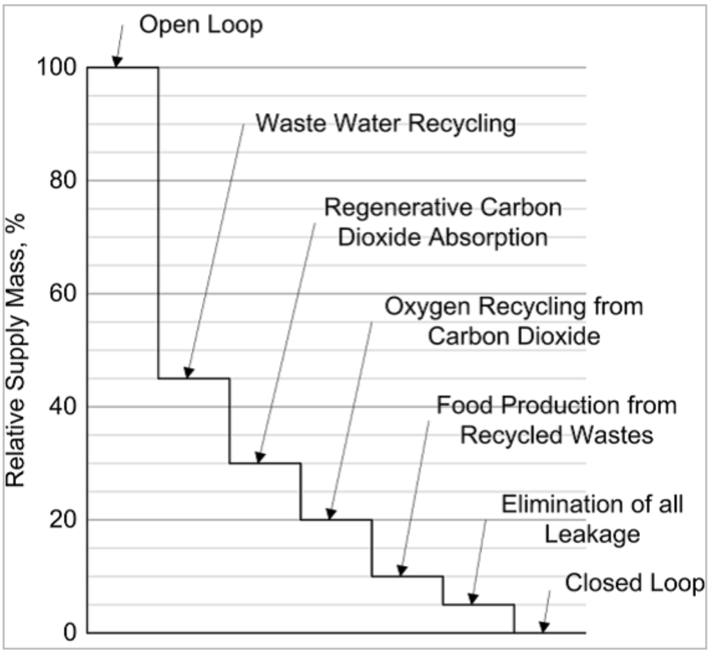


Figure 2.1: Possible steps for closing loops in LSS and the resulting reduction in relative resupply masses [8]

In completely open LSS all consumables like oxygen (O_2) and food have to be stored for the entire operation time of the mission, or they have to be resupplied periodically. The more resource loops that are closed, the lower the relative resupply mass gets. The biggest mass savings are realized by waste water recovery. Long-term goal is an entirely closed ecosystem with no resupplies needed.

2.1 Tasks of Life Support Systems

Life support systems are important for manned space missions to guarantee livable conditions for the crew members. In general, this includes providing the required environment and resources for the crew to stay healthy and safe. Considering the human being as a subsystem, inputs (needs) and outputs (waste products) can be set. These needs and waste products have to be provided to, and absorbed from, the subsystem to maintain the desired subsystem performance. Additionally, specific ambient parameters have to be kept within certain ranges. Figure 2.2 shows the subsystem human being with its inputs and outputs as well as important ambient parameters. [9, 10]

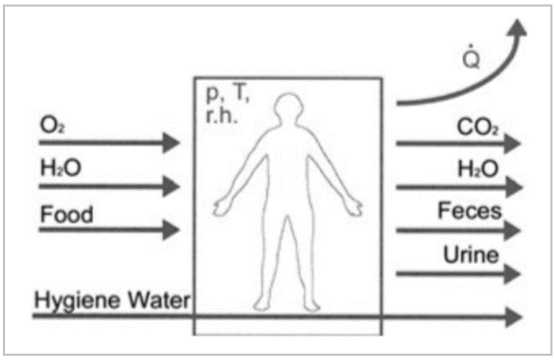


Figure 2.2: Inputs (needs) and outputs (waste products) of human beings and important ambient parameters [9]

To guarantee sufficient flow of the mentioned inputs and outputs, as well as to keep the ambient parameters within their limits, several tasks need to be fulfilled. Those tasks are independent of the type of LSS which means they are applicable on physicochemical LSS as well as on biological LSS. Table 2.1 gives an overview of these tasks and describes their necessities.

Table 2.1: Tasks and subtasks of life support systems

Task	Subtasks	Comment
atmosphere management	air ventilation	because of limited natural convection in micro- and reduced gravity environments the cabin air needs to be circulated to avoid local enrichment of CO_2 and heat
	temperature control	keep temperature in a livable range
	humidity control	keep humidity in a livable range
	atmospheric composition	keep atmospheric components within their limits (e.g. O_2, N_2, CO_2, trace gases)
	atmospheric pressure	keep atmospheric pressure in a livable range
	air filtration	remove particles and trace contaminants
	O_2 generation	O_2 needs to be consumed by the crew permanently
	N_2 provision	to counteract leakage
	CO_2 removal	CO_2 is produced by the crew permanently

Task	Subtasks	Comment
water management	water supply	water needed e.g. for crew consumption, payloads, washing, hygiene
	waste water treatment	waste water needs to be recycled to reduce the amount of water which needs to be (re-) supplied
	waste water disposal	disposal of highly concentrated waste water which is a leftover after water recycling
food production	provide food and beverages	crews diet needs to cover all necessary nutrients
waste management	metabolic output of crew	solid waste can originate from different sources and needs to be processed or disposed of
	food preparation waste	
	payload waste	
	subsystem waste	
crew safety	avoid contamination	e.g. due to a fire

Table based on information from [9] and [10].

The interrelations of the tasks are complex and need a very accurate coordination. The single tasks and their interfaces are visualized in Figure 2.3. Connections are divided into primary and secondary functions. Primary functions guarantee and control the required conditions (solid links). A system with only these interfaces would be an entirely open LSS. By adding the secondary functions (dashed links) possible regenerative processes would be included. [9]

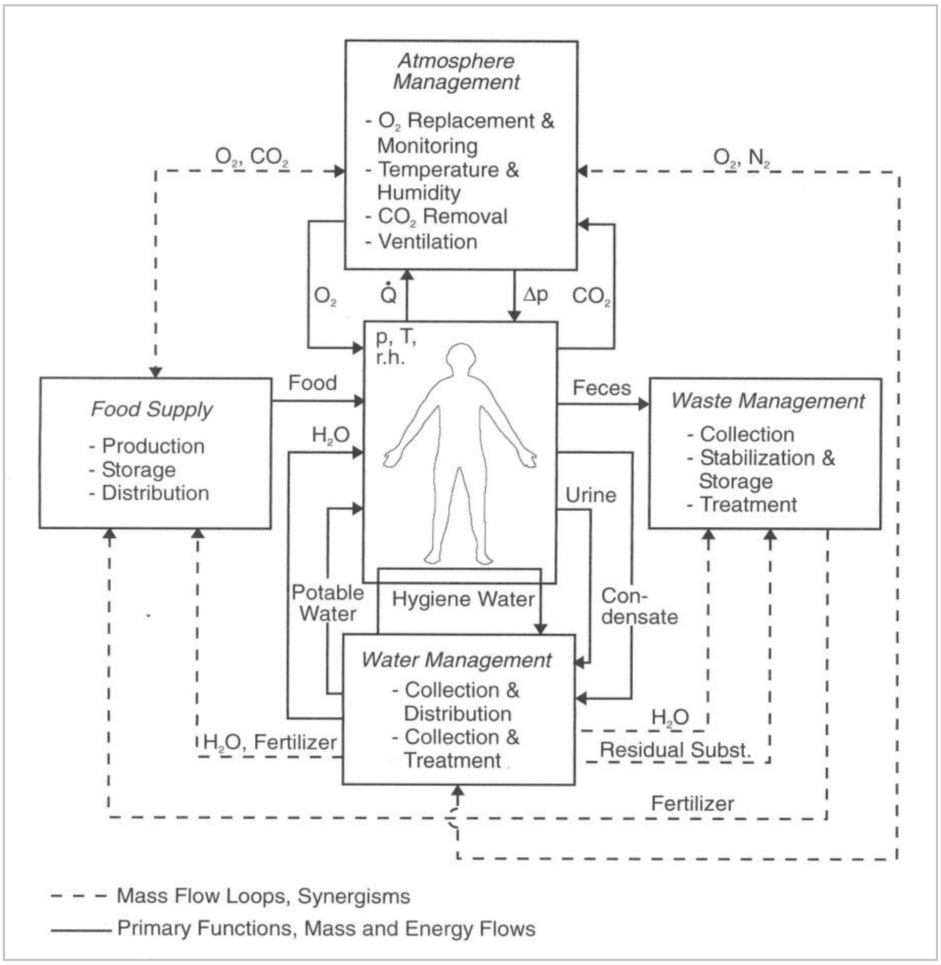


Figure 2.3: General tasks and interfaces of Life Support Systems [9]

As already mentioned, two basic approaches to fulfill the tasks of LSS exist. The technologies utilized in these two basic approaches are described in the following two chapters. As the scope of this thesis is limited to the atmosphere management system design of the EDEN Next Gen greenhouse module, the focus of the technology review will be on the AMS of LSS. That means only the tasks that are covered by the AMS will be discussed and not the total LSS.

2.2 Physicochemical Life Support Systems

The mentioned tasks of an AMS and their possible realizations in physicochemical systems are surveyed in the following chapter. Space mission examples from the past and today are used to explain the different available techniques.

Ventilation of air

In micro- and reduced gravity environments, natural convection is diminished in comparison to the Earth environment. As such mechanical ventilation of cabin air is needed to prevent local enrichment of CO_2 and heat [9, 10, 11, 12]. This guarantees fresh air for the crew all the time, independent of the position. Depending on size and complexity of the spacecraft there has to be intermodule ventilation additional to the intramodule ventilation. Air circulation usually is realized with a setup of fans and ducts equipped with louvers [9, 10, 11, 12]. Due to a pressure difference generated by a fan the air is sucked in at an air outlet louver, distributed to the air processing system and then injected via an air inlet louver. Figure 2.4 shows the ventilation system of the US on-orbit segment (USOS) of the ISS [12]. In this case the air is sucked in at the bottom and supplied from the top on the module. The components and configuration of the fan assembly of the ventilation of the USOS can be found in Appendix 1.1.

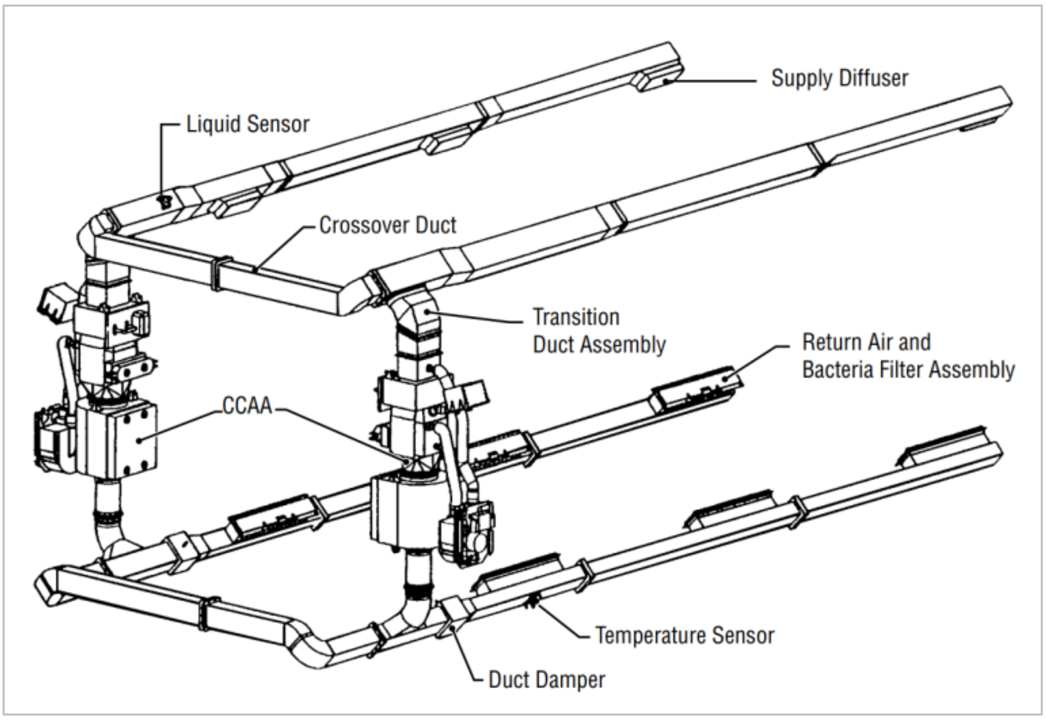


Figure 2.4: Ventilation system of the US segment of the ISS [12]

The difficulty is to ensure a uniform flow velocity at all areas. This is a compromise between, on the one hand, counteracting air pockets and, on the other hand, being comfortable for the crew [13, 14]. Air pockets can be avoided by bathing every area of the spacecraft with fresh air and the implementation of a high air flow velocity. Permanent air draft in turn is uncomfortable for the crew members. In addition, a high air flow results in a high acoustic noise level, which also is not comfortable for the crew [13, 14].

Temperature and humidity control (THC)

Temperature and humidity are two main parameters which need to be controlled to create a safe and comfortable environment for the crew and equipment [9]. Usually condensing heat exchangers (CHX) are used to dehumidify the wet exhalation air [9, 10, 12]. With the help of a cooling fluid the air is chilled to below its dew point so that droplets arise [12]. In micro- or reduced gravity environment these droplets would continue to move with the air stream [9, 10]. For that reason, centrifuges are used to separate water and air [9, 10, 12]. To avoid microbial growth the air side passages of the CHX are impregnated with silver oxide which slowly dispenses to the condensate water [10, 12].

In order to guarantee an adequate temperature of the air supply either heaters or a bypass parallel to the CHX are used [9, 12]. As an example the CHX of the US segment on ISS is shown in Figure 2.5 and a detailed view of the functionality of the Japanese experiment module (JEM) CHX is shown in Appendix 1.2.

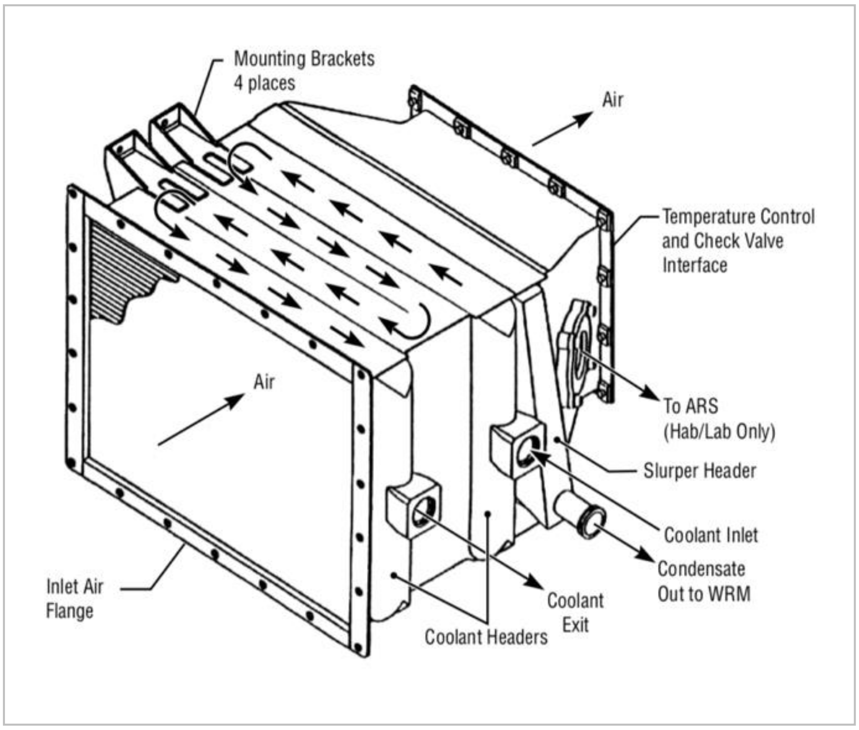


Figure 2.5: CHX used at the US segment on ISS [12]

Details on the water separator used in the US segment on the ISS can be seen in Figure 2.6. The functional elements of the water separator are a rotating drum, a pitot tube, a centrifugal fan and different valves and sensors. By the influence of centrifugal action on the water/air mixture the water is forced to the outside. To capture the water there is a Pitot tube at the outer wall. The rotation forces the water into the Pitot tube, further through valves, and finally into the condensate line. [12]

Even if heaters are installed to adjust the air temperature after the CHX, an additional, more powerful thermal control system (TCS) is essential to handle external and internal thermal loads. Such a TCS uses additional components (e.g. heaters, heat pipes and radiators), in order to transport heat away from heat sources towards heat sinks and heat rejection units.

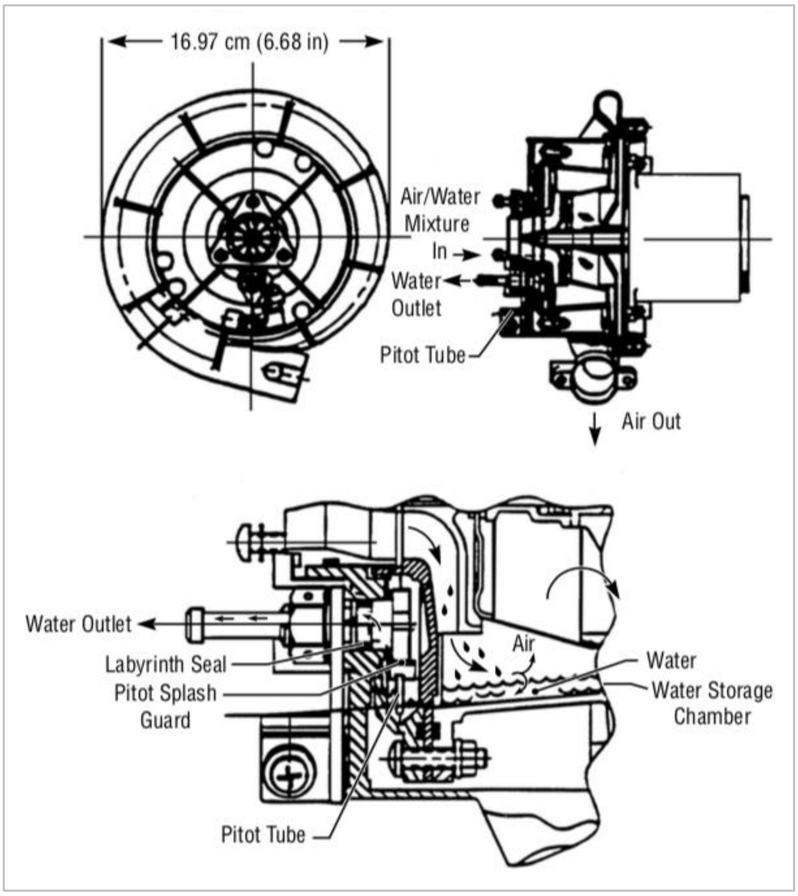


Figure 2.6: Water separator of US segment on ISS [12]

Detailed information about the combined THC and TCS rack packaging of the US segment on the ISS can be found in Appendix 1.3. Schematics of the common cabin air assembly (CCAA) of the US segment on ISS and of the THC subsystems of the Japanese and European modules on ISS are attached in Appendix 1.4 to Appendix 1.7. For more details see [9], [10] and [12].

Air composition control

Controlling the atmospheric composition within a spacecraft includes monitoring and regulating all atmospheric components within human tolerance limits. In general, that means supplying oxygen (O_2) and nitrogen (N_2) to the inside environment as well as extracting carbon dioxide (CO_2) and trace gases from it [7, 9]. For short term stays in space the air composition control is not as essential as it is for long term space missions. For example, the first US American manned space missions (Mercury, Gemini, Apollo) provided a 100% oxygen environment to the astronauts which worked out well but would not be an option for a longer period of time due to medical and safety reasons [7, 15].

The monitoring of the atmospheric composition can be performed by a variety of different methods [15]. Essential devices to mention in this thesis are the major constituent analyzer (MCA) and optical multi-gas monitor technology demonstrator. The MCA is the major device to monitor the atmospheric composition on ISS [10, 12]. Its main functional component is a mass spectrometer, which determines the concentrations of nitrogen (N_2), oxygen (O_2), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4) and water vapor (H_2O) [10, 12]. A schematic of the functionality of the MCA is attached in Appendix 1.8. The optical multi-gas monitor is a technology demonstrator, which was operated on ISS [15]. This portable device detects ammonia in real-time, in addition to water vapor (H_2O), carbon dioxide (CO_2) and oxygen (O_2) [15]. A vertical cavity surface emitting laser is used to sense the mentioned substances [15]. More details about atmospheric composition monitoring can be found in [12] and [15].
In the following sections, the physicochemical options to supply oxygen and nitrogen, and to remove carbon dioxide and trace contaminants, are presented.

Generation of oxygen
Due to consumption by crew and leakage oxygen needs to be resupplied constantly. It can be carried in different ways. One option is to store it under high pressure, cryogenically or in a supercritical state. Alternatively, oxygen can be stored in chemical compounds. Two different compounds, so-called oxygen candles and electrolysis cells, are in practical use [10]. Oxygen candles, or Solid Fuel Oxygen Generators (SFOG) are cartridges filled with Lithium perchlorate ($LiClO_4$) which emits oxygen after ignition [10]. The second option of electrolysis of water can be carried out with different technical variations [10, 16]. All of these variations split liquid water into its molecular components, hydrogen and oxygen, with the help of electric power [10, 16]. [9]
On the ISS the main production of oxygen is done by electrolysis of water. Oxygen candles and pressurized oxygen containers are available as primary and secondary backup systems [10]. For more details see [7], [9], [10], [12], and [16].

Provision of nitrogen
Usually nitrogen is injected into spacecrafts to compensate for pressure losses which occur from leakage and extra-vehicular activities (EVA) [12]. Just like oxygen, nitrogen can also be stored under high pressure, cryogenically or in a supercritical state. For storing nitrogen as a chemical compound hydrazine is often used because it is already available anyway as propellant. Its catalytic dissociation results in nitrogen and hydrogen. [9]

Removal of carbon dioxide
Carbon dioxide removal is essential to prevent hazardous build up due to permanent crew metabolic output [9]. Several techniques are available for this [9]. In the following section those different methods are described to provide an understanding of their functionality. For more details and the particular advantages and disadvantages of different methods, see [9].
The simplest method is executed with the help of Lithium hydroxide (LiOH). When adding CO_2 to LiOH it generates lithium carbonate (Li_2CO_3) and water (H_2O). With this method the CO_2 is chemically bound and cannot be used afterwards. This makes it an open-loop process and therefore not suitable for long-term usage due to high mass flows. Figure 2.7 shows the

LiOH process in the shape of a block diagram. The values listed in the diagram are for one person per day. [9]

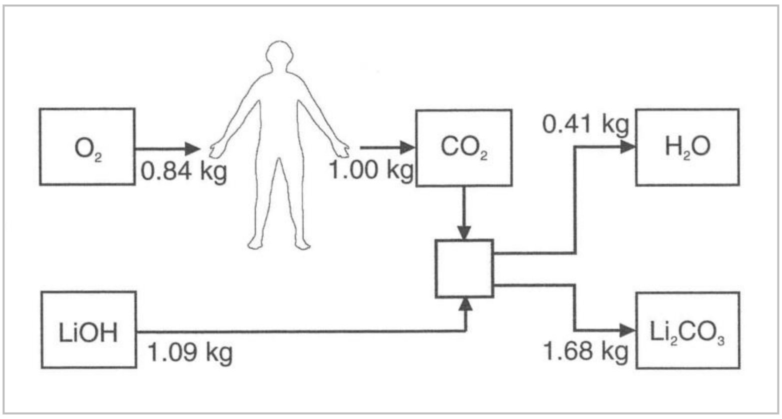


Figure 2.7: Block diagram of LiOH method [9]

The next technology to be presented is not an actual CO_2 removal technology but more an air treatment process. It is called electrochemical depolarized CO_2 concentration (EDC) and increases the carbon dioxide saturation of the treated air. This method is related to a fuel cell reaction, as can be seen on the left side of Figure 2.8. Inputs for the process are, apart from CO_2, also hydrogen (H_2) and oxygen (O_2). Carbonate ions are generated at the cathode from hydroxyl ions and dissolved carbon dioxide. Those carbonate ions drift from the cathode to the anode where they are segregated. Water (H_2O), thermal power and electrical DC power need to be discharged. On the right side of Figure 2.8 is a block diagram with mass turnovers of the process for one person per day. To gain pure CO_2 the carbon dioxide enriched air needs a further treatment. [9]

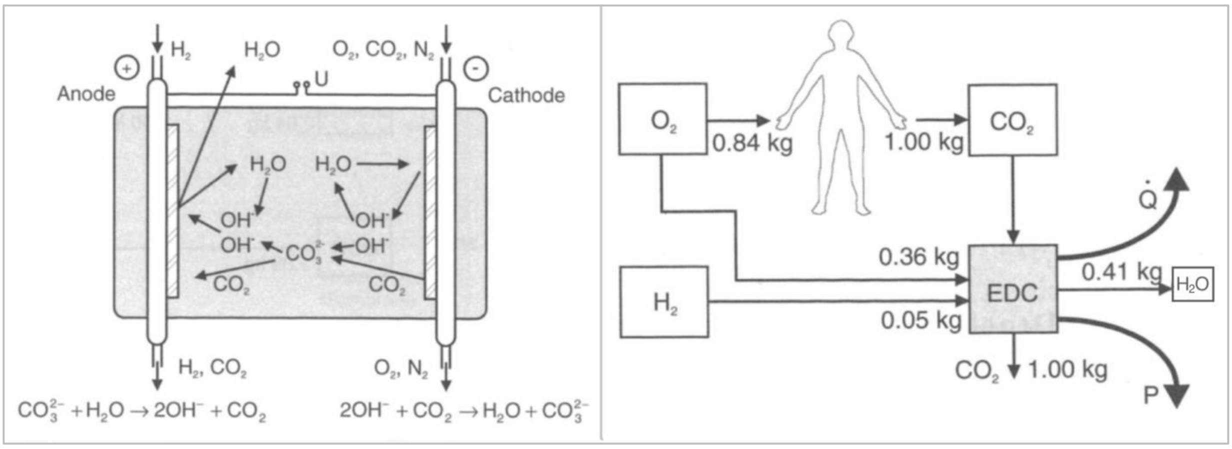


Figure 2.8: Principle (left) and block diagram (right) of an EDC cell [9]

Molecular sieves are the oldest and most matured regenerative CO_2 removal technique. For this method the cabin air is circulated through a bed of zeolite or aluminosilicate which adsorbs the CO_2 [10, 12]. After the bed is saturated the separated CO_2 can be desorbed by using heat and vacuum [10, 12]. The practical implementations of this method, two-bed molecular sieves (2BMS) and four-bed molecular sieves (4BMS), are shown in Figure 2.9. 4BMS have desiccant beds upstream of the CO_2 adsorbent beds in order to enable selective water adsorption [12]. In contrast to 2BMS this avoids water in the CO_2 adsorbent bed which would get lost by venting the adsorbent bed content to space vacuum. Using a 4BMS provides the possibility to collect the CO_2 for other applications. To guarantee a permanent operation mode the adsorbent beds alternate as the active adsorbent and desorbent [12]. [9]

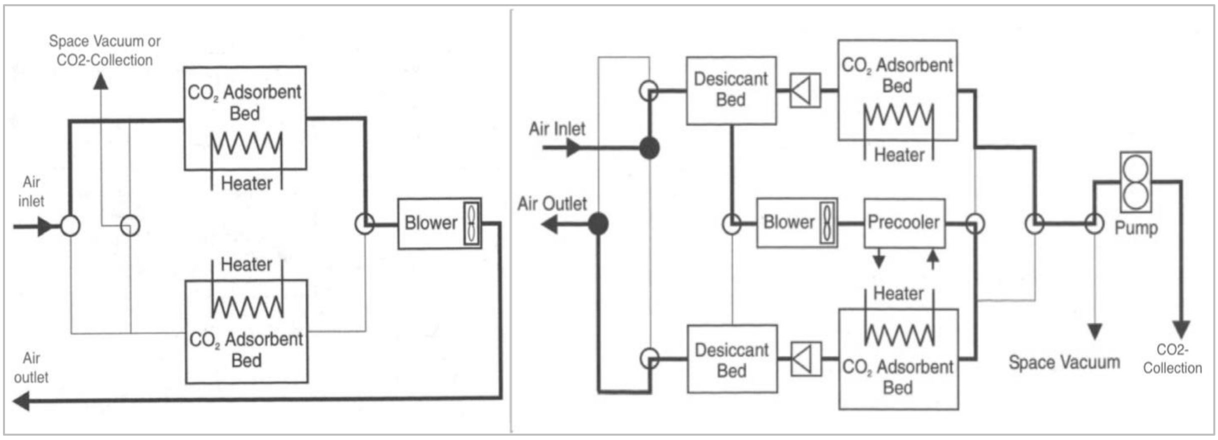


Figure 2.9: Block diagram of 2BMS (left) and 4BMS (right) [9]

The 4BMS used on the ISS is divided into two Orbital Replacement Units (ORU). Each ORU has one desiccant bed and one CO_2 adsorbent bed. A figure of one of those ORU can be found in Appendix 1.9. [12]
The final method used for carbon dioxide removal is solid amine water desorption (SAWD), which involves circulating the cabin air through a granulated resin. Together with water, the granulated resin generates a hydrated amine, which, combined with CO_2, forms a bicarbonate. For desaturation of the system, water steam is drawn through the amine bed. The heat splits the bicarbonate bonds and lets the CO_2 leave the amine bed. Downstream of the SAWD there has to be a CHX to dehumidify the output air. Figure 2.10 depicts a block diagram of the SAWD process and shows the two alternating adsorbing and desorbing amine beds. [9]

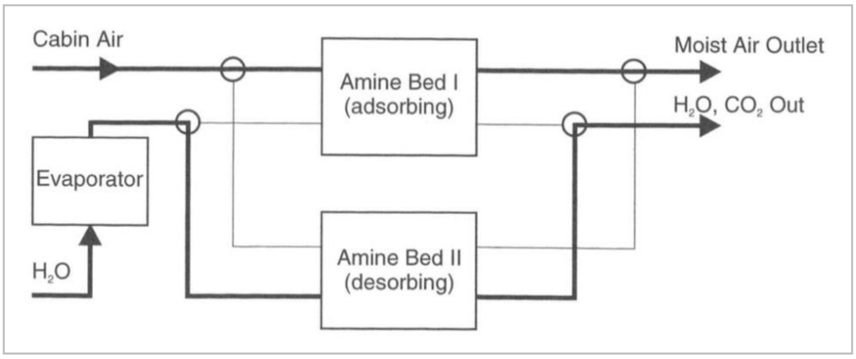


Figure 2.10: Block diagram of the SAWD process [9]

More possibilities to remove carbon dioxide, which still need further development, can be found in [9].

Removal of trace contaminants

If a specific concentration of a trace contaminant is exceeded it can have negative consequences for the crew [10]. Therefore, especially on long-term missions, also trace contaminants of the atmospheric environment have to be monitored and removed [9]. Trace contaminants result from subsystems, payload operation, outgassing materials, and human

metabolism [7, 9, 10]. As already mentioned before, on the ISS trace contaminants supervision is realized with a mass spectrometer (O_2, N_2, CO_2, H_2, CH_4, H_2O) [10, 12]. To monitor all other volatile organic compounds (VOC) a volatile organic analyzer (VOA) was used until 2008 [10, 17]. This VOA first separated the gases using gas chromatography before analyzing them with an ion mobility spectrometer [10, 17]. In 2009 the ISS got upgraded with the Air Quality Monitor (AQM), which is a gas chromatograph - differential mobility spectrometer (GC-DMS) [17, 18]. To split ions at higher resolutions it applies radio frequencies and electrostatic potentials [18]. For more details on the GC-DMS see [17], [18] and [19].
To remove trace contaminants the following methods are used. For trace gases with a higher molecular weight activated charcoal filters are applied [9, 10]. To eliminate trace gases with a low molecular weight, e.g. CO_2, CH_4, H_2 and other hydrocarbon gases, a catalytic oxidizer converts them to compounds such as carbon dioxide, water, nitrogen compounds, sulfur compounds or halogen compounds which can be adsorbed by a LiOH bed (chemical adsorption) [9, 10]. A schematic of the trace contaminant control subassembly (TCCS) used at the ISS is shown in Figure 2.11. Visible are the sequential components: charcoal bed assembly, catalyst assembly and sorbent bed assembly.

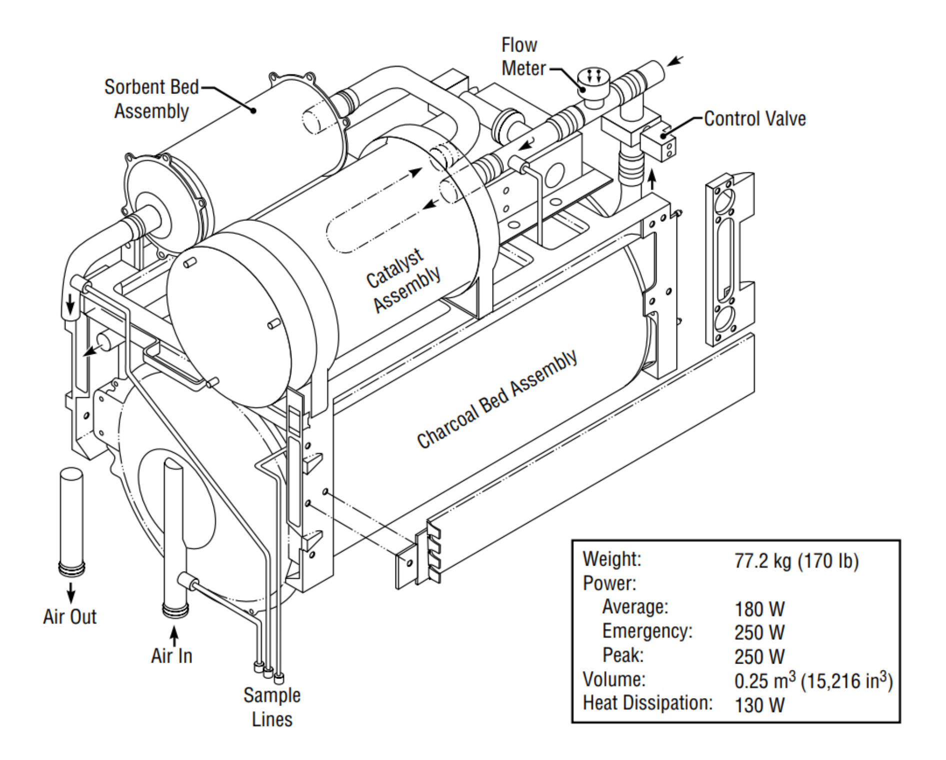


Figure 2.11: Schematic of the ISS TCCS [12]

Appendix 1.10 gives an overview of the rack packaging of the air revitalization (AR) system on the USOS. The functional interrelations within the AR are shown in Appendix 1.11. Detailed exploded views of the components can be found in Appendix 1.12 to Appendix 1.14. The contaminant groups which can be removed with those assemblies are listed in Appendix 1.15. An overview of the maximum allowable concentrations of various contaminants in spacecraft, which is important for the design process later on, can be found in NASA's published standard SMAC (spacecraft maximum allowable concentration for airborne contaminants) [19].

Atmospheric pressure

The atmospheric pressure needs to be maintained within a range suitable for the crew [9]. Therefore, the inside pressure of the spacecraft is monitored. On the ISS this is done once every second [12]. To counteract a pressure below the minimum limit nitrogen (N_2) is injected [9, 12]. In addition, also the maximum pressure limit and the maximum pressure differential (inside spacecraft to outside spacecraft) need to be considered. To prevent a pressure above those mentioned limits vent and relief valves (VRV) are used [12].

Regenerative functions for AMS

By using regenerative processes to recover the oxygen bound during human metabolism mass savings can be achieved [9]. Relevant methods are the Sabatier process, the carbon formation unit (CFU) and the Bosch process. At the Sabatier process carbon dioxide and hydrogen are split into methane and water in a reactor [9]. To accomplish this, a catalyst like ruthenium on an aluminum substrate is needed [9]. The generated methane can then be transformed by a carbon formation unit. In a CFU methane is decomposed into hydrogen and elemental carbon with the help of thermal energy [9]. Besides combining a Sabatier reactor with a CFU also the Bosch process can be used [9]. Similar to the Sabatier process, in the Bosch process carbon dioxide and hydrogen are combined, but instead of methane, elemental carbon is obtained as a byproduct [9]. The corresponding reaction equations of all three processes are given in Table 2.2. For more details about regenerative processes see [9] and [12].

Table 2.2: Reaction equations of regenerative functions for AMS [9]

Regenerative process	Reaction equation
Sabatier	$4H_2 + CO_2 \rightarrow 2H_2O + CH_4$
carbon formation unit (CFU)	$CH_4 + E_{therm} \rightarrow C + 2H_2$
Bosch	$2H_2 + CO_2 \rightarrow 2H_2O + C$

Air filtration

To keep the air clean within a spacecraft particle filters are used [9]. High efficiency particulate air (HEPA) filters remove 99.97% of particles like dust, spores, aerosols and microorganisms [12]. Those filters have to be cleaned by vacuum regularly and need to be replaced after a certain period of time [12]. The HEPA filter assembly used at the US segment on the ISS is given in Appendix 1.16.

2.3 Biological Life Support Systems

In this chapter biological LSS and their technologies to fulfil the AMS tasks are discussed. Commonalities and differences to physicochemical LSS are analyzed and the advantages and the current challenges of biological LSS are characterized.

First of all, no complete, space proven, biological LSS for space applications exists so far. Currently just prototypes and test stands of parts of biological LSS are available on Earth or

undergoing testing in space. Besides the already introduced EDEN research initiative there are a lot of other research projects on plant cultivation in space. A selection of significant projects from the past and today, which have a similarity to the EDEN initiative, is given in the following. The so-called Salad Machine is a grow chamber developed by NASA at Ames Research Center [20]. It is a payload rack sized module from the nineties with different cultivation areas for germinating and full-grown lettuce plants [20]. The research objective was to add fresh salad to astronauts diet and to gain knowledge for future biological LSS [20]. In 2013 Beihang University started the Lunar PALACE (Permanent Astrobase Life-Support Artificial Closed Ecosystem) project to practically investigate closed ecosystems and their interactions [21]. The artificial closed ecosystem contains two cultivation modules with around 60 m^2 ground area [21]. Within multiple missions the main focus was on plant cultivation, animal breeding, and waste treatment [21]. A cooperation of the University of Arizona, NASA, and the Sadler Machining Company works on the Mars-Lunar Greenhouse (MLGH) [22]. The main goals of the semi-closed system for future planetary colonies are food production, air revitalization, and water recycling [22]. A prototype of the cylindrical greenhouse module is already available and measures 2.06 m in diameter and 5.5 m in length [22]. More research projects on grow chambers and bioreactors are introduced later in this chapter. For more detail on Salad Machine see [20], on Lunar PALACE see [21], and on MLGH see [22].
Additionally, not every task of a LSS can be covered with biological methods. Nevertheless, as in the previous chapter, every AMS function is considered for the sake of completeness. Not all of the presented technologies are currently under space related investigation, but they are conceivable for space applications.

Ventilation of air

As in the case of physicochemical LSS, an artificial ventilation of air is also needed for biological LSS in micro- and reduced gravity environments. Since no method for the biological circulation of air is available the same physical techniques as in conventional LSS have to be applied. Depending on the size of the modules for the habitat and the greenhouse a natural ventilation might appear. But even for very large modules, in which slight temperature and pressure differences may occur, this ventilation would be insignificant and is neglected for the design of the ventilation system.

Temperature and humidity control

Controlling the temperature and humidity has the same importance in biological LSS as it has in physicochemical LSS. Especially when cultivating higher plants in biological LSS those two parameters need to be maintained within certain limits. Therefore, the same components have to be used as in physicochemical systems because no biological methods exist.

Air composition control

To control the atmospheric composition the atmosphere’s components need to be monitored and regulated. This includes oxygen, nitrogen, carbon dioxide and trace gases. However, their monitoring is realized with the same sensors as within physicochemical systems. For regulating these parameters different methods apply. In the following the biological possibilities to regulate the air composition are described.

Generation of oxygen

The applied biological process to realize oxygen generation is photosynthesis. This metabolic process can be performed by different organisms. These are higher (vascular) plants and microorganisms like algae, bacteria or fungi. Photosynthesis is driven by light and metabolizes light energy into chemical energy [23]. This occurs within the chloroplast of green plants and algae and within the chromatophores of photosynthesis bacteria [23]. The following equation (1) is the simplest version to describe this process [24].

$$6CO_2 + 12H_2O \xrightarrow{light\ energy} C_6H_{12}O_6 + 6H_2O + 6O_2 \tag{1}$$

According to equation (1) the input quantities are carbon dioxide, water, and light energy, which are transformed into carbohydrates (glucose), water, and oxygen [25]. Only photosynthetic active radiation (PAR) is utilized for the photosynthesis process [25]. PAR is very similar to the visible spectrum (wavelength: $380\,nm \ldots 710\,nm$), but mainly blue and red light is represented. A more profound analysis of photosynthesis can be found in [24] and [26] but is not considered for the work of this thesis. As the main focus of this thesis is on the AMS the facts of CO_2 reduction, O_2 generation and water transpiration are sufficient to consider.

To guarantee a photosynthesis process with accurately defined input and output quantities and environmental conditions grow chambers for higher plants and bioreactors for microorganisms can be used. Figure 2.12 shows the grow chamber Veggie (Vegetable Production System) which was developed by ORBITEC, now part of Sierra Nevada Corporation, and NASA which is currently operating on the ISS. Also shown in Figure 2.12 is the bioreactor PhotoBioReaktor (PBR). The PBR is a cooperation of DLR, the University of Stuttgart and Airbus and was also tested on the ISS.

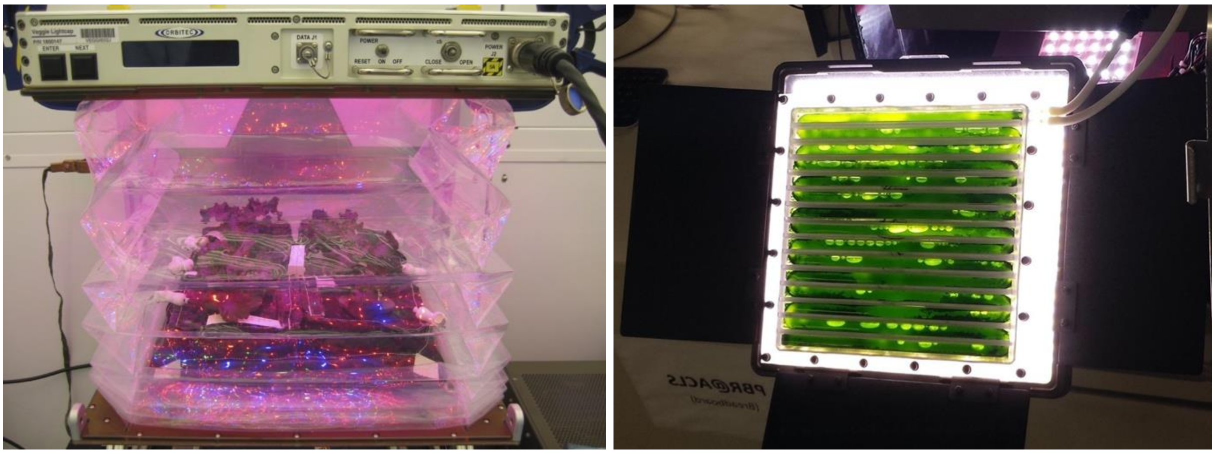


Figure 2.12: Veggie grow chamber (left) [27] and PhotoBioReaktor (PBR) (right) [28]

If the only consideration is the CO_2 reduction and O_2 production, then no higher plants are needed. At the same volume and light conditions microorganisms transfer much more CO_2 to O_2 [29]. Additionally, microorganisms are less demanding concerning the ambient conditions than higher plants [29]. This allows a higher degree of automation, which results in less crew time demand [29]. Two widely researched microorganisms suitable for CO_2 reduction and O_2 production are the algae Chlorella and Spirulina. They are very productive biomass and oxygen producer [7, 25]. More special characteristics and an extensive comparison of higher plants and cyanobacteria representative for microorganisms can be found in [29]. By cultivating higher plants or microorganisms not only the air composition can be influenced advantageously. Supplementary benefits, which make higher plants interesting again for space missions, are listed and explained in chapter 2.3.1.

Provision of nitrogen

Nitrogen is not metabolized by higher plants. A biological way to generate nitrogen is the usage of microorganisms like agrobacteria. Mineral nitrates in soil and nutrient solutions are denitrificated and nitrogen and oxidized nitrogen are generated. [30]

Even though it is unlikely to be required to remove nitrogen, the possibility is still mentioned for the contingency. Free-living microorganisms (e.g. Azotobacter) are able to fix some nitrogen into nitrogenous compounds. A bigger quantity of N_2 can be turned over to organic compounds by legumes together with symbiotic rhizobium. [30]

Removal of carbon dioxide

Due to the direct connection of CO_2 reduction and O_2 generation within the photosynthesis process all details about CO_2 removal are given under the heading of oxygen generation.

Removal of trace contaminants

Volatile organic compounds (VOC) can be removed with biofilters and algae reactors [10]. According to [31], [32] and [33] proven biological techniques to treat air in terms of VOC include biofilters, biotrickling filters, bioscrubbers and membrane reactors. The basic functionality of all mentioned methods is very similar [31]. A porous medium, with aerobic microorganisms placed on the medium surface, is used to provide a large contact area between polluted air and the microorganisms [31, 32]. As the air passes the filter media it comes into contact with the biofilm of microorganisms and the targeted contaminants are then processed by the microorganisms in an aerobic environment [31]. In the final stage only more or less harmless and stable products like CO_2, H_2O, sulfate or microbial biomass remain [31, 32, 34]. One differentiating factor of the methods is the water flow inside the porous media [31]. Figure 2.13 shows the schematic functionality of biofilters in general.

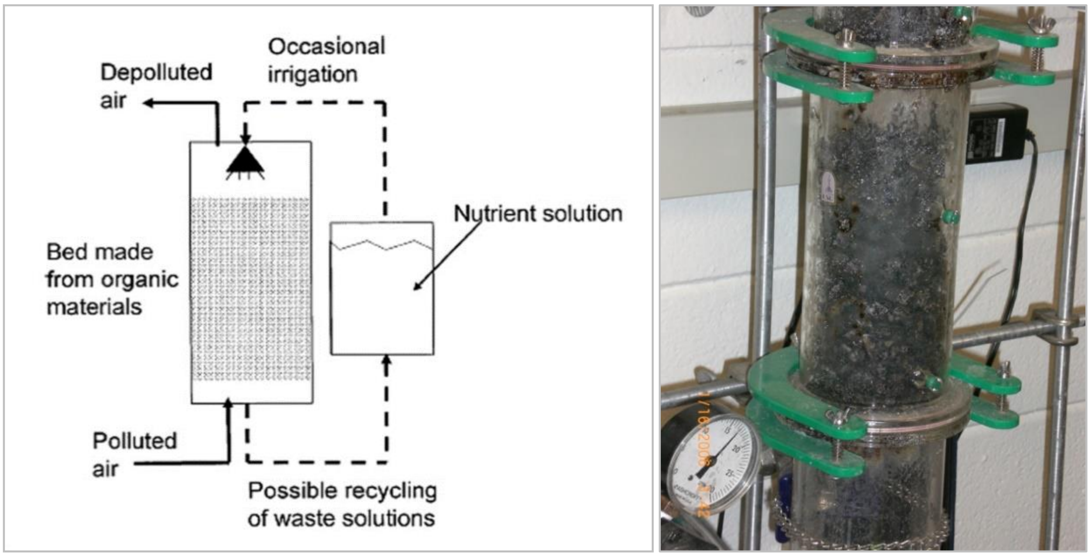


Figure 2.13: Schematic functionality of biofilters [33] and photo of a biofilter bed [35]

In the following section the main differences of the mentioned techniques are described. In biofilters the polluted air is pushed through porous supporting packing media which is coated with the microorganisms [31]. Bioscrubbers feature two units [31]. One for absorption and the other one for biodegrading of the microorganisms [31]. In membrane bioreactors the pollutants are transferred through a microporous hydrophobic hollow fiber membrane [31]. A selective diffusion between the gaseous medium and the active liquid medium takes place [31]. This can be traced back to the concentration difference between the gaseous medium and the biofilm (Henry's law) [31]. Similarly, in biotrickling filters the polluted gas is infiltrated through a porous bed [31]. Simultaneously a hydrous solution irrigates the microorganisms and provides necessary nutrients to them [31]. The biodegradation occurs within the biofilm and pollutants are discharged by the hydrous solution [31]. For all the mentioned variations of biofilters the utilization within micro- or reduced gravity needs to be considered. Performance losses or even complete failure might be expected.

By using different microorganisms, different pollutants can be removed. In [31], [32] and [33] overviews of trace contaminants and the microorganisms suited for their degradation are given. Depending on the biofilter method, in addition to VOC also odors can be removed [31, 32]. More details about the introduced methods including advantages and disadvantages can be found in [31], [32] and [33].

The selective removal of trace contaminants by higher plants was already investigated in the late nineties [36, 37]. Within their *clean air study*, NASA proved the ability of higher plants to remove airborne VOC [36, 37]. Also younger studies about the influence of higher plants on the air quality show that different plants are able to remove different amounts of VOC [38]. However, the quantitative results of those studies disagree among each other [38]. But mutual consent is that in general the amount of VOC removeable by higher plants is too minor to be practical [38]. [36], [37], and [39] give more detailed information about which plant species are able to remove which kind of VOC.

Besides the removal of trace contaminants, the management of ethylene needs to be considered [10]. It cannot just only be removed because ethylene is a plant hormone and has a very different influence on different plants [10]. The usage of ethylene for plants reaches from detecting objects over initiating blossom or the ripening process to triggering its dieback [10]. To avoid fault indications to the plant in a small artificial ecosystem an ethylene handling system needs to be developed.

Atmospheric pressure

No biological method to maintain atmospheric pressure is available so far. To still guarantee a stable pressure the same approach would be used as for physicochemical LSS, but the nitrogen could be gained with biological techniques instead of being supplied from Earth.

Air filtration

Since no biological method exists to filter particles HEPA filters also have to be used for air filtration in biological systems.

2.3.1 Advantages and challenges of biological LSS

In this chapter advantages and current challenges of biological LSS are presented. Most benefits are already identifiable from the explanation of the functionality of the techniques of biological LSS. Therefore, at this point only a summarizing overview of the advantages concerning the AMS but also other main benefits are given in the shape of a table. In Table 2.3 the advantages are listed and their resulting positive impacts are named. Afterwards the current challenges to realize a biological LSS are analyzed. Main focus for that is also on the realization of an AMS.

Table 2.3: Main advantages of biological LSS and their positive effects

Advantage	Effect
Photosynthesis: [7, 9, 10, 25, 40, 41] - CO_2 reduction and O_2 production within one regenerative process	- closing the carbon loop results in less resupply mass [9]
Air filtration: [9, 31, 32, 34] - volatile hydrocarbons and other contaminants serve decomposing microorganisms which transform them into harmless end products	- no harmful substances to handle - potentially less resupply mass
Biomass production: [7, 9, 10, 25, 40, 41] - edible biomass can be used for food - inedible biomass can be used for nutrient recovery (Algae only little part of human's diet (10%). But in combination with vegetables 20% can be reached. By adding grain crops and leguminous crops 70% of human's nutritional needs are possible. [40])	- less resupply mass - reducing non regenerable waste - more balanced diet
Psychology: [9, 10] - positive effect on psychological wellbeing	- specially on long-term missions the psyche of the crew members can be critical
Water recovery: [7, 9, 10, 23, 25, 40, 41] - waste water, urine and even salined water can be purified - evaporative cooling of plants - transpired water is pure enough to use for drinking	- energy savings [9]
Waste material recycling: [7, 10, 23, 41] - all animal, human and other organic waste can be processed by plants and/or microorganisms for growth	- nutrients in waste (e.g. N, S, P, K) can be reused - less resupply mass

Since the LSS is an essential system for the survival of the crew it has to be very reliable [10]. Usually redundancies are used to guarantee a safe and stable operation [10]. For biological systems the implementation of two redundant LSS comes along with difficulties [10]. If one system is contaminated the other one needs to be protected from it. Which means, for example, it is impossible to feed both systems with a crew's waste products [10]. Also unclear is how a contaminated or collapsed system can be cleaned and set up again in orbit [10]. The contamination of that kind of system is very complex because aside from the air also the water, food, and the surfaces can be contaminated [7, 10].

All in all, it is extremely difficult to ensure a robust and stable system because of the complexity of processes in ecosystems [9, 10]. For many processes there is only a very small understanding so far which makes it impossible to fully control them in an artificial ecosystem [9].

Another open question is the handling of contaminant substances [10]. Some pharmaceutical products for example are not completely decomposed by the human body [10]. To avoid a re-consumption a further processing of those contaminant remains is necessary.

According to experiments, the biological performance of plants changes over several generations [10]. This genetic stability needs to be investigated further. Likewise, a critical area of investigation is the influence of micro- and reduced gravity, as well as radiation, on living organisms [9]. Plant growth within micro gravity is already under investigation but is still in an early stage.

2.4 Summary and conclusion of the literature research

The literature research gives a general overview of LSS. After a brief explanation of the overall tasks of LSS for space applications especially tasks of the AMS were defined. LSS in general guarantee livable conditions for the crew members which includes providing the required environment and resources for the crew to stay healthy and safe. Needs and waste products have to be provided to, and absorbed from, the crew. Additionally, specific ambient parameters have to be kept within certain ranges. Overall tasks of LSS include atmosphere management, water management, food production, waste management, and crew safety. Particular subtasks and more details are given in Table 2.1. Subsequently two basic approaches to fulfil those tasks were examined in detail. The main focus at this technology research on physicochemical and biological LSS is on the processes belonging to the AMS.

The classification of the approaches is dependent on the applied techniques. This passage gives a very brief summary on the existent technologies of both approaches. The following tasks of AMS are treated: ventilation of air, temperature and humidity control, air composition control (including: generation of oxygen and provision of nitrogen as well as removal of carbon dioxide and trace contaminants), atmospheric pressure and air filtration. In physicochemical systems air circulation usually is realized with a setup of fans and ducts equipped with louvers [9, 10, 11, 12]. Since no biological method of air circulation is known the same approaches are utilized as at physicochemical systems. Also for the temperature and humidity control the same technologies are used in both approaches as no biological method exists to regulate these two parameters. Usually, CHX are applied to dehumidify the wet exhalation air [9, 10, 12]. To ensure an adequate ambient temperature of the air supply either heaters or a bypass parallel to the CHX are commonly used [9, 12]. Main differences of the two approaches are found in the gas composition control. In physicochemical systems different options exist for oxygen supply. This includes storing it under high pressure, cryogenically or in a supercritical state. Alternatively, oxygen can be stored in chemical compounds within so-called solid fuel oxygen generators (SFOG) or it can be generated by the electrolysis of water [10]. Also nitrogen can be stored under high pressure, cryogenically or in a supercritical state [9]. To store nitrogen in a chemical compound often hydrazine is taken because it is already available anyway as propellant [9]. By the catalytic dissociation of hydrazine, nitrogen and hydrogen results [9]. For the removal of carbon dioxide in physicochemical systems the following methods can be applied: LiOH method, electrochemical depolarized CO_2 concentration (EDC), two-bed and four-bed molecular sieves, and solid amine water desorption (SAWD). Trace gas removal is divided into two sections. For trace gases with a higher molecular weight activated charcoal filters are applied [9, 10]. The elimination of trace gases with a low molecular weight is performed with a catalytic oxidizer which converts them to compounds that can be adsorbed by a LiOH bed [9, 10]. In biological systems oxygen and carbon dioxide removal is associated. The light driven

process of photosynthesis performed by higher plants and microorganisms like algae, bacteria or fungi is used to reconvert gases. For nitrogen provision in biological systems microorganisms like agrobacteria can be applied [30]. Volatile organic compounds can be removed with biofilters and algae reactors [10]. Proven biological techniques to treat air in terms of VOC include biofilters, biotrickling filters, bioscrubbers and membrane reactors [31, 32, 33]. To counteract a too high or low atmospheric pressure at both approaches nitrogen is injected [9, 12] and vent and relief valves are used [12]. To keep the air clean high efficiency particulate air filters (HEPA) are used in physicochemical and biological systems. They are able to remove particles like dust, spores, aerosols and microorganisms [12].
The mentioned two basic approaches of LSS can both be more or less open or closed. The more closed a system is, the more regenerative processes take place in it. The aim is to close more and more loops because this is expected to result in mass savings. Although a fully closed system is likely to be heavier than an open system there will be cost savings over the entire mission lifetime due to lower amounts of needed resupply. This makes closed-loop systems especially important to long term missions.
To finish, advantages and current challenges were listed and discussed. Table 2.3 gives a detailed overview on the benefits and their impacts. One of the main advantages is the possibility to further close loops by the interlocking of the different processes (e.g. water recycling, food production, waste recycling). In addition, the presence of plants has a positive effect on the psychological well-being of the astronauts. Both advantages are significant for long-term missions. Challenges of biological systems reach from contamination issues [10], over genetic stability uncertainties [10] to the influence of micro- and reduced gravity [9] and radiation [9]. In addition, many processes in ecosystems are only understood very little so far which makes it impossible to fully control them in an artificial environment [9].

Since there is no biological method for every single task of a LSS, a hybrid system is very likely to be the next advanced LSS for long-term missions. In this kind of system technologies from physicochemical and biological LSS are united in one single system [10]. That combines the particular advantages of both and also comes along with design trade-offs in terms of initial and resupply masses. Also the EDEN Next Gen greenhouse module which was introduced in chapter 1 is part of a hybrid LSS for long-term space missions. It must be noticed that the greenhouse in total is part of a hybrid LSS, but the AMS of the greenhouse module itself is exclusively physicochemical. This shows again the dependence on physicochemical technologies.
The literature research from this chapter serves as basis for the next steps in the thesis but also for other further developments on the greenhouse module. Introduced technologies can be selected by means of their functionality and suitable advantages.
For reliability reasons, by designing the AMS redundancies should be applied to the introduced technologies. Therefore, a hot redundancy should be utilized for all components which are essential for the safety of the crew and could already cause danger if failing for a short time (e.g. O_2 and CO_2 sensors). A cold redundancy is sufficient for components which are not critical if failing for a short time (e.g. humidity control). For functions being essential for survival such as oxygen supply dissimilar redundant technologies should be applied to guarantee their realization.

3 Review of initial situation of this research

As discussed in chapter 1, this work builds on the design of the EDEN ISS AMS, the operational experiences with the system and the initial ideas for an adaptation towards a space-rated system (EDEN Next Gen). This chapter gives a brief overview of the necessary facts of the preceded work to be able to design the AMS of the EDEN Next Gen greenhouse module. In the following the EDEN ISS greenhouse module is introduced. First a general overview is given followed by the design of its AMS. Subsequently, the EDEN Next Gen greenhouse module is presented including the possible mission scenarios and its preliminary design.

3.1 EDEN ISS

Chapter 1 already introduced the research on biological life support systems of the EDEN group. Supported by the European Union Horizon 2020 project the EDEN team designed and manufactured the EDEN ISS greenhouse, a space analogue mobile test facility (MTF). The MTF was deployed in Antarctica near the German research station Neumayer III in January 2018. Since then there have been three overwintering operation phases and the fourth is currently planned for 2021 with new experiments in cooperation with NASA. Figure 3.1 shows the EDEN ISS MTF from the outside and the inside cultivation area. [6]

Figure 3.1: EDEN ISS Mobile Test Facility (left: outside view; right: inside view of cultivation area just after seeding) [6]

The MTF is housed in two 20-foot-long high cube shipping containers. The first container contains a cold porch and the so-called service section. The service section includes a working area, sub-systems (e.g. air management, power management, control systems) and an international standard payload rack (ISPR) with a plant cultivation system. This ISPR, which is a prototype for future on orbit food production, was removed and brought back to Europe after the first operation phase. The actual cultivation area is accommodated in the second container. It is called the future exploration greenhouse (FEG). Different kinds of crops are cultivated in plant racks and can be reached by a middle gangway. Figure 3.2 shows the floor plan of the EDEN ISS MTF. [6]

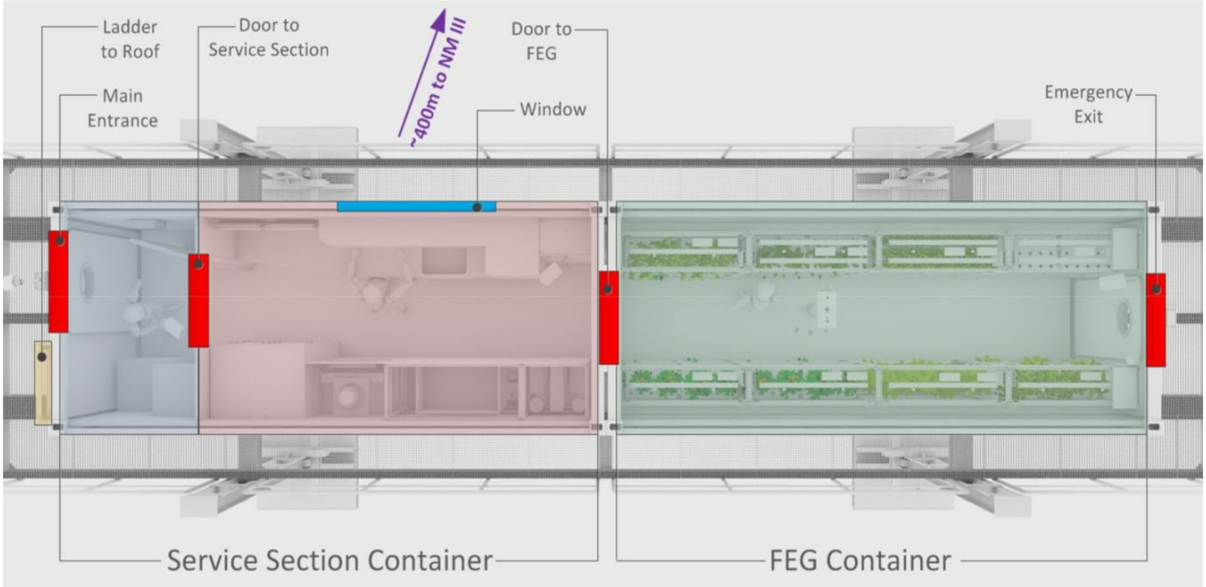


Figure 3.2: Floor plan of the EDEN ISS Mobile Test Facility (blue: cold porch; red: service section; green: cultivation area (FEG)) [6]

The AMS of the MTF can itself be divided into two sections. The main part of it is located in the service section container. It monitors and controls the atmospheric conditions in the cultivation area (FEG). The second part is responsible for the air distribution and dimensioning in the FEG. Figure 3.3 and Figure 3.4 show the components of the AMS of the EDEN ISS MTF. [42]

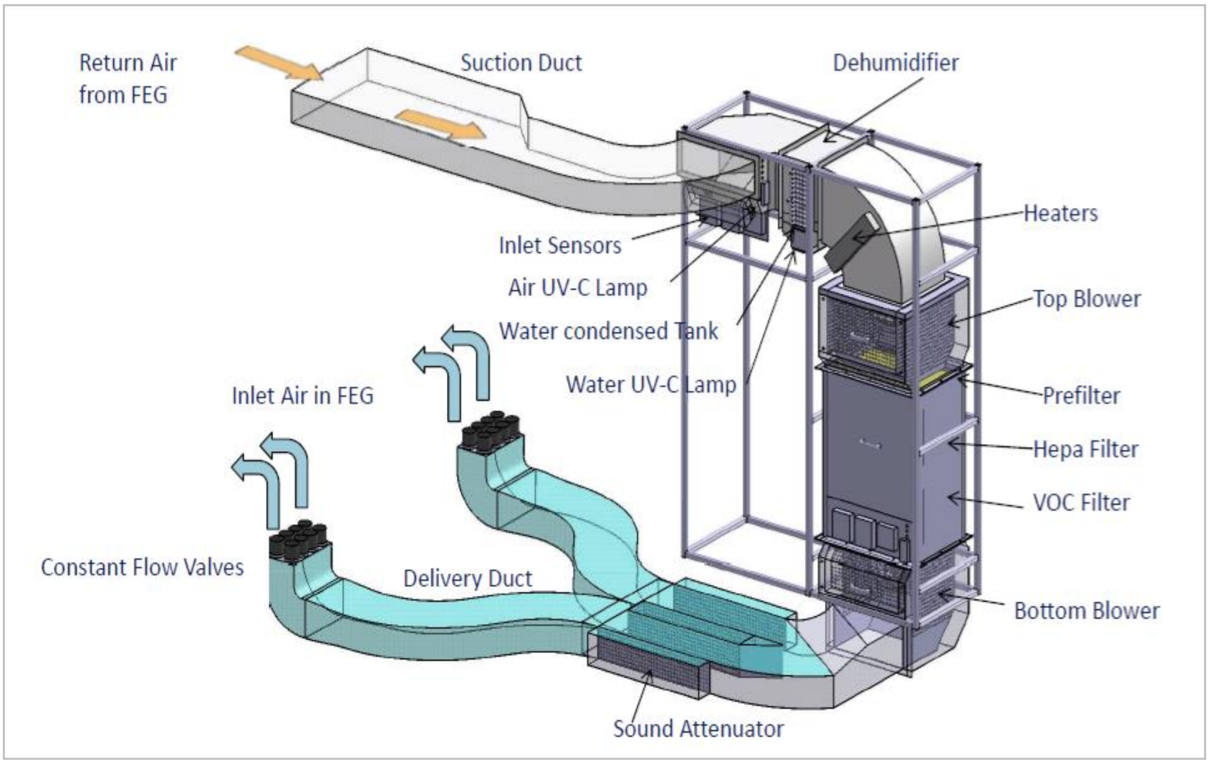


Figure 3.3: Components of the AMS located in the service section [42]

The return air from the FEG is first treated by an UV-C lamp to prevent microbial build-up. Subsequently the air passes a dehumidifier which dehydrates the air by reducing the temperature such that water condensates. The condensate water is collected in a water tank and also treated by an UV-C lamp. Afterwards the cold air is warmed up by heaters. Temperature sensors at the FEG air outlet and inlet give information of how much heating power is needed to reach the set point. To keep the air moving at all times there are two fans operating continuously. One upstream and the other one downstream of the filter block. The filter block contains a pre-, HEPA- and VOC-filter to extract dust, pollen, particles and volatile organic compounds (e.g. Ethylene). After the second fan the air stream is distributed into two ducts and led to the outside walls of the container. The O_2 level is measured at the FEG outlet and recorded to observe the O_2 production. On the other hand, the CO_2 level is recorded at the FEG outlet and inlet. If the CO_2 level drops under a certain limit additional CO_2 from a gas cylinder is injected at the FEG inlet. [42]

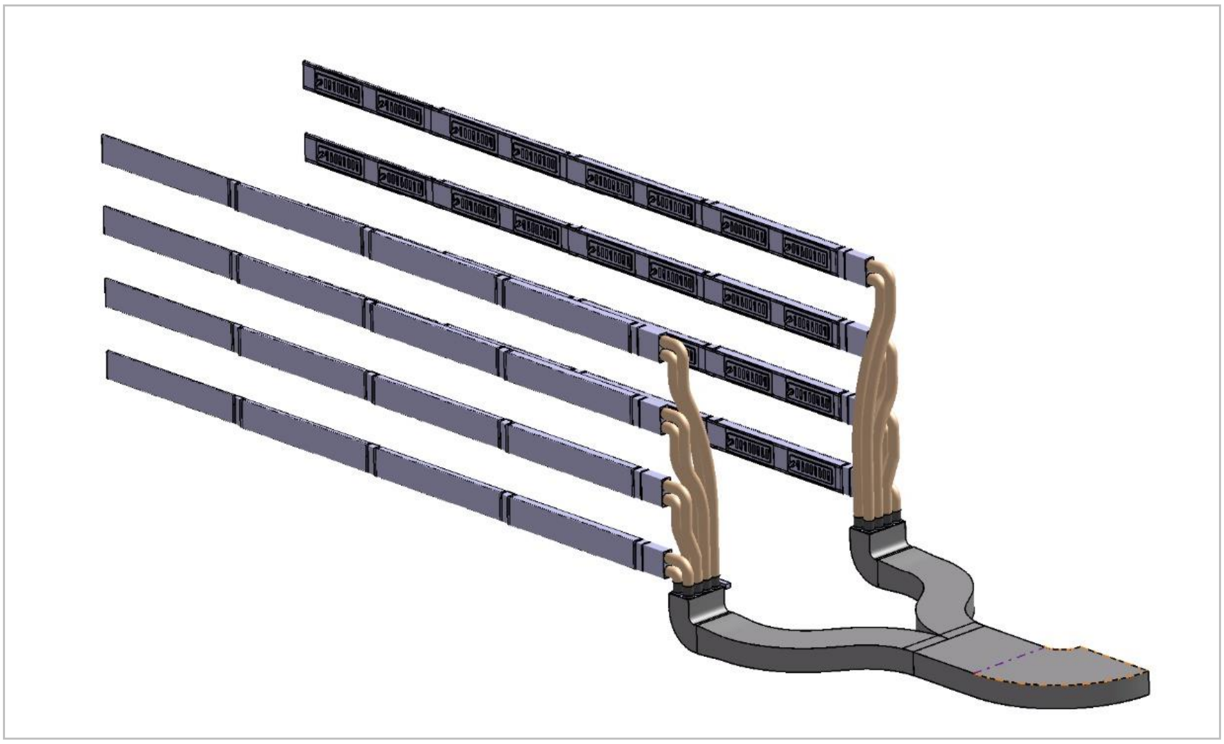


Figure 3.4: Components of the AMS located in the FEG [42]

Each of the two ducts is again distributed into four ducts. Finally, on four different heights the revitalized air is injected into the FEG. Balanced air distribution results from the horizontal ducts getting narrower to their ends. The ventilation rate and thereby the air dimensioning can be manually adjusted by partially or entirely closing the louvers facing to the inside. This makes zones with different ventilations rates possible. A further distribution of the air is fulfilled by fans located overhead at both sides of the aisle. In total eight tangential fans (four at each side) are applied. [42]

During the last three years of operating the MTF prototype in Antarctica a lot of knowledge could be gained and lessons were learned. Several optimizations and improvements concerning performance and reliability of the technology and their handling were already implemented. In Table 3.1 a selection of lessons learned, relevant for this thesis, are listed. This includes only lessons learned directly or indirectly influencing the AMS.

Table 3.1: Selection of lessons learned from MTF concerning the AMS

ID	Lesson learned	Consequence for EDEN Next Gen
LL-AMS-01	CHX performance too small. Since the water load was larger than originally anticipated not enough water could be recovered.	Besides larger margins for expected condensate, more buffer for the heat exchange should be applied. Since the temperature of the cooling fluid cannot be lowered, as this would come along with icing at the fins of the CHX, three adjusting parameters are left: increase of the condensation area of the CHX, increase the mass flow rate of the fooling fluid, increase the mass flow rate of the air.
LL-AMS-02	Sensors for monitoring trace contaminants make the work at the greenhouse module safer.	Since risk of enrichment of VOC is higher in the EDEN Next Gen several sensors to monitor trace contaminants should be applied.
LL-AMS-03	Microbial loads are a major problem. Especially at the CHX microbial growth is critical and the applied UV-C lamp was not sufficient. But since contamination was mainly found at the opposite side of the UV-C lamp either the lamp is preventing properly or there is no need of a lamp on the frontside. In addition, the access to clean the CHX from microbial growth was difficult due to the interfaces with the secondary structure.	To reduce the risk of contamination of the CHX the HEPA filter should be located upstream the CHX. In addition, an access opening for cleaning the fins of the CHX should be applied. The effect of UV-C lamps on microbial loads should be studied. For the first design at least one UV-C lamp should be applied. Dependent on the results of the study either no lamp, one lamp on the backside, or two lamps (one on the front- and one on the backside) should be applied.
LL-AMS-04	Humid air has a negative effect in the efficiency of the charcoal filter.	Charcoal filter should be located downstream the CHX.
LL-AMS-05	UV-C disinfection lamp should be downsized and also a cooling for the lamp is required. In addition, a redundancy should be applied.	Apply a separate cooling and a redundancy strategy as well as downsize the UV-C lamp if possible.
LL-AMS-06	HEPA-filter is more effective at a low humidity.	HEPA-filter should be applied downstream the CHX.
LL-AMS-07	No actual use of the possibility to regulate the air dimensioning of the air supplying ducts at the four different levels.	No adjustable louvers are applied anymore.

Data from [5], [43] and conversations with EDEN team members who played a significant role in designing, testing, and operating the MTF.

As apparent from the consequences from the last row of the table some lessons learned are conflictive which results in the impossibility to fulfil all of them. In chapter 4.3.3 a trade-off on the sequential arrangement of the components is performed. This gives a clearer overview on the importance of the lessons learned and their implementation. To directly apply those lessons learned to the design of the EDEN Next Gen greenhouse module they were considered by defining the requirements for it. An entire listing of the requirements defined during the preparation of this work can be found in Appendix 3.1 to Appendix 3.3. The selection of requirements which influence the design of the AMS of the EDEN Next Gen greenhouse can be found in chapter 4.1. More detailed information concerning the AMS of the EDEN ISS MTF can be found in [6], [42], [43] and [44].

3.2 EDEN Next Gen greenhouse module

3.2.1 Mission scenario

An exact mission scenario does not exist in so far as no detailed mission is actually planned [5]. Most likely a long-term mission which requires a greenhouse module will target Moon or Mars as final destination. A rough overview of a potential mission scenario with and without orbit infrastructure can be seen in Figure 3.5.

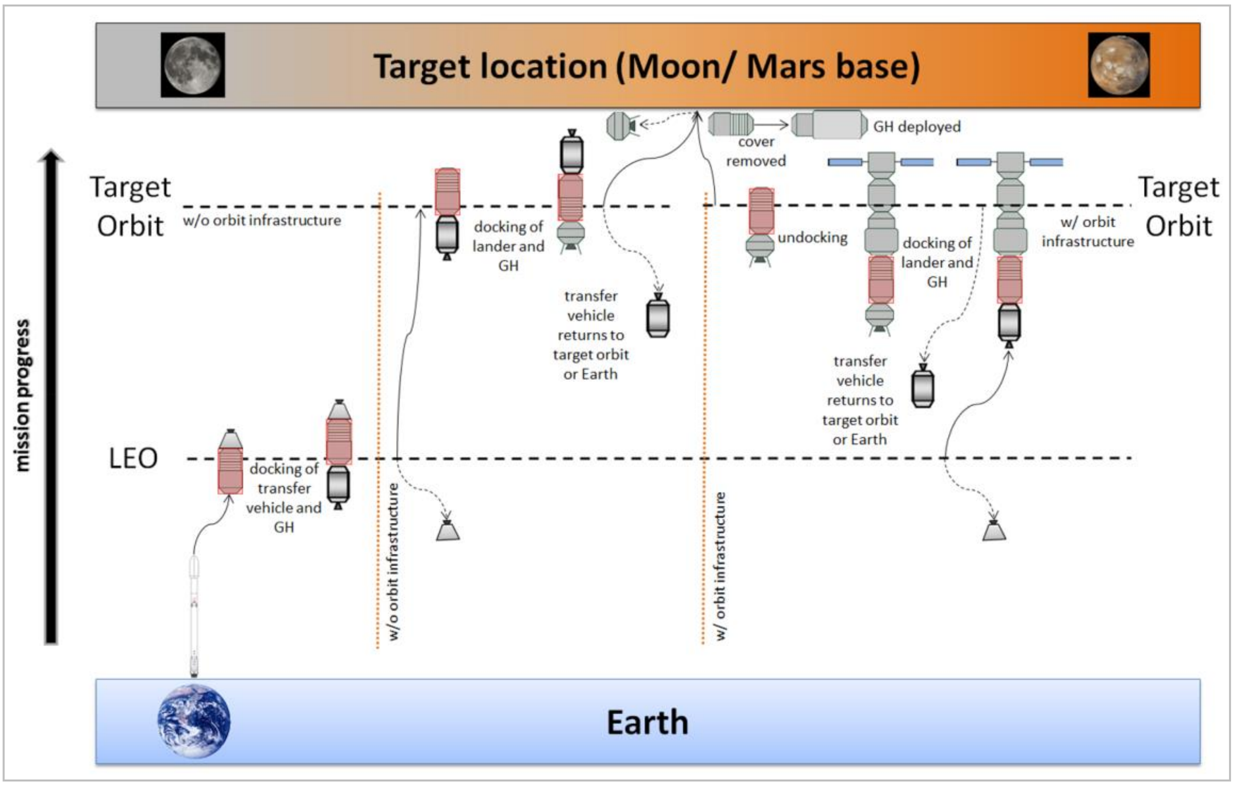


Figure 3.5: Possible mission scenario with and without orbit infrastructure [6]

The greenhouse module will be launched into Low Earth Orbit (LEO) with a Falcon 9 launcher. Due to the delay of the Space Launch System (SLS) development SpaceX's Falcon 9 Launcher is chosen because it already exists and has flight heritage. After being ejected in LEO the service vehicle is in charge of attitude and orbit control. Spacecrafts like Dragon and Cygnus, which are space transportation vehicles to carry cargo and/or humans, could be considered as baseline to design a service vehicle. As soon as the transfer vehicle docks with the greenhouse module the service vehicle is undocked and sent back to Earth. The transfer vehicle carries the greenhouse module to the target orbit. This is either to a target infrastructure in the orbit or directly to the target orbit. Subsequently the greenhouse module docks with a landing vehicle. After undocking the transfer vehicle, the lander lands the greenhouse module on the surface. The final steps are transporting the module to the final destination along the surface, shedding the protection cover against debris and radiation during transfer, attaching the greenhouse module to the habitat, deploying the greenhouse module to its full dimensions and covering the greenhouse with regolith. At this stage the greenhouse module is ready to be fitted with remaining equipment and plant seedlings. [5, 6]

3.2.2 Preliminary design

Based on an initial mission scenario, lessons-learned from the Antarctic prototype and defined requirements, a preliminary greenhouse module was designed. In March 2019 a session was held at the concurrent engineering facility (CEF) at DLR in Bremen with experts from DLR, LSG, and AS. They developed the preliminary design of the so-called EDEN Next Gen greenhouse module. In the following this preliminary design is introduced, the subsystems are briefly described and the AMS is presented. [5]

To meet the launch dimension requirement (FR-GHM-01), whereby the module shall fit within a Falcon 9 launcher, as well as the cultivation area requirement (FR-GHM-09), which requires at least 25 m^3 of cultivation area, the decision was made to design a partly deployable module. Cylindrical rigid sections are attached to both ends of the deployable section to guarantee a safe accommodation of the subsystems and to have defined airlocks. The stowed and deployed greenhouse module can be seen in Figure 3.6. This approach enables the stowage in the payload fairing of a Falcon 9 launcher (Figure 3.7) but still offers the required cultivation area. Detailed dimensions of the GHM in the stowed and deployed configuration can be found in Appendix 2.1 and Appendix 2.2. [5]

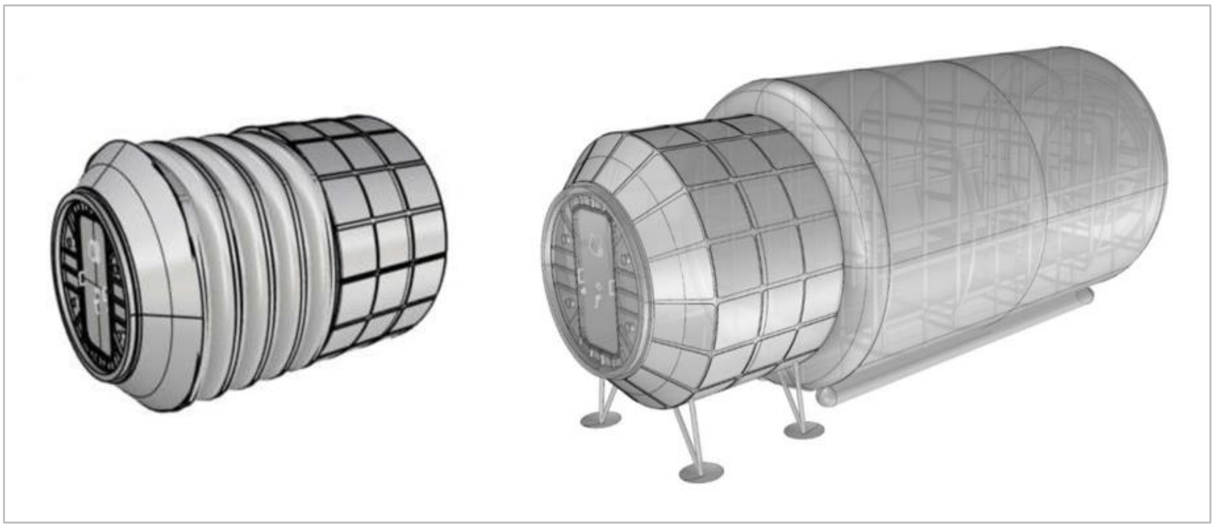


Figure 3.6: EDEN Next Gen greenhouse module (left: stowed with secondary entrance in the front; right: deployed with primary entrance in the front) [5]

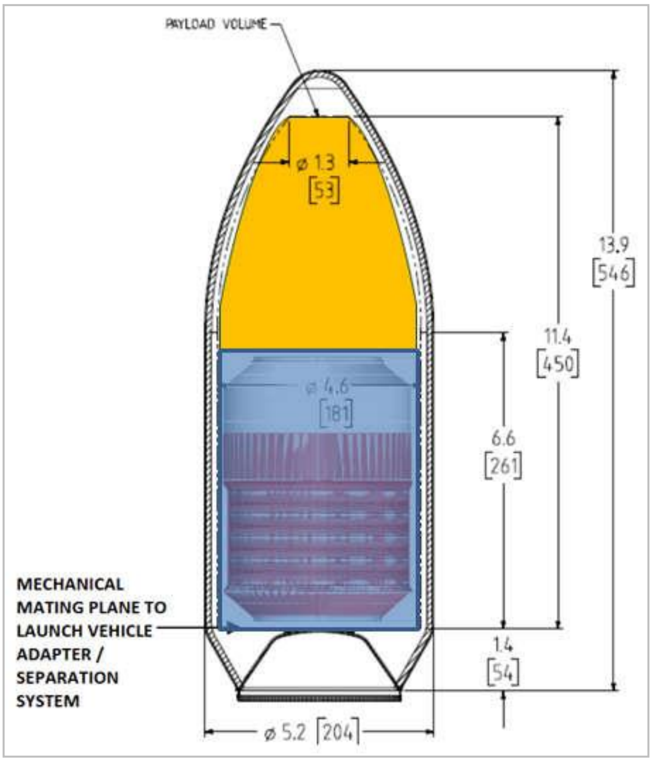


Figure 3.7: Fairing of Falcon 9 launcher with stowed greenhouse module including the protection shield (blue, ca. 30 cm thickness) and volume for the service vehicle (orange) (dimensions in meters and [inches]) [5, 45]

The rigid part with an aluminum shell features solid structure to host the subsystems and their interfaces. A layered membrane enables the deployable part to expand axially and radially. More detailed information about the primary and secondary structure are available in the appendix. The primary structure includes the primary rigid core (Appendix 2.3), the secondary rigid core, membrane shell and supportive legs and pillows (Appendix 2.4). The secondary structure consist of the rigid frames (Appendix 2.5 / Appendix 2.6), the spacers (Appendix 2.7), the longerons (Appendix 2.7), the floor elements (Appendix 2.7) and the shelves (Appendix 2.8). Additional information about the structural design including a membrane trade-off can be found in [5]. Details about the structure which are relevant for the design of the AMS are given in the design process later on when they are necessary. [5]

Besides the illumination system and parts of the nutrient delivery systems and the AMS all other subsystems are based in the rigid section of the greenhouse module. The preliminary placement of the subsystems can be seen in Figure 3.8 and Figure 3.9. At the end of the concurrent engineering study everything was in an initial stage. This is the starting point of this thesis. [5]

The following gives a brief overview of the subsystems and their tasks. The nutrient delivery system (NDS) is responsible for the perfectly adjusted mix ration of the nutrient solutions and the continuous supply of the plants with it. Incoming power from the habitat is divided and spread to the different subsystems by the power control and distribution system (PCDS). The thermal control system (TCS) manages to keep the temperature in the greenhouse module within a defined range. All systems are controlled and monitored by the control and data handling system (CDHS). Data from sensors and the cameras is also processed by the CDHS. The illumination system (ILS) illuminates the inside of the greenhouse module. This includes the area with the subsystems, the workbench and especially the cultivation area. Light with specific wavelengths targeted to the plants is used for the cultivation area. Task of the atmosphere management system (AMS) is to guarantee defined atmospheric condition in the greenhouse module. Firstly, the air is treated, by filtering, dehumidifying the air, and regulating the O_2 and CO_2 level. Secondly, the revitalized air is distributed and dimensioned to the cultivation area. [5]

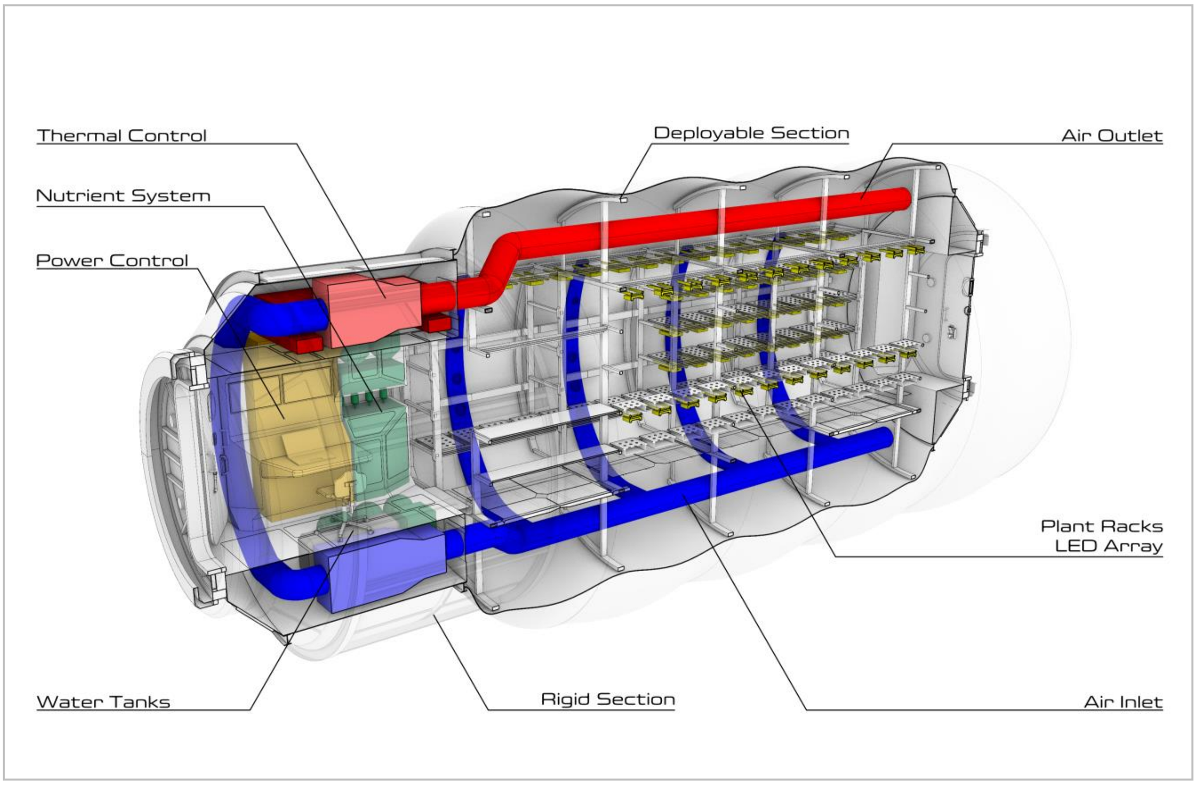


Figure 3.8: Cut-away view of the left side of the preliminary design of the greenhouse module [6]

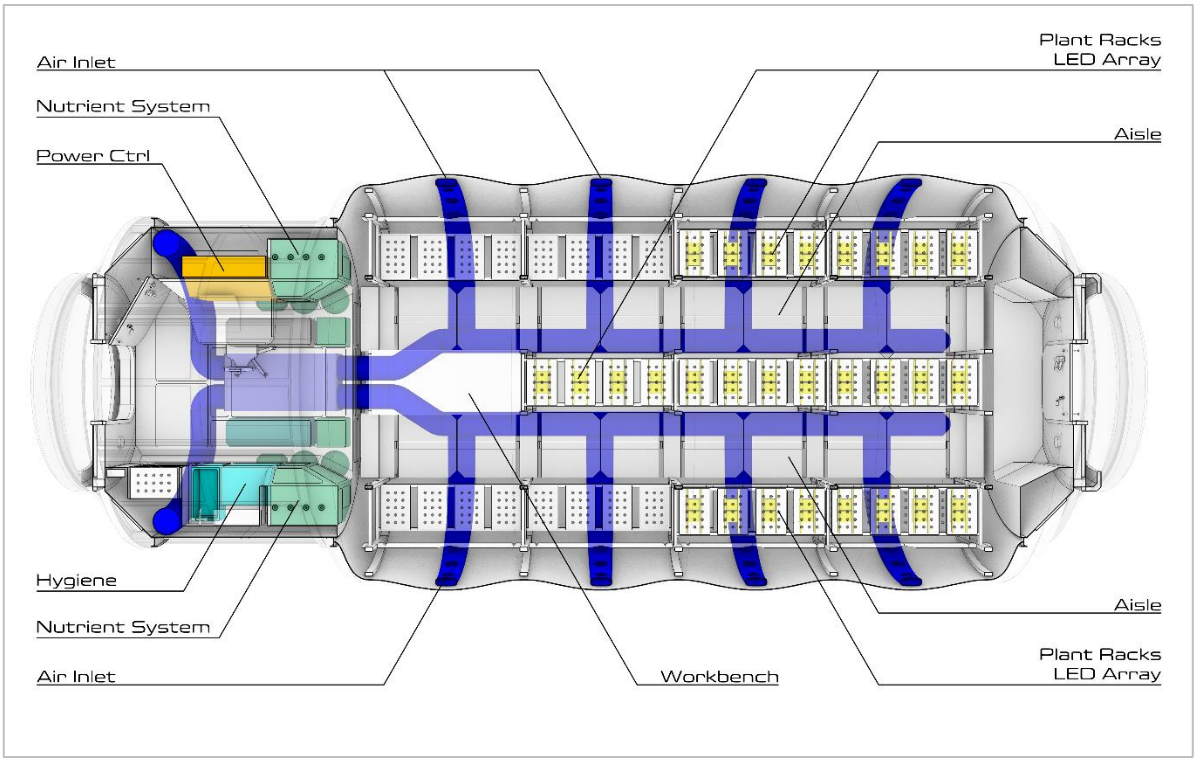


Figure 3.9: Top view of the preliminary design of the greenhouse module [6]

According to Figure 3.8 and Figure 3.9 all blue parts, and all red parts directly connected to the blue parts, belong to the AMS. Since the design is preliminary there is no concrete internal layout and for the subsystems and their components only placeholder volumes are used. The size of those placeholders is only roughly estimated and will probably change during the development process of the subsystems. The position of the subsystems is also not fixed yet. In the rigid section there is space available for the AMS as follows: Components are foreseen centrally under the floor and centrally overhead with vertical duct connections at the walls. The final layout of the components of the AMS will be heavily dependent on the necessary interfaces of the AMS to other subsystems. The deployable part accommodates the air inlet and air outlet infrastructure for the cultivation area. Here also the concrete realization is not defined so far. The rough design features the air inlet infrastructure under the floor. The two stumps at the end of the air supply underfloor ducts does not have a functional background. In further development steps it should be trade-offed whether those stumps are cut or they are connected for pressure balance. Air distribution and dimensioning is managed via curved vertical ducts and the air outlet infrastructure is found centrally overhead. Even though the available spaces do not have fixed dimensions yet it is important to consider the approximate available space for the development of the AMS. The CAD (computer-aided design) model shown in Figure 3.10 is equipped with placeholders to indicate available spaces for components of the AMS. For a clear arrangement all other subsystems are removed except for some of the structure.

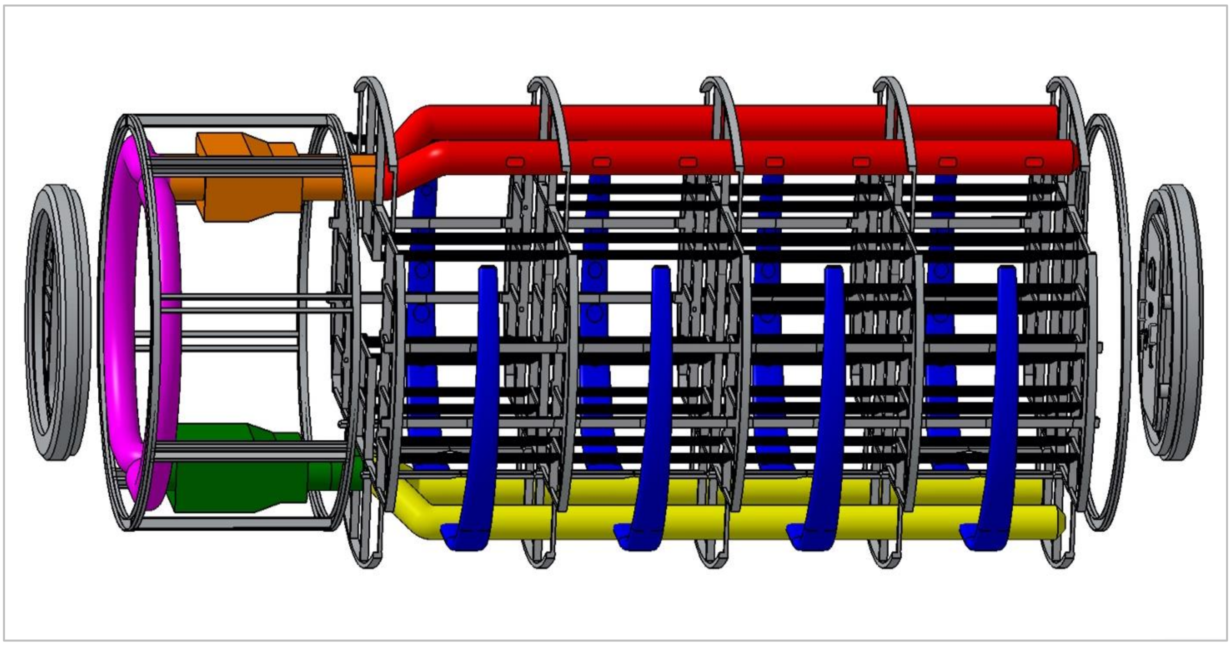


Figure 3.10: CAD model with indicated placeholders for AMS components

For more details Table 3.2 gives all relevant basic geometric data for developing the AMS which are given by the preliminary design. Attention should be paid to the overhead (red) and underfloor (yellow) spaces in the deployable part. Most likely those spaces are divided by the packed membrane material in the stowed configuration. Dimensions specified in Table 3.2 give the full size of divisions. This is partly a larger volume as indicated by the placeholders. Also, all stated dimensions are only rough orientation values.

Table 3.2: Resulting geometric characteristics of the greenhouse module important for the design of the AMS

Characteristic	Value at stowed configuration	Value at deployed configuration	Comment
effective inside volume	---	$V_{GHM} = 225\ m^3$	important for the circulation rate
inside diameter of the rigid part	$d_{rigid} = 4\ m$	$d_{rigid} = 4\ m$	important for maximum size of components for air revitalization
length of the rigid part	$l_{rigid} = 2.4\ m$	$l_{rigid} = 2.4\ m$	important for maximum size of components for air revitalization
underfloor space in the rigid part (total / foreseen for AMS) (green area in Figure 3.10)	$V_{rigid\ underfloor\ total} \approx 2.4\ m^3$ (cylinder fraction shaped volume: $2.4\ x\ 2.2\ x\ 0.0 \ldots 0.9\ m^3$) $V_{rigid\ underfloor\ AMS} \approx 1.34\ m^3$ (cuboid shaped volume: $2.4\ x\ 0.8\ x\ 0.7\ m^3$)	$V_{rigid\ underfloor\ total} \approx 2.4\ m^3$ (cylinder fraction shaped volume: $2.4\ x\ 2.2\ x\ 0.0 \ldots 0.9\ m^3$) $V_{rigid\ underfloor\ AMS} \approx 1.34\ m^3$ (cuboid shaped volume: $2.4\ x\ 0.8\ x\ 0.7\ m^3$)	important for maximum size of components for air revitalization
overhead space in the rigid part (total / foreseen for AMS) (orange area in Figure 3.10)	$V_{rigid\ overhead\ total} \approx 2.4\ m^3$ (cylinder fraction shaped volume: $2.4\ x\ 2.2\ x\ 0.0 \ldots 0.9\ m^3$) $V_{rigid\ overhead\ AMS} \approx 0.62\ m^3$ (cuboid shaped volume: $1.1\ x\ 0.8\ x\ 0.7\ m^3$)	$V_{rigid\ overhead\ total} \approx 2.4\ m^3$ (cylinder fraction shaped volume: $2.4\ x\ 2.2\ x\ 0.0 \ldots 0.9\ m^3$) $V_{rigid\ overhead\ AMS} \approx 0.62\ m^3$ (cuboid shaped volume: $1.1\ x\ 0.8\ x\ 0.7\ m^3$)	important for maximum size of components for air revitalization
inside diameter of the deployable part	$d_{deployable\ part} = 3.8\ m$	$d_{deployable\ part} = 4.9\ m$	important for air inlet infrastructure
length of the deployable part	$l_{deployable\ part} = 2.4\ m$	$l_{deployable\ part} = 8.4\ m$	important for air inlet and outlet infrastructure
underfloor space in the deployable part (yellow area in Figure 3.10)	$V_{deploy\ underfloor} \approx 1.1\ m^3$ (cylinder fraction shaped volume: $2.4\ x\ 2.7\ x\ 0.0 \ldots 0.35\ m^3$) (stowed membrane divides the spaces between the rigid frames)	$V_{deploy\ underfloor} \approx 17\ m^3$ (cylinder fraction shaped volume: $8.0\ x\ 2.7\ x\ 0.65 \ldots 1.0\ m^3$)	important for air inlet infrastructure
overhead space in the deployable part (red area in Figure 3.10)	$V_{deploy\ overhead} \approx 1.1\ m^3$ (cylinder fraction shaped volume: $2.4\ x\ 2.7\ x\ 0.0 \ldots 0.35\ m^3$) (stowed membrane divides the spaces between the rigid frames)	$V_{deploy\ overhead} \approx 17\ m^3$ (cylinder fraction shaped volume: $8.0\ x\ 2.7\ x\ 0.65 \ldots 1.0\ m^3$)	important for air outlet infrastructure
space to connect underfloor and overhead components (pink area in Figure 3.10)	Not specified but limited by the design of other subsystems. The pink ducts shown in Figure 3.10 have an approximate diameter of $d \approx 0.35\ m$ and a radius of curvature of $r_{curvature} \approx 2\ m$.	Not specified. The pink duct shown in Figure 3.10 has an approximate diameter of $d \approx 0.35\ m$ and a radius of curvature of $r_{curvature} \approx 2\ m$.	important for the connecting ducts for overhead and underfloor components.
space for air distribution ducts (blue area in Figure 3.10)	Not specified but limited by the design of the racks for the plant trays and by the stowage strategy.	Not specified but limited by the design of the racks for the plant trays.	important for the vertical curved air distribution ducts.

(for orientation only; no precise dimensions)

3.3 Summary and conclusion of the initial situation

Within this chapter a brief overview of the preceded work was given. The main focus was on the EDEN ISS mobile test facility and on the EDEN Next Gen greenhouse module.
Supported by the European Union Horizon 2020 project the EDEN team designed and manufactured the EDEN ISS greenhouse, a space analogue mobile test facility. The MTF was deployed in Antarctica near the German research station Neumayer III in January 2018. Since then, there have been three overwintering operation phases and the fourth is currently planned for 2021 with new experiments in cooperation with NASA. The MTF is housed in two 20-foot-long high cube shipping containers and its inside is divided into three sections: cold porch, service section, and cultivation area. The AMS of the MTF can itself be divided into two sections. Main part of it is located in the service section. It monitors and controls the atmospheric conditions in the cultivation area. The second part is responsible for the air distribution and dimensioning in the cultivation area. During the last three years of operating the MTF prototype in Antarctica a lot of knowledge could be gained and lessons were learned. In Table 3.1 a selection of lessons learned, relevant for this thesis, are listed.
Next step towards a space rated greenhouse module is the EDEN Next Gen greenhouse module. As no detailed mission is actually planned so far, an exact mission scenario does not exist [5]. Most likely a long-term mission which requires a greenhouse module will target Moon or Mars. A rough overview of a potential mission scenarios is given in Figure 3.5. In March 2019 the preliminary design of the EDEN Next Gen greenhouse module was developed at the concurrent engineering facility at DLR in Bremen [5]. The result was a cylindrical and partly deployable module which fits in the payload fairing of the Falcon 9 launcher at its stowed configuration. Most of the subsystem's components are located in the rigid part of the module. The deployable part accommodates the actual cultivation area. Figure 3.8 and Figure 3.9 give more details on the general internal setup. So far no subsystem was designed. Therefore, only placeholders are inserted into the model of the preliminary design. Available spaces and their locations are presented in Figure 3.10 and Table 3.2. In Figure 3.11 a basic development roadmap of the EDEN greenhouse module is given. The Antarctic analogue mission with the MTF prototype serves as basis for the design of the EDEN Next Gen module for Moon and Mars.

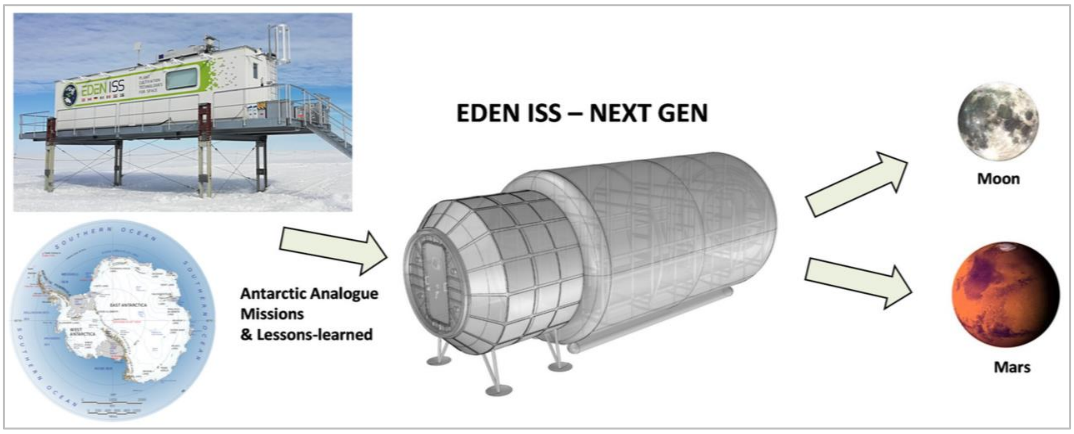


Figure 3.11: Development roadap of the EDEN greenhouse module [5]

In this chapter especially important for the work of this thesis are on the one hand the lessons learned from the prototype mission and on the other hand the locations and volumes of the available spaces in the preliminary design of the next generation greenhouse module. Lessons learned not only include failures but also the well performing components which can be transferred to the EDEN Next Gen module.

4 System analysis

4.1 Requirement definition

Lessons-learned from Antarctica and the initial mission scenario concept lead to assumptions and requirements [5]. The defined requirements are classified into three categories. With the first category the requirements concerning the supporting infrastructure (SI) are covered. This includes requirements related to the necessary support infrastructure at the final destination. Every supporting infrastructure will go via the habitat which makes the greenhouse module dependent on it. The second category outlines the overall greenhouse module (GHM) requirements. Those are the requirements related to the entire greenhouse module. The last group contains the detailed requirements related to the AMS of the greenhouse module.
The following Table 4.1 shows the main requirements from each of these categories which directly impact the design of the AMS. A complete collection of all three groups of requirements can be find in Appendix 3.1., Appendix 3.2 and Appendix 3.3. Available requirements for the EDEN ISS greenhouse module were mainly adopted from [5] and [46], and adapted to a space environment as well as adjusted to the different conditions.

Table 4.1: Selection of functional requirements which directly affect the AMS including detailed functional requirements for the AMS, overall greenhouse module requirements (GHM) and infrastructure functional requirements (SI)

ID	Requirement	Comment
FR-AMS-01	The AMS shall monitor and control the inside temperature and the inside relative humidity within the following ranges (measurement at different significant locations of the greenhouse module): - temperature 16 °C - 30 °C (accurate to a set point of ± 0.5 K) - relative humidity 70 % - 100 % (accurate to a set point of ± 1 %)	Temperature and relative humidity controlled at level required for successful plant growth as well as acceptable for human comfort. In addition, relative humidity controlled such that dew point does not lead to condensation on internal surfaces (risk of microbial and fungal growth).
FR-AMS-02	The AMS shall monitor and control the inside O_2 and CO_2 concentration as well as the inside total pressure within the following ranges (measurement at different significant locations of the greenhouse module): - CO_2 concentration 350 ppm – 5000 ppm (accurate to a set point of ± 50 ppm) - O_2 concentration 21 % - 24 % (accurate to a set point of ±1 %) - total pressure 101.3 kPa (accurate to a set point of ± 10 kPa)	Chosen for optimal plant growth.

ID	Requirement	Comment
FR-AMS-03	The AMS shall monitor and control the air flow rate and air flow velocity at the plants within the following ranges (measurement at different significant locations of the greenhouse module): - air flow rate that is required to guarantee a safe environment for plants and humans (determined later) - air flow speed at plant 0.3 m/s – 0.7 m/s (accurate to a set point of ± 0.1 m/s)	Chosen for optimal plant growth.
FR-AMS-04	The AMS shall monitor and control the ethylene level within the defined range, and limit the level of all other VOC, odor, the microbial load, and the airborne particles (measurement at different significant locations of the greenhouse module): - ethylene level below 50 ppb - minimize all other VOC - minimize odor - minimize microbial load - minimize airborne particles	Chosen for optimal plant growth.
FR-AMS-05	The AMS shall be designed to exchange gases with the habitat.	- CO_2 from habitat to greenhouse module - O_2 from greenhouse module to habitat
FR-AMS-06	The AMS shall allow easy access to each component of the AMS to guarantee quick maintenance.	- only short shutdowns - ensure continuous plant production - keep component replacement and maintenance as simply as possible (no need to remove other components)
FR-GHM-03	The greenhouse module including all pre-installed equipment shall withstand launch loads as well as loads during transfer and landing on the planetary surface. It shall also withstand the loads which might occur due to the regolith layer.	g forces: *(tbd)* acoustic forces: *(tbd)* thermal loads: *(tbd)* loads due to regolith layer: *(tbd)*
FR-GHM-04	The greenhouse module shall be fully operational at an external ambient temperature of $T_a = 254\ K$.	Expected temperature in Moon environment after covering the greenhouse module with a regolith layer $t_R \geq 0.3\ m$. [47, 48, 49]
FR-GHM-05	The greenhouse module shall be operational for at least two years without resupply except from habitat.	Resupply from habitat includes mainly CO_2, power, nutrients, manpower, spare parts, seeds.

ID	Requirement	Comment
FR-GHM-08	The greenhouse module shall house the following required subsystems in the service section: - air management system (AMS) (air distribution ducts are located in the deployable part) - nutrient delivery system (NDS) - power distribution system (PDS) - command and data handling system - thermal control system - desk, chair and locker - general storage facility - sink - safety equipment - C.R.O.P.	- workspace for pre- and post-processing of the plants - storage for various equipment
FR-GHM-14	The overall noise level of the greenhouse module shall be within the range of European work regulations (concrete values at [50])	---
FR-GHM-17	The greenhouse module shall be one failure tolerant for functions relevant to keep the plants or crew alive.	---
FR-GHM-18	Piping and harness diameters shall be similar among all parts of all subsystems.	To limit the number of connectors/interfaces.
FR-GHM-19	The level of autonomy shall be at least equal to EDEN ISS.	Harvesting, seeding etc. conducted by the crew.
FR-SI-04	The greenhouse module shall have a thermal and electrical interface to the main habitat, allowing power transfer and thermal heat load transfer.	---
FR-SI-06	The atmosphere for pressuring the greenhouse module shall be supplied by the habitat.	---
FR-SI-07	The greenhouse module shall allow resources to be transported between the habitat and the greenhouse module, via piping (FR-SI-08; FR-SI-09; FR-SI-10) and airlock tunnel as well as harness for data (FR-SI-11; FR-SI-14) and power (FR-SI-05).	---
FR-SI-10	The habitat absorbs up to 4.92 $\frac{kg}{day}$ O_2 (0.82 $\frac{kg}{day\ person}$ [51]) and supplies up to 6.24 $\frac{kg}{day}$ CO_2 (1.04 $\frac{kg}{day\ person}$ [51]) from/to the greenhouse module.	Six crew members are assumed. O_2 output of the plants reaches from 0 $\frac{kg}{day}$ (before germination) to 0.914 $\frac{kg}{day}$ (fully cultivated) which requires an additional O_2 source for the habitat. CO_2 uptake of the plants reaches from 0 $\frac{kg}{day}$ (before germination) to 1.266 $\frac{kg}{day}$ (fully cultivated) which requires an additional CO_2 disposal. For more details see chapter 4.5.1.1.

4.2 Assumptions

For the development of the AMS, which fulfills all defined requirements, a model of the greenhouse is built up in the following two subchapters. This includes external and internal loads which have influence on the greenhouse module. To keep the model clear and simple only loads affecting the AMS are considered.

The final destination of the greenhouse module has a significant influence on the occurring external loads. According to the global exploration roadmap of ISECG in Figure 1.1, Moon and Mars are the next targets for human long-term stays. The environmental conditions on Moon and Mars differ strongly concerning atmosphere, temperatures, orbit and orbital period (solar radiation), gravity, and regolith composition. For that reason, the greenhouse cannot be optimized, simultaneously, for both Moon and Mars conditions. Since the Moon is more probable to be the first mission location of those two, in this thesis lunar environmental conditions are considered. Depending on where on the lunar surface the human outpost will be located some environmental conditions are very different. This concerns especially solar irradiation and the thereby affected temperature. The options vary from regions with permanent solar irradiation as well as permanent shadow at the poles to equatorial areas with even balanced day and night times, which have high temperature differences due to the long orbital period. A list with assets and drawbacks of lunar polar regions and non-polar regions (Earth side and far side) is given in [52].

The internal loads of the greenhouse module are highly dependent on the size, which is proportional to the crew size, assuming the greenhouse is designed to provide a certain percentage of the crew's diet. A bigger cultivation area means more plant loads like transpiration and CO_2 – O_2 conversion. Also, more powerful subsystems are needed, which additionally increases the internal thermal load. In this thesis a crew size of six members is considered.

To keep some complex processes simple, assumptions are made. In the following Table 4.2 assumptions are listed which directly or indirectly affect the AMS, such as the destination and crew size decision. Table 4.2 is not a complete listing of all assumptions made in this thesis. Only the main assumptions which have a significant influence on the design are listed. All other less influential assumptions are introduced at the specific point of use.

Table 4.2: Assumptions made for the development of the AMS

ID	Assumption	Reason	Applicable Reference
A01	Due to a protecting regolith layer: 1. the ambient temperature of the greenhouse module is constant at $T_a = 254\ K$ 2. radiation (particles, solar, galactic cosmic) is on a safe level	For radiation protection the regolith cover is expected to be $t_R > 0.5\ m$. As a result, the (subsurface) temperature is expected to be stable. At equatorial regions temperature stability is guaranteed at regolith layer thicknesses of $t_R \geq 0.3\ m$).	temperature: [47, 48, 49] radiation: [53, 54, 55]

ID	Assumption	Reason	Applicable Reference
A02	There is no heat transfer via the basement infrastructure (pillows and legs).	Every heat transfer regarding the basement infrastructure is neglected to keep the model of this thesis simple. When designing the TCS of the greenhouse module these thermal influences should be considered.	---
A03	At the outside surface of the greenhouse module there is only radiation for heat transfer.	Due to the negligible atmosphere on the Moon heat transfer via convection can be neglected.	[47]
A04	Internal thermal loads, including the AMS, all other subsystems, and plants, will be estimated by scaling the (empirical) values from the EDEN ISS MTF.	More details on scaling and resulting values in chapter 4.5.	---
A06	Unexpected changes of external and internal thermal loads can first be buffered by: 1. the TCS of the greenhouse module and 2. the connected TCS of the habitat.	Due to applied safety margins it is very unlikely that the two backup systems are needed.	---
A07	The gravity acceleration of the entire operation phase of the greenhouse module is constant at $g_M = 1.625\ \frac{m}{s^2}$.	This value is the mean normal gravity acceleration on the Moon surface.	[56]
A08	Pressure losses (e.g. due to leakage) are neglected. The atmospheric pressure inside the greenhouse module is guaranteed by the AMS of the habitat.	The AMS of the greenhouse module is connected to the AMS of the habitat anyway.	---
A09	All metabolic rates concerning plants are considered to be static.	Since the design process of this thesis is only a very first step for rough performance estimation it is sufficient to consider the process of photosynthesis to be static even though it is a light driven process and dependent on the dynamic light intensity.	More details in chapter 4.5.1.1.
A10	To determine the metabolic loads of the plants a sample plant configuration is used.	Due to the early stage of the development process but also during the mission this configuration might change. To cover that a margin is applied.	Sample plant configuration from [6]. More details in chapter 4.5.1.1.
A11	Plants effects on trace contaminants in atmosphere is not considered.	The influence of higher plants on the concentration of trace gases is very slight and can be neglected.	[38]

ID	Assumption	Reason	Applicable Reference
A12	Thermal loads induced by humans working in the greenhouse are not considered.	The influence of emitted heat by humans is neglected at the first development step ($Q \approx 150\ \frac{W}{person}$ expected at greenhouse work). The working hours in the MTF were around $20\ \frac{h}{week}$. It is expected that this time can be reduced with more reliability and more automation even though the greenhouse module has a bigger cultivation area.	[51, 57]
A13	The metabolic impact of O_2 to CO_2 conversion by humans working in the greenhouse is not considered.	Expected O_2 consumption of $\dot{m}_{O_2} \approx 0.05\ \frac{kg}{h}$ and CO_2 output of $\dot{m}_{CO_2} \approx 0.065\ \frac{kg}{h}$ at a working time of $t_w \leq 20\ \frac{h}{week}$ are neglected.	[51, 57]
A14	The metabolic impact of transpiration (perspiration and vaporized exhaling air) from humans working in the greenhouse is not considered.	Expected transpiration rate of $\dot{m}_{H_2O} \approx 0.12\ \frac{kg}{h}$ at a working time of $t_w \leq 20\ \frac{h}{week}$ is neglected.	[51]
A15	The metabolic impact on trace contaminants by humans working in the greenhouse is not considered.	Expected metabolic impact on trace contaminant concentration during working time of $t_w \leq 20\ \frac{h}{week}$ is negligible.	[58]

4.3 Components, elements and their functions

For designing the AMS of the greenhouse module it is important to build up a model first. The model has to include the external and internal loads the AMS has to handle and the components of the AMS which respectively consist of several elements. In addition, the interfaces of the AMS to other subsystems and the habitat AMS have to be added to the model. In the same step the boundaries of the AMS have to be defined. First of all, this model will help to understand the functionality of the AMS. Furthermore, with added natural scientific (physical, chemical, biological) interrelations and practical numerical values the model can be used to get a rough dimensioning of the required performances of the components and elements.

According to the tasks of an AMS, as listed in chapter 2.1, components can be defined to perform them. As the EDEN ISS MTF is seen as a prototype the components are partly adopted in the EDEN Next Gen. Nevertheless, some adaptations, improvements, and complements are implemented. For those innovations technology trade-offs are performed to find the most suitable method for the AMS.
In general, the components can be divided into functional components and monitor and control components. Functional components are needed to directly fulfil the tasks, like a fan and a dehumidifier. Monitor and control components guarantee the surveillance of critical

parameters at different significant locations and the control of the functional components based on those measurements. Monitoring is performed by different types of sensors and is discussed later in this chapter. The control components which are responsible for the operating mode are considered in chapter 5.2.2. Table 4.3 shows an overview of the functional components and their functions. Afterwards the technical elements for the practical implementation are introduced.

Table 4.3: Components of the AMS and their functions

Component (Sub-assembly)	**Functions**
air outlet	- air suction
air inlet	- air distribution - air dimensioning
fan	- pressure loss compensation - air circulation
dehumidifier	- dehumidify air - treat condensate - store condensate
heater	- temper air
filters	- reduce microbial load - mechanically filter particles like dust, spores, aerosols and microorganisms - chemical treatment of air
air composition control	- CO_2 and O_2 exchange with habitat - control level/concentration of CO_2 and O_2 and trace contaminants

4.3.1 Adaptations from the MTF

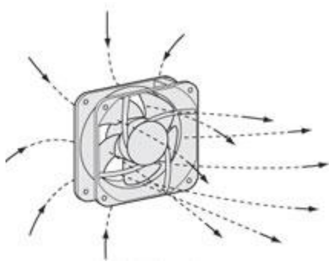
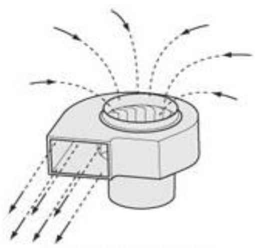
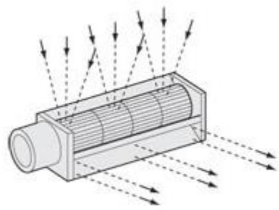
Components which proved their qualification in the MTF and are not affected by the different environmental conditions of the Moon are adopted for the EDEN Next Gen. This includes the following components:
The general design of the air distribution (air inlet ducts / roof fans) and of the air suction (air outlet ducts) underwent iterative development with the help of CFD (computational fluid dynamics) simulations and did not cause any problems in the MTF. As presented in chapter 2.2 air distribution is also managed with similar approaches in modern spacecraft like the ISS. For that reason, the general implementation will be the same at the EDEN Next Gen. However, as already mentioned in the lessons learned, the possibility to regulate the dimensioning of the air was not used in practice. With respect to that fact this function is cut out of the EDEN Next Gen.
Although the dehumidifying unit caused some problems in the prototype the overall setup will be adopted. Condensing heat exchangers are well approved in different gravitational conditions (Earth / ISS) and are the state of the art for dehumidifying air in space. Besides the CHX also the other elements of this assembly, UV-C lamp, water pump, and condensed water tank, are transferred to the next generation greenhouse module.

For both manned and unmanned space missions, electrical heaters are the choice of device to warm up all different kinds of items. They feature an efficient and safe operation combined with the possibility of very accurate regulation. For those reasons electrical heaters will also be used for the reheating of the dried air in the EDEN Next Gen greenhouse.
The use of diverse types of filters using different approaches (mechanical / chemical) is the standard practice for space application. The same concept is applied in the MTF. The sequence of pre-filter, HEPA-filter, and VOC-filter is respectively filtering large particles, small particles, and trace gas contaminants. Based on the literature research in chapter 2 it can be concluded that biological methods to filter trace contaminants are not mature enough and for the design of the new EDEN greenhouse module the well-established VOC-filters are considered.
In general, every technology used in the MTF needs further qualifications and tests to space-rate the components. In the following, technology trade-offs are performed for the practical realization of those elements which are not directly adopted from the MTF.

4.3.2 Trade-off on fans

Mechanical ventilation can be done with different techniques. This section focuses on the commonly used types of fans and provides a trade-off for the fans required for the AMS. This includes, firstly, the fans within the duct system to counteract pressure losses and guarantee air movement, and, secondly, the fans located in the overhead space within the deployable part which distribute air all over the cultivation area. Table 4.4 gives an overview of types of fans and shows their working principles and properties. For the ranking within the table 1, 2, and 3, meaning best to worst, is chosen. The characteristics for both fan applications ideally are the following: high flow rate, low required space, low noise load, and high available static pressure.

Table 4.4: Common types of fans and its characteristics

	Axial	**Centrifugal**	**Tangential (Cross-flow)**
Principle	 [59]	 [59]	 [59]
Flow rate	1	3	2
Required space	1	3	2
Noise load	3	2	1
Available static pressure	2	1	3
Specialty	- space flight approved - unidirectional applicable	- 90° turn of air flow - low but steady flow rate - ability to handle heavily contaminated air	- wide and uniform air flow

Data based on [59], [60], [61], [62], and [63]. Ranking: best to worst (1 – 2 – 3)

Axial fans and centrifugal fans can again be classified in sub-categories [61, 62]. Those are tube axial, vane axial, and propeller for axial flow fans [61, 62]. The essential types of centrifugal fans are radial, forward curved, and backward curved [61]. Furthermore, a variety of hybrid types of those basic principles exists. For this trade-off only the basic principles are compared. This is sufficient to serve as basis for the decision-making.

Special attention for the application in the duct system should be paid to the noise load, available static pressure, and required space. Besides a low acoustic impact and a small installation space, a high static pressure is required. On account of those characteristics the first choice should be a centrifugal fan. If the available space is not enough a centrifugal fan of the required performance, the best compromise is an axial fan. As axial fans are in use on the ISS there is already a lot of flight experience with them [12, 13, 14]. However, a recently published numerical analysis of the air distribution in the crew quarters on the ISS proposes to replace them with tangential fans [14]. According to the comparison in Table 4.4 axial fans typically generate more noise compared to other fan types. It has to be checked whether this is within the limits for human space flight (see [51] and [50]). Since humans are only in the greenhouse for short times it might not cause big issues. Furthermore, acoustic cancelation blankets can be used to reduce the occurring acoustic load for humans working in the greenhouse [12, 13].

For the overhead fans located in the deployable part it is important to consider the flow rate, the noise level, and the required space. A low acoustic impact is also requested for those fans. The needed installation space is especially critical due to its location within the deployable part. It is not necessary to have large flow rates but they should be stable. The static pressure is not critical for these fans. Diagonal ventilators which are similar to axial ventilators could be interesting for the overhead fans to distribute air in the cultivation area. Their air output is cone-shaped and offers the opportunity to distribute the air to a larger volume compared to conventional axial fans. Alternatively, cross-flow fans might be a good choice due to their wide airflow. Another option for air distribution would be to replace those overhead fans by fans attached to grid shaped floor panels. For those underfloor fans the same requirements would apply as for overhead fans. Important for the choice of one of those placements is to consider the capability to distribute the air within the entire cultivation area. Induced turbulences have an advantageous effect on the distribution, especially on catching areas surrounded by plants. For that reason, in this thesis the distributing fans are considered to be overhead. Since the air suction ducts for the air outlet are considered to be overhead a uniform and laminar airflow might occur if the fans would be underfloor. By placing them next to the air outlet duct it is expected to generate turbulences due to their countercurrent circulation.

To make a final decision for one of the two preferred fan types mentioned for each application case their geometric compatibility concerning air stream angles, and the effort for replaceability in the specific case, should be compared. This can be done after more detailed data on other subsystems is available.

Since the actual characteristics of the utilized fans are still dependent on the selected sub-category their suitability finally needs to be examined with the help of a CFD analysis. Because of uncertainties in the CFD model due to the unpredictability of plant growth, experiments are needed to verify the results of the CFD model.

Independent of the types of fans used for the two different applications there has to be a redundancy. This is important to prevent a single point failure. A permanent operation needs to be guaranteed even in case one fan stops working. This requirement is realized by implementing multiple fans for each application. The fans can be combined in two different strategies [61, 62, 63, 64, 60]. By installing fans in series the static pressure can be increased by keeping the maximum flow rate the same [61, 62, 63, 64, 60]. Parallel fans can increase the flow rate but static pressure stays the same [61, 62, 63, 64, 60]. In the crew quarters' ventilation system on the ISS a serial fan configuration of two fans was selected after a comparison of the two introduced strategies concerning power efficiency, pressure head capability, packaging, acoustic interactions, and failure modes [13]. According to the duties of the fans the redundancy strategies are adopted from the MTF. For the fans in the duct system it is significant to ensure a static pressure which is able to overcome the pressure losses. On that account a serial configuration is chosen which is able to buffer the failure of one fan. Since the continuously ongoing low air flow rate is important for the overhead fans in the deployable part a parallel fan assembly is applied.
A concrete number of fans for the specific application will be discussed during the sizing of the fans in chapter 5.1.1. More about the redundancy of the fans can be found in this chapter as well.

4.3.3 Trade-off on sequential arrangement of components

As already mentioned in chapter 3.1 the lesson got learned that the sequential arrangement of the components of the AMS should be rearranged. One particular lesson was that the HEPA-filter has a better performance at a low humidity (LL-AMS-06). The effectiveness of a HEPA-filter degrades over the operating time. Due to clogging the resulting pressure loss via the filter increases. According to [65] this pressure drop is also dependent on the relative humidity of the air streaming through the filter. The practical effect of the relative humidity is again dependent on the kind of filter (flat / pleated) and on the clogging state [65]. Also [66] and [67] investigated the influence of the relative humidity on the effectiveness of HEPA-filters. The broad agreement is that a low relative humidity should be aimed for to guarantee best performance of the filter. A low relative humidity is present downstream the CHX. In contrast to that the CHX is especially critical concerning microbial growth (LL-AMS-03). The HEPA-filter can significantly reduce the microbial load at the CHX but only if applied upstream of it. This is at a conflict with the preferred location of the HEPA-filter. Since the replacement of the HEPA-filter is significantly easier than cleaning the CHX the requirement of the CHX has a higher priority.
To also cover all other potential disadvantageous arrangements Table 4.5 is a compilation of the different components and their respective required operating conditions.

Table 4.5: Components, their required operating conditions and the resulting consequences

Component	Required operating condition	Resulting consequence
Air outlet / Air inlet	---	---
Fan	no bigger particles	downstream of pre-filter
Dehumidifier	no microorganisms	UV-C lamp directly at or upstream the dehumidifier. Pre- and HEPA-filter upstream of dehumidifier.

<table>
<tr><th>Component</th><th colspan="2">Required operating condition</th><th>Resulting consequence</th></tr>
<tr><td>Heater</td><td colspan="2">cold air needed</td><td>downstream the dehumidifier</td></tr>
<tr><td rowspan="3">Filters</td><td>pre-filter</td><td>---</td><td>---</td></tr>
<tr><td>HEPA-filter</td><td>low relative humidity</td><td>downstream of dehumidifier and heater</td></tr>
<tr><td>VOC-filter</td><td>low relative humidity</td><td>downstream of dehumidifier and heater</td></tr>
<tr><td>Air composition control</td><td colspan="2">---</td><td>---</td></tr>
</table>

Respecting all consequences from Table 4.5 the filters, which were installed as a bundle in the MTF, need to be separated. Also, as already analyzed, it is not feasible to fulfil all needs of the components. One possible sequential arrangement, where only the less prioritized need of the HEPA-filter is unmet, is presented in the following. The air is sucked from the cultivation area at the air outlet duct. Before reaching the first fan the pre- and HEPA-filter extract particles with an efficiency of 99.995 % (HEPA 14 EN 1822-2009). This avoids a jamming within one of the fans as well as reduces the microbial load at the CHX. Subsequently, the dehumidifier, equipped with a UV-C lamp, dries the humid air. If against expectations microorganisms reach the CHX the UV-C lamp stops them from growing and prevents clogging of the dehumidifier. Afterwards the chilled air is warmed up to the required input temperature by a heater unit. At this point the second fan can be placed. Downstream of this fan the VOC-filter can be applied. This guarantees dry air for an optimum operation of the VOC-filter. Afterwards the air composition control monitors and adjusts the air composition. Before the treated air is finally again distributed to the cultivation area by the air inlet ducts a third fan can be applied to ensure the permanent air movement. Positions for gas sensors to monitor their concentration and feed the DCHS are discussed later in this chapter.
Little changes in the presented sequential arrangement are still possible. As the concrete number of fans is not yet final their positions may shift. Also the air composition control placement is still flexible because there are no required operating conditions for it. The two main drivers for those open decisions are the available space at the appropriate positions and the suitability for the interfaces to other subsystems and the habitat.

If for any reason the sequential arrangement should be changed that the HEPA-filter and the VOC-filter form a unit again, a so-called CHIPS filter (Charcoal HEPA Integrated Particle Scrubbers) could be considered in further development steps. More information about this type of filter which combines HEPA- and VOC-filter can be found in [68]. At the moment they are not mature enough but this might be different at later design steps.

4.3.4 Trade-off on sensors for air composition control

Another lesson learned from the MTF is the deficiency of air composition monitoring. Currently only two CO_2 sensors (upstream and downstream of the air revitalization), one O_2 sensor (downstream of the air revitalization), and no trace contaminants sensor are available [42]. Existing sensors are adopted and completed with an additional O_2 sensor upstream of the air revitalization. This is important to supervise the active process of air composition control concerning CO_2 enrichment and O_2 reduction. Since trace contaminants did not cause any problems in the MTF it is not absolutely necessary to upgrade VOC sensors. However, because of possible hazardous effects of VOC on humans when exceeding their maximum allowable limits VOC sensors are installed anyway. To select a suitable sensor the literature research from chapter 2.2 is taken in account. The Air Quality Monitor (AQM) is the latest technology which is still flight approved on ISS [17, 18, 69]. It is capable of monitoring all important trace contaminants on ISS and should be able to monitor all trace gases which are particularly critical when dealing with plants (e.g. ethylene). According to [17] the dimensions of the revised second generation of the AQM are L 23.2cm x W 13.0 cm H 13.2 cm.

In the EDEN greenhouse prototype module a similar approach is used to remove VOC as on the ISS. It is a combination of activated carbon for contaminants with higher molecular weights and an oxidizer for contaminants with a low molecular weight [42]. For the oxidation process alumina impregnated with potassium permanganate ($KMnO_4$) is used [42]. This is able to remove H_2S, SO_2, NO_x, ethylene, kerosene, and hydrocarbons [42]. The mix ratio of activated carbon and impregnated alumina is 1:1 [42]. Since the trace gas removal was sufficient in the MTF the same approach is applied for the EDEN Next Gen.

As the VOC reduction procedure is a passive process of stationary filtering a single VOC sensor is sufficient. This is placed downstream of the VOC filter to monitor the trace contaminant content of the air injected to the cultivation area. For ground test a second VOC sensor is applied upstream of the VOC filter to supervise the VOC extraction process.

The exact locations of all gas sensors (in duct or just outside the air inlet/outlet) cannot be determined during this thesis, due to the early stage of the development. For this placement in later development steps the necessary redundancy of all sensors needs to be considered. For the test phase, more additional sensors in the cultivation area might be informative. After the expected air distribution within the cultivation area is verified those additional sensors can be removed. Especially for a well-founded confirmation of the sufficiency of the applied VOC filter, as already mentioned, one or more additional VOC sensors are useful, because such an analysis was not performed for the MTF.

More details about the interface with the AMS of the habitat (gas exchange strategy) are given in chapter 4.4.

4.3.5 Trade-off on stowage of components located in deployable part

Due to the deployable set-up of the greenhouse module special attention needs to be paid to all components located in the deployable part. These have to fit within the rigid frames of this section and have to be able to tolerate the deployment. In addition, after the deployment they have to be in their final position and be able to operate without manual interference. Alternatively, the final positioning could be done by the help of astronauts, but this should be avoided due to the aim of having a high level of autonomy. In practice, for the AMS this affects the supply air ducts for air distribution, the air suction duct for air return, fans, and possible sensors in the deployable part. This described demand can be implemented by designing the components to be flexible or deployable, or by integrating the components to fit in the stowed configuration. The following gives an overview on the possibilities to realize the mentioned components.

Both fans and ducts could be designed to be flexible and/or deployable. Nevertheless, due to its error-proneness the fans are decided to be in a rigid design. This setting means that for the fans selection the full fan size has to be considered in connection to the available space in the stowed configuration. The same applies to possible sensors. If there are sensors remaining in the cultivation area after the test phase, they are in an inflexible and undeployable design and need their full size in the deployed setup. Ducts are more robust and can be designed to be flexible and/or deployable. The following gives an outline of needed ducts and their requirements on the ability of deployment, existing terrestrial technologies which might be able to be transferred to the given application, and a concluding proposal for a design solution.

First of all, for the following proceeding the duct system within the deployable part is divided into three types of ducts: the horizontal air input ducts, the vertical, curved air input ducts, and the horizontal air suction duct. There is no concrete design of the primary and secondary structure and membrane layout, but it is most likely that the stowed membrane divides the spaces between the rigid frames. This influences the design of all the horizontal ducts. They do not need to increase in length during the deployment process. Instead, they are stowed concertina like (see Figure 4.1), which requests a flat configuration of the ducts. Actually, that means these ducts expand from a flat, concertina like, stowed shape to tubular straight ducts. For the curved, vertical ducts at the outer wall the following two deformations are necessary during the deployment process. First, the enlargement of radius of curvature and second, the unfurl in length due to the increasing perimeter.

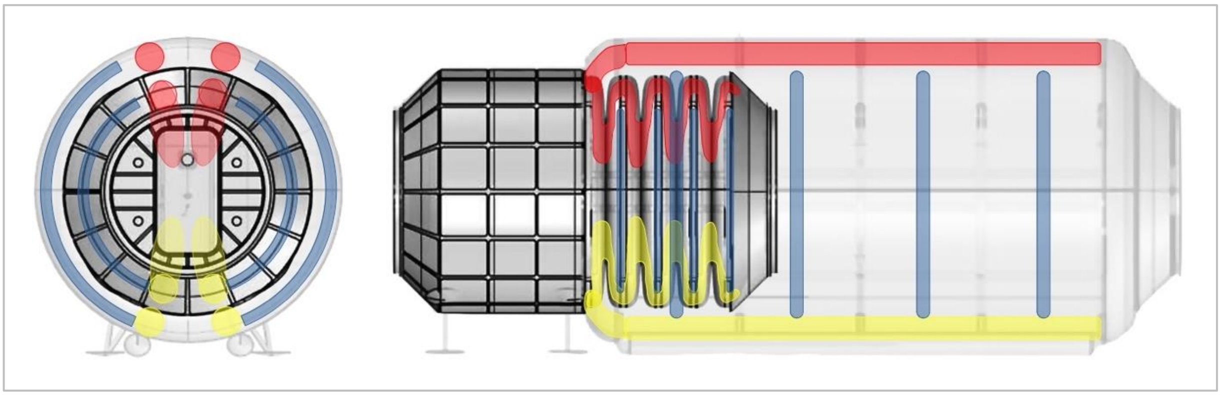


Figure 4.1: Front and side view of each stowed (less transparent) and deployed (more transparent) configuration, with highlighted ducts (deployable part). Yellow: horizontal air input ducts; blue: vertical, curved air input ducts; red: horizontal air suction duct

From research into currently used terrestrial duct systems, which might be suitable for the mentioned applications, the following types stand out. Flexible, lightweight hoses are often made from a plastic/metallic membrane supported by a single helix or separate rings made from a metallic material (see Figure 4.2 left). These ducts are flexible along their axis and extendible in length. Their diameter remains constant. Applications on Earth range from automotive hot and cold air ductings over vacuum cleaner hoses to air ventilation systems and air conditionings. On the contrary lay-flat hoses can change their diameter from a flat shape to a tubular hose but their length stays constant (Figure 4.2 middle). Also lay-flat hoses are flexible along their axis. Lay-flat hoses are available in all sorts of materials, and also diverse lightweight materials are available. Typical terrestrial applications are firehoses due to their small packing space in relation to their operating cross section. Flexible tubes/ducts, which are pushed together by a force, expand to its full size when the force is not applied anymore (Figure 4.2 right). Often made from silicone rubber materials those ducts are in common use in the food industry e.g. at breweries and dairies as well as in pharmaceutical and medical applications.

Figure 4.2: Potential hoses for the deployable part of the greenhouse module (1. Left: Flexible hose with helix/ring structure support [70]; 2. Middle: Lay-flat hose [71]; 3. Right: Flexible tube (rubber tube) [72])

Flexible hoses with helix or ring structure support (1.) and flexible tubes (3.) are available in different cross section geometries, varying from circular to rectangular.

By combining the requirements of the introduced duct types in the deployable part with the characteristics of the available ducts the following design idea arises. For the horizontal ducts for air input and air suction lay-flat hoses provide optimum characteristics. Between the rigid frames the ducts can be stowed concertina style in a flat shape in the stowed configuration. During the deployment process the hoses unfold to tubular shaped ducts. Rigid rings placed at the frames support the inflation process of the hoses and feature good fastening points. For the curved vertical air input ducts flexible hoses with supportive helix/ring structures offer the required transformation. The helix wire or rings give more strength and offer a good opportunity for fastening. Moreover, the supportive structure helps to integrate grid openings for the actual air inlet. Parallel (not absolutely but almost parallel) rings are preferred because they provide optimum conditions for the grid openings and allow an easy change in diameter.

The deployment process needs an extensive testing which gives information about further optimizations. Since the required static pressure to inflate the lay-flat hoses is unknown, possibly additional rigid rings between the frames are necessary to ensure an entire expansion of the horizontal ducts. Furthermore, the functionality of the air suction duct needs to be tested. Problems might arise with respect to keeping the duct in the deployed state because the air is not pushed but sucked. These issues can be eliminated by using special materials.

More about materials and the requested characteristics of the ducts is given in chapter 5.1.6. Since the duct system within the deployable part is a custom-made product in either case the special design of the horizontal lay-flat hoses with rings and the vertical diameter changing ducts can be customized.

Results of technology trade-offs

As a result of the previous technology trade-offs a detailed outline of the AMS evolves. Figure 4.3 shows a possible sequential arrangement of the technical components. A circulation character of the AMS components arises which refers to the recirculation of the air. The air cycle is almost a closed loop. The only gas exchange is with the habitat and is discussed in the following chapter. In Figure 4.3 all sensors included for completeness, even though the location of temperature, relative humidity, static pressure, flow rate sensors is discussed later.

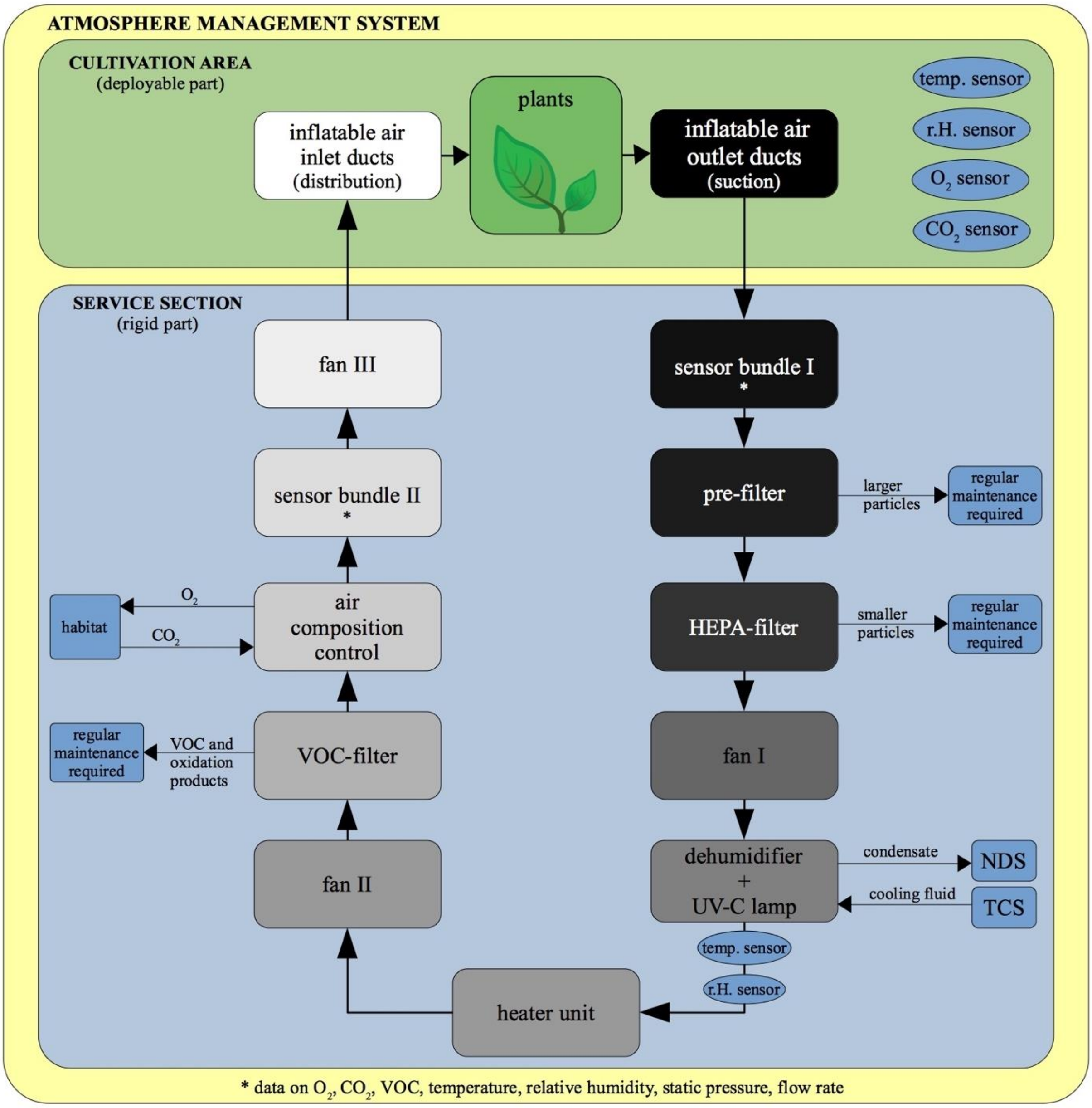


Figure 4.3: Components of the AMS in their sequential arrangement

Other sensors (e.g. for static pressure, temperature, relative humidity) which are needed for the safe and stable operation of the greenhouse module, and their location, are introduced later in chapter 5.2.2.

4.4 Interfaces and system boundaries

The illustrated loop in Figure 4.3 is not a closed loop. There are interfaces of several components with other subsystems or with the habitat. Necessary interfaces are introduced and partly discussed in this subchapter. To limit the scope of this thesis and to distribute responsibilities it is important to define the boundaries of the AMS in advance. Figure 4.4 shows the interfaces of the AMS components among each other, with other subsystems, with the habitat, and with the crew. Main focus is on the interfaces of the AMS components with other subsystems. For that reason only components and subsystems which have interfaces to one another are present. The N_2-chart has to be read clockwise. Interfaces indicated with solid frames are relevant for the AMS.

fans	provide air flow	provide air flow	provide air flow	provide air flow	distribute air						
	heater unit				temper air						temper air
	provide cold air	CHX	provide dry air	provide dry air	provide dry air				processing of condensate *		provide dry air
			ACC		provide CO_2					extract, store, transport O_2	
				sensor bundles	measure data	provide data on **					
		provide humid air	provide O_2	accommodate sensors	plants/ cultivation area						
rotation speed	heating output	cooling fluid flow rate	data on CO_2 injection			CDHS			provide data on nutrient demand	provide all measured data	
provide power	provide power	provide power	provide power	provide power		provide power	PCDS	provide power	provide power		
		provide cooling fluid				provide cooling	provide cooling	TCS		direct thermal link	
					provide nutrients				NDS		
			extract, store, transport CO_2				provide power	direct thermal link	provide nutrients	habitat	provide O_2
sporadic exchange	sporadic exchange	sporadic maintenance work (e.g. cleaning)	sporadic maintenance work	regular calibration	seeding and harvesting	sporadic maintenance work	sporadic maintenance work	sporadic maintenance work	regular maintenance work (e.g. refill)	provide CO_2	human

CHX – condensing heat exchanger
ACC – air composition control
CDHS – command and data handling system
PCDS – power control and distribution system
TCS – thermal control system
NDS – nutrient delivery system

selection of AMS components
plants / cultivation area
selection of other subsystems
habitat
human

* recovery, treatment, storage, and transport
** temperature, relative humidity, flow rates, static pressure, flow velocities gas composition (O_2, CO_2, VOC)

Figure 4.4: Interfaces of AMS components among each other, with other subsystems, with the habitat, and with the crew. Main focus is on the interfaces of AMS components with other subsystems. For that reason only components and subsystems which have interfaces to one another are present. Framed interfaces are relevant for the AMS design, other interfaces are only mentioned for completeleness. (read chart clockwise)

In the following the interfaces of components of the AMS with other subsystems are looked at. The CDHS receives the data measured by the gas sensors (CO_2/O_2/VOC) and all other sensors (temperature, relative humidity, flow rates, static pressure, flow velocities). Those data are used to provide the currently required operation performance to the fans, the heaters, the dehumidifier and the air composition control. The PCDS provides power to all electrical power consuming components including the fans, the heaters, the dehumidifier, the air composition control, and sensors. To cool the air stream down the CHX receives a cooling fluid from the TCS. Condensate recovered by the CHX is provided to the NDS after its treatment. For the interface of the ACC to the habitat a technology trade-off is performed subsequently, but the result is already applied in the N_2-chart (gas exchange strategy with O_2 and CO_2 extraction, storage and injection). For that reason, the ACC and the habitat provide each other O_2 and respectively CO_2 for injection.
The task of the ACC is only to extract O_2 and to inject CO_2. Extraction of CO_2 and injection of O_2 is performed by the habitat. All other tasks such as storage and transport of the gases is competence of the gas exchange interface. For the further processing of the condensate recovered by the CHX system boundaries are as follows. The AMS is responsible for the recovery, the treatment, and the transport of the condensate. Storage is part of the NDS.

Gas exchange interface with habitat

Since there are no interfaces with the habitat in the prototype, trade-offs need to be done for this. Several subsystems have interfaces to the habitat, but in this thesis only the interface concerning the AMS is considered. As already mentioned in chapter 2.3.1, the greenhouse module being a part of a biological LSS for a habitat features complementary advantages for both sides. Plants cover the reconversion of CO_2 to O_2 by the photosynthesis process. To actually use this benefit, a gas exchange interface between the habitat and the greenhouse module needs to be designed.
A couple of challenges arise when designing the gas exchange interface, due to the different preferred environmental conditions of humans and plants [73]. Figure 4.5 gives an overview of the comfort areas concerning relative humidity (rH) and temperature (T) of humans (yellow) and plants (blue). The temperature range for both humans and plants is pretty much the same around $T \approx 18\,°C \ldots 26\,°C$ and causes no issues [73]. With regards to the relative humidity, differences in their comfort zones arise [73]. As visualized in Figure 4.5, for humans the preferred relative humidity is $rH \approx 25\,\% \ldots 70\,\%$ in comparison to plants where the preferred value is $rh \approx 60\,\% \ldots 85\,\%$ [73]. The concrete optimal conditions for plants depend on the type of plant and its growing stage but a relative humidity between $rH \approx 70\,\% \ldots 80\,\%$ is aimed for [73]. The resulting green area of intersection is the common comfort box for humans and plants [73]. To keep environmental conditions within this very slight sector highly accurate controlling technologies are needed [73].

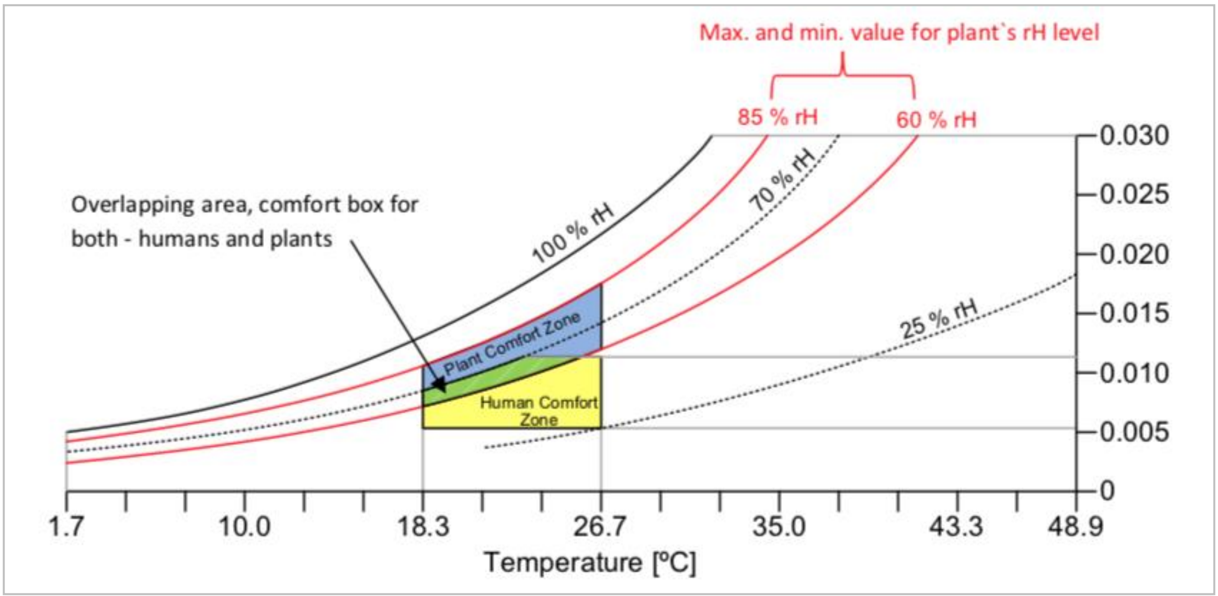


Figure 4.5: Comfort areas of humans (yellow) and plants (blue) and their common comfort sector (green) (vertical axis shows the absolut humidity in $\frac{g}{kg}$) [73] with data from [74]

Another problem arises when considering CO_2 concentration. The concentration of a gas component is given in percentage by volume ($\%\ vol$) or parts per million (ppm). Moreover, it can be specified with the partial pressure (p_p) which always has to be considered in connection with the total atmospheric pressure (p). Generally, humans and plants can survive at the same level of CO_2. However, both have different optimum concentrations for ideal comfort [73]. According to [51] at a nominal atmospheric cabin pressure of $p = 70.3\ kPa$ a nominal CO_2 partial pressure of $p_{p_{CO_2}} = 0.53\ kPa$ ($7500\ ppm$), for the crew, and $p_{p_{CO_2}} = 0.13\ kPa$ ($1800\ ppm$), for plants, are assumed. The nominal value for humans is acceptable but should be reduced if possible, to get closer to Earth atmospheric conditions [73]. Since the EDEN Next Gen greenhouse module is designed for long-term missions, atmospheric conditions like on Earth are assumed for the habitat as this is the most harmless for the crew. In numerical terms this means an atmospheric pressure of $p = 101.3\ kPa$ and a CO_2 partial pressure of $p_{p_{CO_2}} = 0.04\ kPa$ ($400\ ppm$). For the greenhouse module also an atmospheric pressure of $p = 101.3\ kPa$ is assumed. The assumption of [51], concerning a raised CO_2 level being beneficial for the plant growth and development, is confirmed by [75, 76] which also recommend a raised CO_2 concentration, compared to Earth conditions, of $600\ ppm$ to $2000\ ppm$ to provide grow-optimized conditions.

A rising delta of optimum CO_2 partial pressure and the mentioned humidity challenges exclude an integrated cultivation area within the habitat. Separated entities, habitat and greenhouse, make a gas exchange interface between them essential.

For the gas exchange interface two general approaches can be utilized. First, the entire ambient atmosphere is exchanged without an extra treatment. This strategy can have a permanent or a periodic operating mode. Permanent means the continuous exchange of air. Here, the air stream passes only once through the habitat or greenhouse and is then detoured to the other sphere [73]. For the periodic gas exchange one full batch of habitat and greenhouse atmosphere is swapped to the other entity after a certain time when a specific CO_2 or O_2 level is reached [73]. The second basic strategy is to extract CO_2 at the habitat and O_2 at the greenhouse. The pure gases are stored and injected at the opposite entity [73]. In the following, all mentioned approaches are analyzed in detail and rated on basis of significant characteristics.

The direct continuous gas exchange strategy goes along with a simple operation mode but does not provide buffering of gases [73]. This results in the impossibility to adjust atmospheric conditions [73]. For that reason, sub-optimal environmental conditions are to be expected for both, but especially for plants as the crew's needs are preferred [73]. This applies especially to the relative humidity, but also to temperature. More limitations arise by considering the dependency on the daily routine of the crew [73]. A higher CO_2 output of the crew is directly linked to a rising CO_2 level in the greenhouse. This uncontrolled gas exchange leads to an undefined atmospheric composition at the cultivation area and limits the possibilities of CEA [73]. Furthermore, the day/night rhythm of the crew and the plants has to be the same because the photosynthesis process mainly takes place during the light period [73]. Moreover, with this gas exchange strategy there is a higher risk of contamination. This risk can be reduced by applying filter systems for pathogens and particles [73]. Specially, when having several greenhouse modules, for backup reasons, this gas exchange interface is no option.

If the direct gas exchange approach is performed periodically the operation mode gets a little more complex which also results in a higher system mass and more power consumption. In return, due to the oxygenated or respectively CO_2 enriched air, the entities' atmospheres are temporarily adjusted but still not fully controllable [73]. Besides, additional CO_2 for the greenhouse module might be necessary if the CO_2 from the habitat is not sufficient [73]. Another disadvantage is that the volume of the cultivation area(s) needs to be the same as the volume of the habitat. Aside from that, since the gas exchange has to be performed within a short time frame the duct system has a high demand of installation space [73].

A CO_2 and O_2 extracting, storing, and injecting strategy offers the opportunity to completely separate the habitat and the greenhouse. This requires an own air circulation and treatment system of each entity [73]. Disadvantages of such a gas exchange interface are a high system mass, high complexity, and a higher power consumption, which result from the extracting infrastructure, the extra storage capacities, the injection modules, and the control mechanisms [73]. The advantage is that each entity is able to control its atmospheric parameters just as preferred [73]. Optimal environmental conditions, including CO_2, relative humidity, and temperature, can be adjusted by still using the symbiotic gas exchange [73]. Moreover, since only the absolutely necessary gases are exchanged between the two entities there is a lower risk of contamination. As there is already an extracting and storing infrastructure available at this strategy it might be easier to integrate a similar system for ethylene. As already mentioned in chapter 2.3 the ethylene management system is important to manage different growth stages of the plants by selective injection.

In addition to the mentioned basic approaches there can be modified hybrid versions. The following Table 4.6 is established to get an overview of the characteristics of the basic approaches of the gas exchange interface between the habitat and the greenhouse module.

Table 4.6: Overview of the basic approaches for the gas exchange and their characteristics

	Entire ambient atmosphere exchange (permanent)	**Entire ambient atmosphere exchange (periodic)**	**CO_2 and O_2 exchange (extraction, storage, and injection)**
optimum environmental conditions	3	2	1
flexibility in operation	3	2	1
risk of contamination	3	3	1
system mass	1	2	3
system complexity	1	2	3
power consumption	1	2	3

Table widely based on data from [73]. Best to worst: 1 – 2 – 3

In the table the sequence of the characteristics is roughly chosen according to their importance. The main idea of designing a separate greenhouse module is to use the prospects of CEA to provide optimized growing conditions for the plants. This includes not only providing the environmental atmospheric parameters optimal for plants but also the possibility to adjust them during the mission to feature flexibility in operation. Depending on the redundancy of greenhouse modules, contamination can be a critical accident and should be avoided in every case. System mass, complexity, and power consumption should always be kept to a minimum but are assessed as less critical compared to the other characteristics.
According to the overview in Table 4.6, the extracting, storing, and injecting strategy of gas exchange provides the best trade-off of advantages and challenges. Even though it is the most challenging approach, it also offers the most promising characteristics concerning requested environmental conditions in habitat and greenhouse module. More details on the gas exchange interface are given in chapter 5.1.5 and chapter 6.2.

4.5 Numerical values for the system design

In this section all previously identified internal and external loads are quantified. Furthermore, first setpoints for the controlled parameters and their control accuracies are defined.

4.5.1 Internal loads

4.5.1.1 Plant loads

Internal loads can be divided into loads caused by plants and loads caused by other sub-systems. As discussed before, all other loads, e.g. caused by the crew working in the greenhouse, are neglected.
Starting with loads generated by the plants the previously analyzed process of photosynthesis is of importance again. In order to not go into detail too much the cultivation area is regarded as a black box. This helps to identify all inputs and outputs. Figure 4.6 shows schematically all inputs and outputs of the cultivation area, divided in four groups: gases, liquids, solids, and

energy. In the schematic solid arrows represent necessary, and dashed arrow potential, inputs and outputs [24]. By just focusing on loads related to the AMS the number decreases to only a few. All solid loads are omitted because they are not linked to the AMS. Of the liquid loads only potable water as output is considered. This water occurs as transpired water and needs to be regained via the CHX. For gases the following applies: Being part of the photosynthesis process, CO_2 and O_2 remain for the loads considered for development of the AMS. Although leakage and inert gas input are in fact related to the AMS these are not considered at this point because they are not internal loads connected to plants. The same applies for heat inputs and outputs, as well as for electricity, which are considered later as the internal loads of other sub-systems. The work force is not considered here either because of it not being a load induced by plants. Anyway, as mentioned before, all effects traced back to humans working in the greenhouse are neglected. Their impact is only very slight and is covered by the applied margins.

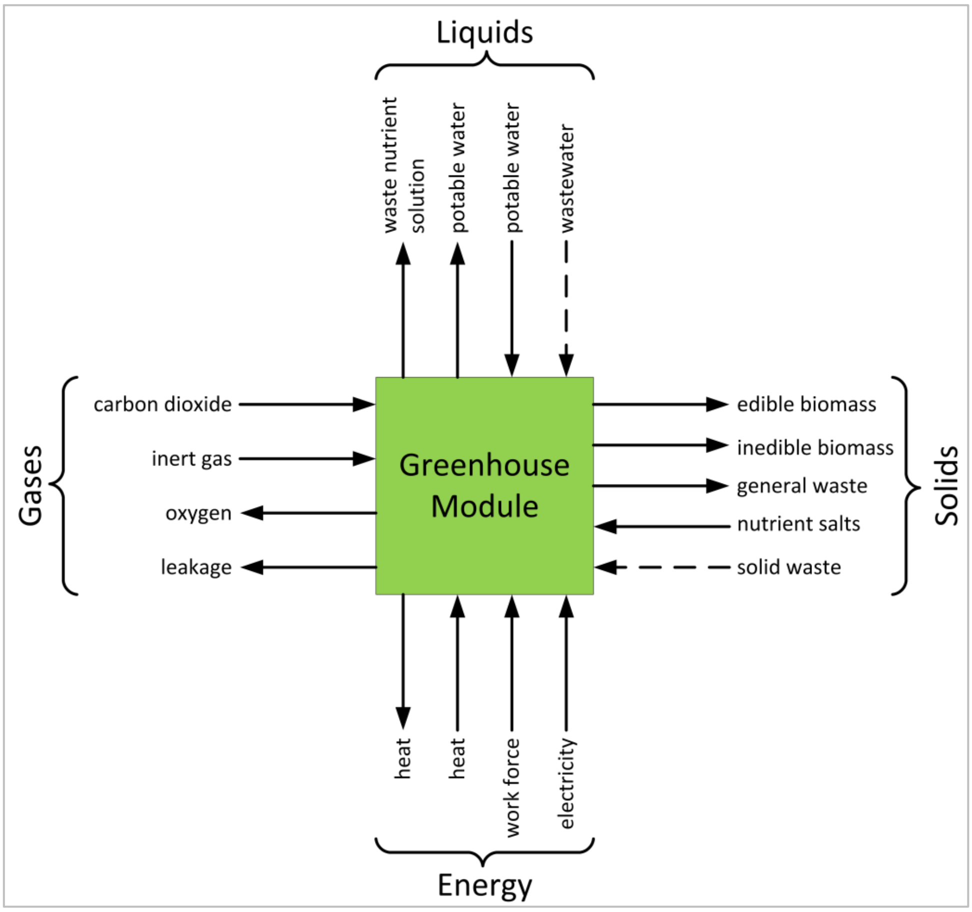


Figure 4.6: Inputs and outputs of the cultivation area [24]

The ethylene production of plants is neglected in this thesis since ethylene is permanently removed by the VOC filter but not actively controlled or injected. An ethylene management system, which is very complex due to the various effects of ethylene on plants (chapter 2.3), should be considered during further development steps.

To quantify the inputs and outputs of the cultivation area a sample configuration adopted from [6] is used. According to that a total of 104 growing trays is accommodated. The cultivation trays are divided into 28 trays for tall growing plants (e.g. cucumber, tomato, pepper) and 76 trays for small growing plants (e.g. lettuce, herbs, tubers) [6]. Each tray has an area of $A_t = 0.328\, m^2$ [6]. This equals a total cultivation area of $A_c = 34.112\, m^2$. By calculating the dimensions of one tray (W 600 mm x D 400 mm x H 120 mm [6]) a slightly different area arises. This discrepancy occurs due to the amount of overlapping. The plants grow and overlap the actual tray area. For the sizing of the components of the AMS, metabolic parameters need to be determined for the sample plant configuration. Generally, it is important to keep in mind that metabolic values are hard to predefine since they not only depend on the cultivated plant but also on a variety of other factors like its growing stage, temperature, humidity, and light intensity [77, 78]. In practice the intensity of the photosynthesis process is not on a constant level [77, 78, 79, 80]. Since light is one of the driving factors of the photosynthesis process the day/night rhythm with its cycling light intensity has a major impact on the photosynthesis rate [77, 78, 79, 80]. Figure 4.7 shows exemplary the dependency of the CO_2 uptake of tomato plants on the light intensity.

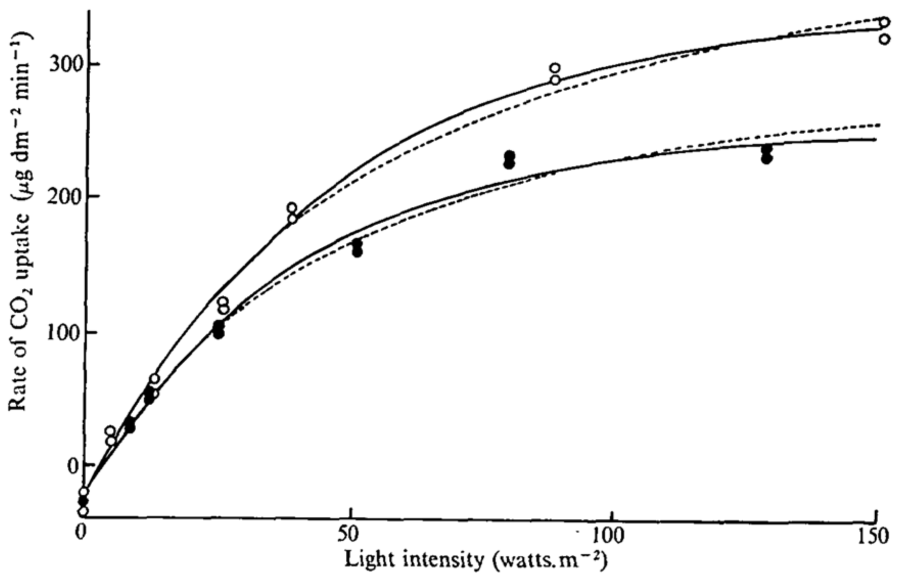


FIG. 1. Rates of CO_2 uptake for two samples of leaf 3 from the low treatment.
○ leaf 6/2; ● leaf 4/3.
— best fitting asymptotic curves.
--- best fitting rectangular hyperbolae.

Figure 4.7: CO_2 uptake of tomato plants depending on the light intensity (curves represent the third leaf of different samples each with one asymptotic and one rectangular hyperbolae curve) [80]

Apparently, the CO_2 uptake turns to negative values under a certain light intensity, which means CO_2 release. Even though the cycling behavior of the mass flow rates is well known, for this thesis a static consideration is sufficient since it is only a first sizing for a rough design and the demonstration of feasibility. For the alternating inputs and outputs, a constant average value is assumed. Figure 4.8 shows the cycling behavior and the simplified averaged rates of CO_2 uptake, O_2 production, and transpiration. The diagram is only a rough visualization and is not meant to extract values. For that reason, there are no values plotted on the vertical axis.

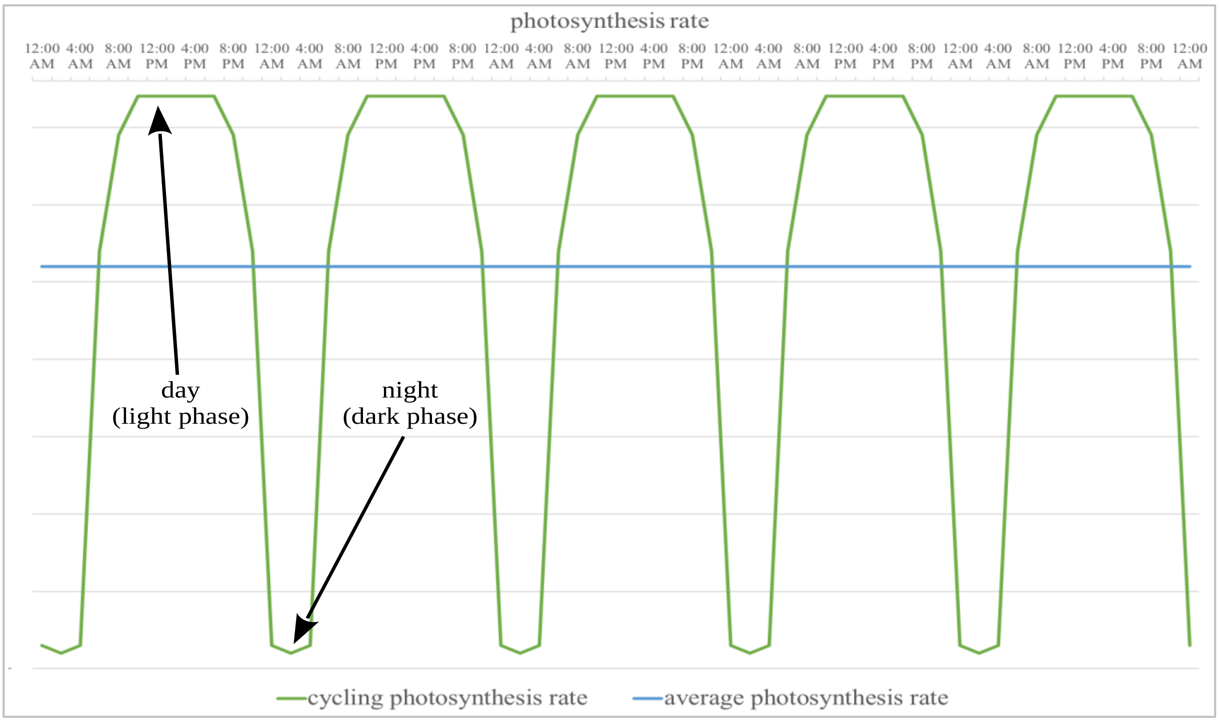


Figure 4.8: Approximate cycling of CO_2 uptake rate, O_2 production rate and transpiration rate (green) and their avarege rates (blue) used for the first design process (ploted with data from [80])

Also, in the end every plant is individual and can vary from empirical data. Nevertheless, by incorporating margins, it is sufficient to apply metabolic values for grouped types of plants. The sample plant configuration, which is a possible selection of plants for a versatile harvest, is displayed in Table 4.7. For each of the four groups of plants metabolic average values are added. At the upper part of Table 4.7 all values are a function of the cultivation area and the time. Values at the bottom of Table 4.7 are absolute values and only dependent on the time. From the bottom values total loads can be calculated. All data adopted from [51] are average values over the whole life cycle of the plants. It is the mean from sprout to fully-grown plant including the day-night cycle. In addition, the data were gained at laboratory conditions. Since Moon conditions cannot be entirely imitated (e.g. reduced gravity) metabolic data of plants actually grown on Moon might be different. For those reasons, a margin of 100 % is applied on the final sum to also cover the peak of daytime with all plants being fully-grown. This gives also the possibility to slightly change the plant configuration.
The total O_2 production mass flow rate, including margin, of the sample configuration yields $\dot{m}_{O_2 production} \approx 914 \frac{g}{d}$. Even at the fully cultivated greenhouse the O_2 production rate is not expected to be sufficient to cover the need of O_2 resupply of the six-person crew. According to requirement FR-SI-10 a minimum average of $\dot{m}_{O_2 resupply} = 4920 \frac{g}{d}$ is required. This means not only for the plants being at an early growth stage but also for full-grown plants additional O_2 is needed. To cover this with a biological system a bioreactor equipped with algae, as introduces in chapter 2.3, would be suitable. In any case an additional backup system should be applied. A total CO_2 uptake mass flow rate, including margin, of $\dot{m}_{CO_2 uptake} \approx 1266 \frac{g}{d}$ requires a supply with the same amount of CO_2. From the habitat an average mass flow rate of $6240 \frac{g}{d}$ is expected. This means a second carbon dioxide disposal is required. In

addition, a total transpiration rate, including margin, of $\dot{m}_{H_2O\ transpiration} \approx 134\ \frac{kg}{d}$ is expected and needs to be covered by the CHX.

Table 4.7: Example of a possible plant constellation adopted from [6] and the corresponding plant metabolism parameters from [51] (top: relative values; bottom: absolute values)

Relative values				
Crop	**Trays (area)**	**Average O_2 production rate**	**Average CO_2 uptake rate**	**Average transpiration rate**
	[-] / [m²]	[g/m²d]	[g/m²d]	[kg/m²d]
lettuce and leafy greens	54 (17.712)	9.01	12.40	1.77
herbs	12 (3.936)	10 *	15 *	1.5 *
fruits	23 (7.544)	26.36	36.24	2.77
tubers	15 (4.92)	11.86	16.31	1.77

Absolute values				
Crop	**Trays (area)**	**Average O_2 production rate**	**Average CO_2 uptake rate**	**Average transpiration rate**
	[-] / [m²]	[g/d]	[g/d]	[kg/d]
lettuce and leafy greens	54 (17.712)	159.59	219.62	31.35
herbs	12 (3.936)	39.36	59.04	5.91
fruits	23 (7.544)	198.86	273.40	20.90
tubers	15 (4.92)	58.35	80.25	8.71
total	104 (34.112)	≈ 457	≈ 633	≈ 67
Total + margin	**104 (34.112)**	**≈ 914**	**≈ 1266**	**≈ 134**

*values for herbs estimated on basis of values of other plants from [51]

Lettuce and leafy greens: 6 trays batavia; 6 trays expertise; 6 trays outredgeous; 6 trays waldman's green; 6 trays arugula; 6 trays red mustard (frizzy lizzy); 6 trays red mustard (red giant); 6 trays swiss chard; 6 trays mizuna
Herbs: 4 trays basil (dolly); 4 trays parsley; 4 trays chives
Fruits: 5 trays cucumber (picowell); 9 trays tomato (orange); 9 trays tomato (cherry)
Tubers: 5 trays radish (lennox); 5 trays radish (raxe); 5 trays kohlrabi

To size the O_2 extraction module and the CHX the following strategy is used to model the loads. It is defined that all components need to be able to permanently operate at full power. However, very probably the full performance is only needed at some few times. To limit the scope of this thesis no extensive operating mode is developed. A mode with a constant performance of the CHX and the O_2 extraction module is sufficient for the current development status. This comes along with alternating relative humidity, CO_2 level, and O_2 level, dependent on the light period. The relative humidity and the O_2 concentration rise through day-time period but drop during night-time period. Since the temperature is higher during the light period compared to the dark period the air can hold more water. This causes a counteraction and stabilizes the fluctuating relative humidity. The absolute humidity is independent of the ambient temperature and keeps alternating. For further design steps the following strategy can be applied to directly include the cycling behavior of the mass flow rates. A more realistic consideration is to assume that all metabolic loads are not averaged on an entire day (24 h) but on the light period (16 h) only. The total values per day (24 h) from Table 4.7 need to be covered by the CHX and the O_2 extraction module within the 16 h day-light period. This also offers the opportunity to stabilize the cycling photosynthesis rate and counteracts fluctuating atmospheric parameters.

4.5.1.2 Subsystem loads

Another internal load is the heat rejected from the subsystems. According to [42] in the MTF the AMS and the ILS dissipate the most thermal energy. Additionally, the PCDS, the CDHS, the NDS, and the workbench area are considered in this thesis. Since the greenhouse module is still at a very early development stage the critical subsystems are not designed yet, which demands an upscaling of the subsystems used in the MTF. Due to the transpiration process also the plants have a thermal influence. Latent heat is absorbed by this process. Even though the plants are not a subsystem their thermal impact is characterized at this point. The following Table 4.8 shows the upscaling process, including the applied conversion strategy, the used margins, the calculation, and the results of the expected dissipated heat of the subsystems during the day-time period and the night-time period.

Table 4.8: Upscaling of heat dissipation of the subsystems

Subsystem	Applied conversion strategy	Upscaling calculation		Day-time period	Night-time period
AMS Main heat comes from the fans and ~ 20 % of their power is dissipated to environmental air [42].	Volume, the air is distributed to, is taken as equivalent to the required fan power. A margin of 10 % is applied due to the additional gas exchange interface. This strategy is applied to the in-duct fans and to the overhead air distribution fans.	In-duct fans: Heat dissipated in MTF: day-time 400 W [42] night-time 400 W [42] MTF: $31\ m^3 * 12.9 \approx 400\ W$ EDEN Next Gen: $225\ m^3 * 12.9 * 1.1 \approx 3193\ W$	Overhead fans: Heat dissipated in MTF: day-time 115 W [42] night-time 115 W [42] MTF: $31\ m^3 * 3.7 \approx 115\ W$ EDEN Next Gen: $225\ m^3 * 3.7 * 1.1 \approx 916\ W$	$\approx 4109\ W$	$\approx 4109\ W$
ILS Heat dissipation only during day period.	One LED panel per cultivation tray [5] is applied with a heat dissipation of 120 W per LED panel. LED panels are water cooled by a direct connection to the thermal loop of the habitat. According to [81] 70 % of the total power input is heat. Therefrom 90 % can be covered by the water cooling. This equals a percentage of 37 % (30 % luminous and 7 % heat) of the total power input which is dissipated to the air. For details on the distribution strategy see Appendix 4.1.	Heat dissipated in MTF: day-time 4800 W [42] night-time 0 W [42] MTF: 40 $trays$ [3]$* 120\ W = 4800\ W$ EDEN Next Gen: 104 $trays * 120\ W = 12480\ W$ $12480\ W * 0.37 \approx 4618\ W$		$4618\ W$	$0\ W$
CDHS Thermal load fraction ~20 % [42].	More data is recorded compared to the MTF (more cameras, gas-, humidity-, and temperature sensors). Number of cultivation trays is taken as equivalent to the required power for the CDHS.	Heat dissipated in MTF: day-time 202 W [42] night-time 170 W [42] day-time: MTF: 40 $trays$ [3]$* 5.05\ W = 202\ W$ EDEN Next Gen: 104 $trays * 5.05\ W \approx 526\ W$ night-time: MTF: 40 $trays$ [3]$* 4.25\ W = 170\ W$ EDEN Next Gen: 104 $trays * 4.25\ W \approx 442\ W$		$\approx 526\ W$	$\approx 442\ W$
PCDS Thermal load fraction ~20 % [42].	More power is required compared to the MTF. Number of cultivation trays is taken as equivalent to the required power for the PCDS. The same heat dissipation is assumed at day- and night-time.	Heat dissipated in MTF: day-time 23.2 W [42] night-time 23.2 W MTF: 40 $trays$ [3]$* 0.58\ W = 23.2\ W$ EDEN Next Gen: 104 $trays * 0.58\ W \approx 61\ W$		$\approx 61\ W$	$\approx 61\ W$

Subsystem	Applied conversion strategy	Upscaling calculation	Day-time period	Night-time period
NDS Thermal load fraction ~20 % [42].	Number of cultivation trays is taken as equivalent to the required power for the NDS. A margin of 20 % is applied due to longer nutrient supply ducts.	Heat dissipated in MTF: day-time 125.5 W [42] night-time 125.5 W [42] MTF: 40 $trays$ [3]$*$ 3.14 $W \approx 125.5\ W$ EDEN Next Gen: 104 $trays * 3.14\ W * 1.2 \approx 392\ W$	$\approx 392\ W$	$\approx 392\ W$
workbench area and scientific needs Likely to be electronic equipment which dissipates heat.	Service section in the MTF is the workbench area in the new generation greenhouse. The same heat dissipation is assumed at day- and night-time. To guarantee enough capability for extensive processes the dissipated heat of the MTF is quintupled.	Heat dissipated in service section of MTF: day-time 30 W [42] night-time 0 W [42] $30\ W * 5 \approx 150\ W$	$\approx 150\ W$	$\approx 150\ W$
plants Even though the plants are not a subsystem they have a thermal impact due to latent heat with regards to the transpiration process.	As for the MTF the amount of transpired water determines the latent heat by applying the vaporization heat. [42] density water: $\rho_{water} = 998\ \frac{kg}{m^3}$ enthalpy of vaporization: $\Delta H_{water} = 2257\ \frac{kJ}{kg} \approx 627\ \frac{Wh}{kg}$	Transpired water in EDEN Next Gen: maximum (day-time and full-grown plants): $136\ \frac{l}{day} \approx 5.67\ \frac{l}{h}$ minimum (before germination): $0\ \frac{l}{day}$ maximum: $5.67\ \frac{l}{h} * 0.998\ \frac{kg}{l} * 627\ \frac{Wh}{kg} \approx 3548\ W$ minimum: 0 W	$\approx -3548\ W$	$0\ W$
Total	---	---	$\approx 6308\ W$	$\approx 5154\ W$
Total relevant for first design (without plants)	(for more details see chapter 5)	---	$\approx \mathbf{9856\ W}$	$\approx \mathbf{5154\ W}$

As is apparent from Table 4.8 not all thermal loads expected are considered for the development of the AMS. It is assumed that the ILS, as the most heat dissipating subsystem, is water cooled and has a direct connection to the thermal loop of the habitat. Therefore, only a fraction of the total power of the ILS has to be considered at the AMS design. Since the cooling system for the ILS is not designed yet it is still possible that the ILS will be fully air cooled (passive of active by small fans). In that case the AMS has to cover the complete heat dissipated by the LED panels. Latent heat of the plants required for vaporization is only present when plants are fully grown. Until that time the latent cooling by transpiration is smaller and it can become zero at the time before the first germination phase when all plants are in a very early stage. The same applies for the night period. For that reason, the influence of latent heat is not considered for the first design to keep it conservative. Even though the amount of transpired water is much smaller in that case, for the sizing of the components the maximum load of condensate is considered.
To conclude, the thermal loads that need to be considered for the dimensioning of the AMS are stated in last row of Table 4.8. The maximum thermal load induced by heat dissipation of the subsystems is expected to be $\dot{Q}_{subsystems\ day} \approx 5238\ W$ during the day-time period and $\dot{Q}_{subsystems\ night} \approx 5154\ W$ during the night-time period.

4.5.1.3 Pressure losses due to components and duct system

To complete the internal loads that need to be covered by the AMS the pressure losses due to the different components and resulting from the duct system need to be determined. The total of all losses is the required static pressure the in-duct fans need to counteract. Important to determine the necessary performance are geometric and component-based pressure drops [42]. Geometric pressure decreases include all losses caused by duct element e.g. contractions and recesses and are influenced by their characteristics e.g. surface roughness, angle, and radii of curvature. The component-based pressure drops are all losses via components e.g. filters and the CHX.
A concrete calculation of the pressure losses is not possible at this early development stage since too many influencing factors are not finalized yet. Concrete components and type of ducts are only some of the undefined influencing parameters. Additionally, the final air flow velocities within the ducts and components are still undefined. Those air flow velocities have a major influence on the pressure drop (see equation 2). For that reason, it is assumed that the air flow velocities are similar to the ones in the MTF. For their design process the value of $v_{air} = 3\ \frac{m}{s}$ according to recommendations of [82, 83] is aimed for to reduce noise and keep duct pressure losses low. With the help of the air flow velocity and the discharge coefficient ζ the pressure drop can be calculated easily as follows [84]:

$$\Delta p_x = \frac{\zeta_x * \dot{V}^2 * \rho}{A^2 * 2} = \frac{\zeta_x * \rho_{air} * v_{air}^2}{2} \quad (2)$$

Here ζ_x is an individual constant for each component, $\dot{V}$ is the air volume flow rate, A is the cross-section area, ρ_{air} is the density of the air, and v_{air} is the air flow velocity. This formula is valid for incompressible fluids. Technically the ambient air is not incompressible but for our case no compression is expected and for that reason all processes are assumed to be isobaric. Since the discharge coefficients ζ_x are usually ratios of geometric data the pressure losses are expected to be similar to those of the MTF. Also for the component-based pressure drops determined by the manufacturer mainly geometrical data are used. Therefore, assuming the same air flow velocity within the ducts as in the MTF the pressure losses identified for the MTF are widely adopted. For all components where there is no available value from the MTF, a conservative estimation is used for the first design. As a precaution a margin of 100 % is applied to also cover potential changes in geometry compared to the MTF. In later design steps more realistic data can be used and the margin can be reduced. A certain margin is indispensable even in the final design due to uncertainties of some conditions such as clogging of filters. Table 4.9 gives an overview of the estimated pressure drops caused by the geometry of the ducts and the components.

Table 4.9: Estimation of geometric and component pressure losses

Geometric loss	**Pressure loss Δp in Pa including margin**
air outlet (suction)	300
horizontal overhead air discharging ducts	150
connecting ducts of overhead and underfloor components in rigid section (mainly vertical)	300
horizontal underfloor air supplying ducts + vertical curved air supplying ducts	1500
air inlet	600
Component	**Pressure loss Δp in Pa including margin**
pre-filter	130
HEPA-filter	1300
VOC-filter	440
dehumidifier	320
heaters	3
gas composition control	500
broken fan (stagnant)	80
sensor bundles	50
Total	$\sum \mathbf{5673}$

Widely adopted from the MTF [42] and estimated with data from [85].

For further, more detailed, design steps data of the manufacturers of the different selected components should be used. For additional detailed information on pressure losses in different duct elements see [85]. This *Handbook of air conditioning, heating and ventilating* gives an extensive overview of duct-, elbow-, traverse-, expansion-, contraction-, transition piece-, suction- and outlet geometries.

4.5.2 External loads

As already mentioned in chapter 4.2 external loads depend on the environmental parameters of the final destination of the greenhouse module as well as on the protecting regolith layer composition (density and texture) and its thickness.

For the design of the AMS thermal loads and gravity are considered. Primary radiation is neglected due to the thickness of the regolith layer (assumption A01). Although, regardless of the thickness of the regolith shielding, there is still a fair amount of secondary radiation, every influence of radiation is neglected in this thesis. Nevertheless, radiation resistant electronics shall be considered. According to assumption A07 gravity is assumed to be at a constant level of $g_M = 1.625\ \frac{m}{s^2}$. Environmental temperatures are not steady-state due to the planetary motion. But as argued in assumption A01 the regolith layer is thermally insulating the greenhouse module and it is assumed that the surrounding temperature is at a constant level. The subsurface ambient temperature is $T_a = 254\ K$. The thermal energy loss via the outside walls of the greenhouse module is estimated as follows.

It is assumed that there is thermal conduction within the outside walls of the greenhouse module. These are the metallic walls and the membrane for, respectively, the rigid and deployable sections of the greenhouse. Since the 20-layered MLI (multilayer insulation) blanket [42] which is applied at both parts is the main influencing factor concerning thermal insulation for this first consideration the wall model is reduced to the MLI. This is a conservative approach because all other materials used in the outer walls are an extra thermal insulation. At the outside surface of the module only radiation is considered due to the thin atmosphere of the Moon (assumption A03). With reference to assumption A02 the heat loss via the support structure (legs and pillows) is neglected. Figure 4.9 summarizes all data necessary for the calculation of the thermal loss via the outside walls.

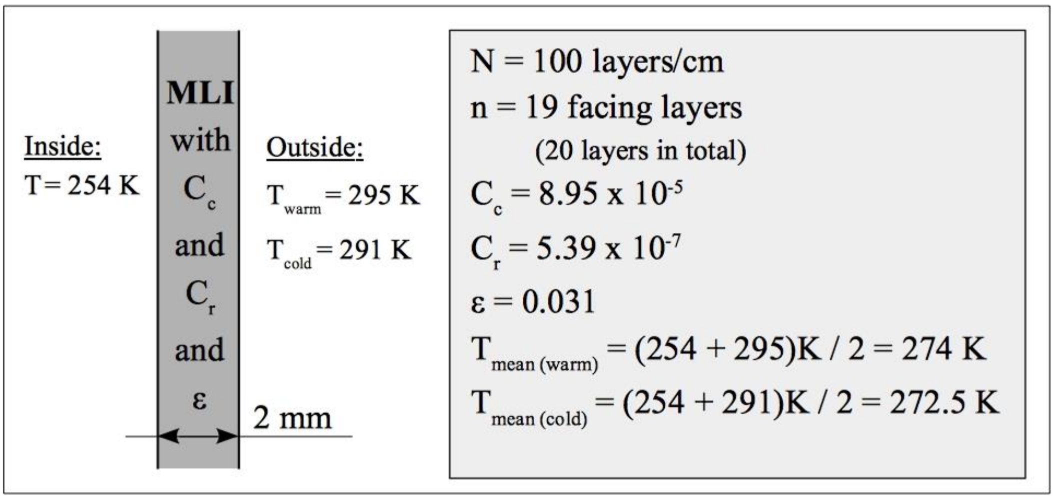


Figure 4.9: Heat transfer at the outer walls of the greenhouse module

For the first estimation of the external thermal loss it is sufficient to consider the process to be static with the ambient temperatures at each side being equal to the surface temperature on the respective side. In practice the heat transfer process is dynamic and the thermal loss is unsteady. The empirical equation (3), developed by NASA, is utilized to estimate the heat flux q via the MLI considering conductance of the space material (q_c) and radiation (q_r) [86, 87].

$$q = q_c + q_r = \frac{C_c * N^{2.56} * T_m}{n}(T_{inside} - T_{outside}) + \frac{C_r * \varepsilon}{n}(T_{inside}^{4.67} - T_{outside}^{4.67}) \quad (3)$$

With C_c being a conduction constant, C_r being a radiation constant, N being the MLI layer density in $\frac{layers}{cm}$, T_{mean} being the mean MLI temperature, n being the number of facing pairs of low-emittance surfaces within the MLI, T_{inside} being the inside temperate, $T_{outside}$ being the outside temperature, ε being the MLI shield layer emissivity [86, 87]. For the design of the AMS in general two cases (warm/cold) have to be considered. More about the necessity of the two cases is given in the next subchapter. By inserting the given values from Figure 4.9 a total heat flux of $q_{warm} \approx 7.13 \frac{W}{m^2}$ ($q_{cold} \approx 6.39 \frac{W}{m^2}$) can be calculated. The area of the outside walls is roughly calculated to $A_{total} = A_{rigid} + A_{membrane} \approx 156\ m^2 + 71\ m^2 = 227\ m^2$. Connecting these two values the heat flow rate of $\dot{Q}_{extern\ (warm)} \approx 1619\ W$ ($\dot{Q}_{extern\ (cold)} \approx 1451\ W$) via the outside walls of the greenhouse module can be determined. In later design steps the heat transfer process via the outside walls of the module should be analyzed in more detail.

4.5.3 Setpoint values

The cultivation area is not divided into different sections in terms of atmospheric parameters. The setpoint values of the different atmospheric parameters shown in Table 4.10 are the same in the entire cultivation area. Even though plants prefer different atmospheric parameters at different growing stages there will not be a seasonal change of the atmospheric conditions since the growing periods of diverse types of plants are not equal. However, to enable later modifications of the atmospheric parameters margins are applied later in the design process of the single components in chapter 5.

Table 4.10: Overview of setpoints for atmospheric parameters [42]

Atmospheric parameter	**Setpoint warm period**	**Setpoint cold period**	**Accuracy**
temperature	295 K	291 K	0.5 K
relative humidity	70 %	70 %	5 %
O_2 concentration	24 %	24 %	1 %
CO_2 concentration	650 ppm	650 ppm	50 ppm
ethylene/VOC level concentration	50 ppb	50 ppb	---
air flow speed at plant	0.4 m/s	0.4 m/s	---
atmospheric pressure	101.3 kPa	101.3 kPa	10 kPa

In Table 4.10 setpoint values for warm and cold periods are given. It is very important to consider that all multi-annual plants need a cold period between the harvest seasons to initiate the next bloom phase. Depending on the type of plant the requirements on that cold period are

different. It is assumed that an ambient temperature of $T = 291\ K$ is sufficient. The minimum period of time can be determined when all plants which are cultivated during the mission are defined. During that time the transpiration rate is expected to be smaller. For the design process it is assumed to be the same to be conservative.
The air flow speed at the plants is independent of plant metabolism parameters. That means air ventilation and distribution can be designed while neglecting the plants and their growing process. Since it is hard to predefine an optimum for all the atmospheric parameters in advance without having operating experiences of the greenhouse module a margin (dependent on parameter) has to be applied for potentially changing setpoint values for the atmospheric parameters. The particular quantities of the margins for the different parameters are given later in chapter 5.1.

4.6 Summary and conclusion of the system analysis

In this chapter a system analysis was performed. With lessons learned from the MTF in Antarctica, and the initial mission scenario concept, requirements and assumptions were defined. Requirements are classified into three categories: supporting infrastructure (SI), overall greenhouse module (GHM), detailed requirements related to the AMS. Table 4.1 gives an overview of all requirements directly and indirectly affecting the design of the AMS. The complete lists of requirements can be found in Appendix 3.1, Appendix 3.2, and Appendix 3.3. Furthermore, assumptions were mode on the basis of the final destination being the Moon. Listed assumptions affecting the AMS are given in Table 4.2.
In the next step components, which fulfil the defined tasks of the AMS, were defined. The MTF prototype served as basis for this process. Several adoptions concerning components and general implementation and handling could be made. For those elements which were not directly adopted from the MTF technology trade-offs were performed. Those trade-offs include: fan types (4.3.2), the sequential arrangement of the components (4.3.3), sensors for the air composition control (4.3.4), and the stowage of components located in the deployable part (4.3.5).
Subsequently the interfaces of components of the AMS with other subsystems and the habitat were defined and partly discussed. Figure 4.4 gives an overview on those interfaces. The gas exchange interface with the habitat was analyzed in more detail and different approaches were discussed and evaluated. After this extensive study the approach with only CO_2 and O_2 exchange by extraction, storage, and injection was found to be the most suitable.
To finish, all previously identified internal and external loads were quantified. Internal loads were divided into loads caused by the plants and loads caused by the subsystems. An overview of plant loads including oxygen production rate, carbon dioxide uptake rate, and transpiration rate is given in Table 4.7. Subsystem loads are mainly their dissipated heat. A detailed upscaling of the heat dissipation of the subsystems is given in Table 4.8. Additionally, the pressure losses due to the air treatment components and the duct system were roughly estimated (Table 4.9). The external loads highly depend on the environmental parameters as well as on the protecting regolith layer composition (density and texture) and its thickness. With the assumptions made concerning the ambient temperature, estimation of the external thermal loss via the outer walls of the greenhouse module was done (Figure 4.9). An

overview of the defined setpoint values for the controlled parameters (temperature, relative humidity, O_2 concentration, CO_2 concentration, VOC level concentration, air flow speed at plant, atmospheric pressure) and their control accuracies is given in Table 4.10.
To conclude this chapter an overview of all considered internal and external loads is given in Figure 4.10. It shows the greenhouse module (circular) covered by the regolith shield (semicircular). Inside the greenhouse module two different black boxes indicate the loads that need to be covered by the AMS. This is on the one hand the plant black box (green) and on the other hand the subsystem black box (blue). The box at the top (grey) shows the preliminary setpoint values. Additionally, the outside environment parameters for the design of the AMS are given.

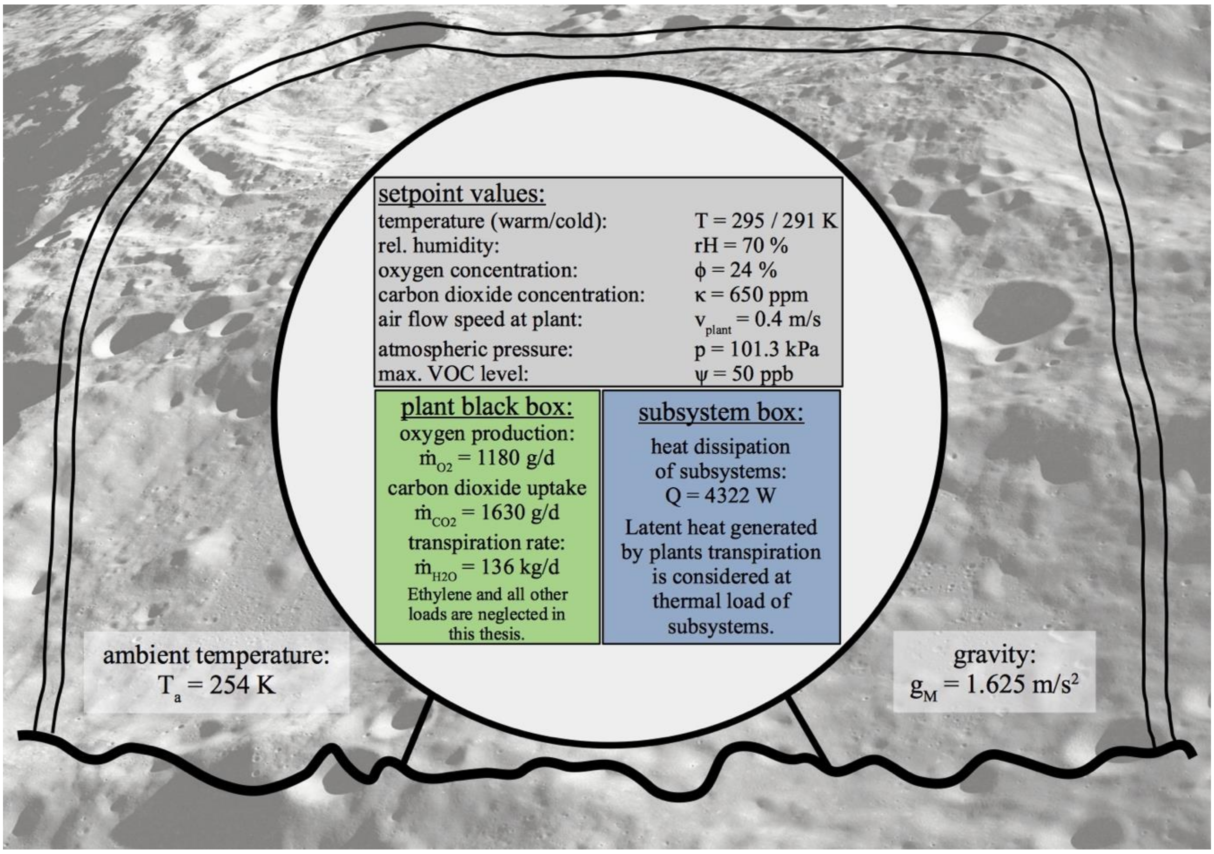


Figure 4.10: Overview setpoint values, internal loads, and external loads

In the following design process in chapter 5 aside of the requirements and the assumptions especially the determined numerical values of the internal and external loads and the defined setpoints are relevant. An overview of which component covers which load is given in Table 5.1. Even though the design of the gas exchange interface is out of scope of this thesis it is important to consider the presence of it since it has an impact of the design of different components e.g. the location of gas sensors (O_2/CO_2/VOC), the injection valve for CO_2 at the air composition control, and the ethylene management unit. In addition, the gas exchange interface has an effect on other subsystems e.g. PCDS and CDHS.

5 First design of AMS

This chapter is structured as follows. The single components are sized in chapter 5.1 to meet the necessary performances determined in the previous chapter. In this process only very rough sizing of the components is done since the main focus of this thesis is to get a general outline of the feasibility and to generate a base for further, more detailed, developments of the components and interfaces of the AMS. After the sizing process the common proceeding would be to find concrete components which suit the determined performances of the single parts. But due to the very early stage of the development (pre-phase A) changes are highly probable and the research on concrete components would not be very meaningful. This means also a final layout of the components within the available spaces inside the greenhouse module cannot be performed at this stage. In addition, since the layout of the components is the ensemble of all subsystems and their components all other subsystems have to be designed first. For now, only first potential placements of the components are given. To finish, possible modes of operation are introduced in chapter 5.2.2. The following table gives an overview of all determined values of parameters which are covered by the AMS and assigns the particular component which needs to be sized for this deficit. The sizing procedure in the following subchapters is similar to the design process of the MTF in [42].

Table 5.1: Overview of values of the loads covered by the AMS

Load	**Component**	**Calculated value**	**Design value** (inclusive margin)	**Origin**
pressure loss	fans	$5673\ Pa$	$6000\ Pa$ (5 % margin; redundancy strategy gives possibility for more performance (chapter 4.3.2 and chapter 5.1.1))	Table 4.9
transpired water	CHX	$67\ \frac{kg}{day}$	$134\ \frac{kg}{day}$ (100 % margin)	Table 4.7
heat balance	CHX + heaters	[internal heat] – [heat loss via outside walls] = [thermal load to be covered] day period (warm/cold): $9856\ W - 1619\ W = 8237\ W$ $9856\ W - 1451\ W = 8405\ W$ night period (warm/cold): $5154\ W - 1619\ W = 3535\ W$ $5154\ W - 1451\ W = 3703\ W$	warm: $8237\ W$ cold: $8405\ W$ (margins already applied at the upscaling process of the subsystems; no margin for the heat loss via the outer walls, because dependent on the overall heat balance this has a positive or negative effect)	Table 4.8 + chapter 4.5.2
air flow rate	fans	warm case: $8116\ \frac{m^3}{h}$ cold case: $8281\ \frac{m^3}{h}$ (determined later in this chapter)	warm case: $8116\ \frac{m^3}{h}$ cold case: $8281\ \frac{m^3}{h}$ (margin already applied on the thermal load (only variable influencing parameter))	chapter 5.1.1

Load	Component	Calculated value	Design value (inclusive margin)	Origin
particle removal	particle filters (pre- and HEPA-filter)	continuous removal at a high level	continuous removal at a high level	chapter 5.1.4
microbial load	UV-C lamp	continuous treatment at a high level	continuous removal at a high level	chapter 5.1.4
VOC removal	VOC filter	continuous removal at a high level	continuous removal at a high level	chapter 5.1.4
O_2 production	O_2 removal module	$457\ \frac{g}{day}$	$914\ \frac{g}{day}$ (100 % margin)	Table 4.7
CO_2 uptake	CO_2 resupply module	$633\ \frac{g}{day}$	$1266\ \frac{g}{day}$ (100 % margin)	Table 4.7
air distribution and dimensioning	duct system	continuous air movement all-over the cultivation area	continuous air movement all-over the cultivation area	chapter 5.1.6

As discussed in chapter 4.5.1.2 for the heat balance the ILS and the latent heat of the plants are neglected. External thermal losses are fully considered since variations towards both directions are possible. Concerning this matter more specific data on the mission scenario and the structure (especially MLI in membrane) will have an influence on the sizing of the components later on.

5.1 Sizing of the components

5.1.1 Fans

For the design process of the fans the following parameters need to be considered. The performance of the fans needs to be sufficient to fulfil the required air flow rate and the pressure loss that needs to be compensated. In addition, the temperature the fans are exposed to during their entire lifetime, which includes the storage during transport and the operation mode, needs to be considered. More factors are the fan size and their geometry. Those need to be suitable for the specific application. Also, the construction material is a parameter which needs to be respected during the fan selection. Beside the material characteristics, e.g. density, also a space permission of the material is important. [42]
Starting with the air flow rate a required estimation is done. The air flow rate is influenced by the comparison of two parameters [42]. Those two factors are on the one hand the temperature rise of the air within the cultivation area (ΔT_{ca}), which is dependent on the internal thermal energy being dissipated, and on the other hand the required atmosphere exchanges within a certain time frame [42]. As for the MTF the temperature rise shall roughly be $\Delta T_{ca} = 3\ K$ [42]. To estimate the air flow rate $\dot{V}$ the following equation (4) is applied [42]:

$$\dot{V} = \frac{\dot{Q}_{max}}{\Delta T_{ca} * c_{p\ air} * \rho_{air}} \tag{4}$$

Where $\dot{Q}_{max}$ is the maximum thermal load, $c_{p\ air}$ is the specific heat at constant pressure of the air, and ρ_{air} is the air density [42]. By inserting $\dot{Q}_{max} = 8237\ W$ (from Table 5.1),

$c_{p\,air} = 1.015\ \frac{kJ}{kg\ K}$, $\rho_{air} = 1.2\ \frac{kg}{m^3}$ an estimated required air flow rate of $\dot{V} \approx 8116 \frac{m^3}{h}$ results [42]. Even though the data on air are dependent on a variety of parameters, e.g. temperature and relative humidity, they are assumed to be constant for the calculation of all processes within this thesis. For commercial, terrestrial, greenhouses the standard volume exchange is once to twice per minute [42, 88]. Main reason is to prevent a rising inside temperature due to solar radiation and the glass architecture [88]. In modules for humans in space lower exchange rates are applied. Aboard Spacelab the atmosphere is exchanged approximately ten times per hour [9]. In the crew quarters on the ISS the exchange rate is adjustable via the fans between around once every 30 seconds to every five minutes [13]. According to crew feedback a tendency towards low or medium fan speeds is detected [13]. On the basis of those data a possible exchange rate of $\frac{15}{h}$ which means every four minutes is defined. Equation (5) is used to get a check value for the air flow rate. Since the greenhouse module has no internal partition not only the volume of the cultivation area but the entire volume of the module ($\approx 225\ m^3$) is inserted.

$$\dot{V} = 225\ m^3 * \frac{15}{h} = 3375\ \frac{m^3}{h} \tag{5}$$

The air flow rate calculated with the air exchange requirement is smaller than the air volume rate required for the cooling. Therefore, this value is used for the following design processes of the components. The same procedure is performed for the cold case to determine the maximum required air flow rate. Table 5.2 is a summary of the calculations for the warm and the cold case.

Table 5.2: Calculation steps to compare the required performance of the fans in the warm and cold case

	Warm case	**Cold case**
maximum thermal load: $\dot{Q}$	$8237\ W$	$8405\ W$
specific heat capacity at constant pressure of the air: $c_{p_{air}}$	$1.015\ \frac{kJ}{kg\ K}$	$1.015\ \frac{kJ}{kg\ K}$
temperature rise across the cultivation area: ΔT_{ca}	$3\ K$	$3\ K$
density air: ρ_{air}	$1.2\ \frac{kg}{m^3}$	$1.2\ \frac{kg}{m^3}$
atmospheric volume (greenhouse module): V	$225\ m^3$	$225\ m^3$
air flow rate required for cooling: $\dot{V}$	$8116\ \frac{m^3}{h}$	$8281\ \frac{m^3}{h}$
air flow rate required for min. atmospheric exchange: $\dot{V}$	$3375\ \frac{m^3}{h}$	$3375\ \frac{m^3}{h}$
Maximum required air flow rate	$8116\ \frac{m^3}{h}$	$\mathbf{8281\ \frac{m^3}{h}}$

For the selection of the fans within the duct system also the static pressure needs to be considered to ensure the compensation of the pressure drop via filters, ducting, and other losses. The estimation of pressure losses caused by the different components was done in chapter 4.5.1.3 and yielded $\Delta p = 5673\ Pa$.

As discussed in chapter 4.3.2 redundancy is ensured by using several fans in serial. The quantity is set to three which results in a lower required static pressure per fan. Anyway, two fans shall be able to counteract the pressure of the system plus the pressure drop caused by one fan being out of service to guarantee continuous operation until the replacement of the broken fan. The flow rate remains unaffected by the serial arrangement. To conclude, this requires three fans with a nominal air flow rate of $\dot{V} = 8300\ \frac{m^3}{h}$ and a static pressure of $\Delta p = 3000\ Pa$. For the air flow rate no additional margin needs to be applied as margins were used for the thermal loads which are the only variable influencing parameters.
For the overhead fans no specific characteristics are defined. As mentioned in chapter 4.3.2 a stable and continuous air flow is requested combined with a low noise exposure. Redundancy of the overhead fans is ensured with several fans being installed in parallel. This is not an actual redundancy, but it is sufficient for this application because it is not very critical if one of the fans is stagnant for a short amount of time until being exchanged. For the first design eight fans at each aisle are foreseen. This number might be reduced after gaining more data from the CFD analysis and at the ground tests.

5.1.2 Dehumidifier

By adding the transpiration rate and the defined setpoint conditions from chapter 4.5 to the defined temperature gradient the input and output conditions of the air can be identified [42]. The setpoints can be extracted from Table 4.10. To determine the input and output temperatures half of the assumed temperature gradient is subtracted from the setpoint temperature to get the input temperature and also half of the temperature gradient is added to the setpoint temperature to get the output temperature [42]. Quantified this yields an input temperature of $T_{input} \approx 293.5\ K$ and an output temperature of $T_{output} \approx 296.5\ K$. At a defined relative input humidity of $rH_{input} = 70\ \%$ the absolute humidity of $aH_{input} = 10.5\ \frac{g}{kg}$ ($\rho_{air} = 1.2\ \frac{kg}{m^3}$) can be extracted from the Mollier diagram in Figure 5.1. To determine the relative output humidity the increase of water content needs to be identified. By dividing the transpiration rate $\dot{m}_{transpiration} = 134\ \frac{kg}{day}\left(5584\ \frac{g}{h}\right)$ by the air mass flow rate $\dot{m}_{air} \approx 9740 \frac{kg}{h}\left(\rho_{air} = 1.2\ \frac{kg}{m^3}\right)$ the water content increase is calculated to be $\Delta m_{water} \approx 0.58\ \frac{g}{kg}$ [42]. This yields an absolute output humidity of $aH_{output} = 11.08\ \frac{g}{kg}$ which results, at the previously calculated output temperature, in a relative output humidity of $rH_{output} = 63\ \%$ (from Mollier diagram in Figure 5.1).

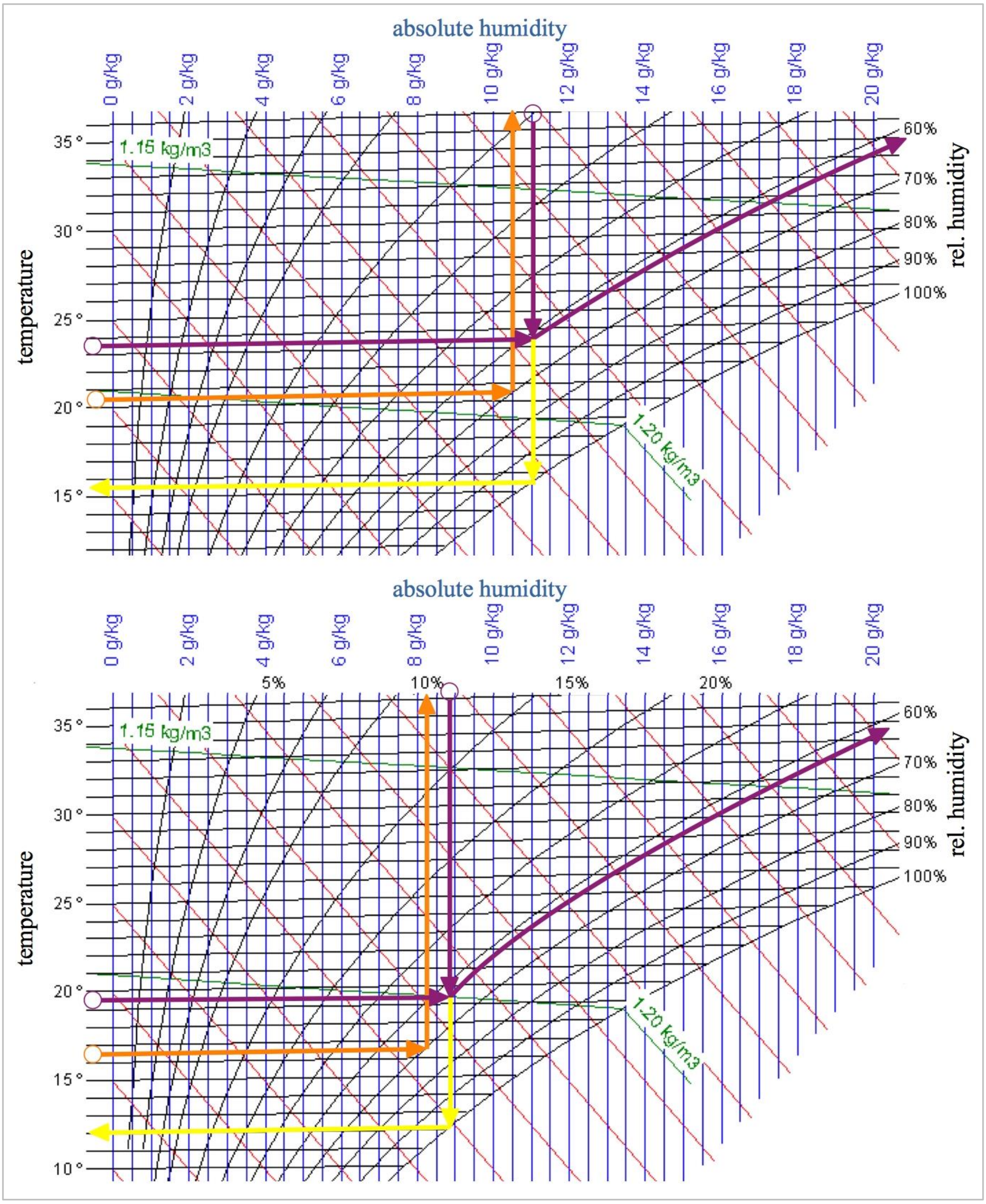


Figure 5.1: Mollier diagrams to determine the absolute input humidity (orange), the relative output humidity (purple), and the dew point (yellow). (top: warm case; bottom: cold case) [89]

To reset the air parameters to the input conditions the dehumidifier and the heaters are provided [42]. In the reverse process the air is first cooled under the dew point to generate condensate. The mass flow rate of condensed water has to equal the mass flow rate of transpiration ($\dot{m}_{condensation} = \dot{m}_{transpiration}$) to reset the absolute humidity to the air input conditions. Therefore, sensible heat needs to be detracted from the air stream until its temperature is just below the dew point of $T_{DP} = 288.6\ K$. The dew point can be extracted from the Mollier diagram in Figure 5.1. The amount of detracted heat is calculated with a modified version of equation (4).

$$Q_{sensible} = \dot{m}_{air} * \Delta T * c_{p_{air}} \tag{6}$$

Where ΔT is the temperature difference ($296.5\,K - 288.6\,K = 7.9\,K$) and again $c_{p_{air}}$ is the specific heat capacity at constant pressure of the air. Inserting the values into equation (6) leads to a sensible heat of $Q_{sensible} \approx 21693\,W$. In addition, latent heat needs to be removed from the water to condense it. This amount of heat is calculated as follows:

$$Q_{latent} = \Delta H_{water} * \dot{m}_{condensation} \tag{7}$$

Here, ΔH_{water} is the enthalpy of condensation of water. By adding $\Delta H_{water} = 2260\,\frac{kJ}{kg}$ a required latent heat of $Q_{latent} \approx 3506\,W$ is computed. The total necessary thermal capability of the dehumidifier, including sensible and latent heat, needs to be $\dot{Q}_{CHX} \approx 25198\,W$ in the warm case.

To ensure enough power to also perform the cold case the same procedure is executed. The following table is a comparison of the single calculation steps performed for the hot- and the cold case to determine the maximum required performance of the dehumidifier.

Table 5.3: Calculation steps to compare the required performance of the CHX in the warm and cold case

	Warm case	**Cold case**
required cooling power (thermal load): $\dot{Q}$	$8237\,W$	$8405\,W$
constant air volume flow rate: $\dot{V}_{air}$	$8116\,\frac{m^3}{h}$	$8281\,\frac{m^3}{h}$
constant air mass flow rate: $\dot{m}_{air}$	$9740\,\frac{kg}{h}$	$9938\,\frac{kg}{h}$
temperature rise across the cultivation area: ΔT_{ca}	$3\,K$	$3\,K$
input temperature: T_{input}	$293.5\,K$	$289.5\,K$
output temperature: T_{output}	$296.5\,K$	$292.5\,K$
input relative humidity: rH_{input}	70 %	70 %
input absolute humidity: aH_{input}	$10.5\,\frac{g}{kg}$	$8.2\,\frac{g}{kg}$
max. transpiration rate: $\dot{m}_{transpiration}$	$134\,\frac{kg}{day}\left(5584\,\frac{g}{h}\right)$	$134\,\frac{kg}{day}\left(5584\,\frac{g}{h}\right)$
water content increase: Δm_{water}	$0.58\,\frac{g}{kg}$	$0.57\,\frac{g}{kg}$
output absolute humidity: aH_{output}	$11.08\,\frac{g}{kg}$	$8.77\,\frac{g}{kg}$
output relative humidity: rH_{output}	63 %	62 %
dew point: T_{DP}	$288.6\,K$	$285\,K$
specific heat capacity at constant pressure of the air: $c_{p_{air}}$	$1.015\,\frac{kJ}{kg\,K}$	$1.015\,\frac{kJ}{kg\,K}$

	Warm case	Cold case
enthalpy of condensation of water: ΔH_{water}	$2260\ \frac{kJ}{kg}$	$2260\ \frac{kJ}{kg}$
required sensible heat: $Q_{sensible}$	$21693\ W$	$21014\ W$
required latent heat: Q_{latent}	$3506\ W$	$3506\ W$
Total thermal capability of the dehumidifier	$\sum \mathbf{25198\ W}$	$\sum 24519\ W$

Since there are already adequate margins applied at the transpiration rate (100 %) and at the thermal loads (upscaling process) there is no need to apply another margin at this point because the main influencing parameters (amount of condensate, thermal load, volume flow rate) are already covered by a margin. According to the two calculated cases a nominal performance of $\dot{Q}_{CHX} = 26000\ W$ is aimed for. In addition, a water pump to discharge the condensate to a water tank is required. Its nominal performance is $\dot{m} = 134\ \frac{kg}{day} \approx 93\ \frac{g}{min}$. Furthermore, UV-C lamps to treat the air before entering the CHX and to treat the condensate are necessary. At this point only the UV-C lamp for the condensate is regarded. The air treating UV-C lamp is part of chapter 5.1.4. To find a suitable UV-C lamp for the condensate the concrete local flow velocity is needed. Since this is dependent on the local pipe cross-section area a nominal performance of the UV-C lamp cannot be determined at this development stage.
During the initial phase, where all plants are only at germination state, it might be necessary to humidify the air. For further development steps it should be considered to potentially apply a humidifier too.

5.1.3 Heaters

Before entering the cultivation area again, the heaters reheat the air to $T_{input} = 293.5\ K$ in the warm case and to $T_{input} = 289.5\ K$ in the cold case. By reconditioning the input temperature, the relative humidity decreases to $rH_{input} = 70\ \%$ input condition for both cases. To determine the necessary performance of the heater equation (6) is utilized again. The temperature difference for this process arises by subtracting the dew temperature T_{DP} (temperature of the air downstream the CHX) from the desired air input temperature. This yields $\Delta T = 4.9\ K$ for the warm case and $\Delta T = 4.5\ K$ for the cold case. The air mass flow, $\dot{m}_{air}$, and the specific heat capacity at constant pressure, $c_{p_{air}}$, are assumed to be the same as used before. The necessary power of the heater to temper the air for input conditions requires $\dot{Q} \approx 13455\ W$ in the warm case and $\dot{Q} \approx 12608\ W$ in the cold case. Since this process is independent of the transpiration rate in the cultivation area a margin of 20% is added to the warm case. A nominal performance of $\dot{Q}_{heater} = 17000\ W$ is aimed for. For redundancy reasons two heaters are applied. To guarantee the performance of the heater unit if one heater fails both heaters have to have the required performance of $\dot{Q}_{heater} = 17000\ W$.

5.1.4 Filters

As mentioned in chapter 4.3.3 different filters are positioned at different locations to enable an optimal operation of the AMS. In this section first the mechanical pre-filter and HEPA-filter are discussed. Secondly, even though an UV-C lamp is not an actual filter it is considered within this chapter since it treats the air. To conclude a suitable VOC-filter is selected.

Pre- and HEPA-filter are designed without any required design value. Since those mechanical filters are continuously removing particles without being adjustable their lifetime depends on the particle load. The particle load of the greenhouse module is very hard to predict. Also, during terrestrial tests the loads might not be realistic. Anyway, testing will give a better understanding of how often these filters need to be replaced. After collecting data of the particle load a certain operating time can be defined after which the pre-filter and the HEPA-filter needs to be exchanged. Another, more precise, strategy of maintenance is to install a sensor to measure the pressure drop via the filter which indirectly measures the clogging of the filter. If the pressure drop exceeds a certain value the filter needs to be replaced. The final maintenance strategy should be defined after the terrestrial tests. If a steady clogging occurs the first strategy is the choice. If the clogging behavior is unsteady the second method should be applied to avoid blocked filters or replacing a fully functional filter. For the pre-filter a class F7 (EN ISO772) is applied [42]. During the further development a suitable filter for the present air volume flow rate of $\dot{V} = 8281 \frac{m^3}{h}$ should be researched for the local cross-section area. The HEPA-filter class is HEPA 14 (EN 1822-2009) which has an efficiency of 99.995 % [42]. Also for the HEPA-filter the next step is to find a suitable one for the local cross-section area and the air volume flow rate. As described before the lifetime of both pre- and HEPA-filter cannot be determined at this stage of development.

To counteract contamination of the surfaces of the CHX and to inactivate airborne contamination to minimize the microbial load an UV-C lamp is applied [42]. The CHX is especially critical for contamination by microorganisms due to a very high humidity and its labyrinthine setup. For that reason, it is important to place the lamp upstream of the dehumidifier [42]. As for the mechanical particle filters also the UV-C lamp for air treatment is free of a design value. The only characteristic to consider is the air flow rate which usually has a wide range. The local air flow rate at the UV-C lamp cannot be determined at this development stage since the local cross-section area is not defined yet. For redundancy reasons two UV-C lamps are applied. This offers the possibility to keep the lamps operating until they break down. For surface irradiation, in following development steps, when detailed data on the geometry is available, the necessary performance of surface treating UV-C lamps, dependent on the area which needs to be disinfected, can be determined.

Last filter in the treatment sequence is the VOC-filter which has a chemical character. Design parameters for the VOC-filter system are usually the accruing VOC-load (in our case mainly ethylene) and the air flow speed at the filter which is important for the efficiency [42]. As was the case for the MTF a maximum continuous ethylene load of $15\, ppb \triangleq 0.015 \frac{g}{kg}$ (ppb - parts per billion) is assumed [42]. Since the plant density $\left(\frac{grow\ area}{volume\ covered\ by\ AMS}\right)$ in the EDEN Next Gen is only about half of the plant density in the MTF the ethylene load is conservative enough and does not need an extra margin. At a maximum air mass flow rate of $\dot{m} = 9938\ \frac{kg}{h}$ (in cold case) the maximum load of ethylene results in $\dot{m}_{ethylene} \approx 149.07\ \frac{g}{h}$. The air flow speed depends on the air flow rate and the filter cross-section area. As determined before the maximum air flow rate is $\dot{V}_{air} = 8281\ \frac{m^3}{h}$. Dependent on the cross-section area of the filter the air flow velocity can be determined. For the further development either cross-section area or a concrete VOC-filter model should be set. Subsequently either a filter for the arising air flow velocity (dependent on the cross-section area) is searched for or the local ducting has to be fit to the defined VOC-filter. For the lifetime calculation of the VOC-filter the removal capacity of the type of filter media (in % by weight or $\frac{g}{cm^2}$) is essential [42]. With it the maximum quantity of adsorbed ethylene can be determined [42]. By dividing the maximum quantity by the foreseen ethylene load the lifetime of the VOC-filter is determined [42].

5.1.5 Oxygen and carbon dioxide modules

The oxygen and carbon dioxide modules as main part of the gas exchange interface are very complex and essential components. An extensive analysis and development of those modules is out of the scope of this thesis. A brief analysis of potential approaches in chapter 4.4, an indication of the tasks of those modules within this chapter, and an outlook with ideas and possible approaches in chapter 6.2 shall be sufficient for this work.
For the oxygen and carbon dioxide treatment in each module four units are necessary. Those units are able to extract the particular gas, store and transport it to the other entity (habitat/greenhouse), and inject it again at the final entity. In addition, sensors and control mechanisms need to be applied. The distribution of the gases does not need special attention because it is fulfilled by the air circulation system. For the sizing of the units in later development steps the expected loads of O_2 and CO_2 can be taken from Table 4.7.

5.1.6 Air distribution and dimensioning

Design parameters for the air distribution and dimensioning system are the total air flow rate, the air flow speed at the plant, and the launch depth (injection depth) in the cultivation area [42]. The air flow rate was previously defined to be $\dot{V} = 8281\ \frac{m^3}{h}$ (cold case). As already mentioned before not only the duct system itself but also the air flow velocity inside the duct system has a major impact on the pressure drop and on the generated noise. According to [82, 83] it is aimed to be around $v_{air} = 3\ \frac{m}{s}$. The launch depth which is directly connected to the air flow velocity at the plant is a design characteristic of the air inlet louvers. These air inlet louvers cannot be predicted at this point of the development. For that reason, the launch depth and the air velocity at plant are not further discussed in this thesis. Different to the MTF for further development steps no adjustment for the louvers is foreseen. This is a result of the lessons learned from Table 3.1.
To come back to the different duct types introduced in chapter 4.3.5 in the following a feasible possibility of duct cross-section areas for all duct types is presented. The theoretically

calculated values for air flow velocities need to be verified by a CFD analysis and demonstrated through ground tests. The main ducts need to cover half of the air flow rate because all of them are in duplicate. Those main ducts include the horizontal overhead air outlet ducts (air suction), the horizontal underfloor air supply ducts, and the vertical curved ducts within the rigid part which connect the overhead and the underfloor components of the AMS. Since there are eight vertical curved actual air distribution ducts each of them has to cover one eighth of the air flow rate. By dividing the air flow rate by the air flow velocity the total cross-section area of $A_{ducts\ total} \approx 0.767\ m^2$ arises. This total cross-section area is split to two main ducts of $A_{main\ ducts} \approx 0.384\ m^2$ and to eight distribution ducts of $A_{distribution} \approx 0.096\ m^2$. For the eight vertical curved ducts this is only the initial cross-section area. Their cross-section area has to continuously decrease to keep the air flow velocity at a constant level because it is an indicator for the injection depth. For the first, very rough, design the vertical curved air distribution ducts are divided into three segments of about one meter length. At the present air flow rate that means an injection rate of $\dot{V}_{injection} \approx 346\ \frac{m^3}{h}$ per meter length. For the cross-section areas this means the initial segment with $A \approx 0.096\ m^2$ is followed by a second segment with $A \approx 0.064\ m^2$ and a third segment with $A \approx 0.032\ m^2$. In the final version of the duct system this reducing will be stepless commensurate to the remaining air flow rate or at least using smaller segments.
For the main ducts a circular cross-section area is likely which would mean a diameter of around $\emptyset_{main\ ducts} \approx 0.70\ m$. If the air distribution ducts have a circular cross-section as well they would have a diameter of $\emptyset_{distribution} \approx 0.35\ m/0.29\ m/0.21\ m$. Also possible for the distribution ducts is an oval or flat shape. This offers the opportunity to inject the air not only in 'lines' but 'areal'. Outside of the ducts the further air distribution is taken over by the overhead fans.
For the material selection of the ducts, requirements should be named and compared with available materials of manufacturers. When defining the requirements the following characteristics should be considered: tear flexibility, flexibility at high and low temperatures, resistance to oils, fats, solvents, chemical agents and UV-light, antistatic, surface roughness. Afterwards a trade-off should be performed to find the most suitable material.
A volume flow controller might be useful for ground tests to verify the results of the CFD simulation and to easily investigate the relation of air flow rate and the injection depth. For the space flying module such a controller is not absolutely necessary but should remain in the system as a backup for flow rate regulation.

5.2 Layout and mode of operation

5.2.1 Layout

As already mentioned, usually the next step after sizing the single parts would be the selection of specific components which perform the determined performances. Afterwards a layout would be defined. Due to the high probability of changes, in this thesis only a potential placement of the main components is given. The underfloor space in the rigid section could house the first sensor bundle (O_2/CO_2), the pre-filter, the HEPA-filter, the first fan, and the dehumidifier with UV-C lamps. Accommodation of the heater unit, the second and third fan, the VOC-filter, the air composition control, and the second sensor bundle (O_2/CO_2/VOC) could be provided by the overhead space in the rigid part. Figure 5.2 gives an overview of the potential locations of the main components of the AMS.

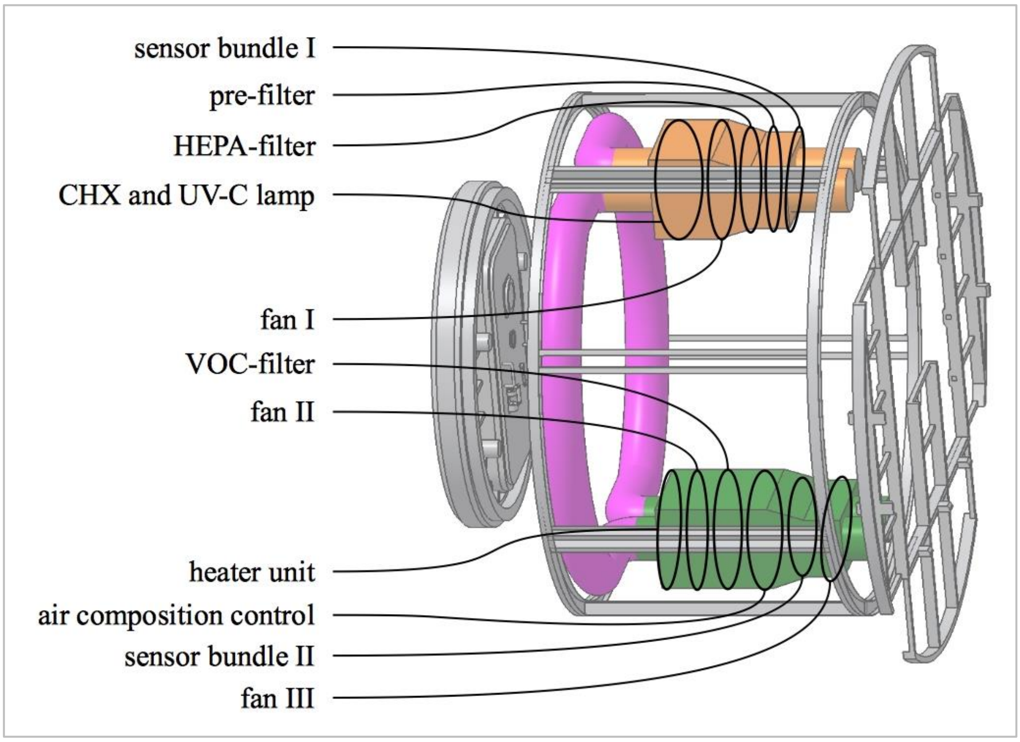


Figure 5.2: Potential placement of main components in the service section (rigid part)

Theoretically components could be placed at the connection ducts (pink). If so, it has to be considered that those components need to be applied twice due to the split air flow. Since for this area only parts of the middle of the components sequence can be considered, the only option for that is the heater unit. To split the dehumidifier, the fans, or the VOC-filter is not practical.
After a brief research on potential components with the required performance it is determined that the available space within the preliminary design of the greenhouse module is most likely sufficient to accommodate all necessary components of the AMS.

5.2.2 Mode of operation

In this section the mode of operation of the dimensioned components is presented. Since this is the first development stage of the AMS only ideas and suggestions are made and potential control elements are named for further design steps. Components that have to be actively controlled are the fans, the heaters, the dehumidifier, and the air composition control including the linked gas exchange interface. Components which operate continuously e.g. filters, UV-C lamp, and sensors, do not need an active regulation.

Fans
The air flow rate is directly dependent on the rotation speed of the fans. They should be stepless adjustable. For the ground tests a manual control of the fans should be implemented to identify which air flow rate corresponds with which injection depth. Additionally, an

automatic safety switching which increases the rotation speed if a local enrichment of CO_2, O_2, or a VOC is detected by the sensors should be implemented. Later on, for the actual flight module some sort of automated control unit which is fed with data from a variety of sensors should be applied for the normal operating state. The automated control unit has to incorporate a control logic to allow operating in case of a fan failure, or other malfunction. This control system is out of scope of this thesis. The possibility to manually adjust should be kept. An individual control of the single fans is not necessary.

Heaters

The heaters' operating power is dependent on data from a temperature sensor and should be stepless adjustable. For the control of the heaters a two-position controller with hysteresis can be used. The temperature sensor which feeds the two-position controller needs to be downstream of the heaters in the duct system or in the cultivation area. The hysteresis is dependent on the thermal inertia of the system and can be identified during the ground tests. A manual adjustment for safety reasons should be applied in the test model as well as in the flight module.

Dehumidifier

The dehumidifier is fed with data from humidity sensors within the cultivation area. The temperature adjustment of the thermal loops can be realized by applying three-way valves which mix the in- and backflows [5]. The volume flow at the AMS cooling coil can also be regulated with a three-way valve [5]. Also for the operation of the dehumidifier an automated control system should be designed which is outside of the scope of this thesis. For safety reasons a manual switching should be considered.

Air composition control

Potential operating modes for the air composition control unit and the linked gas exchange interface are treated later in the outlook in chapter 6.2.

Sensors

In general, for the ground testing a large number of sensors should be applied to gain as much data as possible. For the flight module a trade-off should be performed with respect to installing additional sensors and the resulting complexity, power consumption, weight, and costs. All of those parameters should be reduced to a minimum while still providing all necessary data for a 'safe' operation. This counts for sensors for static pressure, temperature, relative humidity, air flow rate, oxygen, carbon dioxide, and VOC.

5.3 Summary of the detailed design

Within this chapter the single components of the AMS were sized to meet the necessary performances determined in the previous chapter. Since the main focus of this thesis is to get a general outline of the feasibility and to generate a base for further development steps this process was only a rough sizing. Table 5.4 gives an overview of the first results of the required performances of the single components.

Table 5.4: Overview of preliminary required performances of the single main components

Component	Preliminary required performance
main fans	flow rate: $\dot{V} = 8300\ \frac{m^3}{h}$ static pressure (each): $\Delta p = 3000\ Pa.$
CHX	$\dot{Q}_{CHX} = 26000\ W$
heater unit	$\dot{Q}_{heater} = 17000\ W$
pre-filter	continuous removing
HEPA-filter	continuous removing
VOC-filter	$15\ ppb \triangleq 0.015\ \frac{g}{kg}$ $\left(\dot{m}_{ethylene} \approx 149.07\ \frac{g}{h}\right)$

As changes of the made assumptions are very probable at this early stage of the development the common proceeding of finding concrete components which suit the required performances is not meaningful. In addition, as the layout of the components is the ensemble of all subsystems and their components it is not possible to define a final layout at this point since the AMS is the first subsystem to be designed. Only a potential placement of the main components of the AMS was given (Figure 5.2).

To finish possible modes of operation were introduced. Since this was the first development stage of the AMS only ideas and suggestions were made and potential control elements were named for further design steps. Actively controlled components are the fans, the heaters, the dehumidifier, and the air composition control including the linked gas exchange interface. Components which operate continuously e.g. filters, UV-C lamp, and sensors do not need an active regularization.

6 Critical review and outlook

6.1 Critical review

This chapter provides an evaluation and a critical assessment of the thesis, including the utilized methodology, the weaknesses, occurred challenges, incompleteness, and the results.
The applied methodology for the development is based on identifying the requirements, researching existing technologies to fulfil those requirements, trade-off those technologies, and finally on basic physical relations to get a rough dimensioning of the technologies. This delivers only very basic results which still need further processing. For the first development step this is sufficient since it is only to point out tendencies and to get a sense for the roughly required performances of the AMS.

In general, there are a lot of uncertainties since it is a very early stage of development (pre-phase A). In the following the three main uncertainties are given.
First, as there is no concrete mission scenario yet the environmental conditions are very unspecific. It makes a significant difference where the final destination will be. The environmental conditions on Mars are very different to those on Moon. Even another location on Moon would change the boundary conditions, which would mean other requirements for the subsystem performances. In addition, the plant configuration used in this thesis is only a sample plant selection which is highly possible to change. By growing a different plant configuration, the overall plant loads may significantly change. In this thesis the greenhouse module is only designed for one special case picked by trying to find the most probable scenario for destination and plant configuration.
Second, the AMS has a lot of dependencies on other subsystems. Since the AMS is the first subsystem to be designed a lot of necessary data required for a detailed design are still not defined yet. This makes it important to handle the results with care. An iterative revision of the AMS needs to be performed when a first design of the other subsystems exists. The especially critical subsystems are pointed out later in this chapter.
Third, the general design of the habitat and especially its involvement to the greenhouse module is still completely unclear which makes it hard to predict the effects of the habitat on it. Since it is certain that there will be a close relation between habitat and greenhouse this should not be neglected but defined as soon as possible.

To counteract these open questions in this thesis assumptions were made. In addition, margins were applied at different design steps to compensate the lack of concrete data. But it needs to be kept in mind that only some factors are good to estimate. Those assumptions generate very probable realistic values. Some other factors are hard or nearly impossible to predict. Without detailed data these assumptions are only very rough and have the possibility to be significantly different to the later occurring loads. This results in highly possible alteration of those assumptions when more concrete data is available. In other words, a lot of assumptions were made but their quality concerning applicability cannot always be assessed.
With additional data better assumptions or maybe already concrete predictions can be made. The best proceeding is to determine the assumptions with the most uncertainties and to start to

clear those up. Particular fundamental data would be generated by working on the following fields.
Especially two subsystems have a major impact on the later design of the AMS. The illumination system (ILS), more precisely the LED panels, dissipate a large amount of heat when operating. Two cooling strategies are conceivable for this application. On the one hand an air-cooling system and on the other one a water-cooling system. If an air-cooling is applied it would mean that the AMS has to cover the total power output load of the LED panels. At a water-cooling system not the entire occurring heat can be discharged. As mentioned in chapter 4.5.1.2 a certain amount of heat is still dissipated to the air. Also the structure should have a high priority in future work, especially the outer shell because it is significantly dictating the thermal insulation of the module. The MLI, which is part of the membrane's most influencing factor for the thermal properties, should be defined to get a realistic thermal loss via the outer shell.
As already mentioned before, the mission scenario and influence of habitat have a significant effect on the AMS design. Fundamentals like the final location of the mission, details on the protection regolith shield, and the influence of the habitat on the greenhouse module including all interfaces should be identified as early as possible. This will give a more realistic overall picture.
Additionally, the influence of the crew should be investigated. What are the working hours of the astronauts within the greenhouse module and how are the internal loads of oxygen, carbon dioxide, VOC, heat, and humidity affected by that. It is expected that humans will not have a large influence on the required performances of the AMS and it is covered by the applied margins, but if so, it should be considered at further development steps.
In summary no final decision can be made without detailed data on all factors influencing the AMS.

For the sake of completeness two additional points of criticism are mentioned. At this thesis the photosynthesis process is considered to be static. To get a more realistic view on the occurring loads this process should considered to be dynamic. The photosynthesis rate, which is representative for the transpiration rate, the O_2 production rate, and the CO_2 uptake rate, is highly dependent on the light intensity. This lets the photosynthesis rate cycling as a function of the light and dark periods.
Regarding the interfaces of the AMS it turned out that their design process is out of scope of this thesis. As support for further development steps concerning the interfaces the following was prepared during the generation of this work. All interfaces between the AMS and the other subsystems as well as the AMS were defined. Additionally, the most complex interface of the AMS, which is the gas exchange interface with the habitat was analyzed in detail and a trade-off of different approaches was performed. After determining the most suitable approach, design and technology recommendations and ideas are given at the outlook. But, this can only be seen as groundwork for further development steps.

To conclude an evaluation of the meaningfulness of the results of this thesis is given. As previously discussed, limitations occur due to the simplifications and assumptions made because of the early-stage uncertainties. Even though the results of this thesis are only a very first step of the design of the AMS for the EDEN Next Gen greenhouse module they are still very meaningful and serve as a good base for further developments steps. The usability of this thesis is not only for concretizing the AMS design but is also important for the first design of the other subsystems especially for the PCDS, the TCS, and the CDHS.

6.2 Outlook

Since this thesis is only one single step within the whole development process of the EDEN Next Gen greenhouse module an outlook is given in this chapter. As in the rest of the thesis only the AMS is discussed and all other subsystems are excluded. The main focus is on verifying the air distribution, on a potential passive thermal regulation, and on the atmosphere composition control with the connected gas exchange interface with the habitat. All considerations are only brief ideas or impulses for further brainstorming and not extensive analyses as this would be out of scope of this thesis.
Figure 6.1 visualizes the long-term goal of the EDEN initiative, a greenhouse module for food production as an integrated part of a closed loop life support system.

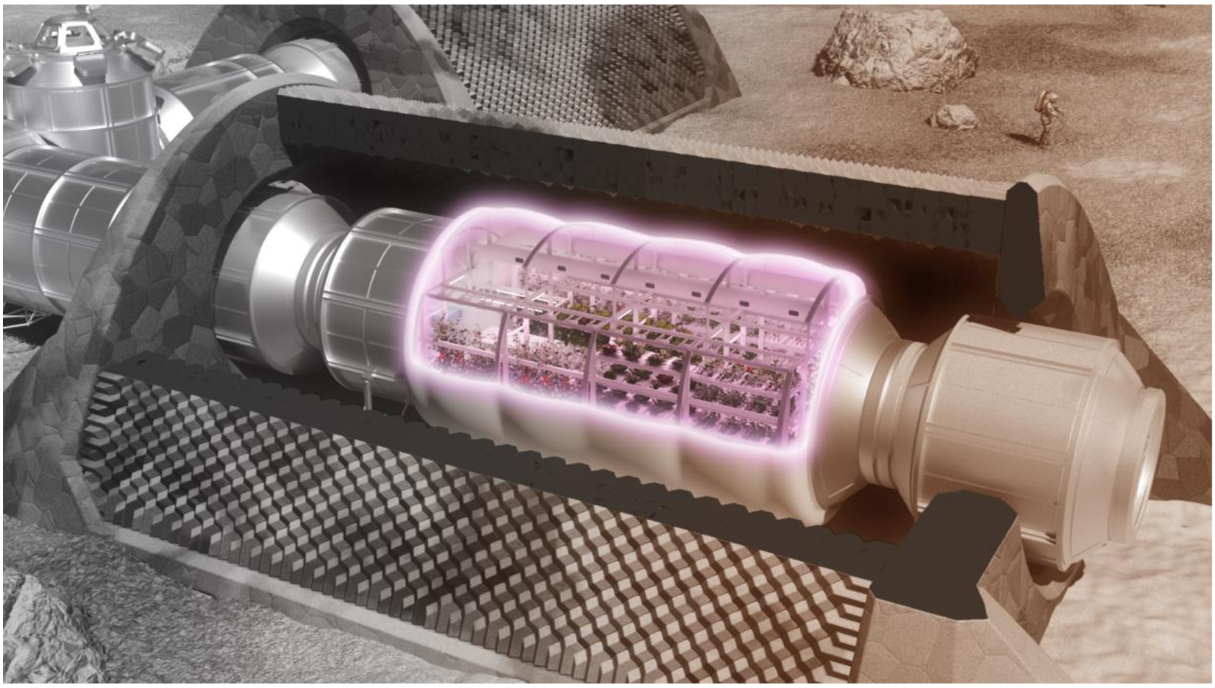


Figure 6.1: EDEN Next Gen greenhouse module on Moon/Mars surface [5]

Verification of the air distribution system
The air distribution system, including all air supply and air suction ducts as well as both types of fans, still needs a lot of further development. In this thesis only a very basic concept was introduced and a rough estimation of dimensioning of the ducts on basis of defined boundary conditions was performed. At the point where a concrete design exists a CFD analysis should be applied to verify the performance of the fans and the capability to distribute the air all over the cultivation area. With this analysis optimizations can be implemented before manufacturing the first prototype. Because of uncertainties in the CFD model due to the unpredictability of plant growth, ground tests are needed to demonstrate the results of the CFD analysis.

Passive thermal regulation via a latent heat storage

The AMS and the TCS (thermal control system) have intersection in any case since the AMS plays an active role in thermally balancing the greenhouse module. At the final design both systems are strongly linked to each other and need to be considered conjoined.

Since the outside temperature is assumed to be stable and the inside heat dissipation cycles, a passive heat regulation with a latent heat storage might be feasible. This latent heat buffer would enable sizing the radiator for the average thermal load not for the peak load. The idea is that by end of the day period (more heat dissipation) the phase changing material within the latent heat storage is nearly completely liquid. After solidifying again during the night period (less heat dissipation) the day period starts just before the phase changing materials is entirely in solid state. The feasibility needs to be checked with the concrete final values of external temperature and internal heat dissipation during day and night period as well as the influence of the habitat on the thermal balance of the greenhouse module.

Atmosphere composition control and gas exchange interface

In this paragraph the ethylene management and the gas exchange interface are discussed. As already mentioned in chapter 2.3 ethylene is a VOC that cannot only be continuously removed. The influence of ethylene on plants can be very different dependent on the type of plant and on its grow stage since ethylene is a plant hormone [10]. The usage of ethylene reaches from detecting objects over initiating blossom or the ripening process to triggering its dieback [10]. These, partly contrary, reactions to ethylene request an ethylene management system to avoid fault indications to the plants in this small artificial ecosystem. For optimum growing conditions for each plant an ethylene management system seems to be indispensable. Such a systems would be very complex since it has to offer the possibility to inject the extracted ethylene at each plant tray which would lead to a lot of extra piping. In addition, an intelligent control module needs to be developed. On the other hand, no ethylene handling system is applied in the MTF and the plant growth with their successive stages works properly. In later studies a trade-off should be performed with data gained, from VOC sensors within the cultivation area, during the ground tests. If ground testing delivers good cultivation results without an active ethylene management, it might be best to accept the not 100 % optimum growing conditions for the plants and to cut out the luxury of a complex ethylene management system.

In this passage the atmosphere composition control concerning oxygen and carbon dioxide and the gas exchange interface to the habitat are considered as one unit. On basis of the trade-off on the different gas exchange interface approaches from chapter 4.4 the *extraction, storage, and injection* approach was selected to use the symbiotic gas exchange of CO_2 and O_2. Ideas and possible approaches for the extraction and the injection control of the two gases are introduced in the following.

Since oxygen extraction from ambient air is not directly part of current LSS the literature research in chapter 2.2 cannot be used for a technology selection for oxygen extraction. Also in the MTF no mechanism is available to be adopted. With a brief search two technologies were detected that should be further investigated. The conventional pressure swing adsorption is a technically matured method to extract oxygen from atmospheric air [90, 91]. General components are molecular sieves and high pressure tanks or compressors [73, 90]. The two stage device swings between high and low pressure and removes different gases like nitrogen and argon [73, 90]. The result is a high pressure and high purity O_2 enriched air [73, 90]. This technology was once contemplated as process to produce high purity oxygen for EVA on the ISS, the so-called cabin air separator for EVA oxygen (CASEO) [90]. But downsides such as the high energy demand [91] and the high acoustic loads due to the compressors [90] are especially disadvantageous for the use in space. Due to the similarity of the application of high purity oxygen for EVA and extracted oxygen for habitat injection this process can be envisioned for the interface between the greenhouse module and the habitat.

A newer method is oxygen separation by using membrane technologies [91]. With this technology ambient air is sucked and streams through a membrane module [91]. The separation itself relies on the difference in diffusivity and solubility [91]. Oxygen is extracted upstream the membrane due to the high diffusivity [91]. Different membrane materials and their performances are given in [91]. Compared to the pressure swing adsorption less energy is required and also less noise is generation [91]. Not only for these reasons, membrane technologies seem to be suitable technologies for separating oxygen at the greenhouse side of the gas exchange interface, even though they are not technically matured yet. One issue that needs to be identified is the possibility of precise regulation.

For finding a suitable method to separate carbon dioxide the literature research from chapter 2.2 can be utilized. In general, as for the extraction of oxygen, only a high concentration is needed, not pure gas. Two technologies should be paid special attention. The first technology are molecular sieves. Their functionality is explained in chapter 2.2 in the literature research. Molecular sieves are a matured regenerative CO_2 removal technique [9]. Using a four-bed molecular sieve provides the possibility to collect the CO_2 for other applications [9]. A permanent operation mode can be guaranteed with alternating adsorbent beds [9, 12]. Second method is the electrochemical depolarized CO_2 concentration. This process increases the carbon dioxide saturation of the treated air [9]. The detailed functionality is explained in the literature research. Several inputs and outputs need to be considered for the assessment of applicability for our case. A detailed trade-off on the suitability of these two and maybe other technologies for the carbon dioxide extraction should be performed to find the most promising strategy.

For the injection of oxygen at the habitat and of carbon dioxide at the greenhouse module some thoughts are given in the following. The carbon dioxide injection should be regulated dependent on its level within the ambient air. In this thesis it is assumed that at all times enough CO_2 is available. Even though different CO_2 sources are required it might be sufficient to have one single reservoir to store it. This container provides the CO_2, e.g. brought form Earth, for the initial phase. Afterwards both the habitat and another source feed the reservoir with CO_2. Since for the injection itself a two-way valve is used the reservoir needs to be a high pressure storage. For the control of the injection of CO_2 a two-position controller with hysteresis can be used. The CO_2 sensor which feeds the two-position controller should be placed upstream the injection valve. Only very low mass flow rate should be applied at the injection valve since the volume of the module is very big and due to air distribution it takes some time to get a realistic measurement of the CO_2 level. Using high mass flow rates can result in injecting too much CO_2.

For the oxygen injection at the habitat side a similar strategy could be applied. In any case at least one backup system for oxygen supply should be applied, not only for the initial germination phase of the plants.

7 Summary and conclusion

At the end of every chapter a summary is given. At this point an overall summary and conclusion presents the main content of the entire thesis. Besides the initial situation also the utilized approaches, the methodology, occurred challenges, and the results are described.

After a general literature research on life support systems (LSS) and their tasks in space applications, an extensive analysis of methods and technologies to fulfil those tasks was performed. Within this research both physicochemical and biological approaches were investigated with a special focus on atmosphere management. Currently only physicochemical LSS are in use in space. Only prototypes and test stands of parts of biological LSS are available on Earth or undergoing testing in space. Due to the advantages of biological LSS there are several research projects at a variety of institutions in academics and industry. One of them is the EDEN research initiative which uses food production by plant cultivation as an integrated part of biological LSS for space. The so-called controlled environment agriculture (CEA) is utilized to provide the environment requested by the plants. One important aim for space application is to close more and more loops to reduce the required resupply which is especially important for long-term missions.

Initial situation of this thesis is the EDEN ISS mobile test facility (MTF). This analogue test site located in Antarctica is an entirely functional prototype of a greenhouse module for space application. Over the last three years a lot of knowledge and data could be gained which are used for the preparation of this thesis. This prototype is only one step towards a space ready greenhouse module for future long-term space missions to Moon or Mars. The so-called EDEN Next Gen module is the next iteration to reach the long-term goal. So far only a rough preliminary design of it exists. The partly deployable cylindrical module with a cultivable area of $\sim 34\ m^2$ is foreseen for a crew of six astronauts.

Main goal of this thesis was to develop a first design of the atmosphere management system (AMS). This includes the sizing of the different components and the proof of feasibility concerning the required dimensions of the components compared to the available space in the module. Therefor, requirements regarding the supportive external infrastructure, the overall greenhouse module, and the AMS were identified. In addition, assumptions for the implementation of the AMS were defined. After a detailed systems analysis including the single components, their interrelations, the required interfaces, the occurring internal and external loads, and the definition of system boundaries, a system strategy was developed. Although the AMS of the MTF was completely redesigned for the operation in space conditions some adoptions could be made. Also during the design proceeding, particularly at the dimensioning process of the single components, some practices adopted from the MTF could be applied. The final outcome is a modular concept with the following components. Air circulation generated by fans guarantees a continuous air movement within the cultivation area and counteracts air pockets with the help of a duct system. This loop of cycling air forces the warm, humid, and VOC (volatile organic compound) enriched atmosphere of the cultivation area through the duct system equipped with a sequence of air treating units. After mechanically removing particles with a pre- and HEPA-filter, a condensing heat exchanger (CHX) dehumidifies the air and a heater unit tempers the cold air again. Afterwards trace contaminants are chemically eliminated by a VOC-filter. Finally, the air composition control regulates the oxygen and carbon dioxide concentration. Figure 7.1 shows the AMS of the EDEN Next Gen including its components and their potential location in the greenhouse module.

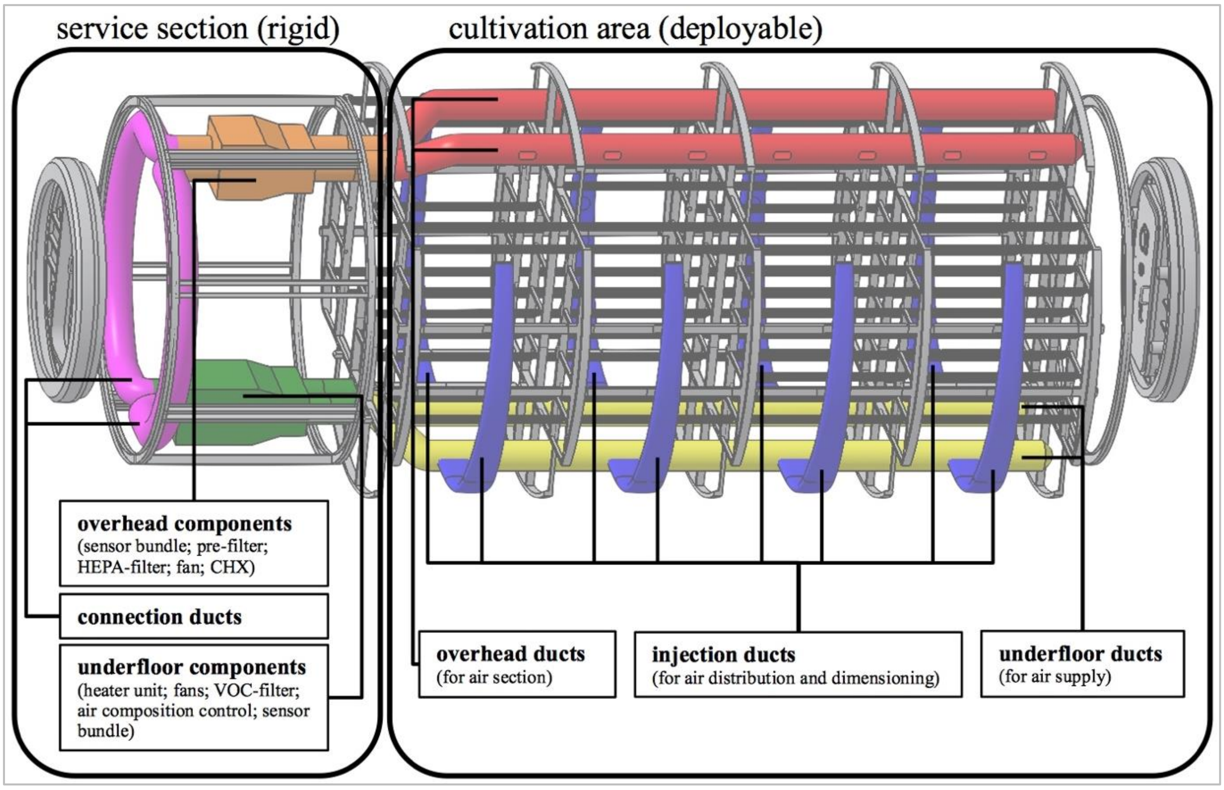


Figure 7.1: Overview of the main components of the AMS and their potential placement

To summarize the dimensioning process of the AMS Table 7.1 was established. In the table first the defined boundary conditions and second the resulting required performances of the different components are given. Those are an orientation guide and important for further development steps.

Table 7.1: Boundary conditions and the resulting required performances of the different components

Boundary condition	**Value**	**Comment**
atmosphere exchanges	15 times per hour $\left(\frac{15}{h}\right)$	Defined for the first dimensioning on basis of current manned space modules. [9, 13]
volumic air flow rate	$\dot{V} = 8281\ \frac{m^3}{h}$	Calculated by applying the required cooling performance of the AMS.
air flow velocity in ducts	$v_{air} \approx 3\ \frac{m}{s}$	This is aimed for to keep the pressure drop and the generated noise low. [82, 83]
Component / Unit	**Required performance**	**Comment**
in-duct fans	air flow rate: $\dot{V} = 8300\ \frac{m^3}{h}$ static pressure: $\Delta p \approx 6000\ Pa$	The fans' performance is determined by the air flow rate and by the pressure drop which needs to be compensated. For redundancy reason three fans are applied in serial which results in increasing their static pressure [61, 62, 63, 64, 60]. Two fans should be able to cover the total pressure drop ($\Delta p \approx 3000\ Pa$ per fan) if one fan fails. Every single fan needs to cover the full air flow rate.

Component / Unit	Required performance	Comment
overhead fans	---	No concrete design value determined. Since a continuously ongoing low air flow rate is important a parallel fan assembly is applied. If one fan fails, this offers the opportunity to raise the air flow rate of the other fans [61, 62, 63, 64, 60]. The static pressure is not critical.
CHX	$\dot{Q}_{dehumidifier} = 26000\ W$	The required performance of the CHX was calculated for the warm and the cold case. Since the cold case requires more performance this is the relevant case for the dimensioning.
heaters	$\dot{Q}_{heater} = 17000\ W$	The required performance of the heater unit was calculated for the warm and the cold case. Since the warm case requires more performance this is the relevant case for the dimensioning. For redundancy reasons two heaters are applied. To guarantee the performance of the heater unit if one heater fails both heaters have to have the required performance.
condensed water pump	$\dot{m}_{H_2O\ transpiration} \approx 134\ \frac{kg}{d} \approx 0.1\ \frac{kg}{min}$	The water condensed by the CHX which is the same amount of water transpired by the plants needs to be discharged by the water pump.
UV-C lamp for air	$\dot{V} = 8300\ \frac{m^3}{h}$	For the design of the UV-C lamp just upstream the CHX the local air flow velocity is important. Since the cross-section area of the duct at the UV-C lamp is not identified yet the air flow rate is the only indicator for the UV-C lamp dimensioning.
UV-C lamp for condensate	$\dot{m}_{H_2O\ transpiration} \approx 134\ \frac{kg}{d} \approx 0.1\ \frac{kg}{min}$	For the design of the UV-C to treat the condensate, flow velocity is important. Since the cross-section area of the condensate pipes is not identified yet the mass flow rate of the condensate is the only indicator for the UV-C lamp dimensioning.
pre-filter	---	No concrete design value. To determine the lifetime of the pre-filter the particle load is required. This is not possible to determine at this development stage.
HEPA-filter	---	No concrete design value. To determine the lifetime of the HEPA-filter the particle load is required. This is not possible to determine at this development stage.
VOC-filter	$15\ ppb \triangleq 0.015\ \frac{g}{kg}$	As for the MTF a maximum continuous ethylene load of $15\ ppb$ is assumed. For the first design of the EDEN Next Gen this results in a maximum ethylene mass flow rate of $\dot{m}_{ethylene} = 149.07\ \frac{g}{h}$.

More details in chapter 5.1.

To come back to the key question of feasibility concerning available space in the greenhouse module potential components with the required performance got briefly researched. It is determined that the available space within the preliminary design of the greenhouse module is most likely sufficient to accommodate all necessary components of the AMS. Although a real guarantee of feasibility can only be done with concrete existing components and in connection with all other subsystems the goal of this thesis was achieved.

The entire developed AMS with its components, their interactions, and interfaces to other subsystems, the crew and the habitat is given in the functional diagram in Figure 7.2.

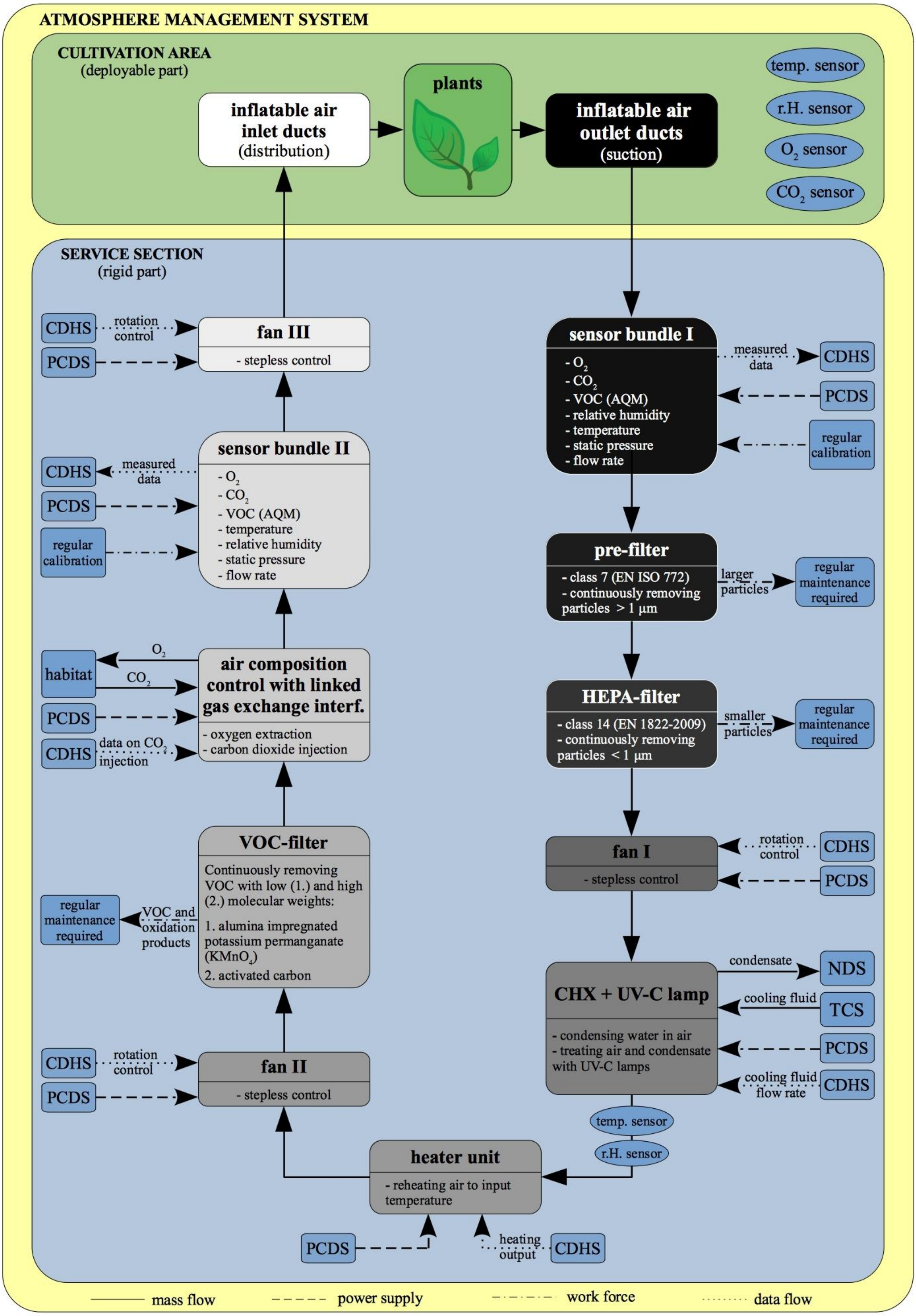


Figure 7.2: Functional diagram of the developed AMS with its components, their interactions, and interfaces to other subsystems, the crew, and the habitat

Only regular maintenance work such as filter cleaning and calibration of sensors is visualized in Figure 7.2. Sporadic maintenance work such as fan exchange are not shown.
In the following the main differences of the EDEN Next Gen greenhouse module to the EDEN ISS prototype are featured. The upsizing process was complex due to a lot of uncertainties. Since no other subsystem was designed so far it was very hard to predict the loads that are traced back to the subsystems. Asides from upsizing, also important lessons learned from the prototype were taken into account. This especially includes major rearrangements of the sequential arrangement of the components (LL-AMS-03/LL-AMS-04/LL-AMS-6), added VOC monitoring (LL-AMS-02), and an UV-C lamp redundancy (LL-AMS-05). Entirely new in the EDEN Next Gen greenhouse module is the gas exchange interface with the habitat which does not exist at the prototype. Even though this interface could not be defined because this was out of scope out of this thesis a first analysis could be made, and a basic approach was introduced for further development. Furthermore, a significant difference to the EDEN ISS MTF is the partly deployable design. For the AMS that means a complex duct system which inflates autonomously due to being linked to the deployable structure. Additional, the overhead air distribution fans are located in the deployable part and have to be designed stowable for launch.
The content of this thesis is only a small part within the development of the EDEN Next Gen greenhouse module. To put this work in context of the entire development of the AMS in chapter 6.2 an outlook was presented. Therefor comments and recommendations for further development steps were given and ideas for more detailed component design were introduced.

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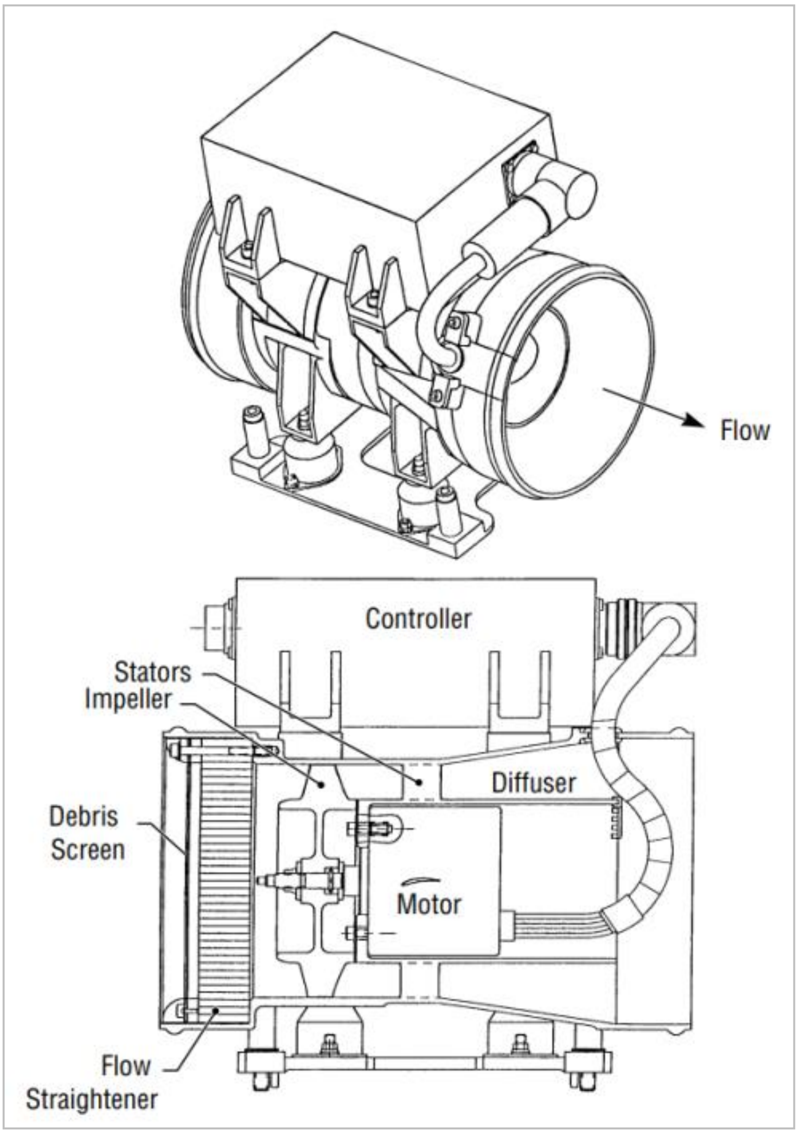
[91] K. Chong, S.-O. Lai, H. S. Thiam, H. C. Teoh and S. Heng, "Recent progress of oxygen/nitrogen separation using membrane technology," 2016.

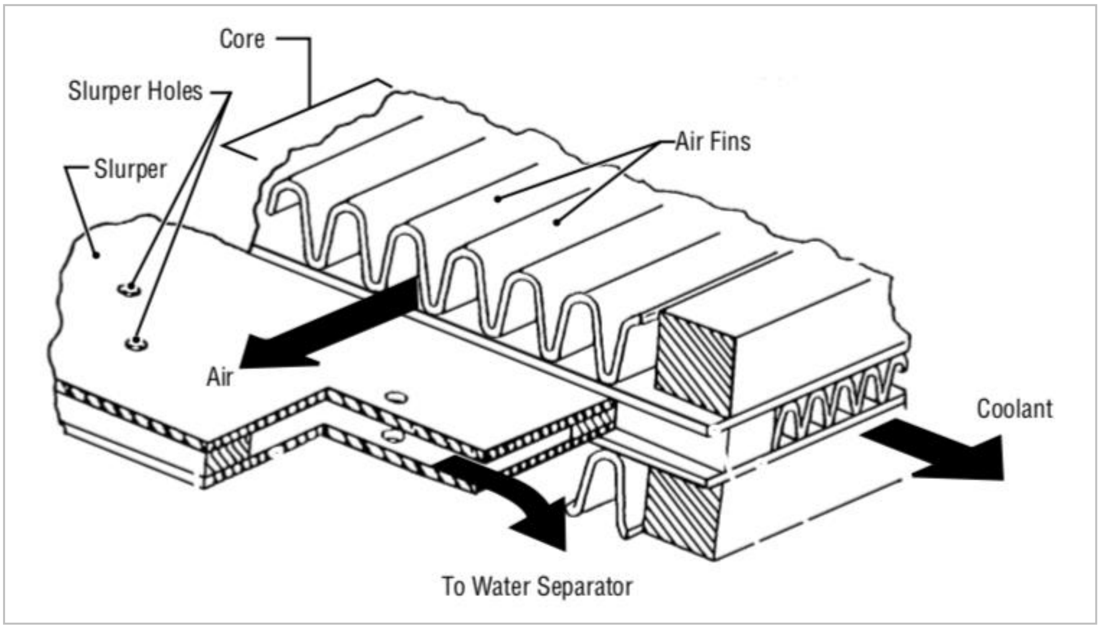
[92] G. B. T. Tan, "Air Revitalization - Preparing for the Future," Noordwijk; The Netherlands, 1993.

Appendix

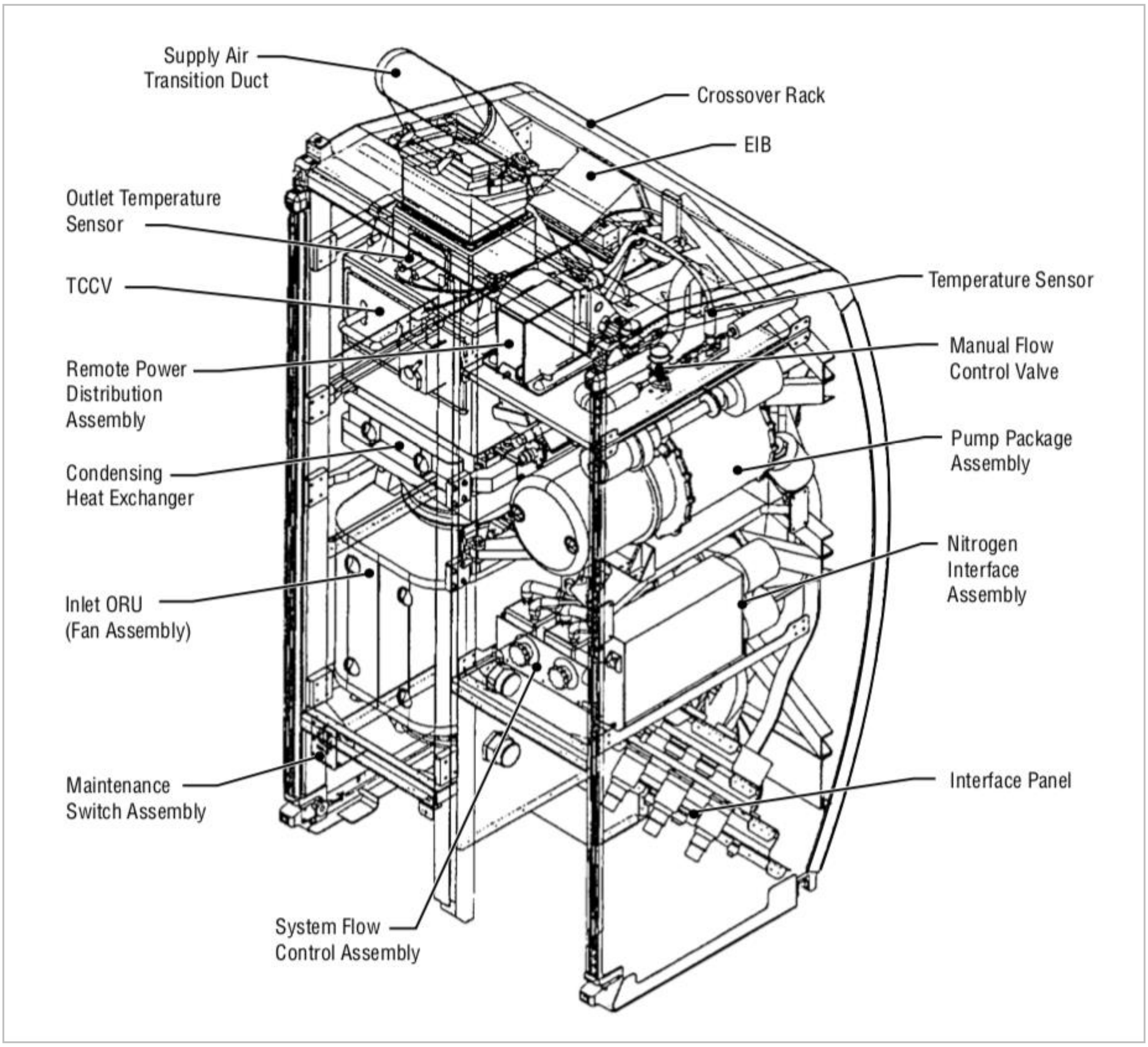
1 Appendix: State of the art physicochemical LSS



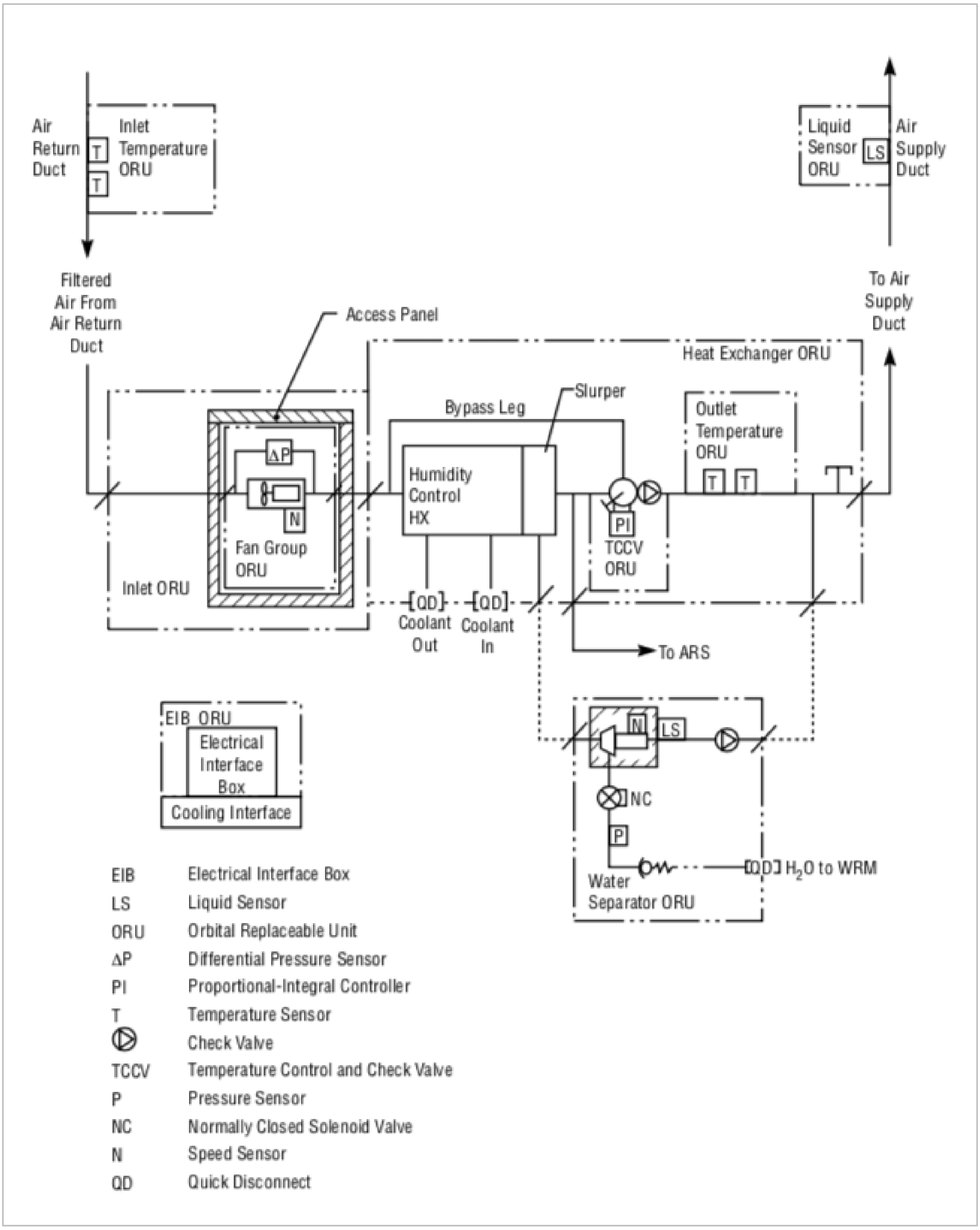
Appendix 1.1: Fan assembly of the intermodule ventilation of the USOS on ISS [12]



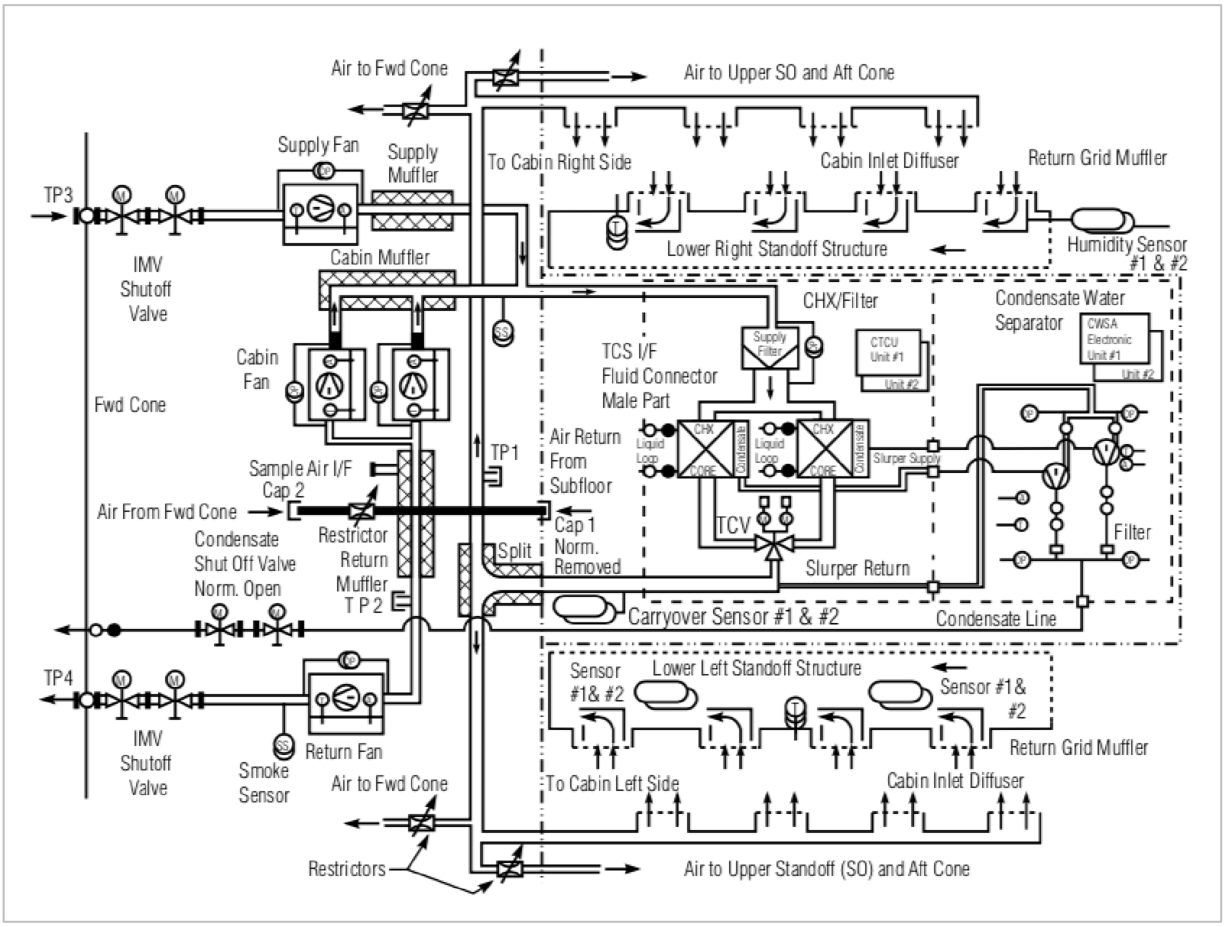
Appendix 1.2: Detailed view of the CHX of the JEM on ISS [12]



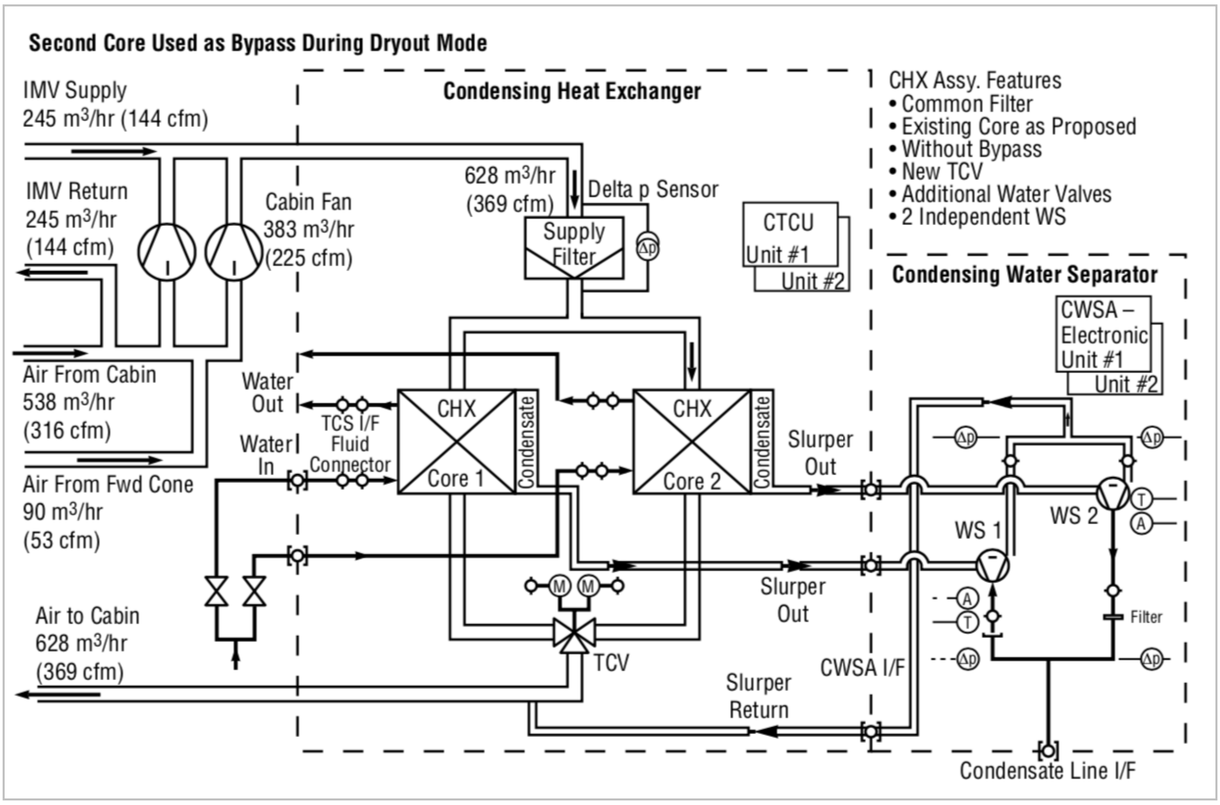
Appendix 1.3: Rack packaging of the THC and TCS of the US segment at ISS [12]



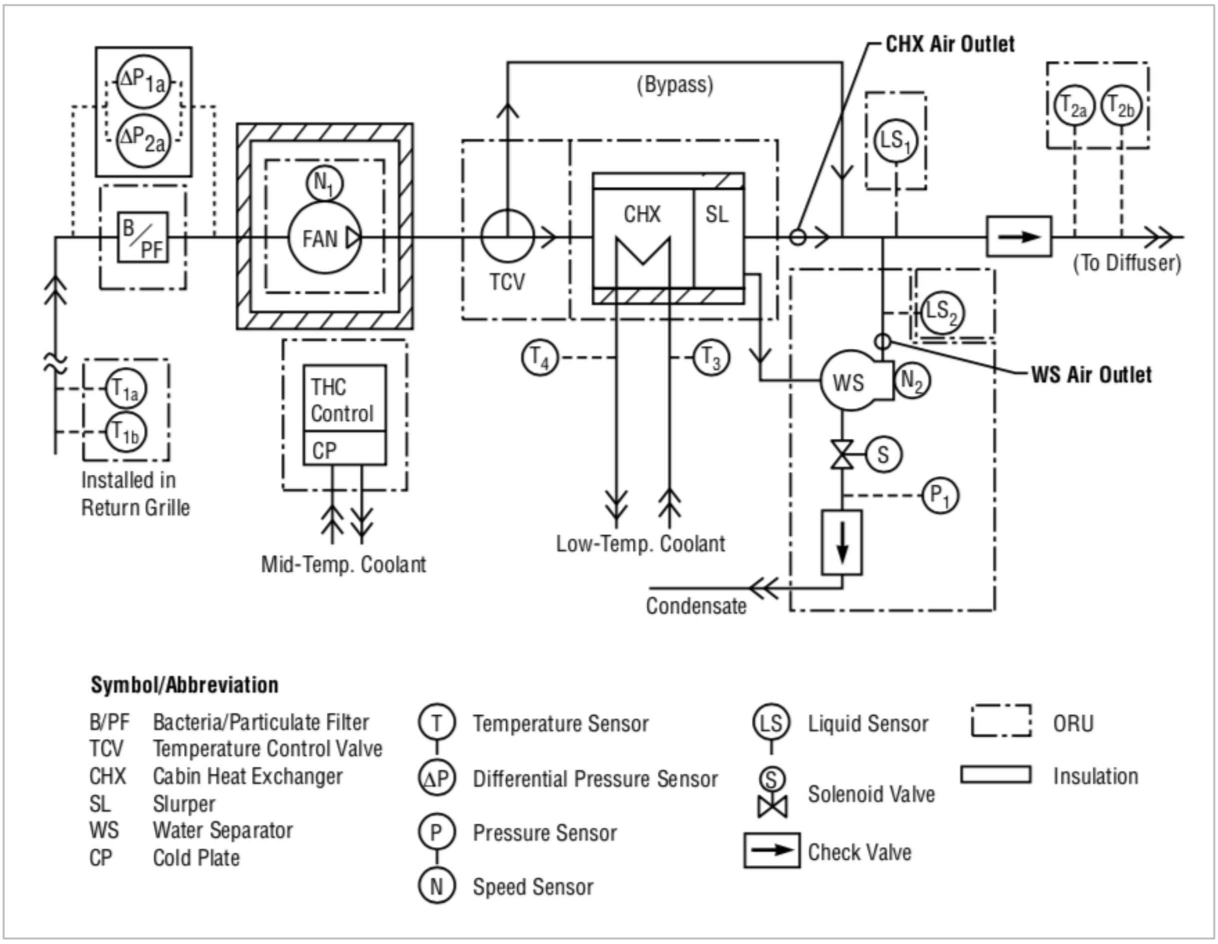
Appendix 1.4: Common cabin air assembly process schematic of US segment on ISS [12]



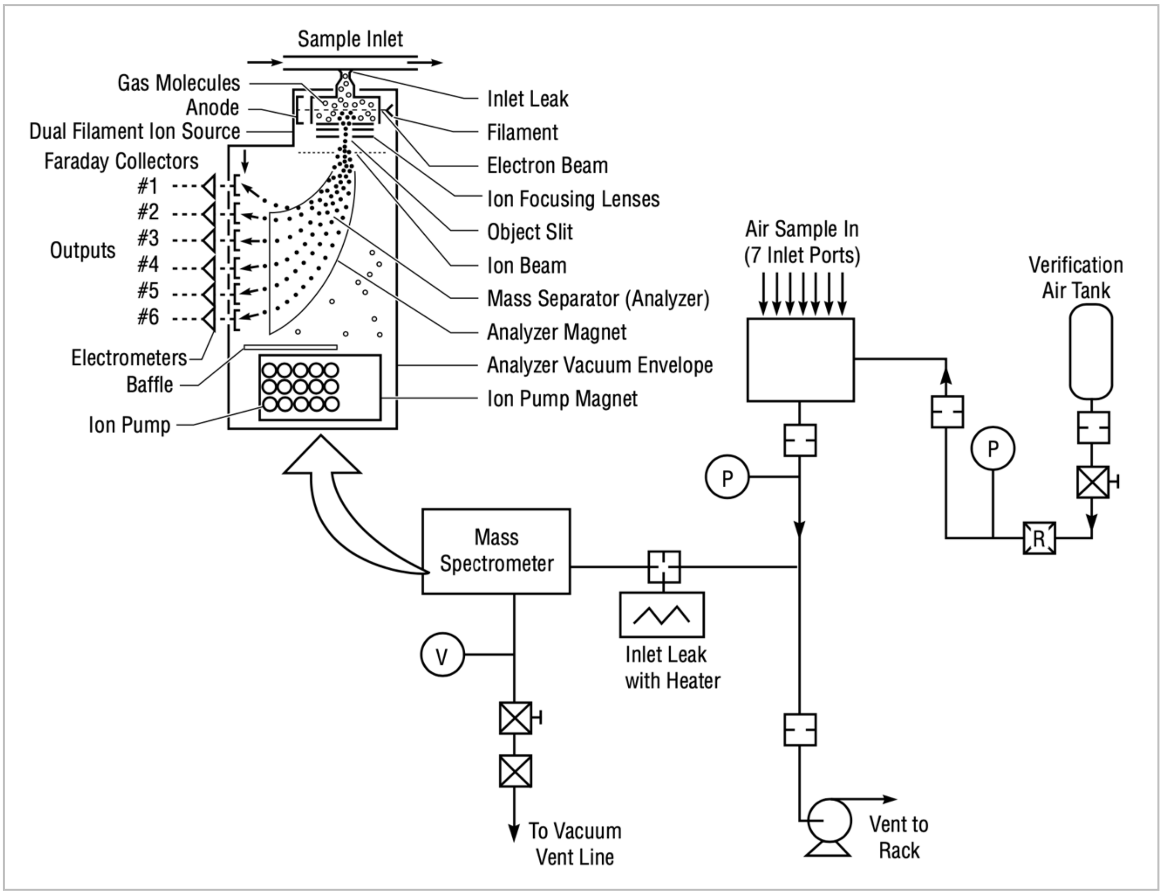
Appendix 1.5: THC subsystem schematic of European attached pressurized module (APM) on ISS [12]



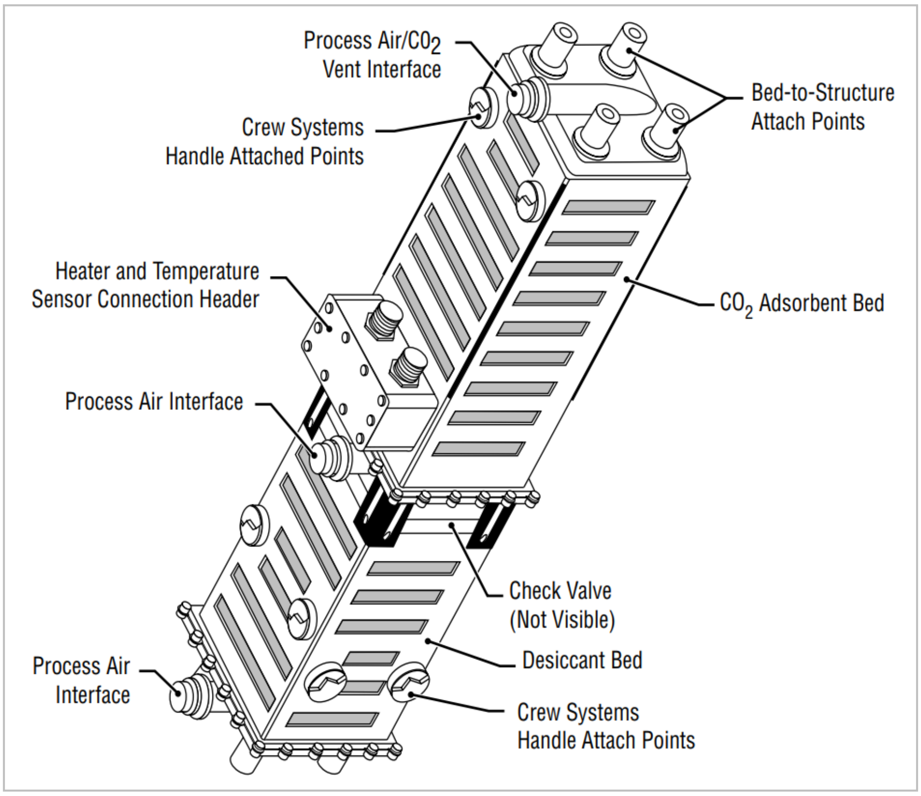
Appendix 1.6: THC subsystem detailed CHX schematic of European attached pressurized module (APM) on ISS [12]



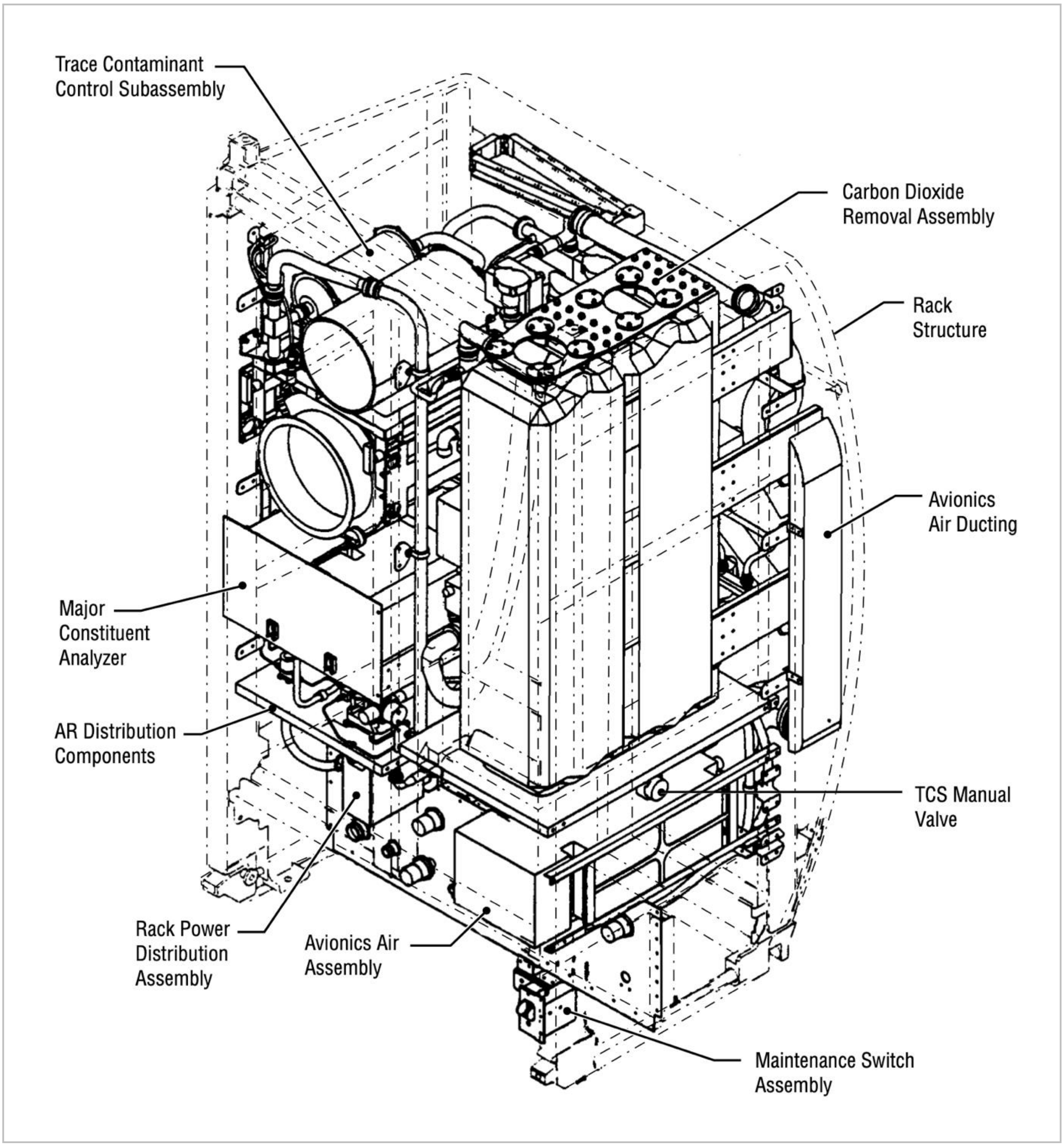
Appendix 1.7: THC subsystem schematic of Japanese Experiment Module (JEM) on ISS [12]



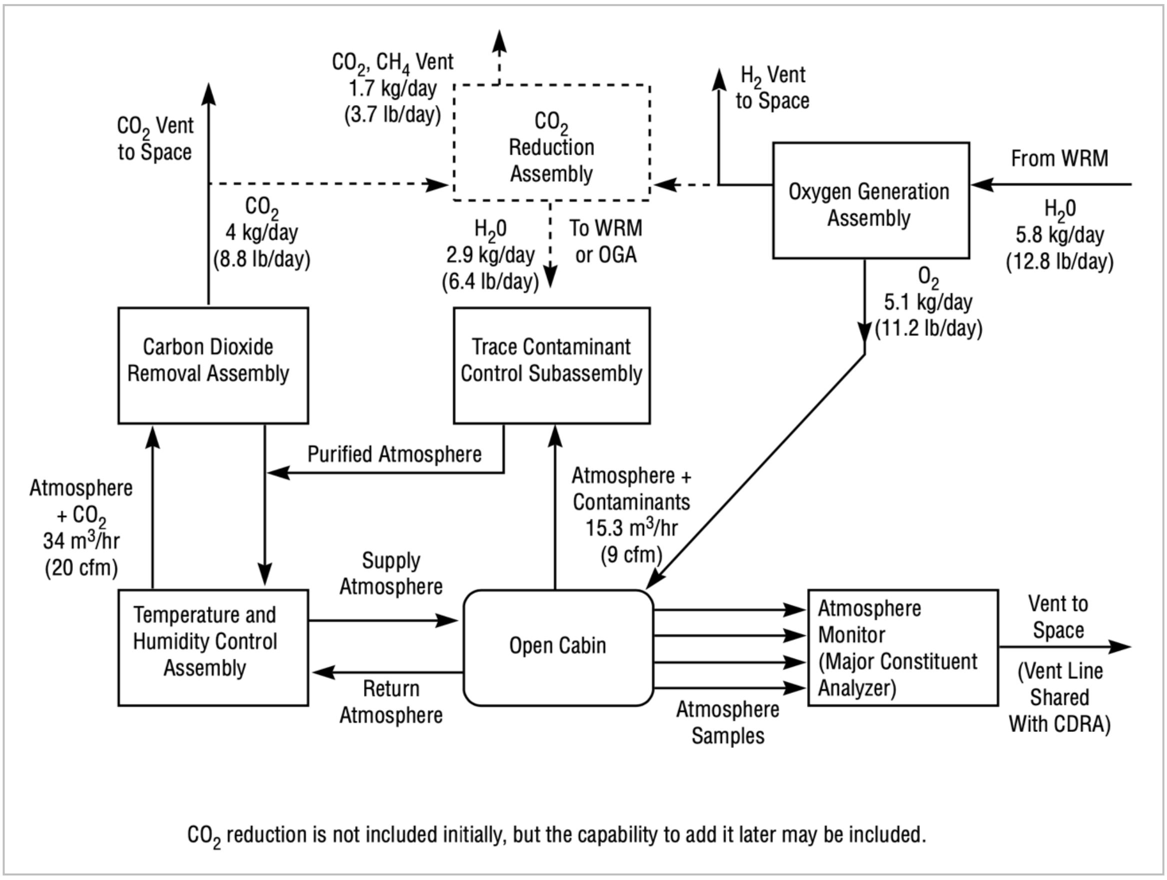
Appendix 1.8: Schematic of the MCA process [12]



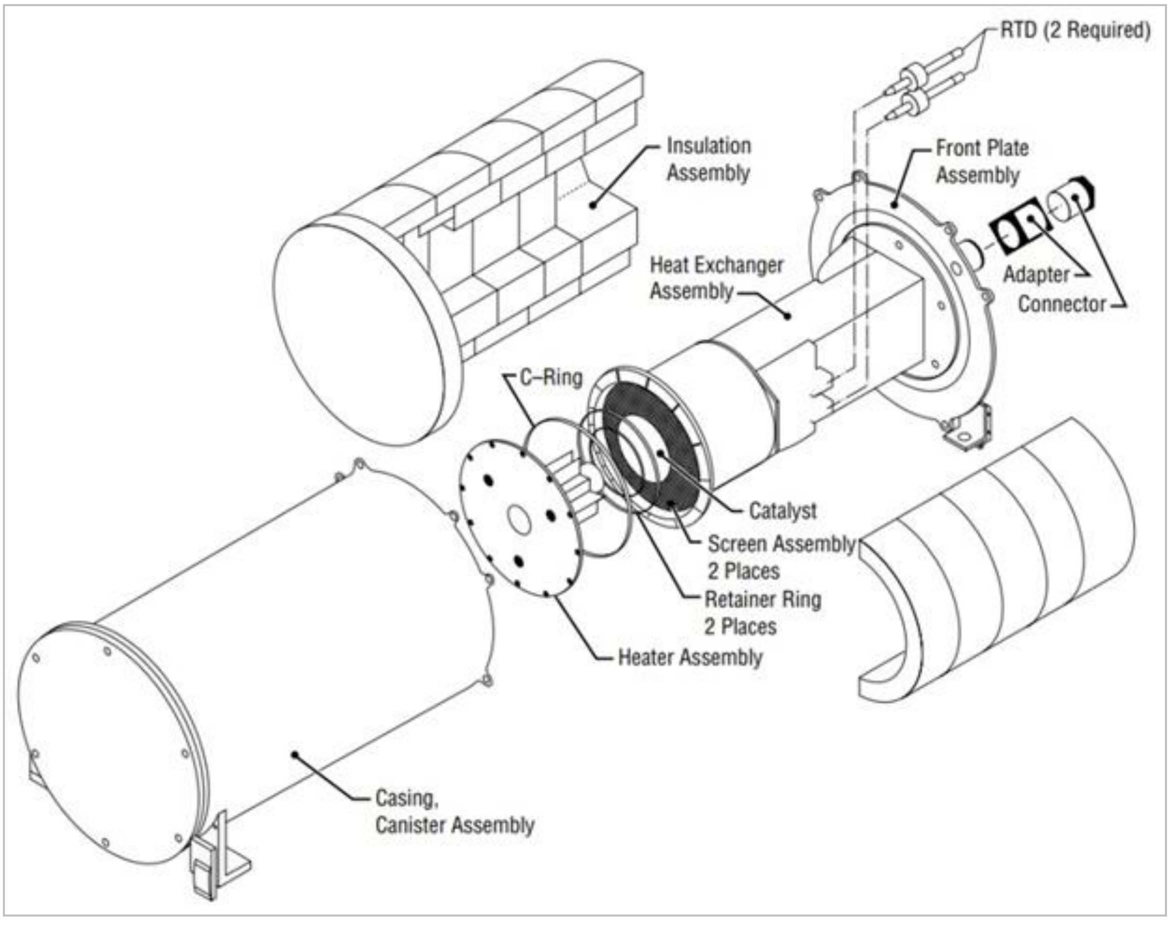
Appendix 1.9: One 4BMS ORU with one desiccant and one CO_2 adsorbent bed [12]



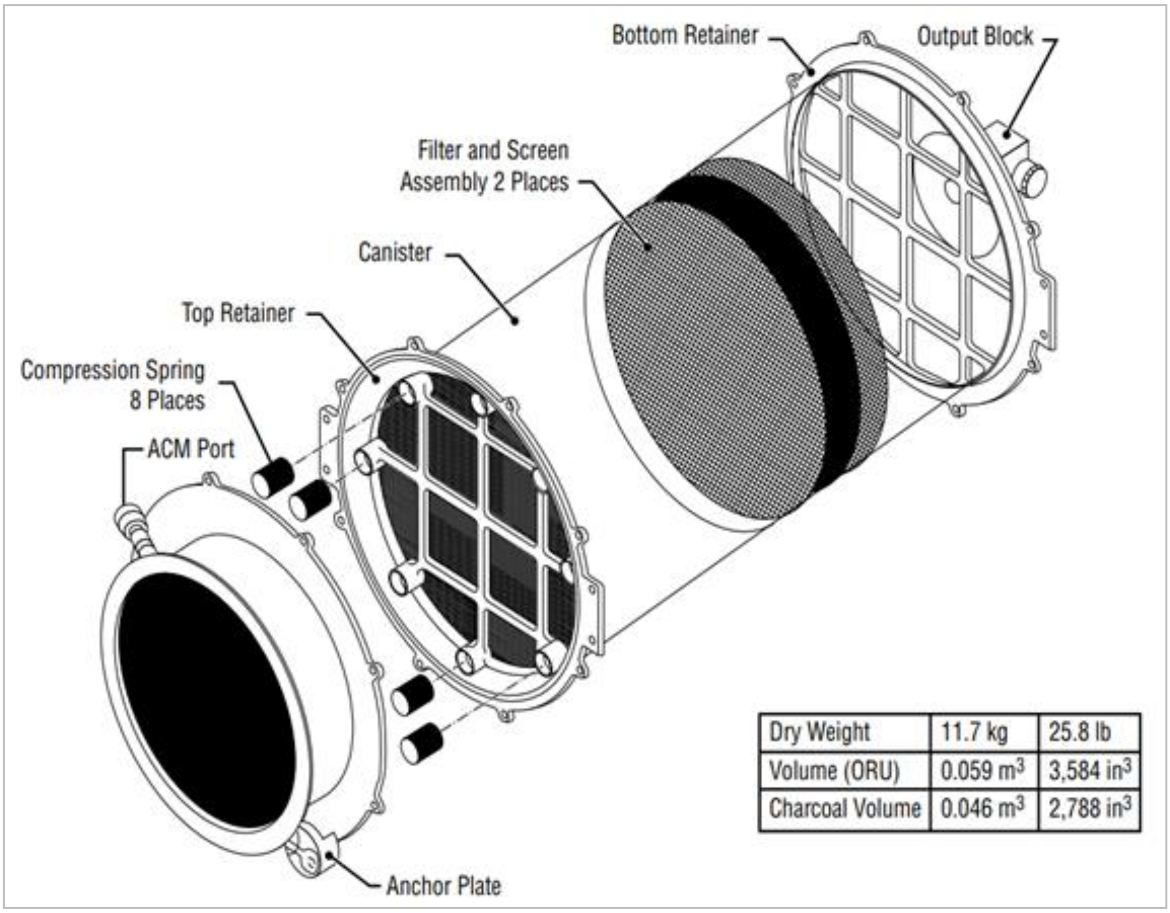
Appendix 1.10: USOS air revitalization rack packaging [12]



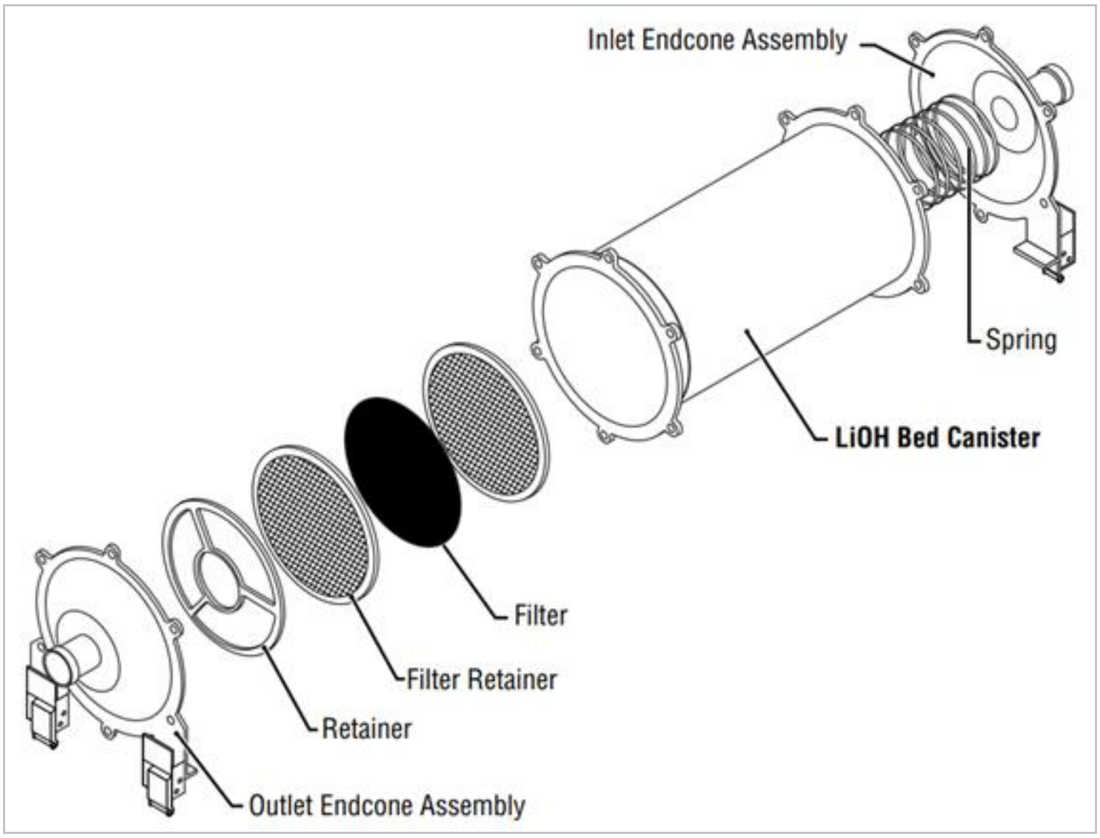
Appendix 1.11: Diagram of the USOS air revitalization subsystem [12]



Appendix 1.12: Charcoal bed assembly of the TCCS on ISS [12]



Appendix 1.13: Catalytic oxidizer assembly of TCCS on ISS [12]

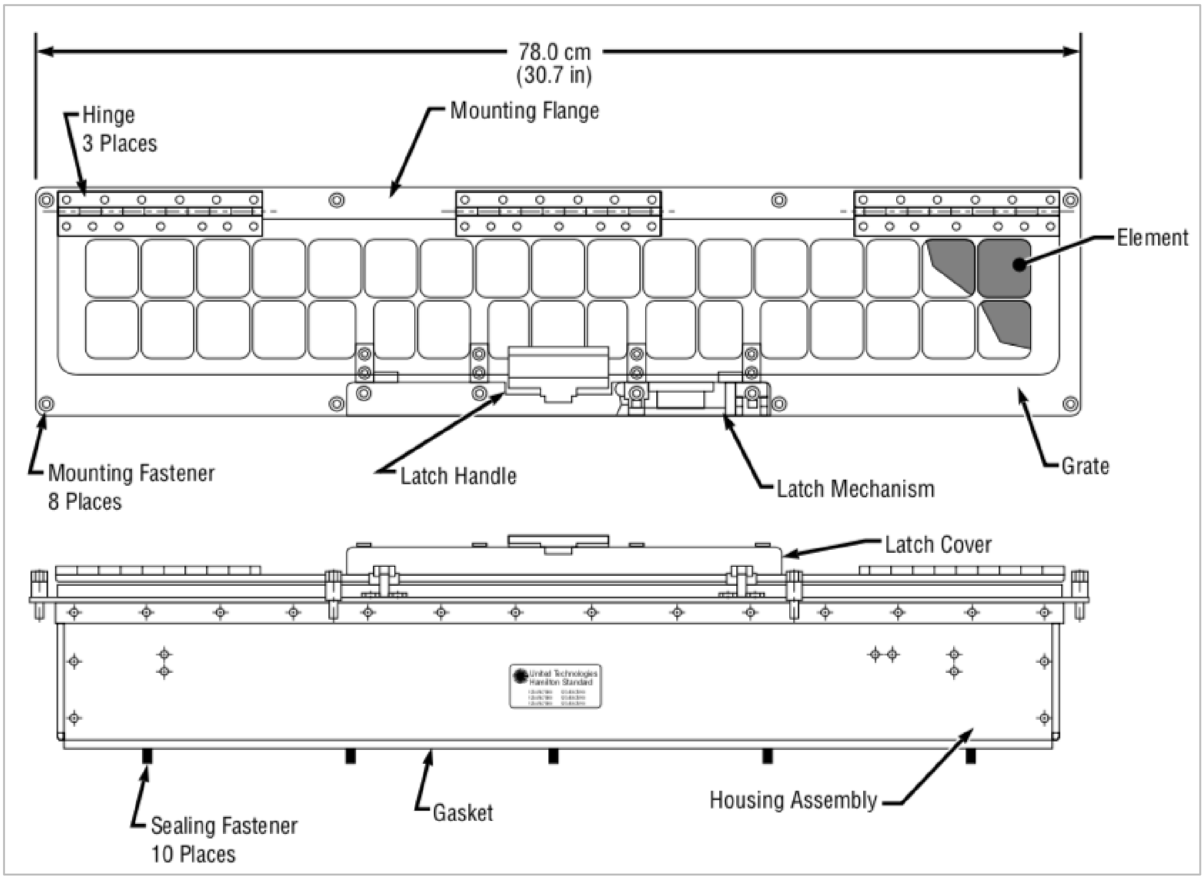


Appendix 1.14: LiOH bed assembly of the TCCS on ISS [12]

Contamination Group	Removable by Means of		
	Activated Charcoal	Chemisorption	Catalytic Oxidation
1 Alcohols	X		X
2 Aldehydes	X	X	X
3 Aromatics	X		X
4 Esters	X		X
5 Ethers	X		X
6a Halocarbons, low b.p.[a]	Non-Removable		
6b Halocarbons, high b.p.[a]	X		
7a Hydrocarbons, low b.p.[a]			X
7b Hydrocarbons, high b.p.[a]	X		X
8 Ketones	X		X
9a Ammonia		X	
9b Acetonitrile	X		X
9c Carbon Monoxide			X
9d Dimethyl Sulfide		X	
9e Hydrogen Sulfide		X	
9f Hydrogen			X
9g Ozone		X	X
9h Sulfur Dioxide		X	
9i Nitrogen Dioxide		X	
9j Nitrogen Monoxide		X	

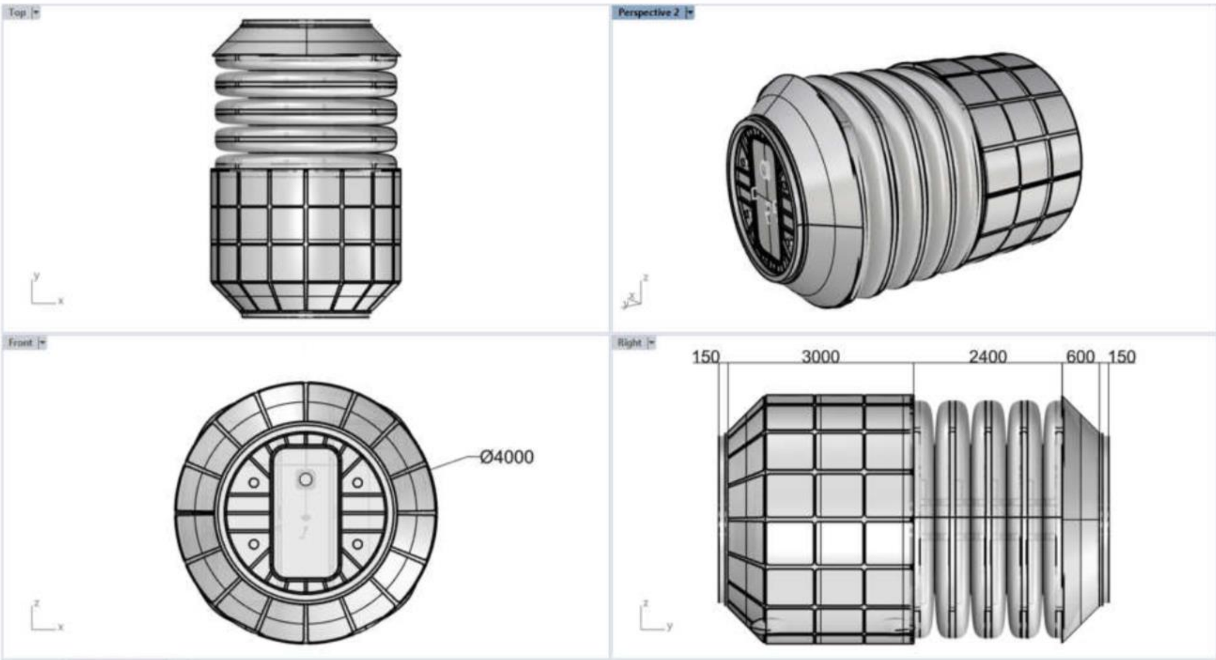
[a] b.p.: boiling point

Appendix 1.15: Possibilities for trace contaminant removal [92]

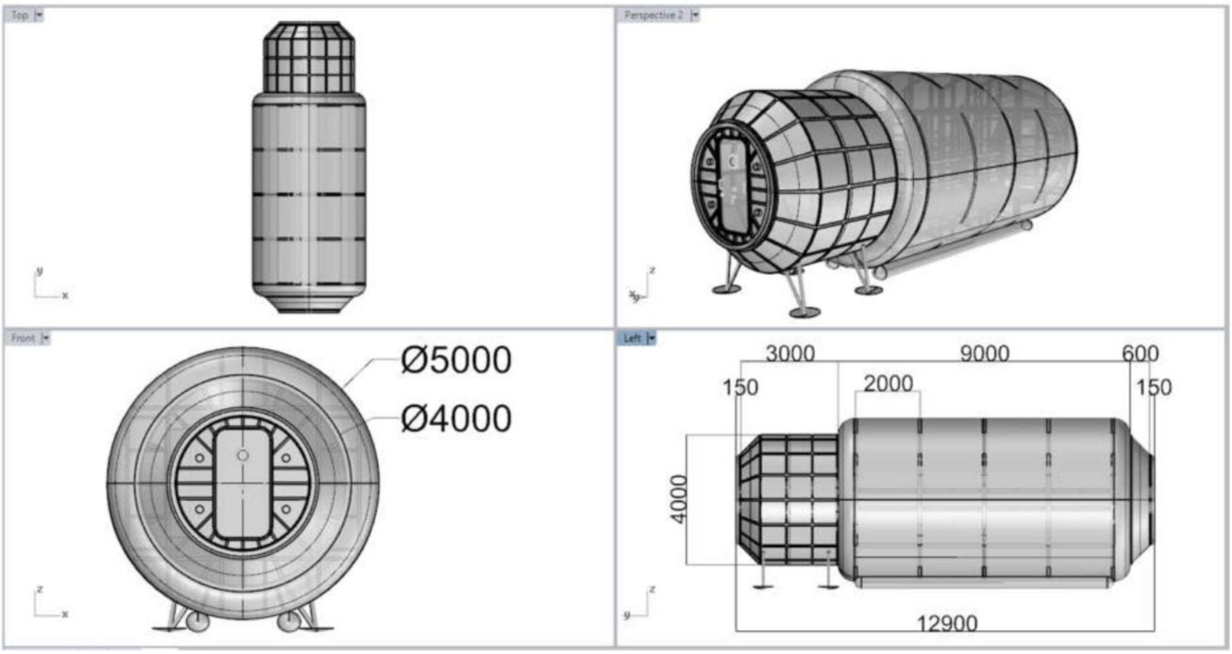


Appendix 1.16: HEPA filter assembly on ISS [12]

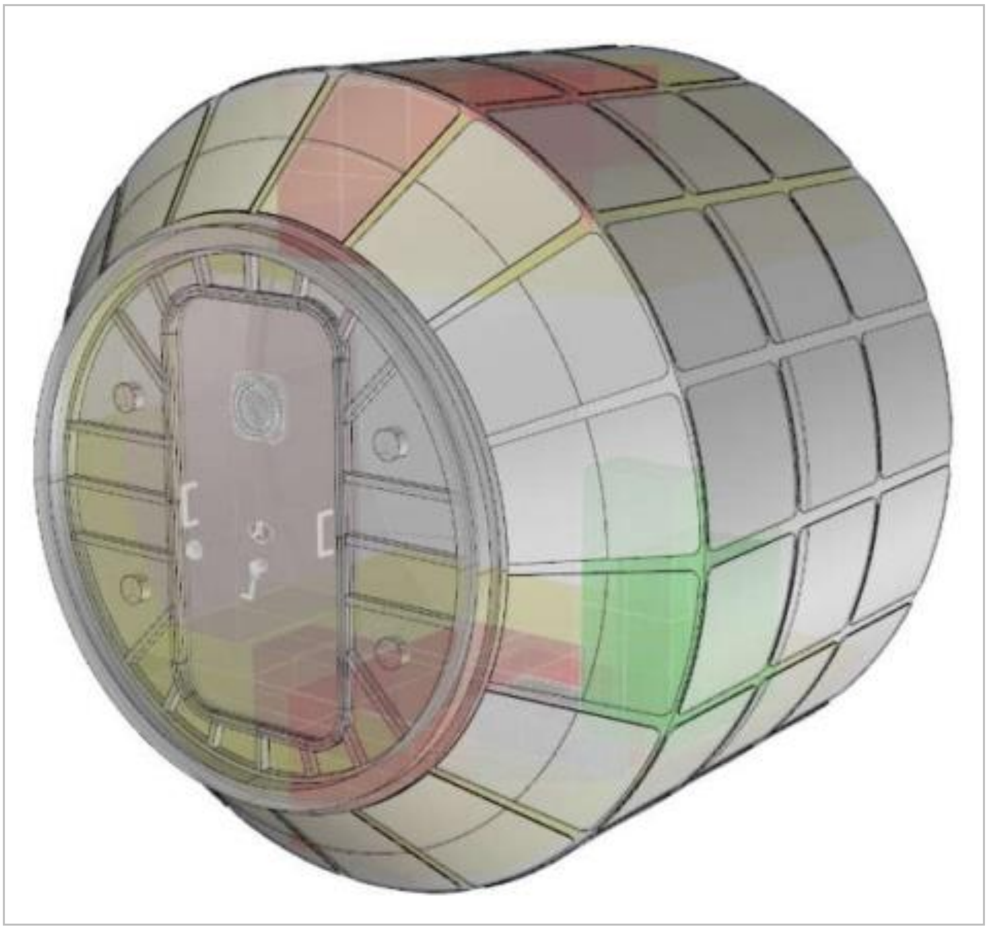
2 Appendix: Preliminary design of the EDEN Next Gen



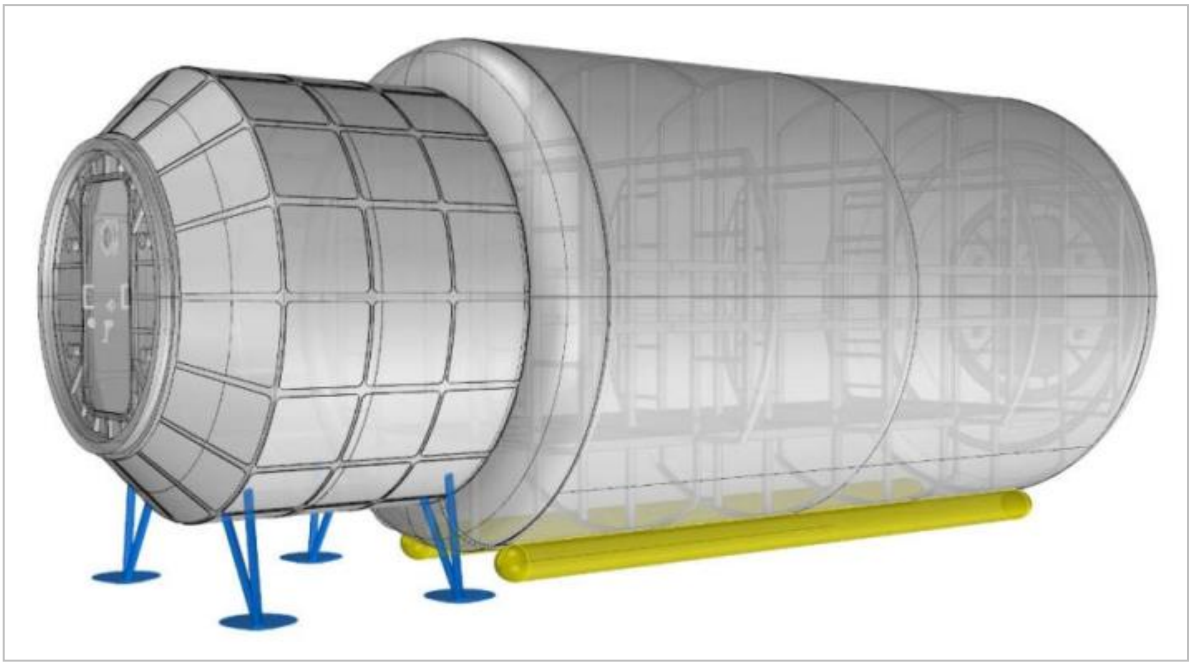
Appendix 2.1: Dimensions of the stowed greenhouse module [5]



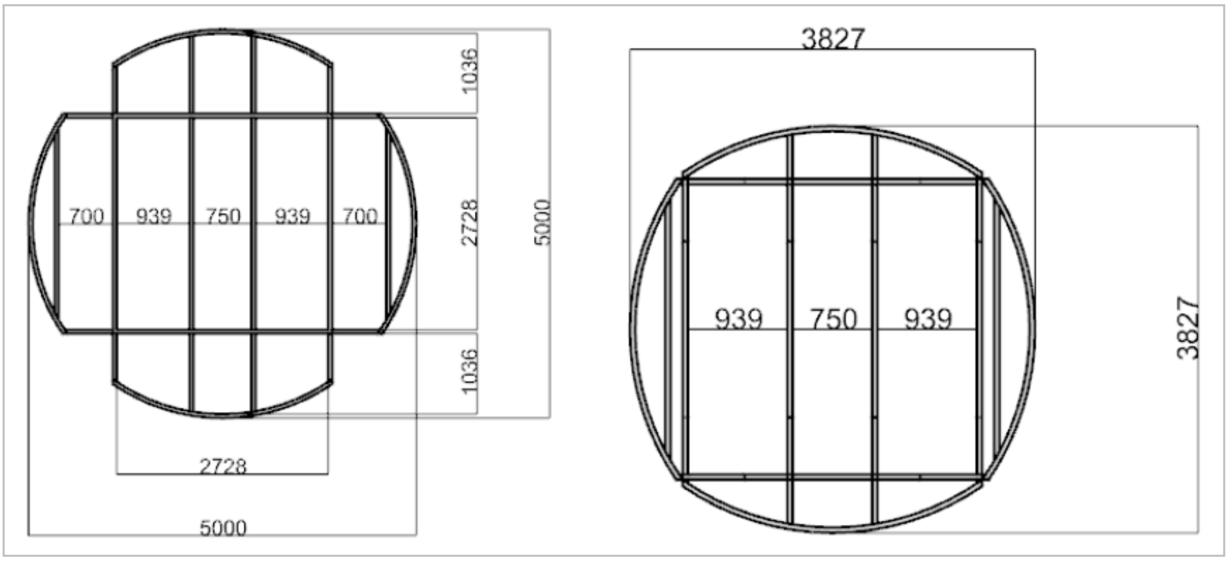
Appendix 2.2: Dimensions of the deployed greenhouse module [5]



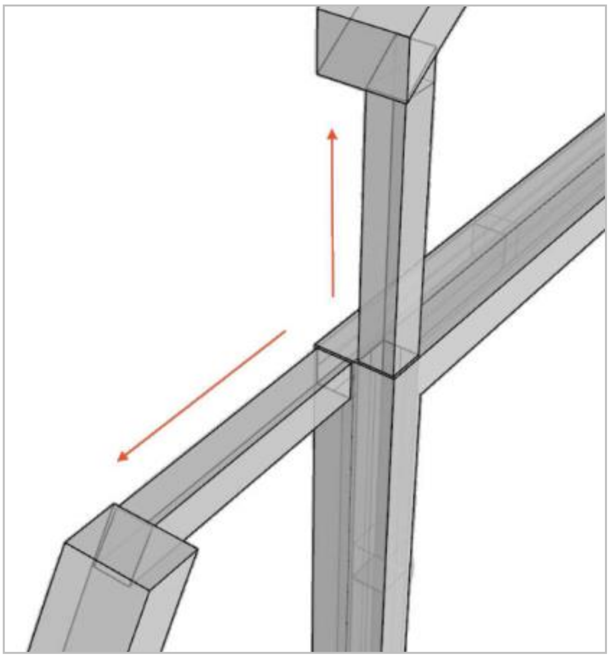
Appendix 2.3: CAD model of the primary rigid core [5]



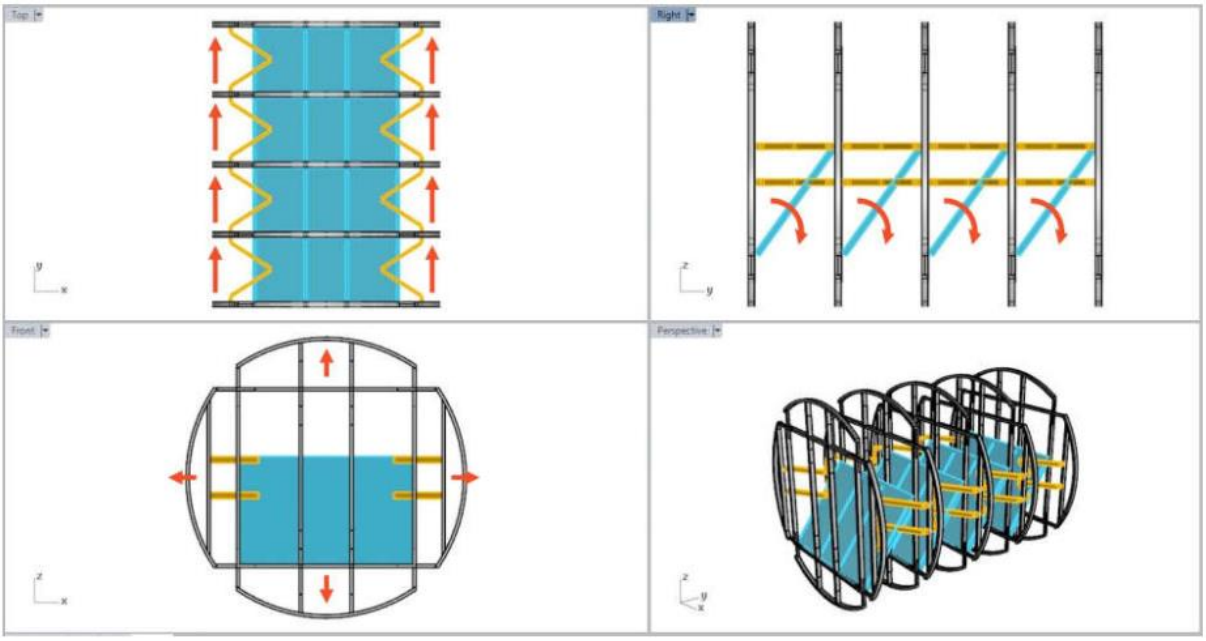
Appendix 2.4: Supports for the greenhouse module structure (blue: legs; yellow: pillows) [5]



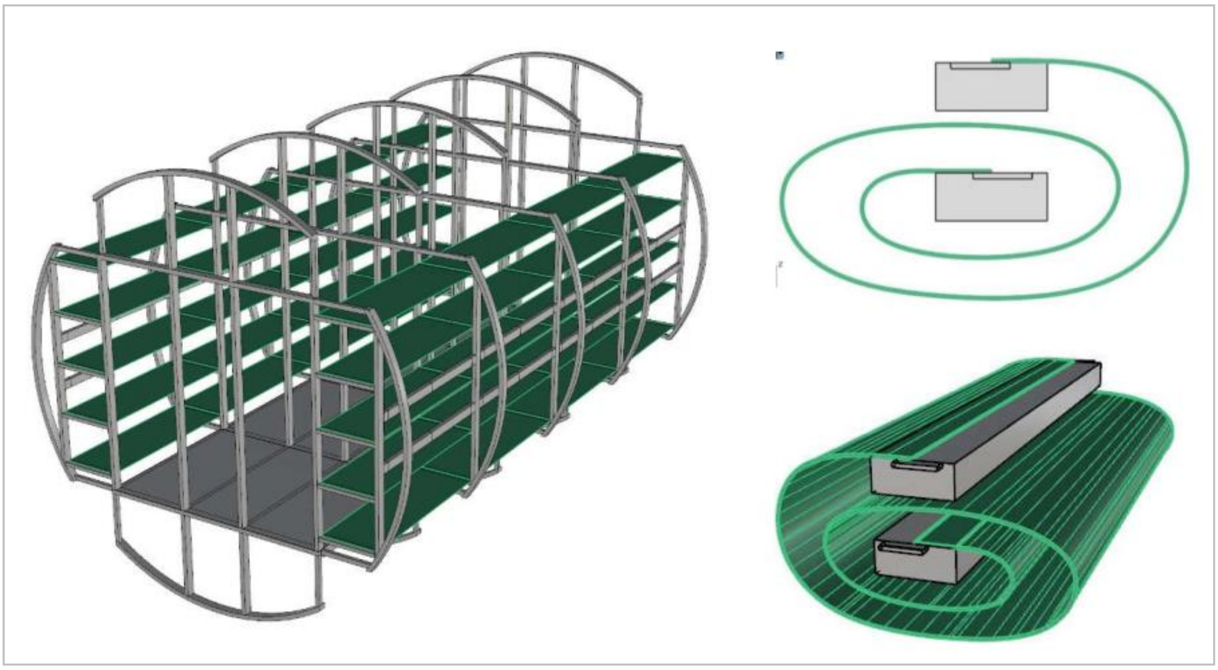
Appendix 2.5: Design of the rigid frames (left: deployed; right: stowed) [5]



Appendix 2.6: Telescopic geometry of the flanges [5]



Appendix 2.7: Secondary structure (dark blue: floor panels; light blue: longerons; yellow: spacers) [5]



Appendix 2.8: Shelves (left: installed in the greenhouse; right: stowed) [5]

3 Appendix: Tables of requirements

Requirements are partly adopted from [5] and [46], and adapted to a space environment as well as adjusted to the different conditions.

Appendix 3.1: Support infrastructure functional requirements

ID	requirement	comment
FR-SI-01	The greenhouse, habitat and all other modules etc. are launched from earth, transported and touched down at final destination by any other system.	At this thesis SpaceX's Falcon 9 launcher is chosen for now.
FR-SI-02	The habitat provides all necessaries to inflate the greenhouse module.	Not specified so far.
FR-SI-03	Inflatable support (two `pillows`) underneath the greenhouse shall be inflated by the habitat.	Inflatable support pillows maybe only for a certain, short amount of time. This guarantees a quick and save transit to operation mode. For long term it should be thought about another solution to avoid a permanent monitoring which comes along with complexity.
FR-SI-04	The greenhouse module shall have a thermal and electrical interface to the main habitat, allowing power transfer and thermal heat load transfer.	---
FR-SI-05	The habitat supplies continuously electrical power with *(tbd)* kW at 230 VAC (three phase; 50 Hz).	Supplying all subsystems and other electrical power consuming components.
FR-SI-06	The atmosphere for pressuring the greenhouse module shall be supplied by the habitat.	---
FR-SI-07	The greenhouse module shall allow resources to be transported between the habitat and the greenhouse module, via piping (FR-SI-08; FR-SI-09; FR-SI-10) and airlock tunnel as well as harness for data (FR-SI-11; FR-SI-14) and power (FR-SI-05).	---
FR-SI-08	The habitat shall provide *(tbd)* $\frac{l}{day}$ of potable water.	Required for the NDS to supply the plants.
FR-SI-09	The habitat provides between *(tbd)* $\frac{l}{day}$ to *(tbd)* $\frac{l}{day}$ of waste-water to the C.R.O.P. system to produce nutrient solutions.	In exchange for water which leaves the greenhouse by biomass.
FR-SI-10	The habitat absorbs up to 4.92 $\frac{kg}{day}$ O_2 (0.82 $\frac{kg}{day\ person}$ [51]) and supplies up to 6.24 $\frac{kg}{day}$ CO_2 (1.04 $\frac{kg}{day\ person}$ [51]) from/to the greenhouse module.	Six crew members are assumed. O_2 output of the plants reaches from 0 $\frac{kg}{day}$ (before germination) to 0.914 $\frac{kg}{day}$ (fully cultivated) which requires an additional O_2 source for the habitat. CO_2 uptake of the plants reaches from 0 $\frac{kg}{day}$ (before germination) to 1.266 $\frac{kg}{day}$ (fully cultivated) which requires an additional CO_2 disposal. For more details see chapter 4.5.1.1.
FR-SI-11	The habitat provides a two-way communication link to earth mission control, for transfer of data and video communications.	To transfer monitored parameters, experimental data and video (max. data rate of 150 kbit/s).

ID	requirement	comment
FR-SI-12	The habitat shall provide storage for seeds, failed components, spare components, cleaning wipes, laboratory gloves and other analysis consumables e.g. for food quality and safety analysis.	All supplies and waste generated by greenhouse have to pass the habitat.
FR-SI-13	The habitat shall provide storage for produced food.	---
FR-SI-14	An acoustic alarm shall be sound in the habitat if there is smoke/fire in the greenhouse or CO_2 or O_2 levels exceed/falls below their pre-defined limits.	---

Appendix 3.2: Overall greenhouse module requirements

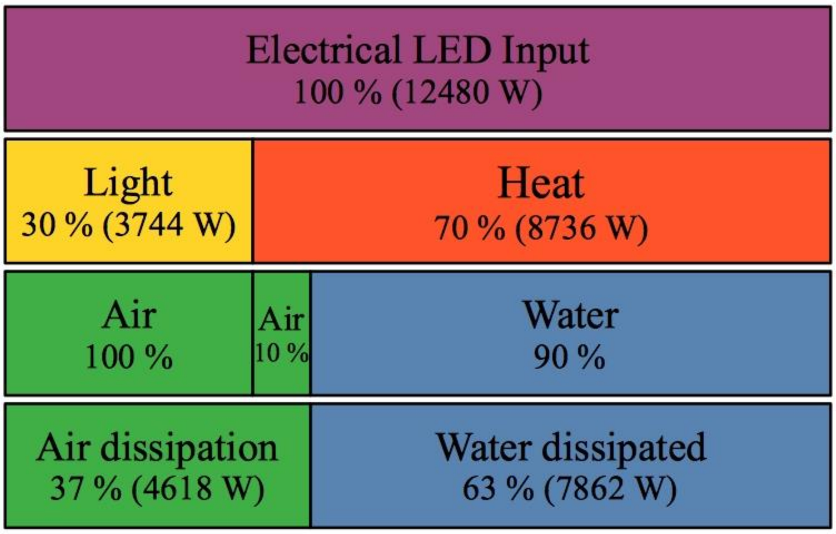
ID	requirement	comment
FR-GHM-01	Max. dimensions including service vehicle and protection cover of the greenhouse module shall not exceed the following: - truncated cone-shaped part: diameter 5.2m – 1.3m x height 4.8m - cylindrical part: diameter 5.2m x height 6.6m	The dimensions are the maximum payload fairing dimensions of a Falcon 9 launcher. (single launch) [45] The cover protects the greenhouse module against debris and radiation during transfer.
FR-GHM-02	The total mass of the final integrated greenhouse module including all installed systems, loose content and consumables as well as the service vehicle and the protection cover shall not exceed 22,800 kg.	The mass is the maximum payload launch mass of a Falcon 9 launcher to LEO. (single launch) It is assumed that a transfer vehicle will be assembled in LEO. [45]
FR-GHM-03	The greenhouse module including all pre-installed equipment shall withstand launch loads as well as loads during transfer and landing on the planetary surface. It shall also withstand the loads which might occur due to the regolith layer.	g forces: *(tbd)* acoustic forces: *(tbd)* thermal loads: *(tbd)* loads due to regolith layer: *(tbd)*
FR-GHM-04	The greenhouse module shall be fully operational at an external ambient temperature of $T_a = 254\ K$.	Expected temperature in Moon environment after covering the greenhouse module with a regolith layer $t_R \geq 0.3\ m$. [47, 48, 49]
FR-GHM-05	The greenhouse module shall be operational for at least two years without resupply except from habitat.	Resupply from habitat includes mainly CO_2, power, nutrients, manpower, spare parts, seeds.
FR-GHM-06	The greenhouse module shall be sectioned in: - 2 airlocks (FR-GH-07) - 1 service section (FR-GH-08) - 1 cultivation area (FR-GH-09)	---
FR-GHM-07	The airlocks shell be standardized airlocks to be flexible in the overall setup. The crew access shall be achieved by doors of at least 1.6 m height and 0.8 m width.	The greenhouse module shall allow connection to other modules on both ends for variable habitat configurations.

ID	requirement	comment
FR-GHM-08	The greenhouse module shall house the following required subsystems in the service section: - air management system (AMS) - nutrient delivery system (NDS) - power distribution system (PDS) - command and data handling system - thermal control system - desk, chair and locker - general storage facility - sink - safety equipment - C.R.O.P.	- workspace for pre- and post-processing of the plants - storage for various equipment
FR-GHM-09	The cultivation area shall have a minimum area of 25 m^2 (60% leafy plants and 40% tall growing plants).	The cultivation area shall be at least twice as large as at the EDEN ISS MTF.
FR-GHM-10	For the selected crops the greenhouse module shall provide vital resources supply within defined acceptable ranges and quality including the following: - water - macro- and micro-nutrients - O_2 - CO_2 - illumination	Detailed data on the acceptable ranges is found at the requirements of the specific subsystem.
FR-GHM-11	The greenhouse shall provide means to manage produced wastes, such as: - depleted growth media - inedible plant material - depleted nutrient solution/ waste water - waste gas	C.R.O.P. processes wastes from habitat and greenhouse for using them at the nutrient delivery.
FR-GHM-12	The greenhouse module shall reduce debris and dirt to a minimum and allow cleaning with water with subsequent water removal.	---
FR-GHM-13	The greenhouse module shall allow easy access to each component to guarantee quick repair and maintenance.	- only short shutdowns - ensure continuous plant production - keep component replacement and maintenance as simply as possible (e.g. no need to remove other components)
FR-GHM-14	The overall noise level of the greenhouse module shall be within the range of European work regulations (concrete values at [50]).	---
FR-GHM-15	The greenhouse module shall provide fire detection and suppression.	---
FR-GHM-16	The greenhouse module shall provide contingency equipment for breathing in case of a fire.	---
FR-GHM-17	The greenhouse module shall be one failure tolerant for functions relevant to keep the plants or crew alive.	---
FR-GHM-18	Piping and harness diameters shall be similar among all parts of all subsystems.	To limit the number of connectors/interfaces.
FR-GHM-19	The level of autonomy shall be at least equal to EDEN ISS.	Harvesting, seeding etc. conducted by the crew.

Appendix 3.3: Detailed functional requirements AMS

ID	requirement	comment
FR-AMS-01	The AMS shall monitor and control the inside temperature and the inside relative humidity within the following ranges (measurement at different significant locations of the greenhouse module): - temperature 16 °C - 30 °C (accurate to a set point of ± 0.5 K) - relative humidity 70 % - 100 % (accurate to a set point of ± 1 %)	Temperature and rel. humidity controlled at level required for successful plant growth as well as acceptable for human comfort. In addition, rel. humidity controlled such that dew point does not lead to condensation on internal surfaces (risk of microbial and fungal growth).
FR-AMS-02	The AMS shall monitor and control the inside O_2 and CO_2 concentration as well as the inside total pressure within the following ranges (measurement at different significant locations of the greenhouse module): - CO_2 concentration 350 ppm – 5000 ppm (accurate to a set point of ± 50 ppm) - O_2 concentration 21 % - 24 % (accurate to a set point of ±1 %) - total pressure 101.3 kPa (accurate to a set point of ± 10 kPa)	Chosen for optimal plant growth.
FR-AMS-03	The AMS shall monitor and control the air flow rate and air flow velocity at the plants within the following ranges (measurement at different significant locations of the greenhouse module): - air flow rate that is required to guarantee a safe environment for plants and humans (determined later) - air flow speed at plant 0.3 m/s – 0.7 m/s (accurate to a set point of ± 0.1 m/s)	Chosen for optimal plant growth.
FR-AMS-04	The AMS shall monitor and control the ethylene level within the defined range, and limit the level of all other VOC, odor, the microbial load, and the airborne particles (measurement at different significant locations of the greenhouse module): - ethylene level below 50 ppb - minimize all other VOC - minimize odor - minimize microbial load - minimize airborne particles	Chosen for optimal plant growth.
FR-AMS-05	The AMS shall be designed to exchange gases with the habitat.	- CO_2 from habitat to greenhouse module - O_2 from greenhouse module to habitat
FR-AMS-06	The AMS shall allow easy access to each component of the AMS to guarantee quick maintenance.	- only short shutdowns - ensure continuous plant production - keep component replacement and maintenance as simply as possible (no need to remove other components)

4 Appendix: Light and heat power distribution of LED panels



Appendix 4.1: Light and heat power distribution of LED panels (generated with data from [81])