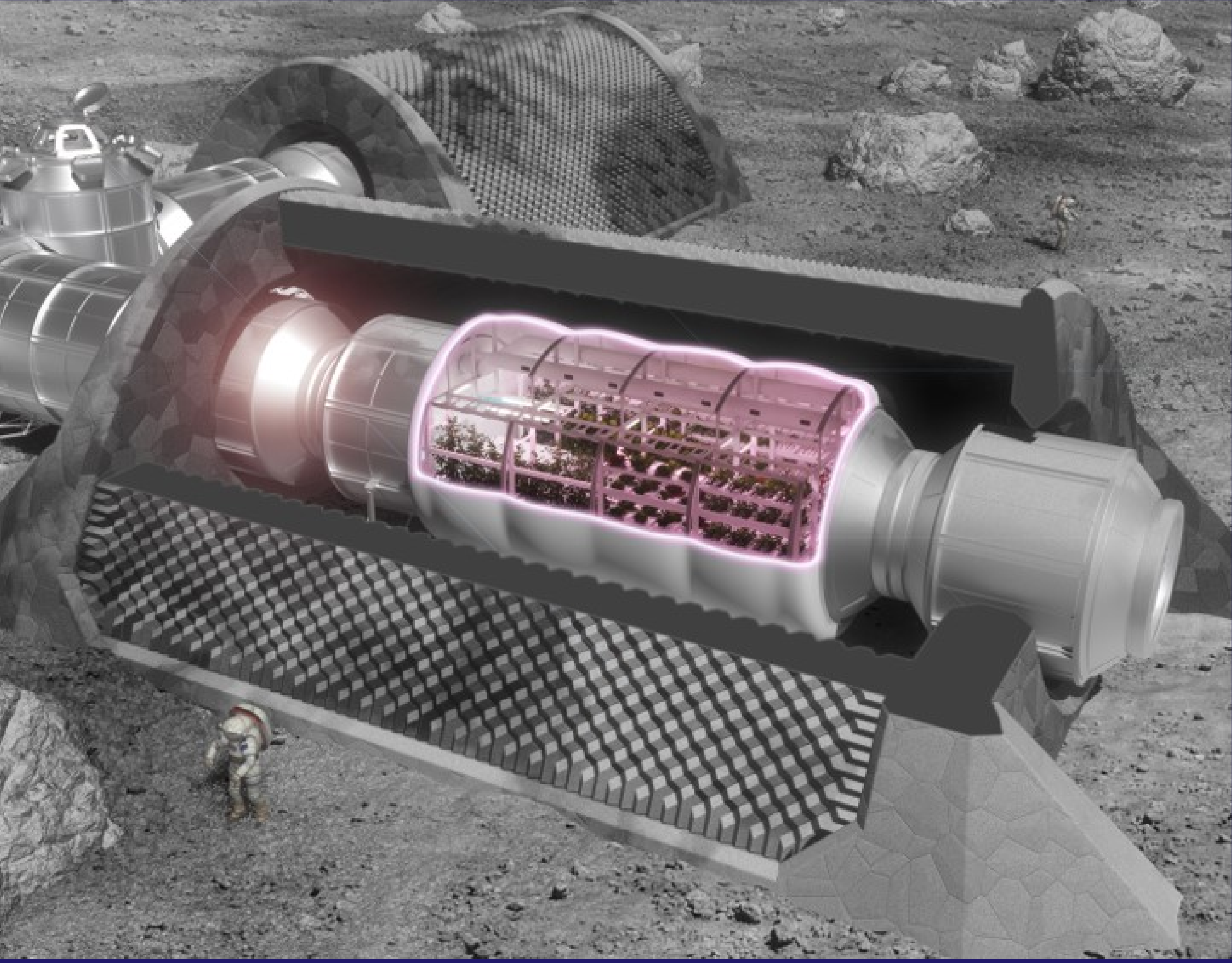

Technische Universiteit Delft

Masterthesis

Design of the Nutrient Delivery System for the EDEN NextGen Greenhouse Module

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TUDelft

Masterthesis

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by

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Project duration:	March 01st, 2021 – November 29, 2021	
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Cover image by the institute of space systems of the German Aerospace Center in Bremen

Abstract

Completely regenerative life support systems are essential to the long-term exploration of far-off locations in space. The shift from physico-chemical to bio-regenerative life support systems has the potential to be a major step towards that goal. The cultivation of plants as part of such a system not only provides life support functions and fulfills the dietary needs of the crew, but it also favorably affects human psychology. To maximize these benefits, a potential greenhouse module needs to provide a completely controlled environment for the plants. In this thesis, the Nutrient Delivery System, which is responsible for the root environment for a greenhouse module on the Moon, is designed.

The result is an aeroponic cultivation system supplying two different nutrient solutions of independent compositions to a total growth area of 30.8 m^2. The distribution can be adapted depending on the respective share of plant species. The important parameters to enable a favorable root environment for plants including the necessary technological capabilities are discussed. For the aeroponic system, diaphragm pumps are chosen that operate at a pressure between 7.6 and 10 bar. They are supported by accumulator tanks reducing pressure spikes and the required number of pump cycles, thus increasing pump lifetime. To provide the optimal root conditions with a minimum of required crew time, the electrical conductivity and the pH are measured and adjusted automatically. Two 550 l tanks are used to store premixed nutrient solutions and are refilled automatically from storage containers. Microbes in the nutrient solution are eliminated by an ozone concentration of 1-3 mg/l. The System is designed to operate autonomously for one month at a time. A preliminary selection of components results in acquisition costs of roughly 32 000 €, a mass of around 612 kg and a power consumption of 650 W.

The design decisions and key parameters established in this thesis provide a foundation for the execution of the project and its potential far-reaching benefits. As such, the nutrient delivery system design presented here may play a small part in helping to establish self-sufficient settlements in outer space.

Contents

List of Abbreviations

AHP	Analytic Hierarchy Process
AMS	Atmosphere Management System
APS	Aeroponic System
CE	Concurrent Engineering
DFT	Deep Flow Technique
DLR	German Aerospace Center
dO	dissolved Oxygen
EC	Electrical Conductivity
EDEN	Evolution and Design of Environmentally-closed Nutrition-sources
EG	Exploration Greenhouse
ESA	European Space Agency
ESM	Equivalent System Mass
EU	European Union
FEG	Future Exploration Greenhouse
GHM	Greenhouse Module
ISS	International Space Station
LED	Light Emitting Diode
MELiSSA	Micro-Ecological Life Support System Alternative
MTF	Mobile Test Facility
NASA	National Aeronautics and Space Administration
NDS	Nutrient Delivery System
NEV	Normalized Eigenvector
NFT	Nutrient Film Technique
NS	Nutrient Solution
pH	potential Hydrogen
pOH	potential Hydroxide
PTFE	Poly (Tetra Fluoro Ethylene)
PVC	Polyvinyl chloride
SES	Service Section
TBC	To Be Confirmed
TBD	To Be Determined
TRL	Technology Readiness Level
UV	Ultra-Violet
VPD	Vapour Pressure Deficit

List of Symbols

Symbol	Description
A	Area
CI	Consistency index
CR	Consistency ratio
$C_€$	Cost in Euro
D_P	Pipe diameter
D_{Drop}	Droplet size
D_{NO}	Nozzle orifice size
EC	Electrical Conductivity
g_M	Moon gravity
L_{eq}	Equivalent fitting length
L_p	Pipe length
m	Mass
M_H	Hydrogen molarity
p	Pressure
Δp	Pressure difference
P	Power
Q	Flow rate
RI	Random index
t	Time
$t_{1/2}$	Half-life
T	Temperature
V	Volume
$V_D D$	Draw down capacity
v_F	Flow velocity
ρ	Mass concentration
ρ_{NS}	Nutrient solution density
ζ	Resistance coefficient

1 Introduction

By mutual influence of science and popular culture on each other, the interest in human space exploration is increasing. The redirection of funds from the National Aeronautics and Space Administration (NASA) from the International Space Station (ISS) project to further exploration of the Moon and Mars by the year 2025 [1] is an indicator for ever-increasing mission duration and distances to Earth and the, therefore, increasing costs for potential resupply missions. Establishing self-sufficient settlements for long-term human occupation requires life support systems capable of regenerating all essential resources for survival [2, 3]. Therefore, the transition from traditional physico-chemical to bio-regenerative life support systems has been subject to scientific studies all over the world for many decades [4]. Examples include Russia's Bios3 facility [5], NASA's bio-regenerative life support systems test complex (BIO-Plex) [6] or the Micro-Ecological Life Support System Alternative (MELiSSA) project of the European Space Agency (ESA) [7, 8]. Compared to their physico-chemical counterparts, bio-regenerative systems use processes as found in ecosystems here on earth to accomplish the given tasks. More on this topic can be found in an extensive literature study previously conducted on the subject [9]. Besides the usual tasks of life support systems on previous or current space stations, the production of food for the crew on site can have a large impact on the required resupply mass and the psychological well-being of the crew [2].

As an essential part of such systems, the cultivation of plants or algae in space environments does not only reduce the resupply-need for food but also helps with other important life support tasks like waste processing, water recycling, and air revitalization [5, 7, 10, 11]. In the ESA roadmap [2] one of the key open questions to supporting life in hostile environments is identified as: "What are the best (and most sustainable) cultivation systems and technologies to maximize plant growth and productivity on the ground and in space?" At the German Aerospace Center (DLR) these research areas were investigated at the Institute for Space Systems in Bremen since 2011 within the "Evolution and Design of Environmentally-closed Nutrition-sources (EDEN)" initiative. To study these plant production systems in harsh environments, and gather implications for their use in space, the Mobile Test Facility (MTF) was developed within the EDEN ISS project at DLR in Bremen. This greenhouse module showcases the possibility to cultivate plants even in the most hostile and remote environments like Antarctica, reassembling conditions of outer space in many ways [12]. The lessons learned here can be applied to the design of a new greenhouse module generation designed for use in space and on other planetary bodies. Due to the harsh conditions of outer space and the high risks in case of failure, the plant environment needs to be monitored and controlled precisely [10]. The EDEN NextGen project is a concept for the deployable controlled environment plant growing chamber of a bio-regenerative life support system and the successor of the EDEN ISS Greenhouse Module (GHM).

To provide optimal growing conditions for the crops, a range of subsystems need to be designed. Currently, a preliminary design for the overall structure, as well as the technical budgets for the individual subsystems have been developed in a concurrent design study in 2019. One of these subsystems is the Nutrient Delivery System (NDS). It is responsible to preserve a specified root environment for the plants. To provide a versatile diet to the crew, the nutrient supply for the roots needs to be designed such that it can adapt to different plants and their respective growing cycles. The main goal of this thesis is the initial design of such a system. Since so far only one other subsystem – the Atmosphere Management System (AMS) – has been designed to some degree, the result will be a preliminary design including recommendations on design aspects dependent on other subsystems. Further iterations may be necessary once all designs are completed. Therefore, the research questions that will be addressed in the following thesis can be defined as:

How can a consistently favorable root environment for plants be ensured in a deployable greenhouse for the Moon?

What cultivation method is best suited for this purpose and how can it be implemented into the given preliminary design?

What components are needed to make the root environment for the plants dependable?

How can the key factors be controlled and monitored?

How could the operational phase of the system look like?

The approach to answering these questions is visualized in the flowchart in Figure 1.1. First, a basic understanding of plant cultivation needs to be developed. The environmental factors affecting the root zone are analyzed and potential technical solutions are introduced. From there, the state of the art of plant production chambers for space as well as commercial use on Earth is analyzed. The focus is put on the specific tasks and components of the NDS and different approaches that have been utilized to fulfill them. Special attention is given to the EDEN ISS project with the MTF, as it is the predecessor for the design. The relevant insights and lessons learned are then collected to be used in the requirement generation in Chapter 3.

In Chapter 3 the state of the preliminary design of the EDEN NextGen is analyzed. All assumptions that have been made during the thesis work are collected and a preliminary functional risk analysis that will be expanded to the component level at the end of the design phase is conducted. This information is then translated into requirements which are expanded based on stakeholder needs and other sources like the collected lessons learned. These are converted into weighted selection criteria using the Analytic Hierarchy Process (AHP).

In Chapter 4 concepts for each desired functionality are gathered in a design option tree. Components that have been identified as unproblematic and do not yield the potential to enhance the system performance based on the selected criteria are adapted from the MTF. The others are reevaluated in a classical trade-off table using the weighted selection criteria. Finally, a functional architecture is developed for the component sizing.

The next step is the detailed design of the individual components in Chapter 5. Quantitative relations between the requirements, set-points and design dependant parameters are established. Then the working ranges for the individual components are determined and compared to commercially available products. The design phase is concluded by fitting the components into the preliminary structural design of the greenhouse module and an estimation of the technical budgets. Finally, the requirements are verified and an outlook on the operational phase is given including the modes of operation and a final risk and dependability analysis. The thesis is concluded by a summary of the results and recommendations for future work.

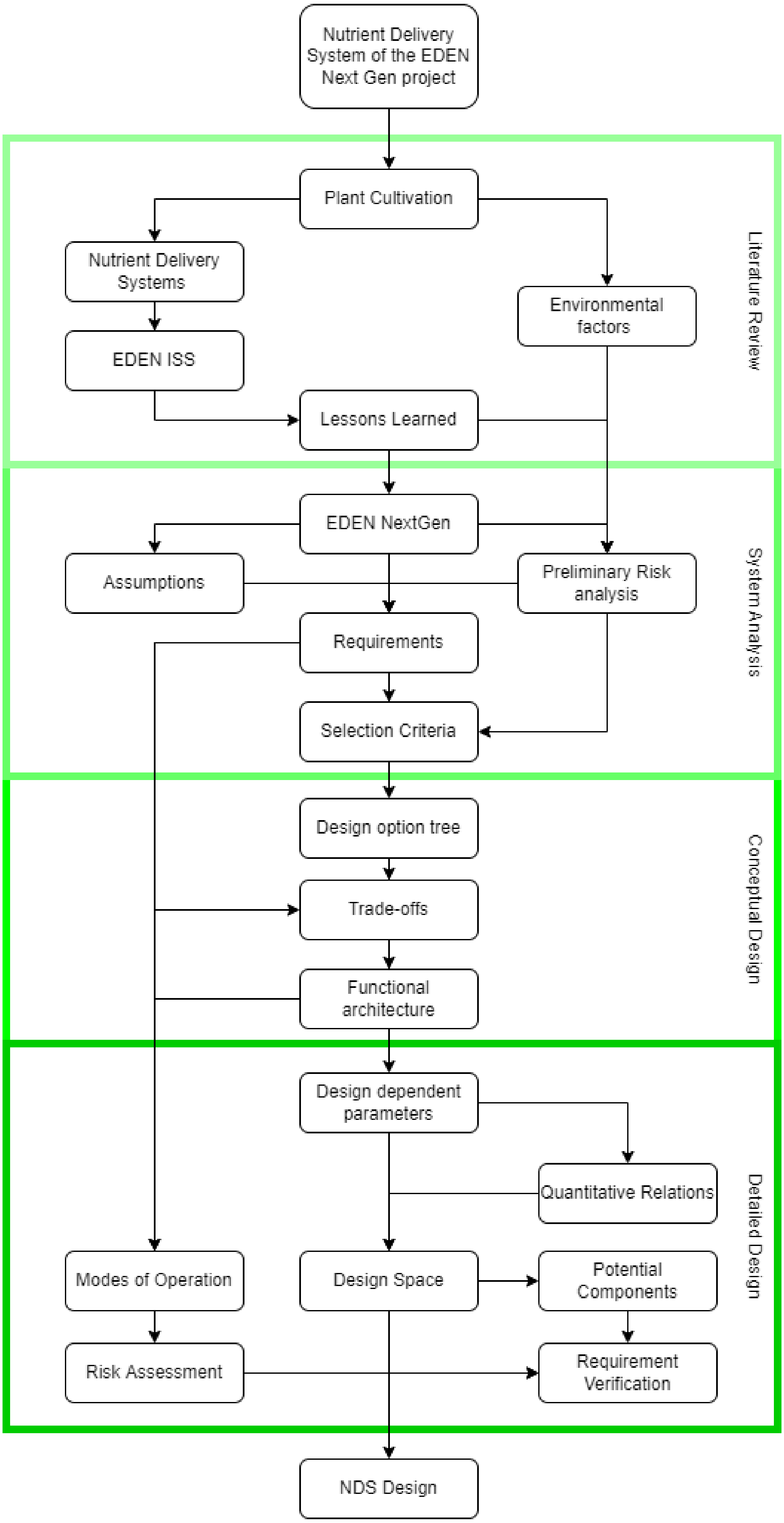

Figure 1.1: The methodology used in this thesis project to design the EDEN NextGen nutrient delivery system.

2

Plant Production for Space

The production of plants has a variety of benefits for long-term human space missions. An adult person's daily food intake is about 0.64 kg dry mass or 1900 to 3200 kilo-calories [13, 14]. But plants do not only contribute to food production. In the semi-closed ecosystem facility Bios 3, a 13 m^2 sowing area was sufficient to provide 35 % of a person's food, while the entire oxygen need of that person is covered by the plants' photosynthesis [5]. According to more conservative estimates growing 50 % of the crew's diet on-site is sufficient to convert all of the crew's metabolic CO_2 to O_2 [10, 11]. Since more than 95 % of the water taken up by plants evaporates from the leaves in the transpiration process, volatile compounds are filtered out by the plants resulting in the collection of clean condense water. Estimates suggest that growing 50% of the caloric requirements of the crew will suffice to produce all of the required potable water for the crew to drink [10]. Since this water is very pure, water from other sources can be used as technical or irrigation water which does not have to meet the strict requirements for drinking water. Therefore, the system complexity of the wastewater management system can be reduced.

As can be seen in Figure 2.1, these benefits of plant cultivation meet the four most impactful target areas for a reduction in the resupply mass for human spaceflight [5, 8]. Besides the obvious technical aspects, plants have a positive impact on the psychological well-being of the crew [2, 5]. To maximize these benefits in the most efficient way possible, an optimal growth environment has to be created. The required factors are summarized in this chapter with a focus on their implications on the root environment. Subsequently, different ways to create such a root environment are addressed. In addition, the state of the art of NDSs is evaluated with example systems as used in commercial applications, in space, and as prototypes in analog test projects as shown in Table 2.2. Finally, DLRs greenhouse module for the EDEN ISS project, which is located in Antarctica, is examined in detail with a focus on the NDS.

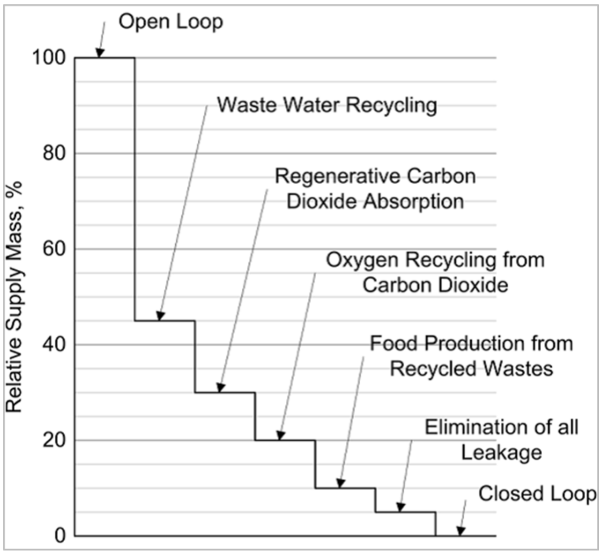

Figure 2.1: Relative supply masses and possible savings by category [14].

2.1. Plant Cultivation

Although plants are adapted to the respective climate they naturally grow in, these usually encountered conditions can be vastly different from the optimal climate conditions [15]. The success of plant growth is generally measured by either fresh or dry biomass, which is essentially determined by the cumulative amount of gas exchange via photosynthesis and respiration over time [16]. The water content or the difference between fresh and dry mass is a factor affecting the taste of the produce. A further measure of success is the harvest rate, which is determined by the ratio between edible and non-edible biomass of the plants.

Aside from the nutrient and water supply, the air quality, composed of the CO_2 and O_2 content, humidity, and airflow, is an important factor for transpiration and gas exchange. Another essential factor for photosynthesis is lighting. Since the mechanisms behind this are not necessary to understand for the purpose of this thesis, only the processes affecting the design of the NDS are analyzed further. For more details on photosynthesis, the reader is referred to Kozai et al [15]. The gravity at the cultivation site might influence the plant production performance as well. However, only little information is available about this topic. Although micro-gravity does not need to be considered here, as the proposed system is designed for use on the Moon or Mars surface, the reduced gravity might still have an impact.

2.1.1. Nutrition

Out of the 92 natural elements, about 60 can be found in plants. 17 of these are essential for plant growth and can not be substituted by other elements. The amount required by plants is characterized by the division of micro-nutrients (or trace elements) and macro-nutrients (or major elements). In addition, there are further elements that are not necessary but may benefit the growth of some plants [17]. Of the macro-nutrients oxygen (40-45%), carbon (40-45%), and hydrogen (6%) are provided by O_2 and CO_2 inside the air and by water. Table 2.1 shows the compounds for the supply of the remaining essential nutrients as fed to tomato plants [18]. The respective micro- and macro-nutrients including their mass proportion in every nutrient salt are also shown. An understanding of the amount of nutrients necessary for optimal growth can be derived from the mineral concentration in the dry matter of healthy plants. This differs for different plant species and even for the same species in different environments. For more detailed information on the essential nutrients, the reader is referred to [17]. For most common vegetable crops the compositions are well defined and do not need any further investigation.

	Compound	Macro Elements	Micro Elements
Stock A	$Ca(NO_3)_2$	15.5% N; 19% Ca	
	KNO_3	13% N; 38% K	
	NH_4NO_3	25% N	
	different FE-chelates		Fe
Stock solution B	$MgSO_4$	10%Mg; 13% S	
	$Mg(NO_3)_2$	11% N; 9% Mg	
	$NH_4H_2PO_2$	12% N; 7% P	
	KH_2PO_4	23% P; 28% K	
	KNO_3	13% N;38% K	
	K_2SO_4	45% K; 18% S	
	HNO_3	11.5% N	
	H_3PO_4	23.1% P	
	$MnSO_4$		32% Mn
	$CuSO_4$		25% Cu
	$ZnSO_4$		23% Zn
	$Na_2B_4O_7$		11%B
	Na_2MoO_4		40% Mo

Table 2.1: The molecules in which nutrients are dissolved in water by the example of two stock solutions that are combined for tomato cultivation [18].

Example compositions for other plants were collected by Lattauschke [18]. These stock solutions are usually 100 to 200x concentrated [18]. In highly concentrated solutions some of these compounds can react with each other forming undesired materials. The most significant reaction is between calcium nitrate ($Ca(NO_3)_2$) and magnesium sulfate ($MgSO_4$) forming plaster ($CaSO_4$).

Therefore, they should only be combined in the lower concentrated bulk solution, where the separately stored stock solutions are mixed with water before being supplied to the plants [18]. To know when new stock solution should be added, a way of monitoring the nutrient content is essential. Generally, there are two options to determine the content of a given NS: Electrical Conductivity (EC) and ion-specific measurements.

The most common way to estimate the concentration of nutrients in the solution is by measuring the EC in Siemens per meter [S/m] and, therefore, the overall amount of dissolved ions in the solution. Especially in closed systems, the determination of the ion content by EC measurement can have considerable downsides due to the following mechanisms:

The intake of nutrients by ion-specific transport proteins is an energy-intensive selective process that is regulated by the plants' current needs. Thus, nutrient intake is not proportional to the ratios of nutrients in the growing medium [19]. Since the needs and thus the absorption rate of the plants is not constant over time, the control over the EC might lead to the accumulation of one sort of ions and the depletion of others. In a closed system, the correct balance in the NS composition is essential as otherwise some ions might build up and render EC measurements useless.

Besides that, large quantities of exudates are released during the absorption process. These are composed of photosynthetic products containing carbon compounds and other particles such as H^+, inorganic ions, water, and electrons depending on the plant species, cultivar, age, and stress factors [20]. As some of these affect the EC as well and others affect the growth of the surrounding plants or microorganisms, the usability of the EC measurements in a closed system decreases over time. Regular intervals for a complete NS renewal are therefore critical.

Additionally, the discharge of some ions affects the acidity of the root environment due to an unbalanced cation and anion absorption. Since the process is selective and therefore not constant, the release of H^+ from the roots during cation absorption and (OH^-) or (HCO_3^-) during anion absorption causes fluctuations in the potential Hydrogen (pH) value of the root environment. This plays an important role in the usability of some nutrients. A change in pH from between 5 and 6 to 7 for example results in a decrease in the availability of the main Phosphorus (P) supply ($H_2PO_4^-$) from 80% to 30%. This leads to nutrient deficiencies, despite enough P being present in the fertilizer. In general, a slightly acidic pH between 5.5 to 6.5 is preferable with variations for different plants like 4.5-5.5 for leaf onions [17]. In commercial farms the preferred substances for adjustments are nitric acid (HNO_3) for a pH reduction or potassium hydroxide (KOH) for a pH increase [18].

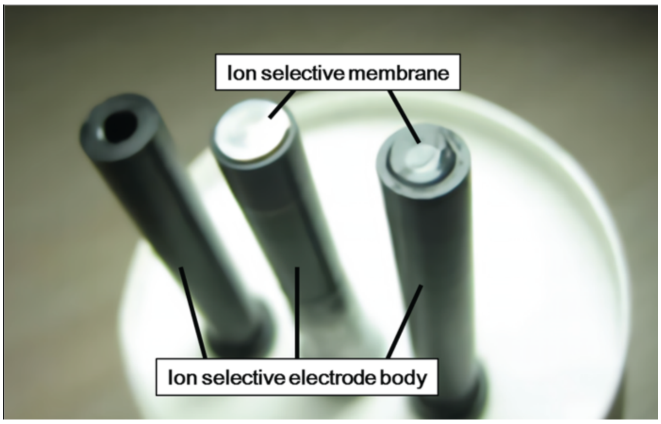

Figure 2.2: Ion Selective Electrodes used by Cho et al. [21].

To minimize the necessity of disposal and reduce the risk of unfitting nutrient concentrations at least sample-wise measurement of individual ion concentrations should be considered [22]. For measuring the concentration of individual ions, ion-selective electrodes as seen in Figure 2.2 can be used. The Technology Readiness Level (TRL) of these sensors is, however, quite low. Moreover, the electrodes are not 100% selective but respond, to some degree, to a variety of interfering ions [23]. Furthermore, a high signal drift and the reduction of sensitivity over time make them not well suited for long-term missions. Nevertheless, they were successfully used for a control strategy using different stock solutions for individual ions. In that case, samples were taken and the sensors were calibrated automatically [21]. Currently, there are ion-selective membranes, for most of the important hydroponic nutrients. These include NO_3, K^+, Ca_2^+ and Mg_2^+. However, they are highly prone to becoming clogged by biofilm accumulation [23].

A further approach to measure the individual components are optical sensors like ion-selective optrodes [22, 24, 25]. These consist of a light source, optical fibers, and a spectrometer. The concentration is measured in three steps namely dark spectrum measurement, reference spectrum measurement, and sample spectrum measurement [24]. The spectrum is then used to determine the ion concentration in the sample. The chemical specifics of the reactant inside the housing and how the ion selectivity is reached are not relevant for the overall purpose of this report and can be found in [22].

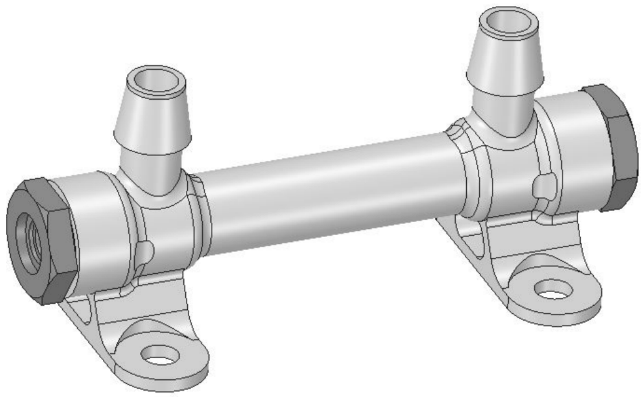

Figure 2.3: The housing of an optical fiber for spectral measurements of nutrient solution samples [24].

2.1.2. Nutrient Movement

The physiology of plants supports different distribution methods of the individual nutrients and water [17]. In [26] calcium distribution in plants is analyzed showing that the transport of some ions is passive and driven by the mass flow of water, which in turn is driven by the gradient of water potential from the root zone to the atmosphere. Another reason why these factors have to be controlled is the effect on the crops' water content. In case of high water availability in the root zone, i.e. high root pressure, but low evaporation, the water content of the crops rises, reducing the dry to fresh mass ratio [15].

Although mainly associated with the photosynthetic process, the light intensity also affects this process due to its effect on the temperature of the leaves. Together with the atmospheric conditions above ground this is not just affecting the photosynthetic process but is also the main contributor to the difference in Vapour Pressure Deficit (VPD), i.e. the difference between the amount of moisture in the air and how much moisture the air can hold at the same air temperature [27]. The VPD along the gas phase from the internal leaf to the atmosphere is a function of the humidity, temperature, and airflow along the leaves and affects the transpiration – the evaporation of water from the leaves [28] and, therefore, the water transport. Thus, the atmosphere and lighting affect the nutrient and water absorption of the plants. Since plants have distinct night and day cycles in which light, as well as temperature, differ, the transpiration rate varies. The root pressure in different cycles can be adjusted to the respective conditions by reducing the irrigation rate at night. However, it has to be noted that light also creates a favorable environment for algae and microorganisms. The root environment should, therefore, be strictly isolated from the light.

For other ions, absorption is an active process requiring energy. Ion-specific transport proteins directly or indirectly depend on the energy released by cell respiration under the use of O_2. Thus, nutrient deficiencies and other issues like root rot can be caused by insufficient oxygen supply to the roots [26]. The solubility of O_2 in the irrigation water depends on the water's temperature. For applications that do not ensure sufficient oxygenation otherwise, this needs to be taken into account in the NDS design.

2.1.3. Contamination

In addition to growth-promoting factor management, research is conducted into the prevention and removal of any sort of contamination. Providing an overall healthy environment for plants reduces the symptoms of diseases [29]. In addition, contamination of crops in closed systems is generally lower than in soil cultures as some pathogens can be eliminated by strict sanitation and quarantine procedures. However, pathogens can still cause plant diseases, reducing or destroying the harvestable yield. Moreover, pathogens can spread quickly traveling with the recycled materials, which makes active contamination removal essential [23].

A common result and source of further contamination are microbial biofilms on system components. They are formed by surface adherent microbial communities that produce an extracellular polymeric substance matrix for structure adhesion and protection purposes [30]. Besides infections, allergic and toxigenic effects on the crew members and the plants, the results of this sort of contamination have severe technical consequences for the components of the NDS [29]. These include clogging of the connection tubes or nozzles, corrosion of the used materials, degradation of electrical sensors, and interference with desired microbial processes.

While using corrosion-resistant materials and surfaces that offer little possibilities for biofilm accumulation can help avoid the symptoms, there are several methods to reduce the pathogen load. In literature [23, 29–31], the following methods are mentioned:

- Microbial inoculation
- Microfiltration
- Chemical treatment
- Heat treatment
- Radiation
- Oxidants

Bacteriazation or microbial inoculation describes the use of a microbially diverse and competitive ecology to increase the microbial stability of the system [29]. Although untargeted, this is the case in every environment. Therefore, it is not recommended to remove all microbial activity from the root zone. Furthermore, some microbes can be introduced to the system to compete with harmful microorganisms and reduce their occurrence. For this purpose non-corrosion inducing and low slime producing bacteria are chosen. Even the use of certain viruses and tardigrades have been proposed to fight harmful microbes [30]. These microorganisms are usually targeted at specific pathogens and are less effective against others. So far, only little is known about the individual pathogens in the EDEN ISS facility and even less about the impact of reduced gravity. Thus more research needs to be conducted to make the targeted introduction of microbes a feasible method [32].

Aside from the necessary filter for the removal of larger organic components, microfiltration can be used to filter out certain pathogens [31]. A membrane that allows the water and nutrients to flow through, but prohibits larger pathogens from passing is used for this purpose. This process, however, enables only location-specific pathogen removal. More importantly, it is slow and leaves a highly contaminated brine, that needs to be disposed of or cleaned.

Inactivating pathogens, for example in food preparation, by heating (pasteurizing) is a very old form of disinfection. The processed solution is heated up to a lethal temperature, which differs for different targeted pathogens [23]. It is kept at that temperature for the thermal death time and subsequently cooled down again. In greenhouses for commercial hydroponics heat treatment at 95 °C for thirty seconds is recommended to eliminate the targeted pathogens [31]. The limiting factor for using this method in this project might be the power consumption and the ability of the AMS to handle the excess heat.

Another method for sterilization of the NS is the use of Ultra-Violet (UV) light, which kills microorganisms. The current state of the art are UV Light Emitting Diode (LED) lamps with wavelengths between

200 and 300 nm. Other radiation types with higher energy content like gamma radiation have been proposed and are currently in use for sterilization of medical devices. In confined spaces, however, radiation might be problematic for the crew and the plants.

The most effective solution is chemical treatment. Due to the high amount of potential substances, only a selected few are examined further. An overview of more choices was collected by Zea et. al. [30]. On Earth pesticides in agriculture, metal ions like copper, or silver as used in antibacterial coatings and surfactants could be considered. These are, however, hard to manufacture on-site and can leave toxic byproducts that are potentially harmful to the crew and the plants. Due to the high amount of potential substances, these are not further discussed individually. More information on these and their effects can be found in [30].

Another group of sterilizing agents are oxidants. One of the most prominent is chlorine bleach (NaOCl) that breaks down into salt and oxygen, denaturalizing microbes that come in contact with it. Chlorine in general is another possibility as used in pools and to some extent in drinking water. Although there are methods like electrochemical hypochlorination to recapture chlorine, the technology level is not advanced enough to be considered in this thesis [33]. Other oxidizing agents, that are easy to produce on-site, leave no residues, and are very effective against any kind of microbes are hydrogen-peroxide and ozone. Ozone has been used for years as a drinking water disinfectant. It is produced by energizing O_2 and splitting it into two monatomic O_1 molecules. Upon collision with other O_2 molecules ozone O_3 is formed. The loosely bonded third oxygen atom is readily available to attach to and oxidize, other molecules making it a powerful oxidant that destroys microorganisms [30].

Although not essential, it can be beneficial to know the current pathogen load in the NS. The state of the art in determining the pathogen load is the cultivation of samples from the NS in a laboratory. After a defined duration under certain conditions, the number of grown microorganisms is determined. The examined microorganisms are considered to be the same as surface-attached microorganisms in the system. This method requires specific equipment that might not be available in the habitat [34]. The details can then be used for target-specific decontamination methods. Biological details on the specific types of microorganisms found in closed systems and on space stations are not covered in this review. For more information the reader is referred to [29] and [30].

2.2. Nutrient Delivery Systems

The individual environmental factors and their influence on the nutrition and the design of the NDS are now established. It has been mentioned how external factors (e.g. temperature and light) and, therefore, different subsystems like the AMS and the lighting system affect the performance of the nutrient absorption and transport. In this section, the state-of-the-art of NDSs is examined by introducing the most common types of NDS. Furthermore, a summary of previous or current systems for commercial purposes, for research of plant cultivation in space, and selected analog test sites is given.

2.2.1. Types of NDS

The oldest and most widely used method to deliver water and nutrients to plants is agriculture in soil. The plants are watered and nutrients are provided using the natural elements in the soil or by adding artificial fertilizers. However, due to the growth disturbing properties of aluminum, lunar and martian soil is not usable for this purpose [35]. Therefore, the soil has to be brought along from Earth, or other equipment is needed to process in-situ resources. Other substrates can be used which either already contain the required nutrients or are continuously or periodically replenished by NS. Furthermore, some systems do not require a substrate but rather directly apply the NS to the roots. Systems in which the main nutrient supply is achieved with an NS are called hydroponic systems.

Due to their high nutrient density, the use of ion-exchange resins or other inherently nutrient-containing ion exchange media like Agar-Agar is a common method when mass is a limiting factor. Substrates that do not contain nutrients themselves can be replenished with different methods. Figure 2.4 contains schematics of common simple types of hydroponic systems. Wick systems are the simplest to set up

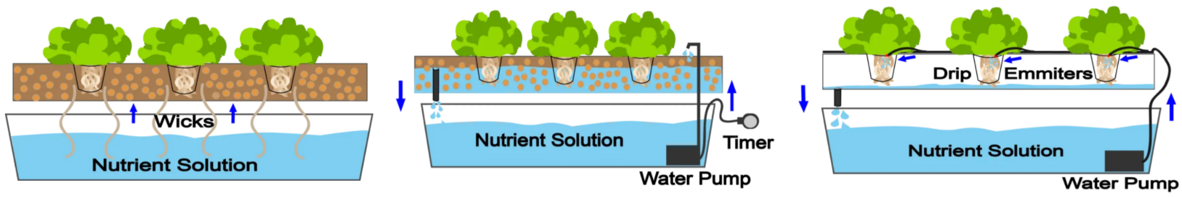

Figure 2.4: Different types of hydroponic systems: Wick (left), Ebb Flow (middle), and Drip (right) [36].

and maintain. The NS is transported passively by capillary forces to the growing medium. In contrast to the other types of NDS introduced here, it does not require power to run. On Earth, this system is usually used for young potted plants, seedlings, and leafy herbs [15]. A similar approach is used in many of the flown plant growth chambers in form of porous tubes or similar structures.

As the name suggests, the ebb and flow systems work by flooding the root space of the plants in intervals and draining it afterward to ensure proper root oxygenation and prevent root rot. Usually, the plants are grown in substrates like rock wool cubes that can hold water for some time.

The drip irrigation system can be designed with or without a growing medium. Here, the nutrient solution is distributed to the plants by dripping the necessary amount directly on the base of the plant. Excess solution is recycled to the nutrient solution tank via an overflow drain. This system requires active pumps and therefore electricity.

Although the initial investment is high compared to the other systems, the purely NS based designs like the Deep Flow Technique (DFT), the Nutrient Film Technique (NFT), and Aeroponic System (APS) are most commonly used for large commercial purposes, due to their higher yields [15]. Since the initial investment for a system used in space is overshadowed by other costs like the launch, these are promising solutions for long-term space flight applications.

Deep Flow Technique

The basic principle of this method is that the roots are suspended in the NS. Since the roots are not in contact with air, oxygenation needs to be achieved by other means. Therefore, the solution is recirculated along the entire length of the growing bed or an additional pump is used for oxygen supply. The support structure usually floats on top of the nutrient solution. Despite the power needs for the pumps, the nutrient solution is available for some time even in case of a power outage. On the other hand, the system is comparatively heavy due to a large amount of water that is in circulation at all times.

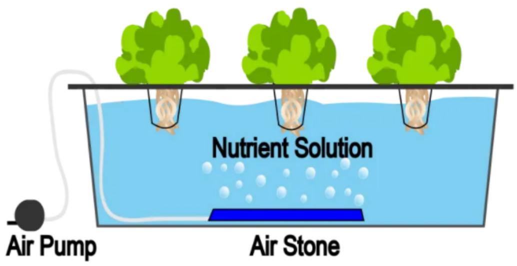

Figure 2.5: Schematic of a Deep Flow Technique hydroponic system [36].

Nutrient Film Technique

In this technique, a shallow 2-3 mm film of nutrient solution in a cultivation bed is used for irrigation and nutrient delivery. This stream covers the lower part of the roots while the upper parts are exposed to air, ensuring sufficient oxygenation. Usually, the slope is selected between 1:70 and 1:100 depending on the exact cultivation conditions. The excess solution is collected and fed back into the system [15]. A hybrid between NFT and DFT can be easily realized by adding sluice doors to the cultivation beds.

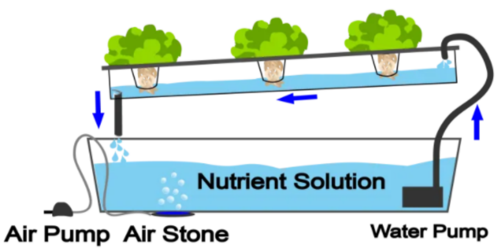

Figure 2.6: Schematic of a Nutrient Film Technique hydroponic system [36].

Aeroponic Systems

In an APS or spray hydroponic system, the nutrient solution is atomized and sprayed directly on the roots [15, 23]. These are hanging in the air, thus receiving sufficient oxygenation. Although this system usually produces the highest yield, some disadvantages have to be considered. A power outage or a pump malfunction for example results in immediate drought and can therefore be catastrophic for the harvest in a comparatively short time. Furthermore, misting nozzles tend to clog easily due to the crystallization of fertilizers, plant residues, or microorganisms. Therefore, considerable effort has to be put into the dependability during the design phase of a system like this. Moreover, a purely spray-based system requires a large cultivation bed since the roots need to be suspended in air, which reduces the yield-to-volume ratio of the system [15].

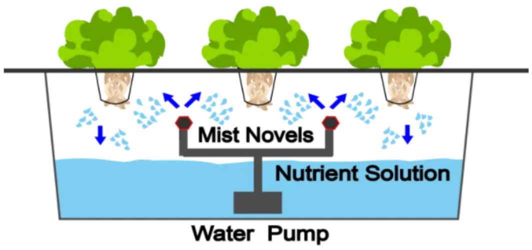

Figure 2.7: Schematic of a Spray Hydroponic or aeroponic system [36].

2.2.2. Example Systems

In this review, three types of systems are examined. The first is commercial plant cultivation facilities that are not based on soil culture. The second one is small-scale growth chambers designed to research plant cultivation in space and the third is the plant production chambers designed for use in biological life support systems in space. Since none of these have been used for actual space missions yet, these are all analog test sites or prototypes. An overview mentioning the mission or company and the approach for nutrient delivery can be found in Table 2.2. Subsequently, one example from every category is examined further.

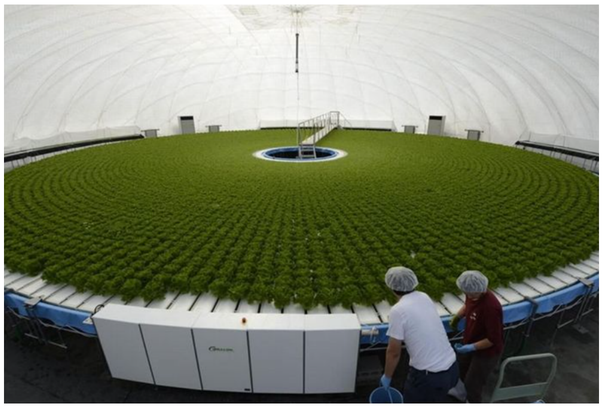

Figure 2.8: Japan Gandpa Dome with a circular DFT NDS [37].

In the selection it can be seen, that systems from mid-, to large-scale like commercial farms and analog test sites usually use some sort of hydroponic NDS. On Earth, the use of DFT combines a low initial investment compared to NFT and APSs with better yields than simpler systems giving it high accessibility. APSs on the other hand involve high initial investment costs, that are offset over time by the superior yields [40].

Figure 2.8 shows a DFT system as used by the ”Japan Gandpa Dome” company that was founded in 2016 [37]. After germination, the young plants are inserted into a circular structure in the middle of the dome. Over the cultivation period, the plants are moved along rails in circular paths to the outside, slowly increasing the available growing area. At the end of the cultivation period, they arrive at the outside where they are harvested. The growing bed is 8 cm deep and NS is circulated and replenished at all times. The EC, the pH and the temperature are constantly measured and adjusted. Figure 2.9 shows the automated mixing unit for the NS including pump piping and storage tanks. For NS cleaning, a reverse osmosis filtration system is used. It is designed to produce one type of crop in large quantities while keeping the investment and running costs minimal.

	Mission	Nutrient delivery subsystem
Commercial systems	Japan Gandpa Dome	Circular DFT as described in more detail [37].
	InLoCo	Shipping container systems using mainly APSs and utilizing a fish farm to provide nutrients called aquaponics [38].
	Sci tech farm	For seedling propagation the DFT is used and for vegetable cultivation the NFT [38].
	Aerofarms	Using an APS with the goal of producing two million pounds (over 900 tonnes) of leafy greens per year in the self proclaimed largest vertical farm in the world [39].
Research in space	Oasis 1	Two compartment system (water and ion exchange resin) that was later exchanged with fibrous or cloth ion exchange mediums.
	Vazon	Cloth sack filled with ion exchange resin.
	Malachite	Using ion exchange resin and a water supply.
	Svetoblok	Used Agar based nutrient mediums which changed to other media later.
	Phyton	1.5% agar nutrient medium.
	SVET	Perforated tubing wrapped in a wick within zeolite based substrate enriched with nutrients.
	ASC	Porous tubes in a matrix.
	BPS	Porous tubes in a matrix.
	Lada	Perforated tubing wrapped in a wick within a matrix.
	PEU	Rock wool fed by integrated water line.
	VEGGIE	Passive NDS using rooting pillows and manual water and nutrient supply.
Analog test sites	Bios3	Artificial substrates fed with hydroponic solutions [5].
	Lunar greenhouse	Cable culture = NFT like structure with the plants suspended in plastic envelopes from a cable. Reservoir control sensors located outside are used to allow for reduced complexity and modular design [10].
	EDEN ISS	APS with elements of NFT. The NDS and the supporting infrastructure are explained in more detail in section 2.3.

Table 2.2: A summary of commercial farms (sources see individual systems), the NDSs used in flown plant growth chambers [3], and analogue test sites for biological lief support systems.

Figure 2.9: The NDS's mixing unit of the Gandpa Japan Dome farm [37].

Within the systems tested in space a trend from ion exchange resins or other ion exchange substrates, towards NS-based systems with higher reusability, can be seen. Although ion exchange resins have a high nutrient density, their production usually requires oil and other synthetic substances [41] that would have to be provided in long-term missions. Therefore, while being well suited for short missions to study plant growth in space, they are not feasible for long-term and mid-, to large-scale applications. The other advantage of being easier to handle in micro-gravity does not apply to a design for the Moon.

The later systems in contrast tend to be hydroponic systems as described above since they require high yield-to-space ratios and need to be more sustainable. In Figure 2.10 a prototype of the VEGGIE plant growth system currently located on the ISS can be seen. The plants grow in clay-based growth media pillows and are provided with fertilizer and water by a passive wicking system from a root mat water reservoir. The clay provides a good balance between water, fertilizer, and air. It is optimized for plant cultivation in micro-gravity since the clay prevents the formation of water bubbles. Sanitation of the system and the crops is achieved by food-safe citric acid-based wipes [42]. For more information on the individual plant growth chambers for research in space and their other subsystems, the reader is referred to Zabel et al. [3].

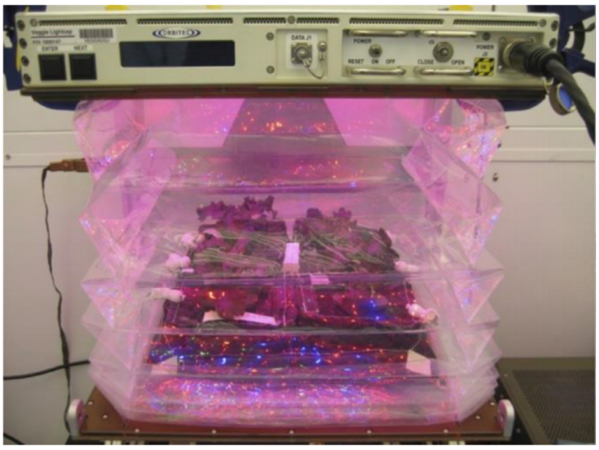

Figure 2.10: "Veggie" plant growing chamber prototype on the ISS to provide fresh lettuce to the crew [3].

2.3. EDEN ISS

An example for a greenhouse module specifically designed for research of food production systems for human space exploration was developed EDEN ISS Project funded by the European Union (EU). It is an analog test site in which technologies for the production of food on the lunar or martian surface are tested. Figure 2.11 shows the MTF, a prototype greenhouse, that was tested in Antarctica near the German research station Neumayer III in semi-continuous operation since January 2018. Although other greenhouses have been operated in Antarctica, it is the first for the research of plant cultivation in space. Besides the extreme outdoor conditions that result in a high dependency on technology, Antarctica was chosen as a location for various reasons. The possibility for resupply is limited since shipments are only possible during summertime from November until March each year. Therefore, the systems need a high degree of self-sufficiency. Furthermore, the small overwintering crew acts as a reasonable approximation of an astronaut crew concerning the food consumption and the psychological benefits of plants in an otherwise barren environment. All in all, it provides a mission setting in which operation, maintenance, and repair are decoupled from a laboratory environment.

Figure 2.11: The outside view of the MTF on its platform in Antarctica (left) and the inside view of the Future Exploration Greenhouse (FEG) including young plants (right) [12].

The MTF is composed of a Service Section (SES) and a greenhouse section, called the Future Exploration Greenhouse (FEG) for crop cultivation. Each is located in an individual 20 foot shipping container as can be seen in Figure 2.12. The SES contains the main parts of the individual subsystems including the NDS. The FEG contains eight racks for the cultivation of various kinds of crops [12]. Each rack can hold a maximum of eight 400 x 600 x 120 mm polypropylene growing trays. To accommodate different plant sizes some only hold two to six trays resulting in a total of 42 trays or $11.9m^2$ of growing area. In the first season in 2018 from February 7th to November 20th 268 kg of fresh produce were harvested. This results in an average production of 0.916 kg per day [12].

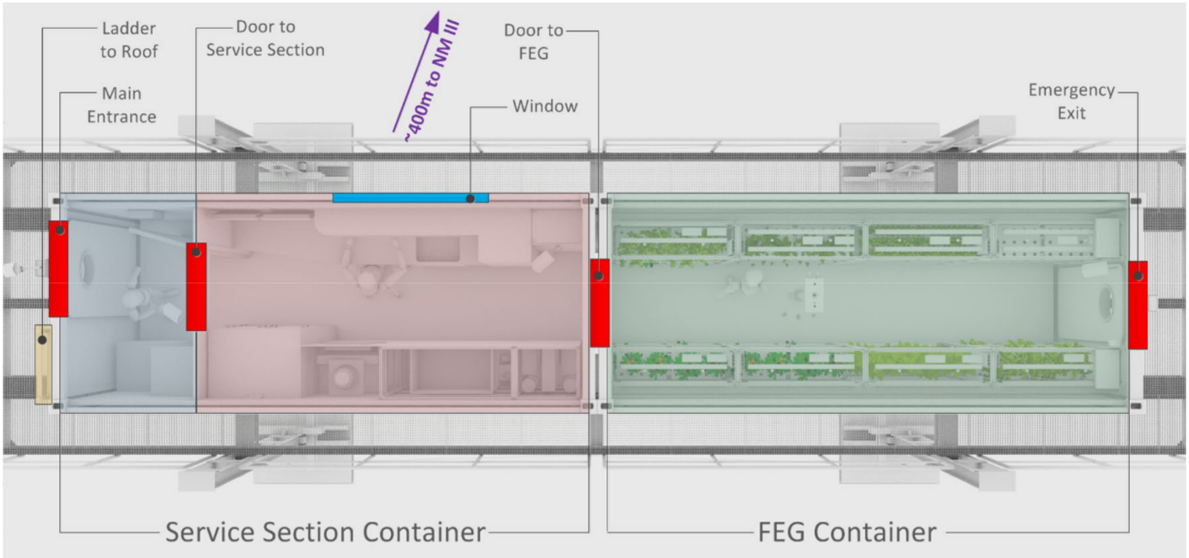

Figure 2.12: Schematic overview of the EDEN ISS MTF [12].

2.3.1. NDS

In Figure 2.13 the architecture of the NDS and the supporting infrastructure can be seen. The equipment for all measurements, storage, and mixing capabilities is located in the SES. The bulk solution is collected in two 250 l stainless steel tanks for different plants and different set points. Redundant EC, pH, temperature, and level sensors are suspended directly into the tanks. When necessary, freshwater is supplied from a freshwater tank. Evaporated and transpired water is recovered by the AMS and fed back into the freshwater tank. Dosing pumps located in the SES are used to adjust the EC by adding different stock solutions. There are a total of four stock solutions to enable the separate operation of the two bulk tanks. The pH of both tanks is regulated by one acid and one base container. To ensure a homogeneous NS, it is constantly circulated by a mixing pump.

Manual sampling is possible from both bulk solution tanks. A semi-automatic ozonation method is used for sterilization. Ozone (O_3) is dissolved in the solution, killing microorganisms by its oxidation capacity. Therefore, an ozone generator is combined with the normal air inlet used for the oxygenation of the solution. A production of 50 mg/h was used for batch decontamination of two bulk tanks and 11.9 m^2 of cultivation area [43].

The distribution and return lines, as well as the plant compartments, are contained in the FEG. Each rack – L1 to L4 and R1 to R4 – is supplied by a high-pressure pump that can be fed from either bulk nutrient solution tank via manual valves. After the first operational season, the number of active pumps on one side was halved combining two racks respectively. The leftover pumps were used as spares in case of failure. This reduced the overall number of pumps to 6. The three-way-manual-valves and the under-floor-piping are accessible via removable floor panels. The pumps are fed by 19 mm PVC pipes with a 178 μm stainless steel filter to reduce the risk of clogging. The NS is returned by gravity from the plant trays to a sub-floor reservoir via 40 mm PVC piping. This size was chosen for easy maintenance and to reduce the risk of being clogged by roots and other plant debris. Once the level sensors in the sump reservoir signal that enough NS has been collected, it is pumped back into the bulk solution tank by submersible pumps.

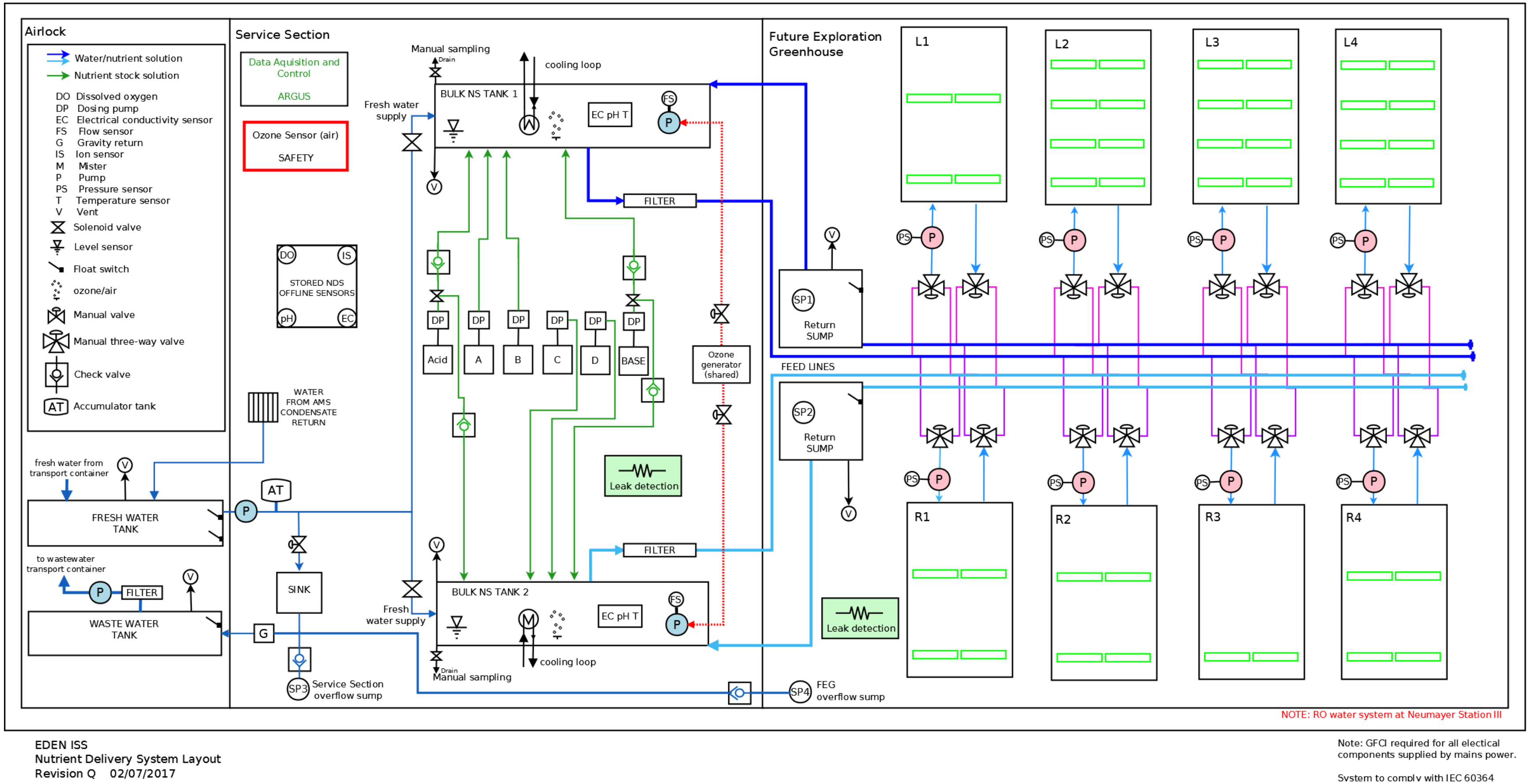

Figure 2.13: Block diagram showing system flow and components of the NDS [43].

The plants are supplied with nutrients and water via a high pressure misting APS. With a depth of 120 mm, the elements containing the plants are smaller than in usual APSs, due to volume restrictions. Thus, some roots of more mature plants might touch the ground where they can be submerged in small amounts of NS. From the high pressure pumps the NS is directed through 6.35 mm polypropylene tubing to the misting nozzles. The misting nozzles have an aperture of 0.5 mm. To prevent clogging, this is chosen far larger than the filter screen in front of the pumps.

2.3.2. Lessons Learned

The generation of knowledge applicable for a future space-graded greenhouse is one of the main objectives of this greenhouse prototype. During the operational years, the encountered challenges were collected. In this section, the main lessons learned concerning the NDS are summarized. Some of the lessons learned do not directly impact the design phase but might lead to recommendations for future work or the operations phase and are, therefore, mentioned here [44].

ID	Title	Description
LL-006	The sub-floor compartment was too densely packed.	It has to be designed such that enough space to step in is provided.
LL-007	Piping and harness has to be rearranged for cleaning.	Large-scale cleaning has to be feasible.
LL-010	A modular configuration for tall growing plants advantageous.	The crew shall be able to change the allocation of trays for tall and small growing plants.
LL-011	Metal piping would have reduced leakage.	Glued connections of current design are problematic.
LL-012	The piping should be redesigned to prevent leakage.	No U-turns as they cause bubbles.
LL-015	Equipment sizing (esp. piping/ harness) should be singular.	A change of pipe size requires connectors which increase the possibility of leaks and introduces complex replacement situations.
LL-016	The current height for racks is difficult to work on.	The rack height for the uppermost and lowest parts is difficult to handle. Alternatively, the trays should be made removable to enable work at a work table.

Table 2.3: The applicable Lessons Learned from the operational period of the MTF with the IDs taken over from [44].

2.4. Summary and Discussion

In this chapter, a basic understanding of the physiological needs of plants was established. The mechanisms that affect nutrient absorption and their effects on the NDS were examined, including common ways of determining whether the conditions are met. Furthermore, the interactions between environmental factors above ground and the root zone were summarized. Afterward, different methods of providing the necessary root environment were collected and systems that use them were briefly introduced. One commercial system and one system for use in micro-gravity were examined closer. Finally, a description of the NDS of the EDEN ISS analog test site was given in more detail. The gathered insights can already be summarized in some system objectives. Some technical capabilities and, therefore, tasks of supporting infrastructure are common in all systems.

First of all, the needs of the plants need to be considered. Therefore, the right amount of water and nutrients have to be supplied in accordance with the VPD and light conditions. Since also an oversupply can be harmful, they need to be mixed in the correct concentrations for which some parameters need to be known. These include the EC, the pH, the dissolved Oxygen (dO) the flow rate, and possibly the individual ion concentrations. Since other environmental factors also influence the absorption, as well as the distribution, the system needs to be capable of adapting to failures in the respective subsystems. Furthermore, it has to be ensured that no harmful substances, pathogens, or pesticides reach the plants. The fresh water and the stock solutions need to be stored. Since the greenhouse is designed for a long-term sustainable mission, the leftover NS needs to be re-purposed in some way.

3
System Analysis

As mentioned in Chapter 1, the MTF is a test-facility with the main purpose of gathering information towards the design of a space-graded GHM. The associated project, for which initial design suggestions were generated in March 2019 in a Concurrent Engineering (CE) workshop at DLR in Bremen, is called the EDEN NextGen project. The current state of this project is presented in this chapter as part of the preliminary system analysis [44].

First, the design study report is analyzed [12, 44]. Besides the mission scenario, the structural design and the interfaces to other subsystems within the habitat and the GHM are specified. As a preparation for the requirement generation and the concept selection, a preliminary functional risk analysis is conducted. Influencing factors of other subsystems, that have not yet been designed, are estimated and collected with other assumptions and simplifications. Subsequently, requirements are derived from the relevant facts presented in Chapter 2, as well as interviews with stakeholders, and a range of different documents concerning the design of a GHM [12, 44–46]. With all this information the final step in the system analysis is the definition of the resulting trade-off selection criteria.

3.1. Preliminary Design of the EDEN NextGen Project

Although no detailed plans for actual greenhouse missions exist, a possible mission scenario was created to support the design phase. Due to the continued delay of the Space Launch System, Space X's Falcon 9 is chosen as a baseline launcher. The technical budgets like mass and volume are constrained by the payload fairing and the necessary transport module. For more information on the transport process and the budget estimations of the supporting infrastructure, the reader is referred to [44]. After arrival and detachment from the transport and protection infrastructure, the greenhouse module is docked to an already established habitat. On-site, it is deployed and covered with regolith for protection from debris and radiation. Power, thermal, and life support infrastructures are expected to be part of the habitat and are therefore not included in the module. Additionally, construction tools for the setup are also assumed to be available on-site [44].

With a growth area of $A_{cult} = 30.8\,m^2$ one EDEN NextGen module is intended to provide fresh food supplementing the crew's main diet, rather than providing all of the required food. Similarly, the module will provide oxygen and remove carbon dioxide as a side effect of plant cultivation but will, initially, not act as the primary life support system. Multiple modules may be integrated into the habitat architecture, eventually increasing the cultivation area to enable the fulfillment of 100 % of the crew's dietary needs [47]. To avoid cross-contamination and allow the use of any number of modules, every module is supposed to be a stand-alone system. With the current configuration a harvest of 3.4 kg of fresh produce per day is estimated for each module. This includes about 55 % of lettuce and leafy greens, 24 % fruity crops, 13.5 % tubers, and some herbs. It has to be noted that this selection was made for test purposes and is not based on an optimized nutrition plan for the crew [12]. Therefore, the selection might change in the course of the project. Although all calculations in this report are based on this selection, margins are used to enable possible changes.

3.1.1. Structure

To withstand the external environmental conditions a cylinder structure was chosen for the EDEN Next Gen GHM. Together with dome and spherical shapes, their robustness against the dominant internal pressure loads outperforms other structures. Of these three, the cylinder structure has the most similarities to the MTF making the lessons learned more applicable. It further allows cleaning it with water hoses and collecting the water at the lowest point [44].

The GHM is divided into a rigid part called the service section (SES) and a deployable section which houses the actual plant cultivation area called the Exploration Greenhouse (EG). This allows for the desired cultivation area while the module still meets the volume requirements of the chosen launcher. The mass and volume budgets were estimated based on past and present structures and concepts [44]. The dimensions of the greenhouse in the deployed and stowed configurations can be seen in Figure 3.1. The length of 6.3 m and diameter of 4 m were determined from the payload fairing size, as well as the space reserved for the additional components needed for transportation of the GHM. A packing ratio of 1:3.75 in length and 1:1.3 in diameter is aimed for. It has to be noted that the feasibility of this is highly uncertain. It is considered achievable as the wall thickness of the EG can be reduced by replacing the debris and radiation shielding, with a removable cover, during transport, and by regolith shielding, during the operations phase [44]. This results in an overall length of 12.9 m and a diameter of the deployable part of 5 m. The deployable section, and thus the plant cultivation area, has a length of 9 m, while the rigid service section is 3 m long. The remaining 0.9 m is required for the rigid end cone, as well as the docking interface rings. The difference in diameter between the rigid service section and the deployable section requires the service section to be supported by leg structure at the desired height [44]. For insulation and support reasons of the cylindrical structure, 8 m long pillows are designed to hold the EG in place.

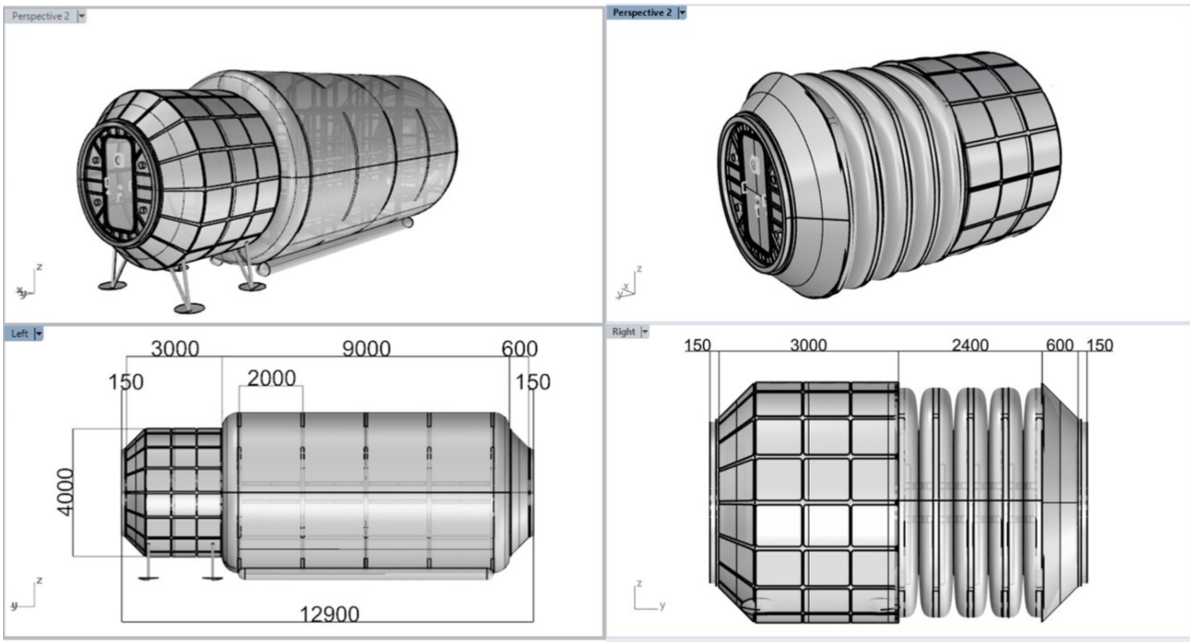

Figure 3.1: The EDEN NextGen GHM in the deployed (left) and the stowed state (right) including dimensions [44].

The deployable section is composed of four identical rigid metal frames for axial and radial expansion as seen in Figure 3.2. They are covered by a layered membrane system. In the operational state, the frame segments are 2 m apart and floor segments, longerons, as well as spacers are used to connect them. In the stowed state these are folded as shown in Figure 3.3 in order to fit in the available storage space during transport.

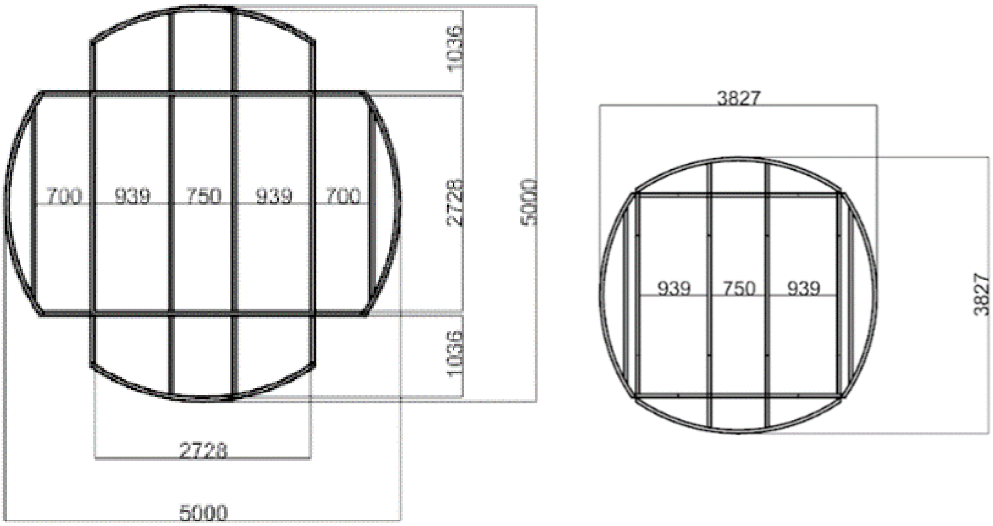

Figure 3.2: The dimensions of the rigid frames in deployed (left) and stowed (right) configuration [12].

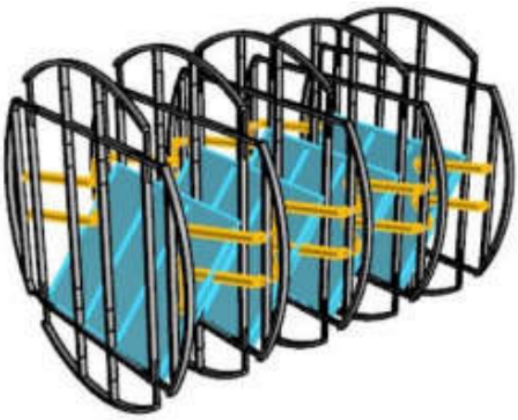

Figure 3.3: The internal structural elements during deployment [12].

As the two sections are radially aligned, cylinder segments under the floor panels provide a sub-floor space. With an inside-diameter of 4 m as assumed in [44], the resulting maximum available sub-floor space is 636 mm at the deepest point of the service section. In the deployed state, this amounts to the given 1036 mm. Taking LL-006 into account a corridor should be left empty reducing the available space for NDS components by a width of around 0.8 m. The exact volume dedicated to the NDS is discussed in the following section.

3.1.2. Subsystems and Interfaces

In Figure 3.4, the interior of the GHM including the preliminary locations for the individual subsystems, can be seen. The subsystems in the rigid part are pre-installed without the need for further assembly. The equipment reaching into the collapsible part of the GHM may be installed on-site, if necessary. In the CE workshop, the subsystems of the MTF are used as a baseline for the preliminary design of the GHM. The space indicated by the green components is dedicated to the NDS and mirrored along the cutting plane. In the sub-floor space, 0.8 m are taken up by the AMS displayed in blue. The growth area is composed of three rows of racks. They are separated by a 1.2 m corridor for comfortable passage. Each rack contains a different amount of levels for the cultivation of small, medium, or large plants as in the MTF. The EG has space for four racks per row. Because the first rack in the middle is replaced by a work table, 76 trays for small and 28 for tall-growing plants are distributed between eleven racks [47]. Currently, the trays are assumed to be of the same design as in the MTF. In the preliminary design, the piping to the plant racks is located in the sub-floor space under the racks.

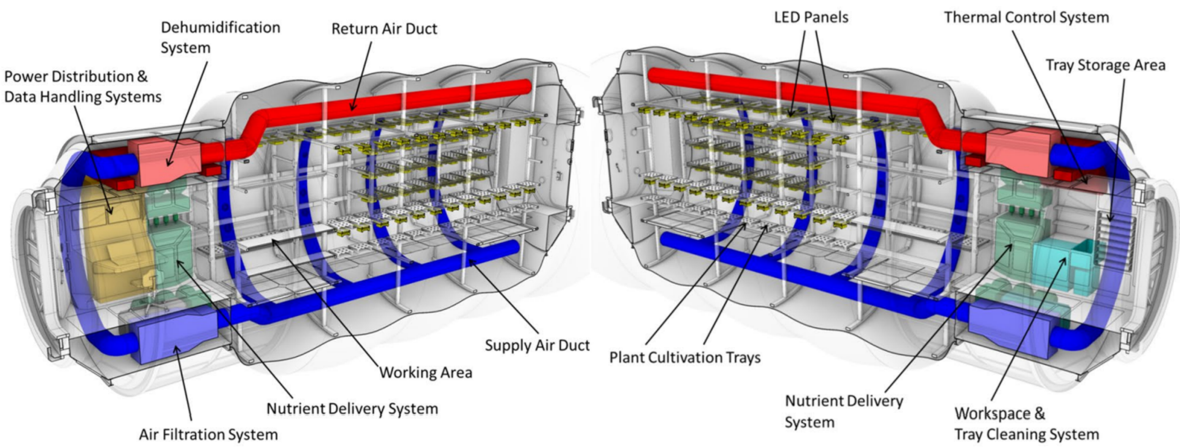

Figure 3.4: The internal layout of the greenhouse module.

	Input		Output	
Subsystem	**Desired**	**Undesired**	**Desired**	**Undesired**
Structure	• Housing • Radiation shielding	• Volume constraints	• Mechanical loads	• Corrosion through leaks
AMS	• Water from condensation • Oxygen for the root zone • Air temperature • VPD change	• Heat from the air (in case of cooled NS)	• Water from evaporation and transpiration	• Out-gassing e.g. escaping ozone • Waste heat from components
Lighting-system	• VPD change	• Light in the root-zone		
Habitat	• Water and nutrients from the waste treatment • Nutrients, acid, and base from storage	• Contamination by microbes		• Noise • Contamination by microbes
PMS	• Power	• Power-spikes or outage		• Short circuits
Crew	• Maintenance and operations	• Contamination	• Removal of biofilms • Dirty equipment	• Contamination
CDHS	• Input commands		• Sensor data	• Noise
Plants	• Left over NS	• Plant debris • Exudates	• NS for biomass production	• NS with wrong composition
Lunar environment	• Potentially water and nutrients from in situ resources	• Dust		• Microbes

Table 3.1: Input output matrix of the NDS. For the empty elements no aspects with an impact on the design decision were found.

For the subsequent preliminary risk analysis and requirement specification, the interfaces between the various subsystems and the NDS are listed in Table 3.1 as an input-output chart. The desired, as well as the undesired, interactions are gathered to develop an overview of the challenges to consider when determining the requirements. The previously mentioned impact of the AMS and the lighting system on the VPD and, therefore, the nutrient movement only affects the NDS indirectly. However, the resulting change of the plants' water intake is mentioned here as direct input to the NDS. It is located in the "desired" section since the day and night cycles are necessary during nominal operation. However, in case of failures of these systems or signs of nutrient deficiency, the undesired effects need to be taken into account for the introduction of countermeasures. Otherwise, only direct interfaces to the NDS are shown. For some subsystems, the interactions are limited such that not all fields in the table are filled. A complete overview of all interfaces can be found in [44] and in Appendix B.1 in the form of an N^2 chart.

Due to the early stage of development, quantitative input and output values are not available for all interfaces. If needed for calculations, these are roughly estimated and a large margin is used in the respective sections. Some of the tasks attributed to subsystems that are not yet designed have a large impact on the design of the NDS and the other way around. Although these are not part of the NDS, recommendations for their design process are made, which also act as assumptions for this thesis. This is especially applicable to the control system. Since radiation shielding, insulation, and temperature control are taken over by other subsystems, the only interaction with the lunar environment is considered to be the reduced gravity.

3.1.3. NDS

The space dedicated to each subsystem was estimated from the area allocated to it in the MTF by adapting it to 2x the growth area with a scaling factor for the respective systems. Since the size of tanks and pumps does not necessarily scale proportional to the NS-flow rate, the scaling factor for the NDS is chosen as 1.5. For an initial footprint of $A_{MTF} = 0.9\,m^2$, this results in an area of $A_{NG} = 1.35\,m^2$ which is split between both sides of the service section. The footprint is then translated to the actual growth area of 30.8 m^2 and the total volume is estimated to be $V_{NG} = 4.52\,m^3$. From the extrapolation of the MTF-subsystems the mass of the NDS is estimated as $m_{NDS} = 766\,kg$ including a 20% margin as determined in [12]. Although not mentioned in the reports, the power consumption is estimated as well. The MTF-NDS peak power consumption during the operational phase was 256 W and the nominal power was 165.9 W. Assuming that the power consumption is proportional to the cultivation area, a scaling factor of 2.464 is used to estimate the power consumption. The scaled power consumption of the GHM is, therefore, estimated between P_{NG}=408.8 and 630.8 W.

Task	Component	Comments
Provide Nutrients	• Aeroponic System	As used in the MTF
Irrigate plants	• One high pressure pump per bulk tank, possibly supported by accumulator tanks • Piping in the sub floor space under the plant racks	One spare pump per tank
Regulate concentrations	• Redundant senor bundle for pH, EC, dO • Flow and level sensors • Dosing pumps for distribution	The exact algorithm is provided by the CDHS
Contamination removal	• Ozone and filters in front of the high pressure pumps	Distributed with an air stone
Oxygenation	• Air stone and air pump are already available	Not essential due to APS
Store water and nutrients	• Two tanks for the bulk solution with circulation pumps for continuous mixing • One fresh water tank • Four stock solution tanks	As used in the MTF
Minimize waste	• Gravity return of the used NS to a sub-floor reservoir.	At a certain level it is pumped by a sump-pump back into the bulk tank.

Table 3.2: A rough summary of the design suggestions for the EDEN NextGen GHM.

The volume, mass, and power values serve as initial upper limits for the NDS design. However, these values should not be considered finalized, since the scaling factors used to estimate the required mass and volume for the different subsystems are uncertain. In the recommendations from the CE workshop, most of the concepts are taken over from the MTF. The preliminary choices for the NDS leave only a limited design space to work with. Since the workshop was only supposed to give rough guidelines, the choices are open for change, if necessary. Because the architecture of the MTF was already described in detail, only a summary of the proposed components for each of the tasks explored in Section 2.4 is given in Table 3.2. The main changes are the reduction of the number of high pressure pumps to one per bulk tank with one redundant pump respectively and the possibility of accumulator tanks for a longer pump life.

3.2. Preliminary Risk Analysis

Since life support systems are critical for human presence in space, the design of any subsystem, like a GHM, requires a high degree of risk mitigation. To develop an understanding of the possible consequences of different design choices, a preliminary functional risk analysis is conducted. Therefore, the effects of not fulfilling individual functions discussed in Section 2.4 are summarized in Table 3.3. Failure propagation and examples of how these failures could occur in the preliminary design are evaluated.

Without considering any countermeasures the severity (S) of each failure mode is categorized on a scale from one to four, one being minor and four being catastrophic. Catastrophic failures (4) are life-threatening for the astronauts and shall be two-failure tolerant to prohibit their occurrence. Critical (3) failures are those leading to minor injuries or damage to nearby systems and shall be one-failure tolerant. Major (2) failures prohibit full mission success without posing any immediate danger. This will give an initial estimate of the critical functions and components that should be addressed first in the concept selection process. After the detailed design phase, the table will be reiterated on a component level of the chosen design options.

In the first phases of the mission, the GHM will only be used as a support for a dedicated life support system. For the production of the entire food supply, more modules are needed. Therefore, not even the loss of an entire harvest is classified as a catastrophic event. Biological contamination and substances to prevent it can have severe detrimental effects on the health of the crew. However, a life threat can only be expected after a long time without detection. Therefore, it is also considered critical but not catastrophic. Without catastrophic failure modes, the critical category requires the most attention.

ID	Failure Mode	Effect	S	Possible cause
R-01	The NS does not reach the plant roots	Within only a short time drought occurs, leading to plant loss.	3	• clogged filters or nozzles • Pump malfunction • Major pipe leak • No bulk solution available
R-02	Too much NS reaches the plants	The oxygen supply is reduced leading to nutrient deficiency and possibly root rot.	1	• Failed flow sensors • Blocked drain
R-03	Wrong NS composition	Nutrient deficiencies in plants and pH change can immediately damage the plants.	2	• Salt accumulation in the NS • Sensor data faulty • Inhomogeneous solution
R-04	Plant Infections	• Infections are easily transmitted between the plants and can lead to harvest loss. • The contamination can have a detrimental effect on human health.	3	• Decontamination problems • Stagnant NS • Light influx
R-05	Biofilm formation	The increase in microbes might lead to infections. The biofilm matrix can clog pipes and nozzles.	2	• Decontamination problems • Stagnant NS • Light influx
R-06	Decontamination Substances	• Some decontamination methods use toxic substances. • Ozone can be detrimental to plant as well as human health.	3	• Leaks • Overproduction
R-07	Data transmission failure	Can trigger most of the above.	3	• Short circuits due to leaks • Calibration errors
R-08	NS outside of the NDS	Provides good growing conditions to microbes. In case this is not detected for a long time corrosion and contamination might increase the threat level.	2	• Leaks • Tank overflow

Table 3.3: Preliminary risk analysis based on the functions of the NDS and the design suggestions [44].

3.3. Assumptions

Before defining the requirements, some simplifying assumptions have to be made. Some of these arise from preliminary design suggestions of not yet developed subsystems, while others are simplifications of the actual environment. Table 3.4 lists the main assumptions, which are updated throughout the project. Some smaller assumptions that only affect individual elements of the NDS are introduced in the respective sections.

ID	Description	Rationale
A-010	The NDS has no contact with the temperatures outside of the greenhouse module.	The air temperature is controlled by the AMS.
A-020	Power shall be provided by the infrastructure of the habitat.	The GHM does not [produce its own power.
A-030	Waste NS shall be processed by the habitat infrastructure.	In the MTF drained NS amounted to 340 l/week including 83.3 l/week nutrient solution, 250 l/week cleaning water and 5 l/week germination water [48].
A-040	The plant selection is equivalent to the example configuration used in the MTF [12].	Although this is only an example configuration and not optimized for nutrition, it was chosen as baseline for the plant needs.
A-041	Nutrients are stored or made available by the habitat waste management or in the form of nutrient salts.	The MELiSSA cycle will provide a NS obtained by the wastewater and bio-waste processing cycle.
A-050	The NS composition is known and optimized for the selected plants.	For the case that the uncertainty in the composition is larger than assumed here, strategies are recommended in the outlook.
A-060	The loads of the crops are identical within the two categories of fruit bearing crops and leafy greens respectively.	Only two different NS compositions are intended to be used.
A-061	The plant needs on the Moon are equivalent to those on Earth.	Since Moon conditions, like the reduced gravity, cannot be entirely imitated, metabolic data of plants grown on the Moon might be different.
A-070	The used parameters per plant like growing area, stock solution, and other plant needs are as determined in the MTF.	The functionalities of the EDEN ISS NDS are sufficient and can be seen as a working baseline.
A-071	If not indicated otherwise, a conversion factor depending on the number of trays of $\frac{104}{42} = 2.48$ is used in all preliminary calculations.	The water and nutrient needs are proportional to the growing areas.
A-080	The gravity acceleration of the entire operation phase of the GHM is constant at $g_M = 1.625\, m/s^2$	
A-090	The supplied water is clean of any contaminants or left over salts and has a neutral pH.	The fresh water is mainly collected from transpiration and is, therefore, free of contaminants.

Table 3.4: The most recent list of assumptions made in the design of the NDS. To not change any ID once given, The last digit in the ID is only used if an assumption is changed or an associated one is added.

3.4. Requirements

In this section the gathered information is condensed to NDS specific requirements for the EDEN NextGen GHM. Aside from the general literature review, the requirements are derived from different documents within the EDEN Group, interviews with stakeholders, and general requirements from bio-regenerative life support systems. The most important documents are the EDEN NextGen design study report [44], the EDEN ISS requirement document [49], the plant selection report [50], the transition report from EDEN ISS to EDEN NextGen [12], and the MELiSSA GHM requirements [45]. The requirements are split into different categories: System Objectives (SO), Operational (OP), Transport and Irrigation (TI), NS Conditioning (NC), and Health Monitoring (HM) requirements as indicated in the ID column. If not justified by the gathered information, a rationale is given together with the source of the requirement. Due to the early stage of development, some values are not known or not finalized yet. These values are denoted as To Be Determined (TBD) and To Be Confirmed (TBC), respectively. Finally, a verification method is recommended for each requirement. Table 3.5 shows a selection of requirements that are of particular importance for the design choices throughout the thesis. The full requirement document can be found in Appendix A.

Table 3.5: Selection of the most important Requirements for the design choices of the NDS.

ID	Description	Rationale	Verification
SO-NDS-030	The NDS shall have a system volume of maximum 4.52 m^3.	Limited by the payload fairing and a subsystem specific scaling factor from the MTF. [44]	Analysis
SO-NDS-040	The NDS shall have a mass of less than 766kg.	The GHM shall be launched with one rocket and a scaling factor from be MTF is applied. [12, 44]	Analysis
SO-NDS-060	The power used by the NDS shall be less than 660 W (TBC).	The peak power of the MTF is 256 W and the nominal power is 165.9 W [43, 49]	Analysis
FR-OP-010	The NDS shall be operated and maintained by the crew with a level of autonomy at least equal to the MTF: Maximum work time: TBD.	The working time of astronauts is extremely valuable and should therefore not be wasted. [44]	Scenario tracing Later: Time Log
FR-OP-021	The use of harmful substances shall be avoided and adhere to safety regulations and standards where they can not.	To maintain a sustainable life on another planetary body, the work environment has to be safe. [44]	Component data sheets Later: Test
FR-OP-040	Redundancy shall be implemented such that the removal for cleaning and maintenance or failure of individual components does not compromise the ability of the NDS to provide functions relevant to keeping the plants or crew alive.	In case one component fails or has to be cleaned, the overall system needs to compensate until the issue has been resolved. [44, 45]	Scenario tracing Later: Test
FR-OP-060	Required resupply for maintenance and operation shall be kept to a minimum: • The used substances shall be replaceable by substances generated on site (optional). • The amount of different spare parts shall be limited by using the same kind of component for similar tasks.	To sustain a long term colony after the initial phases of frequent resupply missions, the habitat needs to function independently. [44]	Scenario tracing

Continuation of the requirement Table 3.5

ID	Description	Rationale	Verification
FR-OP-070	The NDS shall be designed to include a minimal number of moving parts to improve system reliability.	Less moving parts require less maintenance. [12, 51]	Inspection
FR-TI-040	The NDS shall be able to provide two different root zone environment compositions from two bulk solution tanks. The allocation to the available racks shall be predetermined but rearrangeable with medium effort.	Fruit building and leafy plants require different root zone conditions but need to be cultivated simultaneously. The lessons learned concluded that changes in the distribution are rarely necessary justifying some effort for rearrangement. [12, 44, 49, 52]	Inspection
FR-TI-070	Excess NS shall be recirculated into the bulk solution tanks, with the primary replenished NS for a minimum of 4 weeks.	To reduce the need for resupply the use of substances shall be as efficient as possible. [44, 45, 49]	Test
FR-TI-110	The materials used for the irrigation system shall be suitable for long term exposure to the used substances.	Some materials are more prone to corrosion and other problems than others. [49]	Inspection
FR-NC-010	The composition of the nutrient solution shall be controlled at the respective setpoints with a maximum deviation of: • EC: 0.8-4.5±0.17mS /cm • pH: 4.5-7.5±0.12 • T: 15-20°C ±TBD • dO: 80-100%	The set points and accuracies are the current values of the MTF. These result in sufficient plant growth and are considered acceptable. [45, 51]	Test
FR-NC-052	The stored amount of stock solution, acid, and base shall be enough for a full growth stage of the most requiring selected crop.	Maintenance is kept to a minimum as the containers only have to be refilled when nutrient demands change with the different growth stages. [44, 49]	Inspection; Test
FR-HM-030	Frequent health monitoring (TBDx per month) shall be possible to determine the pathogen contamination. Therefore, access to the bulk solution tanks to take samples shall be available.	An easy way to take samples is desired for multiple uses including health monitoring. [49]	Test
FR-HM-040	Substances for pathogen limitation shall be sustainable in a space environment. • Safe to use in confined spaces. • Replenishable on site. • No pesticides or substances with toxic byproducts.	For long term missions sustainability is essential. [49]	Inspection

Since writing the requirement document is an iterative process, it is open for change in every project stage. All previous versions are archived, including any changes made to them. The most recent version can be found in Appendix A. To increase traceability, the requirement-ID from the respective source can be found in the full requirement document if they were already defined as such. IDs that are assigned to a requirement once are not reassigned to others. To allow for the addition of related requirements or the division of requirements, the last ID-digit is reserved for these cases. The separation of two requirements was, for example, the case for FR-OP-020, which previously included the adherence to EU work safety standards, since it was not specific enough. Besides noise and operating conditions, FR-OP-021 resulted from this separation.

3.5. Resulting selection criteria

Besides the upkeep of the root environment, high durability, ease of maintenance and repair, safety, timely failure identification, and easy-to-use man-machine interfaces are other key factors [13]. As a preparation for the concept selection, several criteria are derived from the requirements. To make sure every requirement is represented by the criteria, they are included in the verification column in the requirement document in Appendix A. Subsequently, the criteria are compared pairwise and a weight is determined using the AHP. The selection criteria with the respective weights can be seen in Table 3.6.

Criteria	**Notes**	**Weight** [%]
Safety (S)	Risk of crew or system damage	26.7
Reliability (R)	Failure tolerance, technology readiness level, and robustness	21.0
Maintainability (M)	Necessary crew time, effort, and ease-of-use	15.8
Yield (Y)	Expected yield, effectiveness (for components not directly associated with the yield)	15.8
Sustainability (Su)	Resupply, production effort on site, and resource efficiency	8.1
Mass (ma)	System mass	3.8
Volume (V)	The volume that can not be utilized otherwise because of NDS components	3.8
Flexibility (F)	Controllability, modularity, and scalability	2.9
Power (P)	Electrical power usage	2.1

Table 3.6: Selection criteria derived from the requirements.

Considering the high per kg launch costs, the difference in material costs between the design choices will be overshadowed, thus making the cost score negligible to the other criteria. Therefore, it is intentionally left out. The impact of the system complexity on cost and assembly of the different designs is considered negligible, while an increase in points of failure or a higher effort of the crew is taken into account by reliability and maintainability.

In the AHP pairwise comparisons between the selection criteria are used to determine the overall weights of each criterion. To compare the importance of one criterion with another, specifically for quantifiable criteria such as mass, volume, yield, and power, the Equivalent System Mass (ESM) can be used as a guide. The ESM is a measure to determine the overall launch cost by estimating the mass over an entire mission scenario for a given design solution or architecture. Although it is not used for the complete trade-off in this thesis, as this would reduce the transparency of the selection process, it can provide some insight into the relative importance of various design aspects.

As an example, an assumed baseline NDS design has an estimated mass of 766 kg, a power consumption of 660 W, a system volume of 4.52 m^3 and an estimated yield of 2160 kg (90 kg/month) during a two-year mission. These are the preliminary estimates for the EDEN NextGen GHM. An alternative design option has a 1% increase in mass, power, and volume but also provides 1% more yield. The ESM provides conversion factors for power, volume, and other parameters, to get the equivalent cost in terms of mass. Taking the worst-case conversion factor for the power generation using photo-voltaic cells and a battery storage system, 476 kg of launch mass are estimated per kW of power consumption. The volume for inflatable lunar surface modules is converted by 133 kg/m^3 [53]. This way, the relative cost, or importance, in kg, of a 1% change in any of the aforementioned criteria is estimated.

Applying these numbers to the alternative design option, a 1% increase in mass has a cost of 7.66 kg, while a 1% increase in power and volume costs around 3.2 and 6 kg, respectively. A 1% increase in yield results in an additional 21 kg of output, justifying an increase in equivalent system mass of 21 kg. Based on these numbers, a rough pairwise comparison suggests, that mass is about 2 to 3x as important as power, with yield being about 3x as important as mass. Since two years is the lower boundary and the mission might last for 10 years, the yield is, instead, scored 4x as important as the mass. Consumables like stock solution, acid, and base are not taken into account since the goal is a closed-loop system. Purely following this logic, the mass should be valued at about 1.5 times the volume. The total estimated mass of the GHM is 5736 kg for the subsystems and 8900 kg for the structure. With a payload capacity of the Falcon 9 of 22.800 kg even after accounting for debris shielding and other elements for transport, a large margin is already included. Since the fairing size is set and an increase in volume would decrease the space the crew can operate in, thus reducing maintainability, the two are defined to be equally important.

Although there are some estimations of the ESM of the other criteria, the values are dependant on a multitude of factors that are all undefined in this mission. Therefore, the comparisons between them are made on a relative basis. The safety of the crew is of the highest importance. As described above, a system failure is not considered an event endangering the lives of the crew. However, since reliable food production is the purpose of the entire system, this is the next priority. Since yield (productivity) is the measure of success, it is rated the same as the crew time and, therefore, the maintainability. A 10% increase in yield and a 10% increase in required crew time are regarded to balance each other out since the effort to yield ratio stays the same. Since the system is supposed to be a closed-loop system, any detrimental substances that are not recycled stay in the system indefinitely or require some sort of disposal and, therefore, resupply. For long-term missions, this may result in high mass penalties. Therefore, sustainability is rated higher than the rest of the ESM factors above. Finally, the importance of flexibility of the NDS can be easily compensated by a well-planned plant selection beforehand. It is therefore valued somewhere between power, mass, and volume. This is not to be confused with the modularity of the greenhouse as a whole in combination with the habitat, but with the effort needed to adapt to a different distribution of tall or small growing plants.

$$\mathbf{W} = \begin{array}{c} \\ S \\ R \\ M \\ Y \\ Su \\ ma \\ V \\ F \\ P \end{array} \begin{array}{c} \begin{array}{ccccccccc} S & R & M & Y & Su & ma & V & F & P \end{array} \\ \begin{bmatrix} 1 & 4/3 & 5/3 & 5/3 & 5 & 7 & 7 & 8 & 10 \\ 3/4 & 1 & 3/2 & 3/2 & 4 & 5 & 5 & 6 & 8 \\ 3/5 & 2/3 & 1 & 1 & 3 & 4 & 4 & 5 & 7 \\ 3/5 & 2/3 & 1 & 1 & 3 & 4 & 4 & 5 & 7 \\ 1/5 & 1/4 & 1/3 & 1/3 & 1 & 3 & 3 & 4 & 5 \\ 1/7 & 1/5 & 1/4 & 1/4 & 1/3 & 1 & 1 & 3/2 & 2 \\ 1/7 & 1/5 & 1/4 & 1/4 & 1/3 & 1 & 1 & 3/2 & 2 \\ 1/8 & 1/6 & 1/5 & 1/5 & 1/4 & 2/3 & 2/3 & 1 & 3/2 \\ 1/10 & 1/8 & 1/7 & 1/7 & 1/5 & 1/2 & 1/2 & 2/3 & 1 \end{bmatrix} \end{array} ; \; NEV = \begin{bmatrix} 26.7 \\ 21.0 \\ 15.8 \\ 15.8 \\ 8.1 \\ 3.8 \\ 3.8 \\ 2.9 \\ 2.1 \end{bmatrix} \tag{3.1}$$

The AHP matrix 3.1 shows the pairwise comparison to determine the individual weights. The corresponding maximum Eigenvalue to this matrix is $\lambda = 9.16$ which leads to a consistency index CI of

$$CI = \frac{\lambda - n}{n - 1} = 0.026. \tag{3.2}$$

Since the number of criteria n equals 9, the consistency ratio CR with the random index $RI = 1.45$ is calculated to be CR =1.42% which is below the 10% threshold and therefore consistent. The normalized weights for the individual selection criteria are then determined by the Normalized Eigenvector (NEV) in equation 3.1.

4 Conceptual Design

In the previous chapter, the state of the project was analyzed from a variety of viewpoints. Further thoughts to enable informed decision-making were presented and critical elements in the design were identified. Building on this knowledge, a conceptual design is presented in this Chapter. First, a design option tree is established with tried and true as well as less well-known concepts. Subsequently, the decisions are justified in trade-offs. Infeasible or practically dominated options, meaning viable options that are inferior in at least one of the analyzed categories and superior in none compared to at least one other, are eliminated, while others are compared by the scores defined in 3.5.

4.1. Design Option Analysis

Figure 4.1 shows the functions of the NDS and the different options of fulfilling them. Although some of these have been implemented and proven to work in the MTF, decisions that might have a large impact on the system design, based on the selection criteria, are reconsidered. For simplicity, only the subcategories of the selected options are shown. Chosen concepts are colored green, while eliminated ones are colored yellow. In cases where the outcome can not be determined by elimination alone, each option shown in white is scored on a scale from 1 to 5 and an overall score is calculated based on the weights. The decisions with the highest impact on the rest of the concepts are made first. That is why the cultivation method can be found very high in the tree, while the equally important decontamination method, which greatly depends on the storage methods, is found lower. For simplicity, some levels are left out as their decision was straightforward and would distract from the important ones. Further thoughts on even smaller concepts are shared within the respective subsections.

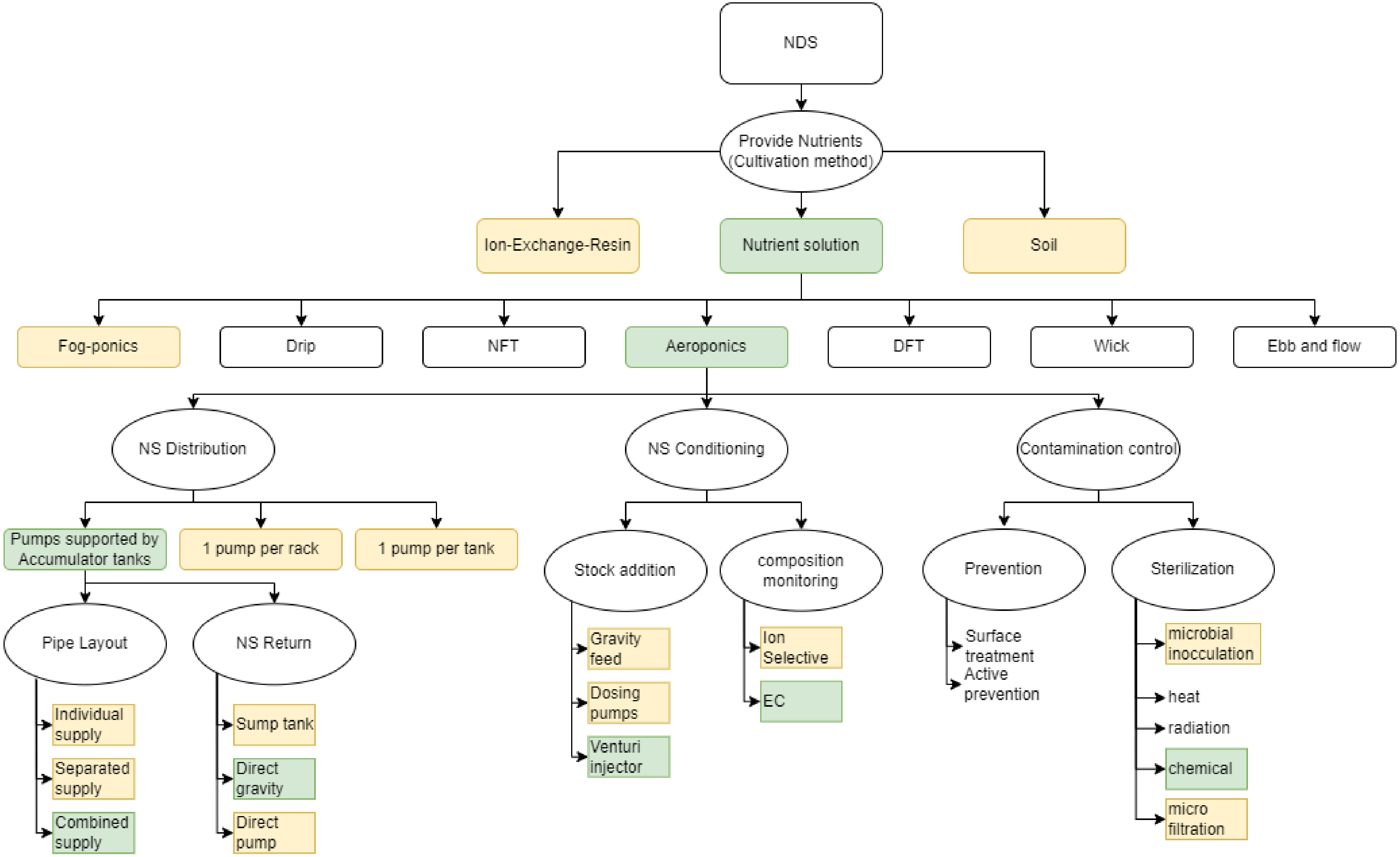

Figure 4.1: Design option Tree.

4.2. Trade-Offs

Each trade-off follows the same steps. First, the potential options are introduced. In case any designs are eliminated immediately by violating any hard constraints or requirements, it is mentioned then. In case the decision is not explained by arguments or requirements, a trade-off table is used to determine a numerical score.

4.2.1. Cultivation Method

The type of cultivation method that is most suitable for the given circumstances has a large impact on all other decisions. Furthermore, since the options are all preferred in different applications due to their strengths they bear a large potential for improvement. Therefore, this aspect is considered first. In Chapter 2, the different types of NDS were introduced. Due to the growth disturbing properties of aluminum in lunar and martian soil, this cultivation method is infeasible since it requires bringing along soil from Earth or novel technologies to process regolith [35]. These are not yet advanced enough to rely on and are, thus, already eliminated by requirement FR-TI-010. The example system from Chapter 2.2.2 showed that ion exchange resins were often used in actual applications for space due to their high nutrient density. Since the production usually requires oil and other synthetic substances [41], recycling on-site is not feasible. Thus, a focus is put on nutrient solution-based systems with higher re-usability. These are more suitable for long-term missions. In this section, hydroponic cultivation methods are compared with respect to the aforementioned selection criteria. The APS as mentioned here is defined as the system developed for the MTF. The NDS was designed as an APS with slightly reduced root space [43]. This design negates the volume disadvantage of a pure APS while providing an efficient nutrient and oxygen supply. Fog-ponics is eliminated since the TRL is not advanced enough to estimate the scores reliably. Since all other concepts are legitimate choices and can not be ruled out right away, the numerical scheme is used. In cases where numerical values can not be found, relative scores are used.

	Weight	NFT	APS	DFT	Wick	Ebb/Flow	Drop
Safety	26.7	4	4	3	5	3	4
Reliability	21.0	4	3	4	5	4	4
Maintainability	15.8	5	4	3	3	2	2
Productivity	15.8	3	5	2	1	2	1
Sustainability	8.1	4	5	3	2	1	1
Mass	3.8	4	3	1	5	2	4
Volume	3.8	4	5	1	5	3	3
Flexibility	2.9	4	5	2	1	3	3
Power	2.1	3	3	4	5	4	4
Score	100	397.90	404.70	289.20	369.30	271.50	290.00

Table 4.1: Cultivation method trade-off.

The scores reflect the most common usage for the individual systems. The ”Ebb and Flow”, as well as the ”Drop”-system, is rarely used in any large-scale farm or highly technical field of application. Using substrates as support makes them less controllable and adds a component that needs to be maintained. Moreover, they provide optimal growing conditions for pathogens. On the other hand, it provides a better buffer to failures as it can hold NS for a while. Nevertheless, these systems are ruled out, especially due to the increased maintenance effort. The cost advantage of DFT compared to NFT and APS does not matter as much in space missions. Additionally, a large amount of NS is locked up in circulation, which in turn requires a higher decontamination effort. These bulky systems are, therefore, ruled out as well. The wick system, the NFT, and the APS all score comparatively high. These are also the most used among the analyzed systems.

While wick systems also require a growth medium, there is no need for power-consuming and moving components, giving them a high reliability and safety score. Due to their low mass and high reliability, they were used in a series of space-flight applications [3]. However, they are not as easily scalable, as they require a tank close to the growing trays for the wicks to deliver NS. Furthermore, they are not controllable precisely enough to keep up with the higher yields of other systems.

The NFT, on the other hand, requires active pumps to keep the NS flowing, increasing the power consumption. A power outage or a pump malfunction, for example, results in immediate drought. This can be catastrophic for the harvest in a comparatively short time since no buffer is available. Although this is also the case for APSs, these two systems score best for the given circumstances in the EDEN NextGen. The most substantial advantage of the NFT is that no high-pressure components are necessary. That reduces the complexity and, therefore, the probability of failure. On the other hand, constant contact with the fluid increases the infection risks and spread.

Since the NS in APSs is directly atomized on the roots, contact between plants is minimized. In combination with the superior oxygenation, this drastically lowers the risk and spread of plant diseases [54]. Although, reducing the tray size, such that the roots of plants in advanced growing stages are in contact with the tray, increases the risk of spreading infections, this reduction in reliability is small compared to the other aspects since the amount of NS in contact with the roots is significantly smaller (i.e. ml/min instead of l/min) than in NFT systems. The MTF and the studies at the Guelph University have shown that this is acceptable compared to the high yield to volume ratio that is achievable [43]. The increased oxygenation and the high controllability of the system also increase yield by up to 20%, compared to other closed-loop cultivation methods, since the nutrients can be taken up under optimal conditions [40]. Since the oxygen does not come from the dO content, the artificial introduction of oxygen into the NS is not required. Due to a significant amount of heat exchange with the air during the misting process, temperature control is more difficult than in other systems [55]. Therefore, the higher complexity due to the necessary high-pressure components is offset to some extent. A section with the pressure of the MTF requires some precautions in terms of maintenance and safety but, if handled correctly, does not bear any critical risks. The safety difference, due to the high pressure, is compensated by the increased susceptibility to pathogens in the NFT. The reduced score in reliability of the APS is mainly because the misting nozzles tend to clog easily due to crystallization of fertilizers, plant residues, or microorganisms. Furthermore, the reduced root space bears the risk of roots growing into the drainpipe and clogging it. Therefore, more effort has to be put into the maintenance compared to an NFT.

The flexibility and scalability are largely dependent on the exact configuration. Therefore, the score was iterated after the trade-off about using an accumulator tank. The result is very high scalability without the immediate need for more pumps. Since the duty cycle of the pumps is generally only a short period, the increased flow rate can be buffered by adding accumulator tanks. Although the pumps and the accumulator tanks in pressurized systems are larger than others, the low throughput of NS allows for a smaller mixing tank and, therefore, an increased volume score.

Although this fact is not considered in the rating, since it is not included in the system objectives, the NFT is not suitable at all for micro-G applications. In case this system is at some point used on transition flights, this fact might tip the scale in favor of the APS since the scores are very close together. Furthermore, the APS has already been developed to a high degree at DLR. The gained experience through first-hand lessons learned increases the confidence in the system. Although the NFT score is almost the same as the APS score, the tried and true option is chosen, as the overall score and the additional aspects suggest.

Accumulator Tank

For the integration of accumulator tanks, three different scenarios are considered. The first option is a configuration as currently used in the MTF. One high-pressure pump supplies one rack respectively and each tank can supply each pump. The second one includes a reduction of the active pump count to one per tank with adaptable connections to the different racks. In the third configuration, accumulator tanks, as seen in Figure 4.2, are implemented to enable constant pressure in the system. An accumulator tank acts as a buffer for NS. Since liquids are incompressible, a gas-filled bladder is used to compensate for volume changes due to an in- or out-flow of NS while keeping the pressure within predefined boundaries.

When using one high-pressure pump per plant rack to distribute the NS, a direct connection between the pumps and the misting nozzles is required. Since the provided NS is incompressible, the flow rate of the pump needs to be the same as in the nozzles. The feed-line can be switched between the different bulk tanks, making it possible to use both NS compositions for all racks. Indeed it is possible to feed all trays using one bulk tank in case the other one needs to be cleaned or replaced. Manual three-way valves minimize the effort for a change. However, this increases the necessary amount of piping. The resulting increase in maintenance time for cleaning was found to outweigh the advantage of short recombination times [12]. Moreover, if additional racks are added, each one would require its own pump. Since multiple pumps are used, the chances of failure are higher and, therefore, more spare parts or redundant parts need to be brought.

In this configuration, the misting cycles are simply regulated by turning the pump on and off. This has the advantage of low-pressure phases, in which the pump allocation can be adapted without problems and maintenance can be conducted. In case the pumps have roughly the same amount of plant trays to supply and, therefore, about equal flow rates that fit the design specifications of the pumps, no problems would arise with this system. However, since not all racks have the same amount of nozzles and these are prone to clogging, pressure spikes can occur. The internal pressure regulator of the pump will correspondingly turn off the pump to protect the mechanics. Since no buffer is available, the pressure immediately drops under the shut-off pressure resulting in high-frequency pump cycling, which is detrimental to the lifespan of the pump. The discrepancy between the maximum necessary flow rate and the actual flow rate affects the frequency of the shuttering since the pressure can build up faster. Thus, scalability of the available pumps is hard to achieve, and supplying different flow rates at the same pressure requires different or more complex pumps.

The second configuration would only consist of one larger pump for each of the tanks. This system reduces the complexity in terms of pump count. However, if the entire greenhouse needs to be supplied from one tank, the pumps need to be designed such that they can deliver a very high flow rate. This increases the discrepancy between the maximum and the nominal flow rate, increasing the shuttering effect of the pump. Moreover, the trays are further away from the pumps resulting in a high dynamic pressure drop along the feed lines. Since this is dependent on the length of pipe, the distribution of NS between the closer and the further trays is inconsistent. Furthermore, this requires the three-way valves for the distribution to be in the high-pressure section, which has to be considered in the component selection.

Figure 4.2: An accumulator tank [56]

The third configuration aims to reduce the number of pump cycles by adding an accumulator tank as a buffer for the NS. A constant high-pressure part is established, eliminating pressure spikes. The misting cycles are then regulated with solenoids and, therefore, decoupled from the pump cycles. In this case, the NS for each cycle is supplied by the accumulator tank, while the pumps are only used to refill the tanks once the system pressure drops below a predefined value. The duty cycles can be continuous without rapid on-off cycling, thus enhancing the expected lifetime of the pumps. The amount of accumulator tanks is influenced by their respective design and is not directly considered here. However, an accumulator tank is preferable to a pump as the tanks are usually cheaper and lighter. Moreover, an accumulator tank fulfills Requirement FR-OP-0070, generally only requires little maintenance, and has no moving parts that are prone to break [57]. In addition, the pumps only need to provide a small flow rate since the tanks can be refilled during the long dry periods. With a misting cycle of 30 s every 330 s, the maximum pump-flow rate can theoretically be lower than 10 % of the flow necessary to supply all trays at the same time.

However, some downsides have to be considered as well. In this alternative, exchanging a pump or a change in the tray allocation would require depressurization of the entire system. During nominal operations, fragile parts like valves would, furthermore, also be under constantly high pressure requiring sturdier designs. Since experiences in the MTF showed that changes in the distribution allocation are rare, rearranging the piping for these occasions is an acceptable solution without violating Requirement FR-TI-0040 in case manual valves are too fragile. Another point to consider is the increase of NS locked up in the system. More stagnant NS increases the susceptibility to pathogens and the amount of wasted NS whenever it is unusable due to pathogen or nutrient salt accumulation. In addition, a change in the solution composition is delayed since the left-over NS in the tanks is supplied first. On the other hand, it adds a buffer that still provides NS for a short time during a pump malfunction. This gives the crew valuable time for maintenance before the plants suffer from drought. As long as the flow rate of the pump is not the absolute minimum required, additional trays can easily be added in combination with more accumulator tanks. Since the pressure is kept closer to the point of use, dynamic pressure loss is kept to a minimum.

In conclusion, the first two choices are inferior to the third choice in almost every selection criterion except sustainability. While using an accumulator, the amount of drained NS, in case of a strict monthly exchange, is slightly increased, due to an overall higher volume of NS in the system. This can, however, be offset by the increased buffer capability and the resulting decrease in tank capacity. Most of the risks concerning safety can be addressed by a suitable design and maintenance strategy and can, therefore, be mitigated. Overall the third choice practically dominates the others. Architectural considerations are not made yet as the component size plays a crucial role in the amount and positioning of the accumulator tanks.

4.2.2. Functional infrastructure

Tanks

The most impactful decision in this section is whether or not the returned NS is first collected in a sump tank as it was in the MTF, where the bulk tanks were placed above ground for accessibility reasons. Since only a limited amount of NS flows back from the trays, a pump directly back to the bulk tanks was not favorable. Therefore, the excess NS was collected in a sump tank until it was enough to pump back into the bulk tank. The sump tank was located in the sub-floor compartment to enable gravity return. It was, however, not connected to the ozone generator making the stagnant NS a good breeding ground for bacteria. Compared to a pure gravity return-based solution, the use of pumps adds moving parts, thus reducing the reliability and increases the maintenance effort.

It was already suggested in the lessons learned that removal of the additional tank's sensors and pumps can lead to a simplified design. To enable this, a gravity feed to the bulk solution tanks would be preferable. For this design solution, the bulk tanks need to be placed in the sub-floor compartment. With some precautions in terms of accessibility, there are no downsides, making this configuration an inferior choice to the design in the MTF. As a result, the sump tank is eliminated from the design choices. One of the design aspects to consider is the sub-floor space to enable accessibility even if the tanks are not above ground. This, however, requires the tanks to be in the deployable part since the sub-floor compartment under the corridor in the solid part is occupied by the AMS.

Since the additives are injected locally in a large tank, the NS is not immediately homogeneous. Furthermore, salts can precipitate in periods of stagnation. To prevent these effects, a stirring mechanism has to be included. In the MTF this task was accomplished by a small submerged circulation pump. In larger commercial applications, a separate tank for the mixing process is often implemented. This is preferable since the stock solutions are highly concentrated and mixing these immediately into the existing bulk solution can cause regions with stronger concentrations. When the NS is constantly delivered to the plants directly from the mixing tank, without the necessary time for homogenization, the plants can receive sub-optimal NS. As a result, only very small amounts can be added at any given time in case direct mixing in the bulk tank is preferred.

Since the acid also affects the EC and the stock solutions have a small effect on the pH, all constituents have to be added simultaneously in case the NS is mixed in the bulk tank [52]. This makes the usual process of first adding the entire water, then the acid, and finally the stock solutions infeasible. To not exceed the acceptable ranges, the constituents need to be added more frequently and the amounts need to be estimated more carefully. Since only small amounts can be added at a time, negative effects of the recirculated NS have a more significant impact on the composition. With a dedicated mixing tank, this process can take more time, while the separate delivery cycle can provide NS to the plants. Then only the pre-mixed solution is added to the bulk tank. The composition of it is not the desired one but takes the changes in the NS due to nutrient uptake of the plants into account. Therefore the tank could be sized to barely fit the amount necessary to supply in the desired frequency.

The use of accumulator tanks should provide enough time for the nutrients to be mixed before new NS is pumped into the high-pressure section. Replenishment has to be planned frequently enough that only small amounts of stock solution need to be mixed into the bulk solution. This way, homogenization can be reached in-between two pump cycles. These factors are considered in the detailed design of the accumulator tank volume, the bulk-tank volume, and the refill frequency. Therefore, a configuration that uses accumulator tanks would not benefit significantly from having a separate mixing tank, and the advantages would not compensate for the increase in mass and volume.

The last design option that is discussed concerning the tanks is how samples can be taken with the least effort. One is taking them directly from the tank. Although the tank can be accessed for cleaning, a simpler method for this task can easily be designed since the pump and the piping close to the workbench are available anyways. Therefore, this method is eliminated. To reuse existing infrastructure, the mixing pump or the high-pressure pumps can be used. The change necessary to use the mixing pump is relocating the pipes from inside the tank to a work location. The alternative of using NS from the high-pressure section requires only a pressure reduction and a manual valve since piping is already available at the workbench in the EG. A further advantage is that the samples are taken from the exact NS composition that reaches the plants and, therefore, yield the most useful information.

In conclusion, if the bulk tanks can be fit into the deployable section, no sump tank is implemented due to the additional complexity and the obsolete advantages. A further tank for mixing is not implemented but suggestions for the sizing of the individual components are made to replicate the advantages of such a system. Sampling is enabled by adding a pressure reduction valve at the work bench in the deployable section, since piping and pumps are already available.

Piping and Transport Configuration

In the piping, several design-dependent parameters have to be considered concerning the selection criteria. The overall length of the pipes influences the mass of the system. The fittings at which the pipes need to be assembled pose weak points for leaks which affect the reliability and the maintainability of the system. On the other hand, the transport constraint limits the length of each pipe segment in case they are chosen to be rigid. Requirement FR-OP-040 implies that the entire system shall be able to be supplied by either of the tanks. During nominal operation, one tank supplies fruit-bearing crops, while leafy greens are supplied by the other. A deviation from the initial allocation requires a change in the supply lines. The ease of this task affects flexibility as well as maintainability.

To assess this aspect, it is necessary to define the aim of this allocation change. The first option is an emergency change in case the pumps or the composition control of one of the tanks fail. The composition of each tank is optimized for specific plants and can drastically differ from the others. Therefore, an emergency swap that has to occur in just a few minutes is only advantageous in case of a complete pump failure or extremely deviating compositions. This scenario was identified as critical, but not catastrophic and, therefore, one-failure tolerance is deemed necessary. Since a failed pump inevitably needs replacement, redundancy is already implemented on the component level. The other scenario in which switching is necessary is a long-term adaptation of the plant allocation. From the lessons learned, it is evident that this event does not occur frequently, allowing for larger changing times in favor of general maintenance reduction.

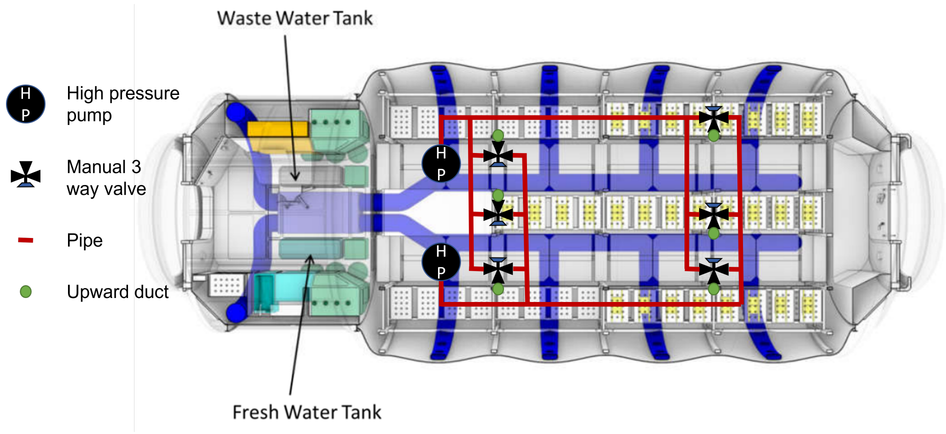

Figure 4.3: Simplified schematic of a configuration enabling the individual allocation of each upward duct to each pump.

Another scenario is the maintenance of the tanks. Here again, two cases can be examined. One is batch cultivation, in which all plants of a similar kind are harvested at the same time. After each such period, the tanks can be cleaned while no plants are present. In this case, a change in the tray allocation is only applicable if the maintenance is unscheduled, which is unlikely. The other case is continuous cultivation in which saplings are transplanted as soon as the more mature plants are harvested. Due to the different cultivation times, some plants are always present, which is preferable to achieve a constant food output without production spikes during harvest or lows during earlier growing phases. This is especially important when only one GHM is used. For the unscheduled as well as the scheduled maintenance, the second case might necessitate the supply of the sub-optimal solution for a short while. In both cases, the entire system is supplied by one tank and no individual allocation of trays is necessary.

The above scenarios for short-term changes both lead to the supply from the same bulk tank for all racks at the same time. Only the long-term scenario requires a more precise allocation of the racks. After discussion with the stakeholders, it was determined that combined supply lines for two racks at a time are desirable for a trade-off between the number of pipes and the flexibility [52]. This results in two upward pipes at the second and fourth frames in each of the respective racks.

With this information, the design options are now presented. The first one is analog to the MTF design in that both tanks have one long supply line along the axis under the outer racks. From there, pipes are routed to the upward ducts, which are connected to the trays. For every rack, manual valves are used to open the channel for the NS of choice. The one way length of pipes as seen in Figure 4.3 would amount to 2x 4 m + 4x 2.7 m = 18.8 m. The preliminary architecture suggests that this design can be realized with a minimum of 21 fittings. These already include directional changes. Accumulator tanks and fittings between the tanks and the pumps are not included in this estimation as these are necessary for all configurations. The flexibility of this design is the highest of the presented options. The biggest downside of this configuration is the high amount of fittings and longer pipes, posing a higher risk for leaks. Furthermore, a leak or maintenance in one of the main lines makes the entire respective NS cycle unusable. This design offers the best accessibility for sample taking since both tanks have a constantly pressurized part close to the work table.

Another possibility is a circular design, as seen in Figure 4.4. Here the two cycles share the same pipes. Different sections of the network can be cut off from the undesired NS cycle, which achieves almost the same flexibility with fewer fittings and fewer pipes. Using eight manual three-way T-valves and two three-way fittings, this system can supply all racks with the desired NS. It is, however, only possible to supply continuous parts with the same NS.

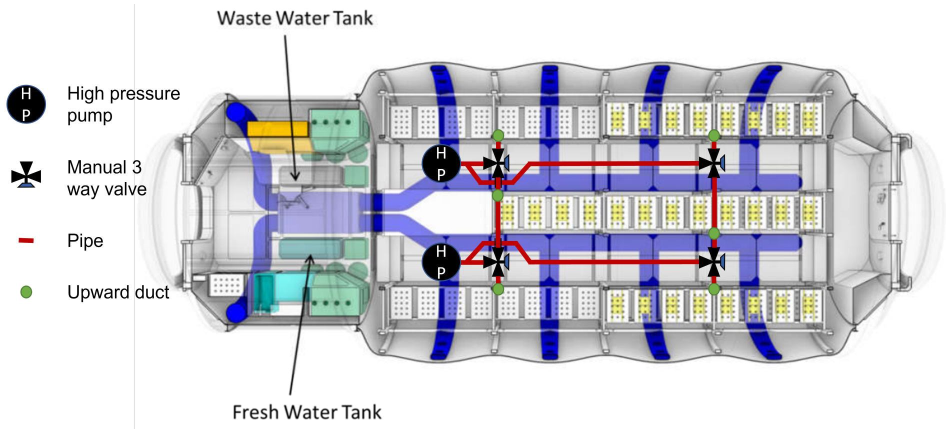

Figure 4.4: Simplified schematic of a circular piping design to minimize the number of fittings and the length of the pipes.

The third design to be considered is routing the pipes from the tanks only to the predetermined racks. Taking into account that in this configuration no manual valves are necessary the number of fittings would reduce drastically and only $\approx 11\,m$ of pipe would be required for the sub floor section of the supply lines. Since this design requires complete re-plumbing in case the allocation is changed, four end caps are included to enable the addition of pipes as in design 2. In addition to the small number of parts, no pipe in this system contains stagnant NS. This reduces the risk of pathogen formation since the sheer forces of the flow hinder biofilm formation. However, this design offers the least flexibility and no way to supply all racks quickly with the same NS in case of an emergency. Additionally, the last two designs require extra pipes for sample taking via the high-pressure pumps.

One problem not yet discussed is the gravity-based return. If option 2 is chosen, the return line does not have a gradient since it would have to be possible for the NS to run in both directions depending on the current allocation. To tackle this problem, a hybrid design between options one and two is introduced. Here the supply line is designed as in option two, while the return line is designed similar to the return in the MTF. This way, a sufficient gradient for gravity return can be ensured. Due to the small height difference available, the exact design of these pipes, however, requires a location for the bulk tanks to establish a sufficient gradient for the return in moon gravity. To determine the locations, the exact tank size is necessary to know. This decision is, therefore deferred to Section 5.1.5. Since ball valves are highly reliable, the flexibility of switching freely and being able to remove pipes for maintenance by closing the respective valves compensates for the modest reduction in reliability of option two [58].

As per Requirement SO-NDS-021, the parts in the SES of the GHM shall be pre-installed, while the parts of the EG can be assembled on site. Since the membrane and the floor panels block most of the deployable section in the stowed configuration, rigid pipes in axial direction need to be stored in the SES and are assembled on-site. Otherwise, they need to be limited in length to the diameter of the stowed frames. The maximum length is, therefore, around 3800 mm. A length of less than 2700 mm is preferred to attach the pipes to the rectangular inner frames. If limited to 2000 mm they can be directly attached to the floor panels and simply have to be connected on site. The radial pipes in all three designs can be pre-assembled since they are attached to the rigid part of the frame.

The other option is the use of flexible hoses. These might allow for complete pre-assembly. One possibility is the use of braided stainless steel hoses with Poly (Tetra Fluoro Ethylene) (PTFE) inlay. These are optimized for high pressures and are easy to handle and clean. Moreover, they are corrosion resistive and the PTFE is well suited to prevent biofilm formation. Cleaning of the outside can, however, lead to challenges. A further option is using the same material as in the MTF pressurized section. It is, however, not sure if the bending radii are small enough to fit within the stowed configuration until the exact pipe diameter is known. Furthermore, strong structural mountings are necessary for flexible hoses in high-pressure applications.

If attached to the floor panels and the structural frames, a rigid piping system would not require overly long assembly procedures. It would, however, increase the structural integrity of the system. The most significant advantage of flexible tubes is therefore seen in easier maintenance in case they are removed. This is, however, less relevant due to the infrequent removal of tubes observed in the MTF and does not compensate for the more complex cleaning procedure of the tube outside. Therefore, rigid piping is chosen for the supply lines.

As discussed in the lessons learned section, instead of Polyvinyl chloride (PVC) tubes, metal pipes are recommended for the feed lines to prevent leakage. Therefore, stainless steel with food-grade surface roughness is used. If deemed worth the effort in further studies, a PTFE coating should be considered. To accommodate Requirement FR-OP-060 and lessons learned LL-015, the same pipe sizes are used for the return ducts.

4.2.3. NS Conditioning

Temperature Control and Oxygenation

The temperature of the NS is one of the factors that is supposed to be controlled and monitored according to requirements FR-NC-010 and FR-NC-020. When consulting about this topic with Markus Dorn, the DLR expert for plant biology, this was attributed to the increased dO capacity of colder water [52]. A lower temperature allows for more dO and is, therefore, preferable down to a plant-specific minimum temperature [59]. Since the main advantage of an APS is the high oxygenation due to air contact of the roots, the dO of the solution is not as impactful as in other hydroponic systems. Nevertheless, at least monitoring of the temperature and the dO should be included for a complete picture of the system parameters.

For test purposes, a cooling unit shall be included as a black box in the design. The cooling coil black box is directly placed in the bulk solution tank since this is the main point of oxygenation. To utilize the benefits, some means of increasing the dO needs to be included as well. This showcases one advantage of using ozone as a decontamination agent in the trade-off in Chapter 4.2.4 since the air stone, as well as the venturi-injector, can be re-purposed for oxygenation. Therefore, only some easily implemented architectural considerations have to be taken into account for this.

Simple implementations in the piping are, for example, that the NS should cascade from the return pipe to fall through clean air. Furthermore, the surfaces of tanks and pipes can be colored white to reduce heat taken up from surrounding radiation. Options like sprinklers that require more components and can not be realized by already available infrastructure are not considered necessary.

Composition Control

A further control parameter from Requirement FR-NC-010 is the nutrient concentration and the acidity of the NS. The trade-off between ion selective and EC based measurements introduced earlier is discussed in detail here. Furthermore, common practices of control strategies are introduced and their impacts on the design are assessed. In this design iteration, it is assumed that the nutrients are provided in the form of two individual nutrient solutions. At the beginning of the mission, powdered nutrient salts are used due to easier transportation. Since the exact compositions of these solutions are known, at least partial control can be exerted on the ion composition of the solution according to requirement FR-NC-032.

Another approach, as used in Cho et al. [21], is to provide a multitude of stock solutions that allow for different ions to be added separately. In that case, however, inline measurements or at least frequent manual samplings are required. Furthermore, a method to separate the ions from the waste into different stock solutions is necessary, increasing the complexity of the waste processing unit in the habitat.

As explained in Chapter 2, the accuracy of ion-selective electrodes is strongly affected by signal drift, and the sensitivity is reduced over time. Therefore, they need to be re-calibrated regularly [21] increasing the maintenance effort. Furthermore, the usable lifespan is comparatively short [60]. In addition to the high cost of these systems, the current state of the art does not allow for stand-alone continuous inline measurements. Thus, it can only be used in a separate sampling cycle or via manual test samples, reducing the score in maintainability, mass, volume, and power consumption.

The main advantage of ion-selective measurements is an increase in sustainability due to less NS that needs to be disposed of. Furthermore, in case this is automated, the complexity is increased, thus reducing the reliability. Estimations suggest that complete control of individual ions could increase the overall yield by about 10% [52] compared to simple EC control and regular disposal. This, however, would also require the possibility of adding the ions individually. Since the current assumptions do not allow for individual addition of ions, the NS will still have to be disposed of regularly. Thus it is only useful to minimize the waste by enabling a more accurate timing. Finally, since it is assumed that the NS composition is known, the lessons learned from the MTF can be used to estimate the timing with only EC measurements quite accurately.

Ion-selective measurements are, therefore, superseded by the simpler approach of pure EC measurements. Current advances in the development of ion-selective measurement techniques should be watched closely and sampling for manual measurements should be made possible. The sensors can be incorporated as a modular black box segment for later addition once the TRL is more advanced.

As mentioned in Chapter 2, the two stock solutions should not be combined in high concentrations. The addition should be managed separately with individual cycles and components. To add the individual constituents dosing pumps, gravity feed with valves, or venturi-injectors can be used.

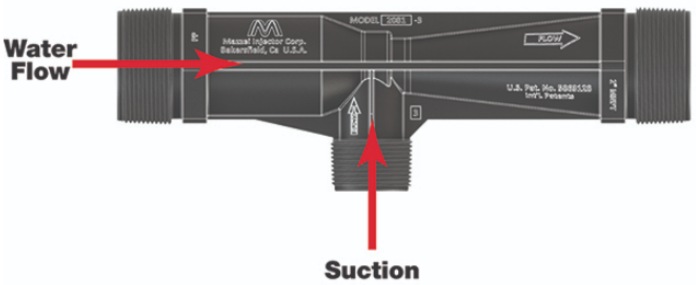

Figure 4.5: A venturi-injector by Mazzei [61].

Venturi-injectors, as seen in Figure 4.5 or gravity-fed valves, are generally more durable. Dosing pumps, on the other hand, are precise and were proven to work without issues in the MTF. To fulfill Requirement FR-NC-010 concerning the accuracy of the EC control, it is necessary to control the volume of stock solution which is added to the bulk NS. Assuming a linear relationship for the change in EC in the bulk solution tank as a result of adding stock solution, the following equations can be used to determine the maximum amount of stock solution which can be added at a time without exceeding the control accuracy requirement.

$$V_{Stk}EC_{Stk} + V_t EC_t = (V_{Stk} + V_t)(EC_t + \Delta EC) \tag{4.1}$$

$$V_{Stk} = \frac{V_t \Delta EC}{EC_{Stk} - EC_t - \Delta EC} \tag{4.2}$$

With a target volume of $V_t = 250\,l$ in the MTF, a set-point of $EC_t = 2\,mS/cm$ and a 100-fold concentrated stock solution $EC_{Stk} = 200\,mS/cm$, the accuracy of $\Delta EC = 0.17 mS/cm$ translates to a stock solution volume of $V_{Stk} = 0.21\,l$. With likely lower concentrations and a higher tank volume, this will even increase. Typical peristaltic dosing pumps of this manufacturer have a flow rate of 15-160 ml/min [62] and the later chosen venturi-injector [63] has a flow rate of around 380 ml/min. The accuracy of the stock solution injection methods is, therefore, not a deciding factor in the trade-off.

Figure 4.6: The dosing pumps used in the MTF.
[43]

In the MTF dosing pumps, as can be seen in Figure 4.6, were used since the stock solution tanks were located below the bulk tanks. This necessity can be easily avoided, as the tanks can be placed freely within the GHM. Although the complexity of pumps is higher than that of a simple valve, the tank design for only using dosing valves results in even more complexity. In the valve configuration, the first choice would be a normally closed valve directly at the bottom of the container so the liquids can flow directly to the bulk tanks. This, however, introduces a potential leakage point that is always in contact with liquid. Furthermore, the handling of the containers is harder since the connection is more permanent than in the configuration with dosing pumps as implemented in the MTF. Since 20-30 % nitric acid can lead to irritations of mucus and is toxic even after short-term exposure to lungs, potential leaks, especially in the acid container, affect the safety aspect more than would be acceptable from the advantages. Although the dosing mechanism in the MTF led to leaks, this was only caused by non-acid-resistant tubing elements, which can easily be avoided.

In conclusion, an active mechanism is chosen since they are rated higher in safety, maintainability, and flexibility and are only inferior in reliability, mass, volume, and power which are overall less valued. Whether venturi-injectors or dosing pumps are chosen depends on other factors. If a separate mixing cycle is implemented, the venturi-injectors are the logical choice. Otherwise, dosing pumps are recommended. This decision is, therefore, delayed to the detailed design chapter.

4.2.4. Decontamination

Biological contamination poses a significant threat to the produce and the astronauts. Aside from the infection risk, these microbes form colonies in which they are suspended in a matrix of extracellular polymeric substances called biofilms. These cause bio-fouling of the underlying material and increase the rate of bacterial growth. Moreover, these biofilms can detach from the surfaces and clog nozzles and valves. Bio-fouling poses a risk to all solid-liquid interfaces, including materials like polymers, composites, and stainless steel [29]. This was addressed in the preliminary risk analysis since microbes can be the reason for most critical failures. Although providing an overall healthy environment for plants reduces the symptoms of diseases from these pathogens [29], preventive measures should be taken. These can be divided into the removal of microorganisms and the prevention of their formation. Since generally, substances that are detrimental to microbes can also harm the plants and the crew, this design aspect also has a serious impact on the safety of the astronauts.

Contamination Prevention

The structural and physiological features of microbial cells within biofilms make them significantly more resistant to adverse environmental conditions and, therefore, removal strategies. Consequently, procedures to avoid the formation of microbial communities are discussed first. For space flight applications, some of the most common pathogens can be avoided by a strict quarantine and sanitation procedure before departure. Since humans are part of the system, this method does not work for all microbial life. Besides the usual antimicrobial coatings as used in the ISS for wastewater treatment, other fields like food processing, industrial applications, medical technology, or shipbuilding offer more methods that might be useful.

Technique	Example	Notes
Low surface energy coatings	• Hydrophobic surfaces • PTFE coatings • Lubricants	Often used in medical applications, these have a high potential to reduce the cleaning effort and the formation of biofilms [64]. Due to their complex chemical structure, reapplication on site might be problematic.
Micro-topography	• Shark skin • Small diameter nano-scale pores (d ≈ 15-25 nm)	The surface mobility and strength of adhesion of microbes are reduced. Generally no complex chemical structure is necessary and no possibly toxic byproducts can be released. Manufacturing, however, is more complex and might be unfeasible on site, if renewal is necessary.
Biocidal coatings	• Chemical biocides • Metal ions: Ag^+, Cu_2^+	These may release possibly toxic byproducts that can accumulate in organic tissue and need more investigation. Furthermore, they need to be replenished after some time, although that might be longer than the mission duration. If used in a filter, these can even be used as a localized active contamination removal strategy.
Highly corrosion resistant coatings	• Stainless steel • Titanium alloys.	These do not necessarily prevent the formation of biofilms, but reduce the corrosive effects of bio-fouling and other corrosive reactions with the NS.
Signal disrupting coatings	• Chemicals • Enzymes	They prevent the formation of biofilms on a biological basis. The TRL of these coatings is not advanced enough to be considered in this thesis.

Table 4.2: Different types of coatings to prevent the formation of biofilms.

Especially food processing industries need to apply methods that are not harmful to the produce or the humans eating it. In some sorts of packaging, silver nano-particles are used as antimicrobial agents. Nickel, copper, or silver coatings are also often used in industrial food processing applications. However, little information about any toxic effects is available with both proponents as well as opponents [65]. It has, however, been shown that some elements can accumulate if ingested [65]. Since astronauts eat the food that is in constant contact with those particles if used in the NDS, more information is needed before incorporating them.

Next to these antimicrobial surfaces, there are coatings or surface topologies that reduce surface energy and the ability of microbes to adhere to the surface. This not only reduces biofilm build-up but also simplifies cleaning. Most of these methods were developed for stainless steel surfaces in food processing plants. Some are also found in ship coatings or occur naturally like sharkskin [30]. Some of the coatings used in ships, however, release biocidal compounds that need to be replenished after some time and that might be detrimental to the plants and the crew. A recently developed environmentally friendly ship coating that mimics the bio-fouling resisting properties of sea urchins was also taken into consideration. After E-Mail contact with the manufacturer ”Micanti”, this was however eliminated since it is targeted at larger organisms like shellfish or barnacles [66].

Due to an abundance of different working principles and even more types of coatings, these are not all mentioned here. More information can be found in [30, 67]. Table 4.2 shows some of the most common working principles with examples and thoughts on the application in the GHM.

Furthermore, the flow rate of the nutrient solution impacts the build-up speed of biofilms. Although this does not require a discussion here, it can be considered in the piping design. Slow flow rates impose low shearing stresses, which should be taken into account in the detailed design phase [29]. This principle is also used in some industrial applications. Here ultrasonic devices are used to prevent the formation of biofilms in pipes or tanks by applying high surface forces by vibration [68].

Most of the passive methods like quarantine, sanitation, or opaque trays, pipes, and tanks to prevent the formation of photosynthetic microbes are easy to apply and are, therefore, used in any case. All coatings that need periodical replenishment or release toxic substances are eliminated as well. In stainless steel, a roughness of R=0.8 μm, as is used as a hygienic standard in the food processing industry, reduces topological sites for bacterial adhesion and increases corrosion resistance [67]. A trial in a test facility to determine whether the use of PTFE is worth the downsides described in Table 4.2 is encouraged. Since no prevention methods can guarantee complete efficacy, they can not substitute an active contamination removal. Therefore, they are not considered as an alternative, but only to reduce the maintenance effort for the cleaning of biofilms.

Contamination Removal

Although the prevention of biofilms is an important step, floating microbes can still form within the NS. It is not possible and not recommended to completely eradicate these, as some of them are even advantageous for the plants [69]. In case the other environmental factors are sufficient, the plants also have some resistance to pathogens. Nevertheless, the NDS is a very small system that does not have the buffer capabilities to keep a natural microbial balance [69]. Although contamination of crops in hydroponic systems is generally lower than in soil cultures, the pathogens' ability to spread quickly with the circulating NS makes active contamination removal essential [23].

In the MTF, decontamination was achieved in the form of frequent ozonation and periodical addition of hydrogen peroxide. This proved sufficient for healthy plant growth. Nonetheless, after a leak led to the exchange of some of the pipes, severe biofilm formation was discovered, especially in the pipes. Thus, higher concentrations or some form of mechanical treatment should be considered.

Some of the treatment methods mentioned in Chapter 2 are localized procedures within the cycle (i.e. a stop for the microbes in a particular location). The location has to be chosen carefully since all NS needs to pass through it periodically. The best examples for this type are micro-filtration, ionization radiation, or heat treatment, as their effects are localized, and the NS is returned to its original state afterward. These are used if there is one particular location in which no microbes are allowed or if implemented in a separate cycle. The alternative is substances that are added to the NS and that travel with it while inactivating microbes. Considering the small weights of the mass and volume scores, these are only roughly estimated without actually finding example systems. After the overall score is determined, the necessity of a more accurate iteration is checked.

Table 4.3 shows the final scores given to each of the potential decontamination methods that are not eliminated by requirements. It can be seen that the rough estimations of the mass and the volume scores do not make a difference even if they were completely turned around. Therefore, oxidizing chemicals and especially ozone, still score the best. Not included in the list are microbial inculcation and micro filtration. The individual justifications for each score can be found in the subsequent sections.

Although altering the micro-biome of the root zone is highly promising, the biological details are outside the scope of this thesis. Moreover, even beneficial microbes can contribute to clogged nozzles if unregulated, such that other methods to control the micro-biome are still required [70]. It is highly recommended to consider implementing it in future iterations since it is potentially less disruptive and affects the entire system instead of a local removal.

As explained in Chapter 2, micro filtration is very slow and leaves a highly contaminated brine that needs to be disposed of or cleaned [31]. Concerning the overall habitat, this system is dependent on another decontamination method and, therefore, not considered further as a pathogen removal method in this trade-off.

	Weight	Heat	Radiation	Chemical
Safety	26.7	3	5	3
Reliability	21.0	5	2	4
Maintainability	15.8	3	2	5
Productivity	15.8	3	3	4
Sustainability	8.1	4	2	4
Mass	3.8	1	3	4
Volume	3.8	1	2	4
Flexibility	2.9	2	3	5
Power	2.1	1	5	4
Score	100	325.7	308.9	392.0

Table 4.3: Decontamination method trade-off.

Heat Treatment

For efficient energy use, a hypothetical heat exchanger is presumed to transfer the heat after decontamination to the incoming fluid flow. To determine the ratings for the heat treatment method, an efficiency of 90 % as advertised in [71] is used as a baseline. The efficiency is the ratio between a real and an ideal heat exchanger with the same exchange surface. For the estimation of the required energy to heat the NS to 95°C, more information about a particular design would be necessary. The effectiveness of a heat exchanger is the ratio of the actual heat transfer to the heat transfer in an ideal infinitely long counterflow heat exchanger [72]. Since the flow and the material properties of the NS are the same for the in and outlet no more energy would be required for heating or cooling. The heated solution at the outlet would have the same temperature as the cooling solution at the inlet and vice versa. Since the effectiveness is per definition lower than the efficiency, the remaining required heat for an assumed 90 % effectiveness is significantly lower than for a heat exchanger with 90 % efficiency. Since it is assumed that the power consumption for heat treatment is too high for the GHM anyways, a first estimation is based on an effectiveness of 90 %. If the assumption proves to be true, heat treatment can be eliminated. If not, a more detailed analysis is conducted.

Some cooling agents are flammable and the excess heat is transported to other subsystems which need to deal with it (Safety: 3). This method is highly reliable since the processed NS is decontaminated with high certainty (Reliability: 5). The heat exchanger and the cooling unit are comparatively complex and need more maintenance than other systems (Maintainability: 3). Only small amounts of liquid can be handled at a time (Productivity: 2) [15]. Since the cooling agent is not consumed or depleted, it is theoretically able to be used indefinitely. However, it is unlikely that the cooling agent can be produced on-site, if ever necessary (Sustainability: 4). For the required flow, the systems are likely to be comparatively heavy and large (Mass, Volume: 1). This is also the reason why the location is likely not flexible. In addition, it is harder than in the alternative systems to use one unit for decontamination of both nutrient cycles (Flexibility: 2). Heating up the NS with a heat capacity of $c_p = 4.18{-}4.21 kJ/kg/K$ to to 95 °C (i.e. a difference of 75 K) requires $E = 315 kJ/Kg$. With the use of a heat exchanger with an effectiveness of up to 90%, this still results in an energy-use of 31.5 kJ/l. Assuming the decontamination of 20 l per irrigation cycle every 6 minutes requires a constant power of 1752 W. This is significantly higher than the other two methods, even before considering that the effectiveness was used instead of the efficiency (Power: 1). Furthermore, only enough NS is sterilized to cover the actual flow without considering the stagnant solution.

Ionizing Radiation

For the estimation of the radiation scores, a UV water purifying system as sold by ISC is assumed [73]. The fluid flows through a glass pipe that is exposed to UV light with an intensity of at least 250 $\frac{mJ}{cm^2}$ from all sides. This method can be used to sterilize large amounts of solution in a short time [23]. Other radiation types with higher energy content like gamma radiation have been proposed and are currently in use for sterilization of medical devices [74]. Due to the required shielding of the plants and the crew, this method is not utilized in space.

UV light is easy and safe to handle while stronger radiation types are eliminated (Safety: 5). However, this method causes severe plant chlorosis in lettuce and tomato by destroying the chelating agents for iron Fe ions leading to precipitation of Fe nutrient salts [29]. Moreover, it tarnishes the solution, which weakens the light permeation reducing the overall effectiveness. In addition, radiation sources need to be designed carefully since non-lethal doses might even enhance biofilm formation [30] (Reliability: 2). To reduce the effects of tarnished NS more filters and more frequent maintenance are required (Maintainability: 2). From experiments, it is known that different levels of radiation are needed for various organisms to achieve the same level of efficacy. Any turbidity reduces the transmittance and, therefore, the efficacy (Productivity: 3). Although the lamps themselves do not require any chemicals, the iron-chelating agents need constant replenishment (Sustainability: 2). This system is likely lighter and smaller than the heat exchanger (Mass: 3; Volume: 2). Although it is also a localized procedure, the size advantage allows for a more flexible positioning (Flexibility: 3). Commercially available UV disinfection systems require about 50 W for a flow rate of 45 l/min. Therefore, decontamination of the same amount of NS as for the heat-treatment of 20 l/cycle results in a power consumption of 3.6 W which is only a fraction of the energy required in a heating system (Power: 5) [75].

Chemical treatment

The whole category of pest control biocides used in conventional farming is eliminated by Requirement FR-OP-060 (substances shall be generated on-site) and FR-HM-040 (used substances shall be sustainable, safe to use, and have no toxic byproducts). Some surfactants proved to be effective against zoospores. Despite having no apparent phytotoxic effects, surfactants degrade over time and need to be reapplied periodically. Therefore, they are also not suited for the intended purposes [31]. Antibacterial metals are not used for disinfecting the solution since performance against pathogens is poor and they need to be replenished regularly [76]. All these elements are not easy to produce or to recycle on-site and are, therefore, not sustainable on space missions without using in situ resources. As explained in Chapter 2 the use of oxidants is the most promising approach. Since hydrogen-peroxide is already harmful to plant roots in very small concentrations, it is especially helpful for cleaning the watering system after harvest, but not efficient for continuous decontamination [76].

As stated in Chapter 2.3, the NS in the MTF was decontaminated with ozone. Ozone O_3 can be produced on-site with a simple ozone generator. Ozone is dissolved in the solution, killing microorganisms by its oxidation capacity. With a half-life in water of only about 22 minutes at room temperature and only oxygen molecules as constituents and byproducts, it is well suited for a closed system [74]. Therefore, it is considered the most attractive option for chemical sterilization.

Ozone in gaseous form is explosive once it reaches a concentration of 240 g/m^3. Since most ozonation systems never exceed a gaseous ozone concentration at the output of 50 to 200 g/m^3, this is generally not a problem. Since it is still hazardous even in lower concentrations, caution needs to be taken. Human exposure to the ozone that is vented from the system or the storage tanks should be avoided since even a short exposure time of a concentration of 0.1 mg/l of ozone may irritate mucous membranes. This is somewhat compensated by the short half-life of ozone and sensors in the GHM(Safety: 3). Although less severe than for radiation, the ozone also reacts with other organic compounds and iron-chelates, reducing the reliability if these are not filtered out (Reliability: 4). Since the ozone generator is not in contact with the NS, it generally requires very little maintenance (Maintainability: 5). Ozone is very efficient in eliminating pathogens, including viruses (Productivity: 4) [59]. Due to the still noticeable amount of destroyed iron-chelates, higher dosages of iron are needed, and measures need to be taken to deal with iron deposits in the system [76]. Ozone forms from oxygen molecules and even the destroyed compounds only leave the basic elements H and CO_2 [77] (Sustainability: 4). The systems are comparatively small, lightweight, and O_3 can be injected anywhere in the NS cycle via venturi-injectors. Since it travels with the NS every part of the system can be reached, and one generator can be used to supply both cycles (Mass: 4; Volume: 4; Flexibility: 5). The ozone generator used in the EDEN ISS MTF was able to produce 200 mg/h at 10 W. This equals an energy requirement of 36 kJ per 200 mg of ozone or 180 J/mg. For an upper limit of 3 mg/l 60 mg are necessary for the decontamination of 20 l every 6 min. The resulting energy consumption is 10.8kJ J in 6 min or 30 W (Power: 4).

Ozone can be applied by an air stone in the tank or venturi-injectors wherever a flow is present. The venturi-injector is installed on a pipe bypass and can be controlled by a valve in the pipe. This leads to a good distribution within the NS. If injected into the tank itself, an air stone is used to produce tiny bubbles with a high overall surface. This leads to exposure of the most amount of NS. Since the tanks are the most susceptible to pathogen formation decontamination should be started there.

Discussion

As can be seen in Table 4.3 ozonation was determined to be the best choice for the application in this project. With the use of bubble-diffuser and venturi-injectors, almost any part of the NDS can be reached. If an air stone is installed in the freshwater tank, this can be treated as well. For the freshwater tank, however, UV light is a compelling alternative as no chelating agents for Fe are precipitated. Furthermore, the freshwater does not contain particulate materials letting the light penetrate further. Thus, the reliability, maintainability, productivity, and sustainability are all increased, boosting the overall score to 403.5. Since UV lights are used for sterilization in the AMS, spares are brought along anyways and requirement FR-OP-060 is not violated. The score difference for the NS does not justify using UV light just because of that requirement. Therefore, this argument also does not support the use of an air stone in the bulk tanks. Since venturi-injectors are used to distribute the ozone to different parts of the system, one inlet can also be used to redirect it into the bulk tanks, such that no air pumps are necessary.

Now that this method was chosen, some further considerations are required. The use of sanitizers and biocides in cleaning and sanitation is not sufficient to remove cells within biofilms. Proper cleaning procedures are essential for their removal and eradication before they become recalcitrant in mature biofilms [78]. The lack of mechanical cleaning was found to lead to large biofilms, especially in the pipes. This will be taken into account in the operational phase. Moreover, some way of monitoring needs to be implemented. In quality testing, it is important to examine and understand the number of bacteria and fungi [69]. As explained in Chapter 2, this requires sampling, since the available measurement methods are not suited for in-line testing. As a purely biological topic, this is outside the scope of this thesis.

If the ozone system is poorly sized ozone can be harmful to the plants. It should be considered whether to use continuous ozonation during plant cultivation with an amount small enough that it doesn't reach the plant trays or whether a batch approach when necessary is more suitable. Conducting the decontamination manually in batches also reduces the possibility of unnoticed O_3 outgassing that may potentially harm the crew [43]. For the ozone to work effectively, a filter is needed before the NS reenters the bulk tank. While this also helps to protect the pumps and nozzles from being clogged by suspended matter, these need to be replaced and cleaned frequently [29].

4.2.5. Material Selection

Experience from previous projects showed some materials to be undesirable for use with ozone, acid, wet surfaces in general, or due to them giving of volatile compounds that may be hazardous for the plants or the crew. Other materials are sufficient for Requirement FR-TI-110.

Table 4.4 shows the different categories, including the identified example materials. In this section, no final decision is made since the specific set points like the individual concentrations or the pressure in the pipes are necessary to determine the best choice. Therefore, this is deferred to Chapter 5 when the components are chosen. PVC is a special case since it is used in most hydroponic farms on Earth. However, it is classified as not usable in space, due to out-gassing in a vacuum, resulting in the loss of

	Reason	Example
Desired	Desirable for corrosion resistance when in contact with water.	• Stainless steel • Glass • PTFE • Polypropylene • Baked enamels
Undesired	Easily corroded materials or materials that release toxic or irritative byproducts, for example by outgassing.	• Polyethylene • Metallic coatings such as brass, copper, and zinc • Plastics with high level of plasticizers or non-healthy plasticizers such butyl- phythalates • PVC • Styrofoam bits
	Biofilm promoting properties. Susceptible to decontamination agents.	• Buna-N (Nitrile) • Natural rubber • Nylon • Steel (mild, HSLA) • Zinc

Table 4.4: Materials selection with the respective desired or undesired traits [49].

some of its properties [79]. Although the GHM has an internal atmosphere, materials should be chosen to withstand the launch conditions. Since the fairing itself is not pressurized and the pressurized Cygnus-module is likely to be replaced with a lightweight radiation and debris shield, PVC is eliminated as a choice [44].

Some materials have properties that might make them seem like a good choice but are eliminated by other factors. For completeness, some of these are explained here. High-density polyethylene is often used for pressurized piping. This is however not desirable since combination with acids and base might lead to corrosion. Although stainless steel is mentioned in the category with desired properties, only type 304/316 has an excellent ozone resistance rating of A, while other grades show worse performance [80]. The scale is divided into four segments starting with ”excellent” (A) and ending with ”poor” (D).

Especially for the connectors in use with acids and bases, PTFE is recommended. This material would also lead to increased maintainability and decreased biofilm formation but may not be sustainable during the entire mission duration. Another material often used for its lightweight properties is Titanium. Although the price of the material is negligible compared to the price of the launch, any tests would be expensive too.

4.3. Conclusion

In this Chapter, a multitude of options for different tasks of the NDS has been explored for the selection criteria defined in Section 3.5. The decisions with the highest impact on the overall subsystem design were explored in more detail. When these are not eliminated by constraints or requirements, decisions are made based on a numerical scoring theme.

This methodology resulted in an APS with a constant pressure section balanced by accumulator tanks. Every tank has a dedicated pump instead of the rack-wise distribution in the MTF. The piping is designed circularly under the floor to enable the supply of all racks with both NS compositions while keeping the part count and the length of the pipes as small as possible. For a compromise between maintainability and flexibility in the distribution, always two racks are supplied by one upward duct. Manual three-way valves are used to open them up to either side, such that, as long as the upward ducts that are supposed to be supplied by the same pump are connected, each one can be supplied by each tank. Since the return lines require a gradient for the solution to flow to the bulk tanks, the same multi-directional piping is not possible here. A System similar to the return pipes in the MTF does not involve this problem. Since the exact position of the tanks depends on the necessary size, which will be determined in Chapter 5.1.5 the design will be deferred until then.

Due to the use of an APS, oxygenation of the plant roots is already sufficient. While temperature and dO monitoring are still desired for a complete overview of the system parameters, control of the two is not actively designed. The composition of the NS is assured by adding two different stock solutions using venturi-injectors or dosing pumps. It is monitored by EC probes and, although ion-specific measurements can be taken from samples, these are not used for daily operation.

To prevent the formation of biofilms, the use of anti-stick surfaces and at least stainless steel with a food-grade surface roughness of $R = 0.8\mu m$ is recommended. To actively manage the pathogen load in the system, the tanks and pipes are sterilized by ozone via venturi-injectors in the low-pressure part of the system. Finally, a collection of materials with generally desired and undesired properties is presented. Since the choices depend on the individual components and the respective loads, no decision is made in that regard.

5 Detailed Design

To make clear recommendations for individual components, some design-dependent parameters need to be estimated based on the requirements in Chapter 3.4. The individual steps of this procedure are depicted in Figure 5.1. Every element of the flowchart includes a reference to the respective section, a summary of the used input values, and the finally determined key parameter. The inputs can contain data from typical commercially available components, data gathered from the MTF, or references to the applicable requirements.

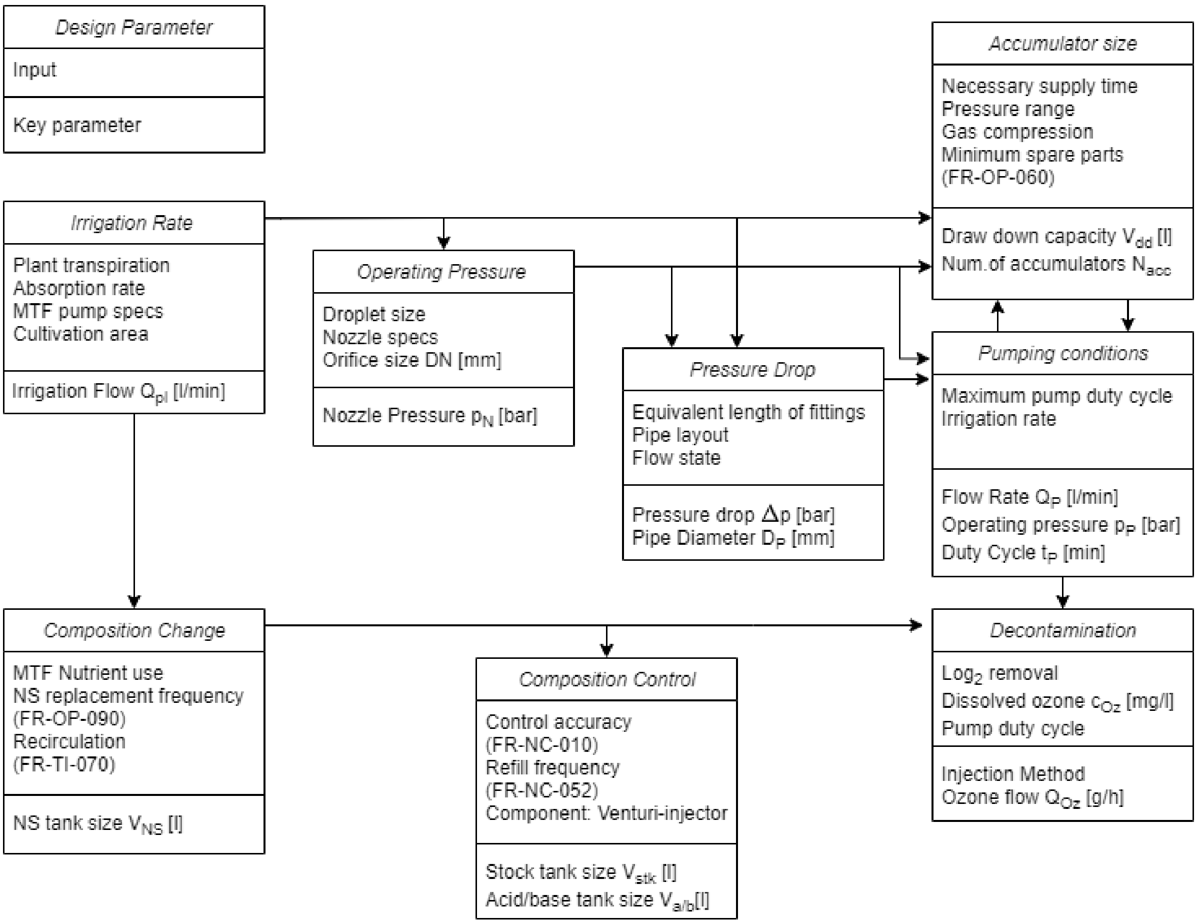

Figure 5.1: The key parameters that are determined in this Chapter, their relations, and source parameters.

First, the necessary irrigation flow rate $Q_P l$ of NS is determined based on transpiration data of the selected plants and available information from the MTF. Starting from the optimal droplet size D_{Drop} for aeroponics and the feed rate, a nozzle orifice size D_{NO} is chosen, and the nozzle operating pressure p_{NO} determined. Using the layout designed in Chapter 4.2.2, the minimum and the maximum pressure drop ΔP from the pump to different locations is determined, and a pipe diameter D_p is chosen accordingly. Subsequently, the maximum accumulator tank size V_{acc} is estimated based on the maximum drawdown capacity V_{DD} needed for an arbitrary pump and manufacturer specifications. In parallel, an example pump with the minimum requirements is suggested by analyzing the flow rates Q_P from a pressure-to-flow diagram. The minimum accumulator tank size is then estimated based on this specific pump.

Starting from requirements and information from the MTF, a maximum necessary tank size V_{NS} is determined. Based on the return rate and the desired time t_{flush} between NS changes, the minimum tank size is discussed. This is done by estimating the nutrient uptake of the plants and the resulting changes in the NS composition and EC value. The stock solution, the acid, and the base tank sizes are approached similarly. Subsequently, the required accuracy is evaluated by analyzing potential venturi-injectors and the concentration of the respective components.

In the following sections, each step is laid out in detail, including the input and output parameters. The results of each estimation step are collected in Table 5.7 at the end of this chapter. Based on the resulting feasible design space, commercially available products are chosen in Chapter 6 to derive the mass volume and cost budgets. To simplify the following explanations, some terminology is defined beforehand. The use of accumulator tanks allows for the decoupling of the irrigation cycle (i.e. opening and closing the solenoid valves to the plant trays) and the pump cycles (i.e. when the pumps start restoring the system pressure in the accumulator tanks). Furthermore, the case that one pump failed or needs maintenance and the entire GHM is supplied by the other one is defined with the term "emergency supply".

5.1. Parameter Estimation

5.1.1. Irrigation Rate

In literature, the amount of NS for aeroponic systems is usually not specified exactly and instead, irrigation time schedules are proposed [81, 82]. This is done since the important parameter is the time the nutrient mist stays in the air. Although this will be affected by the reduced gravity of the moon, the calculations made here are based on the respective parameters on earth. Since the time the mist stays in the air is longer under the Moons gravity, this will result in more conservative parameters. To size the irrigation system, the volume of NS which needs to be transported should be known. For the design of the EDEN NextGen NDS, theoretical and actual data from the MTF is adapted to enable an initial sizing. NS is supplied for 30 s with 5 min and 30 s breaks between cycles. Due to the day and night cycle of the plants, irrigation is interrupted for 8 h during the night. With 16 hours of irrigation time and 10 cycles per hour, a total of 160 irrigation cycles are conducted per day. The necessary irrigation and return rate is determined by comparing available theoretical knowledge of plant transpiration with data from the water recovery in the MTF and the specifications of the used pumps.

Supply Rate

The first point of orientation is the specification of the high-pressure pumps in the MTF. Since the flow rate in the MTF was not measured, the delivery rate is taken from the datasheet as seen in Figure 5.2 [83]. The upper graph, on which the focus is put in this instance, represents the flow rate compared to the pressure difference between in and outlet. The lower graph shows the electrical current necessary to achieve these flow rates, which is disregarded at this stage of the design.

The pressure data of the control system shows pressures between p_P =6.8 (98.6 PSI) and 7.8 bar (113.1 PSI). Since the number of nozzles that are supplied by every pump is different, the pressure and, therefore, the flow rate differ. In this initial estimation, this effect is taken into account using a large margin. Taking the average of the two extremes, 7.3 bar (106 PSI), and applying this value to the chart in Figure 5.2 a flow rate of $Q_P = 0.8$ gallons/min, $\approx 3\, l/min$, or 1.5 l per irrigation cycle is found. Since a maximum of eight trays is sufficiently irrigated by this flow, a feed rate of around 188 ml per tray and cycle is determined. In extreme cases, each pump has to be able to supply the entire GHM as per Requirement FR-OP-040. Applying the same flow rate per tray from the MTF to the EDEN NextGen design, it can be determined that a pump should be able to supply up to 19.5 l each cycle for 104 trays.

To validate the irrigation flow rate of $Q_{pl} \approx 0.38\, l/min$ per tray, a pump was connected to one tray, and the volume flow over a period of time was determined. The measured flow rate was 0.2 l/min but, since only one tray was connected, the pump reached the shut-off pressure (≈ 10 bar), which resulted in the pump turning off and on in quick succession. As this reduces the flow rate to a fraction of the available flow, the pump can likely be scaled up to the flow rate of 3 l/min estimated above, just by adding more trays. If it is assumed that every additional tray receives the same amount of NS and that by adding pumps, any amount of trays can be supplied, this results in a flow of 10.4 l per irrigation cycle for 104 trays. Since the working conditions in this test were sub-optimal, this is considered a lower boundary. Therefore, the nominal flow can likely be found between the measured and scaled 10.4 l per cycle and the estimated 19.5 l per cycle. The higher amount is assumed as a conservative baseline for further calculations.

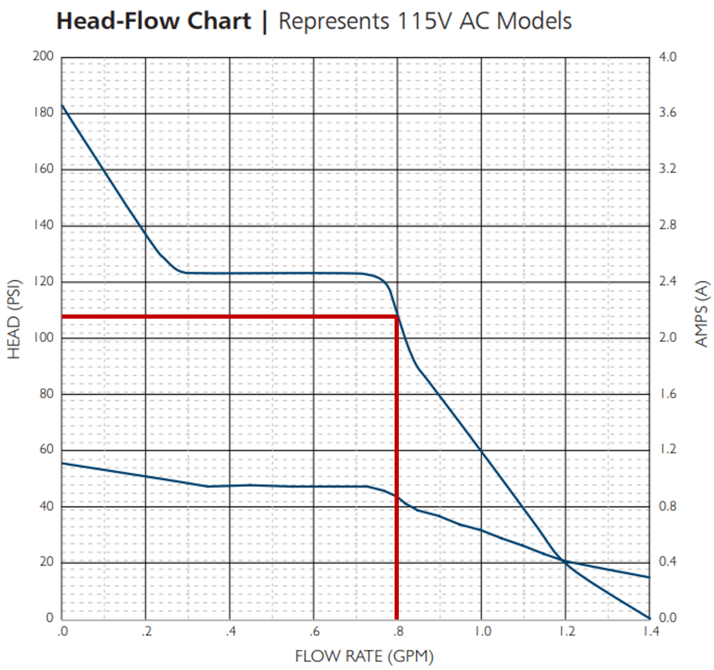

Figure 5.2: The pressure vs. flow rate curve of the MTF diaphragm pump [83].

Absorption and return rate

To determine the return flow, the water uptake of the plants is estimated theoretically. The water that is stored in the plants as biomass amounts to less than 5% of the total amount of water taken up by the plants [84]. The rest is transpired into the air and recovered by the AMS. For the different plants in the example plant composition from [12], estimates of the transpiration rate as seen in Table 5.1 can be found in [53]. These can be used to estimate the entire water need of the sample plant configuration as $69.8\, l/0.95 = 73.5\, l$ per day. Broken down into equal irrigation cycles of 30 s 10 times per hour for 16 hours a day, this is equal to $0.46\, l/cycle$ or $4.4\, ml$ per tray per irrigation cycle.

The other information necessary to size the irrigation system is an analysis of the MTF. Since the system was adapted to fit the biological needs of the plants, the available data is analyzed. The average amount of transpired water in the MTF was 27 l per day while the maximum was 44 l. Assuming a similar average transpiration rate and the increase of cultivation area from 42 to 104 trays, this results in an expected transpiration rate in the EDEN NextGen of 66.9 and 109 l/day respectively. Adding 5% of water for biomass production, a take-up rate of 4.4/7.2 ml per tray is estimated. Using the maximum absorbed amount, the absorption rate is estimated as roughly 7 ml per tray and irrigation cycle.

The estimations for both values are in the same order of magnitude for different methods, respectively. The larger values are used, as the more conservative, for further estimations. If working constantly, the absolute minimum flow rate of the pump needs to refill that amount of NS in the accumulator tanks within 6 minutes. This way, the volume and pressure are kept in the given ranges so that the NS delivery

Plants	**Number of trays**	**A** [m²]	**Transpiration rate** [kg/m²/d]	**GHM transpiration rate**
Lettuce	42	13.78	2.1	28.93
Chard	12	3.94	1.77	6.97
Cucumber	5	1.64	1.77	2.90
Tomato	18	5.90	2.77	16.35
Radish	10	3.28	1.77	5.81
Kohlrabi	5	1.64	1.77	2.90
Herbs	12	3.94	1.5	5.90
Total	104	34.112		69.77

Table 5.1: The plant selection of the MTF[12] and the transpiration rate of the selected plants [53] are adapted to the growth area of the GHM.The transpiration rate for herbs was estimated on the basis of the AMS design sizing [85].

can be handled during the pump cycles. This minimum is, therefore, $Q_{Pl} = 19.5\, l/cycle\; = 3.25\, l/min$. With this value, the emergency scenario that all trays need to be supplied from one tank is considered. In this scenario, the pump would need to run constantly, filling the accumulator tanks. Including a safety margin of 20% results in a required pump flow rate of $Q_P = 3.9\, l/min$. Since the necessity of supplying the entire GHM by one pump is an emergency case that is the result of a failure, the safety margin for the nominal operation (i.e. only supplying half the plants) is significantly higher. Spare pumps are implemented in cold redundancy in case an individual pump fails. Even in case the 20% safety margin is not sufficient due to another failure in the system, the redundant pump can be turned on to support the active one. Theoretically, smaller margins could be considered later if necessary.

Method	**Volume** [l/day]	**Volume** [l/cycle]	**Volume** [ml/cycle/tray]
Datasheet (supply)	3120	19.5	188
Test (supply)	1664	10.4	100
Theoretical (absorption)	73.3	0.46	4.4
MTF Data (absorption)	70.25 (average)-114.45 (max)	0.42-0.68	4.0-7.2

Table 5.2: NS supply and absorption of the plants summarized by estimation method.

5.1.2. Operating Pressure and Nozzles

The pressure in the MTF was adjusted manually and iterative such that minimal shuttering occurred. To provide a more analytical point of view, a range of misting nozzles is analyzed to determine the appropriate pressure range for the desired droplet size. A droplet size larger than necessary decreases the oxygenation of the roots. A smaller size, on the other hand, may increase root hair growth to an undesirable level, reducing the harvest index of the plants [82]. The optimum was found to be around 50 μm with an acceptable range of D_{Drop} =30-80 μm [82]. In Table 5.3 data-sets of different nozzles with 50 μm droplet size are collected and compared in terms of their flow rate, working pressure, and orifice size. As the trays are adapted from the MTF, each tray has a total of 6 misting nozzles resulting in a nozzle flow rate of Q_N =62.7 ml/min. Considering a working range of $\pm 10\%$ around the determined flow rate and linear interpolation within the datasheets of the nozzles results in operating pressure ranges as seen in Table 5.3.

The last two columns of Table 5.3 show the pressure ranges at which the flow rate is within $\pm 10\,\%$ range of the nominal flow. Widely available parts, especially valves, are usually rated up to 10 bar or 145.038 PSI, which is, therefore, taken as maximum pressure. Thus, the first and the third nozzle are eliminated. The second nozzle that requires pressures outside its operating range is eliminated since

Model	Orifice["]	60 PSI 4.1 bar	100 PSI 6.89 bar	150 PSI 10.34 bar	200 PSI 13.79 bar	0.056 l/min*	0.069 l/min*
MC42062	0.015		0.052		0.073	121	181
MC42060	0.02		0.067		0.094	61	107
MC41024	0.012	0.028	0.037	0.045		218	293
MC41020	0.015	0.045	0.052	0.07		113	147
MC41030	0.02	0.057	0.07	0.083		59	97

Table 5.3: The feed rate of a selection of nozzles in l/min [86]. *The pressures for the previously determined feed rate [PSI].

the droplet size may not be achievable. That leaves nozzle MC41020 with an orifice size of 0.015" and a pressure range from 110 to 147 PSI (7.6 to 10.1 bar) or the MC41030 model with a range of 59 to 97 PSI (4.1 to 6.7 bar). Since 60 PSI is at the lowest end of the given operating range, the desired droplet size may not be achieved with that model. Therefore, the operating pressure is set between $p_{min} = 110$ and $p_{max} = 145\,PSI$ (7.6-10 bar).

The design of the trays is not changed from the MTF since they were already adapted from the lessons learned. On each level, one solenoid valve will be used for each rack respectively to open the flow from the high-pressure section to the nozzles. Therefore, groups of four trays are irrigated simultaneously. For individual maintenance, the trays can be decoupled and closed off. The solenoid valves are standard closed to minimize energy usage and not compromise the rest of the system in case of a failure. Cycling of each level of the respective racks individually allows for a more constant NS flow which enables the use of smaller accumulator tanks.

5.1.3. Pressure Drop and Pipes

For the pump and accumulator tank specifications, not only the working pressure at the nozzles is important but also the pressure loss between the tank and the nozzles. This loss strongly depends on the diameter of the pipes. The NS is pumped into the accumulator every pump cycle and supplied to the trays every irrigation cycle by the accumulator tanks. If all solenoid valves open simultaneously, a large load of 19.5 l in 30 seconds flows to the trays. This load is reduced by shifting the irrigation cycles of different trays, which further allows for a smaller and constant flow rate. Thus, smaller pipes can be used, resulting in less weight. To determine the pipe diameter, its general relation to the pressure loss over the entire system needs to be known. Since the acceptable pressure loss is also dependent on the positions of the accumulator tanks and the exact specifications of the pumps, an initial search concluded that pumps with the required flow rate generally work over pressure differences of 80, 120, 150, or 200 PSI. The pipe sizes are, therefore, determined for the acceptable pressure losses for these pumps. Since 80 and 120 PSI is not sufficient they are eliminated. In the following, a model of all pressure losses in a system as described in Section 4.2.2 is created. The maximum pressure loss in the worst-case scenario is then calculated for different standardized pipe sizes. For the accumulator tanks, two different scenarios are considered: One with the usual placement directly next to the pump and one with an accumulator tank for each upward duct. The first option requires both tanks to be sized for the supply of the entire system, whereas the second option does not require this redundancy and each tank can be sized only for the racks it is assigned to. However, they need to be sized for the maximum amount of trays per duct to allow for changes while minimizing the necessity of different spare parts.

First, the inlet pressure is estimated to avoid cavitation (i.e. the reduction of the inlet pressure to such a low level that gas bubbles form) which damages the pump. Since the pumps are located as close to the tanks as possible and at the same height, the pipe length and fittings are considered negligible for this purpose. Therefore, only the filter is considered here. An expert from Priva suggested a filter-size of mesh 100 or 149 μm, which is less than half the nozzle orifice size [87]. Other sources suggest that a finer filter size of 50-80μm is needed to remove undissolved fertilizer salts or precipitates. These are also used as pre-treatment for disinfection methods like ozone decontamination [76]. At this stage, the filter suggested by Priva is chosen. If problems arise during the test phase, it can easily be exchanged with a filter of smaller screen size and a larger cartridge to keep the pressure loss the same.

Since only a very rough estimate is needed, the pressure drop along the filter is calculated using an online calculator for screen basket filters [88]. It is based on a general filter screen size dependent on the percentage of the open area of the screen material and is, therefore, not adapted to a specific mesh size. The resulting pressure drop for the given flow rate is around 0.72 mbar. This can be reduced by providing a larger surface area if necessary [89]. Since the pump is placed at the same height as the tanks and the GHM is pressurized, the inlet pressure is significantly higher than the vapor pressure of water at $20°C$. The net positive suction head (i.e. the difference between the two) is thus large enough that cavitation will not occur.

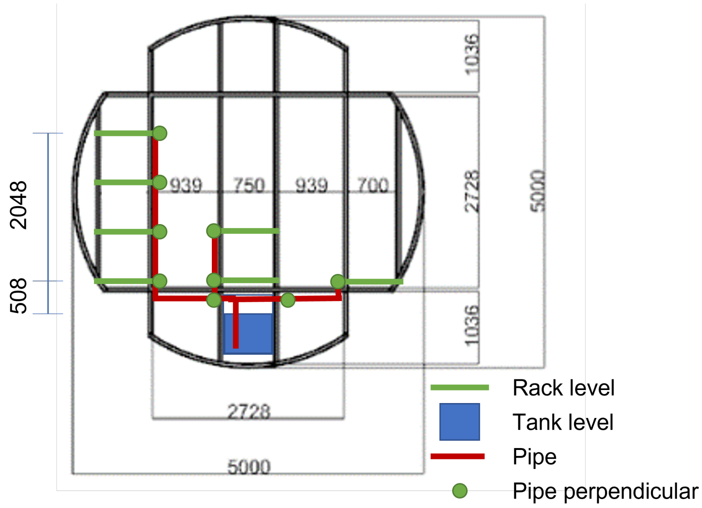

Figure 5.3: The front-view of the GHM for the pressure drop estimation

For the cut-in and cut-out pressure of the pump, the difference between the smallest and the maximum pressure loss is important. For the nozzle pressure not to fall below the threshold, the cut-in pressure needs to be higher than the minimum nozzle pressure and the maximum pressure loss together. On the other hand, the cut-off pressure needs to be lower than the maximum nozzle pressure plus the minimum pressure loss.

The next step is the estimation of the pressure drop due to the change in height. Since this is different for each rack level, all levels will end up with individual pressures. The important parameters are the Moons gravity g_M, the density of the NS ρ_{NS}, and the height from the tank to the respective level. The height of the GHM is divided into 4 growing levels. The lowest level is assumed to be 8 cm above the ground. The overhead space is not included. Therefore, a usable height of 2720 mm is divided into four equal segments of 680 mm. The highest tray is therefore located 2048 mm above the ground as can be seen in Figure 5.3. Adding 50 cm for the positioning of the tank in the sub-floor compartment results in a height difference of 2.548 m. The lowest level height is 0.58 m above the tank. The pressure drop due to the lower Moon gravity is calculated using Equation 5.1.

$$\Delta p_H = \rho_{NS} \cdot g_M \cdot = 998\, kg/m^3 1.625\, m/s^2 = 1620\, pa = 0.0162\, bar/m \tag{5.1}$$

The next source of pressure loss is over tubing and fittings. In straight pipes of length L_p the so-called major pressure drop can be calculated by Equation 5.2.

$$\Delta p = \lambda \frac{L_p}{D} \rho_{NS} \frac{v^2}{2} \tag{5.2}$$

It is further dependent on the fluid density ρ_{NS}, the flow velocity v_f, and the friction coefficient λ. This, in turn, is calculated depending on the flow state (i.e. whether the flow is laminar or turbulent). The flow behavior is described by the Reynolds number which is calculated as in Equation 5.3, where $\nu = 9.7937\ 10^{-7}\ m^2/s$ is the kinematic viscosity of water at $20\,°\,C$. The pipe friction coefficient for laminar flow (Re<2300) can be calculated using Equation 5.4 [90]. The relation between pressure drop and Reynolds number can be found in a moody diagram in Appendix B.2 [91].

$$Re = \frac{vD}{\nu} \tag{5.3}$$

$$\lambda = 64/Re \tag{5.4}$$

For the turbulent flow (Re>4000), an iterative process with the Colebrook-White Equation 5.5 can be used to determine the friction factor. The iterative process is started with the approximation for very high Re as in Equation 5.6 [92]. In between fully laminar and fully turbulent flow, the flow is in a transition state and hard to estimate. In this design stage, the friction factor for the transition state is calculated as the turbulent flow. If the pressure drop is close to being unreasonably high, it is reevaluated. Here $\frac{e}{D}$ is the relative surface roughness. The roughness e is assumed to be food-grade stainless steel with $e = 0.8\mu m$.

$$\frac{1}{\sqrt{\lambda}} = 1.14 - 2log10[\frac{e}{D} + \frac{9.35}{Re\sqrt{\lambda_{prev}}}] \tag{5.5}$$

$$\lambda_{initial} = (100\,Re)^{-0.25} \tag{5.6}$$

The pressure loss in fittings induced by a momentum change of the fluid is called minor pressure loss. It is usually described by an empirical resistance coefficient ζ provided by the manufacturer and used as in Equation 5.7.

$$\Delta p = \zeta\frac{\rho}{2}\omega^2 \tag{5.7}$$

Since no specific parts and pipe sizes have been chosen yet, the more general approach of describing fittings in terms of the equivalent length is chosen. The diameter D_p is related to an equivalent length of straight pipe of the same diameter. In this case, a standard bend radius of R/D=1 is assumed for a threaded $90°$ curve. The equivalent length $(L/D)_{eq}$ as a function of the pipe diameter for elbow pieces is 30 (i.e. a length $L_{eq} = 30\,D_p$ is added to the pipe length in Equation 5.2) [93]. The equivalent length of T-junctions for straight and $90°$ redirected flow is 20 and 60, respectively. For solenoid valves, the equivalent length of $L_{eq} = 340\,D_p$ of globe valves is used since this is the most similar design and a conservative choice. The equivalent length values for different piping sections and components are listed in Table 5.4 below. Furthermore, a rough estimate of the amount of fittings in a scenario with minimum pressure loss and one with maximum pressure loss can be seen.

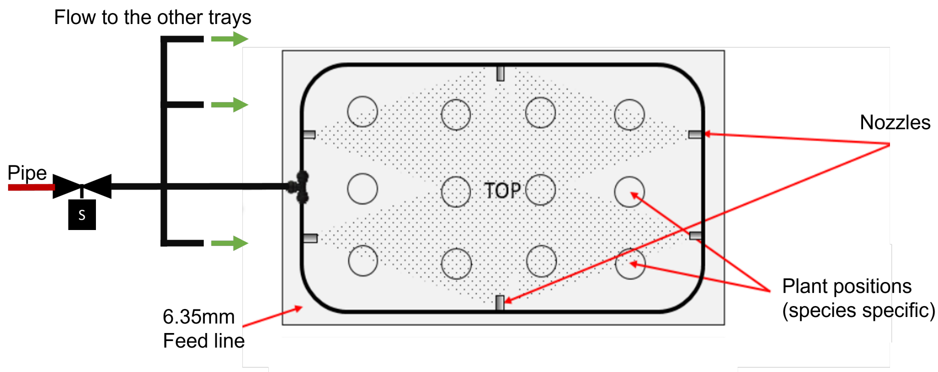

Figure 5.4: The nozzle configuration of the trays in the MTF.

Since the chosen ball T-valves are either completely closed or completely open, they are treated as T-junctions with or without flow separation. To keep the system as simple as possible and the number of replacement parts as small as possible, the used pipes are all of the same diameter. From the upward ducts, the NS is directed to the middle of the racks, where the flow is timed by solenoid valves.

These are then connected to trays of the same design as in the MTF which can be seen in Figure 5.4. In the model, the tubes from the solenoid to the nozzles in the trays are represented by 1 m of flexible 6.35 mm tubing leading to the misting nozzles. The flow difference through the nozzles due to the pressure difference is neglected. As a simplification, the nozzles are handled as T-junctions.

As a starting point for the pipe dimensions, the flow rate in each pipe segment is estimated. For the first section, between the bulk NS tank and the accumulator tank, this is always the pump flow rate of around 3.9 l/min. To allow for the redundant pumps with the same pipe configuration around 4 elbow pieces and 2 half-closed T-valves are necessary. The accumulator tank is connected by a T-junction. In the end, the pressure loss in this initial section will determine the set point of the accumulator tank and the pump cut-off pressure.

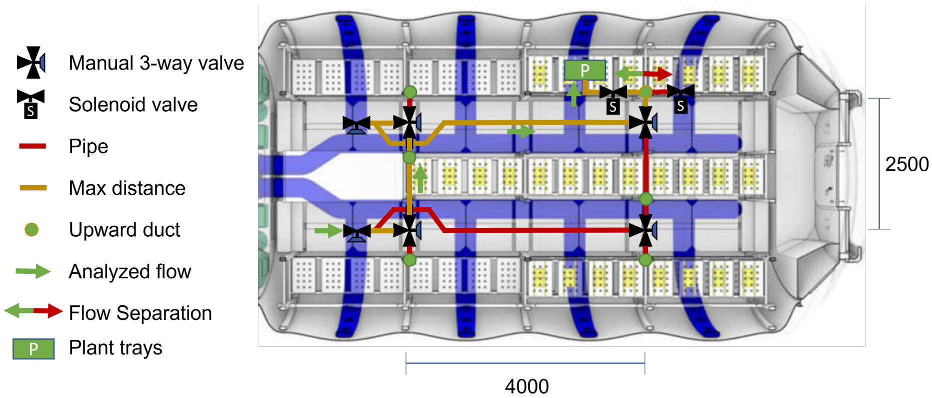

Figure 5.5: A schematic of the flow to the furthest tray [43].

As previously calculated, a constant flow rate of 3.9 l per minute would suffice to supply the entire GHM in the worst-case scenario. At an irrigation time of 30 s every 6 minutes, an average of 8.7 trays have to be supplied at the same time by the accumulator tanks. The highest pressure drop occurs when all this flow is directed to the highest trays of the furthest rack. Although this scenario is easy to prevent by scheduling the cycles of trays in different directions at the same time, it is taken as the most conservative estimate. For the route from the accumulator tank to the furthest tray, which can be seen in Figure 5.5, a conservative estimate of the pipe length up to the highest rack level is 9 m including 2.5 m of height. This estimation also includes the different flow rates after flow separation. On the highest rack level, a T-junction in which 50 % of the flow is separated leads through about 1 m of pipe to the middle of the rack and the solenoids. At that point, the NS flows into the 4 smaller tubes and the tray section. The combined equivalent length of all elements is then translated to the pressure drop in the respective sections. The pressure losses for the different pipe sizes are listed in Table 5.5. The assumed pipe length can be seen in Figure 5.5. A Summary of the different sections, including the number of fittings, the equivalent length, and the assumed pipe length, is shown in Table 5.4.

Component	Elbow	T-junction (s)	T-junction (90°)	Solenoid valve	L_{eq}	L_p
L_{eq}/D	30	20	60	340		
Pump section	4	1	2	0	260 D_p	1 m
Max ΔP	4	9	7	1	1060 D_p	10 m
Min ΔP	1	1	3	1	570 D_p	4.5 m
Tray (D_T =6.35 mm)	2	4	1	0	200 D_T	1 m

Table 5.4: The number of fittings for the shared pump section, the minimum and maximum ΔP path, and the tray section from the tank to the nozzles including the equivalent fitting length and a rough estimate of the pipe length.

The pressure loss for the furthest and the shortest route of the NS for different pipe sizes can be seen in Table 5.5. If the 6.35 mm high-pressure tubes of the MTF are used everywhere, the overall pressure drop equals 1.02 bar. Although it would be possible to choose the pumps accordingly and set the working pressure of the accumulator tank higher by this amount, the route to the closest tray only has a pressure loss of 0.353 bar. The range between cut in at 7.6 bar and cut out pressure at 10 bar of the pump, that is only 2.4 bar to start with, is reduced by the difference of 0.669 bar. This is a reduction in the operating range of 27.9 % for which either the amount of pumping cycles or the size of the accumulator tank has to be increased. To get an understanding of the influence of the pipe size on the system weight, the weight per meter of pipe with the most used medium wall thickness of schedule 40 (on a scale from 5 to 140) is shown as well. For a rough weight estimation, a subfloor pipe length of 15 m, a combined upward duct length of 6 m, and 1 m of pipe per rack level (i.e. for every 4 trays), which equals 1 m 104/4=26 m are assumed. The total length is, therefore, 47 m.

D_p ["(mm)]	ΔP_{max}	ΔP_{min}	Difference	Mass [kg/m]	Tot. mass [kg]
1/8 (6.84)	0.77 bar	0.16 bar	0.61 bar	0.37	17.4
1/4 (9.22)	0.23 bar	0.088 bar	0.142 bar	0.63	29.6
3/8 (12.48)	0.095 bar	0.036 bar	0.059 bar	0.84	39.5
1/2 (15.74)	0.064 bar	0.023 bar	0.041 bar	1.27	59.7
3/4 (20.96)	0.051 bar	0.017 bar	0.034 bar	1.69	79.4
only height	0.041 bar	0.009 bar	0.032 bar		

Table 5.5: The overall pressure difference for using different standardized pipe sizes. The nominal diameter is given in inch, while the internal diameter is given in mm for a medium wall thickness of schedule 40, which is the most used pipe schedule. A mass estimate for 47 m of pipe is also given for that wall thickness [94].

An increase to a 1/4" pipe with an internal diameter of 9.22 mm already results in a pressure difference reduction to 0.142 bar. A further increase to 3/8" or 12.48 mm pipes leads to a pressure loss of 0.095 bar and 0.036 bar, respectively. This reduces the difference to 0.059 bar, which is considered acceptable since the further reduction is only possible to a limit of the static pressure difference of 0.032 bar caused by the height difference. The respective flow differences gathered from a linear interpolation of the nozzle flow rate only amount to 0.6 % and 0.2 %, respectively, which is both unproblematic. However, since the nozzle pressure was chosen at the maximum of 10 bar, the absolute pressure drop of 0.23 bar reduces the operating range by 9.6 %. A further reduction to a pressure difference of 0.041 bar would not be worth an increase in the mass by over 50 % from 38.5 kg to 59.7 kg. Therefore, the 3/8" pipe size is chosen. The higher flow speed is, furthermore, advantageous for reducing the biofilm build-up. The boundary for the pump to start is, therefore, an outlet pressure of 7.64 bar. Since 10 bar was chosen as a maximum to enable the use of more commonly available components, it is also the cut-off pressure. This results in a nozzle operating pressure of 9.9 bar.

Although this pressure difference is already small, it could be optimized further by compensating for the static pressure difference of 0.032 bar by increasing the dynamic pressure loss of the lower levels. This could be achieved by supplying more than the average 8.7 trays for lower levels and progressively less for higher ones. This is, however, not considered useful at this stage of the design.
While the supply pipes are arranged such that they follow the edges of the middle racks under the floor, the return lines can not be routed the same way, since a constant gradient needs to be present. Using the available space below the lowest rack for the return pipes allows for a gradient of 1:25 before reaching the floor level. This way, the reduction of the available height for the tanks is as little as possible.

5.1.4. Accumulator Tank and Pump Size

With the known necessary flow rate as well as the necessary pressures, the accumulator tanks and the pumps can be sized. This needs to be done simultaneously since the effects on each other need to be taken into account.

Maximum Accumulator Volume

For the nominal operation of pumps around the determined flow rate, the recommended minimum run time is one minute to increase the lifetime of the pump [95]. The accumulator tanks need to be sized such that the maximum number of motor starts per day is not exceeded while using the smallest volume to reduce stagnant NS and system mass. Although this number is influenced by the exact pump type, a general rule of thumb is a maximum of 300 starts per day for pumps under 0.75 HP (horsepower) and a maximum of 100 starts per day for pumps up to 5.5 HP [95]. The Power of a pump P [HP] can be approximated with the flow Q_P [l/min] and the pressure p_P [bar] by Equation 5.8 [96].

$$P = 1.36 Q_P \cdot p_P / Y = 1.36 \, \frac{HP}{kW} \cdot 3.9 \, l/min \cdot 10 \, bar/250 = 0.21 \, HP \tag{5.8}$$

Y is an empirically determined pump parameter that is around 250 for small pumps. 1.36 is a conversion factor from kW to HP. Even with the usual margin of 20-40%, a maximum start-up count of 300 starts per day is used for further calculations. This limit is chosen to keep the accumulator tank size as small as possible. Considering that the accumulator tank is sized for the supply of the entire GHM the nominal start count will likely be only half of that. With 160 cycles per day, this results in a pump cycle of every 3.2 minutes or more. In this time, the constant flow achieved by irrigating an average of 8.7 trays at the same time of the entire GHM requires a volume of 10.4 l.

For the sizing of an accumulator tank, the acceptable pressure range and the drawdown capacity are important. The general working pressure to sustain the droplet size and stay within an acceptable irrigation rate is 7.6 to 10 bar. The drawdown capacity can be defined as the total volume that can be supplied by each tank while staying within that pressure range [97]. The maximum accumulator volume can be estimated by assuming a very powerful pump that can supply this amount in a very short time. The flow to the entire system is achieved by the tanks, which are instantly refilled every 3.2 min. The maximum drawdown volume of the accumulator tanks should, therefore, be 10.4 l. Anything above that volume would reduce the frequency the pump needs to be turned on but increase the volume and mass.

Although accumulator tanks are usually installed one per pump as close as possible to the pump outlet, a configuration of one tank per upward duct is considered as well. This might result in a decrease of the overall mass since the drawdown volume of the tanks can be split among them instead of having one for each pump supplying the entire 10.4 l drawdown. In this configuration, each tank is sized for two racks, respectively, making the maximum amount of trays 32 and the minimum 8. This divergence already showcases a downside since either multiple variations or oversized accumulator tanks need to be chosen, thus resulting in a violation of Requirement FR-OP-060 or nullifying the expected advantage, respectively. The necessary NS-volume to supply 188 ml per tray and irrigation cycle to 32 trays is, therefore:

$$0.188 \, l \cdot 32/6 \, min \cdot 3.2 \, min = 3.2 \, l \tag{5.9}$$

Due to the large difference in the number of trays per rack, this results in a total drawdown capacity of 19.2 l, if all rack pairs were supplied by one of these accumulators each. This is more than what is required for one accumulator per pump and, therefore, not considered further. The alternative of different accumulator tanks for each rack depending on the number of trays is disregarded due to Requirement FR-OP-060.

These drawdown volumes already include a safety margin, as is typical in industry, since the necessary total discharge provided by the accumulator tank can be reduced by the amount that is supplied directly from the pumps during the run-time without being stored in the tanks. The exact safety margin is dependent on the flow rate of the pump. When the margin on the pump flow rate is higher, the margin for the accumulator tank gets smaller down to zero at the instant refill scenario from above. Since an accumulator tank, as seen in Figure 5.6, has a flexible bladder with air or nitrogen inside, the necessary size is estimated by using the ideal gas law.

$$pV = mR_iT \tag{5.10}$$

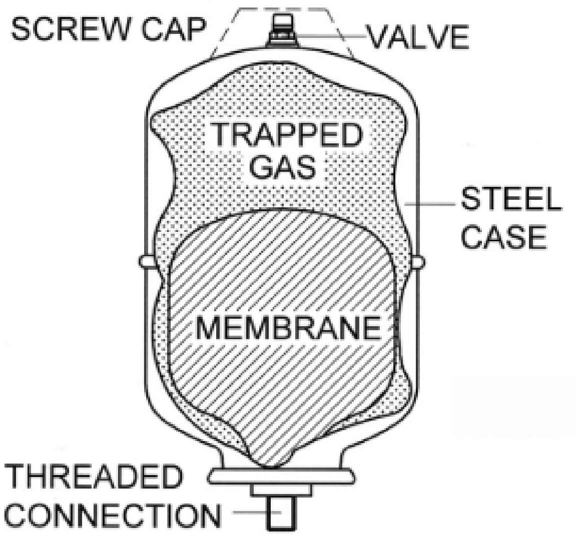

Figure 5.6: Schematic diagram of an accumulator tank [56].

Generally, the isothermal case, in which the tank content is assumed to keep the outside temperature, is used in the first size estimations. This assumption requires a large heat exchange with the environment, which is the case if the pressure changes are slow (i.e more than 3 minutes per cycle) which is the case since the solenoids are opened and closed in a cyclic pattern instead of all at once. In this early stage of the development, the ideal gas law is, therefore, reduced to Boyles law of pV=const. With the ratio between cut-in and cut-out pressure of the pumps, a factor of 0.26 is extrapolated from manufacturer data as the relation between drawdown volume and overall tank size [98]. This includes Boyles law, as well as design specific parameters. Although the table only shows pressures up to 125 PSI, the manufacturer offers tanks in the desired pressure range. If the desired size is not available a nozzle change to a 0.02” orifice should be considered. The respective tank size is $= 10.4\,l/0.26 = 40\,l$. A table with the conversion factors can be found in Appendix B.3. As explained before, this is the absolute maximum necessary and can be decreased depending on the exact pump chosen.

Pump Specifications

Now that the exact working conditions are known, the type of pump can be chosen. Further necessary parameters are the viscosity (water), the corrosiveness (saltwater with a minimum pH of 4.5), and the content of volatile compounds (mostly dissolved and filtered) of the fluid [99]. Because of the high corrosion resistance, diaphragm pumps are generally recommended for aeroponic applications since the diaphragm is the only moving part in contact with the NS. Furthermore, the pumps are small and low maintenance [100]. Comparison between different pump manufacturers shows that diaphragm pumps of the desired operating ranges usually have a maximum flow rate of around 5.5 l/min. Although the MTF pump is advertised with an ”open flow of 5.3 l/min and a maximum pressure of 150 PSI”, the flow rates of the MTF pump are between 0.15 (0.57l/min) and 0.8 GPM (3.0l/min) [101] in the desired pressure range and, therefore, not suitable.

Figure 5.7: Flojet Triplex Hi-Pressure Series Pump [83].

The pump used for further calculations is the ”Flojet Triplex Hi-Pressure” seen in Figure 5.7 with a maximum pressure of 10.3 bar and a flow rate of maximum 5.3 l/min. The pressure-to-flow curve is shown in Figure 5.8. The flow rate in the pressure range is roughly between 3.7 and 4.1 l/min. At the lower end of 3.7 l/min, the pump has to work for a maximum of 5.3 minutes to supply the entire volume of 19.5 l per irrigation cycle. This results in a safety margin of 12 %. Since a lower flow results in decreasing pressure, which, in turn, increases the flow, the safety margin can also be calculated with the higher flow rate at the lower end of the pressure spectrum. This results in a runtime of 4.8 min and a safety margin of 21 %. That means that even in the emergency case, the pump can be used for other tasks or shut down 0.7 to 1.2 min per irrigation cycle. Per pump cycle of 3.2 min and 10.4 l, the minimum flow leads to a run time of t_r =2.8 minutes and a downtime of t_d =0.4 minutes. At the maximum flow, which is used for the estimation of the accumulator drawdown capacity, the times are 2.5 min and 0.7 min, respectively.

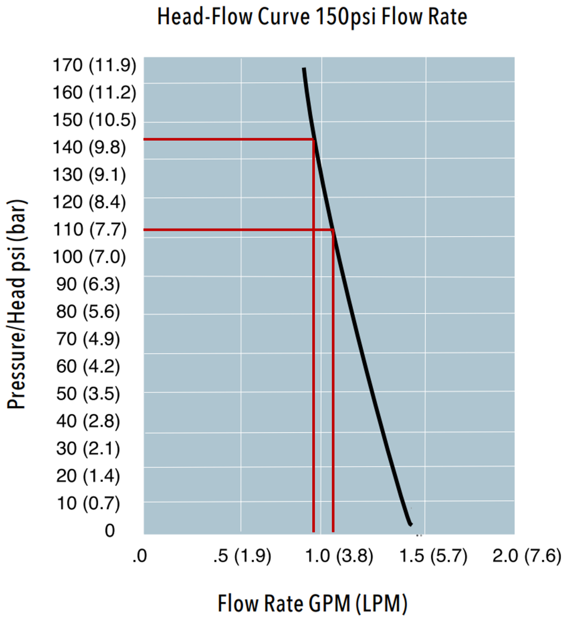

Figure 5.8: Pump pressure to flow curve [83].

With this pump, the minimum accumulator drawdown capacity can be calculated as the volume that needs to be supplied during the 0.7 minute downtime. With an irrigation rate of 3.25 l/min, the absolute minimum drawdown capacity is 2.3 l. Using the conversion factor of 0.26 results in a minimum tank size of 8.75 l. Since many of the assumptions in this initial estimation are only rough approximations, and a more powerful pump might be chosen to enable the supply of more trays with smaller plants, a minimum safety margin in the accumulator volume of 2 should be applied. This means an accumulator tank with a volume between 17.5 and 40 l should be chosen. Although the pump cycles change to 1.25 min and 1.95 min on and off time, respectively, during nominal operation, the accumulator tank size does not need to be larger since the volume to supply decreases at the same rate. Therefore, one accumulator tank with a capacity of 25 l is installed per pump. This safety margin of 2.8 allows for larger pumps in case more trays with small plants are desired later. With the current pump, either the on-off cycles of the pump can be chosen longer, or the pressure range can be reduced.

To enable the control of the system, the functional parameters need to be monitored. Therefore, pressure sensors are placed at all upward ducts. This way, inconsistencies in the pressure distribution could reveal clogged nozzles or fittings. Furthermore, flow sensors are included behind the pump to estimate the use of NS and reveal inconsistencies between tank level and flow. Both of these mechanisms can help to spot leaks in the system due to a pressure drop or an unexpected relation between flow and tank level. To protect the pump and inhibit back-flow from the accumulator tank, a check valve is placed between them. A further safety measure is the addition of pressure relief valves. Since the pumps can deliver up to 10.3 bar, an overload is unlikely unless a stronger pump is chosen later. In any case, the pressure relief valves should open between the operating pressure and the lowest ”maximum allowable operating pressure” of any component [102]. As soon as specific components are chosen, this value will be determined. They are placed at the upward ducts and between the pump and the check-valve.

5.1.5. Composition Change and Tank Volume

The NS in the 250 l tanks of the MTF was flushed after approximately six weeks, but often this was too late as the first signs of nutrient deficiencies would already begin to appear in the plants [52]. The minimum period without excessive nutrient imbalances of one month as per Requirement FR-TI-070 is, therefore, achieved with a scaled version of the MTF tanks. Since the NS shows to be insufficient somewhere before 6 weeks, a safety margin of lower than 50% is given. Scaling the tank by the number of trays in the system results in a tank size of $250\,l \cdot 104/42 = 619\,l$.

Another rough estimate for the necessary tank size can be derived by analyzing the composition of the NS during one month. The maximum amount of absorbed NS for 188 ml of supplied NS was estimated earlier to be around 7 ml and, therefore, around 3.7 %. During nominal operation, a total of 9.75 l per irrigation cycle is supplied by each tank, resulting in the absorption of 363 ml. During one day, this amounts to 58.1 l of which 95 % are transpired and recaptured by the AMS. The 619 l capacity of the scaled tank size would on its own allow for more than 10 days worth of NS. Since it is refilled automatically, the 90 % leftover NS per day is more than enough to act as a buffer for one month if only one failure is considered at a time.

In the following, the amount of nutrients absorbed by the plants is estimated using the limited information from the MTF about the relation between ion content and EC. With this value, the average nutrient absorption per time period is determined. As mentioned before, the tanks in the MTF were flushed approximately every 6 weeks [52]. Due to the selectivity of the plants' ion absorption, a reasonable assumption is that detrimental effects and plant stress only occur when the amount of 'undesired' ions, meaning ions which have been released or rejected by the plants, make up more than 50% of the NS [52]. Based on the absorption rate, the equivalent volume of unbalanced NS which is added per day is determined. Once the 50% threshold is reached a tank exchange is assumed necessary and the tank size to fulfill Requirement FR-TI-070 is estimated.

Over a period of 286 days, 18 kg of mineral salts were used in the MTF. This results in an average of 62.9 g per day or around 2.8 kg during the six weeks between flushing the tanks. For fruit-bearing crops like tomatoes that need the most nutrients, the salt content for the target EC is 1.83 g/l [18]. A total tank volume in the MTF contains, therefore, 458 g of salts. Thus, for two tanks 916 g of the ions, of which about half are 'undesired', were flushed when the first signs of deficiency occurred. If accounting for the assumption that 50 % of the dumped nutrients are ions that were released by the plants or that can not be absorbed over six weeks, around 458 g of 'undesired' ions or 10.2 g per day are added to the NS. This is the amount to create the desired EC for an equivalent NS volume of 5.6 l. Since the absorbed part is replenished by fresh water and stock solution of the desired composition and EC, during each day 5.6 l return with an undesired composition. In the long run, this amounts to 168 l per month. Using the 50% from above, after one month signs of deficiency will latest occur for a total volume of 336 l. Thus, to satisfy Requirement FR-TI-070 for the solution to be reused for one month, the tank size needs to be between 336 l and 619 l. Achieving a similar outcome as in the MTF, while reducing the refill time to once every 4 weeks, the first one would be slightly below the necessary size and the second would have a maximum safety margin of 50 %. Since these values are rather unreliable, a large safety margin is desired. Therefore, 550 l is chosen as the tank capacity.

Three locations are considered for the location of the tanks, as can be seen in Figure 5.9. In configuration 1, they are underneath the working table in the greenhouse section, in configuration 2, under the outer racks in the cylindrical curvature, and in configuration 3 in the service section under the designated NDS area. The differences in piping and, therefore, weight and pressure drop are negligible for all choices. The determining factors are the accessibility, the volume restrictions by the frames, the design of the sub-floor part of the AMS, and the possible transport configuration.

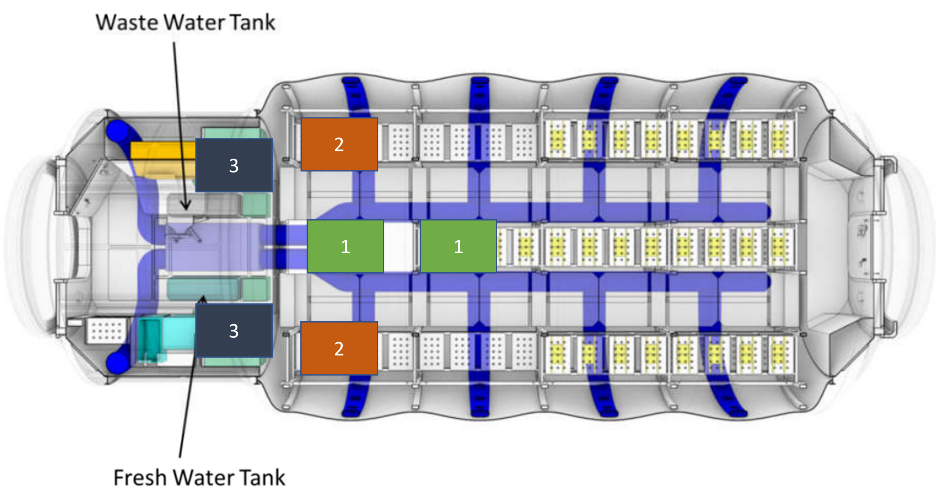

Figure 5.9: The positioning options considered for the bulk tanks.

In configuration 1 in the sub-floor space under the working table, the available cross-section without reducing the space to step into while leaving the bottom 10 cm free for cleaning and the top 10 cm for pipe inlets and sensors is $0.836\,m \cdot 0.750\,m = 0.627\,m^2$. Therefore, each of the tanks needs a length of 0.88 m. Although part of the AMS would need to be moved, this location is feasible since the design of the AMS is not yet finalized. The space between the tanks can be used for piping and pumps. If located directly under the door to the deployable section, about 1.1 m between the tanks are available for other components. For easy accessibility, the floor panels under the table can be designed to be removable such that the tanks can be taken out to the top or by moving them into the corridor and out through the normal floor panels.

At the sides of the greenhouse section, the relocation of the AMS ducts is more problematic as the outlets are necessary for uniform air distribution. The available length is about 0.8 m between the frames and the ducts. The necessary width to accommodate the required tank size in case the tank is custom made to fit the curvature under the floor is 1.24 m. Of the original 0.939 m of stepping space in the corridor, only 0.41 m are left.

Placing the tanks in the service section reduces the available height, as well as the space between the wall and the AMS. Using a length of 1.5 m, a tank of this size requires a width of 1 m. The entire cylinder section at floor level has a width of 2.93 m, leaving a section of 0.93 m for the AMS and as working space. As the AMS filtration system is located here, most of this space is claimed by it. In case the tanks need to be removed, they would be taken out from the top, which, in this location, is hindered by the power distribution and data handling system. Furthermore, the fresh water and the wastewater tanks are located in the service section as well, reducing the space further.

The location under the working table is, therefore, the best choice with respect to the criteria. The biggest downside is that it can not be installed before launch and has to be stored in the service section during transfer. However, the time necessary for installation is made up for by the superior accessibility.

The other tanks are the freshwater and the wastewater tank. In the MTF both had a size of 300 l. The use of a ”dishwasher” for the trays in the new system makes the necessary size unpredictable. It is likely, that this system decreases water use for maintenance, but a final decision for the freshwater tank size is delayed until more information is known. Until then, it is just scaled by tray size to $V_W \approx 750\,l$. The freshwater tank is placed in the service section, where the bulk tanks were originally planned to be since no gravity return is necessary. The waste tank is located in the sub-floor compartment to enable the collection of the wastewater from the freshwater tank and dishwasher by gravity return. Since flushing of the NS is accomplished by the main pump, the height difference to the bulk tanks is not necessary to consider.

It is further necessary to know the exact volume of NS in the mixing and all other tanks to control the added amount of fresh water and stock solutions. Usually, a continuous level sensor is used for this purpose. A variety of different technologies like floating sensors, distance measurements using ultrasonic or infrared devices, dive sensors, or capacitance sensors are available for this task. A further simple solution as used by Priva in their nutrient mixing applications is the use of a pressure sensor at the bottom of each tank. These are low maintenance effective and stable [87, 103]. Although the senor data depends on the specific gravity of the NS which changes with dissolved salt content, these differences can be estimated and are considered negligible.

5.1.6. Composition Control

The first aspect to consider when designing the bulk solution composition control is the monitoring of the current status. This requires EC and pH sensors to be implemented somewhere in the cycle. In the MTF, sensors were directly suspended in the bulk tanks. The corresponding transmitter for the automated system and a handheld device for redundancy purposes can be seen in Figure 5.10.

The position of the stock-solution inlet and the measurements, can cause the NS reaching the plants to differ from the measured concentration due to inhomogeneous conditions. Placing the sensors in the distribution pipes provides data on the supplied NS. For redundancy, a second sensor is placed

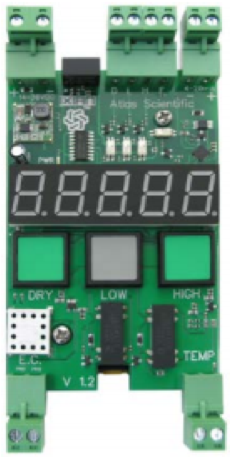

Figure 5.10: The transmitter of the Atlas Scientific Industrial EC sensor (left) and the Dosatron Pro portable EC sensor (right) as used in the NDS of EDEN ISS [43].

directly in the tanks.

In the MTF the addition of the nutrients, acid, and base is achieved by dosing pumps and homogenized by a small circulation pump. As explained by experts from the NDS design firm Priva [87], the most commonly used method in commercial state of the art projects is the use of venturi-systems to inject the NS into a stream that returns to the tanks. This method only requires small solenoids instead of dosing pumps, reducing the number of movable parts. These, however, require a larger pump to create the necessary flow for the venturi-system to work. The use of the accumulator tanks allows irrigation partially independent of the main pumps. Adding solenoid valves to change the pump flow from the accumulator tank to a separate cycle offers a range of different advantages. Besides providing enough flow for the venturi-injection, they can be used to flush the system when the NS is not usable anymore. During nominal operation, small amounts of NS can be supplied after each pump cycle, while more significant adjustments that require more time for continuous mixing can be made during the night when the irrigation is paused. In addition, manual samples can be taken by including a pressure reduction and a manual valve at one of the working areas. Different venturi-injectors can be found in [63]. This separate cycle can also include a set of EC and pH sensors so that the actual composition reaching the plants is monitored. A potential architecture can be found in Figure 5.11.

Fulfillment of requirement FR-NC-052 (i.e a sufficient amount of stock solution, acid, and base is available for one growth cycle) depends on two design-dependent parameters. The concentrations of the stock solution/acid/base and the size of the respective tanks. The more demanding plants are the fruity crops, which have different nutrient requirements during their respective stages of growth. Therefore, the solution needs to be adapted after some time. Usually, stock solutions are prepared 100 to 200x more concentrated than the bulk solution [18]. As determined before, the contents of the bulk solution tanks last for one month, which is roughly the time the plant needs to finish one growing stage. Subsequently, a different composition is necessary. During that time, the entire initial tank filling and the absorbed nutrient salts for an equivalent of 5.6 l/day need to be supplied by the stock tanks. Over one month this results in nutrients for $5.6\,l/d \cdot 30d + 550\,l = 718\,l$ of NS. Here a safety margin is already applied since the flushed NS is calculated as if all nutrients are flushed as well.

At 100x the concentration, a minimum of 7.2 l containers would be required. In the MTF, 20x concentrated stock solutions were used and stored in 20 l tanks. With the estimated use of 5.6 l, this concentration would require a tank size of 35.9 l. Scaling by the number of trays would result in a volume of 49.5 l. Since it is unclear in what way the nutrients will eventually be provided by the habitat, the exact concentrations are not known yet. For the time being, the stock solution tank size is set to 50 l to be on the safe side but should be adjusted once more information is available.

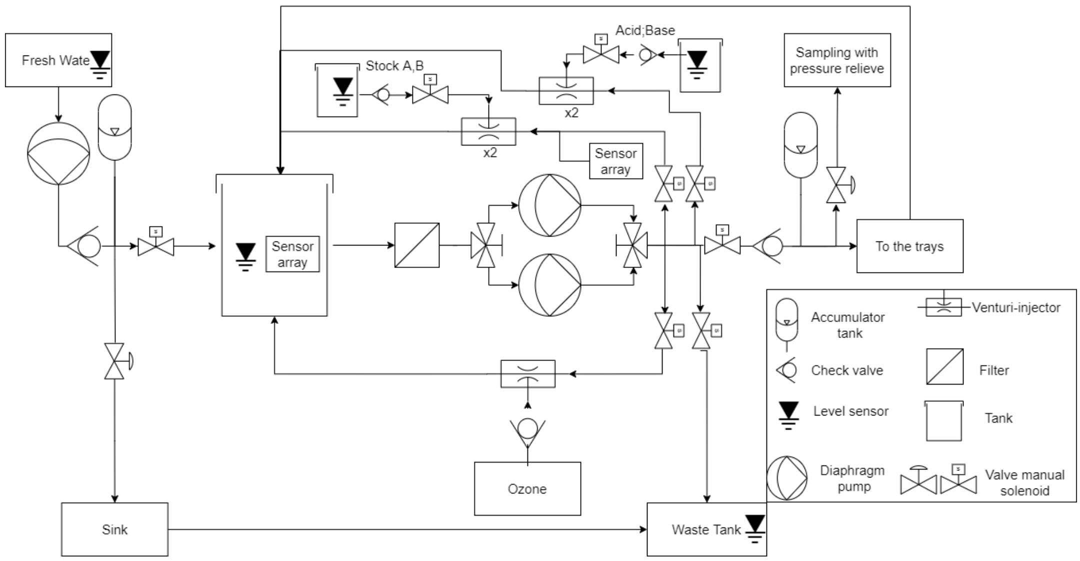

Figure 5.11: Mixing cycle for ozonation and composition control. The sensor array includes EC, pH, O_3, dO, and Temperature sensors. In the future, ion selective sensors are considered as well.

During the operation of the MTF, pre-packaged salt mixtures were dissolved to create the stock solutions. Mixing these and preventing salt precipitation, requires a mixing device. Since nutrient salts are also used in the initial phase of this greenhouse, the same mixing pumps as previously described are taken into consideration. In industry, further mixing technologies that require no in-tank maintenance as no moving parts are in contact with the chemicals are common practice. One alternative are magnetic stirrers. However, these are designed for small and round containers and were disregarded for the rectangular 50 l tanks. For larger industrial applications, air mixers are an option. Pulsair for example, releases pulses of compressed air at the bottom of a tank to keep the liquid moving and particles from depositing [104]. These, however, need an air compressor and are usually found in large applications. The most common and simplest method are stirring mechanisms that are attached to the lid of the tank. A rod connects the motor outside of the tank with a stirrer on the inside. Since the tanks are relatively small, the rotating stirrer can get caught in the foot valve used for the stock solution supply. In case compressed air is available, the Pulsair technology should be considered. Otherwise, the micro-pumps will be used as tried and true option.

A possible 50 l tank as available on [105] has the dimensions of 50x30x37 (length, width, height). Four of these could be located under the work table in the greenhouse section, on a length of 1.20 m. If the space under the table shall be kept free, they can be located in the NDS section on the opposite side of the freshwater tank. In both locations, they are easily accessible for changes in the composition. Both are high enough to support the venturi-system by gravity.

Finally, the target EC_t $[dS/m]$ can be restored by controlling the stock solution and freshwater input flows [23]. The subscript C stands for the current volume and EC in the mixing tank. Since the target volume equals the current volume plus the amount of freshwater and stock solution, as in Equation 5.12, the required volume of the stock solution V_{stk} can be expressed as in Equation 5.11 with the subscript W representing the respective values for the clean water. These values can then be fed to the controller.

$$V_{stk} = \frac{V_t EC_t - V_C EC_C - EC_W(V_t - V_C)}{EC_{stk} - EC_W} \tag{5.11}$$

$$V_W = V_t - V_C - V_{stk} \tag{5.12}$$

As an example, the replenishment of 60 l after one day of nominal operation for the tank with an EC of 3.5 mS/cm requires

$$V_{stk} = \frac{550\, l 3.5\, mS/cm - 490\, l 3.5 mS/cm - 0.05 mS/cm (60\, l)}{350 mS/cm - 0.05 mS/cm} = 0.59\, l \tag{5.13}$$

of stock solution. The smallest available venturi-injectors for the given pressure provide a suction capacity of 0.38 l/min and require a flow rate of 1 to 3 l/min of NS [63]. In this example, the solenoid and the flow through the venturi-injector would be open for 1.55 min.

The necessary accuracy as per Requirement FR-NC-010 is determined by examining a hypothetical case in which changes require a comparatively small amount of stock solution. A low tank capacity of $V_C = 300\, l$ and a solution EC_C of 2 are assumed since the EC changes faster under these conditions than during nominal operation. The stock solution EC is assumed to be 350 mS/cm as in 100x concentrated stock solution of the higher concentrated bulk solution EC of 3.5. A change of EC in the order of the required accuracy of $\pm 0.17 mS/cm$ requires a stock solution volume according to Equation 5.15. These are the more conservative values for each of the parameters.

$$V_{stk} EC_{stk} + V_C EC_C = (V_{stk} + V_C)(EC_C + 0.17 mS/cm) \tag{5.14}$$

$$V_{stk} = \frac{V_C 0.17 mS/cm}{EC_{stk} - EC_C - 0.17 mS/cm} = 0.146\, l \tag{5.15}$$

Injecting the volume in question takes 23 s and is, therefore, easy to control. To reduce the EC on the other hand requires the addition of water. Therefore, the values for the stock solution in Equation 5.15 are exchanged with the values for water. In this case, the values for the stronger NS are used as more conservative. This results in a water volume of 15.5 l. The accuracy is, therefore, only dependent on the control unit and can easily be achieved by the technical capabilities of the system.

The sensors in the MTF were sufficient to fulfill Requirement FR-NC-020 and here no potential for higher efficiency, easier maintenance, or mass reductions was identified. Therefore, the same sensors are chosen. For monitoring purposes, the dO content and the temperature are also measured.

Requirement FR-NC-051 states that nitric acid (HNO_3) shall be used to decrease the pH level. Commercially available 68 % concentrated nitric acid has a pH value of 1.2 [106]. It is a strong acid, meaning when in solution, all H^+ ions are available for reactions. Therefore, Equation 5.16 is used to calculate the molarity M_H [moles/l] of H^+ ions from the pH value.

$$M_H = 10^{-pH} \tag{5.16}$$

To increase the pH level potassium hydroxide (KOH) with a pH value of 10.98 is used. It is a strong base, meaning all OH^- molecules are available for reactions. When combined with the same amount of H^+ ions, they neutralize to water. In watery solutions, the pH and the potential Hydroxide (pOH) always add up to 14, making conversions possible. For more information on the chemistry, the reader is referred to [107].

The relation between the molarity and the volumes when mixing two acidic solutions is shown in Equation 5.17 [107]. Equation 5.18 is used to obtain the amount of acid V_a needed for a given change from the current volume V_c and molarity M_c to a target molarity M_t. This simplified linear relationship is only possible since the solution is acidic and the amount of OH^- ions is negligible.

$$M_c V_c + M_a V_a = M_t (V_c + V_a) \tag{5.17}$$

$$V_a = \frac{(M_t V_c - M_c V_c)}{(M_a - M_t)} \tag{5.18}$$

For the addition of potassium hydroxide, neutralizing effects need to be taken into account. Since both substances contain one H^+ or OH^- respectively, 1 mole of HNO_3 neutralizes 1 mole of KOH to water [108]. The molarity of H^+ ions is, therefore, the ion difference divided by the overall volume. The values for the base have the subscript b.

$$M_t(V_c + V_b) = V_c M_c - V_b M_b \tag{5.19}$$

$$V_b = \frac{V_c(M_c - M_t)}{(M_t + M_b} \tag{5.20}$$

The molarity and the pH of different degrees of dilution of the acid and base can be seen in Table 5.6. Lattauschke recommends using 53% nitric acid and 45% potassium hydroxide [18]. For safety reasons, they were diluted even more to between 1% and 10% in the MTF. For an example calculation to determine the acid and base volumes to stay within the range as per Requirement FR-NC-010, a set point of 6.3 is assumed since the usual range for cucumbers is between 5.8 and 6.7. The last two lines of Table 5.6 show the volume [l] necessary to cause a pH change of ± 0.12 from $M_{NS} = 5.01 \cdot 10^{-7}$ to the shown molarities, respectively. For the calculations a low tank volume of $V_c = 300\,l$ is assumed.

	HNO_3				KOH		
Concentration	0.68	0.53	0.1	0.01	0.45	0.1	0.01
pH	1.2	1.31	2.03	3.03	10.63	9.98	8.98
M(H)	0.06	0.05	0.009	0.0009	2.3E-11	1.0E-10	1.0E-9
pOH	12.8	12.69	11.97	10.97	3.4	4.0	5.0
M(OH)	1.6E-13	2.0E-13	1.1E-12	1.1E-11	0.0004	9.6E-5	9.7E-6
M_{eval}	6.6E-07				3.8E-07		
V[l]	0.0008	0.001	0.005	0.05	0.084	0.38	3.8

Table 5.6: The amounts of acid and base necessary to change the pH of 300 l of NS by the required accuracy of ± 0.12 at the pH setpoint of 6.3.

The amounts of acid are in the range of 0.76 ml to 52 ml. For the highly concentrated acid, the suction capacity of 0.38 l/min = 6.3 ml/s of the venturi-injector is too high for a reasonably controlled time. Even the 10% concentration needs an accuracy of 0.8 s. While this is theoretically possible, the exact amount of required acid needs to be accurately determined and iterative addition is unfeasible. Therefore, a 1% solution as in the MTF is recommended. For the potassium Hydroxide, the volume ranges between 37 ml and over 3 l. As a compromise between safety and volume, a concentration of 45 % as proposed by Lattauschke [18] is recommended. The resulting timing accuracy for the solenoid is 13.3 s. For the pH measurement, redundant sensors are used one in the external cycle and one directly suspended in the bulk tank.

In the MTF 5 l tanks were used, resulting in a scaled volume of 12.4 l. Since these do not offer much room for improvement, the next larger commercially available tank with 15 l is chosen. In the MTF a total of 40 kg diluted acid and 12 kg diluted base were consumed over one season [48]. Approximately 4 kg of acid were added per month resulting in a scaled consumption of 9.9 kg. Since the substances are diluted in water, a roughly similar density is assumed. Adding a conservative safety margin, 15 l tanks are, therefore, considered reasonable to sustain the plants for one month.

5.1.7. Decontamination

The decontamination of the system with ozone is now analyzed by incorporating the determined parameters. The goal is the log_2 removal of microorganisms and viruses (i.e. 99 % are eliminated) [109]. To achieve this without damaging the plants, a defined amount of ozone needs to be dissolved in the NS for a set contact time. The application method is then reexamined based on the necessary ozone input.

For log_2 removal of microorganisms and viruses, 0.01 to 5 mg/l are reported to be sufficient [109] for irrigation purposes. For the use in a closed system, a minimum of 1 mg/l and a maximum of 3 mg/l is suggested by Takashima et al. to prevent plant damage [34]. The half-life of ozone in water at room temperature is $t_{1/2}$ =15 min at $T = 25°C$ to $t_{1/2} = 20$ min at $T = 20°C$. For wastewater treatment, which has a higher degree of contamination than the recycled NS the United States Environmental Protection Agency recommends a contact time of 10 to 30 minutes [110]. For the removal of the most resilient common pathogens for food applications, a treatment supply manufacturer mentions a contact time of around 10 minutes [111]. Therefore, the NS is decontaminated with an ozone concentration of $\rho_{Oz} = 1 - 3$ mg/l and a contact time of 10 minutes.

Applying these parameters to the system design results in a minimum of 0.55g dissolved ozone per 550 l tank for continuous decontamination. The desired residual ρ_t after a contact time of t=10 minutes is above 1 mg/l and below 3 mg/l. The residual can be calculated by Equation 5.21 [112]. If the contact time t starts after reaching the initial concentration ρ_0 and no more ozone is added in that time, the initial quantity is given by Equation 5.22.

$$\rho_t = \rho_0 e^{-0.693\frac{t}{t_{1/2}}} \tag{5.21}$$

$$\rho_0 = \rho_t e^{0.693\frac{t}{t_{1/2}}} \tag{5.22}$$

To determine whether venturi-injectors or bubble diffusers are better suited for the application, the availability of the pump and the necessary ozone flow are evaluated. During nominal operation, the ozone can be added during each 3.2 min pump cycle consisting of around 1.25 min to supply the accumulator and 1.95 min for other operations like venturi-injection. In a hypothetical scenario with a powerful ozone generator that instantly resets the amount of dissolved ozone at the beginning of a t=3.2 min cycle, the ozone concentration shall not fall below 1 mg/l. Using 5.22 and the shorter half-life of 15 min, the initial ozone concentration needs to be at around 1.24 mg/l. Since the decay rate rises with the concentration, this includes a higher decay rate than when the ozone is added slowly. That means that during the 1.95 min, the concentration has to be increased by a maximum of 0.24 mg/l. For the entire tank this equals a flow during the entire pump off-cycle of

$$Q_{Oz,P} = 550\, l\, 0.24\, mg/l / 1.95\, min = 68\, mg/min \approx 4\, g/h. \tag{5.23}$$

Assuming a constant supply as with bubble-diffusers, on the other hand, will result in an equilibrium after an initial phase. The continuous supply for an equilibrium at a certain concentration can be calculated by the current decay rate, which is analyzed by taking the time derivative of Equation 5.21 at t=0.

$$\frac{d\rho}{dt} = \frac{-0.693}{t_{1/2}} \rho_0 e^{-0.693\frac{t}{t_{1/2}}} \tag{5.24}$$

$$\frac{d\rho}{dt}(t=0) = \rho\frac{-0.693}{t_{1/2}} = 1\, mg/l \frac{-0.693}{15\, min} = -0.046\, mg/l/min = 2.77\, mg/l/h \tag{5.25}$$

Equation 5.25 shows the decay at an equilibrium of 1 mg/l in the NS. For the 550 l tanks, the decay of 2.77 mg/l/h requires a constant ozone production of $Q_{Oz,con} = 1.52\, g/h$.

A supply adapted to the pump downtime via venturi-injectors of 4 g/h or a continuous supply via bubble-diffuser of 1.52g/h enable continuous decontamination at 1 mg/l during nominal operation. This, however, does not include the addition of the initially present ozone. The decay during the build-up phase is, however, significantly smaller than with the calculated parameters. Even if no additional ozone is injected, the concentration slowly approaches the equilibrium. Not taking this overproduction into account, build-up of the initial ozone amount of 0.55g in a maximum of 30 min, requires a maximum additional flow of 1.8g/h intermittently or 1.1 g/h in the continuous case.

In case of emergency supply, the intermittent rate will not be sufficient since the downtime of the pump in which it can be used to supply the venturi-system is only 0.7 min long. Since this scenario should not last for a long time and batch decontamination at night is still possible, this situation is acceptable. The bubble diffuser is not affected by this issue.

Figure 5.12: Triogen® LAB2B corona discharge type ozone generator with variable ozone output up to 4 g/h with air as feed-gas, and up to 10g/h with pure oxygen [113].

Figure 5.12 shows a potential ozone generator. If used with air, it has an output of up to 4 g/h at an airflow rate of 4 to 10 l/min. The required gas flow of the venturi-injector is, therefore, $Q_{V,gas}$ = 4 l/min. A potential gas-venturi-injector shows a gas injection rate of around 3.5 l/min under the given working conditions of 4.1 l/min liquid flow and 7.6 bar pressure [114]. The pressure to flow curve of the venturi-system and the pump meet at around 100 PSI, such that the pump will not reach the shut-off pressure.

It has to be noted that ozone generators require enough oxygen to supply their nominal production rate [113]. As shown in Figure 5.13 the ozone production for airflow below the optimum is almost proportional to the airflow through the generator [115]. With an airflow of 4 l/min, the ozone generator above has an adjustable output up to 4 g/h with air and up to 10 g/h with pure oxygen as feed-gas. Combined with the venturi-injector, this model, as is used in laboratories, would produce up to 3.5 g/h or 8.25 g/h, respectively. For the bubble-diffuser, the use of air is, therefore, sufficient. For this particular venturi-injector, pure oxygen would be required to keep the equilibrium.

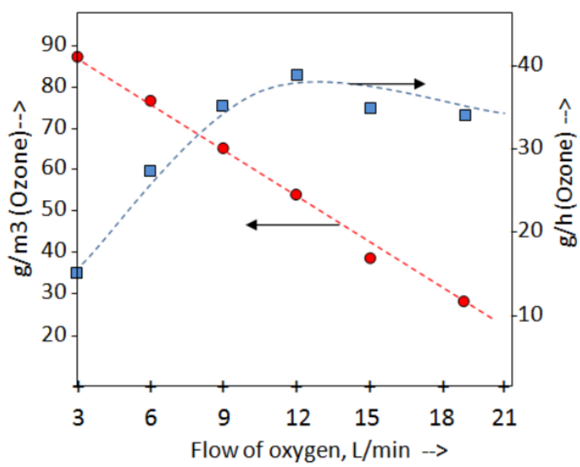

Figure 5.13: The ozone concentration and production in relation to the air flow rate [115].

Due to the circulation cycle introduced for the stock solution injection and mixing, some of the infrastructure necessary for the venturi-injector is already available. In general, a venturi-injector is superior compared to a bubble-diffuser. The mass transfer rate is higher, additional air pumps are made obsolete, and the chance for efficiency decrease due to fouling is smaller. However, introducing an oxygen tank just for this purpose is not worth the advantages since it would require more mass and volume than the alternative. As mentioned in the design of the AMS, an O_2 and CO_2 interface is likely to be implemented to help with the gas exchange between the habitat and the GHM [85]. Although more information is necessary for a final choice, using the air enriched with oxygen might enable the use of the venturi-injectors. Furthermore, components of other manufacturers might have the required air suction rate. Therefore, they are chosen for this design iteration under the condition that one of the factors is true. For the ozone to stay in contact with the most NS, the inlet is directed to the floor of the tanks instead of open above the surface. If the solenoid to the ozone venturi-system is open, but the generator is not operating, only air is dissolved, increasing the oxygen content. The filter in front of the pump also increases the efficacy since suspended particles do not decrease the oxidation capacity and do not clog the injector.

To monitor the O_3 concentration in the NS, the same sensor as in the MTF is used. With the selected lab ozone generator, ozone production can be increased when the concentrations are too low. It has to be ensured, however, that the ozone escaping the tank does not increase the ozone concentration in the air to above the air safety standard of the European Union of 120 $\mu g/m^3$ for a maximum of 8 hours [116]. Ozone in air has a significantly longer half life of $t_{1/2}$ =3 days. Based on Equation 5.25, and a GHM Volume of 225 m^2 the decay rate at the maximum ozone concentration in air is around 260 mg/h. At a continuous production rate of 1.5 g/h, this means that an escape rate of 17 % will eventually lead to a critical ozone concentration. Therefore, an air ozone sensor should be placed in the AMS. If the test phase shows concentrations higher than that, an ozone destructor should be incorporated in the vent of the bulk tanks. Furthermore, a check valve is necessary to ensure that the ozone does not flow back once the airflow is stopped. To determine the frequency of decontamination, more information about the pathogens in the returning NS is necessary. This question is outside the scope of this thesis and not answered here.

5.2. Modes of Operation

Since some of the requirements like Requirement FR-OP-010, which calls for a maximum crew work time, can not be addressed by design choices alone, the interactions with the crew need to be considered as well. Although a complete user manual of operation is desired as per Requirement FR-OP-080, only the basic modes and control scenarios namely ”Nominal operation, Maintenance, system start up, and ”Emergency situations” are described here. A full version of the manual is created for the entire system once the other subsystems are designed as well.

5.2.1. Nominal operation

During nominal operation, an optimal root environment that has already been established only has to be sustained. As described in the previous sections, each day is divided into 16 hours day time and eight hours night time in which the lights are turned off. While the plants do not require water during nighttime, each tray is supplied with NS for 30 s every six minutes during the day. Therefore, the solenoids of an average of 8.7 trays need to be opened at any time. Within the pressure boundaries, the volume is supplied by the accumulator tanks. The pump is switched on whenever the pressure drops below the minimum of 7.6 bar and turned off when it reaches the maximum of 10 bar.

After or before each refill cycle of the accumulator tanks, the solenoids to the venturi-injectors can be opened if the EC or pH deviate from the set-point or decontamination is necessary. Larger amounts of new NS can be mixed during the night. In such cases, the acid or base should be added before the stock solution since they also affect the EC. Since the levels in the stock solution tanks are measured by pressure sensors, a precise volume distribution can be achieved with the proper control.

5.2.2. Maintenance

The components that have to be checked most regularly are the filters and the sieves at the tray drains. To determine the frequency of this procedure, more information on the plant debris and biofilm accumulation for this specific system are necessary. In the first mission stages, it should, therefore, be checked weekly. Whenever the tanks are flushed, the system is cleaned. Completely sterilizing the pipes by flushing them with hydrogen peroxide destroys beneficial microbes as well, leading to even worse contamination afterward. Therefore, the cleaning procedure in the MTF was replaced by flushing the entire system with hot water. Nevertheless, a strong biofilm formed, which needed to be removed mechanically. Recommendations for procedures are considered further in Section 6.3. In the upward ducts, the individual pipe parts are short enough to be cleaned by removing them. The tanks are connected to the pipes by screw connectors which allow for quick removal. The tanks can be slid into the corridor space and lifted through the floor. While basic cleaning is conducted every time the plants are harvested, a complete cleanup, including biofilm removal, should be considered yearly. The accumulator tanks should be inspected at least annually [117]. All sensors are calibrated depending on the specifications of the manufacturer. The diaphragms of the pump should be inspected every 300 working hours [101]. Assuming that half of the pump downtime is used for functional tasks, the currently estimated nominal duty cycles results in a daily run-time of 16 h/day 1.25 min/3.2 min+0.5 (1.95 min/3.2 min))=11.125 h/day. The diaphragm should therefore be inspected roughly every 27 days in the monthly routine check-up.

5.2.3. System start up

At a capacity of 550 l, refilling only one bulk tank requires almost the entire content of the 600 l freshwater tank. Since this would, in turn, be refilled by the water supply of the habitat, it is not worth sizing the freshwater pump to move the entire tank content in a matter of minutes. Furthermore, the freshwater tank is not large enough to supply the entire water for both tanks at the same time. Alternatively, water is added to the bulk tanks manually or directly from the habitat. During start-up time, the mixing pumps should constantly be running to homogenize the stock solutions or the salt mixture with the freshwater. The control accuracy at roughly half-filled tanks has been analytically verified. At this stage, the irrigation could theoretically start if all other parameters are met. At the first start, the accumulator's pre-charge pressure has to be checked at least once a day for the first week of operation.

5.2.4. Emergency Situations

During an emergency, it is assumed that a supply with the sub-optimal solution composition is sufficient for the duration of the failure. The main ducts are designed such that the individual pipes can be taken out without completely shutting off the supply. If an upward duct shows signs of leakage, the respective valve can be closed without inhibiting the supply for the others. The number of trays without supply is, thus, kept to a minimum. In case of a pump failure, the redundant pump can take its place with minimum effort. Most failures can be monitored in the pressure data. If one of the tanks or the composition control is compromised, the entire system can quickly be connected to the other tank. All these tasks are currently meant to be performed manually by the crew, which is informed by an alarm. Since no irrigation is necessary during the night, this will most likely not inhibit sleep. The tasks could also be automated by replacing the manual valves with solenoids. Since the irrigation intervals are chosen such that the minimum necessary humidity is available in the plant trays at any time, skipping a cycle will immediately cause drought and plant damages. To avoid this, the lights should be switched off as soon as a failure is detected since this reduces transpiration and, therefore, the water need [52].

5.3. Design Summary

5.3.1. Summary of the key Parameters

In this chapter, the key parameters of the NDS were estimated. First, the feed rate, the absorption rate, and the return rate of NS were determined based on transpiration data of the selected plants and available information from the MTF. Starting from the optimal droplet size for aeroponics and the feed rate, a nozzle size was chosen and the nozzle operating pressure determined. Using the layout designed in Chapter 4.2.2, the minimum and the maximum pressure drop from the pump to different locations was determined, and a pipe diameter was chosen accordingly. The maximum accumulator tank size was estimated based on the maximum drawdown capacity needed for an arbitrary pump and manufacturer specifications. In parallel, an example pump with the minimum requirements was suggested by analyzing the flow rates from a pressure-to-flow diagram. The minimum accumulator tank size was then estimated based on this specific pump.

Starting from requirements and information from the MTF, a maximum necessary tank size was determined. Based on the desired time between NS changes, the minimum tank size was evaluated, by estimating the nutrient uptake of the plants and the resulting changes in the NS composition and EC value. A position for the tanks in the preliminary architecture of the GHM was chosen accordingly. A similar approach was then taken to assess the stock solution, the acid, and the base tank size. Subsequently, the required accuracy was evaluated by analyzing potential venturi-injectors and the concentration of the respective constituents. Finally the required amount of ozone for the elimination of 99 % of microbes was determined. Taking the half life time of dissolved ozone into account, the required ozone flow was evaluated. From the data-sheet of an example ozone generator the necessary air flow of the venturi-injector was determined. The resulting key parameters can be found in Table 5.7.

	Parameter	Symbol	Value
Irrigation Rate	Flow rate per tray	Q_{Tray}	0.188
	Maximum flow per irrigation cycle	Q_{max}	19.5 l/cycle
	Nominal flow per irrigation cycle	Q_{nom}	9.75 l/cycle
	Irrigation Rate	Q_{Pl}	3.25 l/min
Operational Pressure	Droplet size	D_{Drop}	0.03-0.08 mm
	Acceptable range of the flow rate	-	$Q_{Pl} \pm 10\%$
	Nozzle orifice	D_{NO}	0.38 mm
	Nozzle pressure	p_N	7.6-9.9 bar
Pressure Drop	Minimum equivalent length	$L_{eq\,,min}$	570 D_p
	Maximum equivalent length	$L_{eq\,,max}$	1060 D_p
	Pipe length to furthest tray	$L_{p\,,min}$	4.5 m
	Pipe length to closest tray	$L_{p\,,max}$	13 m
	Pressure drop between tank and trays	ΔP	0.036-0.095 bar
	Resulting pipe diameter	D_p	12.48 mm
Accumulator Size	Irrigation time	t_{supply}	3.2 min
	Drawdown capacity	V_{DD}	2.6-10.4 l
	Number of accumulators	N_{acc}	2
	Accumulator capacity	V_{acc}	17.5-40 l (25 l)
Pumping Conditions	Maximum pump cycles per day	N_{start}	300
	Pump flow rate	Q_P	3.7-4.1 l/min
	Pump operating pressure	p_P	7.64-10 bar
	Pump cycle on/off for maximum flow	$t_{on/off,max}$	2.5/0.7 min
	Pump cycle on/off for minimum flow	$t_{on/off,min}$	1.25/1.95 min
Composition Change	Use time for one batch of NS	t_{flush}	1 month
	Absorbed NS per cycle and tank	Q_{abs}	363 ml/cycle
	Return of undesired ions per cycle	Q_{ion}	10.2g/d
	Bulk tank volume	V_{NS}	550 l
	Fresh and waste water tank volume	$V_{fresh/waste}$	600 l
Composition Control	Venturi-injector fluid flow	$Q_{V,fluid}$	0.38 l/min
	Nitric acid concentration	HNO_3	1 %
	Potassium Hydroxide	KOH	45 %
	Stock tank volume	V_{stk}	50 l
	Acid/base tank volume	$V_{a/b}$	15 l
Deconta-mination	Required ozone concentration	ρ_{Oz}	1-3 mg/l
	Required venturi-injector gas flow	$Q_{V,gas}$	4 l/min
	Continuous ozone flow for ρ_{Oz}=1 mg/l	$Q_{Oz,con}$	1.52 g/h
	Ozone flow per nominal pump off-cycle	$Q_{Oz,P}$	4 g/h

Table 5.7: The estimated intermediate and key parameters per category.

5.3.2. Summary of the System Architecture

During the entire parameter estimation process, small decisions were made that were based on a specific system architecture. A schematic diagram of the proposed architecture can be found in Figure 5.14. For clarity, one mixing cycle is simplified as a black box. The sensors in all tanks are not included for the same reason. Each tank is equipped with a pressure-based continuous level sensor and a float switch to minimize the risk of overflow. The bulk tanks and the freshwater tanks also have a float switch to indicate a low tank level. Sensor arrays with EC, pH, dO, and O_3 probes are located in both bulk tanks and mixing cycles, and pressure sensors are installed at every upward duct and in the mixing cycle. Finally, flow sensors are placed in the suction line of each pump. Sampling for manual measurements is achieved by a manual pressure reduction valve located directly at the work table above the pumps.

The solution constituents are added to the cycle via venturi-injectors since these can be fed during the off-cycles by the main pump and already pre-mix the solution. Since there are many advantages to using venturi-injectors for the ozone flow as well, they are recommended. It has to be noted, however, that the required airflow of the example ozone generator is higher than the suction rate of the analyzed injector. In case other manufacturers also do not offer the required size, bubble diffusers might be a better choice.

The components in the schematic are arranged as in the GHM. The stock solution, acid, and base containers as well as the ozone generator are stored under the working table above ground as long as this space is not allocated to another subsystem in the future. One tank is located in the sub-floor space beneath the working table, while the other is beneath the first rack in the middle. The accumulator tanks are located below the outer racks or in between the bulk tanks. Each of the tanks has a minimum length of 0.88 m. If the tank can be directly located next to the door, roughly 1.1 m between both tanks is available for the pumps and sensors. This parameter might change depending on the routing of the atmosphere management air ducts.

The supply pipes are arranged such that they follow the edges of the middle racks next to the second bulk tank. Between racks 3 and 4 they run along the frame to reach the upward ducts. For every rack, pipes with solenoid valves direct it to the four trays on the respective level. The trays are of the same design as in the MTF and a sieve in the drain prevents debris from clogging the return lines. Due to the use of gravity return, the return lines can not be routed from the outer racks back to the middle since a constant gradient needs to be present. For simplicity, the return ducts from the middle rack are not shown in the diagram. Using the available space below the lowest rack for the return pipes allows for a gradient of 1:25 before reaching the floor level. This way, the reduction of the available height for the tanks is as minimal as possible. The estimated length of the pipes for the supply lines is 47 m. Including the return ducts results in a total length of roughly 100 m.

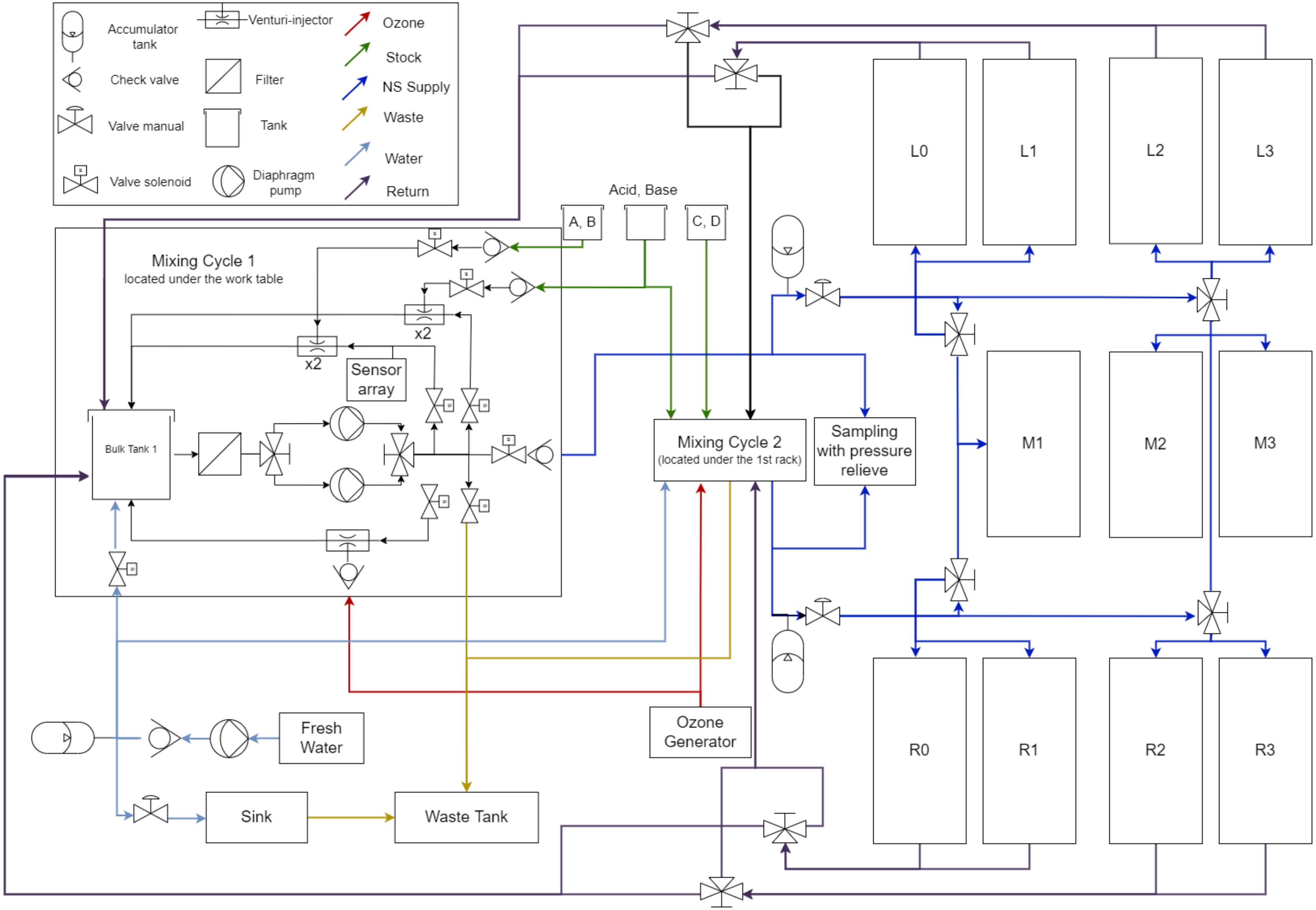

Figure 5.14: Combined system flow diagram of the mixing and simplified irrigation cycle.

5.4. Requirement Verification

The requirement document contains one column stating the methods to verify the fulfillment of the respective requirement. Most applicable analytical or similarity estimations affecting the key parameters have already been made during the design phase. These can only be verified further once the other subsystems have been designed or a prototype is built. With the layout and the design space determined, an example composition of potential components is suggested in Table 5.8. The mass budget is verified and a preliminary cost budget estimation is made. It has to be noted that these are not the finally chosen components since some dependencies on other subsystems like the power and control unit still need to be clarified. At this design stage, structural elements like wall mounts are not included in the selection.

Table 5.8 shows the quantity, the price, and the mass per example component. Especially the number of fittings might change depending on the exact configuration of other subsystems and is estimated very conservatively from the system architecture. The roughly estimated acquisition costs are 31831 €. Adding a 20 % margin results in a overall cost estimation of $C_{€} \approx 39000\,€$. A more detailed cost analysis should be conducted after the initial design of all other subsystems for the entire GHM. The current mass estimate is around 612.1 kg, which is within the required 766 kg and leaves a margin of 24 %.

Table 5.10 shows an estimation of the components power consumption. The included components are the pumps, the solenoids, the ozone generators, and the sensors. The total is then estimated for the average number of components that are working at a time. Since the main pumps have down-times and the freshwater pump is used less, the power consumption is estimated for 2 constantly running pumps. Because the frequency of decontamination is not known yet, the ozone generators are assumed to be constantly running. Of the 26 solenoids for the supply of the trays, an average of 2.2 are active at all times. For the use of the 18 solenoids for functional tasks, a very conservative average number of 9 is assumed to work at the same time. The same ratio is assumed for the 10 solenoids for the venturi-injectors.

Component	**Quantity**	**P** [W]	**Total P** [W]
Pump	2	120	240
Solenoid Pipe	11.2	13	145.6
Solenoid Venturi	5	4.5	22.5
Sensors*	34	1	34
Ozone Generator	2	105	210
Total			652.1

Table 5.9: The individual and total Power consumption P of components with the average quantity of running components. *The sensors are combined into one category and a very conservative P is assumed.. The individual quantities can be found in Table 5.8.

The conservative estimate of the nominal power consumption is, therefore, 652.1W. Compared to the desired maximum of 660 W as per Requirement SO-NDS-060, this is dangerously high. Since the estimates are quite conservative, it is acceptable for this design stage. It should, however, be monitored closely, especially if, against the conclusion of Section 4.2.3, temperature control is ever implemented. This could increase the power consumption significantly.

For the evaluation of the volume, only the parts of the ”main body” category in Table 5.8 are considered. First, the volumes of the individual elements are added together. Then, a factor for the space that is required for connectors and ease of operation is used to establish an overall volume. Simply adding up the component sizes results in a volume of $V_{Com} = 2.859\,m^3$. To enable accessibility especially to the pumps which are located between the two tanks, a conversion factor of 50 % is used. This results in an estimated volume of $V_{NDS} = 4.29m^3$. The safety margin to the required $4.52\,m^3$ is only about 5 % and should, therefore, be closely monitored in further iterations.

Requirements concerning the accessibility and modularity of the system should be demonstrated with a mock-up. At the current design stage, test procedures are not possible, and the verification of the respective requirements will be deferred until a greenhouse prototype is available.

The requirements concerning the dependability of the system have been addressed by implementing redundancy for the identified components and operational procedures as explained in Section 5.2. Exact specifications on part reliability were not collected at this design stage since none of the selected components is space graded. Positioning and functionality of other subsystems introduce uncertainties that might require changes in the NDS. The layout and components were chosen to maximize the maintainability within the given constraints. While the necessary availability in the main circulation for optimal yield is close to 100%, the individual components all have down-times. Furthermore, no individual task is extremely time-critical.

For a final assessment of the risks identified in Section 3.2, these are reevaluated in Table 5.11 by taking the design choices and modes of operation into consideration. In addition to the severity, the detectability is estimated since now the capabilities and positions of the sensors are known. It has to be noted, that a complete failure modes and effect analysis as in [139] for the MTF is outside the scope of this thesis, and the risk assessment is only meant to be an indicator on which areas the focus should be in future iterations. Although some occurrence rates were documented in the MTF, the design is too different to make precise forecasts. These should, therefore, be collected during the test phase of a potential prototype.

Score	Detectability
1	Automatically in the sensor data.
2	During routine maintenance.
3	At close examination of components or small irregularities in the data.
4	Only during complete system cleanup or data analysis.

Table 5.10: Explanation of the detectability scores in Table 5.11.

Furthermore, the system architecture is analyzed for single points of failure and common-mode failures. Although some failures like a pump breakdown or a pipe leak in a central part of the system can make an entire tank unusable, no individual failure in the NDS was identified that results in a complete loss of harvest. All racks can be supplied from the alternative tank, as long as only one pipe section is compromised. The allocation can quickly be switched by manual valves. Although this results in a suboptimal nutrient supply and, therefore, reduced yield, it gives the crew the required time to exchange the faulty components.

The most common pump failures are attributed to too many duty cycles in a given time. Since the maximum number of daily duty cycles has been taken into account in the design, the spare pumps in cold redundancy sufficiently reduce the risk. The only identified common-mode failure that would lead to immediate damage in the new pump is a clogged suction line or filter. Since filters are regularly cleaned and, in particular, before switching the pumps, this risk is minimal. The most susceptible components for common-mode faults are the ozone generators since the ozone output can be reduced by high humidity in the air. When this is the case, even the redundant generator will not produce the required amount. This problem can be handled by the AMS or by an additional air dryer in front of the generator. For contamination to lead to the destruction of the entire yield, not only do the ozone generators and sensors have to be faulty, but the contaminated NS has to get into the other nutrient cycle. Therefore, it is not considered a single point of failure. Finally, the filter size and the decontamination might be a driver for common-mode failures of the nozzles since the chance of clogging increases with the size of volatile compounds in the NS. Therefore, the reason for clogged nozzles should be investigated and the mesh size or the ozone concentration adapted accordingly.

	Component	Q	C_U [€]	C_{tot} [€]	M_U [kg]	M_{tot} [kg]
Main Body	Pump [83]	4	200	800	3.5	17.5
	Freshwater supply [118, 119]	1	200	200	4.5	4.5
	Accumulator [120]	2	45	90	4.8	9.6
	Tank [121]	2	2025	4050	70	140
	Fresh-/waste-water tank [122]	2	200	400	47	94
	Stock tanks [123]	4	100	400	4.5	18
	Acid and base tanks [124]	2	67	134	1.6	3.2
	Ozone Generator [113]	2	3050	6100	6	12
	Sub-total 1			12174		295.3
Piping	Stainless steel Pipe [125, 126]	100 m	8.6	860	0.84	84
	Elbow [127]	100	1.50	150	0.1	10
	T-junction	40	2	80	0.2	8
	4-way junction	30	3	90	0.3	9
	3-way T ball-valve [128]	20	40	800	0.64	12.8
	Check valve [129, 130]	13	30	390	0.2*	2.6
	Filter	4	40	160	0.3	1.2
	Sub-total 2			2530		127.6
Control	3/8" Solenoid [131]	44	80	3520	0.4	17.6
	1/8" Solenoid [132]	10	40	400	0.125	1.25
	EC Sensor [133]	4	250	1000	0.5*	2
	pH Sensor [134]	4	220	880	0.5*	2
	Pressure sensor [135]	12	80	960	0.2	2.4
	Flow sensor [136]	2	250	500	1	2
	Ozone Sensor	4	100	400	0.2	0.8
	dO Sensor	4	100	400	0.2	0.8
	Temperature Sensor	4	100	400	0.2	0.8
	Foot valve [137]	6	60	360	0.4*	2.4
	Venturi-injectors [63]	10	20	200	0.3	3
	Sub-total 3			9020		35
Misc.	Nozzles	624	7	4368	0.02 kg	12.5
	Trays	104	7	728	1.26	131
	PTFE Tray tubing	208 m	13.51	2811	0.04*	8.3
	Pressure reduction valve [138]	2	70	140	0.72	1.44
	Sampling Outlet	2	30	60	0.5*	1
	Sub-total 4			8107		154.2
	Total			31831		612.1

Table 5.8: A selection of potential components with the quantity Q, unit cost $C_{€\ U}$, total cost $C_{€\ tot}$ and mass M_U and M_{tot} estimations. Some values are taken from similar components of the next larger size or are estimated in another way. *rough estimation based on size

ID	Possible Cause	S	D	Notes
R-01	Less NS at the plant roots due to clogged nozzles.	1	4	Clogged nozzles only have a local effect, are, however, hard to detect in the sensor data. Although the yield might be reduced, the plants don't necessarily show signs of deficiency.
	Clogged filters	2	1	Clogged filters reduce the flow and might have detrimental effects on the pump. This can, however, be seen in the flow and pressure data as well as in the pump run-time. The filters are also checked during routine maintenance.
	No NS at the plant roots due to: • Pump malfunction • Major pipe leak • Empty bulk tank	2	1	Although the entire harvest is at risk, the adverse effects can be mitigated by automatic measures like turning off the light. In the short term, all of the instances can be handled by switching to the other tank. Furthermore, this failure is easy to detect by the integrated sensors.
R-02	Too much NS at the plant roots: Blocked drain	2	2	A blocked drain can not easily be noticed with the available data. Therefore, an inspection of the drain sieves is part of the regular maintenance.
	Failed flow or pressure sensors	1	1	This is eliminated by decoupling the irrigation and pump cycle. Moreover, the pressure relief valves protect components from over-pressurization.
R-03	Wrong NS composition	2	2	Due to the tank size, and the monthly replacement of the NS, the impact of ion accumulation is mitigated. The redundant sensors increase the detectability of any deviations. Blocked supply lines are detected by the level sensors in the stock tanks. Using the main pump for cycling the NS provides a constant movement for a homogeneous ion distribution.
R-04	Microbial contamination	3	3	The ozone system provides enough decontamination capacity for continuous supply. The NS is only in contact with the plants from one tray before decontamination. A malfunction of the ozone generator is visible in the sensor data, but since determining the microbial load is still a manual process, it is not regarded as routine maintenance.
R-05	Biofilm formation	2	4	No accurate data is available on the removal of biofilms in the pipes. To detect this build-up, the pipes have to be removed, which might cut off the supply of a certain part of the system or force the supply with suboptimal NS.
R-06	Ozone can be detrimental to plants as well as human health.	3	1	As long as the ozone sensor is implemented in the AMS, detrimental amounts of ozone in the air should be detectable. If the measurements show values above 120 $\mu g/m^3$, an ozone gas destroyer should be implemented in the tank vent.
R-07	Data transmission failure	3	1	Undetected cases will likely result in reduced yield and in extreme cases loss of the harvest. Instances with large and rapid deviations from the nominal values are visible in the data, while slow degradation is detected during sensor calibration.
R-08	NS in the structure due to: • Leaks • Tank overflow	2	2	Minor leaks are hard to detect by data alone. Since the NS accumulates at the lowest point of the cylinder structure, it is visible at routine maintenance. Overflow float switches in the tanks and the level sensors should make a tank overflow unlikely or at least detectable.

Table 5.11: The severity (S) of the identified failures is reiterated and the detectability (D) is introduced after the system design and the modes of operation have been established.

6 Conclusions and Recommendations

Completely regenerative life support systems are essential to the long-term exploration of far-off locations in space. One possibility to achieve this independence from resupply shipments is the shift from physico-chemical to bio-regenerative life support systems. A potential component is a plant cultivation module that produces food for the crew and helps with oxygen and water regeneration. In this thesis, the nutrient delivery system for a greenhouse module for use on the Moon or Mars was designed. Although each of these modules only has a supportive role for a complete life support system, eventually the greenhouse module design might be implemented into a life support system like the MELiSSA project. To accomplish this task, a set of research questions was answered in this thesis:

How can a consistently favorable root environment for plants be ensured in a deployable greenhouse for the Moon?

What cultivation method is best suited for this purpose and how can it be implemented into the given preliminary design?

What components are needed to make the root environment for the plants dependable?

How can the key factors be controlled and monitored?

How could the operational phase of the system look like?

The important parameters to enable a favorable root environment for plants were discussed. These included nutritional information, the impact of other environmental factors on the root zone, and the threat of contamination. Subsequently, the most suitable type of plant cultivation method was chosen according to previously determined weighted selection criteria. Aeroponic systems have been determined to perform best under the given circumstances. While the system was designed to fit the preliminary design and mission scenario for a greenhouse module for the Moon as well as possible, many factors are still unknown, and further iterations are necessary once more information is available.

The types of components and their potential design space have been determined. However, since changes are likely to occur, example components have been chosen only to estimate the cost and mass of the system and as a guideline for future component selection. Furthermore, components critical to the dependability of the system have been identified, and failure mitigation strategies were introduced. For further testing during the prototype and operation phase, the functional parameters are monitored at suitable locations in the loop. Finally, suggestions for the modes of operation were made. These are open for change since maintenance and operation can potentially be combined with other subsystems. Thus, a conclusive manual will be written once all subsystems and particularly the control system are at a further design stage.

The methodology of how these answers were generated is summarized in Section 6.1. The design of the greenhouse module is in a very early stage, and the nutrient delivery system is a complex subsystem with a variety of interconnected parameters. Nevertheless, this thesis attempts to provide a design of the system that is as complete and realistic as possible. To clarify the aspects of the design that most likely need improvement when more information is available, Section 6.2 provides a critical review of the methodology and content of this thesis. Finally, Section **??** makes recommendations on how to improve on this work.

6.1. Summary

To design the Nutrient Delivery System of the EDEN NextGen greenhouse module for missions to Moon or Mars, a literature review was carried out. The main objective was to assess critical factors affecting the root environment of plants. In addition, the most commonly used technologies in plant compartments of commercial applications, analog test sites, and plant growth experiments for use in space were examined. The most important aspects of plant cultivation were analyzed, and the different plant cultivation methods and available technologies were compared. Special emphasis was put on the mobile test facility of the EDEN ISS project that has been deployed in Antarctica since 2018.

Next, an analysis of the current state of the EDEN NextGen greenhouse module was carried out. The interactions of the different subsystems and a preliminary risk analysis were used to define the requirements for the nutrient delivery system design. These can be found in Appendix A. Using an analytical hierarchy process, they were then translated to a set of weighted selection criteria to use as a basis for the conceptual design stage. Including the respective weights, the criteria are safety (26.7%), reliability (21%), maintainability (15.8%), yield (15.8%), sustainability (8.1%), mass (3.8%), volume (3.8%), flexibility (2.9%), and power (2.1%).

In the conceptual design phase, a design option tree was introduced. During the trade-offs, certain options were eliminated based on the selection criteria, the requirements, and the technology readiness level of the concept. In cases where the elimination process did not provide a dominant option, the leftover options were scored based on the individual criteria, and an overall score was established using the selection weights. This resulted in a functional architecture of the nutrient delivery system.

Finally, the key parameters were defined for the selected concepts. These were then determined based on the plant requirements, takeaways from the EDEN ISS, or arbitrary commercially available components. Due to inter-dependencies, some decisions were made iteratively or in parallel with others. The result is a physical architecture and an operating range for potential components. The system will mainly be located in the sub-floor compartment of the greenhouse module, accessible by removing the floor panels. Nutrient solutions with two different compositions are supplied to a total growth area of $30.8\,m^2$ using an aeroponic irrigation technique. The distribution of the different nutrient solutions can be adapted depending on the respective share of leafy greens or fruity crops. Stable conditions are ensured by automated electrical conductivity, pH, dissolved oxygen, and temperature measurements and control.

Although the final operations are dependent on a variety of so far undefined factors, suggestions for possible modes of operation were given. If possible at this stage of the design, some requirements were verified with an example selection of commercially available elements. A system with components that fit the working conditions will have an estimated acquisition cost of around 31 831 €. Including a 20 % margin, this results in a budget of 39 000 €. The system will have a total mass of around 612 kg, which allows for a 24 % safety margin to the required 766 kg, and power consumption of around 652 W.

Finally, the risks that were identified in the beginning are reiterated, and the implemented risk mitigation strategies are summarized. The most critical of the identified risks are still microbial contamination and biofilm formation. Since these have the most adverse effects on the system, the crew, and the plants, and generally require relatively high effort to be detected. The measures taken include an ozone generator and preferred materials to reduce the cleaning effort. At this design stage, no active strategies for biofilm removal except the exchange and cleaning of individual pipe sections have been selected. The proposed strategies all require some testing in a prototype and are summarized in Section 6.3: Outlook and Recommendations.

6.2. Critical review

Although a literature review on plant cultivation has been carried out beforehand and experts were consulted on the matter, more specific knowledge about biological processes and their implications on the root zone are considered beyond the scope of a space system engineering MSc. thesis project. Therefore, only an absolute basic knowledge of plant cultivation was gathered. Especially changes in the assumptions made for the plant selection and their needs might have a significant error propagation rate affecting the final design. As a greenhouse design that has been proven to work, the EDEN ISS performance data was used as a baseline for many requirements and calculations. The underlying assumption is that the nutrient delivery system of the EDEN ISS greenhouse module worked well and met the requirements for optimal plant growth. It is further assumed that any deficiencies were included in the lessons learned. Nevertheless, some impactful decisions have been reviewed. With a deeper knowledge about plant growth, the design could have been attempted from first principles, thus eliminating the risk of taking over potential design flaws.

The risks that were identified were all based on the experiences made with the MTF and the most common problems with nutrient delivery systems in general. For this specific one, different issues might arise. Some of the requirements have been introduced, although the values are not yet confirmed or even determined. Since the design of the overall system is in a very early stage, these requirements might be based on assumptions that prove to be invalid and that have to be re-evaluated once more information on the mission or the underlying subsystems is available. The weights for the selection criteria were estimated based on a pairwise comparison. Depending on other subsystem designs and the fulfillment of the respective budget constraints, this comparison might have resulted in different weights. Although the safety aspect, in general, is highly important, the impact of the nutrient delivery system on the overall system safety is small compared to other threats like space debris or radiation. Rating it as the most important criterion might therefore overestimate its relevance. In addition, the weights of the budgets like mass, volume, and power could be considered negligible while within the budget. If the budget constraints are violated, they could either have a significantly higher impact on the decision or immediately eliminate the respective choices. For this method, however, the budgets would have to be split among the individual components, or designs using different concepts would have to be completed to such a degree that the entire budget can be estimated.

The conceptual design phase was based on the literature review and commonly available technologies. Especially designs with low technology readiness levels may be underrepresented after the trade-offs. Although this is reasonable for the final design of a space-graded system, the test phase beforehand could be a reason to consider less advanced but promising solutions. If these were not eliminated, a selection process based on the weighted criteria might have resulted in a completely different design that would propagate into all subsequent decisions. In addition, the selected options were not analyzed with a detailed sensitivity analysis. As determined in Section 4.2.4, the rating of using ozone as a decontamination method is high enough that individual changes in any of the weights or ratings would not affect the outcome. However, in the trade-off decision for the cultivation method, the aeroponic system was rated only slightly higher than the nutrient film technique. A change in any of the five higher-rated scores in favor of the nutrient film technique would have changed the outcome. Reducing the weight of the safety score as mentioned above, however, would not.

Some of the input parameters used to size the components were very rough estimations. Once a more precise mission scenario is available and the plant selection has been optimized accordingly, many of these estimations can be determined with greater certainty. Although some of the used equations are universally applicable, others were based on the empirical experiences of manufacturers. Since these are not broadly the same, they might not be valid for components of other manufacturers. The example selection was not made based on space-graded components, as it was purely a way to estimate the preliminary budgets for the project. Selecting the final components is not useful at a design stage in which so many uncertainties are still present. As a result, the empirical estimations, like the relation between drawdown capacity and accumulator tank size, are likely to change. This was considered by applying a large margin which can be reduced in the future. Furthermore, the final architecture requires a few changes in the previously designed atmosphere management system. Although this was not identified as a problem so far, some of the parameters in the atmosphere management system might change.

6.3. Outlook and Recommendations

The design recommendations made in this thesis are as complete as achievable in the given time frame and at the current design state. Once the design of the rest of the system is more advanced, however, a range of further steps can be taken. Some of the recommendations made here require the testing of components that can potentially enhance the system performance but are currently not ready to be used.

In Section 5.1.7, methods to reduce the microbial load were chosen. Since these did not include ways to remove already existing biofilms, some suggestions for cleaning methods that can be tested in the EDEN laboratory or a prototype system are presented here. The ”Sonihull” technology was developed to prevent biofilm accumulation in pipes of industrial processes with ultrasonic waves. This technology should be tested in the prototype together with PTFE coatings in the pipes. While the upward ducts are small enough to be removed and cleaned separately, possibly in the tray dishwasher, the sub-floor piping is more difficult to access and contains segments of up to 2 m. Besides flushing the system with hot water, small spherical sponges as used in the cleaning of beer lines can be utilized. This could be accomplished by creating a bypass for each pump, closed with a manual valve such that the sponges can be flushed from one tank to the other. If this proves successful, the technique can also be used for the return lines combined with a small pump and an adapter for the drain. If this method provides satisfying results, a further bypass could be installed at the end of each duct, directly connecting it to the return lines. This way, most of the piping can be cleaned with only small manual labor requirements.

Since the ozone generators are designed for continuous supply, the possibility of cycling them in the required frequency should be investigated. The pumps are needed for less than half of the irrigation cycle, such that ozone can be supplied by one generator to the different tanks, alternating without the necessity of switching off the generator. If intermittent ozone injection proves ineffective, an air pump and air stone can be implemented as in the MTF. In that case, however, another pump and pump type for spare parts would be added. In the trial phase the recommended ozone sensor in the at should be closely monitored. If the concentration exceeds the maximum of $120\,\mu g/m^3$ [116], an ozone destruction catalyst can be considered in the tank vent.

Stock solutions provided by other means than predetermined nutrient-salt mixtures, like human feces and non-edible biomass, will have a sub-optimal composition. Because the plants absorb nutrients selectively, undesired ions will accumulate. If the frequency of complete nutrient solution exchanges is not increased drastically, the composition is locked when the target EC is mainly caused by the respective ions. To limit the adverse effect and potentially even balance the solution with individual ions, it is highly recommended to implement ion-selective measurements in line once the technology is advanced enough.

The entire design of this module was based on it being the only module for a habitat. When larger habitats with multiple greenhouse modules are planned, it could be considered to only produce plants with similar nutrient needs in each module. This would simplify the design since only one cycle is necessary.

To transform the preliminary system design developed in this thesis into a functioning system that is space-graded, a lot of work still needs to be done. After a final selection of plants has been made and the specific needs are known, some requirements can be validated. Once a preliminary design for the other subsystems – and especially their positions and volume requirements – is available, the parameters and the architecture can be re-evaluated, and components for a prototype can be chosen. After a test phase, most of the requirements can be validated and verified. With all in- and outputs of the greenhouse module known, it can be integrated into a habitat test site. Finally, the nutrient delivery system design presented in this thesis may play a small part in helping to establish self-sufficient settlements in outer space.

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A

System Requirement Document

Table A.1: System objectives (SO) applicable to the NDS; Operational Requirements (OP); Transport and Irrigation Requirements (TI); NS Conditioning Requirements (NC); Health Monitoring Requirements (HM); In addition to the source documents, the respective Requirement ID is included as well for transparency. Every Requirement is assigned at least one selection criterion (SC) as added to the verification column to make sure they are all represented in the selection process.

Requirements concerning the NDS of the EDEN NextGen GHM

ID	Description	Rationale	Source	Verification (SC)
System objectives (SO) applicable to the NDS				
SO-NDS-011	The NDS shall function, with minimal maintenance, repair and resupply for 2 to 10 years.		[44]: (SY-DE-0050)	(reliability; maintainability)
SO-NDS-012	The NDS shall provide a suitable root zone environment for the selected plants.		[44]: (MI-OJ-0020)	(reliability; productivity)
SO-NDS-020	In transport configuration, the system shall withstand launch, transfer, and landing loads.		[44]: (SY-PE-0040)	(safety)
SO-NDS-021	The parts of the NDS located in the service section shall be preassembled, while the components in the deployable part can be assembled on-site.	The GHM should be operational with very little effort on-site.	[12]: (SY-DE-0010)	
SO-NDS-030	The NDS shall have a system volume of maximum 4.52 m^3.	Limited by the payload fairing and a subsystem specific scaling factor from the MTF.	[44] (SY-DE-0020) (SY-DE-0110)	Analysis (volume)
SO-NDS-040	The NDS shall have a mass of less than 766kg.	The GHM shall be launched with one rocket and a scaling factor from be MTF is applied.	[44, chapter 4.3] (SY-DE-0060)	Analysis (mass)
SO-NDS-050	The NDS shall support a growing area of at least 25 m^2 on three different rows of racks.	Double the growth area of the MTF.	[44]: (SY-PE-010)	(productivity)
SO-NDS-060	The power used by the NDS shall be less than 660 W (TBC).	The peak power of the MTF is 256 W and the nominal power is 165.9 W. [49] Assuming a proportional power consumption to NS flow rate.	[43]	Analysis (power)

Continuation of the requirement Table A.1

ID	Description	Rationale	Source	Verification (SC)
SO-NDS-070	The NDS shall be modular and upgradeable component wise.	For a mission up to 10 years in a constantly occupied habitat the need or opportunity to reiterate the design or to add more modules might arise.		(felxibility)
SO-NDS-080	The NDS shall be operational under reduced gravity on the moon.	The GHM needs to operate under lunar gravity.	[44]	(reliability)
		Operational requirements (OP)		
FR-OP-010	The NDS shall be operated and maintained by the crew with a level of autonomy at least equal to EDEN ISS: Maximum work time: TBD.	The working time of astronauts is extremely valuable and should therefore not be wasted.	[44] (SY-DE-0080)	Scenario tracing with EDEN ISS users. Later: Time Log (Maintainability)
FR-OP-021	The use of harmful substances shall be avoided and adhere to safety regulations and standards where they can not.	To maintain a sustainable life on another planetary body, the work environment has to be safe.	[44] (SY-DE-0190)	Data sheets of individual components Later: Test (Safety)
FR-OP-022	The NDS together with the other greenhouse subsystems shall have noise levels below the European work standards of 85dB(A) or 135dB(C).	To maintain a sustainable life on another planetary body, the work environment has to be safe.	[44] (SY-DE-0190)	Data sheets of individual components Later: Test (Safety)
FR-OP-031	The NDS shall monitor the following functional parameters: • Flow Rates • Pressure • Tank Levels	To ensure a dependable food supply errors shall be detected and removed as quickly as possible.	ST	Test (Reliability)
FR-OP-032	The NDS shall provide an alarm in case of off-nominal measurements in the functional parameters.	To ensure a dependable food supply errors shall be detected and removed as quickly as possible.	ST	Test (Reliability)

Continuation of the requirement Table A.1

ID	Description	Rationale	Source	Verification (SC)
FR-OP-040	Redundancy shall be implemented such that the removal or failure of individual components does not compromise the ability of the NDS to provide functions relevant to keeping the plants or crew alive: • Failure tolerance • Removal for cleaning and maintenance purposes	In case one component fails or has to be cleaned, the overall system needs to compensate until the issue has been resolved.	[44]: SY-DE-090 [44]: SY-DE-0130 [45]: DR.NDS.7	Scenario tracing Later: test (Reliability; Maintainability)
FR-OP-050	The individual components shall be accessible for maintenance and replacement in less than TBD minutes.	The crew-time is limited, and the system down-time needs to be kept to levels less than the shelf life of the produced food such that a sufficient food supply is ensured.	[44]: SY-DE-0050	Test (maintainability)
FR-OP-060	Required resupply for maintenance and operation shall be kept to a minimum: • The used substances shall be replaceable by substances generated on site (optional). • The amount of different spare parts shall be limited by using the same kind of component for similar tasks.	To sustain a long term colony after the initial phases of frequent resupply missions, the habitat needs to function independently.	IS [44]: SY-DE-050 [44]: SY-DE-0230	Scenario tracing (sustainability)
FR-OP-070	The NDS shall be designed to include a minimal number of moving parts to improve system reliability.	Less moving parts require less maintenance.	[12] [51]	(reliability)
FR-OP-080	A complete user documentation for maintenance and operation shall be available.		IS	Scenario tracing (maintainability)

Continuation of the requirement Table A.1

ID	Description	Rationale	Source	Verification (SC)
FR-OP-090	The nutrient delivery system shall be able to control nutrient solution quality without crew intervention for up to 1 month.	In case the crew is needed elsewhere, the greenhouse should work for some time without being taken care of.	[49]: ISPR-9110	Test (reliability)
		Transport and Irrigation (TI) requirements		
FR-TI-010	The NDS shall utilize a hydroponic soilless cultivation method.	Bringing soil to space is heavy and contains more pathogens than hydroponic methods, while the use of regolith as substrate needs more investigation before being considered. One likely suitable method is the APS method developed by DLR.	IS; [44]; [49]:ANT- 60 [45]: FR.SS.NDS.9	inspection (weight, productivity)
FR-TI-020	The plants shall grow on three rows of up to four racks respectively with the possibility to contain up to sixteen plant trays each. The amount of plant trays differs depending on whether tall growing plants are cultivated. Therefore, the piping shall be modular to accommodate different amounts of plant trays.	A change of the cultivated plants shall be possible.	[44]	inspection (Maintainability, productivity)
FR-TI-030	The NDS shall be able to store 600 l (TBC) of fresh water for irrigation.	In case water resupply is inhibited, the GHM shall keep up it's function. In the MTF this amounts to 300 l.	IS; [49]:ISPR-9030 [45]: FR.SS.NDS.2 DR.NDS.2	Inspection (reliability)

Continuation of the requirement Table A.1

ID	Description	Rationale	Source	Verification (SC)
FR-TI-040	The NDS shall be able to provide two different root zone environment compositions from two bulk solution tanks. The allocation to the available racks shall be predetermined, but rearrangeable with medium effort.	Fruit building and leafy plants require different root zone conditions but need to be cultivated simultaneously. The LL concluded that changes in the distribution are rarely necessary and not worth the complexity that comes with a freely selectable distribution.	IS; [12] [44]; [49]: FEG- 8020	Inspection (maintainability, Productivity, flexibility)
FR-TI-050	The NDS shall be able to store TBD liters of nutrient solution with a predetermined composition in each bulk solution tank.	To allow for a certain buffer effect and reduce the impact of the exudates on the NS composition, a certain amount of ready mixed bulk solution shall be available at all times.	IS, [44]	Inspection (reliability)
FR-TI-070	Excess NS shall be recirculated into the bulk solution tanks, with the primary replenished NS for a minimum of 4 weeks.	To reduce the need for resupply the use of substances shall be as efficient as possible.	IS, [44]; [49]: FEG-8190 [45]: FR.SS.NDS.10	Test (sustainability)
FR-TI-080	NS shall be cleaned of plant debris and other macro particles and sterilized for recovery.	The pumps and nozzles are easily clogged by debris. And contamination can be a serious threat to the plants and the crew.	[51] [45]:FR.SS.NDS.11	Test (Reliability, Maintainability, Sustainability)
FR-TI-090	A TBD l waste water tank with accessibility for sampling shall be available to collect NS that is not replenishable by the given substances.	Due to inconsistent nutrient absorption, some elements might become dominant and the solution becomes unusable. This is either detected by ion selective sensors or by a predetermined time period.	[44]	Inspection (Maintainability)
FR-TI-110	The materials used for the irrigation system shall be suitable for long term exposure to the used substances.	Some materials are more prone to corrosion and other problems than others.	[49]: FEG-7090 FEG-7100 FEG-8200 FEG-8210 FEG- 8220	Inspection (Reliability)
FR-TI-120	The NDS shall optimize duty cycles to maximise pump lifetime.	A high rate of pump failures due to rapid on and off cycles has been observed.	[12]	Inspection (Reliability)

Continuation of the requirement Table A.1

ID	Description	Rationale	Source	Verification (SC)
		NS Conditioning (NC) requirements		
FR-NC-010	The composition of the nutrient solution shall be controlled at the respective setpoints with a maximum deviation of: • EC: 0.8-4.5±0.17mS /cm • pH: 4.5-7.5±0.12 • T: 15-20°C ±TBD • dO: 80-100%	The values are the current values of the EDEN ISS. These result in sufficient plant growth and are considered acceptable.	[51]: 5.2 [45]: FR.SS.NDS.14 FR.SS.NDS.15	Test (productivity)
FR-NC-020	The composition of the nutrient solution shall be monitored with the respective accuracies: • EC: 0.5-5.0±0.1mS/cm • pH: 3.0-8.0±0.1 • T: TBD • dO:TBD • Individual ions (optional)	To be able to control the parameters they have to be measured.EDEN ISS requirements are outside of the controllable zones given in the performance document.	P; [49]:ISPR-9130	Test (productivity)
FR-NC-031	The composition of the nutrient solution shall be controlled by adding two different predefined TBD concentrated stock solutions from stock reservoirs for each bulk solution tank and fresh water from the fresh water tank.	To not only have control over the EC but also a little control over which individual ions are included, two different stock tanks shall be available per bulk solution tank.	IS; [49]: ISPR-9050	Inspection; Test (productivity)
FR-NC-032	The NDS shall have at least partial control over the individual ion concentrations within the nutrient solution(s).	Depending on what is available in terms of ion-selective sensing, or other composition monitoring technologies, perhaps a different approach with additional stock solutions (or even individual salt containers) would be preferable.		

Continuation of the requirement Table A.1

ID	Description	Rationale	Source	Verification (SC)
FR-NC-040	The NDS shall use the following nutrient chemical components: $Ca(NO_3)_2 \cdot 4H_2O$ NH_4NO_3 $C_{14}H_{19}FeN_3NaO_{10}$ (Fe- chelate DTPA) $CaCl_2$ KNO_3 $MgSO_4$ $Mg(NO_3)_2 \cdot 7H_2O$ K_2SO_4 KH_2PO_4 separated from $MnSO_4 \cdot H_2O$ $ZnSO_4 \cdot 7H_2O$ $Na_2B_4O_7 \cdot 10H_2O$ $CuSO_4 \cdot 5H_2O$ $Na_2MoO_4 \cdot 2H_2O$	These chemical compositions are used in recipes developed by the "Stichting Dienst Landbouwkunding Onderzoek" at the univerity of Wageningen [49].	[49]:FEG- 8080	Inspection (productivity)
FR-NC-051	The pH shall be adjusted by adding: • Nitric acid • Potassium hydroxide		[49]	(safety)
FR-NC-052	The stored amount of stock solution, acid, and base shall be enough for a full growth stage of the most requiring selected crop.	Maintenance is kept to a minimum as the containers only have to be refilled when nutrient demands change with the different growth stages.	[44]; [49]: ISPR-9050	Inspection; Test (maintainability)
FR-NC-060	The NDS shall ensure adequate mixing of the bulk solution to prevent nutrient salt precipitation.	If kept still for too long, some nutrient salts could be precipitated. Furthermore, the entrance point for stock solution and acid/base shall not have a higher concentration as the rest.	[51]	Test (reliability, maintainability)

Continuation of the requirement Table A.1

ID	Description	Rationale	Source	Verification (SC)
		Health Monitoring (HM) requirements		
FR-HM-010	The contamination within the nutrient solution shall be limited to TBD ppm of microorganisms by: • Passive bio-film inhibition by coating the tanks (optional). • Active contamination removal.	Bio-films cause bio-fouling and corrosion of the materials. Furthermore they accelerate microbial growth, threatening the health of the plants and the crew.	[9], IS; [49]:ISPR-9160 ISPR:9180 [45]:DR.NDS.3	Test (safety; reliability)
FR-HM-020	The amount of harmful substances taken up by the plants shall be limited to European food standards of TBD ppm.	To protect the crew, the food needs to be safe to consume.	[9]	Test (safety)
FR-HM-030	Frequent health monitoring (TBD per month) shall be possible to determine the pathogen contamination. Therefore, access to the bulk solution tanks to take samples shall be available.		[49]:ISPR-9150 ISPR-9160 FEG- 8170	Test (maintainability; safety)
FR-HM-040	Substances for pathogen limitation shall be sustainable in a space environment. • Safe to use in confined spaces. • Replenishable on site. • No pesticides or substances with toxic byproducts.	For long term missions sustainability is essential.	IS; [49]:ANT- 70	Inspection (safety; sustainability)
FR-HM-060	A procedure and the necessary substances for a complete system decontamination and restart shall be available.	In case of complete system contamination a reset needs to be performed.	[13]	Test (Maintainability; safety)

B

Supporting material

	SM	Housing; structural sensor data	Housing	Housing	Housing	Housing	Housing	Housing	Housing	-	Housing, external protection	Housing, external protection	-
	Plant size data	**CDHS**	Data requests, commands sending	Data requests, commands sending	Data requests, commands sending	Data requests, commands sending	Data requests, commands sending	Data requests, commands sending	Data requests, commands sending	Data requests, commands sending	Warnings, data	-	Data connection
	Corrosion	Nutrient solution data	**NDS**	-	-	-	Dirty equipment	-	Optional waste Heat	-	-	Nutrients, water	-
	-	Plant health data	-	**PCS**	-	-	Crops & Dirty equipment & Plant trays	-	-	-	Plant data by observation	Shoot & Root zones & support structure	-
	Pressure control	Air composition & quality data	-	Ambient & filtered atmosphere	**AMS**	-	Dirty filters	-	Waste heat from water recovery	-	Air composition & quality	Air composition & quality	Delta gas exchange w.r.t. O2, Co2, N2
	-	Lighting data	-	Delta waste heat	-	**LCS**	-	-	Waste heat from LEDs	-	Lighting data, adequate working light	Light quantity & quality	-
	Clean structures	Germination & harvest data	Clean NDS	Clean PCS & Seedlings for cultivation	Clean filters	-	**PPPS**	-	Waste heat	-	Harvesting & cleaning prompts	Clean environment & Work tools	Waste water, inedible biomass, waste
	-	Power	Power	Power (for sensors only)	Power	Power	Power	**PCDS**	Power	-	-	-	Power demand data
	-	Temperature data	Temperature control	Temperature control	Temperature control	Temperature control	Temperature control	Temperature control	**TCS**	Waste heat (tbd)	Suitable temperature	Suitable temperature	Waste heat
	Radiations, MMOD, dust	Environmental data	Optional water & Nutrients (ISRU)	-	-	-		-	-	**Lunar Environment**	Radiations, MNOD, dust	Radiations, MNOD, dust	Radiations, MNOD, dust
	Maintenance & Deployment Operations	Maintenance & Operations	Maintenance & Operations	Maintenance & Operations	Maintenance & Operations	Maintenance & Operations	Maintenance & Operations	Maintenance & Operations	Maintenance & Operations	Lunar surface operations	**Crew**	Seeding, maintaining, harvesting	Lives in
	-	-	-	Plant data	Trace gases, water, O_2	-	Inedible & edible biomass	-	-	-	Food	**Plants**	-
	Connector ring/ Airlock	Main Com line with ground support	Irrigation water	-	Delta gas exchange w.r.t. O2, Co2, N2	-	Potable water	Main power line	Cooling lines	-	shelter	-	**Habitat infrastructure**

Figure B.1: The different subsystems and the interactions with the NDS.

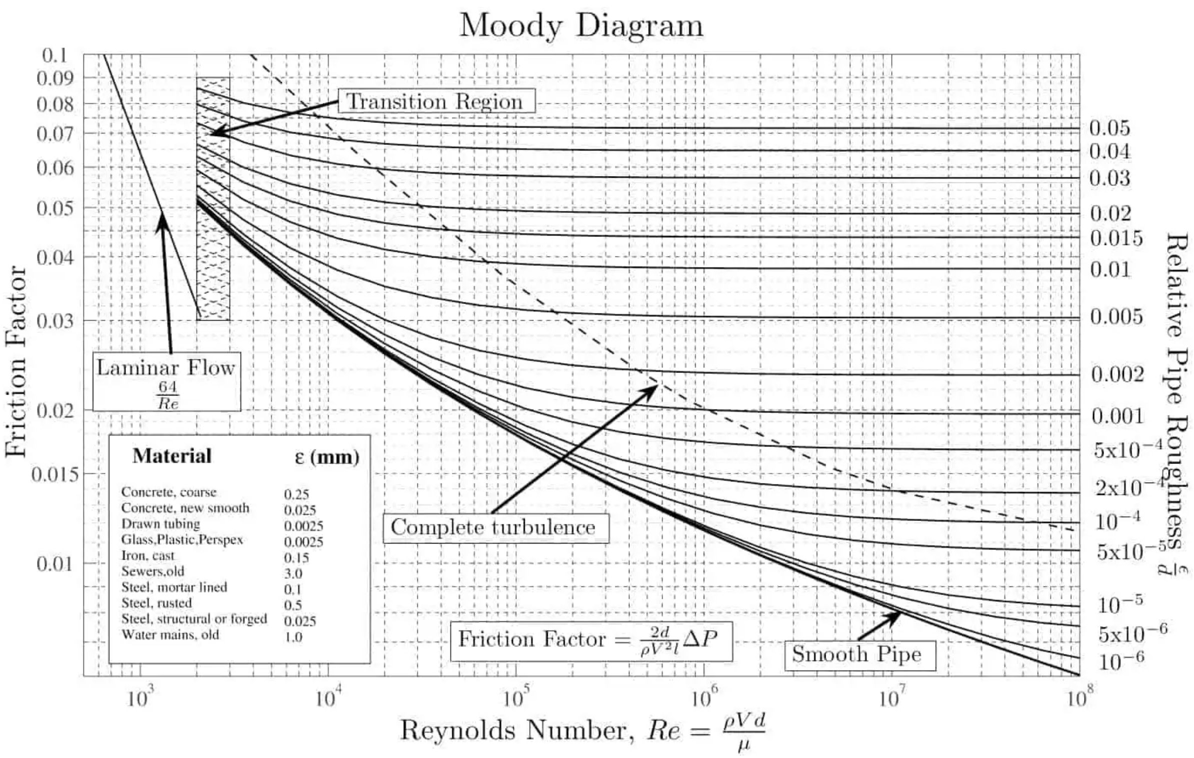

Figure B.2: Relation between Reynolds number and pressure drop in pipes [91].

Höchst-Systemdruck (cut-out) psig/(kPa)/bar	Mindest-Systemdruck (cut-in) psig/(kPa)/bar																		
	20 (138) 1.38	25 (173) 1.72	30 (207) 2.06	35 (242) 2.41	40 (276) 2.76	45 (311) 3.10	50 (345) 3.45	55 (380) 3.80	60 (414) 4.16	65 (449) 4.48	70 (483) 4.83	75 (518) 5.17	80 (552) 5.51	85 (587) 5.86	90 (621) 6.20	95 (656) 6.55	100 (690) 6.89	105 (725) 7.24	110 (759) 7.58
30/(207)/**2.06**	.21																		
35/(242)/**2.41**	.28	.19																	
40/(276)/**2.76**	.34	.26	.17																
45/(311)/**3.10**	.39	.32	.24	.16															
50/(345)/**3.45**	.44	.37	.30	.22	.15														
55/(380)/**3.80**	.47	.41	.34	.28	.21	.14													
60/(414)/**4.16**	.50	.44	.38	.32	.26	.19	.13												
65/(449)/**4.48**	.53	.48	.42	.36	.30	.24	.18	.12											
70/(483)/**4.83**	.56	.50	.45	.40	.34	.29	.23	.17	.11										
75/(518)/**5.17**		.53	.48	.43	.38	.32	.27	.22	.16	.11									
80/(552)/**5.51**			.50	.46	.41	.36	.31	.26	.21	.15	.10								
85/(587)/**5.86**				.48	.43	.39	.34	.29	.24	.20	.15	.10							
90/(621)/**6.20**					.46	.42	.37	.32	.28	.23	.19	.14	.09						
95/(656)/**6.55**						.44	.40	.35	.31	.27	.22	.18	.13	.09					
100/(690)/**6.89**							.42	.38	.34	.30	.26	.21	.17	.13	.09				
105/(725)/**7.24**								.41	.37	.33	.29	.25	.20	.16	.13	.08			
110/(759)/**7.58**									.39	.35	.31	.27	.24	.20	.16	.12	.08		
115/(794)/**7.92**										.38	.34	.30	.26	.23	.19	.15	.11	.08	
120/(828)/**8.27**											.36	.33	.29	.25	.22	.18	.15	.11	.07
125/(863)/**8.62**												.35	.32	.28	.25	.21	.18	.14	.11

Figure B.3: The relation between the drawdown capacity and the accumulator tank volume.