From Antarctic prototype to ground test demonstrator for a lunar greenhouse

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A B S T R A C T

The Moon has returned into the focus of human endeavors regarding human spaceflight, e.g., with NASA's *Artemis* program, ESA's *Moon Village,* and the Russian/ Chinese *International Lunar Research Station*. In difference to the pathfinding missions of the *Apollo*-era, the goal for these future missions is to stay on the lunar surface for longer durations and inhabit the lunar environment (near-)permanently. This requires a different approach to be affordable, i.e., instead of resupply as mostly used on e.g., the International Space Station, resource management has to include recycling and in-situ utilization. The former especially calls for the application of so-called BLSS to allow providing essential life-support services to the crew without prohibitive resource consumption, which is economically not feasible to achieve with resupplies. Bio-regenerative-life-support systems have been researched for decades, yet the system complexity, technology advancements, and singular aspects as e.g., plant biology require more research, especially if combined as in a greenhouse. For instance, the understanding of how a microbiome develops in a closed environment and what implications the microbiome has on plant growth is still insufficient. Within the EDEN project, the German Aerospace Center built a lunar analogue greenhouse and operated it at the *Neumayer-III* research station in Antarctica for four years, testing the technology – which was not space hardware – and operations. Derived from this experience the next step in the project is to design and subsequently operate a ground test demonstrator for a lunar greenhouse, as close as possible to the actual space hardware and operations. This paper explains the current design and trade-offs that led to it. Furthermore, the concept of operations is shown to illustrate the demonstrator's utility for researching bioregenerative-life-support. Overall, the system presented is feasible and useful to close the gaps, currently still existing in this field of research, and thus a mission enabler for future long-duration human space exploration missions.

Keywords: lunar greenhouse, human spaceflight, bioregenerative life-support system, demonstrator

Nomenclature

2nd P/L	Secondary Payload
1st Struc	Primary Structure
2nd Struc	Secondary Structure
AI	Artificial Intelligence
AMS	Atmosphere Management System
BLSS	Bioregenerative life-support system
CE	Concurrent Engineering
CEA	Controlled Environment Agriculture
CEEF	Closed Ecological Experimental Facility
CEF	Concurrent Engineering Facility
CELSS	Controlled Ecological Life-Support System
CROP	Combined Regenerative Organic food Production
CSA	Canadian Space Agency
DHCS	Data Handling and Control System
DLR	German Aerospace Center
ECSS	European Cooperation for Space Standards
ESA	European Space Agency
EU	European Union
FEG	Future Exploration Greenhouse
GH	Greenhouse
GTD	Ground Test Demonstrator
HabSim	Habitat Simulator
HEPA	High-Efficiency Particulate Air
ICS	Illumination Control System
ILRS	International Lunar Research Station
ISECG	International Space Exploration Coordination Group
ISPR	International Standard Payload Rack
ISS	International Space Station
LEO	Low Earth Orbit
MCC	Mission Control Center
MELiSSA	Micro-Ecological Life Support System Alternative
MEPA	Mobile Deployable Plant Growing Device
MTF	Mobile Test Facility
NASA	National Aeronautical and Space Administration
NDS	Nutrient Delivery System
NG	Next Generation
PCDS	Power Conditioning and Distribution System
PHM	Plant Health Monitoring
TCS	Thermal Control System
VOC	Volatile organic compound

1. Introduction

The last human landing on the lunar surface during the *Apollo* program occurred in 1972 with *Apollo 17*. Subsequent to this mission, human spaceflight was exclusively focused on low Earth orbit (LEO) for all space nations, e.g., with the Soviet Union's *Saljut* and *Mir* space stations, the US' *Skylab* station and *Space Shuttle*, more recently the Chinese *Tiangong* stations and the *International Space Station* (ISS). Only at the beginning of the 21st century there have been attempts to extend human spaceflight missions back to outer space, i.e., Moon, Mars and asteroids, e.g., with the *Constellation* program of NASA or the European Space Agency's (ESA) *Aurora* program. These ideas gradually evolved into the current *Artemis* program [1], which aims not only at a human lunar landing, but establishment of *Gateway* in the lunar orbit, akin to what ISS is for LEO, albeit with a shorter mission duration of about a month per crew, and a long-term stay on the lunar surface. ESA has proposed an open architecture for a lunar base, called *Moon Village* [2] and is one partner in the *Artemis* program, e.g., providing the service module for the *Orion* spacecraft, facilitating the return to the Moon. All other partners of the *ISS*, e.g., the Canadian Space Agency (CSA), return as partners for *Artemis* except for the Russian Roscosmos. Together with China, Russia plans to establish the *International Lunar Research Station* [3]. Evidently, there is huge interest in unlocking the lunar surface as a human field of activity for the long-term future.

However, the means to enable long-duration missions on the lunar surface, or possibly even beyond that, do not yet exist. Bioregenerative life-support systems (BLSS) are considered an essential building block for such missions [4], because the mass equivalent compared to non-bioregenerative systems becomes smaller for long mission durations and the different variations of biological waste can only be effectively processed via biological processes [5].

The desire to establish a (near-)closed system, which applies biological processes to sustain an artificial ecosystem for humans, is not new. Research in this field started in the 1960s, e.g., with the Russian BIOS-experiments or Controlled-Ecological-Life-Support-System (CELSS) by NASA [6]. Since the 70s it has been consensus that such systems' complexity prohibits their application for anything not long-term [6]. A steady stability to uphold the regenerative life-support has been a challenge and still has to be achieved [6]. Another NASA research facility was the Biomass Production Chamber, containing 20 m^2 of growth area. Tests with higher plants ceased at NASA in 2005, abandoning ideas of using plants for oxygen supply in a closed loop [6]. However, NASA's Kennedy Space Center has done research in terms of space in-situ plant growth with the experiments *Veggie* and *Advanced Plant Habitat* onboard the *ISS* and plans further research with the Ohalo III facility, which is currently in development [7]. A further overview about closed-loop research and plant experiments on ISS can be found in [8], including a timeline of activities.

Figure 1. The EDEN ISS MTF as operated in Antarctica (top), consisting of two 20-foot containers – one acting as service section and one as greenhouse (bottom) with an aeroponic nutrient delivery system.

The Japanese *Closed Ecological Experimental Facility* (CEEF) [6], started to investigate a closed system approach for plants, animals and humans in the 1990s. The material flows were incomplete however, e.g., in experiments of 2005 and 2006, the CO_2 exhaled by the experiments' participants was not sufficient to supply the plants and the generated oxygen was insufficient to supply the human participants. Up to 2007 the CO_2 supply could be enhanced to 90%. [6]

ESA's Micro-Ecological Life Support System Alternative (MELiSSA) project's "aim is to construct autonomous habitats in deep space, supplying astronauts with fresh air, water and food through continuous microbial recycling of human wastes" [9], incl. urine or CO_2 [10].

Producing (plant) food in human space habitats (e.g., on the Moon) is identified universally as a need in the space community. In addition to the actors previously mentioned, further nations, which have identified this need, are i.a. Australia [11], Canada [4] and China [6].

ESA especially has determined that development of an "advanced environment control and life-support system" is a goal of its Terrae-Novae-Roadmap for the coming decades of space exploration [12, p. 17]. This is to be achieved for "enabling sustainability" [12, p. 22].

The ISECG Global Exploration Roadmap also specifies closed-loop-life-support systems as "key technology" for the international exploration missions planned in the coming decades [13, p. 25]. That roadmap also points out the significant role of analogue and ground testing for technology development [13, p. 27].

The German Aerospace Center (DLR) decided in the past decade to research BLSS, which established the EDEN project. This project comprised to set-up and operate in Antarctica the EDEN ISS *Mobile Test Facility* (MTF) (see Figure 1), a prototype space analogue greenhouse.

1.1 EDEN ISS Antarctic greenhouse prototype

EDEN ISS [14] was an EU-funded project, conducted by a DLR-led consortium of 14 international partners from academia and industry. It aimed at developing and testing of plant-based food production in the context of human space exploration as well as technologies required for bioregenerative life-support. In the course of this project, the MTF greenhouse prototype was developed, assembled and tested. The latter occurred by operating the MTF at the German Antarctic research station *Neumayer III*. Operations began in 2018 and lasted until the end of 2022, when the MTF was disassembled after the last harvest in early 2022, exceeding the originally planned mission duration of one winter season at *Neumayer III*. The prolonged operation necessitated several refurbishment and maintenance activities in-between winter seasons.

The MTF comprises two elements: the service section and the actual greenhouse, each housed in a 20-foot shipping container. Antarctica was selected as a test ground for several reasons, e.g., remoteness, similar crew situation as for a human spaceflight greenhouse in terms of isolation and dependence on technology, and because of pollution prevention protocols similar to planetary protection.

The service section contained the major subsystems components, e.g., of the Air Management System (AMS), Nutrient Delivery System (NDS), and a working area. The greenhouse contained the actual plant growth area, which was based on aeroponic technology delivering nutrient solution to individual racks containing plant trays as well as artificial illumination using LEDs.

The MTF has been successfully operated for more than the initially intended single winter season and has shown that it can substantially improve the *Neumayer III* crew's food supply. In the first season 268 kg of fresh food were produced, equaling to 75 g of food per day and square meter of the 12.5 m² sized growth area. More details about the food production can be found here [15] and about the operation here [16].

Currently, the MTF is planned to be refurbished and attached to ESA's LUNA facility at the *European Astronaut Center* for future analogue testing.

1.2 Motivation and next step

To establish a working lunar greenhouse, several open gaps still exist in technology and theoretical science alike (see Section 2), which require research, development and optimization. Consequently, DLR intends to develop a ground test demonstrator (GTD), dubbed EDEN Next Generation (NG) GTD, which can be operated on ground but is as close as possible to the actual lunar greenhouse in processes and design, further enhancing the analogue testing to space analogue hardware. During operation of the GTD subsystems can be tested, procedures developed and the overall system can be pareto-optimized to be as efficient as possible while requiring as little resources (power, water, crew time) and launch mass as possible. Technology and components can be matured by rigorous testing in a relevant environment – if only simulated. The GTD is to serve as a bus or laboratory. Parts are to be exchanged in between test campaigns to find an optimum configuration. The GTD is to be a versatile science platform. The purpose of the GTD os to mature technology, processes and the overall system via tests up to a point, where a stable operation of a greenhouse is demonstrated.

In addition to the greenhouse functionality, the future EDEN greenhouse is intended to be used as a cargo module during transfer to its target location on the lunar surface. This approach is labeled as logistics-to-green improves the utility of the module, but also requires further testing and specified design. Such an approach would only be beneficial if more cargo can be transported than needed for the greenhouse. Considering that a major part of the greenhouse is empty space, the limit will be the launch mass of a given launcher.

The intermediate step of the GTD is intended to ensure the reliability and efficiency needed to operate a lunar greenhouse in an actual mission supplying not only food but bioregenerative life-support to the crew, as part of a closed-loop of a lunar habitat.

As shown before, such activities build upon previous experience not just within DLR but the worldwide space community, and therefore one goal of EDEN NG GTD is to cooperate with international partners from academia, industry and space agencies, such as CSA, providing the best possible result.

The mission plaque of *Apollo 11* stated that the lunar landing was conducted "for all mankind". It has been shown previously that technology developed for (human) spaceflight has huge potential for terrestrial application and is especially helpful in the context of sustainable development on Earth [17]. Food stress is one relevant subject with regards to sustainability and is expected to become more severe e.g., due to the climate crisis. Thus, one aspect of the design and overall project shall be applicability of technologies on Earth and how food supply can be

Table 1
The mission objectives for EDEN NG GTD, which have been the initial driver for the design process.

ID	Objective
OBJ-001	The mission shall demonstrate the ground-based verification of a closed-loop bioregenerative life-support system (BLSS) with independent fresh food production for humans in the form of a greenhouse for a habitat. The focus shall be on self-sustainable food production (EDEN) with biological waste treatment systems, air revitalization, water recycling and well-being. This demonstration shall occur after the testing campaign has matured a configuration for such a demonstration.
OBJ-002	The mission shall provide a high level of autonomy (robotic support) to reduce interaction with humans during the food production and harvesting period to be able to increase efficiency (AI data evaluation) and reduce system complexity induced by humans.
OBJ-003	The greenhouse shall support related applications on Earth in harsh environments caused e.g., by climate change effects or high density of population. The applicability in agriculture and life stock support shall be considered during the design.
OBJ-004	The mission concept shall include a contribution on a global scale embedded into the international exploration strategy. Therefore, international partners (e.g., NASA, ASI, CSA) and industry must be involved from the very beginning.
OBJ-005	The mission shall provide a minimum of 10% of calorie intake of a three-person crew at the end of the demonstrator mission.

improved especially for vulnerable people, and food production can be conducted with reduced resource usage.

Based on these motivations, the objectives for the GTD have been formulated. They are summarized in Table 1 and formed the basis for the subsequent design process. Focus within these objectives lies on the greenhouse function of the GTD (OBJ-001 and OBJ-005). The greenhouse is to be developed as part of a future BLSS of a lunar base. For this purpose, a closed-loop will be simulated (OBJ-001) providing a habitat environment of which the to-be-developed greenhouse is one part. Within this environment the greenhouse system can be matured and tested.

1.3 Paper outline

In this paper, we explain how, based on the Antarctic prototype, the GTD is evolved. This paper provides the scientific motivation for designing a ground test demonstrator for a lunar greenhouse, the design method, and its actual design, showing its capability to address the scientific and technological gaps related to the realization of a BLSS, based on a greenhouse.

Section 2 will elaborate on the science case for the GTD, explaining why such a vehicle for technological advancement is needed before creating an actual lunar greenhouse that can serve as part of a BLSS. This science case shows gaps and challenges associated with lunar greenhouse technology and thus provides the reasoning for the GTD. Subsequently, in Section 3, the interdisciplinary design process is described, pointing out various parts, e.g., Concurrent Engineering studies and requirements formulation. Section 4 focuses on the results obtained with the process and showcases the current design, including, e.g., mass budget and accommodation of subsystem components. In the following Section 5, these results are discussed in the frame of the mission objectives and presented science case, but also concerning sustainable space missions and open issues to be responded to in the further course of EDEN NG. Section 6 draws the conclusion that the presented design fits the earmarked research activities and at the same time with a mass and size envelope fitting a current launch vehicle presents a realistic approach for a demonstrator.

Preliminary results have been presented at IAC 2022 in Paris [18]. This paper does not only extend or update that paper's information, but also places a different focus, more on technical results and interpretation in the context of the science case than preliminary and conceptual work. Only information relevant for understanding the context is repeated here.

2. Science Case

As laid out in Section 1, BLSS are widely considered an essential technology for long-duration human spaceflight missions to other celestial bodies such as Moon or Mars. Yet, there are a number of obstacles to overcome to realize such a system and generally, sustaining its stable operation – especially concerning microorganisms and trace contaminants – has still not been accomplished [6]. Generally, more research is required to understand how plants grow in closed environments [19].

The closest to a BLSS operations has been the Lunar Palace 1 in China [20]. It is a 500 m³ system that houses animals, plants and crew and has been operated for a 370 day experiment, which ended in 2018 [20]. "Material closure" [21] is stated to be 98.2 %, whereas waste recovery ranged from 67 % (solid) to 99 % (fluid) [21]. Contaminants were analyzed in urine and water [22], however not in the BLSS itself. Trace gases were also detected [21], but no biological contaminant information was published. The system consists of several bio-reactors and greenhouses used for food production and waste management, i.a. using worms and fermentation. According to publications 80% of the food were grown [21]. Especially concerning the waste recycling rate and food production rate, it is unclear what exactly the "material closure" [21] refers to, especially also if it means volume or mass. The system is however, quite large and complex, relying on e.g. worms and fermentation for waste recycling. While closes some gaps in knowledge, the experiment also introduced via system complexity a number of further gaps, which are uncertainties in the lunar environment. One would have to operate a system with less complexity and experiments to close such gaps in the relevant environment, e.g. to understand the behavior and physiology of the used worms. The system design was also not regarding space related constrains e.g. concerning size/ envelopes, equipment. Relevant information is not yet published, e.g. about the nutrient intake of the crew, effect of the reduced food provision. Further research and system development has to be made to progress from Lunar Palace to an actual lunar BLSS. The GTD is to have a less complex design to allow a more relevant verification on Earth and thus application on the lunar surface of its results.

NASA formulates the major challenges in the field of life-support systems as [23]: "increased self-sufficiency" [23], i.e., not relying on external input, "increased loop-closure" [23], i.e., the ability to regenerate (resources) and "high reliability" [23] to supply long-term missions. Open issues to be responded to for development of a BLSS concern several fields, which are summarized in the following subsections. The GTD is to be designed and intended to enable closing these gaps through rigorous testing and maturing technology and processes and eventual demonstration of greenhouse operation. The following subsections give an overview about the necessary gaps that require closing for operating a planetary greenhouse successfully and thus need to be regarded for designing the GTD.

2.1 System

A BLSS is a complex system, comprised of a greenhouse and other biological systems. As opposed to Earth, which is a natural, biological life-support system and thus provides so-called ecosystem services [24] as oxygen supply to its population, an artificial BLSS has less buffers. The GTD will provide the opportunity to test such "system" aspects, by combining the greenhouse and a (simulated) habitat functionality. The complexity of a BLSS is large because each part of the BLSS interacts with each other and there are even unwanted parts, e.g., bacteria which flourish unintentionally (see below). This complexity limits reliability and contribute to losses, which would need to be replenished. Both, reliability and an improved resource loop closure are relevant research goals [23]. Furthermore, scaling of such systems is an open point [25]. How do changes in the system or individual subsystems induce changes in food production? By providing a modular system, e.g. consisting of several growth areas, scaling can be tested, as well as scaling influenced by individual components, e.g., pumps or filters.

Crew time is a crucial resource for any human spaceflight mission, i.e., minimization of crew time needed to maintain the bioregenerative nature of the life-support, but also to supply food, is a desired goal. This can be achieved by improving autonomy, e.g., via robotics [25] or artificial-intelligence (AI) controlled plant-health monitoring [26]. Such AI support also requires sensors within the greenhouse system.

Overall, typical system challenges such as the compact design of subsystems need to be considered as well [25]. Specific BLSS topics for consideration from a system perspective are the efficient delivery of nutrients, fresh and waste water handling and recycling, as well as food, and food waste, processing [25] as well as air regeneration (CO_2 scrubbing, oxygen provision, contaminant removal). These system aspects are to be considered during the design and will be further tested out during the research campaigns utilizing the GTD (see also Section 5.4).

The specific purpose of implementing a logistic-to-green approach addresses the system, especially structure and internal structure, e.g. racks, and requirements as well. The extend and draw-backs and advantages have to be determined during development. This also concerns reusability of cargo transfer related system components for the greenhouse functionality.

2.2 Technology

Not just the overall system, but individual technologies, e.g., nutrient delivery or water sanitation, have to be further researched and this has to occur in a meaningful environment, i.e., a greenhouse instead of a lab, which is something the GTD can provide. Technology maturation is essential for system reliability. Furthermore, their application needs optimization to improve their efficiency, needed crew time and crop yield.

Nutrient delivery, waste handling or recycling and how to post-process produced food are all aspects that are further linked to greenhouses for space [25]. Water sanitation, which could possibly be achieved with plasma activation, needs to be researched [7]. Further research is also needed for plant health monitoring to make plant growth reliable. One technology for that goal could be hyperspectral imaging [7].

2.3 Biology

Integrating plants into a complex system like a BLSS is not a trivial task, e.g., because the effect of the life-support system and the closed environment on plant growth is not yet understood. For example, using biocides for water sanitation for the potable water for the crew could affect plant health and food quality. [25]

The biome of a greenhouse not only comprises the crops, but the overall system, including e.g., contaminants. Their

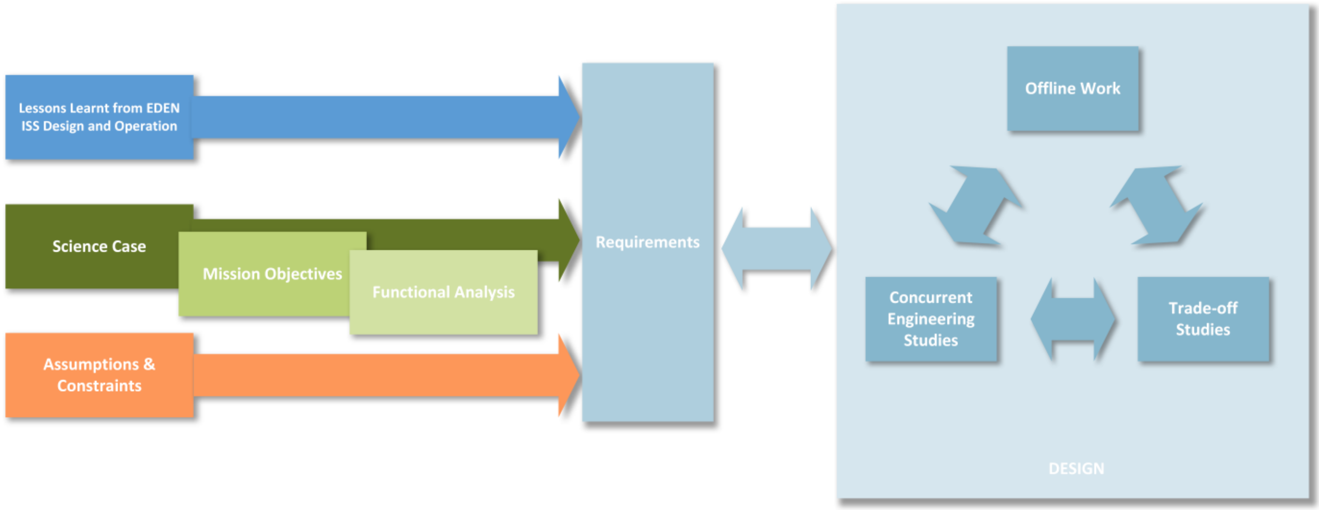

Figure 2. Design process for the EDEN NG GTD with Lessons Learnt, Science Case and Assumptions & Constraints feeding into requirements definition, which in turn drive the design. The design occurs in three elements, so-called offline work by the individual team members, cooperative work in trade-off studies for conceptual content and in concurrent engineering studies for detailed work. Design results in turn can also influence requirements, e.g., on lower levels (for subsystems).

effect on the crops and food quality has to be researched [25]. How to manage the biome and to understand if it is harmful to either crew or crop, has to be researched as well [7].

A major challenge with numerous facets is also plant selection. Plants need to be selected based on e.g., the amount of care needed, harvest yield, nutrition, endurance under stress and useful combinations of crops to find the best fit concerning crew time needed, crew food supply and life-support capability (including e.g., needed area, or resources such as water). For instance, the nutritional value has to be optimized [25], which can compete with crew time needed to care for the plant. Single crop systems might reduce system complexity and needed crew time, but likely will not cover the nutritional needs of the crew [27]. Spread vs. batch harvesting also has need for research [27]. In general, the plants are an integral part of the greenhouse system and how they interact with the system, what their impact is on crew handling (processing plants, but also crew time), will influence e.g., plant selection similarly as nutritional values, robustness, etc. Thus, they have to be part of tests in the GTD. It has also to be investigated if results in the GTD can be transferred to other systems. Microgreens use illumination, fertilization and hydration very efficiently but it is not yet understood how and if they contribute to life-support functions aside from providing some food [7]. They are relevant for providing vitamins to the crew, which cannot be stored in pre-packed food for a long duration. For predicting and controlling plant growth, accurate plant growth models are required. To obtain these, fitting tests need to be conducted in the appropriate environment [7]. The GTD can be used, e.g., for trying out different combinations of crops, analyze these combinations based on parameters such as harvest yield, crew time needed and nutrition value and how they interact with the system and among each other (e.g. by emitting volatile organic compounds (VOC)). Furthermore, data about plant growth can be collected and thus improve growth models.

2.4 Operations

A (near) closed-loop greenhouse has different operating conditions, e.g., start-up, harvesting, germination and various emergency situations (e.g., subsystem failures). These conditions require effective procedures, which have to be developed and optimized to reduce crew time, ensure reliability and maximize crop harvest. They also need to consider the humans in the loop.

Operations also need to be tested out for the logistic-to-green approach, e.g., concerning packing, cleaning and re-arrangement from a cargo module to a greenhouse module. This includes, e.g., deployment of system components or cargo removal.

3. Design Method

This section explains the process applied for developing the design as presented in this paper. Generally, the process has been iterative and based on certain assumptions and constraints. The process is sketched in Figure 2. The design drivers have been the requirements, which have been formulated based on typical guidelines, e.g., given in [28]. In turn, these have been defined based on the previously described science case, assumptions (including the assumed mission scenario) and constraints, and on lessons learnt from the operation of EDEN ISS, e.g., corridor sizes to handle equipment or reachability of plant racks. Once the requirements had been established, the actual design work was conducted in three environments. There was offline work, i.e., individual work and analysis by the design team members, trade-off-studies, which were conducted as a

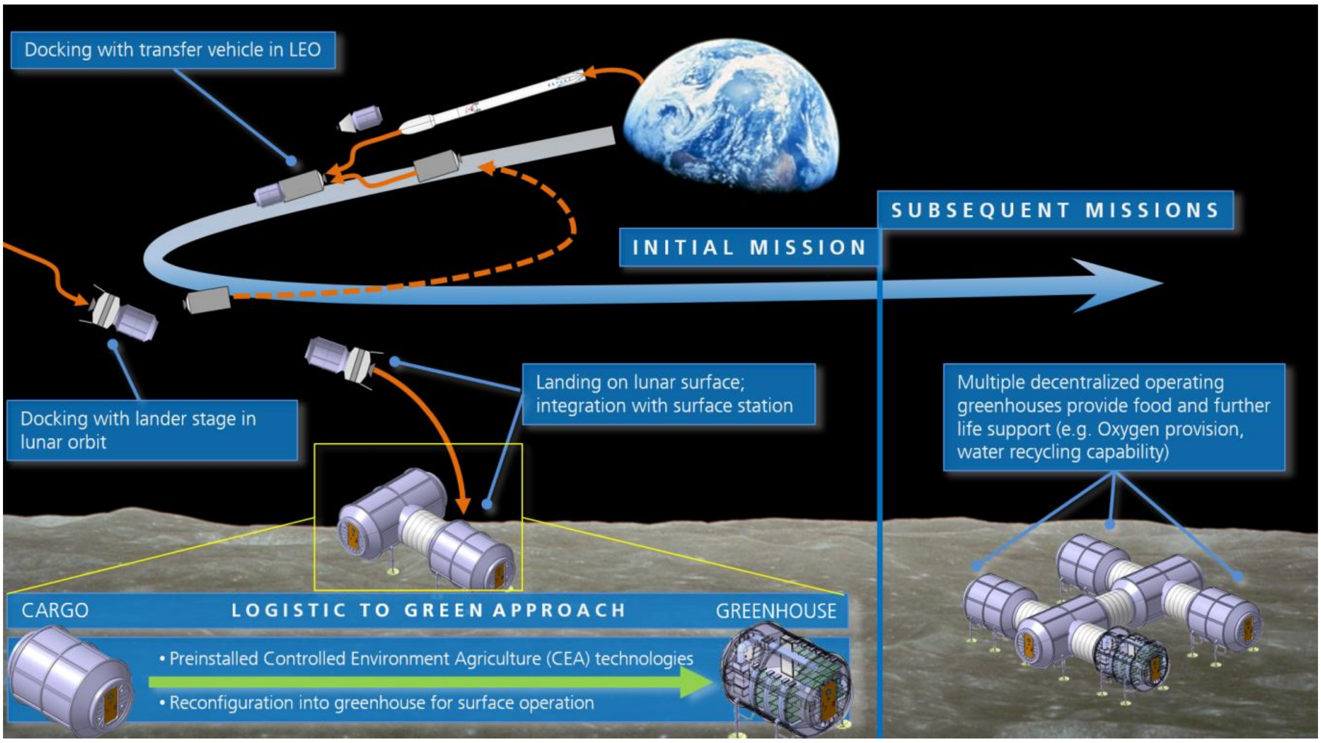

Figure 3. Baseline mission scenario assumed for a greenhouse module derived from the GTD. Once launched, the greenhouse will dock with a transfer vehicle using a orbital stage, which handles orbital and attitude control. After arrival at the Moon, the greenhouse will be docked to a lander to soft-land on the surface. On the surface, the greenhouse will be converted from a cargo to greenhouse module. Subsequent missions would use several greenhouse modules to increase the amount of produced food. [15] (background image: NASA, public domain)

team and covered important design decisions with implications on more than one subsystem, and Concurrent Engineering (CE) studies, a typical, collaborative design approach of DLR [29]. The design work, however, also caused re-iteration or reformulation of requirements, e.g., on lower levels (for subsystems). This way, the design process has been overall iterative.

3.1 Lessons Learnt

The lessons learnt, derived from the operation of the MTF in Antarctica, have been reported in detail in [30]. Therefore, only a quick overview to picture the idea behind them, is given here.

The lessons mostly apply to operations related issues and some design issues, which cause failures or leakage. For instance, the corridor size for the central corridor in the MTF has been found to be too narrow, i.e., the minimum corridor width for the new design was set to 1 m. The plant trays were not easily removable during operation in the MTF, which complicated plant handling, e.g., during harvest. Therefore, the GTD design should include removable plant trays. Another example is avoiding u-shaped piping for the nutrient delivery (or any other fluid), to avoid leakage, due to collecting fluids. Overall 16 lessons learnt were used to defined requirements, which can be found in [30].

3.2 Assumed mission scenario

One major assumption for the design of the system has been the mission scenario of the future lunar greenhouse derived from the GTD. This scenario is shown in Figure 3 and shapes the design of the future greenhouse, but which also has to be reflected in the GTD design to make it an accurate analogue.

For the launch, it is assumed that a currently existing launch vehicle is used, here Falcon 9. During launch and transfer the greenhouse module can act as a cargo module, in a so-called logistic-to-green approach. This way, the greenhouse's racks are filled with cargo bags for transfer of cargo, to use the otherwise empty volume of the disused growth area. Furthermore, no AOCS or orbital debris/ radiation protection has to be provided by the greenhouse itself, but an orbital stage attached to the greenhouse during launch, will provide these functionalities for the early operation. This way and since they are not essential for the greenhouse functionality, these will not have to be developed specifically for the greenhouse and thus will also not be part of the GTD.

Once in LEO, the orbital stage will enable docking of the greenhouse to the transfer vehicle for travelling towards the Moon. After arrival at the Moon, the module will be handed over to a lander, which will softly land the module there. Afterwards, integration into the habitat and reconfiguration of the module from cargo into the greenhouse functionality occurs. Once the greenhouse's reliable operation has been proven, further greenhouses can expand the BLSS capability.

3.3 Further assumptions and constraints

For the design, especially concerning functionalities, several assumptions have been made, to avoid unnecessary regard to subsystems, which are not essential to the greenhouse function. These assumptions are:

Existing lunar infrastructure

For the design it is assumed that an infrastructure exists on the lunar surface which e.g., deals with covering the module with regolith after deployment, handles docking/ berthing with the remaining habitat, e.g., a robotic arm, and other functionalities. This way no such functionality has to be developed for the GTD and universal solutions can be assumed for each module of the theoretical future habitat.

Thermal, power, communication, radiation protection

Certain functionalities essential for the operation of the overall habitat will not be handled by the greenhouse. This includes thermal control, power generation, radiation protection and communication. The thermal control and power generation are functionalities, which require some form of interface to the outside of the system, e.g., via solar panels and radiators. Therefore, these functionalities are excluded and only internal thermal control and power distribution and control will be addressed by the design of the greenhouse and thus the GTD. This means there will be only interfaces to the remaining habitat. Also, communication between the lunar surface and Earth will be addressed by the habitat as a whole rather than per individual module. It is further assumed that radiation protection, mostly concerning the module's structure, will be addressed by the habitat infrastructure, e.g., regolith cover.

Cargo module functionality

The main functionality of the module, producing plant-based food, is not required during transfer. Thus, it is assumed that the module will be used to transfer cargo to the lunar surface, exceeding its own systems. This requires the functionality to deploy components of the greenhouse related subsystems (e.g., tubes for air management) and to foresee structural elements to store cargo similar to e.g., the cargo vessels supplying ISS.

3.4 Concurrent Engineering process

Concurrent Engineering is a collaborative work process applied in studies of early phases for any kind of complex system [29] [31] and has been used by DLR about 70 for various mission designs, including flown missions. The established process is coined by assembling an interdisciplinary team of experts and stakeholders, to ensure that all relevant aspects are considered during design, e.g., technical subsystems, customer expectations, or programmatic constraints.

This leads to a consistent design and ensures that problems are solved quickly and early in the design process. Furthermore, CE-studies involve moderated and non-moderated time slots, where the team is led by a Team Leader or Moderator, who organizes discussions and tracks relevant action items. A common data model is typically used for documenting the design. This process enables quick and effective progress during a design phase.

For the present design a multi-disciplinary study team was assembled, containing the domains system, air management, Robotics, Structure, Configuration, Human Factors, Data Handling, Power Supply, Illumination Control, and Plant Health Monitoring. Based on the requirements, this team designed the GTD greenhouse iteratively, focusing on configuration and mass budget. The individual domains were using mass data of components either used before (e.g. in the EDEN ISS MTF) or specifically selected anew for this study.

4. Results

This section reports on the most recent results obtained via the described process. The focus lies on actual, technical data. More conceptional details, e.g., the functionality analysis and a substantial presentation about requirements have been previously published [18] and shall not be repeated here.

In a very early stage of the design an actual lunar greenhouse has been conceptualized [30], also with the help of the CE process. This greenhouse included a deployable structure, which allowed a larger growth area. However, the complexity of a greenhouse as such has been deemed sufficiently challenging and thus this solution has not been pursued further for the GTD. Also, the required mechanisms of the deployable structure do not interact with the life-support functionality and thus can be developed separately. Once the greenhouse system is understood and such deployable structures have been realized, a future, actual lunar greenhouse can be built with the help of such structures. At this point their common usage is not required for further development of either.

4.1 Overview of Requirements

Currently, hundreds of requirements are already formulated for the GTD. Reporting all of them would be exceeding this paper. A list of top-level requirements is given in [18] and shall not be repeated here. An overview is given to picture the design envelope that was used to get the design presented in the coming subchapters.

The requirements are sorted in several layers, where increasing numbers mean increase in detail. They are beginning with level 0, which formulates requirements based on the constraints and science case mostly (see Figure

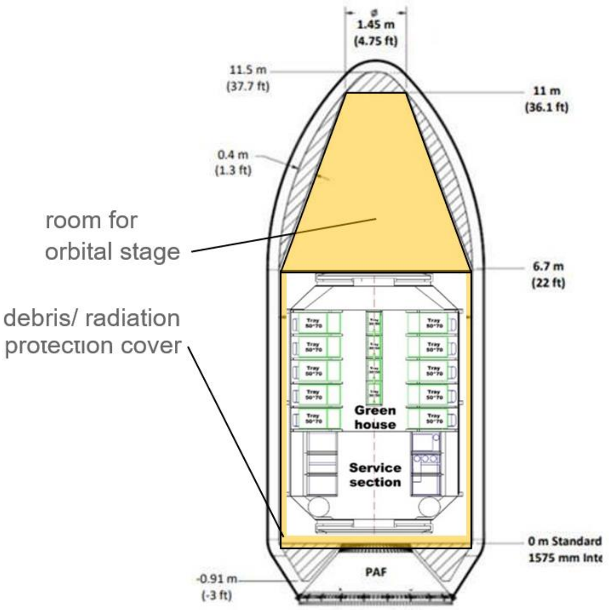

Figure 4. The EDEN NG GTD fitting into the Falcon 9 fairing (as given in [48]) with room reserved for a possible orbital stage responsible for attitude and orbital control and a cover protecting from debris and radiation.

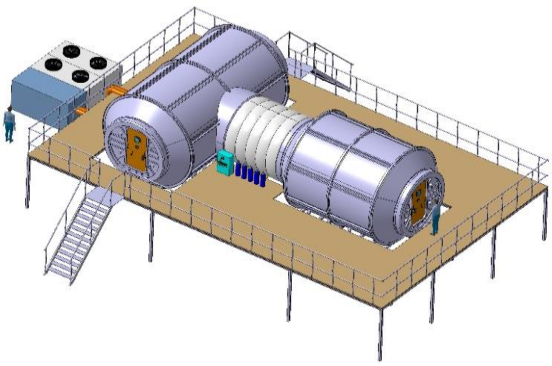

Figure 5. The EDEN NG GTD elements, i.e., the greenhouse (right) connected to the habitat simulator (left) via an airlock (center). Not pictured is the remote mission control center. [15]

2) and addresses all elements of the design (i.e. not just the greenhouse), thus it is regarded as "mission requirements". Here, it is prescribed that the assumed operating environment shall be the lunar surface where possible and Earth were necessary, to remain as close as possible to the actual flight model of a lunar greenhouse, which differs the GTD from MTF, where the focus was not to enable a lunar-analogue environment.

Furthermore, the mission duration of 3 to 10 years, the need to use commercial-of-the-shelf products where possible, as well as the required functionalities which are out-sourced to the habitat are prescribed (see Section 3.3). These elements affect costs, but also cost efficiency.

The next level, level 1, determines the systems of the GTD, detailing material flows between its elements, e.g., between greenhouse and habitat simulator (see below), interchangeability of parts (to limit the type of spare parts needed), temperature control and safety issues such as emergency exit. Single failure tolerance is defined as basis for the greenhouse, i.e. single redundancy is required for all safety and plant related systems, as well as the maximum allowable mass and size. As the greenhouse is meant to be launchable with an existing launch vehicle, in this case a Falcon 9, the size is limited to a diameter of 4.2 m and 6.6 m in length. This fits into the fairing of Falcon 9, see Figure 4, with room left for a cover protecting against debris and radiation as well as some room for an orbital stage. The mass enveloped is limited to 18,800 kg, leaving 4,000 kg for an orbital stage and the debris shield.

The GTD is also to be designed in a way to allow redeployment to another location. This way, the system's utility is more flexible and e.g., partners can switch in main responsibility for operation.

The requirements are presented in more detail in [18].

4.2 GTD elements and Concept of Operations

The GTD consists of several elements to re-create realistic operating conditions. First of all, there is a mission control center (MCC), which controls the system, collects telemetry and simulates an actual control center. It is based on the control center used for EDEN ISS.

There is a so-called habitat simulator (HabSim), which simulates the role of the habitat on the lunar surface with regard to the greenhouse (GH) of the GTD (see Figure 5). It is linked via an airlock and multiple interfaces to the greenhouse, including one which transfers gas into it, simulating "used air" which would need refreshment via the BLSS of the greenhouse.

These elements are used in operational phases to simulate the greenhouse operation on the Moon, as shown in the diagram of Figure 6. The early operation phase starts after the GTD arrives at its location for operation. Communication links from the HabSim to the MCC are established. All subsystems are tested for functionality. It is assumed at this point this phase will last for some weeks. This phase has to be re-run if the GTD is redeployed to a different location as mentioned previously.

Subsequently, the commissioning phase occurs, which is separated into two parts. First, the cargo configuration (see Section 3.2) will be re-arranged to the greenhouse configuration. This means that subsystems have to be deployed in the growth area of the GH and cargo has to be removed. This is mostly to test processes and create lessons learned for the design of the lunar greenhouse. Once all subsystems are fully deployed, they are tested for their functionality. This phase can be re-run in case of initiating a new test campaign.

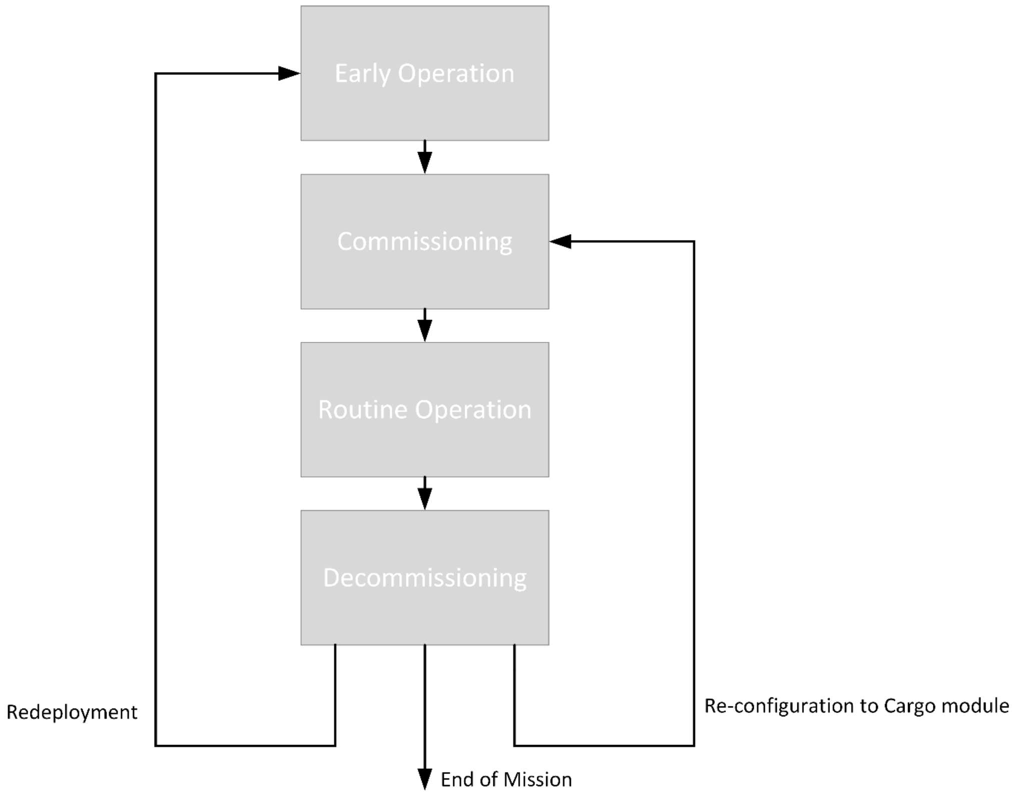

Figure 6. The operational phases of the GTD in possible sequences, where decommissioning can occur to re-start test campaigns by re-configuring the greenhouse back to a cargo module, arrange it for re-deployment to a different location or end the operation altogether.

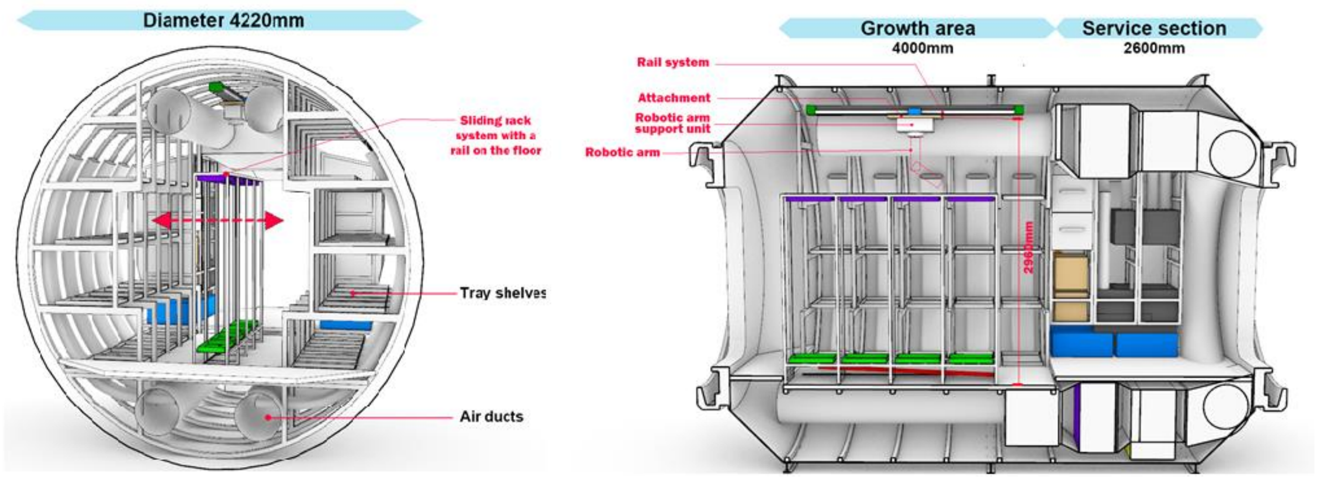

Figure 7. The general configuration of the GH separated into growth area and service section. The tray shelves contain the trays for the growing plants. The center region contains a slidable rack, which can shift to either side of the aisle to create more work space. Note the shelf-structure which allows stepping to reach upper regions.

Afterwards, the routine operation phase begins, which is used to test the BLSS. Actual research campaigns will be run in this phase. They will be run with different durations, purposes and foci. A (near) closed loop is to be tested. Possible research subjects for a campaign are, e.g.:

- plant selection (especially also how different plants react to the system and to each other, as well as affect operations),
- operational processes (e.g., material exchange between HabSim and GH),
- GH subsystem maintenance without disrupting operation of the life-support system, of which the GH is part of (e.g. replacing a component should not cause/ require shut-down),
- best practices and protocols for communication between MCC and GH.

At the end of each campaign, or the overall utilization of the GTD, the decommissioning phase occurs. This involves passivating all subsystems, and removing plants, waste, water, etc. from the system. Afterward depending on whether or not subsequent operation is intended, the GTD might be reconfigured for new tests or put out of use altogether.

4.3 System Design and Configuration

Figure 7 shows the interior of the greenhouse, separated into growth area and service section. The latter contains the major parts of the subsystems, e.g., computers, power distribution and nutrient delivery system. Air ducts reach into the growth area and realize the air exchange, which is driven by fans of the AMS.

As a preliminary design concept for the secondary structure, the subsystems in the service section will be mounted in racks similar to the International Standard Payload Rack (ISPR). The dimensions of the racks will be adapted to the needs of the subsystems, but materials and interfaces to the primary structure can be adapted from existing space station modules.

An initial estimate of the required subsystem volumes, along with a preliminary configuration, resulted in a total of 3 ISPR volumes being reserved in the service section on the left and right. The top and bottom volumes are reserved for the components of the AMS which will likely be mounted with custom structural profiles rather than being fitted into rack systems. The NDS has also components in the service section, e.g., tanks and pumps. Similarly, the Power distribution, and data handling related parts are to be found there. The size of the subsystem components needs to be investigated further to allow more detailed design of the subsystem racks and other structural elements. Aside from technical subsystems, there are also support elements included in the service section, e.g., a work station. The deployable work desk is located between the ISPR and circular air duct as illustrated in Figure 8. A folding pocket chair was also proposed for seating activities. For further study, a deployable sink needs to be designed to wash tools or crops during the GH operation.

Table 2
Preliminary mass budget on system level for the greenhouse of the GTD. Note that the majority of thermal control is handled by the AMS and the current design foresees no extra components yet for TCS.

Subsystem	Total Mass [kg]	Mass w/ Margin [kg]
AMS	643	695,05
DHCS	13	15,60
Hab Interface	0	0,00
ICS	360	432,00
NDS	44,47	48,92
PDCS	200	240,00
PHM	36	39,80
Primary Structure	4750	5700,00
Robotics	59,09	62,98
Secondary Payload (CROP)	91,02	97,44
Secondary Structure	372	355,20
TCS	0	0,00
Safety	64,25	68,19
Cargo	1057,368	1156,24
Totals	7690,198	8911,41
+ System Margin [%]	20	10693,69
Harness [%]	10	1069,37
Sum [kg]		11763,06

The growth area configuration is determined by the cargo functionality as part of the logistic-to-green approach and the plant growth functionality using trays and aeroponic nutrient delivery. To optimize the available plant cultivation area, a total of 5 plant cultivation racks, each with 4 cultivation levels, are implemented in the initial design.

The design of the plant cultivation racks leaves a wide central corridor for the crew to move around and perform plant handling activities or maintenance and repair work. However, when the crew is not present, this corridor space is volume which could be used for plant cultivation. As such, for the preliminary design the option of a moveable center rack, or plant cultivation system, has been added to the design. This system would provide additional cultivation area, and would be moved to either side of the corridor, as needed, to allow the crew sufficient space for work on the other side.

The logistic-to-green design approach foresees the use of the greenhouse structure to transport cargo to the Moon before being outfitted for plant cultivation. To accommodate the cargo bags, and the plant cultivation hardware and lighting units afterwards, structure elements are needed to support and fixate those items.

The preliminary design of the NDS applies plant cultivation trays, similar to those used in EDEN ISS, albeit slightly larger in size. Based on the current tray size, 50 x 70 cm, and an assumed plant canopy overlap of 5 cm in each direction, the plant cultivation racks are being sized to accommodate one tray per rack per cultivation level.

System budgets

The relative mass budget is shown in Figure 9, not including Harness (which is assumed to be 10% of the overall mass at this time). The largest contributor is the primary structure, followed by the equipment for the cargo function. AMS is the third largest contributor.

Table 2 shows the system level mass budget, based on the mass of the individual components. Presenting all subsystems' components is prohibitive for a single paper, the mass budget tables can be found in the supplementals. The first column shows the sum of all components without their margins, the second one the sum of all components with component margins (according to the European Cooperation for Space Standards (ECSS) between 5 to 20% depending on their maturity). All of it is summed up

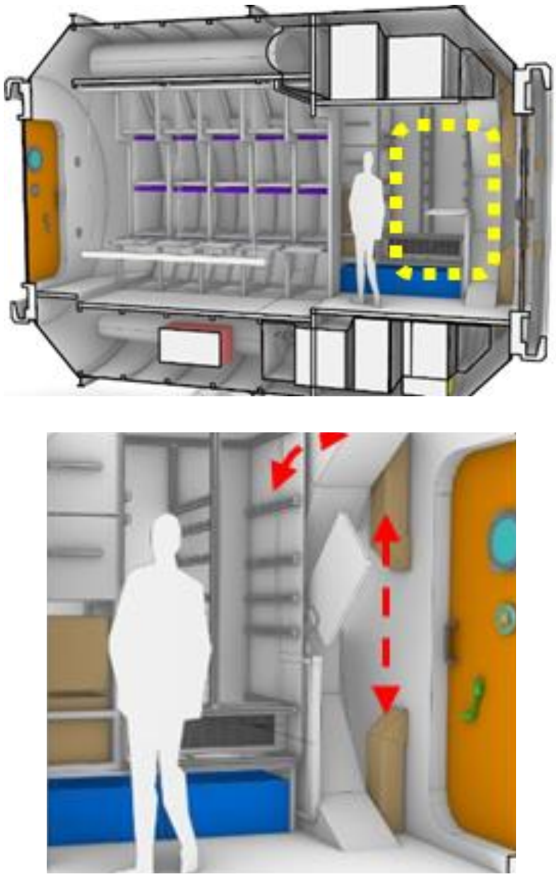

Figure 8. Work station folded (bottom) and unfolded (top) as equipped in the service section.

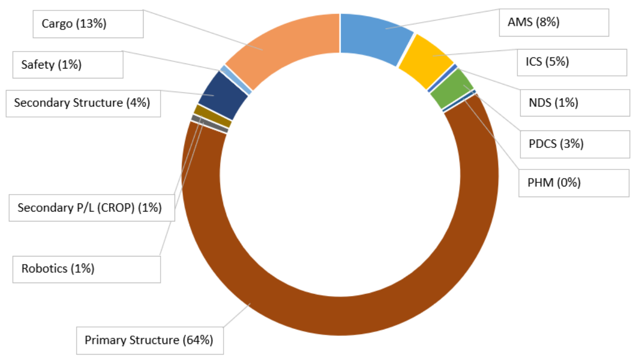

Figure 9. EDEN NG Mass Budget diagram, showing proportions of subsystems of overall dry mass. Values are rounded (and thus not exactly 100%).

modified by the system margin (20% per ECSS standard). Harness is currently assumed to be 10% of the total mass. Overall, the mass adds to 11,763 kg, which is below the set maximum of 18,800 kg. The delta of this maximum to Falcon 9 maximum launch mass into orbit (22,800 kg) leaves mass to include the debris shield and taxi module for orbital docking to the transfer vehicle, as seen in the mission scenario. Therefore, at the moment, the total there is about 7000 kg of mass free for cargo and another 4000 for the debris shield and orbital stage. The entry describing cargo includes mostly racks and cargo bags, which are needed for using the greenhouse as cargo module. Secondary structure entails miscellaneous equipment, e.g., the work station. Safety covers e.g., a fire extinguisher, smoke and carbon monoxide detectors.

Cargo configuration

The preliminary design of the cargo configuration foresees the removal of the plant cultivation trays, as well as the main supply and return air ducts in the growth area. Furthermore, the central plant cultivation system would be removed in this configuration, along with the NDS sump pumps in the subfloor area. The curved ducts along the walls, as well as the majority of the piping and cabling, would remain in place, as would the LED panels.

In the service section, the configuration remains the same between the cargo and greenhouse mode, aside from the interfaces to the habitat and to the growth area which will be connected during commissioning.

Growth area

As seen in Figure 10, the growth area is composed of five racks which have three levels on each side for plant cultivation. Both sides' racks are assigned for leafy green crops, and the central rack is used for middle- or tall-growing crops. The fluid lines, for nutrient supply and return, will be located under the floor, and air-ducts are positioned on the top and bottom of the module. Power lines and cables could be located at the extra space above the top trays.

As an initial design, the 40 x 60 cm aeroponic trays of the EDEN ISS MTF were used as a baseline for the plant cultivation system. A few different configurations were considered with varying tray sizes and in the end a 50 x 70 tray size was selected. This size still allows comfortable handling of the tray by a single crew member, while at the same time providing a larger overall cultivation area than the original 40 x 60 cm size.

Due to the circular cross-section of the GTD structure, the plant cultivation trays in the middle levels of the rack can be pushed further backwards, allowing for the inclusion of a step at the front, which the crew can use to reach the upper levels.

To facilitate plant handling by the crew or the robotic assistant, the trays will be mounted on rail systems, allowing the trays to be pulled forwards into the corridor for easier access.

4.4 Subsystems

An overview about the subsystems is given in Figure 11. The AMS consists of a condensing heat exchanger and heating elements for temperature and humidity control, pre-, HEPA and VOC filters for contaminant control and fans to provide the required air flow and distribution.

As a preliminary design, air from the habitat can be directed into the GH through an interface duct which leads into the pre- and HEPA filter assembly. This way, the air, after revitalization in the BLSS, does not need any processing within the habitat.

The air is then directed from the greenhouse back to the habitat via a second interface duct, which directs (part of) the air coming out of the VOC filter toward the HabSim. Ideally, the interfaces would allow a variable flow rate to simulate either intermittent (air cycles first only through the greenhouse before guided back into the habitat), comparable to breathing, or continuous air exchange (air is immediately guided back into the habitat after passing once through the greenhouse, while "used" air is coming from the habitat) between the habitat and the greenhouse.

Furthermore, CO_2 and O_2 injection and removal capability should be included in the HabSim to simulate the impacts of the crew, as well as possible physico-chemical life support systems [32] (e.g., molecular sieves) which are likely to be present in a future habitat, especially in early phases before BLSS have been proven in operation [33]. Food regeneration is typically not part of physico-chemical life-support, as such methods are not effective [34].

One of the aspects which should be investigated during the GTD operations is the trade-off between direct air exchange compared with the exchange of individual, separated, gases such as CO_2 and O_2. The current design, along with the proposed functionality of the HabSim AMS, should enable tests with both approaches with limited reconfiguration of the GH AMS.

The design of the NDS system derives heavily from the EDEN ISS MTF. The monitoring and control of the nutrient composition in the MTF was generally reliable and as such the same architecture could be applied for the GTD with minor changes (e.g. tank size changes linear to growth area change, i.e. ca. 50%). Tanks, e.g. for stock solution EC control, as well as acid and base tanks for pH control, are connected to the bulk nutrient solution tanks via dosing pumps. Sensors monitor the pH, EC and the amount of the bulk solution and injection of stock solution, acid, base and fresh water is done accordingly to maintain the desired setpoints. To enable experiments with respect to microbial decontamination, a system is foreseen which can inject various additives into the solution, such as ozone or hydrogen peroxide. Alternative decontamination methods may be included based on results from future lab experiments.

The distribution of the nutrient solution to the plants was adapted based on lessons learnt from EDEN ISS (leakage and pump failures), while also providing flexibility for different experiments during the GTD operation. To improve reliability, the aim was to reduce the number of pumps (leading to less connectors and thus reduce leakage as well as decrease failure probability) within the system and to reduce the number of on/off cycles per day to increase pump lifetime. For this reason, for each of the two nutrient solutions a high-pressure pump with a large accumulator tank is selected for nutrient delivery. The pump primes the accumulator tank, which can then supply nutrient solution to the plant cultivation trays for a certain period of time before it needs to be primed again.

A set of valves will control which tray receives nutrient solution, with both the interval between irrigation cycles as well as the duration of irrigation variable to allow for experimentation and optimization based on crop type.

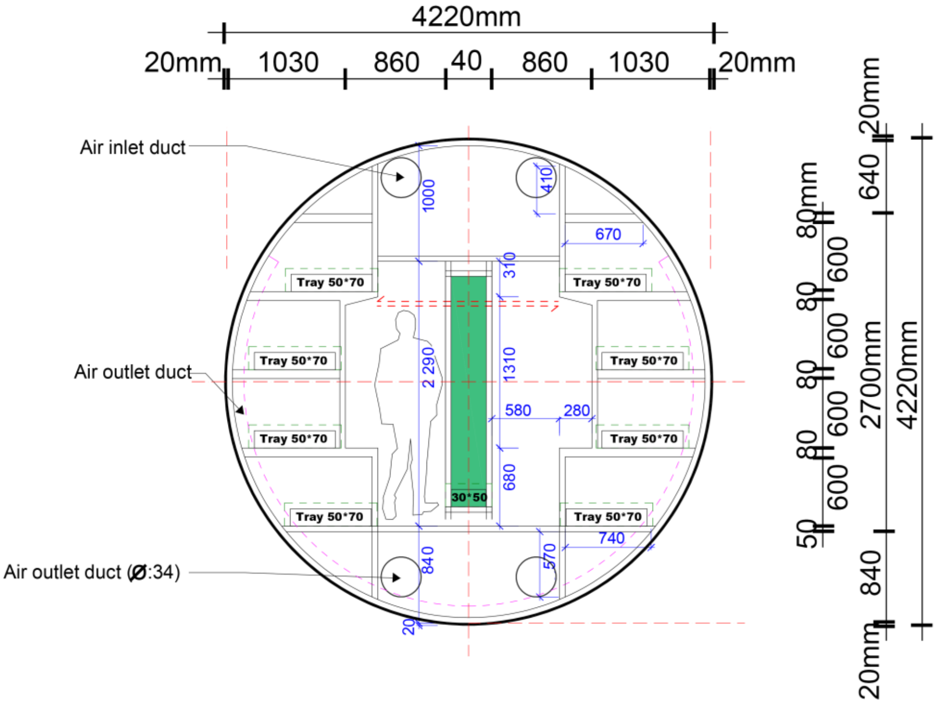

Figure 10. Transverse section of the greenhouse module. Dimensions are given in mm.

Although aeroponic nutrient delivery is considered as the baseline design, alternative nutrient delivery methods can be tested with this setup by including some flow and pressure regulators on the supply lines.

Similarly, the trays could be replaced with alternative structures, such as, for example, the Seed Cultivation Mats developed within the Mobile Deployable Plant Growing Device (MEPA) project [35], i.e. a deployable mat, which contains plant seed containers and is connected to a mobile NDS.

The plants to be cultivated in the greenhouse of the GTD can be divided into two different categories - tall growing plants and small growing plants. In order to be able to illuminate these optimally, the ILS of the GTD is equipped with LED panels. Each plant tray is illuminated by its own LED panel, with different designs for tall-growing plants and small-growing plants to meet the specific needs of the plants. In the GTD's greenhouse five plant racks with four levels each are installed on each side with a tray for each plant. An LED panel (40 in total) for cultivating small plants is mounted above each of these trays. In addition, the moveable center rack is illuminated by five LED panels for the cultivation of tall plants. This makes a total number of 45 LED panels used in the greenhouse.

Each LED panel has four LED channels (blue (450 nm), red (660 nm), far red (730 nm), white (5700 K)), which allows for adjustment of the wavelength and intensity of the LED panel to the plants and ensures an optimal lighting cycle during the day. The target intensities at plant canopy were 300 and 600 micromol/m²/s for leafy greens and fruiting crops respectively. An 8/16 lighting schedule was selected for the design as a baseline – the actual lighting schedule will depend on the selected plants and further experimentation during operation of the GTD, finding an optimum weighing plant needs, operational issues and system complexity. Sunrise and sunset are simulated by reduced intensities. For sunrise, 15 mins of low white light with an approximate ratio of red to far-red light of 0.3 and an intensity of 15% of the nominal intensity were followed by another 45 minutes of 50% nominal intensity. For sunset the sequence is reversed. This approach is based on EDEN ISS MTF operation.

Furthermore, the LED panels have a temperature sensor and over-temperature protection. They are controlled by the GH's general control system, which is connected via a wireless data link, so less wiring harness is required, resulting in mass savings and reduced configuration complexity.

The growth area is equipped with a robotic arm, which can access each tray. It can either use a hand for manipulation of plants and crops, including harvesting, or a camera system for plant health monitoring, instead of several cameras having to be used for each tray. This has the advantage of reducing harness and system complexity.

The Combined Regenerative Organic food Production (CROP) urine processing system is included in the baseline design as a secondary payload. It uses algae and bacteria to process urine and provide nutrients for the plant. Significant characterization of the bio-filters has been done in previous projects and some plant cultivation tests with nutrient solution utilizing the processed CROP output have also been completed. However, there are a number of open research questions related to the integration of the CROP system into a BLSS such as long-term monitoring of the gas exchanges and the impact on microbiome development within the greenhouse.

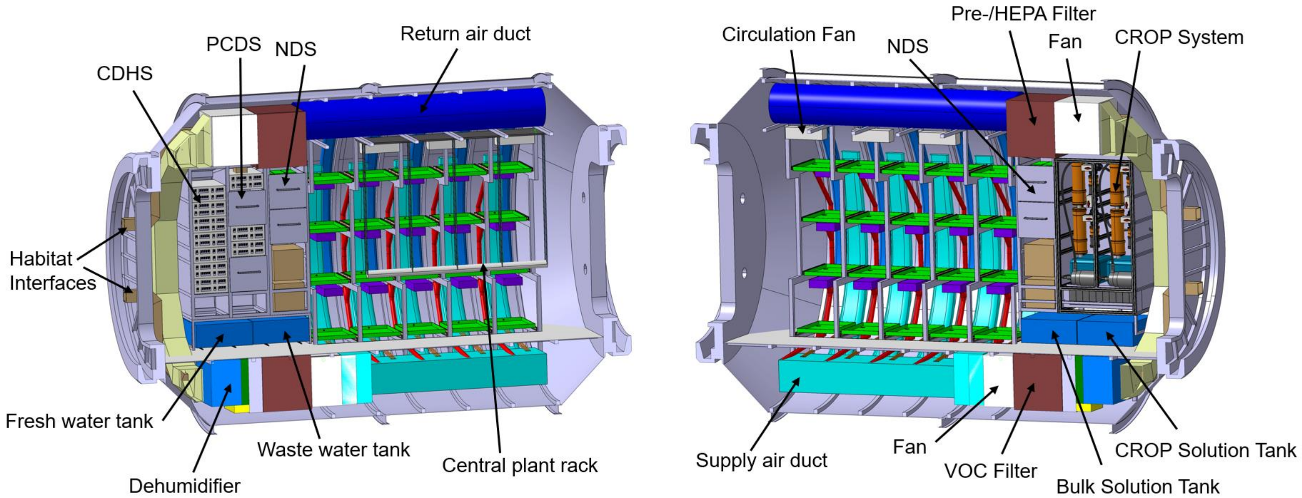

Figure 11. Cut-away view of the greenhouse module intended for the GTD with subsystems and components marked: CDHS: Command and Data Handling System, CROP: Combined Regenerative Organic food Production (secondary payload with algae reactor), HEPA: High-Efficiency Particulate Air, NDS: Nutrient Delivery System, PCDS: Power Conditioning and Distribution System, VOC: Volatile organic compound. Two air ducts remove the air from the growth area to the service section, where it is cleaned and mixed with habitat air, before being returned to the growth area by sub-floor supply air ducts. Tanks are used for nutrient solution, fresh and waste water.

During GTD operation the CROP system could be exchanged for an alternative payload to enable testing of different BLSS architectures. Furthermore, although not yet considered during the current design phase, some payloads could potentially be included in the HabSim to further extend the BLSS capabilities.

5. Discussion

The design presented here enables testing a (near-)closed-loop system by creating a black-box (containing the HabSim, Control Center and operational environment) interacting with the greenhouse. This allows addressing the science case (see Chapter 2), e.g., the GH as a system can be tested in conjunction with a simulated habitat, based on different mission parameters, the tray system is reconfigurable and flexible, which helps with testing of different kinds of plant types to find an optimized plant selection, documenting the plant growth in combination with system parameters (e.g., illumination, gas input) can support the formulation of growth models, which in turn can allow better planning and scheduling of harvests and food production. Once processes, technologies and plant selection have matured, the calorie output is optimized, which then will allow the GTD to supply significant parts of the nutrient needs of a test crew.

5.1 Design Plausibility

The system design is plausible and fits the assumed scenario, as explained in the following. This scenario also allows a flexible integration of the greenhouse into a system architecture of a future lunar base, which improves the likelihood of adoption of the design for future missions. It is prudent to remove functionalities which are not related to the greenhouse function from the testing, e.g., an attitude and orbital control system. This can be added by a separate stage for transfer/ docking on orbit. Separating functionalities needed for transfer and attitude control from the actual greenhouse also allows removing "dead weight" from the module during transfer, landing and handling on the lunar surface. Putting such functionalities into the greenhouse system would mean adding mass, which is not needed on the lunar surface for its primary function as a BLSS. Currently SpaceX Starship is foreseen as the human lander for lunar missions. Other options are expected to be available in the future, especially also commercial systems for scientific or other payloads.

One such example is the Dynetics Cargo Lander [36]. The design can carry a cylindrical module, encased by the lander structure to the lunar surface, which has a length of 4 or more meters and does not exceed 5 m diameter. With a maximum length of 6.6 m and 4.2 m diameter, the greenhouse in its current design would fit that envelope.

Similarly, delegating functionalities such as waste heat rejection or management, power generation, etc. (see Section 3.3) to the habitat is realistic. First of all, incorporating these functionalities into the GTD is not necessary as they are not related to the functionality of the greenhouse as such. Furthermore, it is reasonable to assume that e.g., similarly to ISS there will be a system for the overall habitat handling such tasks, which will in turn be an element of the habitat architecture, e.g., with centralized radiators. If the architecture of an actual implementation is not centralized and individual modules are expected to handle such tasks themselves, it is easy to add them to a flight model. At the moment the heat flux, power flux, etc. are assumed to be just fluxes over the system border of the greenhouse. These fluxes can be realized with an own system handling these tasks or a centralized system for the habitat.

The system is designed to be operational during system maintenance, by keeping elements modular – individual parts can be removed without complete failure of a system function. This is relevant for its application on the lunar surface, as maintenance cannot mean complete ceasing of operations of the BLSS. At the same time, this modularity is required for the GTD to enable technology development by testing new equipment and finding an optimal configuration.

A major drawback of a ground test demonstrator is the lack of reduced gravitation fitting lunar conditions. Such reduced gravitation would have influence on the design as well, e.g., concerning pumps, airflow or accessibility. Reduced gravitation cannot be simulated adequately on Earth for a long-duration as needed for running a research campaign in the GTD. Typical methods applying free fall, are not fitting this problem. The only way to investigate this is to use simulation, e.g. for air flow calculations. This can either be done with simulated data or measurement data, which acts as input for a model which is adapted to a lunar environment.

5.2 Improved autonomy

As shown in [16] [37] [38] [39] [40] crew time is a limited and valuable resource in space missions. Therefore, it has to be optimized to increase the available time of the astronauts for scientific activities [41] [42] [43]. To support this optimization process and improve the autonomy (see OBJ-002) of astronauts from remote support teams on Earth, technologies such as robotics, artificial intelligence, automated plant health monitoring or augmented reality (AR) should be more focused on.

Powerful AR headsets could support the operational work of the astronauts in a planetary surface greenhouse visualizing information such as procedures, plant or greenhouse system data [44] [45].

Artificial neuronal networks trained with diverse datasets of high-resolution images, e.g., with at least 1920×1080 pixels, could be used to detect not only entire plants but also all components of a plant in different states of health from a great distance. This would allow to visualize complete workflows for plant care on AR headsets through precise augmentation. For example, instead of a textual description of where which plant should be pruned and to what extent, an overlay could virtually mark the specific locations on a particular plant. [46]

Furthermore, automated predictions can be made about harvest date and quantity. This data can be used in an automatic crop planning tool to calculate the optimal time and location for seeding, transplanting and harvesting to generate continuous output.

In the case of such precise plant detection, the automation of plant care could follow as a next step. Specialized robots could use plant detection to perform predefined tasks automatically. By detecting and locating particular plant components, the robots would be able to decide when certain parts of a plant need to be pruned, when fruits are ripe, or when plants are ready to harvest and act. [46] The use of the robot could also be supported via an AR interface. Functions that could be implemented would be manual control or autonomous operation of the robot (e.g., plant handling, check environmental parameters, or take photos/videos), visualization of gripping spaces/safety spaces of the robot and subsequent display of the robot path or robot activities performed during autonomous operation. This would allow for increased automation of plant-related tasks in a planetary surface greenhouse and reduced human effort [46].

5.3 Enabled science program

Based on the relevance described before and the gaps, specific scientific programs can be derived, which answer several of the mentioned gaps and issues. The GTD as presented here can support closing these gaps with a science program, e.g., with research in the following aspects:

Power demand over time

One issue that is to be investigated, is the power demand over time. This system aspect can be estimated beforehand, based on the equipment tree, but actual measurement data is important to understand the different operational situations' influence on power demand. Future greenhouse operation on Moon and Mars must rely on adequate power demand estimates, e.g., to design power systems.

These measurements have to be preferably scaled, e.g., by using different amounts of growth area, to establish a power demand per growth area function for future scaling. This way it can be better estimated what a larger greenhouse system needs in terms of power, which would contribute to understand scalability of the system.

Similarly, these measurements vary with the plant needs, i.e., using different plants for different growth cycles can help establish a catalogue of power intensive plants. It would be important to understand how the power demand relates to the various plant properties such as, e.g., robustness (concerning environmental influence due to the system, its operation and other present plants), nutrient amount, or water demand.

Air exchange method

One aspect to be tested under various conditions is the air exchange method, i.e., what is the effect of a continuous air exchange with the habitat, or an alternating mode, where exchange only occurs after a short period of time, where air is revitalized. Such a "breathing" method could depend on the exact operating conditions, e.g., the plants' growth, time of day (e.g., less activity during rest hours in the habitat), which needs to be tested, e.g., by simulating different activity levels in the HabSim.

Operational processes

Operations need to be planned to be most effective and at the same time least time consuming for the crew. Therefore, different procedures need to be tested, e.g., how to start the process and e.g., add more and more life-support functionality to the overall habitat system as initially, the growing plants will require less resources than when fully grown. To avoid drops in life-support capability, resp. fluctuation in air quality, alternating batches of plants have to be used. Best practices for this need to be developed.

Lunar mission campaign

Some campaigns shall be conducted under "lunar conditions", i.e., with time delays, limits in data rates and communication windows. This is relevant mostly for operational research, where processes and procedures need to be tested, but also routines developed for autonomy. These campaigns will increase the fidelity of tests with regard to the actual operation on the lunar surface.

Plant selection

Experiments will also investigate the effect of plant selection to create an optimized plant selection for a lunar greenhouse, possibly with different focus, depending on the exact task of the greenhouse. Optimization will occur based on various parameters, whose influence need to be established by experiments. Relevant parameters are:

- Crew time needed for plant care and processing
- Resources needed (power, water, nutrients)
- Nutritional value
- Cultural acceptance
- Psychological benefit
- Safety
- Reliability and robustness (e.g., against failure of nutrient delivery)
- Yield
- Resource output (e.g., oxygen)
- Food variety

To find an optimum with regards to these parameters, various crops will be tested, also in combination to e.g., combine strengths and balance out weaknesses, e.g., by combining a fruit with high nutritional value and one, which is robust and can produce more oxygen. Depending on the focus of operation, e.g., food production or air revitalization, different sets of plants could be optimal. This has to be determined and tested out in campaigns. Simulated system failures can be used to determine robustness and reliability of plants, or to establish an image database of off-nominal plant growth (e.g., nutrient deficiency, drought stress).

Human factors and Artificial Intelligence and Augmented Reality interaction

The greenhouse environment, the interaction with plants, the fresh food can have psychological benefits, which need to be researched, e.g., by determining the effect of the plants on stress levels or concentration. Furthermore, the design needs to be tested on comfort for working and which elements of the design need to be reworked for ease of access and crew safety.

Further research is required to investigate the effect and utility of AI support and Augmented Reality for the crew and for improvement of autonomy. For instance, Augmented Reality can support the crew during plant care and with plant health monitoring. This requires development of respective technology, but also routines. It has to be researched if such aid is actually helpful and which tasks are best supported with such tools.

Time scales

The aspects that have been mentioned here can be investigated in various time scales, depending on the exact question to be answered, available research personnel and specific campaign. These scales could cover one or several days, a week, months or even a year or more, to understand the time influence on the specific question, e.g., variation over time.

5.4 Terrestrial application of technology and space in-situ sustainability

Services and technologies can have a benefit for sustainable development on Earth [17]. For instance, aeroponic agriculture systems, as applied in the GTD, can reduce water demand for agriculture by 98%, fertilizer need by 40%, remove pesticides from agriculture and improve harvest yield by 75% [47]. Further developing such technologies in the direction of terrestrial application not only reduces resource needs, but also improves handling and covering development costs via space programs allows less costly technology adoption on Earth compared to developing these technologies from scratch. Typically, high costs of space systems can be reduced during adaptation, e.g., because the production number is increased, i.e., costs per piece are less compared to a single instance of a system, reduction of the system down to the most essential (and needed) functions as well as less severe demands in an Earth environment compared to space (e.g., concerning radiation).

One example of application of such technology is MEPA, a system derived from EDEN ISS that can be deployed and act as a greenhouse in remote areas, disaster shelters or refugee camps [35].

5.5 Outlook

A number of issues have to be analyzed in the future, to finalize the design and enable assembly and operation. While the precise power demand – depending on various variables – will be an outcome of experiments (see section 5.3), nevertheless as a next step a better estimate of power demand is required for the thermal analysis.

As a first step operational modes have to be defined, which describe all relevant operational conditions, e.g., start-up phase, nominal operations, recovery, and determine the respective power demand per subsystem. For this a functional analysis can identify, which functions are needed in which mode. Once the power demand is identified, the thermal analysis can be conducted.

Afterwards, a trade-off between an air-cooled LED-system and a water-cooled system will occur. A water-cooled system would reduce the size (and power demand) of the AMS, but at the same time increase the system complexity, especially concerning harness due to the extensive piping needed. Additionally, the risk of leakages would increase. Yet, a final decision requires a trade-off, especially considering size and mass envelopes.

A further relevant aspect is to design an interface, which can realistically simulate the habitat interaction of the greenhouse and thus ensure useful experimentation with a closed-loop and humans-in-the-loop approach. The subsystems required in the HabSim to enable the full scientific program also need to be designed.

6. Conclusion

The currently still existing gaps in understanding operations, biology, system and subsystems of BLSS require extensive experimentation. This paper shows the design for a ground test demonstrator that can act as a research environment to close those gaps and develop a lunar greenhouse that can be part of a bioregenerative life-support system, is reliable and fitting the requirements of long-term human missions. The design is derived from a greenhouse prototype as deployed in Antarctica and aims at a as realistic as possible representation of a lunar greenhouse. With a preliminary mass of approx. 12 tons, a diameter of 4.2 m and a length of 6.6 m, the greenhouse would fit in a currently available launch vehicle. This fidelity is important to not only test the systems, but also operation of a greenhouse.

The system is equipped with various components, which improve autonomy and reduce crew time needed for its operation, e.g., a robotic arm used for crop handling and plant health monitoring, but also an augmented reality system, providing information about plant health and procedures to the crew.

The concept of the logistic-to-green approach increases utility and efficiency of the overall system by combining cargo transport and bioregenerative life-support system. The test demonstrator will provide an environment with which to ameliorate the human interface with designed systems. Moreover, it can provide further spin-off for terrestrial applications, e.g., for urban food production.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] NASA, "Artemis Program," 1 July 2021. [Online]. Available: https://www.nasa.gov/artemisprogram. [Accessed 10th July 2022].

[2] ESA, CDF STUDY REPORT - Moon Village - Conceptual Design of a Lunar Habitat, 2020.

[3] CNSA, "International Lunar Research Station - Guide for Partnership," 2021.

[4] M. Bamsey, T. Graham, M. Stasiak, A. Berinstain, A. Scott, T. Rondeau Vuk and M. Dixon, "Canadian advanced life support capacities and future directions," *Advances in Space Research,* no. 44, pp. 151-161, 2009.

[5] C. Lasseur, "Regenerative Life Support - Status & Challenges," in *MELiSSA-Agrospace-Workshop*, Rome, Italy, 2018.

[6] C. M. Escobar and J. A. Nabity, "Past, Present, and Future of Closed Human Life Support Ecosystems - A Review," in *47th International Conference on Environmental Systems,* , Charleston, South Carolina, USA, 2017.

[7] L. Poulet, K. Engeling, T. Hatch, S. Stahl-Rommel, Y.-A. Velez Justiniano, S. Castro-Wallace, J. Buncheck, O. Monje, M. Hummerick, C. L. M. Khodadad, L. E. Spencer, J. Pechous, C. M. Johnson, R. Fritsche, G. D. Massa, M. W. Romeyn, A. E. O'Rourke and R. W. Wheeler, "Large-Scale Crop Production for the Moon and Mars: Current Gaps and Future Perspectives," *Frontiers in Astronomy and Space Sciences,* vol. 8, 2022.

[8] C. M. Johnson, H. O. Boles, L. E. Spencer, L. Poulet, M. Romeyn, J. M. Buncheck, R. Fritsche, G. D. Massa, A. O'Rourke and R. M. Wheeler, "Supplemental Food Production With Plants: A Review of NASA Research," *Frontiers in Astronomy and Space Sciences,* vol. 8, 10 November 2021.

[9] J. Walker and C. Granjou, "MELiSSA the minimal biosphere: Human life, waste and refuge in deep space," *Futures,* vol. 92, pp. 59-69, September 2017.

[10] C. Lasseur, J. Brunet, H. de Weever, M. Dixon, G. Dussap and F. Godia, "MELiSSA: the European project of closed life support system," *Gravitational and Space Biology,* vol. 23, no. 2, September 2010.

[11] CSIRO, "Space - A Roadmap for unlocking future growth opportunities for Australia," 2018.

[12] ESA, "Terrae Novae 2030+ Stratgy Roadmap," 2021.

[13] International Space Exploration Coordination Group, "The Global Exploration Roadmap," 2018.

[14] D. Schubert, M. Bamsey, P. Zabel, C. Zeidler and V. Vrakking, "Status of the EDEN ISS greenhouse after on-site installation in Antarctica," in *48th International Conference on Environmental* , Albuquerque, 8–12 July 2018.

[15] P. Zabel, C. Zeidler, V. Vrakking, M. Dorn and D. Schubert, "Biomass Production of the EDEN ISS Space Greenhouse in Antarctica During the 2018 Experiment Phase," *Frontiers in Plant Science,* vol. 11, 2020.

[16] C. Zeidler, G. Woeckner, J. Schöning, V. Vrakking, P. Zabel, M. Dorn, D. Schubert, B. Steckelberg and J. Stakemann, "Crew time and workload in the EDEN ISS greenhouse in Antarctica," *Life Sciences in Space Research,* vol. 31, pp. 131-149, 2021.

[17] V. Maiwald, D. Schubert, D. Quantius and P. Zabel, "From space back to Earth: supporting sustainable development with spaceflight technologies," *Sustainable Earth,* vol. 4, 2021.

[18] V. Maiwald, K. Kyunghwhan, C. Philpot, D. Schubert and V. Vrakking, "Lunar Eden: Roadmap and Demonstrator Design of a Lunar Greenhouse Based on an Antarctic Prototype," in *73rd International Astronautical Congress, 19-23 Sep.* , Paris, France, 2022.

[19] ESA, "Roadmaps for Future Research," 2016.

[20] J. Hu, S. Li, H. Liu and D. Hu, "Reliability and lifetime estimation of bioregenerative life support system based on 370-day closed human experiment of lunar palace 1 and Monte Carlo simulation," *Acta Astronautica,* no. 202, pp. 609-616, January 2023.

[21] Y. Fu, Z. Yi, Y. Du, H. Liu, B. Xie and H. Liu, "Establishment of a closed artificial ecosystem to ensure human long-term survival on the moon," *preprint, https://doi.org/10.1101/2021.01.12.426282,* 2021.

[22] T. Zhao, G. Liu, D. Liu, Y. Yi, B. Xie and H. Liu, "Water recycle system in an artificial closed ecosystem – Lunar Palace 1: Treatment performance and microbial evolution," *Science of The Total Environment,* no. 806, February 2022.

[23] M. Kliss, "From ISS to Mars: Understanding the NASA TA6: Human Health, Life Support and Habitat System Technology Roadmap," in *ICES*, Vienna, Austria, 2016.

[24] W. V. Reid, H. A. Mooney, A. Cropper, D. Capistrano, S. R. Carpenter, K. Chopra, P. Dasgupta, T. Dietz, A. Kumar Duraiappah, R. Hassan, R. Kasperson, R. Leemans, R. M. May, T. A. J. McMichael, P. Pingali, C. Samper, R. Scholes, R. T. Watson, A. H. Zakri, Z. Shidong, N. J. Ash, E. Bennet, P. Kumar, M. J. Lee, C. Raudsepp-Hearne, H. Simons, J. Thonell and M. B. Zurek, "Ecosystems and Human Well-Being: Synthesis," Millennium Ecosystem Assessment, Washington, D.C., 2005.

[25] M. Anderson, D. Barta, G. Douglas, B. Motil, G. Massa, R. Fritsche, C. Quincy, M. Romeyn and A. Hanford, "Key gaps for enabling plant

growth in future missions," in *AIAA Space and Astronautics Forum and Exposition*, Orlando, 2017.

[26] M. P. Mathew and T. Y. Mahesh, "Leaf-based disease detection in bell pepper plant using YOLO v5," *Signal, Image and Video Processing,* no. 16, pp. 841-847, 2022.

[27] C. Zeidler, V. Vrakking, M. Bamsey, L. Poulet, P. Zabel, D. Schubert, C. Paille, E. Mazzoleni and N. Domurath, "Greenhouse Module for Space System: A Lunar Greenhouse Desgin," *Open Agriculture,* no. 2, pp. 116-132, 2017.

[28] NASA, System Engineering Handbook, Rev. 2, 2007.

[29] A. Martelo Gomez, S. Jahnke, A. Braukhane, D. Quantius, V. Maiwald and O. Romberg, "Statistics and evaluation of 60+ concurrent engineering studies at DLR," in *68th International Astronautical Congress*, Adelaide, Australia, 2017.

[30] V. Maiwald, V. Vrakking, P. Zabel, D. Schubert, R. Waclavicek, M. Dorn, L. Fiore, B. Imhof, T. Rousek, V. Rossetti and C. Zeidler, "From ice to space: a greenhouse design for Moon or Mars based on a prototype deployed in Antarctica," *CEAS Space Journal,* no. 13, pp. 17-37, 2021.

[31] S. Jahnke, V. Maiwald, C. Philpot, D. Quantius, O. Romberg, W. Seboldt, V. Vrakking and C. Zeidler, "Orbital hub: a concept for human spaceflight beyond ISS operations," *CEAS Space Journal,* vol. 10, pp. 355-379, 2018.

[32] P. Eckart, "Physico-Chemical Life Support Subsystems," in *Spaceflight Life Support and Biospherics*, 1996, pp. 175-248.

[33] P. Zabel, D. Schubert and M. Tajmar, "Combination of Physico-Chemical Life Support Systems with Space Greenhouse Modules: A System Analysis," in *ICES 2013*, Vail, Colorado, USA, 2013.

[34] T. Wydeven, "A survey of some regenerative physico-chemical life support technology," NASA, 1988.

[35] D. Schubert, "MEPA - Mobile Deployable Plant Growing Device," in *Aerospace Technologies in support of Humanitarian Aid*, Online Conference, 2021.

[36] A. Crocker, "Dynetics Human Landing System: Overview and Status of the Development of a Lunar Transportation Architecture," in *74th International Astronautical Congress (IAC)*, Paris, France, 2022.

[37] National Research Council, "Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences," *National Academies Press,* 2003.

[38] C. Stromgren, F. Escobar, S. Rivadeneira, W. Cirillo and K. E. Goodliff, "Predicting Crew Time Allocations for Lunar Orbital missions based on Historical ISS Operational Activities," in *AIAA Space and Astronautics Forum and Exposition*, Orlando, Florida, USA, 2018.

[39] NASA, "Commercial and Marketing Pricing Policy," 29 April 2021. [Online]. Available: https://www.nasa.gov/leo-economy/commercial-use/pricing-policy . [Accessed 30 November 2022].

[40] L. Poulet, C. Zeidler, J. Bunchek, P. Zabel, V. Vrakking, D. Schubert, G. Massa and R. Wheeler, "Crew time in a space greenhouse using data from analog missions and Veggie," *Life Sciences in Space Research,* pp. 101-112, 2021.

[41] P. Eckart, Spaceflight Life Support and Biospherics, Springer Netherlands, 1996.

[42] M. Bamsey, A. Berinstain, T. Graham, T. Neron, R. Giroux, S. Braham, R. Ferl, A.-L. Paul and M. Dixon, "Developing strategies for automated remote plant production systems: Environmental control and monitoring of the Arthur Clarke Mars Greenhouse in the Canadian High Arctic," *Advances in Space Research,* vol. 44, no. 12, pp. 1367-1381, 2009.

[43] P. Zabel, C. Zeidler, V. Vrakking, M. Dorn and D. Schubert, "Crewtime in a Space Greenhouse based on the Operation of the EDEN ISS Greenhouse in Antarctica," in *49th International Conference on Environmental Systems, 7-11 July*, Boston, Massachusetts, USA, 2019.

[44] C. Zeidler and G. Woeckner, "Using Augmented Reality in a Planetary Surface Greenhouse for Crew Time Optimization," in *ACM CHI 2021, SpaceCHI: Workshop on Human-Computer Interaction for Space Exploration, 14 May*, Virtual, 2021.

[45] C. Zeidler, M. Klug, G. Woeckner, U. Clausen and J. Schöning, "ARCHIE²: An Augmented Reality App with Plant Detection to Optimize Crew Time in a Planetary Surface Greenhouse," in *30th IEEE Conference on Virtual Reality and 3D User Interfaces, 25-29 March*, Shanghai, China, 2023.

[46] M. Klug, "Nutzung der HoloLens 2 für die Pflanzenerkennung und Augmentierung im Kontext des EDEN ISS Weltraumgewächshauses," Master Thesis, Universität Bremen, 2022.

[47] F. Oluwafemi, "Space food on celestial bodies and on the way there," in *Future Foods - Global Trends, Opportunities, and Sustainability Challenges*, R. Bhat, Ed., Academic Press, 2021, pp. 451-468.

[48] SpaceX , "Falcon User's Guide," 2020.