Introducing EDEN ISS - A European project on advancing plant cultivation technologies and operations

Paul Zabel[1], Matthew Bamsey[2], Conrad Zeidler[1], Vincent Vrakking[1], Bernd-Wolfgang Johannes[3], Petra Rettberg[3], Daniel Schubert[4] and Oliver Romberg[5]
German Aerospace Center (DLR), 28359 Bremen, Germany

Barbara Imhof[6], Robert Davenport[7], Waltraut Hoheneder[8], René Waclavicek[9], Chris Gilbert[10], Molly Hogle[11]
LIQUIFER Systems Group GmbH, 1020 Vienna, Austria

Alberto Battistelli[12], Walter Stefanoni[13], Stefano Moscatello[14], Simona Proietti[15], Guglielmo Santi[16], Filomena Nazzaro[17], Florinda Fratianni[18], Raffaele Coppola[19]
Consiglio Nazionale delle Ricerche, Piazzale A. Moro 7, 00185 Roma Italy

Mike Dixon[20], Mike Stasiak[21]
University of Guelph, N1G 2W1, Guelph, Ontario

Eberhard Kohlberg[22], Dirk Mengedoht[23]
Alfred-Wegener-Institute Helmholtz-Center for Polar and Marine Research, 27568 Bremerhaven, Germany

Lorenzo Bucchieri[24], Erik Mazzoleni[25]
EnginSoft S.p.A., 24126 Bergamo, Italy

[1] Doctoral Candidate, Institute of Space Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany.
[2] Marie Curie Postdoctoral Fellow, Institute of Space Systems, Robert-Hooke-Str. 7, 28359, Bremen, Germany.
[3] Research Associate, Institute of Aerospace Medicine, Linder Hoehe 51147 Cologne, Germany.
[4] Research Associate, Institute of Space Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany.
[5] Department Head, Institute of Space Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany.
[6] Project management, LIQUIFER Systems Group GmbH, Obere Donaustrasse 97-99/1/62, 1020 Vienna, Austria
[7] Senior project engineer, LIQUIFER Systems Group GmbH, Obere Donaustrasse 97-99/1/62, 1020 Vienna, Austria
[8] Managing director, LIQUIFER Systems Group GmbH, Obere Donaustrasse 97-99/1/62, 1020 Vienna, Austria
[9] Project architect, LIQUIFER Systems Group GmbH, Obere Donaustrasse 97-99/1/62, 1020 Vienna, Austria
[10] Senior project engineer, LIQUIFER Systems Group GmbH, Obere Donaustrasse 97-99/1/62, 1020 Vienna, Austria
[11] Research Associate, LIQUIFER Systems Group GmbH, Obere Donaustrasse 97-99/1/62, 1020 Vienna, Austria
[12] Senior Researcher, Institute of Agro-environmental and Forest Biology CNR, Viale Marconi 2, 05010, Porano (TR) Italy
[13] Doctoral Candidate, Institute of Agro-environmental and Forest Biology CNR, Viale Marconi 2, 05010, Porano (TR), Italy
[14] Researcher, Institute of Agro-environmental and Forest Biology CNR, Viale Marconi 2, 05010, Porano (TR), Italy.
[15] Researcher, Institute of Agro-environmental and Forest Biology CNR, Viale Marconi 2, 05010, Porano (TR), Italy
[16] Postdoctoral Fellow, Institute of Agro-environmental and Forest Biology CNR, Viale Marconi 2, 05010, Porano (TR) Italy
[17] Researcher, Institute of Food Science, CNR,Via Roma 64,83100 Avellino, Italy
[18] Researcher, Institute of Food Science, CNR,Via Roma 64,83100 Avellino, Italy
[19] Full Professor, Institute of Food Science, CNR,Via Roma 64,83100 Avellino, Italy
[20]Professor and Director, CESRF, School of Env. Sciences, University of Guelph, 50 Stone Rd. E., Guelph, ON, Canada
[21] Senior Research Associate, CESRF, School of Env. Sciences, University of Guelph, 50 Stone Rd. E., Guelph, ON, Canada
[22] Coordinator Wintering Teams, Department of Logistics, Am Alten Hafen 26, 27568 Bremerhaven.
[23] Coordinator Arctic and Antarctic Peninsula, Department of Logistics, Am Alten Hafen 26, 27568 Bremerhaven.
[24] CFD Manager, Parco Scientifico Tecnologico Kilometro Rosso, Via Stezzano 87, 24126 Bergamo, Italy.
[25] CFD Analyst, Parco Scientifico Tecnologico Kilometro Rosso, Via Stezzano 87, 24126 Bergamo, Italy.

Viktor Fetter[26], Thomas Hummel[27]
Airbus Defence and Space GmbH, 88039 Friedrichshafen, Germany

Giorgio Boscheri[28], Federico Massobrio[29], Matteo Lamantea[30], Cesare Lobascio[31]
Thales Alenia Space Italia, 10146 Torino, Italy

Alessandro Petrini[32], Marco Adami[33], Giuseppe Bonzano[34], Lorenzo Fiore[35]
Aero Sekur S.p.A., 04011 Aprilia, Italy

Tom Dueck[36], Cecilia Stanghellini[36]
Wageningen University and Research, 6700 AP Wageningen, The Netherlands

Grazyna Bochenek[37], Anthony Gilley[38]
Heliospectra AB, SE-402 29, Göteborg, Sweden

Michelle McKeon-Bennett[39], Gary Stutte[40], Tracey Larkin[41], Siobhan Moane[42], Patrick Murray[38], Peter Downey[39]
Limerick Institute of Technology, Limerick, Ireland

and

Raimondo Fortezza[43], Antonio Ceriello[44]
Telespazio S.p.A., 00156 Roma, Italy

[26] System Engineer, Life Science Department, Claude-Dornier-Straße, 88090 Immenstaad, Germany.
[27] System Engineer, Life Science Department, Claude-Dornier-Straße, 88090 Immenstaad, Germany.
[28] Engineer, Department Life Support and Habitat, Strada Antica di Collegno 253, 10146 Torino, Italy.
[29] Advanced Exploration/EC Programs Manager, Strada Antica di Collegno 253, 10146 Torino, Italy.
[30] Head of Department Life Support and Habitat, Strada Antica di Collegno 253, 10146 Torino, Italy.
[31] Head of Space Flight Environment and Habitat, Strada Antica di Collegno 253, 10146 Torino, Italy.
[32] Strategic Marketing, Aero Sekur S.p.A., via delle Valli 46, 04011 Aprilia, Italy.
[33] Division Manager, Space & Innovation, Aero Sekur S.p.A., via delle Valli 46, 04011 Aprilia, Italy.
[34] Senior Advisor, Space & Innovation R&D, Aero Sekur S.p.A., via Bianco di Barbania 16, 10020 Caselle Torinese, Italy.
[35] Business Development, Space & Innovation, Aero Sekur S.p.A., via delle Valli 46, 04011 Aprilia, Italy.
[36] Senior Scientist, Wageningen UR Greenhouse Horticulture, Droevendaalsesteeg 1, 6708 PB Wageningen, The Netherlands
[37] Plant and Light Research, Heliospectra AB, Frans Perssons väg 6, 412 76 Göteborg, Sweden.
[38] CTO, Product Development, Heliospectra AB, Frans Perssons väg 6, 412 76 Göteborg, Sweden.
[39] Head of Department of Applied Science & PI of CELLS Research Group, Limerick Institute of Technology, Moylish Park, Limerick, Ireland.
[40] Plant Scientist of CELLS Research Group (& Senior Plant Scientist, Vencore Inc., Virginia 20151), Limerick Institute of Technology, Moylish Park, Limerick, Ireland.
[41] Science Lecturer & PI of FOODs, Limerick Institute of Technology, Moylish Park, Limerick, Ireland.
[42] Principal Investigator of Shannon Applied Biotechnology Centre, Limerick Institute of Technology, Moylish Park, Limerick, Ireland.
[43] Technical Manager, Head of Science System & Services, Telespazio Napoli, Via Gianturco 31, 80146 Napoli, Italia
[44] Technical Manager, Science System & Services, Telespazio Napoli, Via Gianturco 31, 80146 Napoli, Italia

Plant cultivation in large-scale closed environments is challenging and several key technologies necessary for space-based plant production are not yet space-qualified or remain in early stages of development. The EDEN ISS project foresees development and demonstration of higher plant cultivation technologies, suitable for future deployment on the International Space Station and from a long-term perspective, within Moon and Mars habitats. The EDEN ISS consortium will design and test essential plant cultivation technologies using an International Standard Payload Rack form factor cultivation system for potential testing on-board the International Space Station. Furthermore, a Future Exploration Greenhouse will be designed with respect to future planetary bio-regenerative life support system deployments. 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. In addition to technology development and validation, food safety and plant handling procedures will be developed. This paper describes the goals and objectives of EDEN ISS and the different project phases and milestones. Furthermore, the project consortium will be introduced and the role of each partner within the project is explained.

I. Introduction

HUMANITY'S plans to further explore space strongly suggest the development of bio-regenerative life support systems (BLSS) fully incorporated into space stations, transit vehicles and eventually in habitats on the Moon and Mars. These concepts aim to decrease the (re-)supply mass by (re-)generating essential resources for humans through biological processes. Within a BLSS, the cultivation of higher plants takes a crucial role as they can contribute to all major functional aspects (e.g. food production, carbon dioxide reduction, oxygen production, water recycling and waste management). Furthermore, fresh crops are not only beneficial for human physiological health, but also have a positive impact on crew psychological well-being. Adding up these features, higher plants represent a unique asset that makes the investigation of their cultivation in closed systems an essential endeavor. However, cultivation in closed environments is challenging and several key technologies necessary for space-based plant production are not space-qualified or remain in early stages of development. The EDEN ISS project, project logo in Figure 1, develops and demonstrates higher plant cultivation technologies, suitable for future deployment on the International Space Station (ISS) and from a long-term perspective, within Moon and Mars habitats.

Figure 1. EDEN ISS project logo

The EDEN ISS consortium will design and test essential CEA technologies using an International Standard Payload Rack (ISPR) sized cultivation system for potential testing on-board the ISS. Furthermore, a Future Exploration Greenhouse (FEG) will be designed with respect to future planetary BLSS deployments. The technologies will be tested in a laboratory environment as well as at the highly-isolated Antarctic Neumayer Station III, operated by the Alfred Wegener Institute. A small and mobile container-sized test facility will be built in order to provide realistic mass flow relationships for the ISPR section and FEG. In addition to technology development and validation, food quality tests and safety and plant handling procedures will be developed. These are integral aspects of the interaction between the crew and plants within closed environments.

II. Objectives

The EDEN ISS project aims to validate selected subsystems and key technologies up to a TRL of 6. Therefore, the project will demonstrate operational capability of key technologies in an environment, similar in certain relevant characteristics to space. A dedicated test campaign at the Neumayer Station III in Antarctica is planned, where a deployed mobile test facility will be operated by an isolated overwintering crew of nine members. This deployment will also be a preparatory research activity for a future plant production system for the ISS.

The defined objectives go hand in hand with a number of international advisory groups and their respective roadmaps. As an example, the project will address several key issues of the THESEUS (Towards Human Exploration of Space: a European Strategy) roadmap, which was developed under the lead of the European Science Foundation. Especially, the issues mentioned in the theme "*Life support: management and regeneration of air, water and food* of *Cluster 4: Habitat Management*" highlighted the necessity to further develop BLSS [1].

The EDEN ISS project also addresses several common goals of the Global Exploration Roadmap listed in *Chapter 2: Common Goals and Objectives of Space Exploration*. This roadmap was defined by ISECG in cooperation with several international space agencies (e.g. ESA, NASA, CSA and JAXA) [2].

The main goal of EDEN ISS is:

The adaptation, integration, fine-tuning and demonstration of higher plant cultivation technologies and operation procedures for safe food production on-board ISS and for future human space exploration missions.

Six objectives are identified to achieve this goal:

Objective 1:	**Manufacturing a space analogue mobile test facility** to provide representative mass flows and proper test environments for plant cultivation technologies as an essential on-ground preparatory activity for future space exploration.
Objective 2:	Integration and test of key elements for plant cultivation in 1) an **ISPR-like system** (International Standard Payload Rack) for future tests on-board ISS and 2) a **Future Exploration Greenhouse (FEG)** to prepare for closed-loop bio-regenerative life support systems.
Objective 3:	**Adaptation, integration, fine-tuning and demonstration of key technologies** and their functionality in respective laboratory environments and (under highly isolated conditions) in an Antarctic environment.
Objective 4:	Development and demonstration of **operation techniques and processes for higher plant cultivation** to achieve reliable and safe production of high-quality food.
Objective 5:	Study of **microbial behaviour and countermeasures** in plant-based closed ecosystems and their impacts on isolated crews.
Objective 6:	Actively **advancing knowledge related to human spaceflight and transformation of research results into terrestrial applications**, by actively leveraging synergies between space and non-space consortium partners.

III. Concept and Approach

A. Main leading ideas

Despite the fact that high-closure BLSS are not required for short-duration missions, it is well accepted that they are a required element for sustained human presence in space[1–4]. Plants flown on various space-based platforms from Salyut to ISS have until now been used to further our understanding of the effects of the spaceflight environment on plant growth and to enhance the technology required for the maintenance of a sufficiently controlled on-orbit growth environment[5]. While small-scale payloads have been sufficient to address these two aims, it is now becoming technically feasible to incorporate larger-scale on-orbit facilities that can provide fresh food on-board. The all-in-one approach of implementing higher plants in BLSS (i.e. air, water, waste recycling, as well as food production and improved crewmember well-being) has a huge advantage for future human space exploration missions. But this approach first needs to be tested on Earth and ISS in order to prove its reliability and applicability. Therefore, the main leading ideas can be summarized as following:

We will assemble existing **CEA knowledge and technologies** into a system suitable for **safe food production** under the constraints posed by the **ISS and future human space exploration missions.**
We will **test a greenhouse** and its interaction **with an isolated crew** in one of the most relevant space analogues on Earth.
We will develop **and exploit the terrestrial potential** of the foreground knowledge and technologies.

EDEN ISS considers the near- to mid-term development pathway of BLSS technologies and operational protocols from terrestrial laboratory to utilization on-board ISS. In particular, the EDEN ISS project focuses explicitly on transferring already tested laboratory technologies into relevant operational use at a crewed space analogue site.

Embedded in these near-term objectives is the long-term objective of large-scale plant production facilities. The commonalities between planetary surface and microgravity-based systems will be emphasised in the project so as to maximize the concurrent advancement of BLSS technologies and operational protocols for both applications.

The pull of space technology for low mass, low volume, low power and minimal waste systems is more and more relevant to terrestrial systems where plants are themselves a required element for our survival. The similarities in technical challenges of space-based and those of remote and harsh environments such as Antarctica will yield opportunities for the European agricultural industry.

B. Approach

The project approach foresees the test of a food production system, suitable for ISS and beyond in a mobile test facility under mission relevant conditions. Here, the focal point of the mobile test facility is the demonstration and validation of the different key technologies and the necessary procedures for safe food production within a (semi-) closed system. The mobile test facility provides the necessary resources for simulating relevant ISS environmental parameters and interfaces, but also a future human outpost environment and the transit mission elements. The test facility is built-up in a multi-section shipping container consisting of a:

- Service section,
- ISPR section,
- FEG.

Figure 2 illustrates a possible internal configuration of the mobile test facility. The actual detailed design will be elaborated during the planned concurrent engineering study in autumn 2015.

The main purpose of the service section is the provision of all necessary resources to the greenhouse sections (ISPR, FEG). The service section houses the support subsystems for the facility and is connected via feed lines with the two other sections (e.g. thermal, power, air ventilation subsystems). Furthermore, the service section offers working space for pre- and post-harvest procedures, a seedling station and other support systems (e.g. monitoring, and sterilization equipment). An airlock segment will be implemented in order to prevent microbial cross-spreading (e.g. bacteria, fungus) between the greenhouse sections as well as the outside.

The ISPR section comprises two full ISPR cultivation systems so that different hardware tests can be accomplished in parallel, as well as to offer the possibility to cultivate different crops at the same time. It will be possible to test different closure scenarios with respect to surrounding environment, both for the air and water loop. As an example, exchanging air with the surrounding environment will increase the possibility of spreading contaminants to other parts of the mobile test facility, while reducing the need for a dedicated air management system within the ISPR cultivation system, thus increasing available growth area.

The FEG consists of a highly adaptable multi shelf growth system and is focused primarily on the large-scale facilities envisioned for planetary surface outputs while also ensuring that the overall mobile test facility provides sufficient food output to further enhance its benefit to Neumayer III crewmembers. Different variable compartments can be built within the FEG in order to establish different environmental settings. Important to note, is the fact that, when possible, the FEG uses the same or similar technologies as used within the ISPR cultivation system, but in a scaled-up configuration. This is particularly relevant with respect to the lighting system, nutrient delivery system, and plant health monitoring and air management.

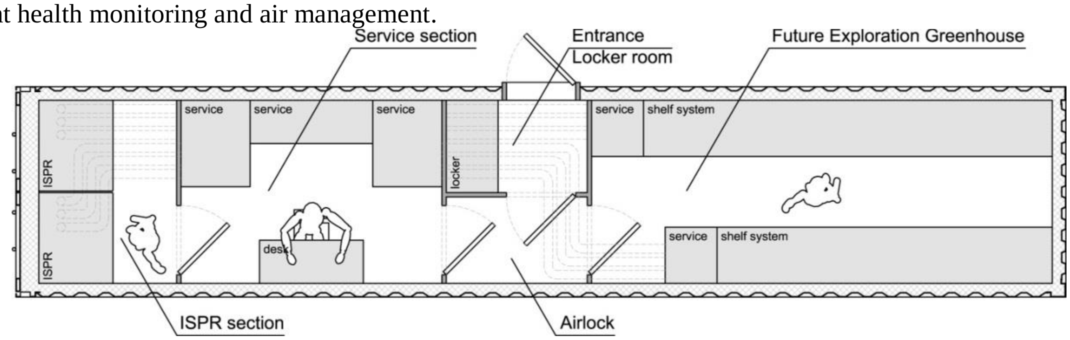

Figure 2. Draft internal configuration of the mobile test facility

In addition to testing CEA technologies, the mobile test facility offers the unique possibility to demonstrate and validate different food quality and safety procedures. Various plant operation procedures will be tested under the same regulations and restrictions already in place for the ISS. Furthermore, post-harvest procedures can be tested with high accuracy. Here, the focus is set on the right definition of working steps (e.g. correct seeding, transplantation into the plant trays, maintenance work algorithms preventing contamination, harvest procedures) but also on the selection and demonstration of promising sanitation technologies in order to increase food shelf life.

Concentrating on the key issue of cultivating healthy plants from germination to harvest, dedicated plant health monitoring infrastructure will be implemented in the mobile test facility. Therefore, sensors and monitoring devices (digital, analogue, visual) will be utilized to monitor and control plant growth, and to detect pathogens during all growth phases. Collected system health data, environment data and images will be saved and sent via a satellite link from the facility. To enhance production reliability further, a backroom operations team composed of experts from domains such as horticulture, plant physiology, microbiology, engineering and others will have semi-real-time access to this data (telepresence). This team will utilize developed control interfaces to collaboratively interact and subsequently remotely command or interface with the analogue test site operations team, see Figure 3. Customized Science Monitoring Control and Distribution (SMCD) software will be deployed, which is an application specifically conceived for ISS payload monitoring and commanding. The greenhouse systems will be linked via satellite to the European control centre and from there via internet, to the expert communities located at their own user home bases (UHB). This way, consortium partners and European scientists have real-time access to the mobile test facility and provide feedback and advice to the expedition personnel on-site.

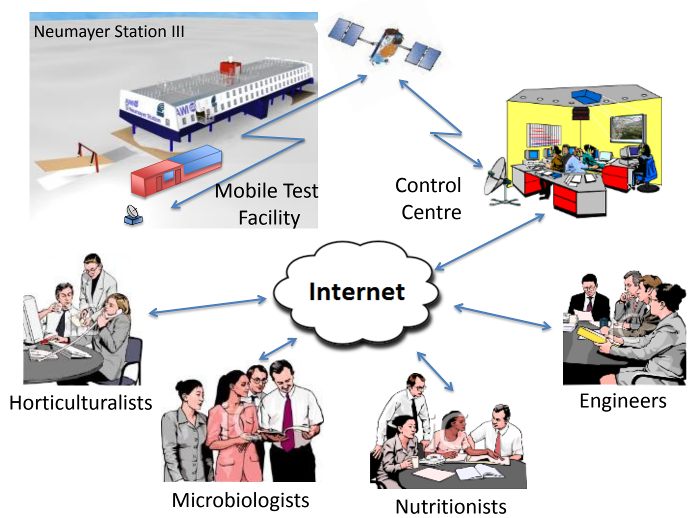

Figure 3. Communication links to be established to permit the quasi-real-time greenhouse operational support from the distributed backroom of experts

C. Analogue test site

The list of potential space analogue sites is long and includes the oceans, polar regions, deserts, mountains, caves, and unique facilities that currently exist or could be constructed. Each site has its own distinct features that make it more relevant to a particular space analogue study[6]. The Neumayer III station has several characteristics that uniquely position it as a valuable analogue for ISS and planetary surface operations[7]. The following features highlight these advantages:

- **Crew size and isolation**

Neumayer Station III crew sizes change depending on the season. Typically there is a main summer team (ca. 50-60 people) that conducts research for 2-3 months, and a small overwintering team (ca. 8-9 people) that keeps the station functional during their 9-10 months of isolation. The size, duration and resupply schedules of the overwintering team aligns well with current ISS operations as well as those typically proposed in Moon and Mars reference missions. In addition to enhancing the desire for increased autonomy of the developed hardware, the crew and isolation factors improve the merit of the proposal with respect to psychological (e.g. group dynamics) and operations/crew time studies. The greenhouse facility will act as a microenvironment which could reduce the stress caused by living in an inhospitable and monotone environment[8].

- **Inhospitable environment and technology dependency**

High winds, heavy snow fall, low temperatures (below -50°C) and seasonal dark periods lasting several months make the Neumayer III test site an extreme environment. Similar to ISS operations, but unlike laboratory-based long-duration isolation studies, Antarctic crewmembers must count on technology to survive. The Neumayer III station crew lives in a highly integrated and technical environment. The environment allows ISS representative study of technology and crew interaction (e.g. psychological tests) and drives, as it does on-orbit, increased system reliability and safety requirements.

- **Extremely low terrestrial biodiversity environment**

The Antarctic continent is not only an extremely cold, but also represents one of the most protected and low biodiversity environments on Earth[9, 10]. With this similarity towards Moon and Mars environments, which have no known microbial life, Neumayer III is an optimal testing ground for microbiological experiments. This unique environmental feature allows further investigation of the microbial contamination patterns within the greenhouse, resulting from the habitat and the human interaction (also of high relevance on ISS). Here, planetary protection-adapted contamination measurements can be tested under space analogue conditions.

- **Habitat interface**

In order to develop future subsystems of BLSS such as integrated ISPR cultivation systems or automated greenhouse modules, the interaction (e.g. water, power, CO_2, O_2, biomass, bacterial contamination) with the crew/habitat is an essential consideration. As a functional habitat itself, considerations of power, data, food and waste interfaces will be important between Neumayer Station III and the mobile test facility.

The Neumayer III analogues test site provides the opportunity to validate complex integrated systems outside the laboratory. The operation of highly integrated systems can be simulated in a laboratory, but an actual deployment with its necessary technological intricacies cannot. The analogue deployment will serve to confirm the functionality of concepts and technologies, adding another degree of security and risk mitigation for future ISS and planetary surface BLSS. The complexity of closed systems and the importance of testing closed systems in a relevant mission setting cannot be overemphasized. While laboratory settings provide a useful environment to test and validate components and subsystems the validation of a completely integrated system is best done in a mission analogue operation, where the simplicity in operation, maintenance, repair, and control system software is essential. Human factors and human interfaces are important to consider. Especially in small closed systems the close proximity of humans and machines drives the design of the facility and the safety regulations[11].

The major difference between a laboratory test environment and an analogue test site is the fact that the experimenter/operator cannot simply walk away from the system but rather lives with it and, in case of a greenhouse, the crew lives from the output of the greenhouse. The crew is also not able to walk to the next electronics store to replace broken hardware. That puts high demands on reliability and robustness of the system[8].

Furthermore, there is a huge difference in human resources between a laboratory setting and an analogue mission. In a laboratory one usually has access to team of scientists, engineers and technicians on site, which are familiar with the system. At an analogue test site the personnel is limited, similar to a space mission. There are usually only 1-2 crew members who received extensive training with the system, while the rest of the crew is responsible for other tasks and systems.

IV. Ambition

The unique aspect of EDEN ISS is the focus on the key technologies and procedures associated with higher plant cultivation. This means that instead of dealing with all the different aspects of a BLSS, the envisioned project focuses on essential target areas. Targeting only these areas, guarantees a higher scientific outcome than spreading the research focus too broadly. Therefore, the EDEN ISS consortium will advance the current state-of-the-art through several means:

- Develop a high fidelity ISPR cultivation system with ~1 m^2 production area, thereby enhancing the feasibility of Europe providing the ISS with a plant production facility capable of almost an order of magnitude increase to current systems.
- Deploy a European constructed, highly integrated, mobile greenhouse module test facility to Antarctica. After completion of the project, the test facility will be used for further on-going BLSS investigations and will be open for experiments to the European BLSS community.
- Increase the TRL of a microgravity NDS built with materials capable of reducing possible biological contamination and including advanced on-line ion-selective sensors.
- Advance the TRL of spectrally tuneable LED lighting systems for highly reliable and remotely operated plant production systems. Energy conservation will be improved through the development and use of advanced LED heat capture techniques and intra-canopy lighting. Experimentally determine optimal light recipes for 5-10 crops and employ these recipes to maximize production within the mobile test facility.
- Increase of the TRL of relevant technologies in the field of bio-detection and decontamination of BLSS.
- Further develop proper plant handling and food safety procedures for higher plant cultivation in closed systems comparable to ISS and future long-duration space missions.

Table 1 provides a summary of the specific advances to the current state-of-the-art for the primary focus areas of the EDEN ISS project.

Table 1. Overview and comparison between state-of-the-art and beyond state-of-the-art

System	State-of-the-art	Beyond state-of-the-art
Greenhouse module test facility	• Simple 'Salad Machines', small food quantities • Cultivation processes and plant health monitoring is rather hands-on with limited automation • Bulk of Antarctic systems have been expeditioner/ hobby- based and constructed with materials found on-site • Limited to no remote commanding • Single surface production systems	• Produce higher quantities of fresh crops in order to achieve higher mission fidelity • Highly integrated test module, considering all necessary subsystems and analysing the overall mass production principles • Detailed quantification of pre- and post-processing analysis, cleaning and general crew time allocations • Enhance reliability of remote greenhouses through telepresence (tools and competency)
ISS plant production facility	• Small-scale production areas (~0.1 m^2) • Science driven • Negligible food production • Low to marginal environmental control reliability (some exceptions) • Non-scalable	• Medium-scale production areas (1 m2) • Food production and psychological benefit driven • Non-negligible food production for repeatable safety evaluation • Focus on quality and safety food attributes • Well characterized and reliable environmental control • Scalable
Nutrient delivery system	• Soil-based and soilless cultivation • On-line nutrient solution status measurements are indiscriminate (e.g. electrical conductivity) • Off-line measurements of ion-selective values are time intensive (e.g. days/ weeks) • Difficult and insufficient bio-contamination prevention	• Soilless cultivation is imperative • Higher yield, low water and nutrient use systems • Real-time online measurements of selective ion concentrations (e.g. new optrodes) • View of root system enhances ability of remote telemetric monitoring (e.g. aeroponic) • Nanostructured coatings for bio-contamination prevention onto surfaces
Light system	• Direct natural light (Sun) not feasible for space greenhouses (e.g. radiation, temporal variability, system complexity) • Fluorescent, high pressure sodium, metal halide, sulphur plasma lamp, induction lamp • PAR-specific multispectral LED light most promising candidate, but in early development stage	• High performance LEDs (combining a variety of monochromatic lights, specifically tailored to plant photosynthetic requirements) • Highly integrated panels and optimized with respect to mass, thermal load (actively cooled), volume, and power demand • Intra-canopy lighting systems
Bio-detection and decontamination	• Bio-detection performed by classical sampling method, wiping followed by incubation in a sample medium • Work intensive spray and wipe decontamination procedures, physico-chemical treatment or steam disinfection of small items • No possibility to disinfect hard-to-reach areas	• Real-time detection of quality and quantity of microbial loads (using gas-analysing instrument E-Nose) • High reachability (e.g. cavities, tubes and harnesses) with TransMADDS • Specific decontaminant depending on the microbial load, preventive effect, no damage of equipment
Food quality and safety	• Sensory evaluation of food products for characterisation of texture, flavour and palatability • Nutrient determination via solvent extraction and analysis via laboratory scale atomic absorption spectroscopy, liquid chromatography and UV-Visible spectroscopy • Lab based PCR or standard plate count techniques and microscopy employed for identification of microbial and infectious agents	• Establish sensor panel response versus physio-metric data analysis to produce a sensory evaluation protocol for use on board ISS • Rapid, non-destructive indicators of food quality • Rapid screen for microbial contamination • Food safety quick tests; new palatability analysis tools • Increase shelf lifetime for produced crops

V. Project Partners

A. Consortium

The EDEN ISS consortium consists of 13 organizations from seven different countries, see Table 2 and Figure 4. Each partner brings a balanced set of competencies to the project. However, there remains redundancy for several required competencies to ensure the progress of the project in the event that one partner leaves the project or is significantly behind schedule. It is worth highlighting that the EDEN ISS consortium covers most European companies that are active in space greenhouse research and all partners have already made significant contributions to the aforementioned state-of-the-art. Therefore, the carefully selected partners form a multidisciplinary and highly qualified team, which is fully aware of and well prepared for the scientific challenges of the proposed project.

Table 2. List of EDEN ISS consortium members

Participant organization name	Type	Country
German Aerospace Center (DLR)	Non-profit	Germany
LIQUIFER Systems Group GmbH	SME	Austria
Consiglio Nazionale delle Ricerche	Non-profit	Italy
University of Guelph	Academic	Canada
Alfred-Wegener Institute for Polar and Marine Research	Non-profit	Germany
EnginSoft S.p.A.	SME	Italy
Airbus Defence and Space	Industry	Germany
Thales Alenia Space Italia S.p.A.	Industry	Italy
Aero Sekur S.p.A.	SME	Italy
Wageningen University and Research	Academic	The Netherlands
Heliospectra AB	SME	Sweden
Limerick Institute of Technology	Academic	Ireland
Telespazio S.p.A.	Industry	Italy

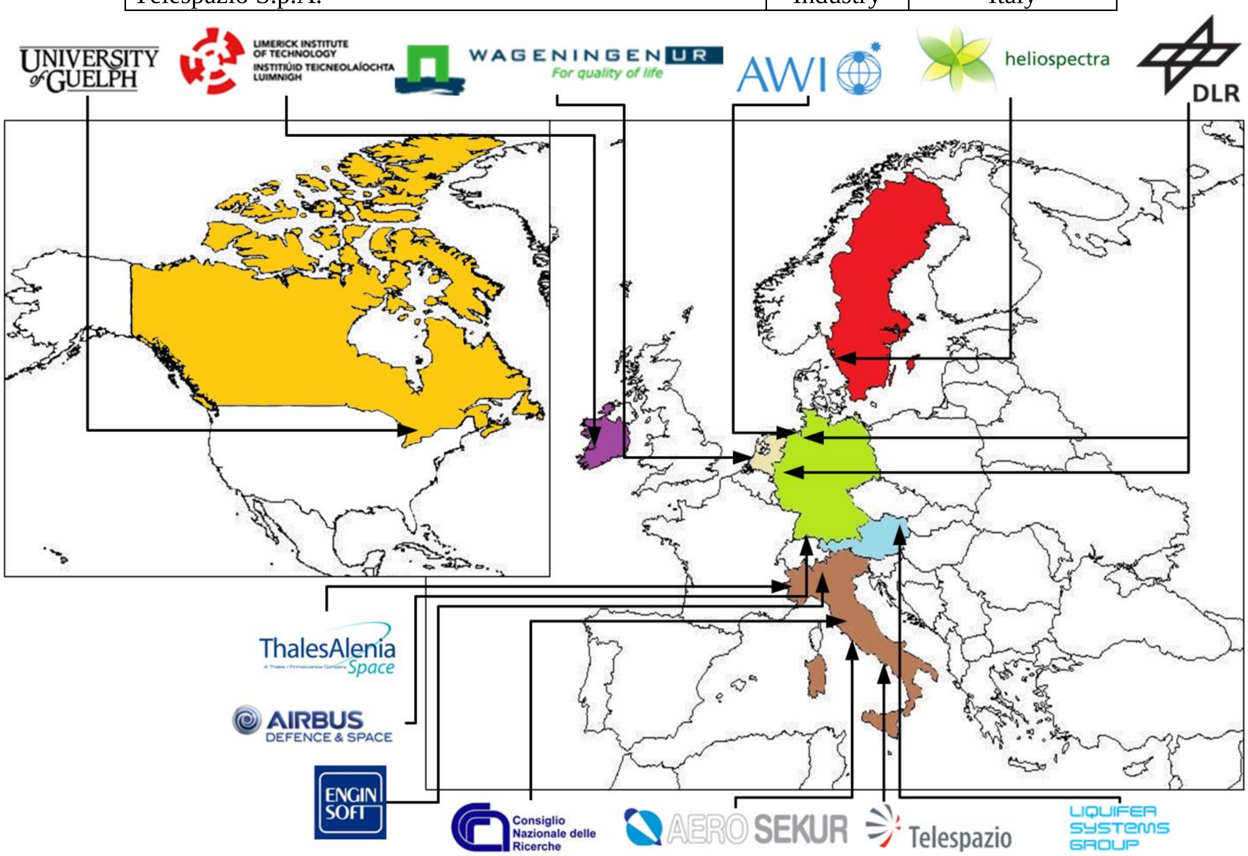

Figure 4. The international dimension of the EDEN ISS project consortium

According to the expertise and the complementarity, tasks of the EDEN ISS project are assigned to the most suitable partners to ensure achievement of project objectives.

German Aerospace Center (DLR) - Institute for Space Systems is appointed as the coordinator due to its experience in managing space projects of different budgets and scopes. The institute covers a broad range of activities related to space greenhouses, e.g. habitat design, system analysis and design of greenhouse modules. Furthermore, The experience of the Institute for Space System in systems engineering, especially in utilizing the Concurrent-Engineering Facility (CEF) in Bremen for a fast and consistent design of the mobile test facility will reduce the duration of the design phase significantly. The recently inaugurated laboratory building (including the new laboratory) with its new cleanroom will provide a suitable environment for the integration and tests of the system and its subsystems.

German Aerospace Center (DLR) - Institute for Aerospace Medicine is the only research institute that primarily deals with life sciences related to spaceflight, aviation and traffic. Its astrobiology group focuses on the investigation of microbial model organisms and their molecular and cellular mechanisms. Furthermore, the institute is known for its involvement in crew psychology studies (e.g. Mars500)

Liquifer Systems Group is assigned as a leading partner in configuration architecture, designing space habitats and space analogue test facilities and is experienced in public engagement activities and exploitation.

Consiglio Nazionale delle Ricerche is the Italian largest public research organisation. Two institutes are involved in the project, the Institute of Agro-environmental and Forest Biology and the Institute of Food Science focusing on plant growth under controlled environments, plant physiology and especially plant food product quality and safety.

University of Guelph has over 20 years of experience in controlled environment systems research specifically related to the study of plant growth and development for advanced life support. Their primary competencies lie in the areas plant physiology, advanced lighting, horticulture, environment analysis, nutrient delivery systems, sensors and controlled environment engineering and operation.

Alfred-Wegener Institute for Polar and Marine Research as the operator of the Neumayer Station III and the Polarstern research vessel and has extensive Antarctica operations and field campaign experience.

EnginSoft as the partner with the strongest experience in FEM, CFD and other simulations is appointed to the thermal, fluid dynamic and environmental simulation tasks.

Airbus Defence and Space (Friedrichshafen site) is one of the leading European space system manufacturers. The Airbus site in Friedrichshafen is engaged in the development of equipment and technologies for ISS in-situ analysis (bio-detection) and decontamination procedures and countermeasures.

Thales Alenia Space Italia (Turin site) is specialized in air and water management systems as well as contamination control for manned spaceflight systems like the ISS nodes, MPLM and the Columbus laboratory. The Turin division has a technological area dedicated to support regenerative life support RTD activities, including water recovery, air revitalization, waste processing and food production through higher plants (ISPR system development).

AeroSekur is a specialist supplier of safety systems and advanced flexible materials to the global aerospace and defence markets. The company has extensive manufacturing and R&D facilities in Italy and representation worldwide.

Wageningen University and Research is probably the largest group of scientists in the world with expertise in all aspects of greenhouse horticulture, from crop physiology and plant protection to greenhouse technology, climate control and farm management.

Heliospectra specializes in smart LED lighting systems for plant science and horticulture applications. The company manufactures fully controllable, “smart”, multi-wavebands LED luminaries. Heliospectra has also plant research facilities and works on optimization of the light environment for crop-specific requirements.

Limerick institute of Technology’s flagship research centre is the Shannon Applied Biotechnology Centre. Here, the Controlled Environment Laboratory for Life Sciences, (CELLS) is a research group that applies techniques and technology developed for long-duration space missions to address the growing demand for safer, healthier, higher quality foods and naturally derived health treatments.

Telespazio Naples (formerly MARS Centre) is the Italian user control centre responsible for the real-time operation of many facilities and laboratories on-board ISS since 2010. It has been deeply involved in space greenhouse projects over the last 15 years (e.g., Space Greenhouse, CAB, SaySoy and others).

B. Scientific Advisory Board

A six member scientific advisory board composed of members from Italy, Germany, Japan, Russia and USA will advise and support the EDEN ISS project. The scientific advisory board will support the research consortium by providing scientific and technical input throughout the evolution of the project. The members of the scientific advisory board will also support the dissemination of project results by assisting in public relation strategies and enhancing the international cooperation and visibility. The members of the scientific advisory board as well as their particular institutes include:

Dr. Wheeler (USA)	Dr. Giacomelli (USA)	Dr. Gunga (Germany)
Dr. Stefania De Pascale (Italy)	Dr. Tikhomirov (Russia)	Dr. Kitaya (Japan)

VI. Work Plan

EDEN ISS is divided into three major project phases: the design phase, the building phase and the experimental phase. Figure 5 shows the highlights of each phase.

The design phase starts with the kick-off meeting (KOM) in March 2015 and focuses on the requirements definition and design of the greenhouse. The operation modes and experiment schedules are also defined in this phase. After elaborating the initial designs, a concurrent-engineering (CE) study will be conducted in DLR's CEF in Bremen, Germany in September 2015. The objective of the study is the generation of a detailed design of the greenhouse facility. The study will last approximately two weeks and representatives of all consortium partners participating to provide their expertise. This project phase is 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 for the different subsystems are divided among the consortium to best fit their experience. In parallel to hardware development, extensive cultivation experiments are performed. With the experiments, the cultivation parameters of the target plants are determined. At the beginning of 2017 the subsystem hardware will be delivered to the DLR in Bremen, Germany for the system assembly integration and test (AIT). AIT will be concluded in August 2017 with a test deployment of the complete greenhouse facility. Following the test deployment, the greenhouse will be prepared for shipping to Antarctica in October 2017.

The experimental phase covers the facility setup in Antarctic, all experiments conducted in Antarctica and the design enhancements based on the lessons-learnt. The selected key technologies and operations procedures will be demonstrated and validated. The results elaborated and the design of the facility and subsystems is further developed to enable terrestrial applications, utilization on-board ISS and in future planetary greenhouse modules.

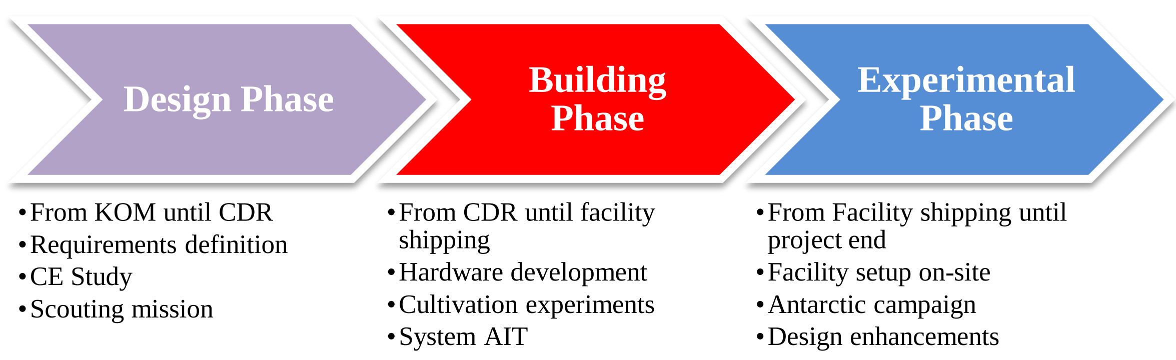

Figure 5. Project phases and corresponding highlights

VII. Outreach Activities

A noteworthy share of the project budget is dedicated to public engagement. The consortium will spread information about the project and its results to interested people and the broad public. It is in the interest of the consortium to show and explain public funded research to European taxpayers.

<table>
<tr><th>Electronic Dissemination</th><th>Key words: website, podcasts, newsletters</th></tr>
<tr><td colspan="2">A website will provide detailed information about the EDEN ISS project to the interested public, scientific and business parties. It will contain milestone results, photos, video animation clips, podcasts, personnel interviews and a live video stream from the inside of the mobile test facility during the Antarctic deployment. The website will function as a nucleus for displaying all major achievements of the envisioned project. For the scientific community an access to key research data will be available. Here, researcher can download essential time dependent raw data (e.g. food output, temperature, RH, pH, access times, power demands) in order to use this data for their own research and analysis.</td></tr>
<tr><td colspan="2">Newsletters will be sent out to respective press agencies and subscribed individuals including images, artists' concepts, diagrams and computer renderings of the greenhouse module.</td></tr>
<tr><th>Viral Marketing/ Public Engagement</th><th>Keywords: social media, live streams, community</th></tr>
<tr><td colspan="2">New communication tools shall be deployed in order to establish broad media attention and to engage the general public towards human space exploration. Here, certain elements of viral marketing will be initiated for the general public like a Twitter project page and an open Facebook group. For the scientific community special platforms at academia.edu, researchgate.net and linkedin.com will be established. All these sites will display the major project highlights, latest news and will give useful background information about human spaceflight and its stakeholders.
Live stream interviews from Antarctica, info podcasts and animation sequences will be deployed on various internet platforms like youtube.com and vimeo.com in order to achieve maximum media dispersion. A 24/7 live web stream from the inside of the mobile test facility during the analogue test mission (e.g. overall view and several close-ups of specific plant trays) will be visible on the project website and as downloadable stream-gadget for the implementation into other websites (i.e. viral marketing). A live chat with the expedition personnel will complete this public engagement element.
The long-term objective is to create a community of interested parties centred on human spaceflight and exploration, BLSS, space greenhouses, terrestrial applications and to foster the awareness for sustainable living on Earth.</td></tr>
<tr><th>Broadcast Media</th><th>Keywords: TV documentary, international broadcast</th></tr>
<tr><td colspan="2">The consortium anticipates inviting well-known broadcasting companies to produce a professional documentary about the design and manufacturing of the mobile test facility and especially during the analogue campaign in Antarctica. For this task, contacts with professional documentary production companies and TV channels are already established (e.g. BBC Horizon, Discovery Channel, National Geographic). With this communication channel, high quality documentary content can be offered to the interested public and further foster the visibility of human space exploration.</td></tr>
<tr><th>Educational Outreach</th><th>Keywords: education material and experiments for school kids</th></tr>
<tr><td colspan="2">The project will address the needs for free high quality lecture material for schools and universities. The consortium is willing to prepare and provide information for school children and university students. The lecture material will be distributed via the website and on request to teachers and professors.
The DLR School_Lab is a facility to give school children an understanding of space research. This educational program can accommodate up to 5000 pupils per year and is an optimal educational outreach instrument for the envisioned project.
Small plant grow experiment tool kits will be developed by the consortium (similar to the ESA grow kit, developed by the consortium partner Aero Sekur in 2012). These experiment tool kits will be distributed to school classes within the European member states and Canada. Here, the pupils can learn different aspects about BLSS and the role of higher plants in human space exploration endeavours. A similar kit will be taken to Antarctica and used for real-time participation/interaction between schools and expedition personnel.</td></tr>
<tr><td colspan="2">Furthermore, European school classes can take part in a special program for dedicated plant trays within the mobile test facility. Certain plant trays (e.g. radish, lettuce) can be adopted by a respective school class. The children can watch their plants and observe the different grow cycles, monitored and broadcasted from Antarctica via the 24/7 web live stream from inside the test facility. Scheduled live web cam interviews with the expedition personnel, including question and answer sessions, shall be performed with the dedicated school class in order to round out this educational outreach element.</td></tr>
<tr><td colspan="2">During the Antarctic Seed Campaign, the expedition personnel will collect and dry several seed types from the grown plants in the mobile test facility. These seeds will then be reproduced and duplicated by a European greenhouse operator. This inexpensive educational/ public outreach element has been successfully performed in Canada (Canadian Space Agency, University of Guelph and others) for a number of years and now reaches over 13,000 Canadian classrooms per year (Tomatosphere campaign), illustrating its potential impact in Europe.</td></tr>
</table>

VIII. Summary

The EDEN ISS project will advance the current state of plant cultivation in space through ground-based demonstration of key technologies. The demonstration of plant cultivation in a large-scale facility at the Neumayer III Station in Antarctica acts as a precursor for future experiments on ISS and strengthens the development of technologies for future missions to Moon and Mars. EDEN ISS will generate and provide scientific data to the whole bio-regenerative life support community. Furthermore, the project will boost the public awareness of plant cultivation in space through its public outreach campaign.

Acknowledgments

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 636501.

References

[1]Leys, N., and Mastroleo, F., *Cluster 4: Habitat Management - Life Support: Management and Regeneration of Air, Water and Food,* European Science Fundation, 2012.

[2]International Space Exploration Coordination Group, *The Global Exploration Roadmap,* NASA Headquarters, 2013.

[3]Wheeler, R. M., *Roadmaps and strategies for crop research for bioregenerative life support systems - A compilation of findings from NASA's advanced life support meetings,* NASA Kennedy Space Center, 2009.

[4]ESA, *HUMEX - Study on the survivability and adaption of humans to long-duration exploratory missions,* ESA ESTEC, 2003.

[5]Zabel, P., Bamsey, M., Schubert, D., and Tajmar, M., "Review and analysis of plant growth chambers and greenhouse modules for space," *44th International Conference on Environmental Systems*, 2014.

[6]Bubenheim, D. L., Flynn, M. T., Lamparter, R., and Straight, C. L., *Remote Sites as Analogs for Lunar and Mars Habitat Pilot Studies,* SAE International, Warrendale, PA, 1994.

[7]Bamsey, M., Zabel, P., Zeidler, C., Poulet, L., Schubert, D., et al., "Design of a Containerized greenhouse Module for deployment to the Neumayer III Antarctic Station," *44th International Conference on Environmental Systems*, 2014.

[8]Bubenheim, D. L., Bates, M. E., and Flynn, M. T., *An Approach for Development of Regenerative Life Support Systems for Human Habitats in Space,* SAE International, Warrendale, PA, 1995.

[9]Horowitz, N. H., Cameron, R. E., and Hubbard, J. S., "Microbiology of the dry valleys of antarctica," *Science (New York, N.Y.)*, Vol. 176, No. 4032, 1972, pp. 242–245.

[10]Convey, P., "Antarctic terrestrial biodiversity in a changing world," *Polar Biology*, Vol. 34, No. 11, 2011, pp. 1629–1641.

[11]Dussap, C. G., "TN 3: Definition of the Ideal Facility for Life Support Issues," *REGLISSE - Review of European Ground Laboratories and Infrastructures for Sciences and Support of Exploration,* ESA ESTEC, 2003.