The preliminary design of the EDEN ISS Mobile Test Facility - An Antarctic greenhouse

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EDEN ISS is a European project to investigate cultivation techniques of plants in space for future bio-regenerative life support systems. The technologies will be tested in a laboratory environment as well as at the highly-isolated German Antarctic Neumayer Station III. A small and mobile container-sized test facility will be built in order to provide realistic mass flow relationships. This paper provides a summary of the activities performed in the early design phase of the project. The design phase started with the kick-off meeting in March 2015 and focused on the requirements definition and design of the greenhouse. The EDEN ISS partners met for a design workshop from September 7th to September 18th, 2015 in the Concurrent Engineering Facility of DLR's Institute of Space Systems in Bremen, Germany. The purpose of the workshop was the generation of a preliminary design for the Mobile Test Facility. The Mobile Test Facility will be built later in the project and used to conduct an over one year long experiment campaign beginning in December 2017 in Antarctica. During the two week workshop, the consortium members worked on their respective subsystems and on how their systems can be integrated in the overall greenhouse. The design of each subsystem was greatly improved. System budgets (e.g. mass, power) were calculated, engineering drawings created and estimates with respect to inputs and outputs made. A very important step was the consolidation of the system and subsystem requirements. This paper summarizes the results of the design work-shop and describes the preliminary design of the EDEN ISS Mobile Test Facility.

I. Introduction

A critical component of future, human exploration to worlds unknown, will be the supply of edible food for crewmembers. The development of plant cultivation technology innovations for closed-loop systems thus becomes an integral near term objective for future missions. The goal of the EDEN ISS project is to advance controlled environment agriculture technologies beyond the state-of-the-art. It focuses on ground demonstration of plant cultivation technologies and their application in space. EDEN ISS develops safe food production technologies and operations for use on-board the International Space Station (ISS) and for future human space exploration vehicles and planetary outposts. A mobile container-sized greenhouse test facility will be built to demonstrate and validate different key technologies and procedures necessary for safe food production within a (semi-) closed system. The plant cultivation technologies will first be tested in a laboratory setting at the sites of the consortium partners. All systems will be integrated at DLR in Bremen, followed by an extensive test period. In October 2017, the complete facility will be shipped to the German Neumayer III station in Antarctica. The station is operated by the

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Alfred Wegener Institute and has unique capabilities and infrastructure for testing plant cultivation under extreme environmental and logistical conditions. It is foreseen that the container-sized greenhouse of the EDEN ISS project will provide year-round fresh food supplementation for the Neumayer Station III crew.

In September 2015, the EDEN ISS project partners sent technical staff to the DLR Institute of Space Systems in Bremen, Germany to conduct a design workshop for the Antarctic greenhouse. DLR's Concurrent Engineering Facility (CEF), a design laboratory, was utilized for two weeks to generate the preliminary design of the Mobile Test Facility (MTF).

This paper gives an overview of the preliminary design of the container-sized greenhouse facility, which will be the newest among Antarctic greenhouses[1]. Following the description of the overall design, the different sections of the facility will be explained in greater detail. The paper concludes with a description of the logistics and operations of the facility, which also includes an illustration of the preliminary system budgets. It should be recalled that this represents the facility design at the completion of the Concurrent Engineering (CE) study and that, as with any design process the design will still evolve over the course of its development.

II. Project Work Plan and Status

A. Work Plan

EDEN ISS is divided into three major project phases[2]: the design phase, the building phase and the experimental phase.

The design phase started with the kick-off meeting (KOM) in March 2015 and focused on the requirements definition and design of the greenhouse. The operation modes and experiment schedules were also defined in this phase. After elaborating the initial designs, a CE study was conducted in DLR's CEF in Bremen, Germany in September 2015. The objective of the study was the generation of a detailed design of the greenhouse facility. The study lasted two weeks and representatives of all consortium partners participated to provide their expertise. This project phase concluded with the critical design review (CDR) in March 2016.

The building phase encompasses the development, fabrication and integration of subsystems and components. The responsibilities of the different subsystems are divided among the consortium to best fit their experience. In parallel to hardware development, extensive cultivation experiments will be performed. With the experiments, the cultivation parameters of the target plants shall be determined. At the end of 2016/beginning of 2017, subsystem hardware will be delivered to DLR in Bremen, Germany for the system assembly, integration and testing (AIT). The AIT phase will also include a test deployment of the facility at a TBD location in Europe, for integrated test and public outreach purposes. AIT will be concluded in August 2017. Following the AIT phase, the greenhouse will be prepared for shipment to Antarctica in October 2017.

The experimental phase covers the facility setup in the Antarctic, all experiments conducted in Antarctica and a final design iteration to enhance the facility based on lessons learned. The selected key technologies and operations procedures will be demonstrated and validated, the results elaborated and the design of the facility and subsystems shall be developed further to improve performance in terrestrial applications, utilization on-board ISS and in future planetary greenhouse modules.

B. Project Status

The project is now in its second year after a successful kick-off meeting in March 2015 and passing the CDR in March 2016. Here, critical design elements were discussed and the main goal was to freeze the essential design issues with respect to the outer- and inner layout of the Mobile test Facility (MTF).

Prior to the CDR, MTF crop selection was examined by the consortium. The key focus was set on pick-and-eat crops with little to no post-processing requirements. After performing a multi-criteria evaluation, a candidate list of ~14 crop candidates (split-up into ~35 cultivar candidates) were selected. Main clusters were created, like small growing plants (e.g. lettuce & leafy greens, radish), tall growing plants (e.g. cucumber, tomato, pepper), herbs (e.g. parsley, basil) and add-on plants with a small quantity output requirement (e.g. strawberry).

Aside from the crop selection, the overall system requirements were created. The requirements document, which functions as a living document, describes all systems within the MTF as well as the mission scenario at the Neumayer Station III. A total of around 200 requirements were worked out. The system requirements review (SRR) was held successfully in June 2015.

Having a robust set of requirements allowed the consortium to move forward to the preliminary design phase of the MTF itself. The following chapter describes the outcome of the CE Study in detail.

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III. Design Study Overview

A. Overview

The following sections review key information from the EDEN ISS CE study conducted September 7-18, 2015. This study took place within the CEF of the German Aerospace Center's Institute of Space Systems in Bremen. The primary goal of the study was the generation of a preliminary design of the EDEN ISS MTF. This design includes details from all MTF subsystems as well as preliminary details on a number of scientific and operational themes relevant to the EDEN ISS project.

B. Concurrent Engineering Background

The applied CE process[3, 4] is based on the optimization of the conventional established design process characterized by centralized and sequential engineering (see Figure 1 top). Simultaneous presence of all relevant discipline specialists within one location and the utilization of a common data handling tool enable efficient communication among the set of integrated subsystems (see Figure 1 bottom).

The CE process is based on simultaneous design and has four phases.

1. Initiation phase (starts months before using the CE facility):
   - Project leader contacts CE team
   - CE team-project leader negotiation: expected results definition, needed disciplines, date

2. Preparation phase (starts weeks before using CE facility):
   - Definition of mission objectives
   - Definition of mission and system requirements
   - Identification and selection of options
   - Invitation of subsystem/domain experts/consortium partners
   - Agenda definition

3. Study phase (1- 2 weeks in CE facility):
   - Kick-off with presentations of key study elements
   - Starting with first configuration approach and estimation of system budgets on subsystem level
   - Iterations on subsystem and equipment level in several sessions; trading off several options
   - In between offline work: subsystem design in splinter groups
   - Final presentation of all disciplines/subsystems at the end of the study

4. Post processing phase (1-3 months after study):
   - Collection of results
   - Evaluation and documentation of results
   - Transfer open issues to further project work
   - Publish results

The DLR's CEF in Bremen is derived from the Concurrent Design Facility at ESA's ESTEC (European Space Research and Technology Centre), which has already been in operation for more than ten years. DLR Bremen's CEF has one main working room where the whole design team can assemble and each discipline is supplied with its own workstation for calculations and interaction with a special design tool developed by ESTEC. Three screens, one of them interactive, allow the display of data in front of the team. Further working positions are provided in the center of the working area and are usually reserved for customers, principal investigators, guests as well as the team leader and possibly the systems engineer. Two splinter rooms provide the design team with separated working spaces where sub-groups can meet, discuss, and interact in a more concentrated manner.

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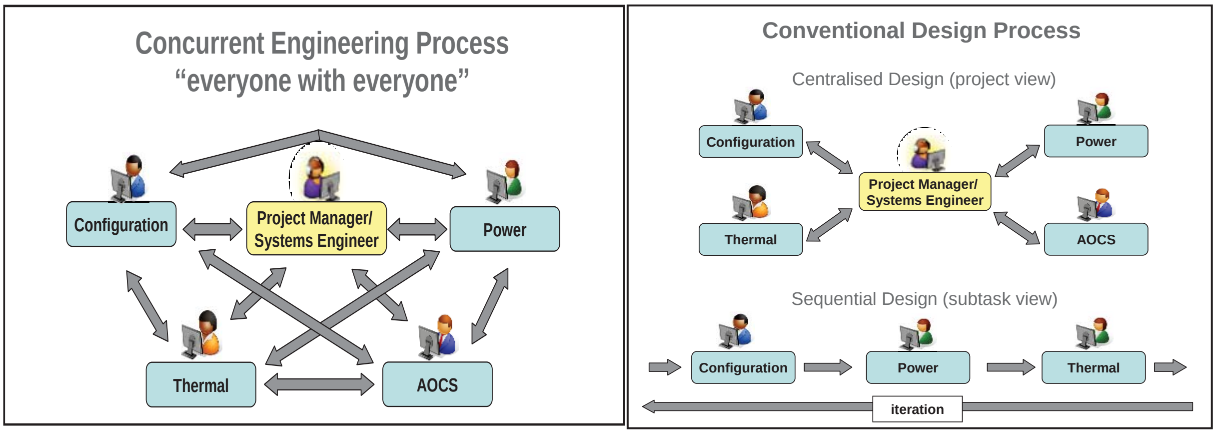

Figure 1. The concurrent engineering approach on the left side compared to projections of conventional design process on the right side.

Figure 2. The main room of the Concurrent Engineering Facility at DLR Bremen (Credit: DLR).

The major advantages of the CE process are:

- Cost efficient early design activity and feasibility studies (Phase 0, A)
- Assembly of the whole design team in one room facilitates direct communication and short data transfer times
- The team members can easily track the design progress, which also helps them identify with the project
- Ideas and issues can be discussed in groups, which brings in new viewpoints and possible solutions; avoidance and identification of failures and mistakes

C. Study Objectives

The following study objectives were defined for the EDEN ISS CE study:

1. Initial design of the EDEN ISS Mobile Test Facility (MTF) layout (e.g. primary & secondary structure, mechanisms, subsystem accommodation, piping, ISPR cultivation system, the Service Section and the Future Exploration Greenhouse (FEG)) including statement of redundant systems/ technologies
2. Design of interface architecture of MTF with Neumayer Station III, with European control center, and with remote user sites
3. Creation of system budgets on the subsystem level, mainly power, mass, thermal, link budget, dimensions and equipment lists for each domain
4. Estimation of required supplies/consumables (e.g. CO_2, tools and spare parts)
5. Investigation of human interaction with systems and documentation of process and operational procedures (e.g. harvest, maintenance as well as layout of an overall mission plan)

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6 Definition of the operational, scientific and hardware development goals during the Antarctic test phase (including measurements to be conducted)
7 Preparation of a list of critical questions per domain

D. Study Domains

The domains of the EDEN ISS CE study are illustrated in Figure 3. Each domain was represented by a team member of the consortium. The study team involved participants from all EDEN ISS project partners. The specific study participants and their responsibilities during the study are listed in Table 1. Figure 4 shows a photo of the EDEN ISS CE-study participants.

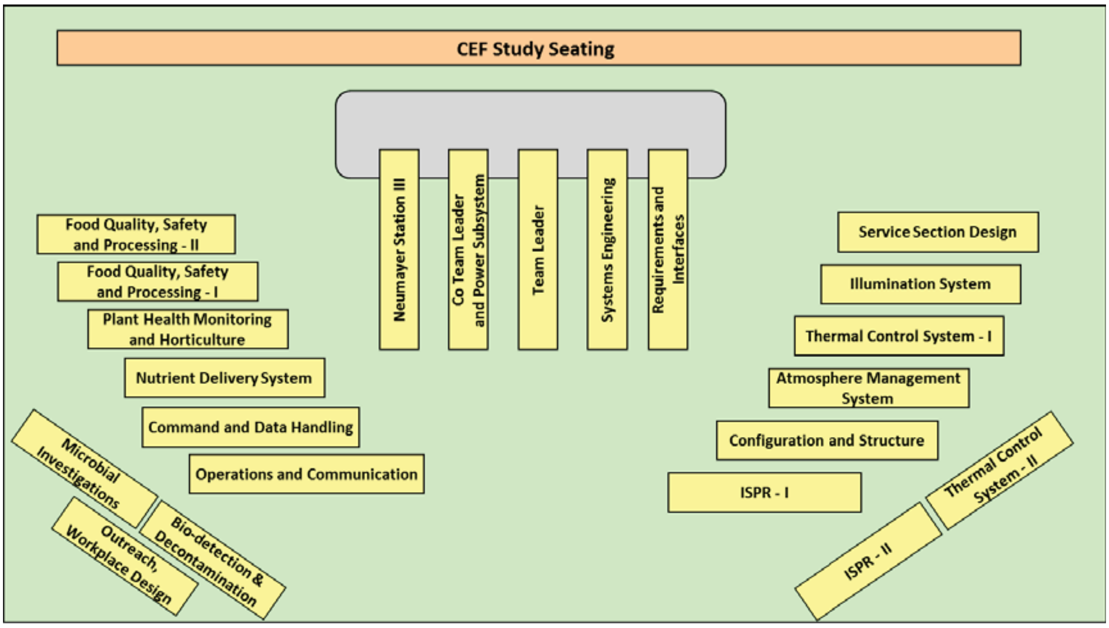

Figure 3. EDEN ISS CE study domain distribution.

Figure 4. EDEN ISS CE study participants (Credit: DLR).

Table 1. CE study team.

Discipline/ Domain	Responsible
Team Leader	Daniel Schubert
Co Team Leader	Paul Zabel
Systems Engineering	Matt Bamsey
Nutrient Delivery System	Mike Stasiak
Illumination System	Anthony Gilley
Atmosphere Management System	Giuseppe Bonzano
Plant Health Monitoring and Horticulture - I	Tom Dueck
Plant Health Monitoring and Horticulture - II	Frank Kempkes
Thermal Control System - I	Erik Mazzoleni
Thermal Control System - II	Diana Magnabosco
Command and Data Handling	Conrad Zeidler
Power Subsystem	Paul Zabel
Operations & Communication - I	Antonio Ceriello
Operations & Communication - II	Raimondo Fortezza
ISPR - I	Giorgio Boscheri
ISPR - II	Christian Lacopini
Configuration & Structure	Vincent Vrakking
Service Section Design	David Gyimesi
Food Quality, Safety and Processing - I	Alberto Battistelli
Food Quality, Safety and Processing - II	Peter Downey
Bio-detection & Decontamination	Viktor Fetter
Neumayer Station III - I	Eberhard Kohlberg
Neumayer Station III - II	Dirk Mengedoht
Requirements & Interfaces	Robert Davenport
Microbial Investigations	Petra Rettberg
Outreach, Workplace Design	René Waclavicek

E. Study Products

The results of the CE study were documented in a detailed project design report. In addition, the study delivered input for the definition of external and internal interfaces, facility CFD analyses, elaboration of the operational modes and test plan documents, and for the different subsystem research and development tasks. The following chapters provide a top-level summary of the complete report and focuses on providing an overview of the complete preliminary design of the MTF.

IV. Mobile Test Facility Design

A. Design Overview

The EDEN ISS MTF is being designed to provide fresh produce for overwintering crews at the Neumayer III Antarctic station, as well as to advance the readiness of a number of plant growth technologies (including a full International Standard Payload Rack (ISPR) plant cultivation system demonstrator) and operational procedures. The MTF will be located approximately 200 m south from the Neumayer Station III, see Figure 5.

The actual MTF consists of two 20 foot high cube containers, which will be placed on top of an external platform as graphically depicted in Figure 6. The MTF is subdivided into three distinct sections, as shown in Figure 7:

- Cold porch: a small room providing storage and acting as a buffer to prevent the entry of cold air into the plant cultivation and main working areas when the main entrance door of the facility is utilized.
- Service Section: houses the primary control, air management, thermal control, and nutrient delivery systems of the MTF as well as the ISPR plant growth demonstrator.
- Future Exploration Greenhouse (FEG): the main plant growth area of the MTF, consisting of multilevel plant growth racks operating in a precisely controlled environment.

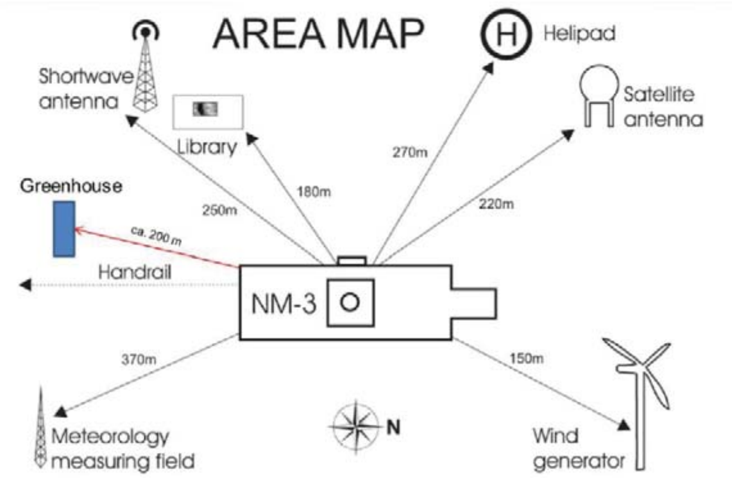

Figure 5. Area map of the Neumayer III Antarctic station, including the proposed position of the EDEN ISS Greenhouse.

Figure 6. Illustrative impression of the EDEN ISS Mobile Test Facility mounted on the elevated platform (note that the image shows the complete platform, the bottom half of the pillars will be buried in the Antarctic ice) (Credit: Liquifer Systems Group).

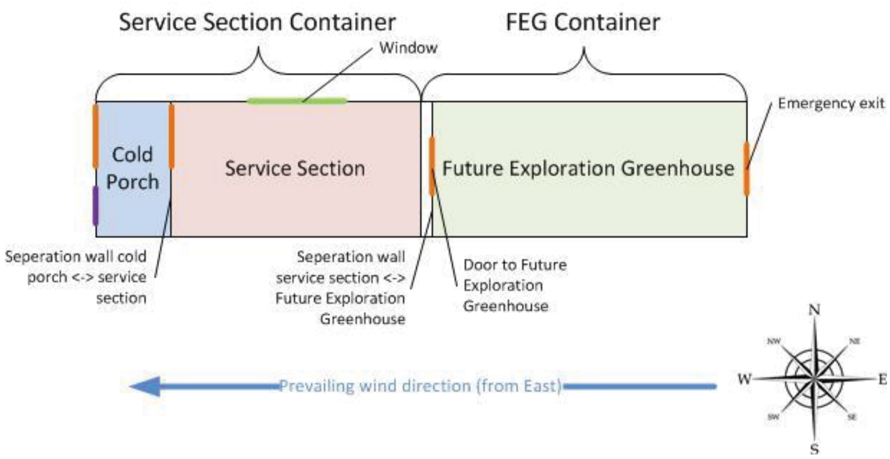

Figure 7. Overview of the EDEN ISS MTF main elements.

B. Cold Porch

The cold porch is the entrance area to the MTF and serves as a buffer zone, separating the Service Section and FEG from the external environmental conditions in Antarctica. Upon entering the MTF, crew members will store their cold weather gear in a storage cabinet and don protective gear (e.g. lab coats and shoes) prior to accessing the Service Section, in order to minimize outside material carried into the MTF and to reduce the risk of contamination.

The design developed during the CE study envisioned a sealed cabinet within the cold porch for CO_2 cylinder storage. This cabinet would have a burst pressure valve to the outside, which would prevent excessive CO_2 build-up in the facility in case of leakage. Following the CE study it was found that the CO_2 cylinders and part of the associated supply system could be mounted external to the facility, while still retaining full operational capability in the harsh Antarctic environment. As this option allows for additional storage space within the cold porch and improved safety, it was deemed preferable.

Aside from the storage cabinet and emergency heater, the cold porch houses safety equipment (e.g. flashlight, first aid kit), as well as a fresh water and a waste water tank. The two tanks, both capable of holding approximately 300 L, are located underneath a raised floor system and will be accessible to the crew by removal of one of the floor panels. For ease of operation, both tanks have a fixed access point which extends above the raised floor, which can be readily connected to mobile tanks with flexible tubing. These mobile tanks will be mounted on sleds to allow for transport of liquids to and from Neumayer station III.

The cold porch does not have an active air management system. Air exchange will take place between the cold porch and the external environment, as well as between the cold porch and the Service Section, when crew members enter and exit the facility. An emergency heater is envisioned within the cold porch to ensure the temperature does not drop below 5°C. The cold porch does, however, house a number of air management components and sections of ducting, located above the storage cabinet and along the ceiling, which provide fresh air from the external environment to the Service Section.

Design efforts for the cold porch are primarily focused on the detailed design of the raised floor structure, the fresh water and waste water tanks and component selection for the Service Section air inlet. An analysis of required storage space is being carried out to generate an optimal usage strategy for the storage cabinet.

C. Service Section

The Service Section houses the majority of the MTF subsystem components, as well as the ISPR plant cultivation system. Additionally, the Service Section provides working space for the crew and it will have the cable and pipe interfaces to the exterior of the MTF. The northern and southern walls of the Service Section are used to place subsystems and other equipment. The center of the Service Section is dominated by a roughly one meter wide corridor.

Most of the subsystems are housed in a rack system along the south side of the Service Section, see Figure 8. It was decided to place the ISPR as close to the cold porch as possible, since there are no interfaces between the ISPR and the FEG, as opposed to the other subsystems which do interface with the FEG. The atmosphere management system was placed directly next to the ISPR to maximize the available space for the air ducts, allowing for smoother curvature and thus more optimal airflow through the ducts. To optimize the volume usage efficiency, the thermal control system components were placed on either side of the AMS components. The nutrient delivery system equipment was placed as close to the FEG as possible as it has the largest number of pipes running to and from the FEG container.

The north side of the Service Section, see Figure 9, is dedicated to crew activities, with monitors, work benches, tool storage and a sink. Additionally, the computers for command and data handling activities and the power control and distribution cabinet are placed on this side. A large window, ~1600 x 600 mm, is located above the fixed workbench and provides a view of Neumayer Station III. The workbench nearest the cold porch is wall-mounted and can be folded up against the wall to increase the space available for operating and maintaining the ISPR. Underneath the work benches, the crew will be able to place waste tanks and temporarily store consumables or spare parts.

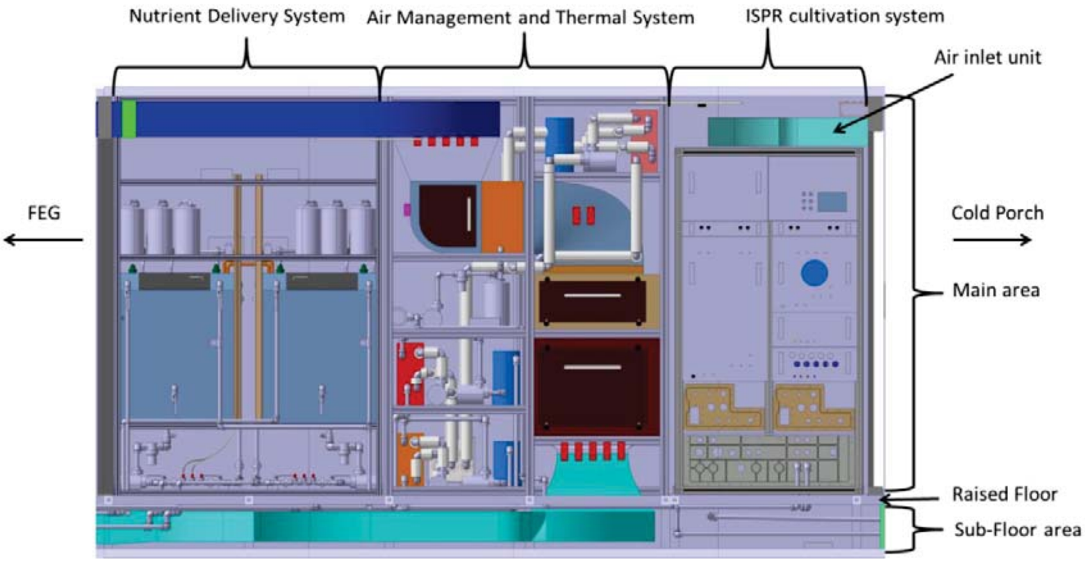

Figure 8. Service Section cut view – South side (Credit: DLR).

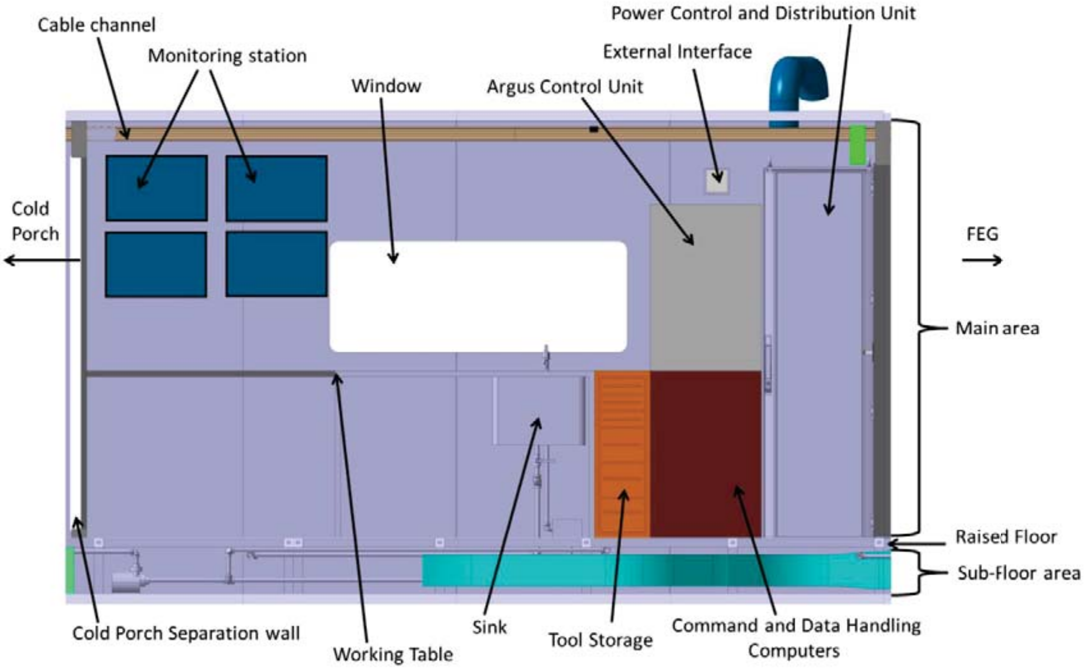

Figure 9. Service Section cut view – North side (Credit: DLR).

D. ISPR Cultivation System

The main objective of the laboratory and Antarctica ISPR plant cultivation system demonstration is to advance the technology readiness level of plant growth facility technologies, in view of a near term experiment on the ISS. This section only gives a brief overview about the design. A detailed description can be found elsewhere[5]. The facility shall represent an increment with respect to current and past flight capabilities[6], mainly in terms of:

- Higher available plant growth surface (0.5-1.0 m^2 range)
- Longer production cycle possible by complete nutrient solution mixing and circulation (and not only watering of substrate with slow release fertilizer)
- Reliable, safe and high quality food production (as the next step to current NASA’s Veggie system great achievements, increasing control capability)

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In order to target a feasible ISS exploitation scenario, the system is being designed as an European Drawer Rack (EDR) II payload. EDR II is a European rack, capable of hosting up to three experimental inserts (EIs). EDEN ISS ISPR will be modular and capable of operating either:

- as a single EI, ¼ rack, to test critical subsystems (i.e. nutrient delivery system)
- as a single EI, ½ rack, to test a complete system with one growth chamber (of incremental complexity)
- as multiple EIs, ¾ or full rack, with up to three, independently controlled, growth chambers

Figure 10 is an image of the CAD model of the EDEN ISS ISPR system preliminary concept. As can be seen, it is clearly designed as precursor of ISS EDR II plant growth payload.

The lower section of the rack is dedicated to the interfaces (power, data and cooling water) with the MTF. Above this section, interfaces are placed the interfaces between the rack and the plant growth facility, exactly as for EDR II EIs interface panels. In the central portion of the system, the following payload drawers are accommodated (see dedicated sections for more details):

- Power, Command and Data Handling Module
- Nutrient Storage and Distribution Module
- Growth Chamber Modules (1 for short plants, 1 for taller plants), including each chamber dedicated air management systems, root modules and crop shoot-zone volumes
- Illumination Modules (one for each growth chamber)

In the top portion of the rack, a panel for manual monitoring and control of some of the rack's key functional parameters will be housed, together with a storage drawer.

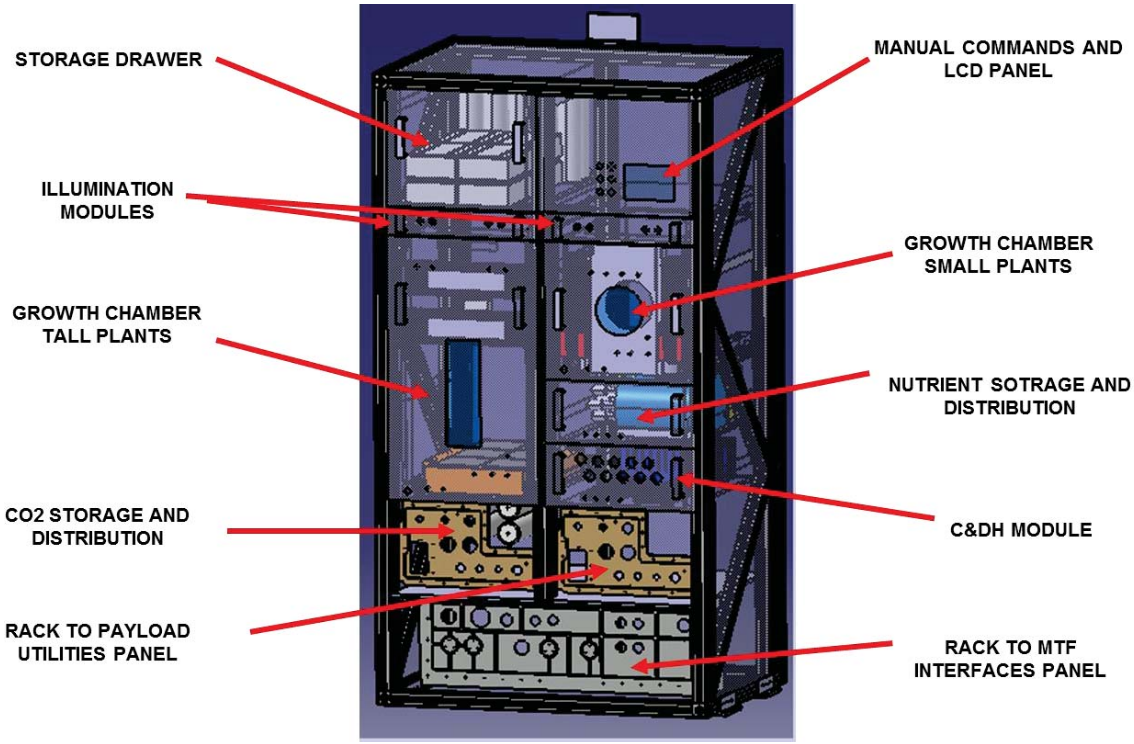

Figure 10. EDEN ISS ISPR cultivation system concept (Credit: Thales Alenia Space).

E. Future Exploration Greenhouse

The Future Exploration Greenhouse houses eight multilevel growth racks which will be used to cultivate the selected crops of the EDEN ISS project (a list of the selected crops can be found in chapter V of this paper). In Figure 11 a top view of the FEG is presented. As seen, each rack will have two growth trays per level, up to a maximum of eight growth trays per rack. A total of 40 growth trays will be placed within the FEG at a time, according to the layout shown in Figure 12. In the baseline design, a movable platform will be mounted on rails fixed to the ceiling of the corridor. A pantographic system attached to this platform will allow for vertical movement of a tray with observation cameras. This system will allow for automated plant health monitoring of each growth tray within the FEG.

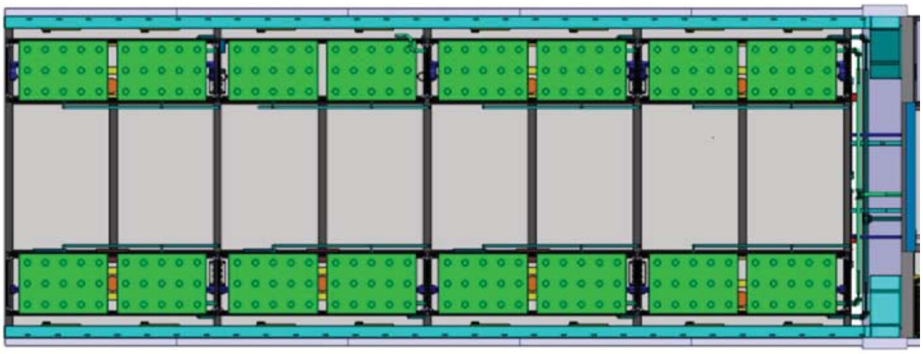

Figure 11. Future Exploration Greenhouse – Top view (Credit: DLR).

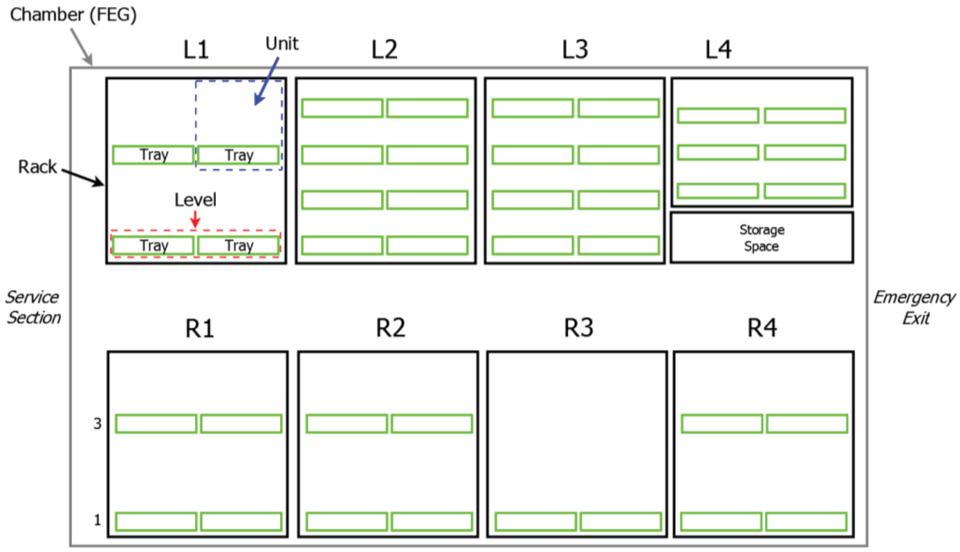

Figure 12. Future Exploration Greenhouse – Plant tray configuration including illustration of the relevant definitions of chamber, rack, unit, level and tray.

V. Logistics and Operations Concept

A. Campaign Logistics

The choice to select Antarctica as the analogue test site for the EDEN ISS project has been explained in previous publications[7, 2, 8, 9]. However, setting up a research facility in Antarctica is always a big logistical challenge. Here EDEN ISS can thankfully rely on the experience of the Alfred Wegener Institute (AWI) in operating Antarctic facilities and supply chains. AWI is not only operating the Neumayer III Antarctic research station in whose proximity the MTF will be set, but also operates a number of its own supply vehicles and is part of the Dronning Maud Land Air Network (DROMLAN), a logistics cooperation between several countries to create a reliable and cost effective supply chain for the involved Antarctic stations.

The campaign logistics for EDEN ISS are divided into the transport of the MTF itself and other campaign supplies, and the transfer of the setup crew and on-site personnel.

1. MTF and campaign supply logistics

The two MTF containers and the campaign supplies, which are stored in the shipping containers, are loaded on the German research vessel Polarstern in the port town of Bremerhaven together with other supplies for the Neumayer Station III. From there, the Polarstern will travel to Cape Town in South Africa. In Cape Town, Polarstern picks up some more supplies and continues its journey to Antarctica. When Polarstern arrives in the Atka Bay, all the supplies are offloaded onto the Antarctic ice, see Figure 13. All the containers are mounted on sledges and pulled by Pistenbullies to the Neumayer Station III. The primary unloading site at the coast is roughly 20 km away from Neumayer III.

Polarstern usually departs Bremerhaven every year in early to mid-October. The vessel arrives in Cape Town in late November to early December and in Antarctica around mid-December. The route from Cape Town to Antarctica is very weather dependent. The existence and the thickness of the sea ice around Antarctica and in the Atka Bay are also very important from this regard.

The tight schedule and especially the strict departure date are very similar to a crewed space mission to Mars.

Figure 13. Research vessel Polarstern unloading supplies for the Neumayer Station III in Atka Bay, Antarctica (Credit: AWI).

2. Setup crew and on-site personnel transfer

While the hardware is mostly transferred by ship, the bulk of crew arrives by plane, see Figure 14. First, crew members must take a regular international flight to Cape Town, South Africa. From there, a customized cargo plane of the type Ilyushin 76 takes researchers and technicians associated with DROMLAN to Novo Airbase. The roughly 800 km transfer from Novo Airbase to Neumayer III is done with smaller airplanes, typically of the type Basler BT 67.

Figure 14. Supply routes from Cape Town to the Ekström-Ice Shelf, location of the Neumayer III Antarctic station (white arrow indicates ship route, blue arrows indicate flight route) (Credit: AWI).

3. Logistical mass restrictions

A number of mass restrictions along the logistics chain are identified and illustrated in Figure 15. The most limiting factor is the Neumayer III crane.

Figure 15. Polarstern crane, Pistenbully/sledge, Neumayer III crane and platform mass restrictions (Credit for small photos: AWI).

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B. Analogue Test Site Operations

Among its general aims, EDEN ISS has the objective to develop and test the MTF greenhouse remote control technologies. The involvement of the experts in the control loop is deemed necessary since it is not possible to deploy all the expertise on-site. As a matter of fact, the EDEN ISS operations will nominally be performed by one single operator, who cannot possess all the needed skills and competencies to manage in autonomy all the EDEN ISS operations.

Space missions have similar constraints. ISS operations, even if tended by six astronauts, are clearly underlining the need to have support from ground operators, due to the fact that the crew cannot train for each and every possible procedure/activity due to crew time constraints. That will be even more critical for missions on planetary outposts. From a scientific point of view, one of the key points of the FEG performance monitoring is plant health monitoring, and most of all, the early detection of plant disease and the subsequent activation of corrective actions. For that reason, a plant monitoring system is foreseen to provide to the agronomists a tool to take pictures of the plants every day, or as required, for their analysis. Of course, images are only a (limited) part of the required scientific data. For that reason the agronomists will receive the FEG telemetry (temperatures, CO_2 level, light intensity, etc.) for data analysis and cross correlation with the images, but also with the other data coming from the harvested plants.

Another key point of MTF control is the monitoring of the health and status of all the equipment. In general, the responsibility of the on-site operator should be limited to the nominal operations of the greenhouse, anomaly resolution in case of known issues and/or malfunctions, and initial responsive actions in case of major issue. Of course, the remote engineering support can only be ensured if the housekeeping telemetry is provided to the remote experts.

For these reasons, a system shall be designed to provide all the necessary data to the remote users distributed in several countries. The top-level ground segment architecture is displayed in Figure 16.

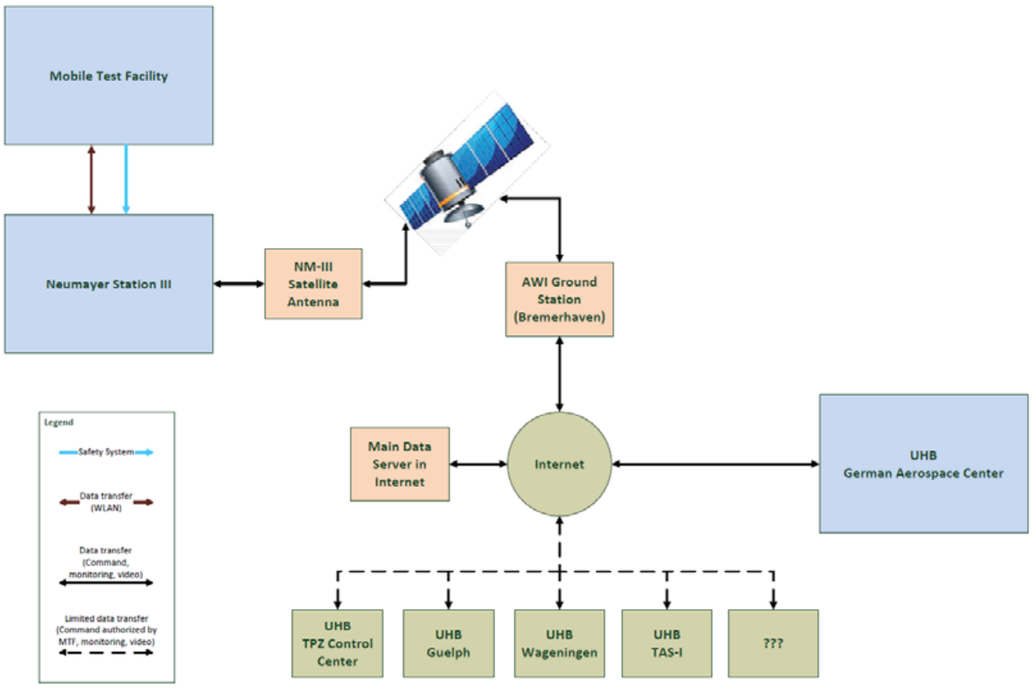

Figure 16. EDEN ISS control network (Credit: Telespazio).

Five locations will be configured as User Home Bases (UHB), i.e. will be provided with systems and tools to receive the EDEN ISS images and data for real time support.

The **on-site operator** will be mainly responsible for the nominal operations such as, for example, sowing/harvesting, plant growth monitoring, sample preparation for offline analysis, system and subsystem management, etc. In case of anomalies, it is expected that the on-site operator will manage them according to predefined procedures if any, otherwise he is only requested to take initial responsive actions and rely on the remote experts' indication on how to proceed.

It is worth noting that the Service Section and Neumayer Station III will be equipped with workstations for MTF and FEG control. In particular, the Neumayer Station III will be configured as the DLR control room to provide the

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on-site operator with the same capabilities as provided to the DLR control center, i.e. the capability to interact with the FEG, with the ISPR and with all the related subsystems.

AWI, responsible for the Neumayer Station III, will receive the EDEN ISS data as part of the data stream over satellite and will make them available to DLR over Internet. AWI is not directly involved in the EDEN ISS MTF operations, but will provide any support for all Antarctica and Neumayer III matters, as required.

DLR is the EDEN ISS Responsible Center and will accommodate the Mission Control Centre. DLR is responsible for the all the EDEN ISS operations. For that reason it will coordinate the entire EDEN ISS team operations, will be responsible for planning activities and the primary responsible for all the commanding activities. Moreover, DLR will be the prime in communication with the on-site operator. It will coordinate all the remote operations as necessary, enabling/disabling the other remote site for commanding. DLR will also coordinate all the troubleshooting activities and recovery actions. DLR is also responsible for managing the development of the thermal control system.

TAS-I is responsible for the ISPR cultivation system operations and will be configured as UHB. It will be equipped with a console for the ISPR rack monitoring and with the dedicated displays for telemetry/telecommand management. In this role, and upon coordination with DLR, it will be responsible for all the remote operations of the ISPR cultivation system, including the commanding of the facility. It is the prime in anomaly handling, troubleshooting activities and recovery actions concerning the ISPR.

Wageningen University and Research is responsible for plant health monitoring. It is configured as UHB, with a workstation for scientific data visualization, and image processing tools for plant status monitoring and early detection of plant disease. In case of anomaly detection, the researchers will coordinate with DLR all the necessary actions to solve the issue, from the change in system settings (for example light intensity) to the definition of the plants' medical treatments. If new procedures for anomaly management are required, Wageningen will provide inputs for procedure development.

University of Guelph is responsible for the EDEN ISS control system (Argus). It is configured as UHB with the workstation and displays to monitor and manage control system performance and to provide additional programming and commands if necessary.

Telespazio is responsible for user segment monitoring and control. It will be equipped with all the consoles and displays, as distributed to the other entities, to be able to solve issue and/or to update the software applications, including displays as required. Telespazio, as lead on the procedures development work package, will participate in all the anomaly resolution discussions, to collect inputs and recommendations for anomaly management procedures.

All the UHBs will be connected to DLR for data reception. Conversely, whenever required, all the commands will pass through DLR to reach EDEN ISS in Antarctica site. A graphical representation of the EDEN ISS User Segment is displayed in Figure 17.

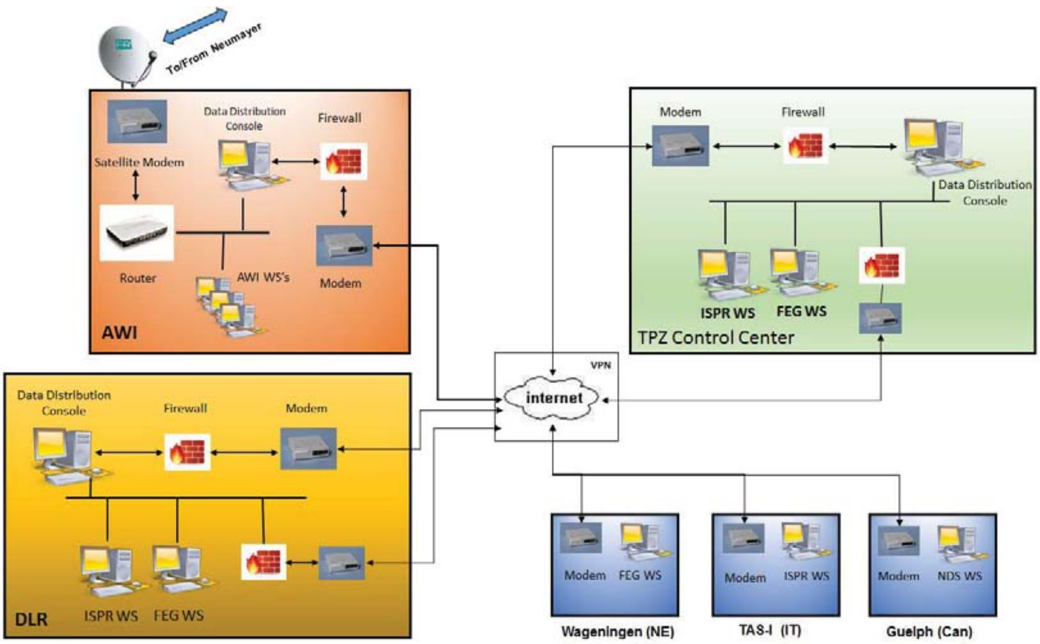

Figure 17. Layout of the EDEN ISS User Segment including the different workstations (WS) (Credit: Telespazio).

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C. Preliminary Crop Selection

The limitations on crop cultivation, in terms of available cultivation area within the MTF and the limited Antarctic campaign duration, require selecting only a number of crops suggested for space life support systems[10]. Researchers from Wageningen University and Research, experts in terrestrial greenhouse cultivation, developed a crop selection methodology[11]. A top-level summary of the results of the methodology are shown in Table 2.

The selected crops will be grown in climate rooms at Wageningen University starting in early 2016. Initially, growth experiments will be conducted in order to define the optimal light recipes (spectral quality, light intensity and photoperiod), as well as to optimize water and nutrient use. Afterwards specific experiments will be performed under similar conditions (size and constraints) as in the ISPR and FEG in order to test the cultivation and management of (combinations of) crops. The main features of the experiments will entail the determination of light recipes, optimizing CO_2 dosage in accordance to plant growth rates, and relative humidity and temperature in relation to the light system being used. Input and output flows (energy and mass) will be monitored throughout the experiments. A monitoring protocol will be defined to determine whether the crops grow as desired.

Table 2. Crop and cultivar selection.

Crop	Cultivar	Crop	Cultivar
Lettuce	Crispy green ‘Expertise’	Strawberry	Delizz
	Batavia ‘Othilie’	Spinach	Gazelle
	Field lettuce ‘Pulsar’		Mandril
	Iceberg ‘Morinas’		Red Kitten
	Lettuce ‘Outredgeous’	Swiss chard	Ruby red
Dwarf tomato	2011-281M	Red mustard	Frizzy Lizzy
	F1 1202		Mizuna
	F12414	Chives	Staro
Cucumber	Quatro		Purly
	Picowell	Coriander	HI 13475 HEC
	Northern Pickling	Mint	to be defined
Bell pepper	Cupid	Parsley	Moskrul
	1601-M		Frise Vert Fonce-rina
Radish	Raxe	Basil	Dolly
	Lennox		Genovese

D. Overall System Budgets

During the CE study the overall system budgets (mass, electrical energy and power, data generation, water usage, nutrient usage and biomass production) were tracked for all domains. The following sections show the estimates of the different budgets as of the end of the study. All the values shown hereafter are preliminary and will likely change over the course of the project. Final system budgets will be published later in the project.

1. Mass

Although the mass budget of the MTF is not as important as in typical space missions, a number of restrictions are identified and shown in a previous section of this paper. The limit, dictated by constraints in the logistics chain, is 10000 kg per MTF container. Table 3 shows estimated values for the equipment dry mass (without fluids, humans, plants, etc.) and for the spare parts and consumables. The mass values are afflicted by high uncertainties at the current state of the design. Therefore a margin of 25% and 100% respectively, are included in the current calculations for the system mass. Table 3 indicates that one or both containers might be heavier than 10000 kg and consequently exceed the lifting capabilities of the Neumayer station III crane.

A thorough calculation of the mass of each container is part of the next stage of the project. In case the equipment dry mass of one container exceeds the 10000 kg limit, there is still the possibility to remove some of the equipment before lifting the container onto the platform.

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Table 3. Estimated mass values for EDEN ISS equipment, spare parts and consumables.

Subsystem	Estimated equipment dry mass (kg)	Estimated equipment dry mass including 25 % margin (kg)	Estimated spares and consumables mass (kg)	Estimated spares and consumables mass including 100 % margin (kg)
Service Section container and structure	6747	8434	143	286
FEG container and structure	6552	8190	50	100
ISPR cultivation system	335	419	146	292
Power control and distribution	523	654	20	40
Thermal control system	308	385	61	122
atmosphere management system	629	787	210	420
Nutrient delivery system	471	589	50	100
Command and data Handling	333	416	69	138
Ops. And Com.	200	250	20	40
Bio detection	10	13	35	70
Food safety and quality	0	0	31	62
TOTAL	**16108**	**20137**	**835**	**1670**

2. *Electrical energy and power*

The average power demand of the MTF calculated over one year is around 11.5 kW. However, the plants require a certain day-night cycle. Where day means the plants are illuminated and night means, that the plants are not illuminated. The cycle results in a different power demand during day and night, because some subsystems are not or only running at a low level at night. During day the average power demand is around 14 kW and during night around 6.7 kW, as seen in Figure 18.

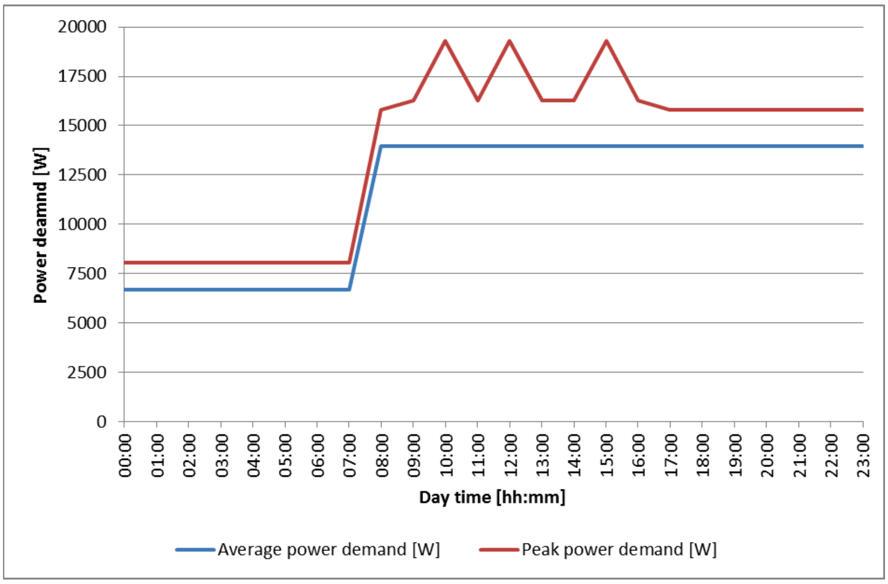

Figure 18. Power demand during nominal operations for a single day-night cycle.

The day-night cycle is currently set at 16 hours day followed by 8 hours night. In Figure 18 the x-axis shows the normal time and the y-axis shows the power demand. There is one data point per hour and the value of the data point is the average power demand during that hour. The period from 00:00 to 08:00 corresponds to night and the period from 08:00 to 24:00 is day. Furthermore, it is assumed that from 09:00 to 17:00 crew is working in the MTF, which results in an additional increase of the power demand during that period. It should be noted that these power estimates include reasonable margin and that it is highly likely that the final power values of the MTF will be considerably less.

3. Data

The MTF has to cope with a Neumayer III satellite link bandwidth of 100 kbps, which is a share of the available bandwidth (more bandwidth is available on request for e.g. videoconferencing). The following analysis will show that, considering all the sensors and the cameras used in the MTF, remote control is possible provided that some limitations in image transmission are adopted. In particular, it is assumed that whatever the image generation rate will be, only one image per day and per tray will be transferred to Europe. Moreover, the transmission will occur overnight. In this way the remote experts (in principle the horticulture experts) can process the images and provide feedback during office hours while at the same time allowing the NM-III crew to utilize higher bandwidths during periods of activity.

The following items will produce data which has to be transferred to the UHB:

- In total 274 sensors will be installed in the MTF (including the external monitoring) as per last findings of the CE-study. These include (approximate numbers provided):
    - Argus system (119),
    - ISPR (52),
    - Safety system (9) and
    - Cameras (94).
- In total 96 actuators will be installed in the MTF. These include (approximate numbers provided):
    - Argus system (77) and
    - ISPR (19).
- Fixed cameras for plant health monitoring (note: although the final conclusion of the CE study was actually a total of 40 fixed cameras within the Plant Monitoring System (PMS) of the FEG this is presently being reassessed and the pros and cons of 40 or 31 cameras are being considered) for top view and 3 cameras for side view installed on the mobile platform, 4 general interior MTF observation cameras and 2 observation cameras installed outside the MTF.
- An E-Nose, for detection of microbial growth cameras in the ISPR rack for plant health monitoring.
- 1 audioconferencing system.
- 1 videoconferencing system.

Figure 19 illustrates the estimated data transmission volume over the course of one day. The figure illustrates a worst case scenario, meaning that the data volume for that day is the maximum foreseen for the analogue test campaign. The three peaks seen in the diagram are caused by the live streams for videoconferencing. During those periods, only absolutely necessary data will be transmitted to reduce the burden on the satellite link.

4. Water

The EDEN ISS MTF has one fresh water tank and one wastewater tank, both with a capacity of roughly 300 liters. The NDS consists of two separate nutrient solution loops. Each loop has a bulk solution tank of 250 liters. The crops inside the FEG will be fed with a half strength Hoagland solution. The current design foresees to continually recirculate the solutions for a minimum of six weeks. Consequently, those assumptions lead to the average water use rates shown in Table 4. Note that the values are worst case estimates and that the values do not account for the water bound in the produced biomass. A thorough investigation of the water use rates still needs to be done.

Table 4. Average water use rates.

Name	Amount (L/week)
Cleaning fresh water	250.0
Germination fresh water	5.0
Nutrient solution fresh water	83.3
Total	**338.3**

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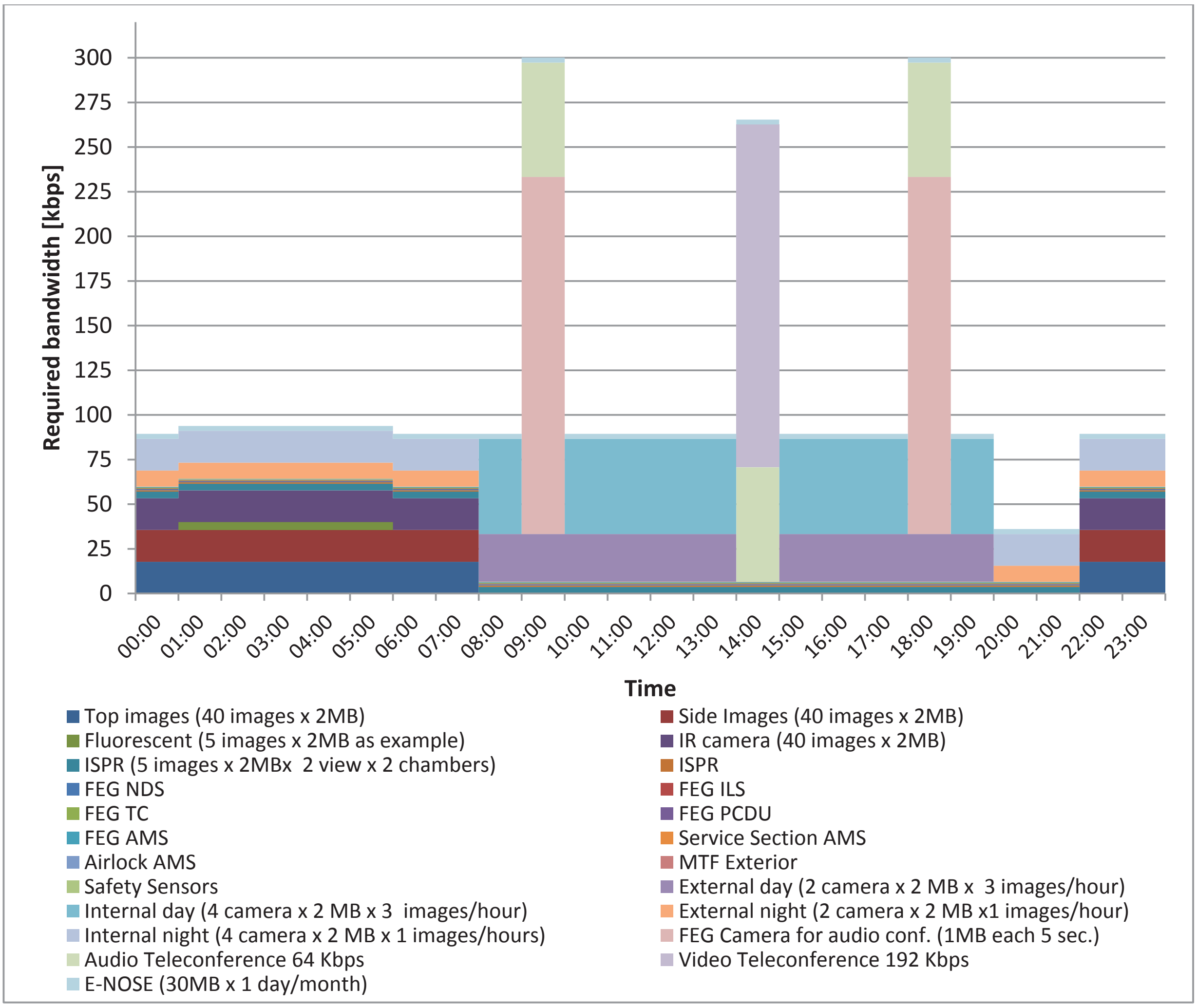

Figure 19. Worst case telemetric data volume during MTF operations.

5. Biomass

Crop productivity is greatly affected by the efficiency with which the absorbed radiation can be used for photosynthesis, also known as the light use efficiency (LUE). In general, the light intercepted is not used with the same efficiency by different crops, thus crops have different LUE's. The crops grown in the FEG (all C3 crops) however, will have a similar LUE. For a full grown, nominally functioning, crop, the LUE will be around 1 to 1.25 gram dry weight (DW) per mol of intercepted PAR light[1].

Canopy structure, and particularly the spatial distribution of (angles of) leaves, has an important bearing on canopy light climate and energy conversion. An even distribution of PAR at leaf surfaces is advantageous for canopy photosynthesis and improves the LUE over canopies where upper (horizontal) leaves intercept most radiation and lower leaves experience greatly attenuated levels. Light absorption at crop level, the percentage of the offered light that is ultimately absorbed by the crop, will never be 100%. Leaves reflect ca. 5% of the PAR light and due to leaf structure[12, 13], distribution and density in the canopy crops are not able to intercept all light.

Spacing of the plants is also an important factor for light interception. The light absorption will vary during the different stages of crop growth and is estimated to be on average around 60% throughout a crop cycle. Not all dry matter will be edible. The edible fraction is called the Harvest Index (HI), and varies between the species from 0.95 (lettuce)[14, 15] to 0.45 (strawberry)[16]. In Table 5 the crop production for the different species has been estimated. The estimated Fresh Weight (FW) production per tray per day varies between 8 g (strawberry) and 76 g (cucumber) per tray per day, meaning the choice of different species has an enormous effect on the edible crop production of the FEG.

[1] Estimation based on experimental experience of greenhouse growers.

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Combining the results of Table 5 with a preliminary tray use schedule, results in an estimation of the overall edible fresh weight production of the FEG. An initial calculation suggests that the potential crop production of the FEG varies between 0 g (first three weeks after start up) and 750 g of fresh weight per day, with a total of ca. 176 kg fresh food per year.

Table 5. Estimated fresh weight production of EDEN ISS crops (values for all crops: LUE=1 gDW/mol; day length = 16 hours; tray area = 0.24 m²).

Crop	Light intensity	Light absorption	Light absorbed	HI	Production edible	DM edible tissue	Product-ion	Product-ion	Product-ion
	µmol/m²/s	(20-60%)	mol/m²/d	%	gDW/ m²/d	%	gFW/ m²/d	gFW/ mol	gFW/ tray/d
Lettuce	300	0.6	10.37	0.95	9.85	0.05	197	19	47.3
Dwarf tomato	500	0.6	17.28	0.55	9.50	0.05	190	11	45.6
Cucumber	500	0.6	17.28	0.55	9.50	0.03	317	18	76.0
Bell pepper	300	0.6	10.37	0.5	5.18	0.08	65	6	15.6
Radish	400	0.6	13.82	0.6	8.29	0.06	138	10	33.2
Strawberry	400	0.6	13.82	0.4	5.53	0.17	33	2	7.8
Spinach	400	0.6	13.82	0.8	11.06	0.08	138	10	33.2
Swiss chard	400	0.6	13.82	0.8	11.06	0.08	138	10	33.2
Red mustard	400	0.6	13.82	0.9	12.44	0.05	249	18	59.7
Chives	400	0.6	13.82	0.9	12.44	0.08	156	11	37.3
Coriander	400	0.6	13.82	0.4	5.53	0.15	37	3	8.8
Mint	400	0.6	13.82	0.7	9.68	0.12	81	6	19.4
Parsley	400	0.6	13.82	0.7	9.68	0.16	60	4	14.5
Basil	400	0.6	13.82	0.9	12.44	0.2	62	5	14.9

VI. Summary and Next Steps

This paper summarizes the results of the CE design workshop conducted to generate the preliminary design of the EDEN ISS mobile test facility. The design is already advanced to a state where subsystem developers can start with their detailed designs. There are still some open issues remaining, especially regarding the hardware and software interfaces. Only a few subsystems, mainly the thermal system, are still in a very early design stage. The overall system architecture and subsystem allocation within the facility are fixed. The described key values (e.g. mass, biomass output) however, are still preliminary. Concrete values for those parameters will be available once the hardware development phase is over or only when the first overall system test are performed.

EDEN ISS is well under way and within the scheduled timeframe. The first phase of the project, the design phase, was concluded with the Critical Design Review in March 2016. The following 18 months until September 2017 are devoted to the hardware development, integration and testing. Some working groups are already building prototypes (e.g. illumination system, nutrient delivery system), performing experiments (e.g. plant cultivation under similar conditions) or are even in the process of ordering final system hardware (e.g. container structure). For the latter, DLR started a procurement process in February 2016 with the goal to select and contract a manufacturer by April 2016. The container structure including insulation, outer surface finish, separation walls and internal surface finish are expected to be delivered to DLR's site in Bremen in autumn 2016. Once the containers arrive, the subsequent integration of subsystems starts with the implementation of the secondary structure and the power distribution, followed by the different plant cultivation subsystems.

The assembly, integration and testing of the subsystems is supposed to be finished in spring 2017. From there on the EDEN ISS team has a couple of months for subsystems and overall system tests. The Mobile Test Facility is scheduled for shipment to Antarctica in October 2017.

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