Human-centered Design of a Workstation for the Lunar Agriculture Module

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Abstract

The Artemis Program is returning humans to the Moon in the aim of establishing a sustainable presence. To address resource scarcity, Bioregenerative Life Support Systems (BLSS) can be considered. Agricultural modules are a component supporting these systems and can provide in-situ edible biomass and breathable atmosphere for astronauts. To this end, the EDEN Research Group at the Institute of Space Systems of the German Aerospace Center (DLR), is developing the Lunar Agriculture Module Ground Test Demonstrator (LAM-GTD). This project will serve as a terrestrial analog in preparation to deploy an agricultural module on the Moon. The LAM-GTD will comprise cultivation and service racks where astronauts will perform diverse activities related to plant cultivation including sowing, pruning, monitoring, harvesting, and cleaning.

To support these operations, the project aims to design a human-centered workstation to optimize cultivation tasks in a constrained space, following the guidelines provided by the NASA's Human Design Integration Handbook (NASA/SP-2010-3407). After reviewing relevant projects, the initial step consisted in performing a User Task Analysis (UTA) by collecting experience from crew members of EDEN ISS missions in Antarctica and developing the Concept of Operations (ConOps). Insight from this study guided an iterative design phase, incorporating continuous crew feedback and trade-off analyses to refine the functional and ergonomic aspects. From this human-in-the-loop approach, the workstation was structured to support four key subsystems: a workbench with an integrated sink, a waste compartment, a nursery and storage. A usability test procedure was developed to verify in future work the compliance with human factors guidelines and generate actionable recommendations for further improvements, ensuring the workstation's readiness for future demonstration under simulated gravity planned at DLR.

This project demonstrates the value of a Human-Centered Design (HCD) and iterative approach in optimizing space workstations, enhancing functionality, operation and crew well-being, and contributing to the readiness of the LAM mission.

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Abbreviations

APH	Advanced Plant Habitat
BLSS	Bioregenerative Life Support System
BPC	Biomass Production Chamber
CE	Concurrent Engineering
CEA	Controlled Environment Agriculture
CELSS	Controlled Ecological Life Support System
ConOps	Concept of Operations
COTS	Components Off-The-Shelf
CROP	Combined Regenerative Organic food Production
DLR	German Aerospace Center
EAC	European Astronaut Center
EDEN	Evolution & Design of Environmentally closed Nutrition sources
ESA	European Space Agency
EVE	EDEN Versatile End-effector
FEG	Future Exploration Greenhouse
HIDH	Human Integration Design Handbook
ICE	Isolated and Confined extreme Environments
ICES	International Conference on Environmental Systems
ISS	International Space Station
ISU	International Space University
LAM-GTD	Lunar Agriculture Module Ground Test Demonstrator
LEM	Lunar Excursion Module
MELiSSA	Micro-Ecological Life Support System Alternative
MTF	Mobile Test Facility
MWA	Maintenance Work Area
RTLX	Raw Task Load Index
SES	Service Section
SFHSS	Space Flight Human Systems Standard
SME	Subject Matter Expert
SPFGC	South Pole Food Growth Chamber
TLX	Task Load Index
UTA	User Task Analysis
Veggie	Vegetable Production System
WSA	Work Surface Area

1. Introduction

1.1. Rationales behind Space Agriculture

Plans to land back humans on the Moon are common to both sides of the world. On one hand, NASA and its partners (CSA, ESA and JAXA) created the famous Artemis Program, on the other hand, China (CNSA) established no less ambitious plans in collaboration with Russia. Projections are striking with similarities: countries want to land within the decade of 2020 and maintain a sustainable presence with the help of a lunar base. (NASA, 2020a).

These challenging missions on the Moon are serving as testbeds for longer crewed missions towards Mars and beyond. Indeed, increasing mission duration and distance to Earth constrain refueling vessels for budgetary and time reasons. Thus, developing the capacity to recycle resources becomes essential. Consequently, stakeholders are pouring efforts notably in the research on Bioregenerative Life Support Systems (BLSS). These artificial systems provide and recycle all resources (oxygen, water, food, etc) necessary to human survival inside a closed environment (Mitchell, 1994). To do so, they usually include a higher plant compartment relying on Controlled Environment Agriculture (CEA). Notable examples of these projects are (Wheeler, 2017):

- *Biomass Production Chamber* (BPC), 20m2 of crop cultivation as part of NASA's Controlled Ecological Life Support System (CELSS) program (1988-2000, Kennedy Space Center, USA)
- *Micro Ecological Life Support System Alternative* (MELiSSA) which has been in development since the late 80s by the European Space Agency (ESA) and the Melissa Foundation,
- *EDEN ISS*, 12,5m2 of crops, focus on the consumption and design side (2015, DLR Bremen, Germany)
- *Lunar Palace*, 69m2 of crops integrated to a full BLSS (Beihang University in Beijing, China).

Another significant added value of BLSS is the psychological benefit of having plants in isolated and confined extreme environments (ICE) (Haeuplik-Meusburger, 2011). Crew's moral and mental health is strongly affected by the harshness of their environment and may cause danger to the crew's safety and the mission success. Studies have proven that the presence of plants significantly improves the mood (Schlacht et al., 2020). Cosmonaut Valentin Lebedev was particularly subject to this phenomenon and placed his sleeping bag next to his "green friend" (Zimmerman, 2003).

However, extraterrestrial cultivating is no easy challenge, and an immense knowledge gap remains to be filled. While the first plant experiments were sent to space in the 70s and continue up to today (Raibyte, 2021), extensive space agriculture required for BLSS is still at the stage of research and Earth analogs. A new work environment needs to be implemented to resolve these challenges. Hence, this thesis aims to answer one human factor gap by proposing a human-centered workbench design adapted to a lunar agriculture module.

1.2. Professional Environment : the EDEN Initiative

This work was conducted at the Institute of Space Systems at DLR in Bremen, Germany, as part of a combined thesis and internship. The EDEN initiative, which stands for Evolution & Design of Environmentally closed Nutrition sources, was launched in 2011 by Prof. Daniel Schubert. Its goal is to develop BLSS with a focus on cultivation modules and their integration into space habitats (DLR, 2020).

The initiative's first major milestone was the construction of the EDEN ISS greenhouse module, which was deployed to Antarctica from 2017 to 2022 (Vrakking et al., 2024). The module has since returned to Bremen, where it is currently being refurbished and enhanced for astronaut training, with a targeted delivery to the European Astronaut Center (EAC) in Cologne by 2026.

In parallel, the Lunar Agriculture Module - Ground Test Demonstrator (LAM-GTD), originally known as EDEN Next Gen, is being developed with a higher level of fidelity for a lunar mission. The project was officially launched with the signing of a collaboration agreement with the Canadian Space Agency (CSA) at the IAC 2022 in Paris. The partnership has since expanded to include the Italian Space Agency (ASI) and NASA (Schubert, 2023).

1.3. Scope of the thesis

The goal of the present work is to design a workstation (or a rack) for the project LAM-GTD. This project is an iteration of EDEN ISS - Luna, building up from lessons learned and advancing it to a higher-fidelity simulation of a lunar mission. LAM-GTD aims to bridge the gap between Antarctic analog and lunar missions by implementing the specific challenges of the Moon, particularly regarding the resources' scarcity which necessitates to improve their recycling (DLR, 2024; Maiwald 2024). As shown on Figure 1, LAM-GTD is currently composed of two modules: the Lunar Agriculture Module (LAM), where the plants are grown, and the airlock module.

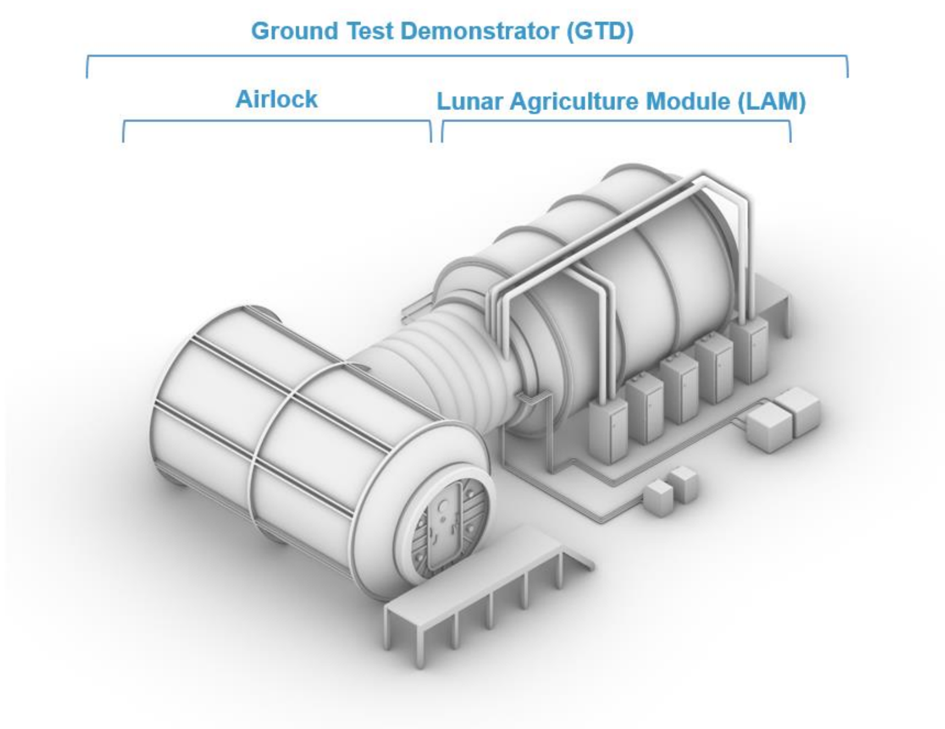


Figure 1: 3D rendering of the current state of LAM-GTD

During the Concurrent Engineering (CE) from the 7th to 15th March 2024, the general design of the module was brainstormed, and a preliminary design of the LAM emerged (Maiwald, 2024). Hereafter, a list relevant for this thesis of the main design's conclusions extracted from the CE. These features are observable in Figure 2 (additional plans are provided in Appendix A1).

- The *primary structure* follows a similar design to the ISS' modules ones,
- The *module internal partition* is composed of original racks optimized for maximum cultivation area,
- The *general design* of the module is composed of a central corridor with the racks located on both sides alike the ISS,
- The *support systems* are located in the sub-floor and ceiling of the module,
- Two *service racks* for storage and the workstation are located at the entrance of the module.

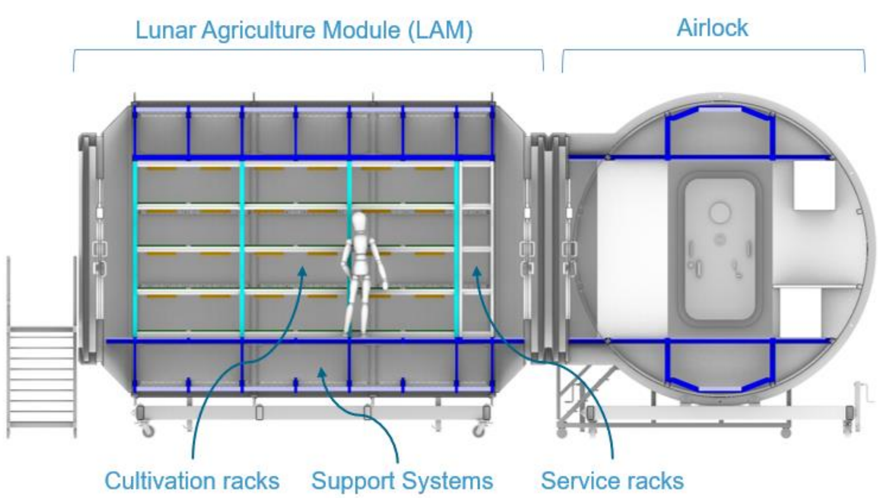


Figure 2: Section of LAM-GTD

Additionally, open issues related to human factors were identified, particularly concerning the design of *a workstation*, *a nursery* and *storage areas* (Maiwald, 2024). Through further discussions with experts, *a waste compartment* and *a sink* were later identified as necessary equipment for the cultivation activity. Indeed, user reviews of EDEN ISS highlighted multiple times the importance of a practical workstation design to optimize work and minimize frustration (Botta, 2022), notably:

- The sink was considered too small, and water spillage occurred regularly.
- Users mentioned that the work desk was too small (0.75 m^2) for daily activities and proposed a foldable design for future adjustments.

The limited space allocated to the workstation in LAM-GTD makes this issue only more imperative to resolve. The design of the workstation had yet not been optimized utilizing human centered design concepts.

The objective of this thesis is to structure all the unresolved components mentioned above into one coherent rack, originally dedicated to the workstation and storage.

Furthermore, the engineering of the assembly should consider both the transport from Earth to the Moon (cargo configuration of the module) and the final deployment for operational use. The design focuses on optimizing human factors to ensure seamless integration and usability of the workstation, supporting the module's primary activity, which is cultivation.

The structure of this document follows the natural flow of the design process. Starting with a review of relevant projects (chapter 2.), including Earth analogs, such as Antarctic facilities, and space systems, covering both cultivation chambers and workstations. As the focus of this thesis is on human factors, the methodology section (Chapter 3.) follows the guidelines of the NASA's Human Integration Design Handbook (HIDH) (NASA, 2014): Conceptual Phase, Preliminary Design, Final Design and, Test and Verification. The result section (chapter 4) is structured identically to the method one, providing the outcome of each step under the form of design and procedures. The final chapter 5 provides the conclusions of the work executed for this thesis as well as recommendations for future work and integration in the evolving LAM-GTD.

2. Relevant Projects

2.1. Overview

This section aims to review plant growth facilities and chambers that are, or are planned to be, part of CEA and/or BLSS. The focus is brought on workstations and the human-system interaction within these facilities both on Earth and in space, aligning with the objectives of this thesis.

The selection process involved identifying CEA systems, notably those in Antarctica, researching each project for relevant information, and assessing their suitability based on the following criteria ensuring comparability with LAM-GTD's workstation:

- Facility size (1-50 m²), this criterion was essential for Earth's facilities for comparative reasons with LAM-GTD, but had to be ignored for space projects where size is extremely limited,
- Presence of a workstation/workbench for cultivation activities,
- Availability of resources, such as detailed information, interior images, operational reviews, etc

Antarctica represents an interesting analog to space projects. With some of the harshest conditions on Earth, growing plants in this extreme environment presents significant challenges. CEA systems require to be carefully picked to resist extreme temperatures and must be highly reliable, as refueling expeditions are limited through the winter season. These challenges present similarities to those faced during space missions, providing a valuable portfolio of projects from which to learn insights for space agriculture.

The heritage project EDEN ISS is the most comparable Antarctic facility to LAM-GTD. The study of this project, especially of its workstation, is a great source of information for this thesis. Additionally, its follow-up project EDEN Luna, updated for astronaut training, presents further mission analogies.

Naturally, space systems related to cultivation also need to be reviewed. However, these systems are often limited to small growth chambers, without dedicated areas for additional cultivation activities, such as workstations. Nevertheless, some of the most documented space projects will be reviewed to extract valuable lessons learned.

2.2. Antarctic Facilities

According to reviews, over 46 plant growth facilities have been operated in Antarctica (Bamsey et al., 2015). For this study, a selection of facilities with strong analogies with the EDEN projects was chosen based on established criteria to ensure operational similarities and valuable lessons. Many facilities were spontaneously constructed by Antarctic crews with minimal documentation, often limited to diary mentions. This lack of detailed records significantly restricted the number of projects available for comprehensive review. Additionally, some projects with high design similarities could not be analyzed further due to the absence of operational reviews.

From this review, a list of notable Antarctic projects was compiled and is presented below. Based on the criteria outlined, only a few could be analyzed in detail and are described in this section. These projects are marked in bold:

- **South Pole Food Growth Chamber (SPFGC), Amundsen-Scott South Pole, USA**
- Hydroponic Garden, McMurdo Station, USA
- Hydroponics Room, Jang Bogo Station, South Korea
- **Hydroponics Units, Scott Base, New-Zealand**
- Mawson Station greenhouse, Australia
- Plant-based unit for life support in Antarctica (PULSA), Mario Zucchelli Station, Italy
- The Vegetable Greenhouse, Great Wall Station, China

The analysis focused on understanding human-system interactions through image analysis of the facilities and gathering lessons learned from detailed crew operations and reviews.

2.2.1. South Pole Food Growth Chamber (SPFGC), Amundsen-Scott South Pole Station, USA

The Amundsen-Scott South Pole Station is located near the geographical South Pole. Since 2004, it has hosted the South Pole Food Growth Chamber (SPFGC), a project developed by the University of Arizona, where NASA conducted experiments to advance knowledge in space agriculture for future space missions. Initially designed to support space research, the SPFGC is now maintained by volunteers to provide fresh vegetables for the station's 60 crew members. It is one of the few Antarctic projects directly linked to space agriculture. This project later inspired the Lunar Greenhouse Prototype, also developed by the University of Arizona with funding from NASA (University of Arizona, 2024; Patterson, 2011).

The SPFGC consists of two rooms: an antechamber measuring 10 m² and a primary growth chamber measuring 23 m², separated by a glass wall. The antechamber is accessible via one of the station's corridors, and two large windows provide an excellent view of both the antechamber and the primary growth chamber in the background (see Figure 3) (Fenstermacher, 2020). This space serves multiple purposes, functioning as a nursery for germinating seeds before transplanting them into the primary chamber and as the location where the nutrient solution is poured into the system. A central table, repurposed from a transport box, provides a surface for sowing and handling nursery trays. The space also serves as a relaxation space, equipped with a sofa that allows crew members to enjoy the view of the growth chamber—a small but meaningful connection to nature in this extreme environment (Gone Venturing, 2019).

In addition to operational reports, valuable observations were made from the numerous pictures shared by the crews. Indeed, besides the layout of the systems supporting the primary growth chamber, the antechamber appears to have been customized and rearranged differently with each crew rotation, highlighting the lack of specific design concept for the workstation. Additional cultivation trays are added in the antechamber and the space below is used as temporary storage. Additional cultivation trays were added in the antechamber, with the space below used as temporary storage. A second table was also observed next to these trays, likely serving as a workbench.

The SPFGC is a practical example of an Antarctic cultivation facility that continues to operate, serving both as a source of fresh food and as a platform for advancing the science of space agriculture. Its flexible design has proven durable over time but also highlights a notable limitation: the lack of sufficient working surfaces.

Figure 3: Comprehensive drawings on the SPFGC. Left, view from the corridor on the antechamber with the primary growth chamber in the background. Right, view inside the antechamber.

2.2.2. Hydroponics Units, Scott Base, New-Zealand

Scott Base is New Zealand's permanent Antarctic station, which opened in 1957. Although it has hosted a total of three agricultural chambers, sufficient photographs and reports were only available for the first facility. This hydroponics unit was constructed from two repurposed, large water tanks that were connected and insulated. It was operational between 1986 and 1999 (Bamsey et al., 2015).

Inside the facility, a basic hydroponic system was installed (see Figure 3), constructed using repurposed water pipes. A unique feature of this design is that the hydroponic system lays on a table that also served as a workbench. The table, positioned at a comfortable standing work height (90–100 cm), was notably large, exceeding the size of the cultivation area. As shown in Figure 4, the space beneath the workbench was used for storage, while the space above was left clear to allow plants to grow taller.

Photographs from previous missions, compared to the one depicted in Figure 4, suggest that additional levels of cultivation trays were once suspended above eye level (Antarctica NZ, 2015). However, it can be inferred that these trays were removed due to their limited accessibility. Nursery trays were also observed on the large surface, though it could not be determined whether they were permanently located there or only brought in during transplantation activities.

The Hydroponics Unit of Scott Base, like the SPFGC, highlights the importance of flexible design that accommodates both functionality and adaptability over time. Trust must be placed in the user to modify their environment and systems to suit their specific needs and utilization.

Figure 4: Comprehensive drawings of the Hydroponics Unit of Scott Base.

2.3. Heritage projects

DLR's project EDEN ISS is the predecessor of LAM-GTD. Currently, it is being updated and refurbished under the name of EDEN Luna to be sent to the European Astronaut Center (EAC) for astronaut training.

2.3.1. EDEN ISS

Launched in March 2015, the project EDEN ISS is an international collaborative project led by DLR. It aims to enhance the state-of-the-art of BLSS by building and testing an analog cultivation facility, named the Mobile Test Facility (MTF). The MTF was sent in October 2017 to Neumayer III in Antarctica to be tested during five years operations. The facility is composed of two connected shipping containers (standardized length of 6 m): the Future Exploration Greenhouse (FEG) and the Service Section (SES) where the workstation and supporting subsystems are located (Zabel et al., 2017) (See Figure 5 and 6).

The SES covers similar functionalities as LAM-GTD's workstation. Most of its volume is allocated to subsystems ensuring the handling of the FEG. The following subsystems can be found in the SES (Vrakking et al., 2017):

- Power control and distribution system,
- Data Handling Control System (DHCS),
- Workbench and sink,
- Nutrient Delivery System (NDS),
- Thermal Control System (TCS),
- Atmospheric Management System (AMS),
- Storage.

These systems are essential to the functioning of the agricultural module and the same systems will be integrated in LAM-GTD and are shown in Figure 8.

Figure 5: Rendering of EDEN ISS in Antarctica (Vrakking, Liquifer System Group, 2017)

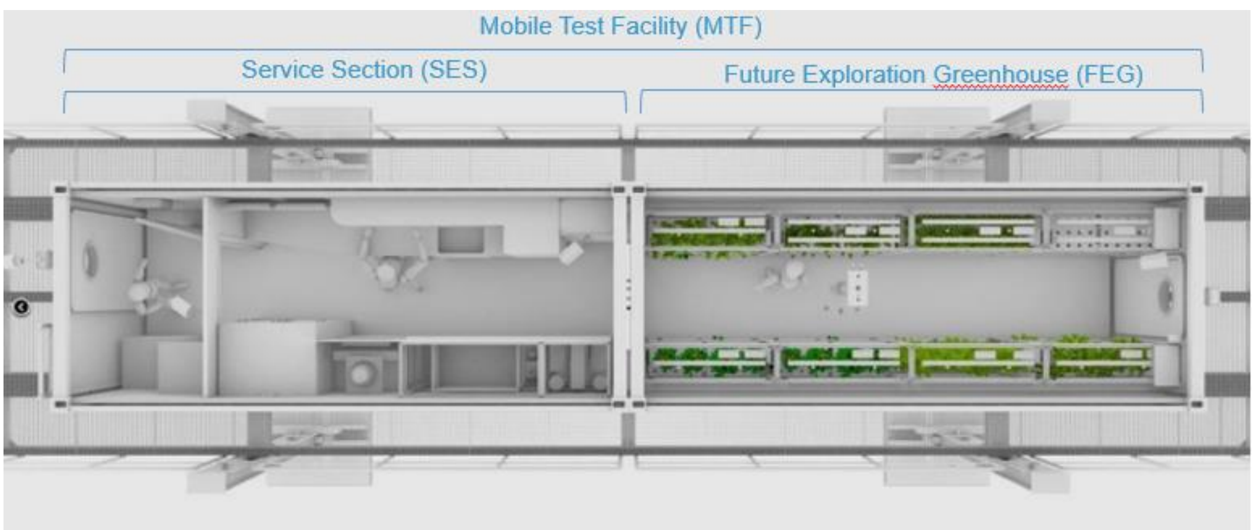


Figure 6: 3D plan of EDEN ISS (Vrakking, Liquifer System Group, 2017)

The workbench is of particular interest to this thesis. It comprises human-centered features such as the workbench, the sink, storage, control panels and screens, etc (see Figure 7). Additionally, a large window was located above the workbench to offer a view on Neumayer III while sitting at the desk (Imhof et al., 2018). Except for the window, the workstation to be designed in this thesis is to host the same equipment within one rack. The design might differ from EDEN ISS to LAM-GTD but function remains. Thus, lessons learned from the operation of EDEN ISS are of high value.

The mission control room was located in DLR Bremen (Imhof et al., 2018). The mission control center used for EDEN Luna and LAM-GTD will be the same, offering a test bed of space remote control for further projects.

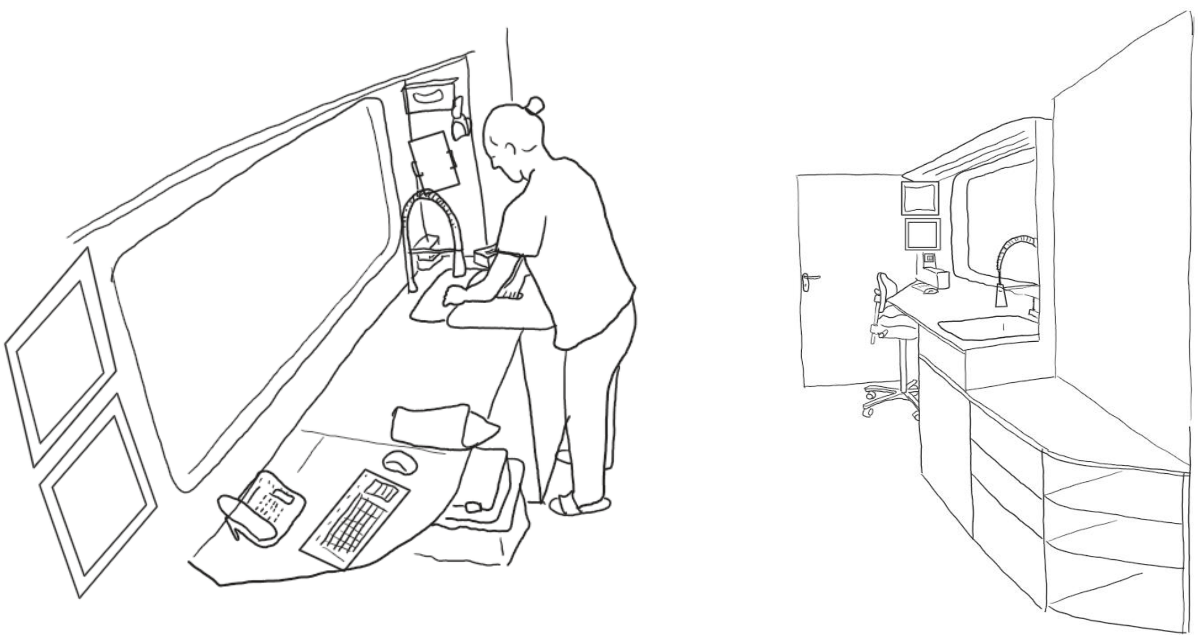


Figure 7: Comprehensive drawings of the SES. Left, view from the porch's door. Right, view from the FEG's door.

2.3.2. EDEN Luna

LUNA is a lunar environment analog facility created in collaboration between DLR and ESA. The facility is located next to the European Astronaut Center (EAC) in Cologne. After refurbishment, the EDEN ISS module is planned to be installed next to the LUNA facility for astronaut training. For this follow up mission, the project has been renamed into EDEN Luna. The facility is being updated according to the lessons learned during EDEN ISS Antarctic analog operations (Vrakking et al., 2024).

The module maintains the same structure and systems with slight adjustments. These changes where inherited from the CE study conclusions regarding human factors concerns. The new objectives were including reduction of operational crew time, as well as enabling astronaut-in-the-loop testing and training. Only two important upgrades were implemented along the workbench adjustment (see Figure 8), as explained hereafter:

- Combined Regenerative Organic food Production (CROP). Located in the SES, its goal is to demonstrate the capability to recycle urine within the agriculture module,
- EDEN Versatile End-effector (EVE) robotic arm. Developed in collaboration with CSA, EVE is located in the FEG. Its aims to advance the state of automatic and remote harvesting.
- Adjustment of the workbench considered too small, and modification of the sink position.

EDEN Luna is structurally like EDEN ISS while increasing closure of the regenerative loop system and improving human-system interaction, which are goals shared with LAM-GTD.

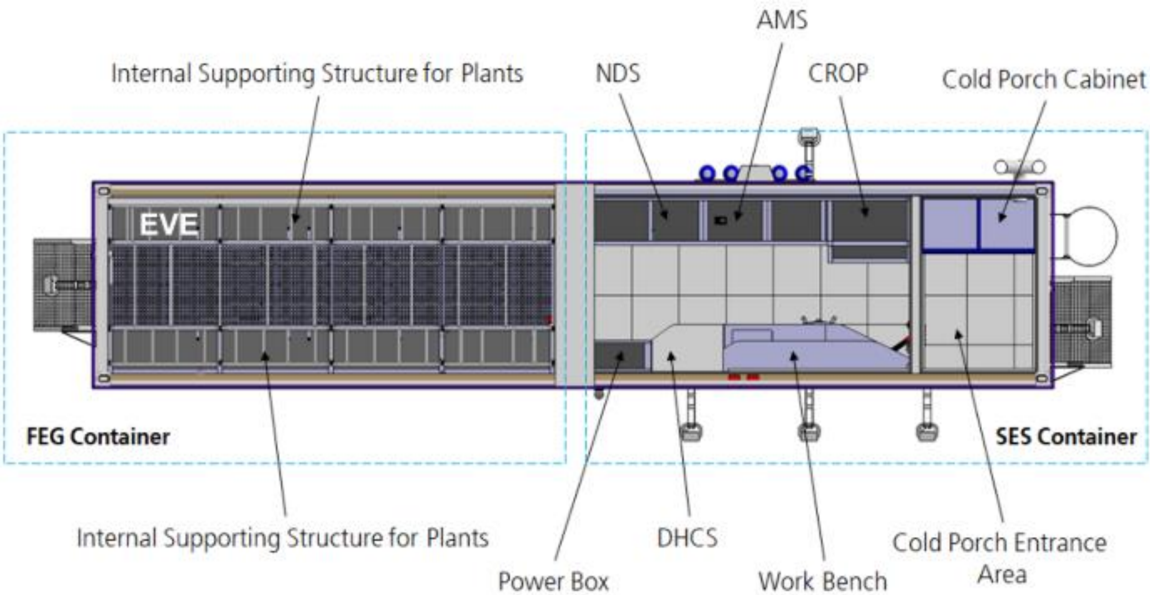


Figure 8: Plan of EDEN Luna (Vrakking, 2024)

2.4. Space Systems

Experience with growing plants in space started in the 70s under the Soviet Union. A team of biophysics was in charge of creating experiments to test the viability of such an endeavor. Until now it had not been proven that plants could grow in microgravity and sustain high load at lift off (Raibytė, 2021). This program led to a long list of tiny to small plant growth chamber, notably the Oasis series flown on four different Salyut mission or Malachite, which was the first plant related psychological experiment in space (Haeuplik-Meusburger et al., 2014; Zabel et al., 2014).

Currently on board the ISS are located reliable and automated plant growth chambers which are paving the way to CEA in space. Notably Veggie and Advanced Plant Habitat (APH), experiment from NASA, are advancing the readiness of space agriculture. However, they do not possess their own workstation and rely on multipurpose ones.

2.4.1. Recent Plant Growth Chambers in Space

Vegetable Production System (Veggie)

The Vegetable Production System, commonly known as Veggie, is an active NASA mission that launched in 2014 (NASA, 2024). The growth chamber features a simple design inspired by greenhouses and operates with minimal power. It consists of a base tray measuring 29.2 x 36.8 cm, to which plant pillows containing seeds are attached. These pillows are embedded with nutrients that are gradually released as water is manually injected into them. A transparent plastic cover encloses the chamber and can be folded down to provide access to the plants (see Figure 9). The cover is magnetically attached to the lighting system, which is located at the top of the chamber at a height of 47 cm from the base plate (41 cm above the plant pillows) (NASA, 2020b; Levine et al., 2016).

Veggie does not have its own atmospheric control system; instead, it relies on the Environmental Control and Life Support System (ECLSS) of the ISS. Air is drawn into the Veggie system, and internal fans circulate it to prevent stagnant air, as convection does not occur in microgravity.

Advanced Plant Habitat (APH)

The Advanced Plant Habitat (APH) is a state-of-the-art plant growth chamber developed by NASA that is fully automated (See Figure 9). Launched in 2017, it is the largest plant growth chamber sent to space (NASA, 2017). With its additional support systems and a cultivation area 1.4 times larger than Veggie, the APH is approximately the size of a mini fridge (ISS National Laboratory, 2024).

To minimize crew time, astronauts are only required for installation, after which the system is controlled remotely from the ground. The APH features its own closed-loop environmental system, making it largely self-sufficient (NASA, 2017). All functions, including nutrient delivery and atmospheric control, are fully automated, ensuring a stable environment for plant growth. In addition, the APH is equipped with 180 sensors and cameras, allowing for continuous monitoring of the cultivation process (NASA, 2023).

The two plant growth chambers currently aboard the ISS represent state-of-the-art advancements in space agriculture. However, they do not include any dedicated supporting systems and notably lack a specific workbench. Instead, they rely on a general workbench, which will be described in the next subsection.

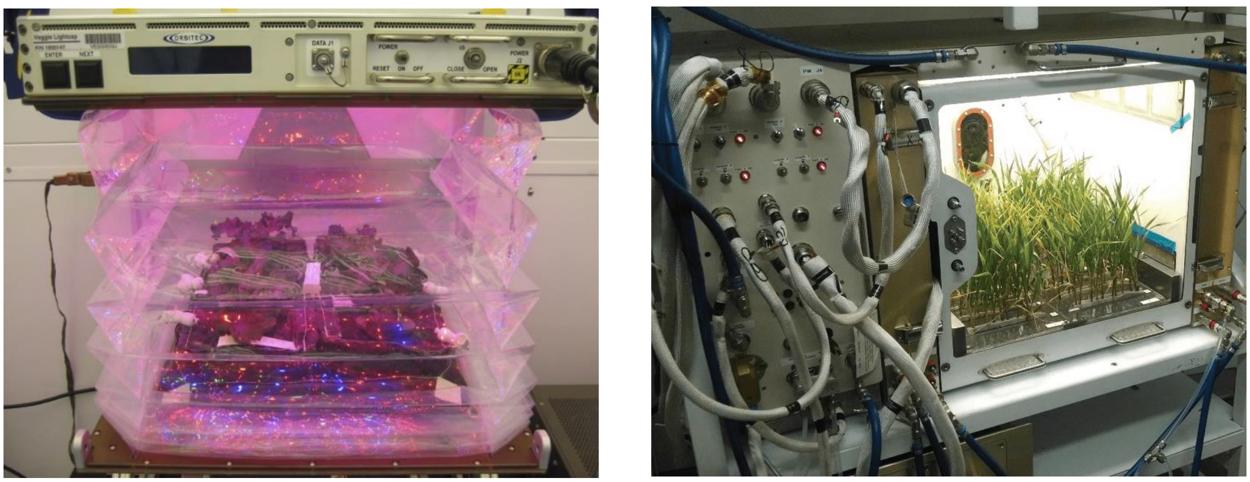


Figure 9: Left, photo of the Veggie system (NASA). Right, photo of the APH system (NASA).

2.4.2. Workbench

Research has been conducted into the design of tables and workbenches adapted for use in lunar environment. However, no such designs were found. During the Apollo program, astronauts were not provided with a table due to the extremely limited space within the Lunar Excursion Module (LEM). Instead, a notepad was used as a rigid surface. Additionally, no official scientific experiments were conducted inside the LEM. Since then, humans have not returned to the Moon.

On the other hand, the ISS serves as a valuable source of information. As all activities aboard the ISS must be publicly accessible, it allows for detailed user-interface analyses through visual content.

Work Surface Area (WSA)

The ISS includes a general workbench called the Work Surface Area (WSA), which is part of the Maintenance Work Area (MWA) located in Node 2. This versatile table is used for both maintenance tasks and scientific experiments, such as harvesting plants. The WSA consists of a rigid surface that can be folded to adjust its size, with a maximum surface area of 63.5 x 91.4 cm. Two detachable arms provide flexibility for securing components that support various activities, such as cameras or computers (NASA, 2020c). Additionally, seat tracks are incorporated on the surface to secure equipment adaptively and effectively during use (see Figure 10).

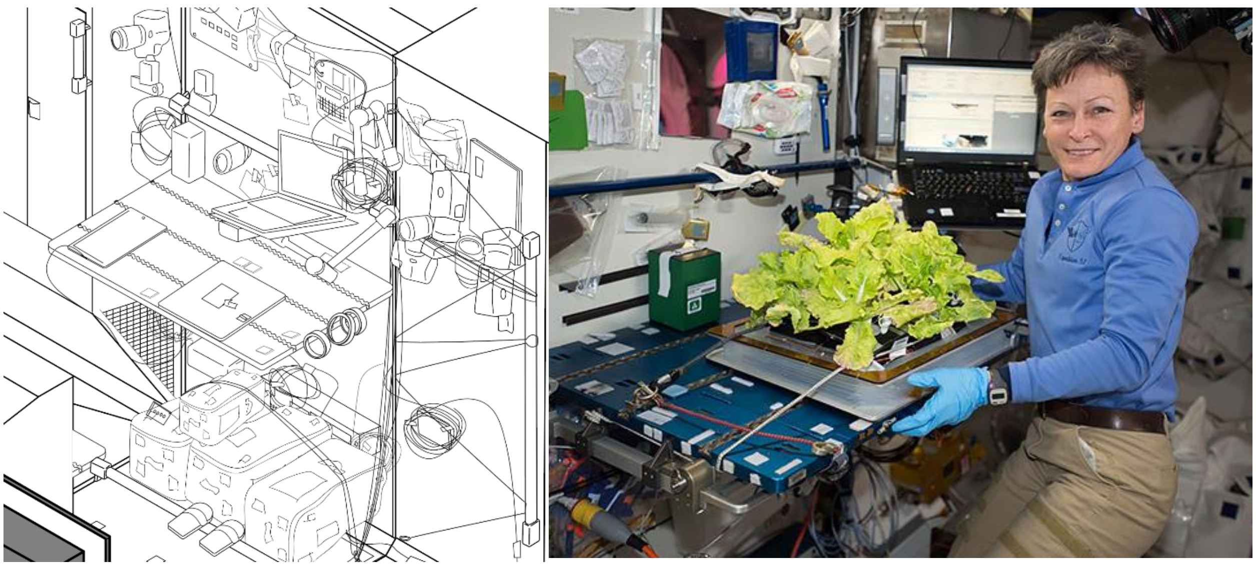


Figure 10: Left, comprehensive drawing of the WSA in Node 2. Right, astronaut Peggy Whitson handling Veggie on the WSA (NASA/Peggy Whitson)

ISS Galley Tables

There are two additional tables on the ISS, both reserved for food-related activities. One is located in the Russian segment (Zvezda Module), and the other in the U.S. segment (Node 1).

The table in the Zvezda Module is highly focused on eating functions, integrating features such as food warmers (see Figure 11). It is a close replica of the table designed for the MIR space station (Haeuplik-Meusburger, 2011).

The U.S. galley table, designed by highschoolers in collaboration with NASA Hunch, has a design similar to the WSA but with different dimensions (which could not be found). Handles are located on the sides of the table to help position the body comfortably relative to the surface and to attach necessary tools, such as scissors. The top surface includes Velcro and tape, allowing astronauts to secure food and utensils in place (see Figure 11). The bottom surface is equipped with seat tracks to secure equipment and storage (Bennett, 2016).

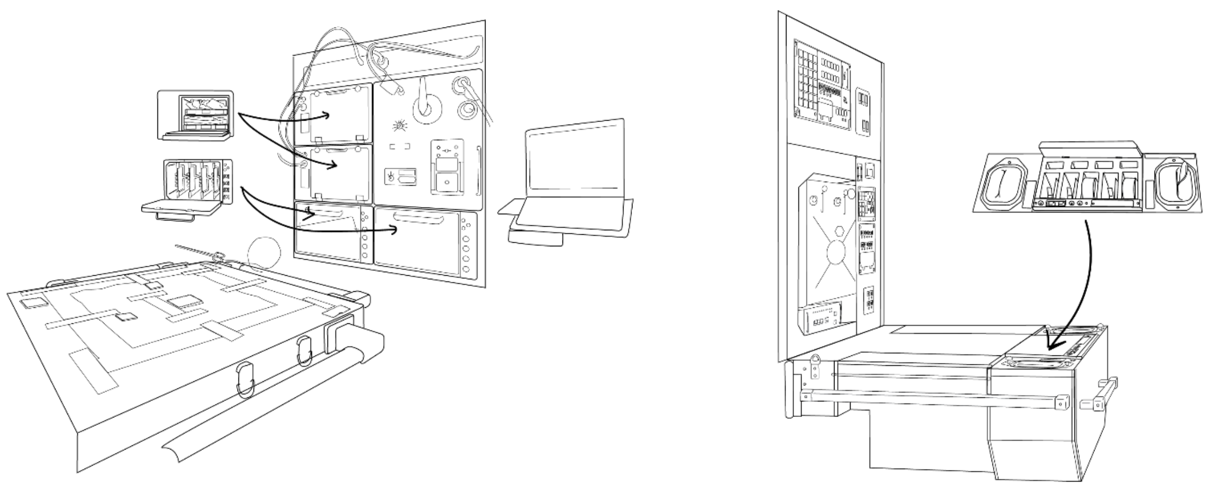


Figure 11: Comprehensive drawings of the US galley table (left) and Russian galley table (right).

Overall, workbenches in space programs are designed with high flexibility to accommodate a wide range of functionalities. As spacecraft volume and payload weight are limited, equipment must be versatile enough to support diverse activities. This necessity drives the clever and efficient designs created by space engineers.

2.5. Lessons learned

After completing the literature review, it can be concluded that no existing system matches the design and challenges of the workstation to be developed in this thesis. Nevertheless, other conclusions have been reached that can positively influence both the design process and the final design of the workstation.

1. DESIGN BASED ON USER EXPERIENCE AND FEEDBACK

   As observed in the development of Antarctic agricultural facilities, users play an active role in shaping their environment. Many facilities are spontaneously created, while planned ones are often customized over time. The updates made between EDEN ISS and EDEN Luna exemplify how user feedback can successfully retrofit projects to enhance usability based on actual experience. Engaging the crew members who have worked on heritage projects of LAM-GTD and present at DLR, is a valuable source of information that should be leveraged in the workstation's design process.

2. FLEXIBLE DESIGN

   Successful designs are often the simplest ones, offering flexibility in their use. Users have their own habits and preferences and should be trusted to decide how best to utilize a design. The simplicity of the Antarctic workbenches and the ISS WSA is a key strength, allowing these designs to remain functional and adaptable over time and across diverse users and activities.

3. ENHANCE FUNCTIONALITY

   Dedicated workbenches, like those found in EDEN ISS and the ISS WSA, are critical for efficient operations. These workstations provide not only physical support for activities but also integration with tools and equipment needed for scientific and maintenance tasks.

4. Reliability and automation

   Antarctic projects and space systems emphasize the need for highly reliable and automated operations due to the limited opportunity for intervention. EDEN ISS and APH rely heavily on automated environmental controls and monitoring systems, minimizing the need for human input and easing the work effort needed by the crew.

5. Resource management

   In orbit, as in Antarctica, space and resources are limited. Designing equipment that delivers maximum functionality with minimal resources and weight is mission-critical.

6. System accessibility

   Maintenance is a critical activity in isolated environments. Ensuring accessibility to supporting systems for maintenance and repair is a key requirement, as highlighted by crews working on EDEN ISS in Antarctica.

7. Nursery in close relation with the workbench

   Antarctic facilities, such as the SPFGC and the Hydroponics Unit of Scott Base, have highlighted the importance of proximity between the workbench and the nursery. Sowing and transplantation activities, in particular, require a large and flat surface for efficient operation.

3. Design Process Methodology

3.1. Method Overview

As the project is rooted in addressing human factors issues, the method follows a human-centered approach inherited from NASA's Human Design Integration Handbook (HDIH), NASA/SP-2010-3407 (NASA, 2014a) and Human Design integration Processes, NASA/SP-2010-3407 (NASA, 2014b). Additionally, the project is developed in the context of a partnership between two space agencies, requiring a rigorous system engineering methodology and ensuring compliance with human factors requirements. This process is called Human-Centered Design (HCD) as it involves the users early in the project (NASA, 2016).

The HDIH is a resource providing guidelines to design human-machine interfaces, such as controls, displays, architecture, environment, and habitability support systems. The handbook is applicable to all human spaceflight projects and operations. The explained methodology that follows is extracted from chapter 3 of the HIDH (NASA, 2014a).

As a primary step, program-specific requirements are extracted from NASA Space Flight Human Systems Standard (SFHSS), NASA-STD-3001, Volume 2. This document provides the human-system interaction standards that are applicable to the project and how to verify them. This step aims to prevent delayed requirements definition which harmfully impacts time, cost and project quality (NASA, 2014a).

The HIDH provides a framework to follow in the design process of the project's development (NASA, 2014) and explained in Table 1:

- The *Conceptual phase* (sections 3.2 and 4.1) defines broad assumptions of the system's goal and human role within,

- The *Preliminary Design phase* (sections 3.3 and 4.2) is an expansion of the conceptual framework and provides basic decisions on system design, including iterations and trade-offs,
- The *Final Design and Fabrication phase* (sections 3.4 and 4.3) describes the finalization of a precise design after trade-offs ready to be build and tested,
- The *Test and Verification phase* (sections 3.5 and 4.4) presents how the system will be tested for verification of the design, with the help of a fabricated mock-up and users,

For this thesis, the aim is to develop the workstation up to the verification phase. Due to time limitation (six months), the later phases as operation, retrofit and close-out are not applicable here. These phases are associated with output deliverables and documents.

Table 1: The next table summarizes the phases associated with the output documents relevant to this project.

Phase	Phase definition	Human factors output documents
Conceptual	System goals and basic mission function requirements	Lessons learned from relevant projects
		Mission scenarios and Concept of Operations
		Human factors requirement document
		Anthropometric Analysis
Preliminary Design	Defined mission with performance requirements, preliminary exterior boundaries, identification of basic items and areas with which the crew interfaces	Crew duties and tasks scenarios
		Selection and preliminary design of equipment that interfaces with crew
Final Design	Basic system layout with crew duties and activity centers defined	Precise trade-offs analysis
		Detailed drawings of the systems
Test and verification	Final system configuration	Low fidelity mock-up
		Usability Test report and recommendations

3.2. Conceptual Phase

3.2.1. Operational Context and Concept of Operations (ConOps)

Operational Context

The workstation operates within the Lunar Agriculture Module (LAM) of the Ground Test Demonstrator (GTD), as shown on Figure 1 (p.12). These modules have a primary structure similar to that of ISS modules, with external dimensions of 6.72 m in length and 4.46 m in diameter. They would be used longitudinally and will be supported by yet-to-be-designed feet (Maiwald, 2024).

Internally, a secondary load-bearing structure supports ISPR-inspired racks, along with floor and ceiling fittings. Systems such as the AMS, NDS, and TCS are integrated within the floor and ceiling. Cultivation racks cover most of the wall surfaces, accommodating 48 trays, each measuring 70 x 70 cm. Near the entrance of the LAM, two small service racks house additional systems, one of which will hold the workstation to be designed (see Figure 12).

The baseline structure of the racks was established during the CE study in March 2024, featuring a C-profile shape that aligns with the module's curvature. Liquifer Systems Group later refined the rack design. The final dimensions of each rack are 250 cm in height, 49 cm in width, and 113 cm in depth, divided into four vertical segments. The top and bottom segments are 61.5 cm high, while the middle segments are 57.5 cm high. Detailed plans of the rack are provided in Appendix A2.

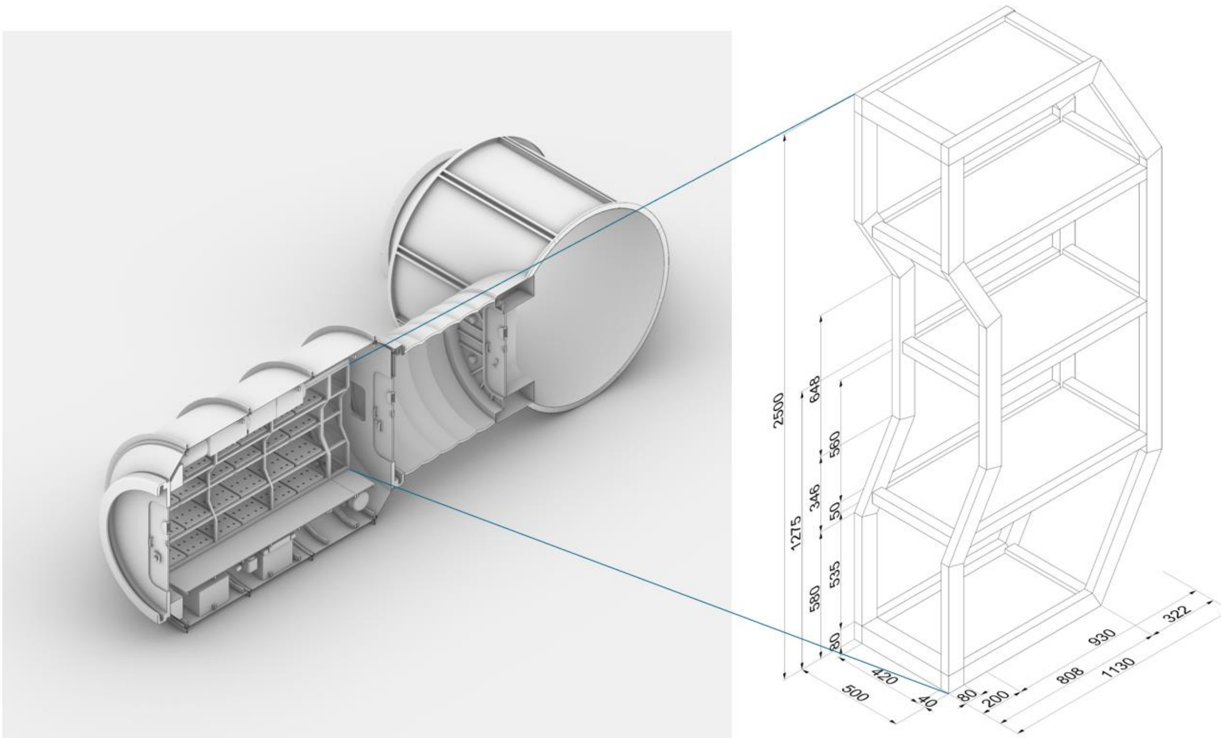


Figure 12: Left, open isometry of LAM-GTD. Right, isometric drawing of the service rack assigned to the workstation.

Concept of Operations (ConOps)

During the CE study, several human factors issues were identified as open considerations. In consequence, the initial required subsystems within the designated rack include a workbench and storage. With more research, the end goal of the ConOps documentation is to provide an extensive list of needed subsystems, alongside their corresponding requirements.

The research included review of similar systems, especially EDEN ISS, Luna and LAM-GTD's reports and articles, discussions with the EDEN Initiative's team about the activities to be performed and feedback from the next subsection 3.2.2. User Task Analysis. This review helped identify crucial gaps allowing a precise list of necessary subsystems within the workstation and their requirements.

3.2.2. User Task Analysis

A User Task Analysis (UTA) is a systematic review of a system by Subject Matter Experts (SMEs) to identify its needs and challenges, focusing on the human-system interaction (Tosi, 2020). In the context of this project, the aim is to help identify the necessary components and their requirements for a workstation in a lunar agriculture module.

The UTA was conducted from August 6 to October 1, 2024, under a questionnaire format. The SMEs profile required them to be experienced professionals in hydroponic systems in extreme and/or closed environments, including both natural scientists and engineers. Identifying the sample population was challenging due to its limited size. The goal was set to 10 responses, ensuring high-quality feedback and confirming that the participants met the criteria to answer the form.

The structure of the form is divided into three sections:

- The first one collects participants data, notably gender, height and professional position,
- The second part focuses on general tasks performed in an agricultural module,
- The last section narrows down on specific elements that would be required by a workstation for an agricultural module. This part mixes both closed and open questions.

The whole questionnaire was created with Google form and can be found in Appendix A6.

Section 1: Sample Population

For this UTA, the sample population was contacted individually to ensure the high quality and relevant answers from experts with sufficient understanding of the system. This resulted in an intentional small sample. Most of the demographic had worked on the legacy project (EDEN ISS), ensuring a good understanding of the future project (LAM-GTD) and its challenges.

Efforts were made to increase the demographic sample size by contacting experts having worked on similar systems, such as the South Pole Station Food Growth Chamber. However, no answers were received. While only 10 answers were collected, their quality was satisfying and valuable conclusions for the LAM-GTD's workstation design could be drawn.

Section 2: General Tasks in Agricultural Modules

The goal of the present section is to verify if any subsystems and associated tasks are missing from the ConOps, as well as to identify the loads and criticality of each task to determine where the focus should be placed.

These tasks were then rated by the participants according to 5 criteria:

- Criticality, define as the degree of impact of a task on the success or failure of the mission,
- Time spent on each task, considering the total amount of time spent in the greenhouse,
- The occurrence or frequency of each task (daily, weekly, monthly, less than once a month, varies on the mission, do not know),
- Physical load associated with a task,
- Mental load associated with a task.

A final open question was included at the end of section 2 to allow participants to comment if any task had been overlooked.

Section 3: Workstation's Equipment Evaluation

This third section of the UTA focuses on the valuation of different equipment that had been identified previously during the CE study and subsequent discussions within the team. These elements are considered necessary but were left as human factors open issues. Some of them could not be accommodated in the final design. All of them are related to the tasks to be performed at the workstation:

- Collapsible table,
- Tool pockets,
- Control Panel,
- Stepping Platform,
- Sink/water access,
- Waste management compartment.

Each element is covered by two standardized questions: one assessing the usefulness of the item and an open question on the features the participants would like to see added or avoided for that exact element. Other questions are added as fit to the elements and degree of complexity. Finally, similarly to section two of the questionnaire, an open question allows the participants to add any comments or express their opinion on elements that could've been forgotten until now.

3.2.3. Anthropometric Analysis

NASA's HIDH advises performing an anthropometric analysis of the environment where the system should be designed to accommodate the optimal operational performance of a large sample of the population. Anthropometry refers to the study of the human dimensions, required clearance and strength. Performing this step ensures that the entire intended population can use properly the system.

For this study, the target population includes astronauts and analog astronauts. Therefore, the same sample population as outlined in NASA-STD-3001 (2014a) has been used. This demographic ranges from the 5th percentile Japanese female (148.6 cm high), as the smallest representative, to the 95th percentile American male (194.6 cm high) as the largest.

A standardized 3D model dummy has been created, with dimensions adjusted to match these previously defined extremes. These dummies were then positioned in various potential postures relative to the rack. This process ensures accessibility for the selected population as well as the necessary clearances.

3.3. Preliminary Design Phase

3.3.1. Crew Duties and Tasks Scenarios

To optimize the design of each workstation component, a comprehensive list of tasks and activities needs to be defined. This list is based on the lessons learned during the EDEN ISS operations from which the crew established an unpublished list of activities, including the average time required for each task, etc. While EDEN ISS and LAM-GTD share similar components, their configuration differs, necessitating a translation of tasks from one to another.

Supporting documentation, such as worksheets and procedures, was used to identify tasks and estimate their duration, occurrence, criticality and location within the workstation. Time spent in the DLR hydroponic laboratory with experienced professionals served as an analog for LAM-GTD operations. Detailed notes were taken from the observation of the performed tasks. Detailed observations of tasks performed in this setting, along with EDEN ISS procedural references, enabled the development of specific scenarios for LAM-GTD.

Additionally, the answers of the UTA provided supplementary insights into the activities and tasks to be carried out using the workstation. A final list of primary tasks and subtasks will be established, along with clear definitions. This list will inform where each task needs to be performed and guide the system design according to these requirements.

Using the task list developed previously, a component tree was established linking the subsystems to their associated tasks. This document illustrates the flow of activities occurring within the rack and provides insights on possible similarities or pain points between subsystems. The task tree was derived from the tables' column of tasks associated to systems and confirmed with a team of experts.

Unlike the previous document, the process is reversed: starting from the systems and assigning then the tasks. This approach acts as a verification step in prevention of overlooked tasks-subsystem assignments. As this document is highly visual, a color code was created for easy readability.

3.3.2. Preliminary Design Configuration

The design process requires an initial configuration of the workstation before further refinement. The rack's structure and dimensions are provided by Liquifer System Group and explained in 3.2.1. Definition of Concept of Operations. The various components must fit within the given rack. Its structure is divided into four segments with two types of dimensions and volumes (middle segments and end segments), each offering a different range of accessibility based on its position and depth.

The workstation subsystems were identified during the ConOps and UTA phases. Estimating their size, volume, and specific requirements helps define preliminary configurations, which can then go through a trade-off analysis to determine the optimal layout. Subsequently, a couple of layouts were designed and analyzed for optimal performance of the users through a trade-off analyses. Results were presented to the team and agreed upon with a majority.

For early configuration modeling, a flexible CAD software was used (Rhino), in combination with 2D illustration tool. Rhino, the same software as Liquifer System Group, was used to extract the isometric drawing of the structure. After the rack structure was extracted, Krita (an open-source illustration software) was used for rapid and adaptable configuration drafting.

In addition to providing preliminary configuration drafts, this step allows for accommodating as many component functionalities as possible, as some will likely be refined or omitted in later designs. The final configuration was agreed upon during a team meeting, selecting the best trade-offs.

3.4. Final Design Phase

Decision Rationale and Design Trade-offs

After agreeing upon a general rack configuration, each component was researched in more detail. Hereafter is provided the list of components used already in the preliminary design:

- Workbench and Sink
- Waste compartment
- Storage
- Nursery

Desired functionalities for each component were extracted from the requirements established in the ConOps. The possible mechanical forms that functionalities might take were then brainstormed for later trade-offs. Research on different types of mechanisms and discussion with the team formed the main source of inspiration. In parallel, objective information, such as dimensions, volume, price, advantages, disadvantages, and other miscellaneous considerations of the possibilities were collected in a working table.

Possibles design for each subsystem was then drafted with the help of a 2D drawing software, for fast brainstorming, and presented to the team for review, alongside the informative tables. An example of these design's ideation in provided in Appendix A3. Suggestion for improvement were suggested during discussions and were studied. Some of these adjustments were integrated into the final design. Tasks that had to be performed were taken into consideration when selecting the final designs. Criteria of selection were including, but not limited to: practicality, ease of use, flexibility, durability, feasibility, etc. Confirmation with the requirement document were made to ensure compliance them.

This process allows for a methodical and comprehensive comparison for each subsystem. This process was repeated for each subsystem, which was agreed one by one with the entire team.

FINAL DESIGN DRAWINGS

The final plans were created using the 3D modeling software Rhino. The drawings were developed with detailed precision and technicality, keeping in mind the goal of building a mockup to test the design's usability. Another objective was to provide the team with an advanced design that would contribute to the overall LAM-GTD project.

3.5. Test and Verification

3.5.1. Low Fidelity Mockup

The first step in the creation of the mockup has been to define the scope and purpose of tests to be performed. Beginning by identifying the key functionalities and interactions provides with an essential component to be built. Compliance with the ConOps and tasks list to evaluate all essential functionalities within the workstation was ensured.

Creating a low fidelity mockup is advised by the HIDH in early projects so that modifications and adjustments in the projects can easily be reflected in the mockup. The choice of the materials needs to be thoroughly considered and be in adequation with the workspace and skill capacity, as well as the budget. Sketches and 3D modeling of the envisioned mockup helped to visualized and increasing the details helped to prevent later errors during the building phase.

3.5.2. Usability Test Procedure

Usability tests are a key process to verify and validate a human-centered design. Through the review of design, it provides supplementary recommendations for further improvements. Usability tests are an iterative process required until flight approved to collect information on the product for further improvement, but we will apply only once to this project that is in earlier development (NASA, 2014b; Tosi, 2020). According to NASA's HIDP, the usability test should be performed following the steps described in Table 2.

Table 2: Steps definition in the development of a usability test and specific steps to the project.

Steps	Description	Project specific steps
1. Define the purpose of the study	Identification of the features of the design that should be tested depending on their criticality (importance, frequency of usage, problematic features, etc).	Table deployment (surface, height), access storage, access waste compartment, sink ergonomy, sink system access.
2. Define the tasks	Develop a task list linked to the tested features, interactions, critical activities, error risks. State operating environment and available resources.	Table deployment and height adjustment
3. Identify the user sample	The user population should be representative of the user group in terms of age, morphology, professional expertise etc.	Same population as the UTA, but limited to the population on site.
4. Select methods and metrics	Select a method and metrics (qualitative and/or quantitative) depending on the type of system, fidelity of the mock-up and the user sample.	After performing the tasks scenarios, a lead interview will be conducted, regarding each task and features.
5. Plan Evaluation Design	Define a number of participants according to the type of data intended to be collected.	Two to four participants with diverse height and skillset will perform the test.
6. Collect Data	Data collection as planned in the previous step. Highlight the mock-up's level of fidelity.	Mostly qualitative data will be collected during the interviews.
7. Analyze Data	Conclusions and recommendations extraction from the data regarding the objectives. Quantitative methods are appropriated for system design comparison for example. Qualitative methods provide user needs and preferences. Decide on the most appropriate descriptive and statistical output.	Conclusions and recommendations will be extracted from the data collected. As the user sample is very limited, quantitative methods will be avoided as much as possible.

During the design process, the nursery has been developed to a lesser extent due to its high technicality. It is represented for the project as a space holder with broad assumptions. It was then decided that the system wasn't ready for the usability test as it would be detailed in later projects. Hereafter, the subsystems' list to be tested:

- the workbench deployment and nominal usage,
- the sink,
- the waste compartment and,
- storage access will be tested.

After the creation of the procedure, dry runs were performed internally the team to ensure its smooth functioning and eradicate any consistencies. Keeping a simple procedure based on the specific tasks will prevent errors.

The usability test procedure was fully developed and the SMEs planned to participate in the test were limited to four on site. As the ambition of this thesis is to follow a scientific approach, the available sample population was considered too small, and the test postponed for future work. A new plan with a wider sample population has been planned to be performed and published for the 54th International Conference on Environmental Systems (ICES), in Prague, 2025.

4. Results and analysis

4.1. Conceptual phase

4.1.1. Concept of Operations and Requirements

From thorough review, a precise list of subsystems necessary to the workstation rack was identified. These elements are mission critical and couldn't be fitted elsewhere in the module. Hereafter in Table 3, the extensive list:

Table 3: Subsystems to be developed for the workstation and their definition.

Subsystems	Description
Deployable Workbench, with integrated sink	The workbench will be composed of a top surface to support agricultural tasks. If possible, it will host a sink necessary for cleaning activities.
Waste Compartment	The waste compartment is necessary to collect the diverse waste created within the module.
Nursery	The nursery, or germination chamber, will host the sowed seeds in waiting of germination and transplantation to the cultivation trays.
Storage	Diverse storage spaces are required to stow tools, material, seeds, crop and maintenance supply, etc.

Additional movable objects were considered, such as a control panel, tools pockets and a stepping platform to access the highest levels of the rack. Initial research of these elements was performed but didn't go through for time and resources constraint.

Finally, requirements were identified from preliminary research and were iteratively updated, notably with the help of the UTA. These requirements were categorized according to subsystems, with an additional general category. A reference code was assigned to each requirement, starting with the two first letters of the subsystem and finishing with a number (eg: WO-01 for the first workbench requirement). The requirements documentation is provided in Table 4.

Table 4: Requirements definition (by subsystems).

General Requirements

GE-01	The workbench shall have a sink large enough to accommodate some of the largest elements of the system.
GE-02	The sink shall be coverable when not in use to allow more surface area.
GE-03	The hydraulic system of the sink shall be easily accessible for maintenance

Workbench Requirements

WO-01	The workbench shall be deployable and shall be stored away when not in use.
WO-02	The workbench shall be adjustable in height to accommodate comfortable standing work position of 5th female percentile to 95th male percentile when standing.
WO-03	The workbench shall be large enough to accommodate a cultivation tray (70 x70 cm). If the table has deployable panels, gaps should be waterproof.
WO-04	When deployed, the table shall sustain a weight of 100kg without breaking, shaking of bending.
WO-05	The workbench shall be deployed in one gesture to ease deployment and storage.
WO-06	The workbench shall have a be easy to clean (material and form) with a simple wipe or sponge.
WO-07	The workbench shall accommodate a "dry area" to leave sensitive elements such as notebooks, electric appliances etc.
WO-08	The workbench shall be equipped with an integrated lighting system that provides sufficient illumination for the workspace.
WO-09	The workbench shall accommodate some storage units and tools holders for items used daily.

Nursery Requirements

NU-01	The nursery shall accommodate at least two cultivation trays.
NU-02	The nursery shall possess its own CEA systems (LCS, NDS, AMS) and be enclosed.
NU-03	The nursery systems (LCS, NDS, AMS) shall be easily accessible for maintenance.
NU-04	The nursery shall be accessible by EVE's robotic arm.
NU-05	The cultivation trays shall be visible and accessible at all time and configuration of the rack.

Waste Compartment Requirements	
WA-01	The waste compartment shall accommodate general and biological waste.
WA-02	The waste compartment shall accommodate a daily amount of waste.
WA-03	The waste compartment shall be easy to clean (material and form) to prevent any residue.
WA-04	The waste compartment shall be accessible at all time and configuration of the rack.

Storage Requirements	
ST-01	The workstation shall have accessible storage
ST-02	The workstation shall have enough storage space for essential items (gloves, daily used tools, sanitizer, ...)

4.1.2. User Task Analysis

While only ten responses were collected, they presented high quality answers, and it was possible to draw some conclusions for the LAM-GTD's workstation design.

Section 1: Sample population

The sample population is 10 persons with 6 men and 4 women. Eight out of the 10 participants worked on EDEN ISS in Antarctica, including two overwintering crews. The participants' profiles were diverse with two interns, five engineers and three natural scientists. The height of the participants ranged from 164 to 197 cm with an average of 178.1 cm, which is around 6 cm higher than the median height (171.6 cm) considered for the anthropometric analysis. Women average of 170 cm and men with 183 cm.

Eighty percent of the population was professionals having worked on EDEN ISS in Antarctica. The 20 % remaining were interns working in the EDEN research group and their labs. Professionals had a higher degree of engagement. The professionals tend to provide longer answers to the open questions, showing more experience and care about the improvement of the system. In terms of background, the sample was perfectly balanced between engineers and natural scientists.

Section 2: General Tasks in Agricultural Modules

As the sample population was limited, trends in the task rating section were infrequent to be found. However, a couple tasks stood up in the answers.

The system maintenance task has been rated by 8 out of 10 participants with the highest level of criticality, emphasizing its importance with very high mental load rating, for both engineers and biologists (see Figure 13). Answer in the open question provided explanation, pointing out the system's lack of access for maintenance. Designing an accessible supporting system would unload the mental weight of this task.

In opposition, the germination task was valued with low rates for the totality of the questions. Eighty percent of the participants considered the task to cover on average 0 to 5 % of the mission time, rating it in general the least time-consuming one (see Figure 14). Similarly, all the participants rated the task as 2 or below (score from 1 to 6 being the highest) for the physical challenge, with a majority choosing the lowest score (see Figure 15). Similar rates were observed for the mental score of the germination task (see Figure 16). Overall, tasks related to germination (nursery), seem to be considered non-critical to the mission.

For the rest of the tasks, no strong trends could be found. This might be due to the small participants population.

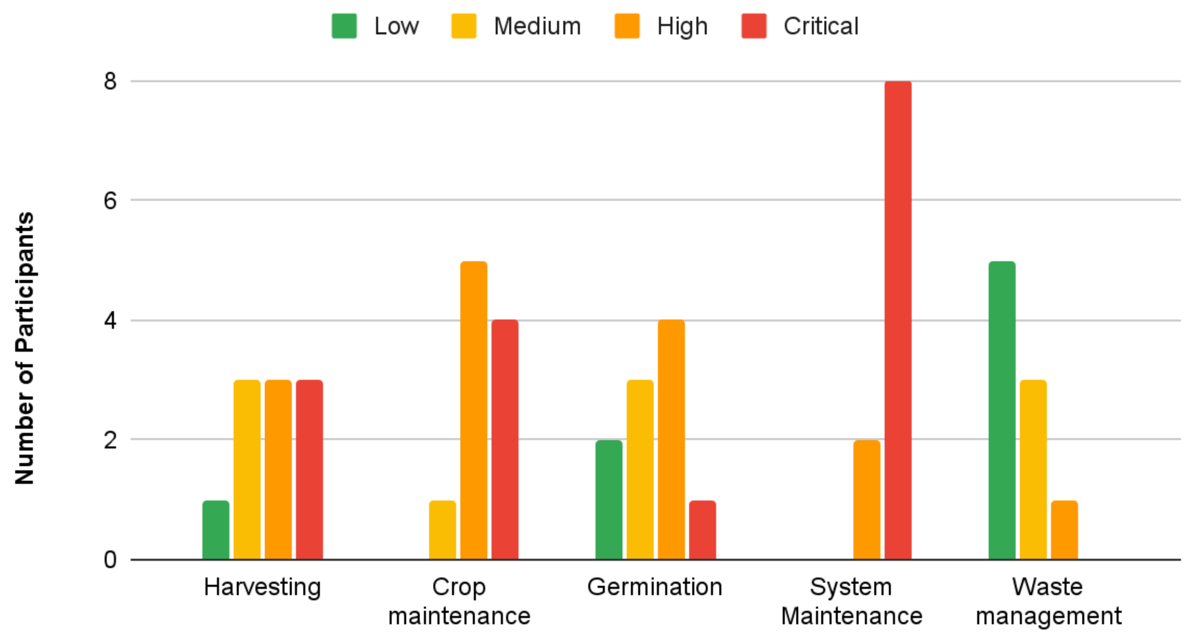


Figure 13: UTA results on task criticality evaluation.

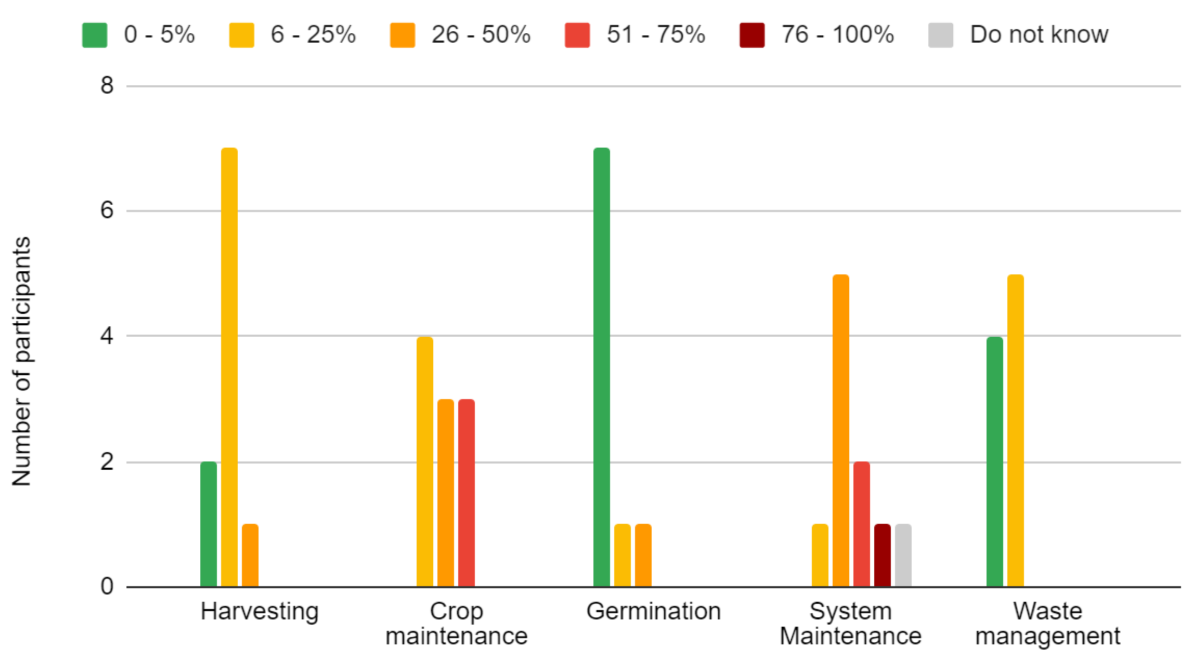


Figure 14: UTA results on average time spent on each task per mission.

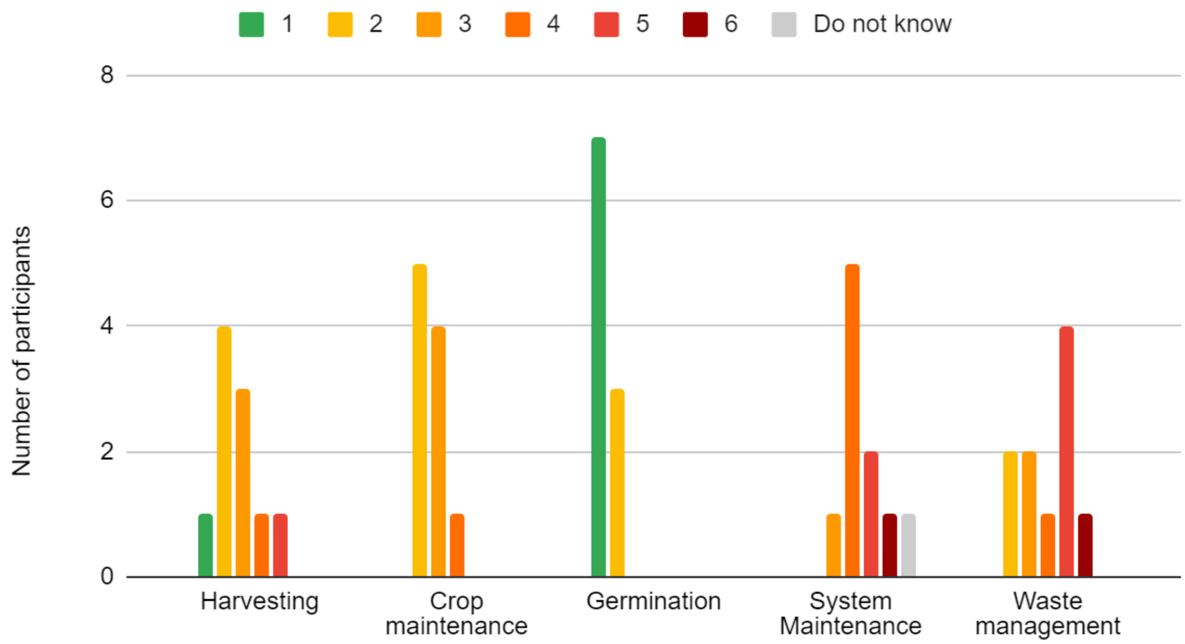


Figure 15: UTA results on physical load assessment related to a task, 1 to 6 being the highest.

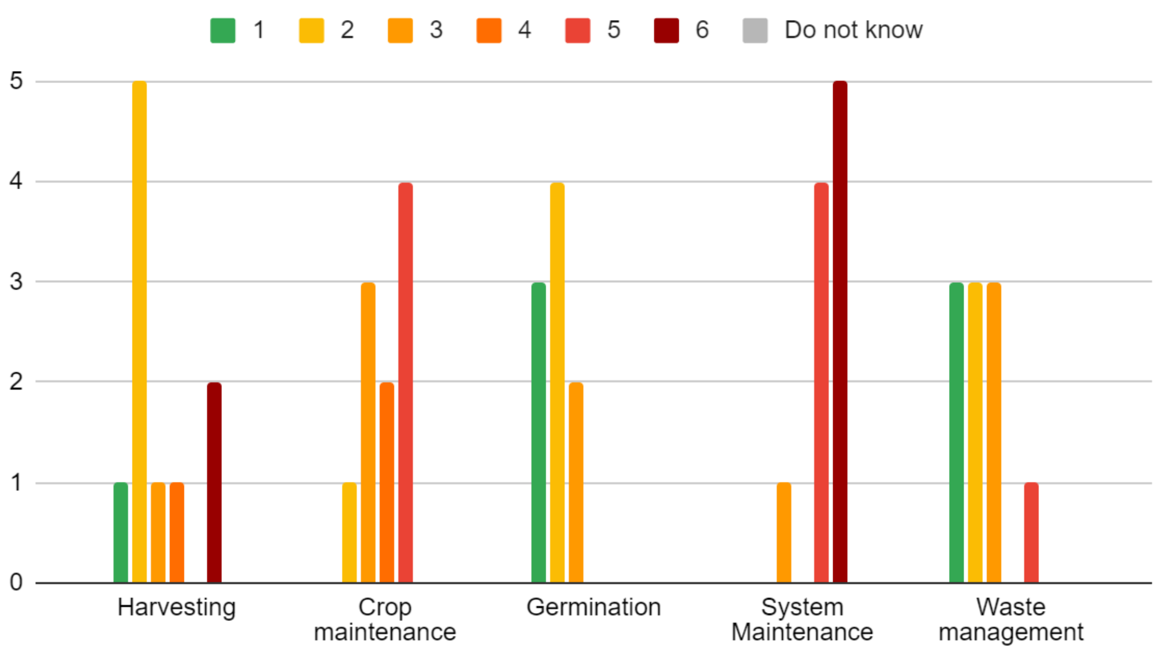


Figure 16: UTA results on physical load assessment related to a task, 1 to 6 being the highest.

Section 3: Workstation's Equipment Evaluation

For this section, questions were ordered by subsystems. The analysis follows the same pattern.

Collapsible table

The first theme of the workstation equipment evaluation focused on the use and design of the table (or workbench). Participants were asked to select the tasks for which they would use the table, with the option to choose multiple tasks as well as an "other" option, allowing for specification of additional uses. Responses were evenly distributed across all tasks, ranging from 6 to 9 selections, except for the waste management activity which received only two responses. Two of the three open-ended responses ("other") fell into the harvest category. One participant specified that they use the table as a temporary surface for storing items. It can be concluded that the table will be extensively used for all types of activities, except for waste management.

The standardized question regarding the advantage of having a collapsible table had a clear answer. The entire participant demographic rated the collapsible at 3 or higher, with 70 % selecting the highest level of usefulness, confirming the necessity of designing a collapsible table.

As shown on Figure 17, when asked to choose a minimum table size (with only one response allowed), 80% of participants selected a size between 0.315 m^2 and 0.4 m^2, while 20 % chose 0.2 m^2. Interestingly, none of the participants selected the maximum option of 0.81 m^2. Two participants mentioned in the open-ended section that they would prefer a larger table to accommodate a cultivation tray (0.49 m^2) but expressed concern about the table reducing available space in the agricultural module to move around, as they did not want to create a cramped environment.

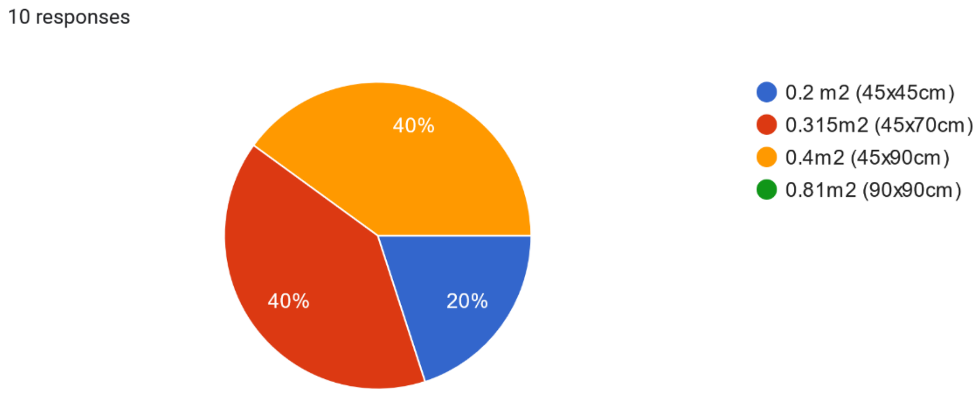


Figure 17: Distribution of the answers regarding the minimum dimensions of the deployable table.

The final question about the collapsible table was open-ended about desired or undesired features. Six recurring themes emerged: storage, item restraints, easy cleaning, dry surface, reasonable size, and ease of deployment. Since these themes were repeated and based on participants' similar experiences (mainly from the EDEN ISS project), they should be taken into consideration when designing the future table.

Tool holders

A section on the design of tool pockets and holders was initially included. The first question invited participants to choose between a worn tool pocket, tool holders attached to the structure, both, none, or other (with the option to specify). Multiple selections were allowed, and notably, no one chose "none." The majority of participants preferred having both a worn pocket and one attached to the structure, while one participant also suggested "fixed tool drawers." These responses clearly indicate a strong need for tool holders in various forms.

In the open-ended question, participants emphasized the importance of having simple yet customizable tool pockets or holders.

However, it was later decided that the tool holders would be integrated into the rack (drawers and flexible storage locations within the workbench). This aligns well with the participants' feedback, allowing users the flexibility to decide how to use these storage options.

Control Panel

A control panel inside the greenhouse was identified in the ConOps as a useful addition to make data accessible and provide control over the system from within. The control panel was also considered for use in data collection (e.g. notes, photos, etc.), which depend on its format (e.g., computer, tablet).

All participants considered the addition of a control panel within the greenhouse to be useful, scoring it 3 or higher. Sixty percent of the participants selected the highest level of usefulness, confirming the need for an easily accessible control panel.

Participants were particularly engaged in the open-ended question regarding the control panel, with nine out of ten providing responses, and seven recurring themes emerging (see Table 5). The two most requested features mentioned by four participants, were the ability to control the settings (not just data visualization) and having an intuitive user interface to easily access information.

Table 5: Reoccurring themes in the open question regarding the Control Panel.

Features	Number of participants
Control and adjustment	4
Intuitive User Interface	4
Mobile Control Panel	3
Touch screen or mic	3
Take notes	3
Show only important info	2
Back-up feature	2

Stepping Platform

We consider a stepping platform to access the highest cultivation rack. The design would likely be collapsible to be stored away when not in use.

Ninety percent of the participants considered a stepping platform necessary to access the highest level of the racks rating it 3 or above. While one participant rated the platform a 1 (the lowest score), 60 % gave it the highest rating. Overall, we can conclude that a stepping platform is needed in the greenhouse.

However, no clear conclusions could be drawn regarding the specific form the stepping platform should take. Responses to the statement, "I consider a stool sufficient to access the highest cultivation rack," showed no strong trend. In the EDEN ISS project, only a stool was available to the crew, and no issues were reported. However, the racks in LAM-GTD are about a quarter higher than those in its predecessor. Further research is needed on an elevated platform, which should be tested during the usability test.

Two recurring themes emerged from the open-ended section. Three participants suggested adding integrated or attachable tool pockets to the stepping platform to free up the hands. The second suggestion was for a deployable platform (whether a stool, ladder, or other type) that could be stored when not in use to avoid unnecessary clutter in the workspace.

Sink

It was identified that a sink might be needed in the greenhouse. Ninety percent of the participants rated the sink's usefulness as 3 or above, with only one participant giving it the lowest score. Most participants preferred a non-collapsible sink, with 80 % rating the collapsible feature 3 or below. Some comments in the open-ended section could explain these values: "A sink is very essential and often used in a greenhouse, so I don't think it needs to be collapsible."

A recurring theme in the open-ended responses was the importance of the sink being large enough to accommodate the tools used in the greenhouse, with four out of eight responses mentioning this.

Waste management

The first question was a multiple-choice question regarding the type of waste compartments necessary inside the greenhouse. All participants selected general waste, liquid waste, nutrient-rich liquid waste, and biological waste. However, hazardous waste (chemical and bio-hazardous waste) was not selected by everyone but received support from a clear majority. This suggests that all types of waste compartments are likely required inside the agricultural module.

In the open-ended section, participants emphasized the need for a waste compartment that is easy to change and clean, a point mentioned by four out of five respondents. Two participants suggested incorporating automated weight measurements to indicate when the compartments, especially for liquids, are full.

Overall open section

A final open question regarding the general design of the agricultural module received responses from 8 out of 10 participants. The answers were varied, with several interesting suggestions to consider in the design process (see Table 6). Participants tended to emphasize points that had already been mentioned in previous equipment-specific questions.

Limitations

Participants have complained about the lack of clarity in terms of definition (eg: mental load) and objectives of the mission. Some of the answers couldn't reach any conclusions due to the lack of trend. Pursuing this UTA with an increased number of participants could potentially palliate to this issue.

Table 6: Selection of answers to the eding open question regarding overall design of the workstation

I like intuitive designs to minimize frustration
a disinfect-station is useful
Storage. Probably add as much storage space as we can manage for consumables, tools and instruments, or to place spare parts or equipment during maintenance and repair activities. The storage spaces should be labeled and some type of storage management / inventory tracking system is probably needed to keep everything organized over time.
Don't overdesign these tools, and make them as adaptable as possible. Each user is different and may want to use these tools for their intended uses, body type, and how they move throughout the facility, as well as in creative ways that they intuitively come up with. Providing flexibility and maximizing how adaptable the tools are will ensure these tools are actually used and are as helpful as possible.
Make sure there is enough free head space in the corridor. Check arrangement of shelf heights (e.g. no small height shelves in the top or bottom layer). Regarding the table: There is an absolute need to have free table area to drop tools, parts, and other things (e.g. camera, notebook). I don't think only having a collapsible table is enough. This one ca only be an addition to a normal table area. Table size in the order of 600x800 mm is normally good. 450 mm sounds to small.
More or bigger work surfaces. The additional table was already suggested here, but I'd like to emphasize that more surfaces to put down tools and supplies would be very useful (by "more" I mean more than in EDEN ISS). Easy access to pipes and cables for maintenance and troubleshooting. EDEN ISS was quite badly designed in that regard. For example it was almost impossible to work on the pipings of the heating/cooling system.
Have a slightly bigger changing area for staff, gaderobe for wet clothes (snow, rain, etc.).
In general, the whole nutrition delivery system (pumps, tubes, nozzles etc.) was very unreliable. We actually spent more time maintaining the system than working with the plants. That should be improved/simplified.

4.1.3. Anthropometric Analysis

The Anthropometric analysis provided two documents: a first one presenting user's dimensions compared to the rack and a second one showing users reach. As explained in the method section, a user's low and high dimension's boundaries were defined: 95th male American percentile (194 cm) and 5th female Japanese percentile (148 cm). The dark grey dummy represents the first case, and the light grey the latter (see Figure 18 and 19).

With this help of the documents, it was possible to observe wide dispersion of height reach between the two extreme morphologies. Standing with arms down, the smallest population could reach above the middle of the rack with only the head. Within reach of the arms, they may access the third highest quarter of the rack. However, the highest quarter of the rack could be within reach only with the help of a stepping platform. The 95th percentile faces little difficulties in height reach, extending their arm almost to the top of the rack.

The width of the rack represents no issues to any of the morphologies as it is limited to 54.5 cm. Howbeit, the depth of the rack cumulating to 1130 cm. Indeed, the C-shape of the rack designed to match and optimize the round envelope of LAM-GTD, increases the total depth. These dimensions burden the entire population to access the back of the rack. While the height access may be resolved with a simple stepping platform, the depth access represents an important challenge, notably for the upper and lower quarters. Thoughtful systems placement should be considered and helpful mechanism studied.

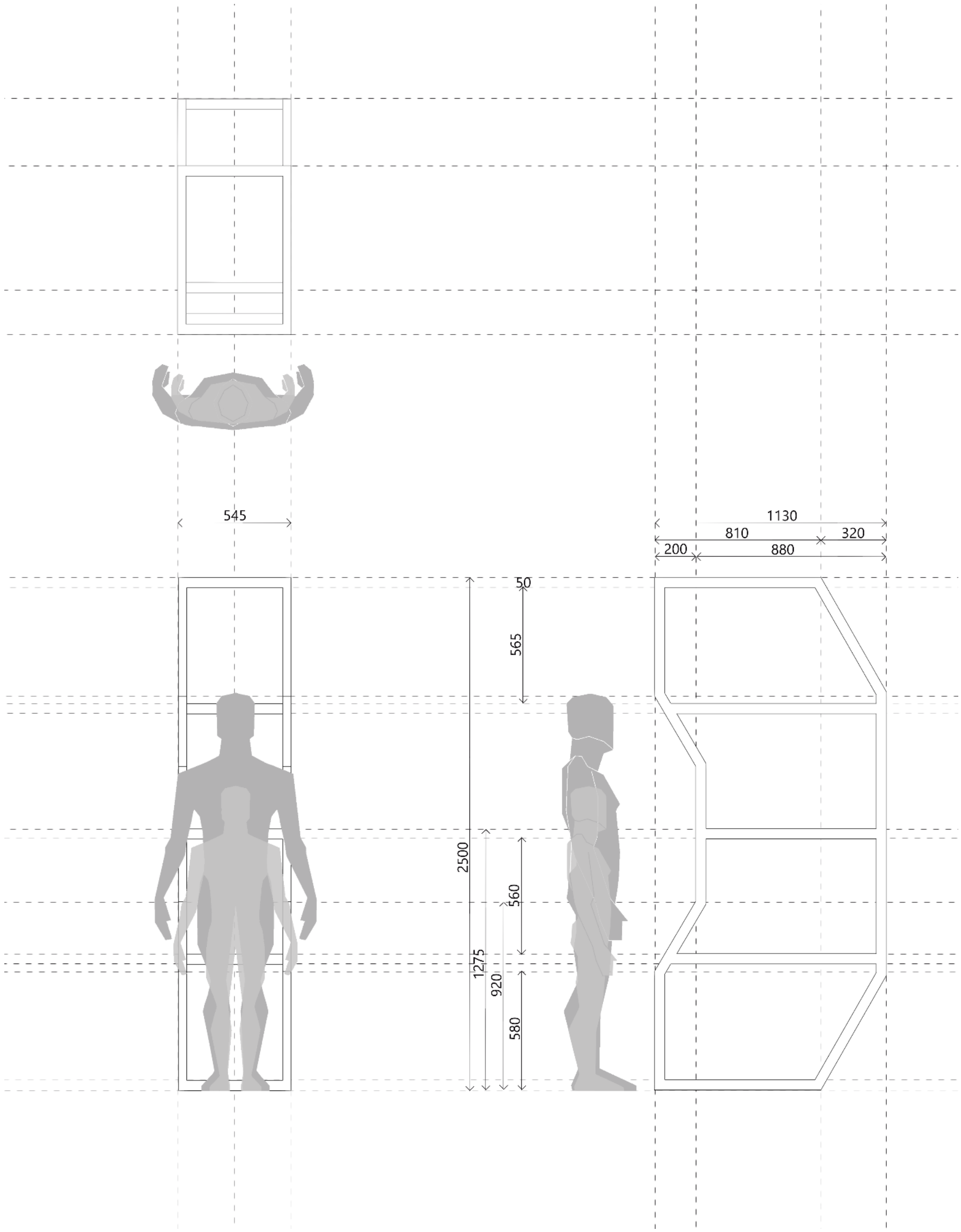


Figure 18: Anthropometric drawings of the rack's structure with the 5th female Japanese percentile (148 cm) and the 95th male American percentile (194 cm)

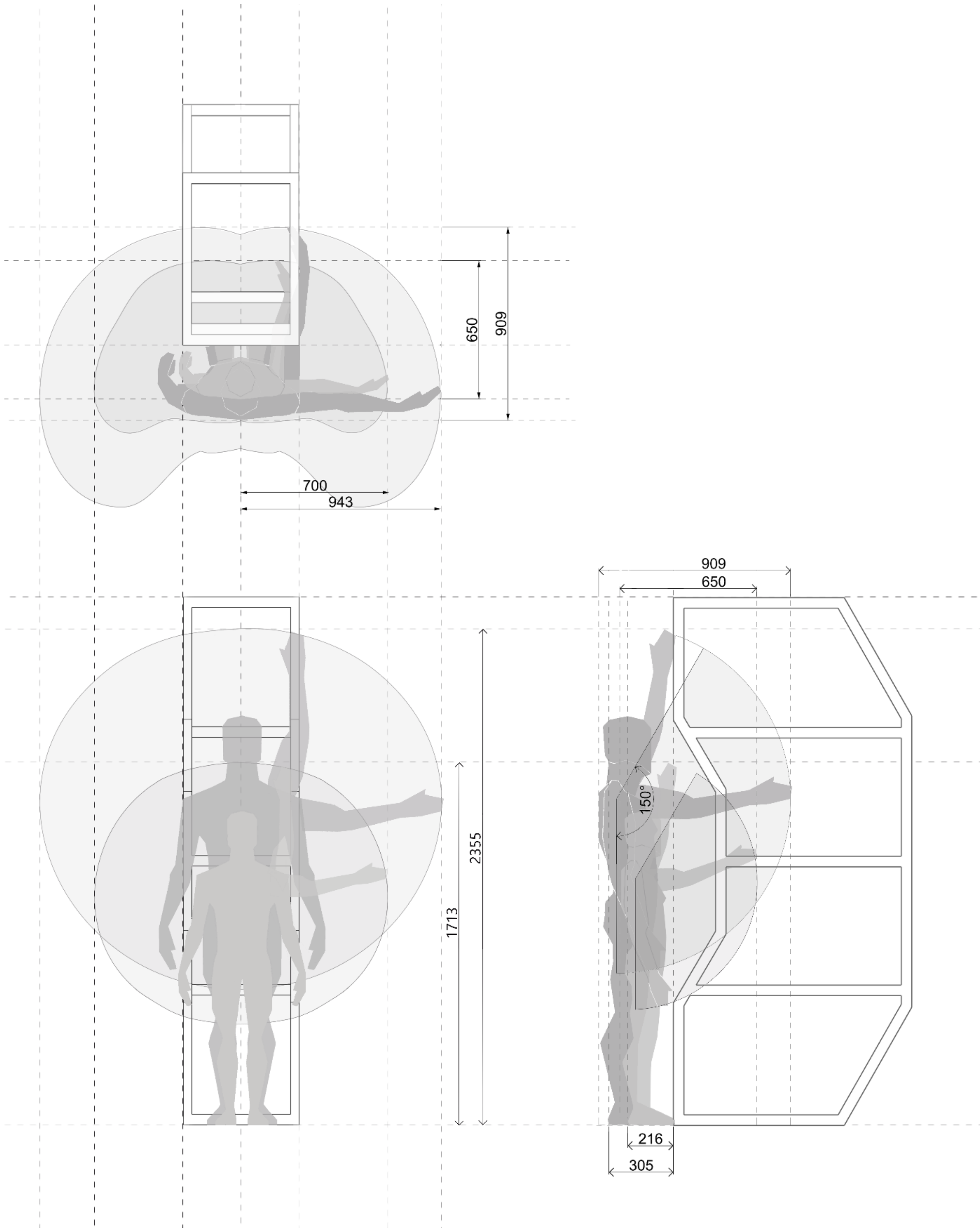


Figure 19: Anthropometric drawings of the reach of the 5th female Japanese percentile (148 cm) and the 95th male American percentile (194 cm)

4.2. Preliminary design phase

4.2.1. Crew duties and tasks scenarios

List of Tasks

As a result of EDEN ISS reviews, discussion with a team of experts and the UTA, a list of crew duties to be performed within the workstation was established. This list is composed of five general tasks defined as follows:

- *Harvesting*, includes crop harvesting, data collection and sampling,
- *Crop Maintenance* involves monitoring of the crop, data collection, pruning, and related activities,
- *Nursery* or Germination covers sowing, transplanting, monitoring and maintenance of the germination processes,
- *System Maintenance* encompass system monitoring, system maintenance, cleaning and repair tasks,
- *Waste Management* addresses various waste types, including general waste, liquid waste, nutrient-rich liquid waste, non-hazardous biological waste and hazardous waste.

These general tasks are further broken down into specific sub-tasks. A definition of these sub-tasks is provided in Table 7 and associated with the systems within LAM-GTD, and with greater details with the workstation's subsystems. This document is essential for understanding the flow of activities performed within the agricultural module and the workstation, equally as within the workstation.

For instance, it was possible to observe that the tasks related to the nursery are predominantly conducted within the workstation rack. These activities flow from the nursery to the workbench, interacting with the plant trays (located in the other module's racks) only at the end of their germination cycle. Similarly, the waste compartment serves as a central system, gathering flows from all parts of the module towards the workstation. The other tasks are more evenly distributed across the entire module and the workstation.

Table 7: List of tasks to be performed in LAM-GTD related to the workstation.

Activity	Tasks	Description	Sub-system affected
1. Nursery	Sowing	Sowing seeds in nursery trays	Nursery, workbench
	Transplanting	After the plant grow enough they can be transferred to the main trays	Nursery, workbench
	Monitoring and Maintenance	Thinning, routine health check-up (visual and nutrient solution levels)	Nursery tray and workbench
2. Crop maintenance	Monitoring	Routine health check-up of the plants (nutrient solution, CO2, pH, lighting, ...)	Plant trays, workbench, monitoring computer
	Data Collection	Weighing, dimensions, color, sampling, packaging, freezing, photos	Plant trays, workbench
	Pruning	Thinning, trellising, waste management	Plant trays, workbench
3. Harvesting	Crop harvest	Cutting, collecting biomass, waste management	Plant trays
	Data collection	Weighting, dimensions, photos, filming	Plant trays, workbench
	Sampling	Sampling, packaging, freezing, ...	Workbench
4. System maintenance	System monitoring	Routine health check-up of the subsystems	Every subsystem
	Maintenance	Hardware/facility routine maintenance	Every subsystem
	Cleaning	Routine and exceptional cleaning	Every subsystem
	Repair	In case of damage or necessary action required	Every subsystem
5. Waste management	General waste	Waste from system maintenance and non-biological nor chemicals waste of crop maintenance	Undefined yet
	Liquid waste	General non-concentrated liquids	Undefined yet
	Nutrient-rich liquid waste	Concentrated stock nutrient solution, acid/base solutions, nutrient solution waste	Cultivation racks, NDS, workbench
	Non-hazardous biological waste	Inedible biomass waste, plant growth substrate	Undefined yet
	Hazardous	Chemicals and bio-hazard wastes	Undefined yet

By reversing the analysis and observing the affected subsystems, the workbench emerges as the most utilized component within the rack. It supports all five tasks and most sub-tasks, making it the cornerstone of the workstation. Its design should therefore be carefully considered to maintain a practical flow of activities between the subsystems.

Tasks Tree

A graphical document (Figure 20) was produced to easily visualize the tasks associated with the rack's subsystems. Using a color code referencing the type of activities (see tasks legend on the left of the image), the primary function of each subsystem is readily identifiable.

The nursery component emerges once again as exclusively utilized for germination activities. The central role of the workbench is reaffirmed by the longest list of assigned tasks, which includes harvesting, crop and system maintenance as well as nursery-related activities. Additionally, the sink is planned to be fitted into the workbench to save space, adding three more tasks not listed already.

The storage unit, which previously had not clearly identified tasks, now appears as an essential system for all activities except waste management.

Some systems, such as the control panel, toolkit and stepping platform, were still under consideration at the time. Their associated tasks were on average shorter, which justified their secondary importance and the decision not to pursue their inclusion in the final design due to time and resource constraints. However, their utility was acknowledged by the team, and it is recommended to revisit their development in future work, particularly for the final version of LAM-GTD.

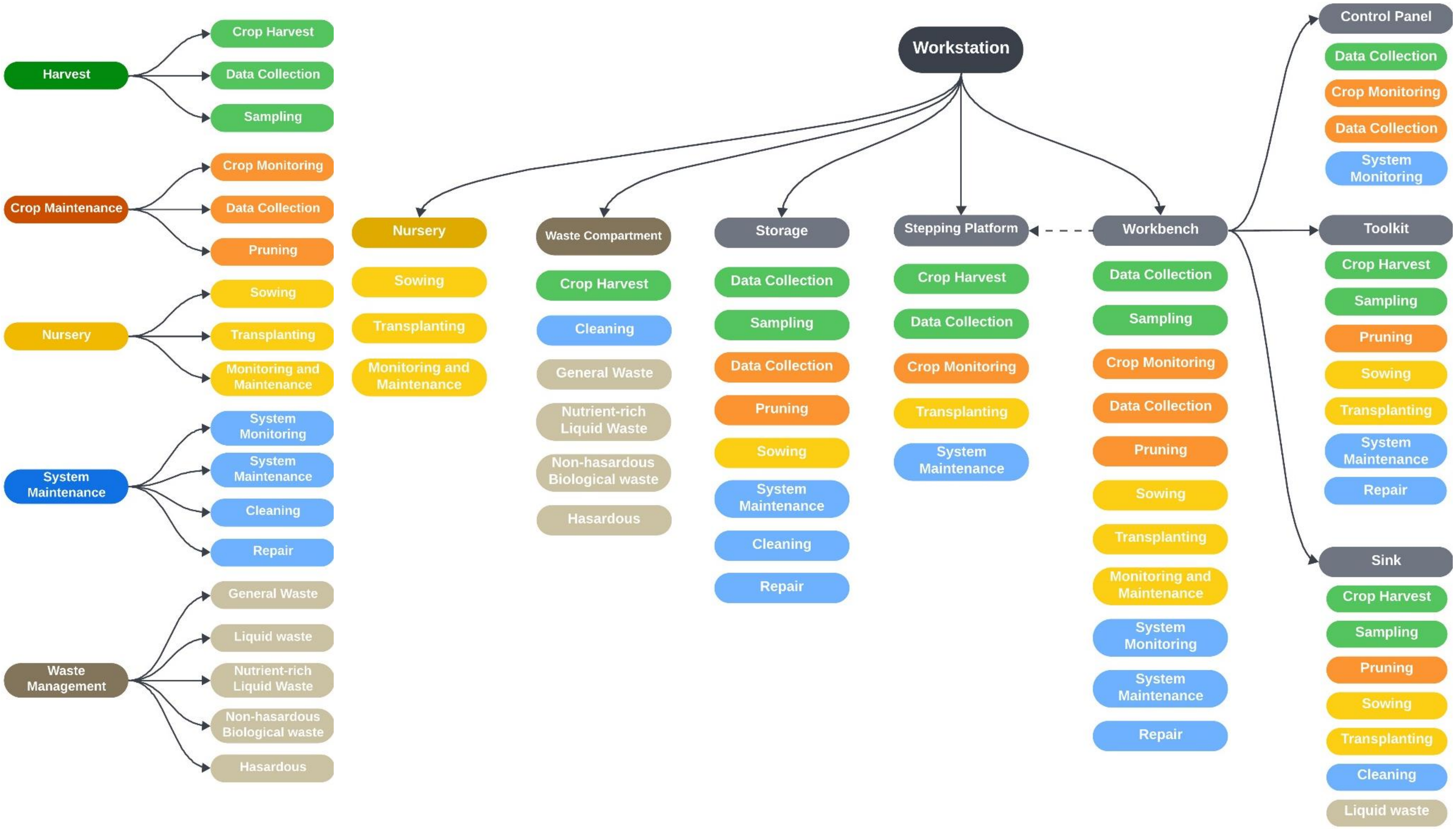


Figure 20: Diagrammatic tree representing the tasks related to each subsystem

4.2.2. Preliminary design drawings

After identifying the list of crew duties and the associated subsystems, optimal layouts of the workstation were drafted presenting the general location of the four identified subsystems. The selection was narrowed down to three layouts considered optimal for the use of all subsystems. These designs were then compared with a trade-off analysis (see Figure 21) and the best design was chosen in agreement with the rest of the team.

The location of the workbench in the second upper quarter of the rack was natural as it had to be located at a working height. Early on, the waste compartment was located at the bottom of the rack in prevention to unsanitary leakage or dripping on other systems. Supporting systems such as power distribution and DHCS (in grey) were decided to be located in uneasy part of the rack to be fitted (triangles shapes created the slanted back of the rack). However, consideration of accessibility for maintenance must be considered in the final design phase.

Discussion turned around the placement of the nursery and the storage. The biologists of the team considered it essential to place the nursery within view of sight, narrowing down the finalist to option 2 and 3. Subsequently, the team agreed that part of the storage had to be within reach of smaller morphologies, making option 2 the selected layout. The team proposed to fit the tanks and pump of the sink (placed in the workbench) within the lowest quarter of the rack and reducing the volume of the waste compartment.

The selected layout was presented during the Technical Meeting (TIM) on the 1st of October 2024, where all LAM-GTD's partners were gathered (CSA, NASA, ASI and DLR). Feedback was mostly positive, expressing concerns about the space allocated to the sink's tanks. Overall, the choice of layout was reaffirmed.

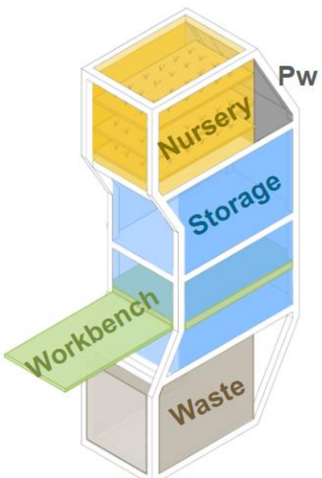
Option 1

Pros

+ Important storage capacity
+ Accessible storage
+ Convenient location of the Waste Compartment

Cons

- Difficult nursery access
- Workbench design limited by storing space allocated
- Difficult to add a sink



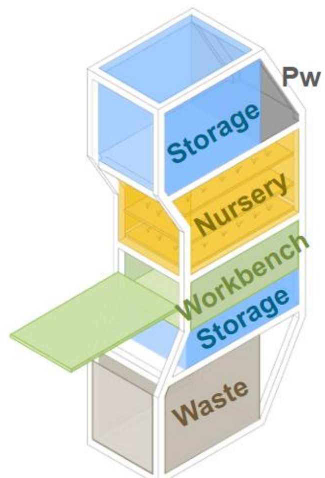
Option 2

Pros

+ Accessible nursery
+ Important storage capacity
+ Accessible storage
+ Convenient location of the Waste Compartment

Cons

- Part of the storage difficult to access



Option 3

Pros

+ Accessible nursery
+ Flexible location and volume allocated to workbench
+ Possibility to add a sink
+ Convenient location of the Waste Compartment

Cons

- Storage difficult to access

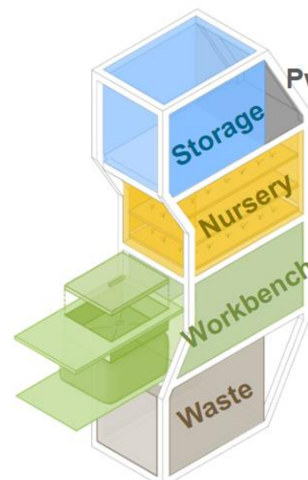


Figure 21: Preliminary design trade-off on the general layout of the workstation

4.3. Final Design Phase

4.3.1. Final Design Overview

After having decided on the general layout of the workstation, subsystems were developed in greater detail. An overview of this final design is shown in Figure 22 and plans are provided in Appendix A4. Due to time constraints, greater attention was devoted to certain systems with a focus on human factors. A general principle for the nursery was proposed and accepted. Given the level of technical complexity, it was decided to concentrate on the detailed design of the workbench, which included an integrated sink. Since the sink system and waste compartment are interconnected, the lowest quarter of the rack was also designed. Finally, the storage unit was completed with a finalized drawing.

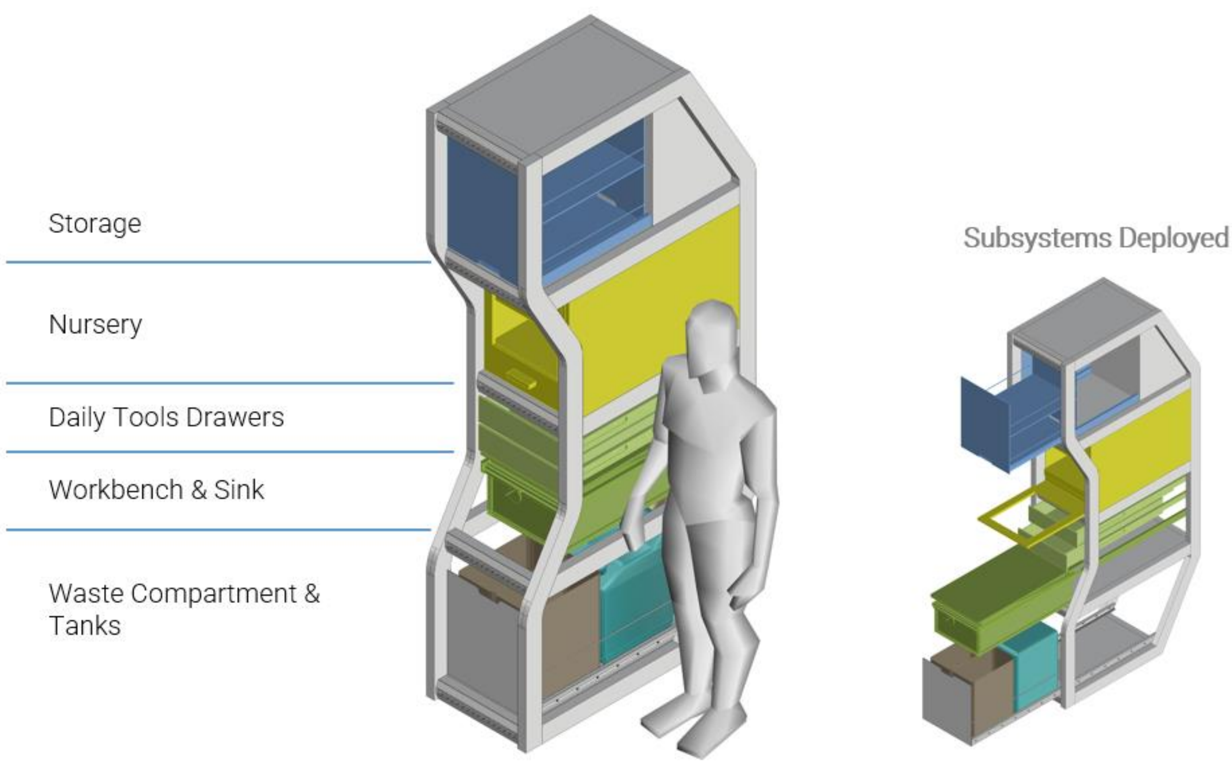


Figure 22: Overview of the Workstation Final Design

4.3.2. Workbench and Sink

Early in the project, the workbench was established as one of the most important subsystems to be designed within the rack, with a focus on human factors. Consequently, the workbench was designed with a high level of detail. This subsystem, located within the second quarter of the rack, is composed of two elements, as detailed below (see Figure 22 and 23):

- Workbench (in medium green)
- Sink (integrated within the workbench) with tanks and systems (in turquoise)

WORKBENCH DESCRIPTION

To comply with requirement WO-01, the workbench was designed to be deployable. The chosen mechanism was a simple sliding rail system (similar to drawer slides), selected for its efficiency, ease of use, reliability, and availability on the market (see Figure 23: Step 1).

Requirement WO-03 specifies that the table must have a minimum surface area to accommodate a cultivation tray (70 x 70 cm). However, the internal dimensions of the rack (42 x 90 cm) prevent the sliding table alone from meeting this requirement. To address this, extension panels were added to the workbench. Two side panels of equal dimensions enable easy and stable deployment (see Figure 23 Step 2). The extensions can open to increase the surface area or fold down vertically to provide comfortable access to the sink when needed (see Figure 23: Step 4). The panel opposite to the access of the sink can remain deployed, offering an additional dry surface to leave clean or sensitive elements, in compliance with WO-07.

In accordance with requirement WO-02 and aligned with the conclusions of the anthropometric analysis, the workbench was designed to be height-adjustable. This adjustment accommodates heights ranging from the 5th percentile of Japanese females (148 cm) to the 95th percentile of American males (194 cm) in a standing position. A scissor lift system was selected for its flexibility and stability (see Figure 23: Step 3).

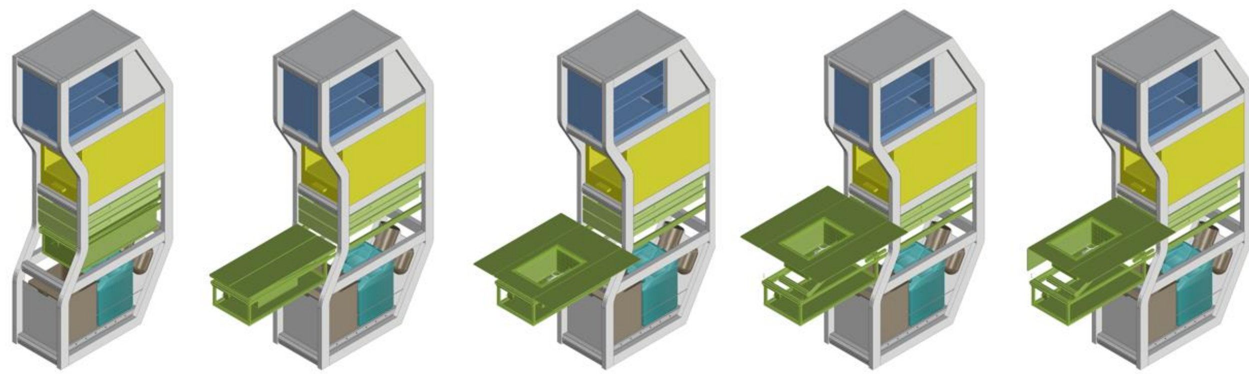


Figure 23: Deployment sequence of the workbench

Additionally, the system was prototyped in the workshop using item profiles and a mechanical handle for height adjustment. The design proved to be reliable and intuitive. This mechanism is also compatible with the integration of a sink, reserving free space in the center of the workbench for a cutout to install the sink. The table can be adjusted from 92 cm (to account for the thickness of the sink and structure) to 123 cm (just below the middle beam of the rack).

Stainless steel was considered as the material for the workbench due to its widespread use in professional kitchens and laboratories. This choice ensures compliance with sanitary and maintenance standards and addresses requirement WO-06 regarding the ease of cleaning the workbench.

SINK AND SUPPORTING SYSTEMS' DESCRIPTION

The sink system was identified early by the team as a valuable addition, and space was allocated to accommodate the entire system. According to the requirements, if a sink was added, it needed to be sufficiently spacious to fit some of the largest elements of the greenhouse. The cultivation tray (70 x 70 cm) was identified as one such element. However, integrating a sink large enough to fit the tray was not feasible within the rack's constraints. Instead, the dimensions were based on the second-largest required objects: the pump filters.

Given that the workbench must be folded and stored back into the rack when not in use (WO-01), the sink's tap and mixer had to be retractable. Such systems are relatively uncommon. However, research into camper van systems provided valuable insights, as these designs address similar challenges of limited space, resources, and power. The *Black Nanotech Sink with Hideaway Faucet* from Tec Vanlife emerged as a standout solution, meeting nearly all requirements except for length and width dimensions (see Figure 24). The sink is 35 cm wide, 38 cm long, and 23 cm deep with a 5 cm high exhaust to conserve space beneath. The faucet includes a pull-out spray that can be retracted and concealed. In this configuration, a lid can be placed over the sink, creating a flat surface for work. This off-the-shelf (COTS) component serves as a reference for the sink's final design.

The dimensions of the sink were carefully analyzed to optimize both its internal capacity and the available workbench surface area. The sink designed for the workstation measures 40 cm in width, 27 cm in length (the maximum possible dimensions), and 25 cm in depth, comparable to a standard kitchen sink. Dry areas were intentionally left on both sides of the sink, providing 16 cm on the right and 30 cm on the left. These areas offer convenient space to place items even while the sink is in use (see workbench plan in Appendix A5).

Figure 24: Photos of the Black Nanotech Sink with Hideaway Faucet. Left, deployed faucet. Right, faucet in hideaway position. (Tec Vanlife)

Another challenge of the hydraulic system was the sink's mobility, due to its placement on the sliding table. Similarly, the tanks and pumps, located within the bottom drawer, are designed to be mobile to facilitate maintenance and the swapping of fresh and waste water tanks. A hydraulic system design was proposed to address these challenges (see Figure 25). Flexible and extensible hoses were incorporated to allow isolated movements between the sink and the hydraulic components in the bottom drawer. The size of the tanks was defined both the space available and the limitation of the crew capacity to carry their weight. These tanks were carried by the crew by hand from Neumayer station and EDEN ISS (about 400m). Building on the knowledge of EDEN ISS, the same tanks of 25L were selected.

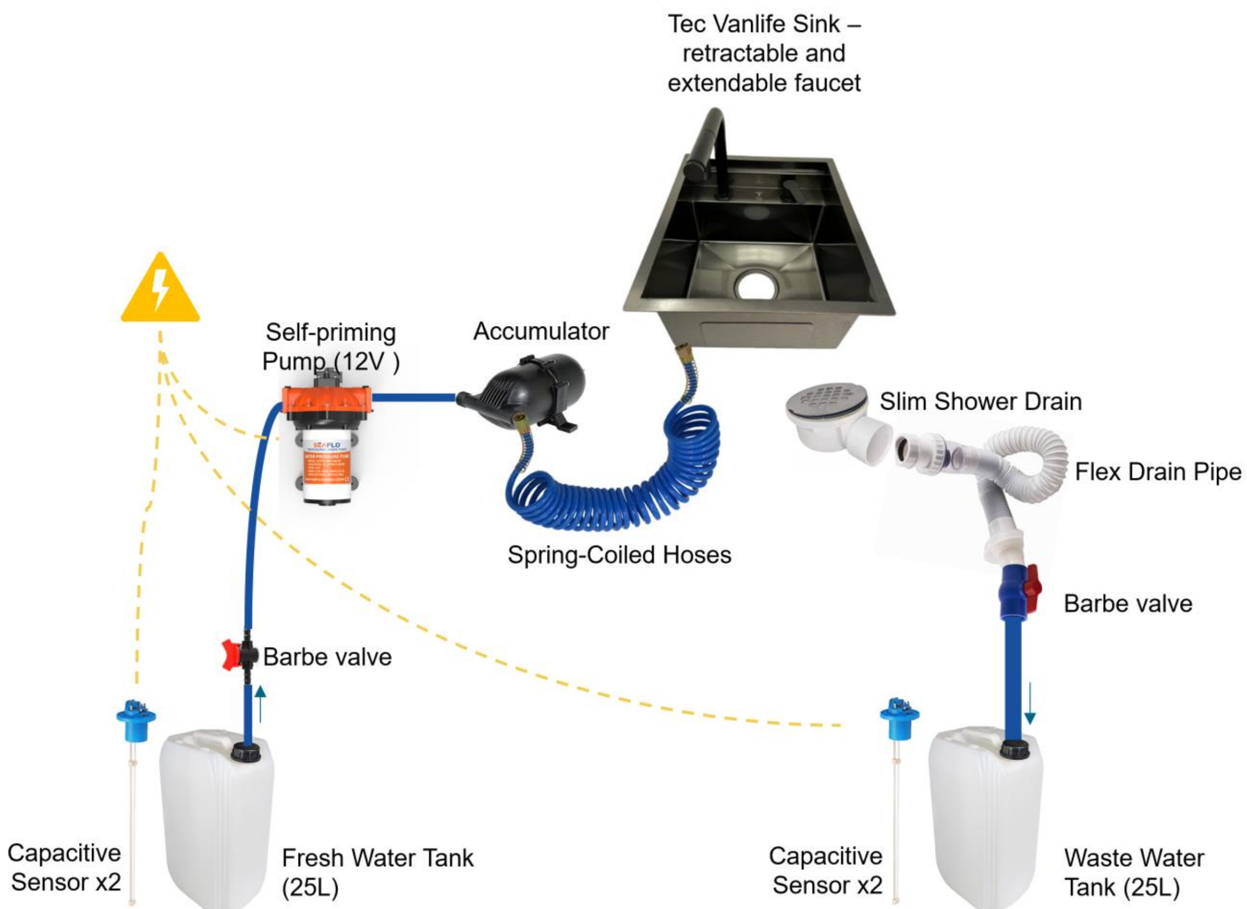


Figure 25: Diagram of the Hydraulic System

4.3.3. Waste Compartment

The different types of waste were identified during the conceptual phase (ConOps) and refined in the preliminary design phase (Table 7). The list includes the following types of waste:

- *General waste*: refers to system maintenance and non-biological nor chemical waste of crop maintenance,
- *Liquid waste*: general but non-concentrated liquids,
- *Nutrient-rich liquid waste*: includes concentrated stock solutions, acid/base solutions, and nutrient solution waste,
- *Non-hazardous biological waste* (also referred to biological waste): includes inedible biomass waste and plant growth substrate,
- *Hazardous waste*: refers to chemicals and bio-hazard waste.

The waste compartment was allocated to the lowest quarter of the rack and consists of a single fully extendable drawer. The waste containers share this space with the sink's hydraulic system. The hydraulic system, comprising two 25 L tanks, a pump, and an accumulator, occupies the back half of the drawer. The front half of the compartment was reserved for the waste containers (see Figure 26).

Due to the limited space allocated to the waste compartment, only a reduced number of waste types could be accommodated. Since liquid waste is already managed by the hydraulic system and hazardous waste cannot be stored within the module, only general waste and biological waste needed to be accommodated. These two waste types are collected in two waste bins, each using plastic bags of the same size as the tanks.

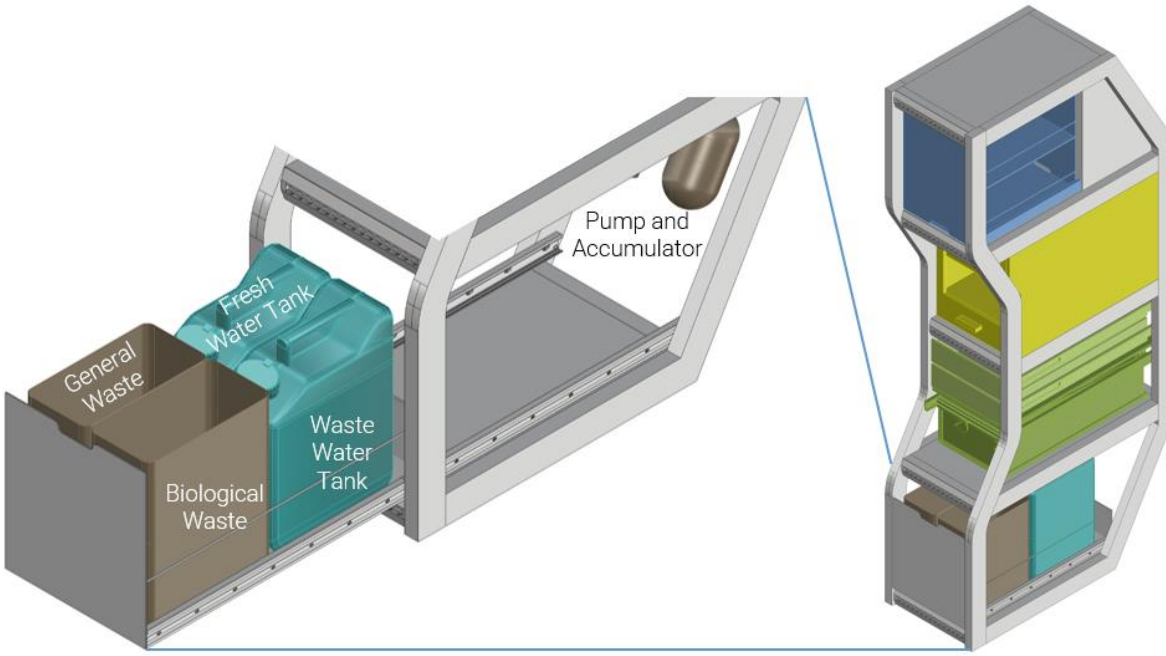


Figure 26: Zoom-in on the Waste Compartment and Hydraulic System.

4.3.4. Storage

The need for storage space was emphasized in the CE study for LAM-GTD. During the preliminary phase, it was determined that two types of storage were necessary: a main storage compartment and drawers for daily tool storage (see Figure 27).

MAIN STORAGE COMPARTMENT'S DESCRIPTION

In the preliminary study, the highest quarter of the rack was assigned to the main storage compartment. Since this compartment is located at the top of the rack (193.5 cm), access is limited for most users and requires a stepping platform. Therefore, it is intended for storing infrequently used items, such as spare parts and stock solutions.

To enhance accessibility, it was decided to incorporate a drawer for this compartment. The drawer, which extends 80 cm, allows users to reach items at the back of the storage space efficiently, offering around 0.2 m^3 of storage. Without the drawer, accessing the rear of the shelf would be difficult due to its depth. To maximize utility, the drawer could potentially be divided into two horizontal sections, accommodating more items provided their height is manageable.

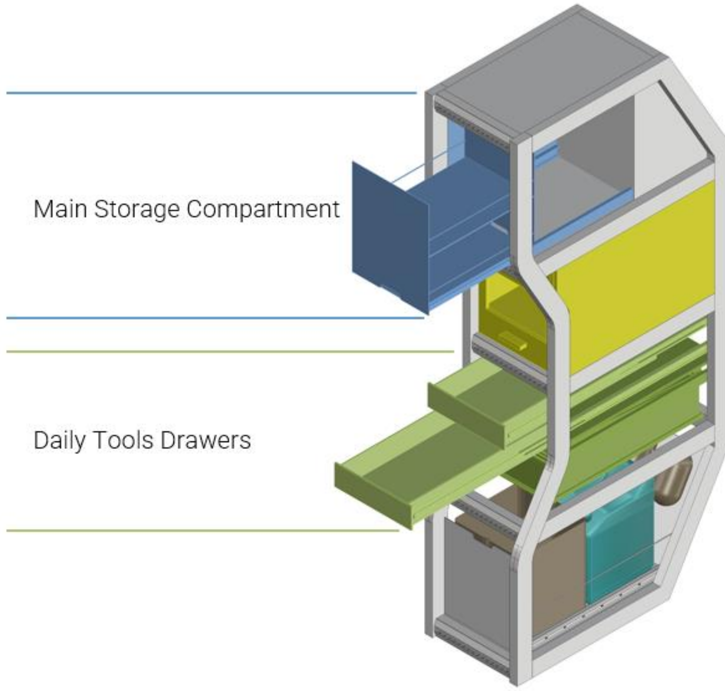


Figure 27: Workstation's storage deployed.

Daily tools drawers' description

At the team's request, easily accessible drawers were added above the workbench. Since the main storage compartment is located at the top of the rack and is only accessible with the help of a stepping platform, these smaller drawers were designed to store frequently used tools, such as scissors and tweezers, essential for tasks carried out in the module and particularly on the workbench. Their proximity to the workbench enhances practicality.

Due to the rack's depth of 90 cm, fully extendable drawers were selected to ensure easy access to the entire storage space. Drawers with a shallow depth, equipped with internal organizers, were selected as the most suitable option. An example of such a drawer organizer is provided in Figure 28. With a total height of 21 cm available, two to three drawers could be added, respectively of 10.5 cm or 7 cm high each. This design optimizes the available volume, adding an extra 0.08 m^3 of storage while ensuring tidy organization of tools and maintaining work efficiency.

Figure 28: Example of workshop drawer with internal organizer. (Stier)

4.3.5. Nursery

The nursery, or germination chamber, was identified as an open issue in the CE study. It was decided to position the nursery in the third-highest quarter of the rack (available space of 0.18 m^3) to ensure it is both visually and physically accessible. However, it was also determined that this subsystem would be less developed due to its technical complexity.

Despite its complexity, preliminary research was conducted to provide direction for the design (Figure 29). The team outlined their requirements, emphasizing the need for control over ambient parameters without reaching the technical sophistication of the APH. The system was envisioned to function as an isolated unit from the rest of the cultivation racks.

Several designs were considered during the research phase, but one stood out for its intuitive functionality and system completeness: the *Plantcube* by Agrilution (Figure 30). This system, used in part by the EDEN Initiative, was available for testing. Unfortunately, Agrilution went bankrupt, and its integrated software left the system unusable. However, *Plantcube* remains a source of inspiration for the future design of the nursery in LAM-GTD.

This system would include its own LCS, NDS and some form of AMS, offering extended control over the conditions of germination of the seeds. These features are designed to offer precise control over the conditions required for seed germination, potentially increasing the germination success rate. Additionally, the design aims to provide a simple and intuitive interface to enhance the human-system interaction.

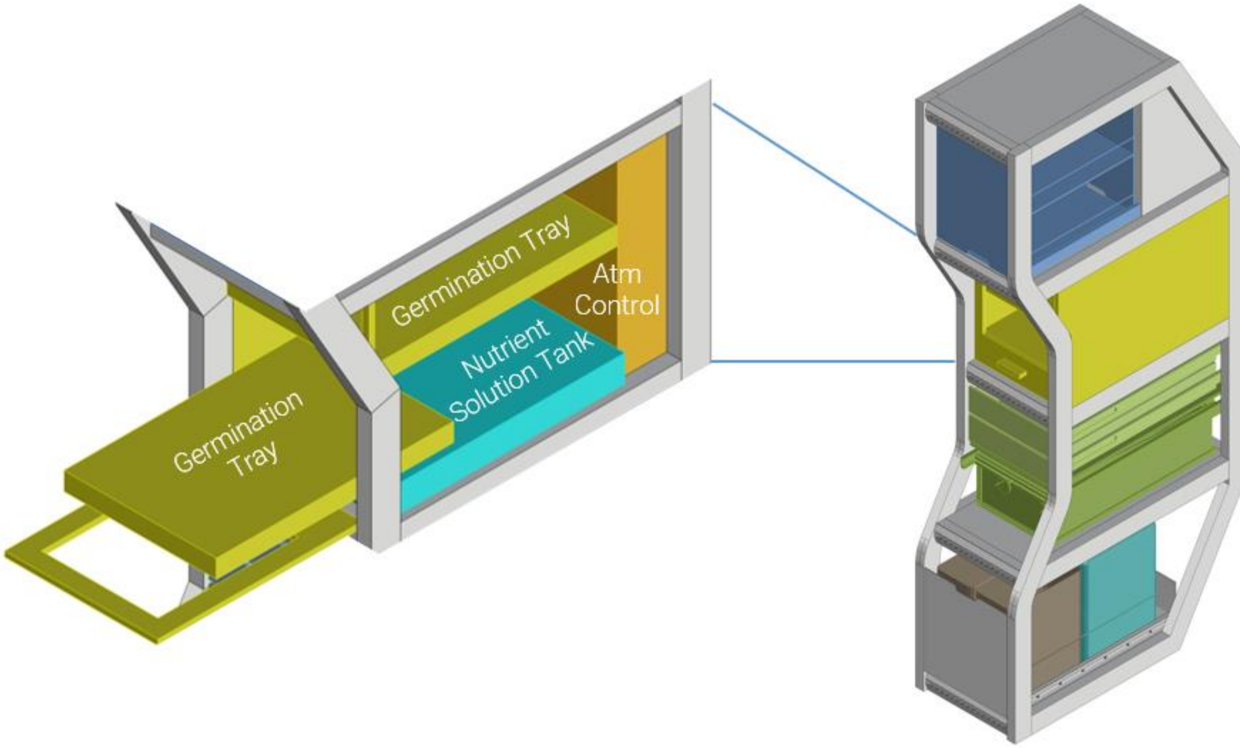


Figure 29: Zoom-in on the Nursery Subsystem.

Figure 30: Plantcube by Agrilution (The Subdivision)

4.4. Test and Verification

4.4.1. Low Fidelity Mockup

A mockup was planned to be built to test the compliance of the workstation design with the technical and human factors requirements. It was quickly decided that the entire structure of the rack should be built, but further discussions were necessary regarding the subsystems and functionalities to be tested.

The workbench, highly detailed in the ConOps and covering the principal human-centered subsystem of the rack, interacts with most systems, making it the cornerstone of the test. The waste compartment, which hosts the sink's hydraulic system, was unanimously included as part of the mockup test. Concerns about the interaction between the adjustable workbench and the drawers led to the storage subsystem being included in the material test. However, the nursery, developed to a lesser extent due to its technical complexity, was represented in the project as a placeholder with broad assumptions. It was then decided that the system wasn't ready to be built. Hereafter, the final list of subsystems to be built in the mockup:

- Structure,
- Workbench,
- Sink and tanks,
- Waste compartment,
- Storage.

During the preliminary design phase, a simple cardboard and tape mockup illustrating the front face of the rack was created to concretely demonstrate the dimensions of the horizontal profile height and protruding volumes (see Figure 31). However, a more detailed mockup representing the entire volume of the rack was necessary for the usability test.

Figure 32: Pictures showing the mockup of the workstation's front face.

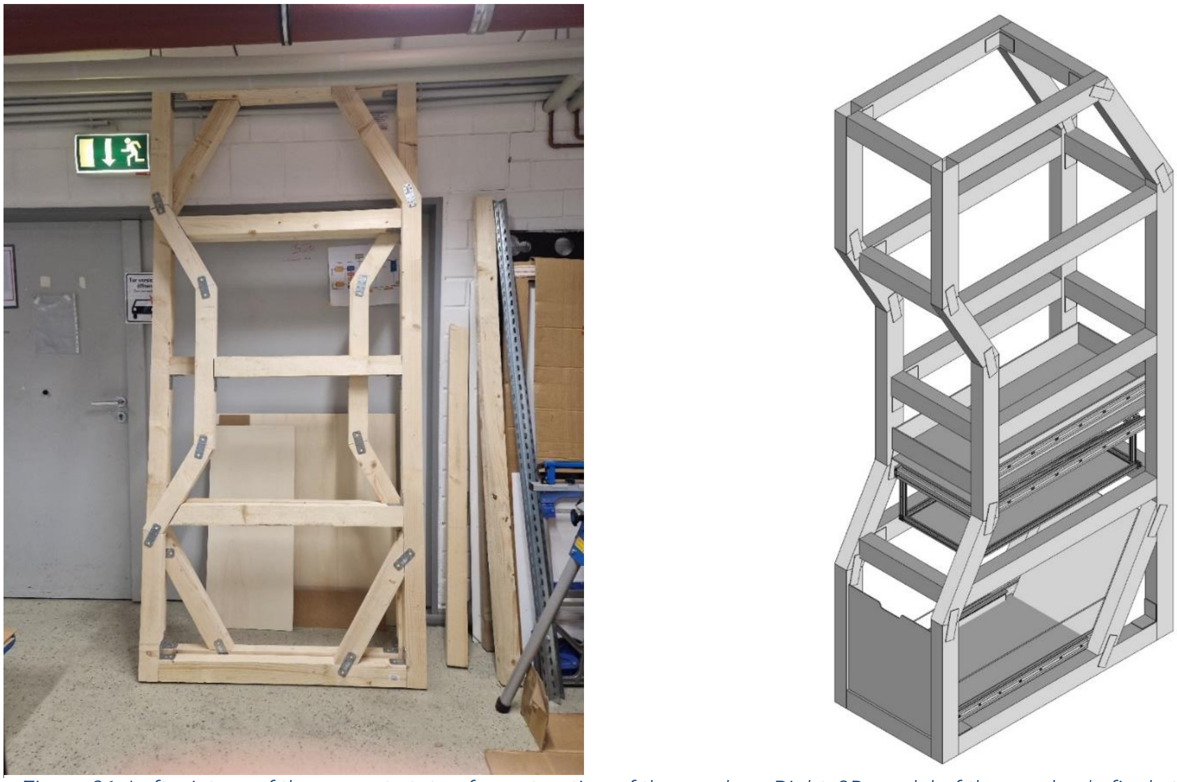


Figure 31: Left, picture of the current state of construction of the mockup. Right, 3D model of the mockup's final state.

The choice of material was defined according to ease of use and budgetary criteria. Initially, Item profiles were preferred for their similarity to the final structure. However, their cost and impracticality for uncommon angles led to reconsideration. Standardized wooden beams (7.8 x 5.8 cm) were ultimately selected as a cost-effective and quick solution, requiring only length adjustments. These beams were connected using metal plates and angles, which were screwed into place. Subsystems were constructed from 8 mm plywood and 3 mm MDF. To prepare for the mockup construction, a 3D model was developed in Rhino to detail the design, create a bill of materials, and prevent errors.

Construction of the mockup began, and the structure was completed. However, as the usability test was deferred, the finishing of the mockup was also postponed. While the construction was paused, some observations could already be reached, notably that the size of the rack had been underestimated by the team, who were surprised by its final volume.

4.4.2. The Usability Test

A fully developed procedure has been created to perform a usability test on the low-fidelity mockup. There are two types of people involved in the execution of a usability test: the moderator and the user (or participants). A set of procedures, composed of three documents, guides them through the test:

- The usability test procedure,
- The user's questionnaire,
- The moderator's questionnaire.

Google Forms was used to create the two questionnaires. This tool was selected for its ease of use, accessibility, and familiarity for both users and moderators. These documents are further detailed in the following paragraphs, with copies provided in the appendices.

Usability Test Procedure

The test procedure is divided into two distinct parts: preparation and procedure. The preparation section is intended solely for the moderator to gather the necessary elements (camera, microphone, list of documents, etc.). It describes how the setup should be installed and provides preliminary explanations to be shared with the user.

The second part of the document is the test procedure itself. It consists of short tasks that the moderator reads aloud to the user, who then performs them on the mockup. These tasks have been carefully selected to test critical human factors features of the design, ensuring the requirements are addressed. The procedure includes eight tasks, each with a maximum of five steps:

1. Workbench deployment
2. Collection of items from the upper storage
3. Collection of tools from the drawer
4. Nominal use of the workbench surface
5. Nominal use of the sink
6. Change of tanks
7. Nominal use of the waste compartment
8. Change of the waste container

Overall, the test procedure serves as a guideline for the moderator and user to follow. Before conducting the test for the first time, it is recommended to organize a dress rehearsal with team members. This will help identify any inconsistencies or errors, ensuring professional and smooth test execution with participants.

The full procedure is provided in Appendix A7.

User's Questionnaire

To collect data efficiently, NASA's Task Load Index (TLX) was used (NASA, 1986). This standardized form has been proven to provide effective qualitative data in a quantitative format for human factors testing (Hart, 2006). The short version, called the Raw Task Load Index (RTLX), was selected to balance the need for comprehensive data collection by the moderator with the prevention of user frustration.

Table 8: Definition of the TLX six rating scales. (NASA)

Scale	Endpoints	Descriptions
Mental Demand	Low/High	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	Low/High	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal Demand	Low/High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Effort	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Performance	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Frustration Level	Low/High	How insecure, discourage, irritated, stressed and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

The RTLX is composed of six scales rated on a 21-point scale (0 to 20), capturing the user's perceived experience of the design. These scales are defined by NASA (1986) in Table 8. The RTLX is administered to the user between each task of the test procedure to ensure the experience remains fresh in their memory and to minimize frustration from repetitive answer to the form. Appendix A8.

At the end of the test and after the RTLX responses are collected, a short open-ended interview (5 to 15 minutes) should be conducted with the user. This discussion aims to highlight the most memorable advantages and pain points of the design, adding an additional qualitative layer to the evaluation of the design's performance.

Moderator's Questionnaire

The moderator's questionnaire will be completed by the observing party, providing additional insights into the design's performance while shifting the effort demand from the user to the moderator, promoting smoother test execution. This questionnaire is inspired by NASA's HDIP recommendations on metrics (effectiveness, efficiency, and satisfaction) and includes specific questions regarding the workstation's design. These metrics are defined as follows (NASA, 2014b):

- *Effectiveness:* The accuracy and completeness with which users achieve certain goal, *Efficiency:* The relation between accuracy and completeness with which users achieve certain goals and resources expended in achieving them,
- *Satisfaction:* Users' comfort with and positive attitudes toward the use of the system.

More specifically, the key indicators used include task error rate, the number of steps required to complete the task, task success rate (categorized as easy, moderate, difficult, or failed), and task completion time. Observational notes and questions are provided for each task to ensure that off-nominal behavior can be accurately documented and analyzed. An example of the questionnaire for task 1. Workbench deployment is provided in Appendix A9. Additionally, the evaluator will have access to video and audio recordings of the test during the analysis.

Creating the supporting documentation was an iterative process, involving continuous refinement between the design requirements and the evaluation methods. A table provided in Appendix A10 summarizes the information present in the three documents highlights their complementary nature and common goal.

In conclusion, a comprehensive procedure has been established to conduct a usability test on the low-fidelity mockup, supported by three essential documents: the usability test procedure, the user's questionnaire, and the moderator's questionnaire. These resources ensure a structured and effective approach to gathering qualitative and quantitative data on the design's performance. The procedure incorporates critical tasks targeting key human factors requirements, while the user's and moderator's questionnaires are designed to capture nuanced feedback on usability metrics such as effectiveness, efficiency, and satisfaction. Additionally, incorporating the NASA RTLX scales and HDIP metrics ensures the evaluation framework is both robust and user-centered. Overall, this methodology provides a clear pathway for identifying design strengths and areas for improvement. The entire usability test has been fully developed but has not yet been tested, and it will likely require adaptation and updates based on initial trial runs and feedback to ensure its effectiveness and reliability.

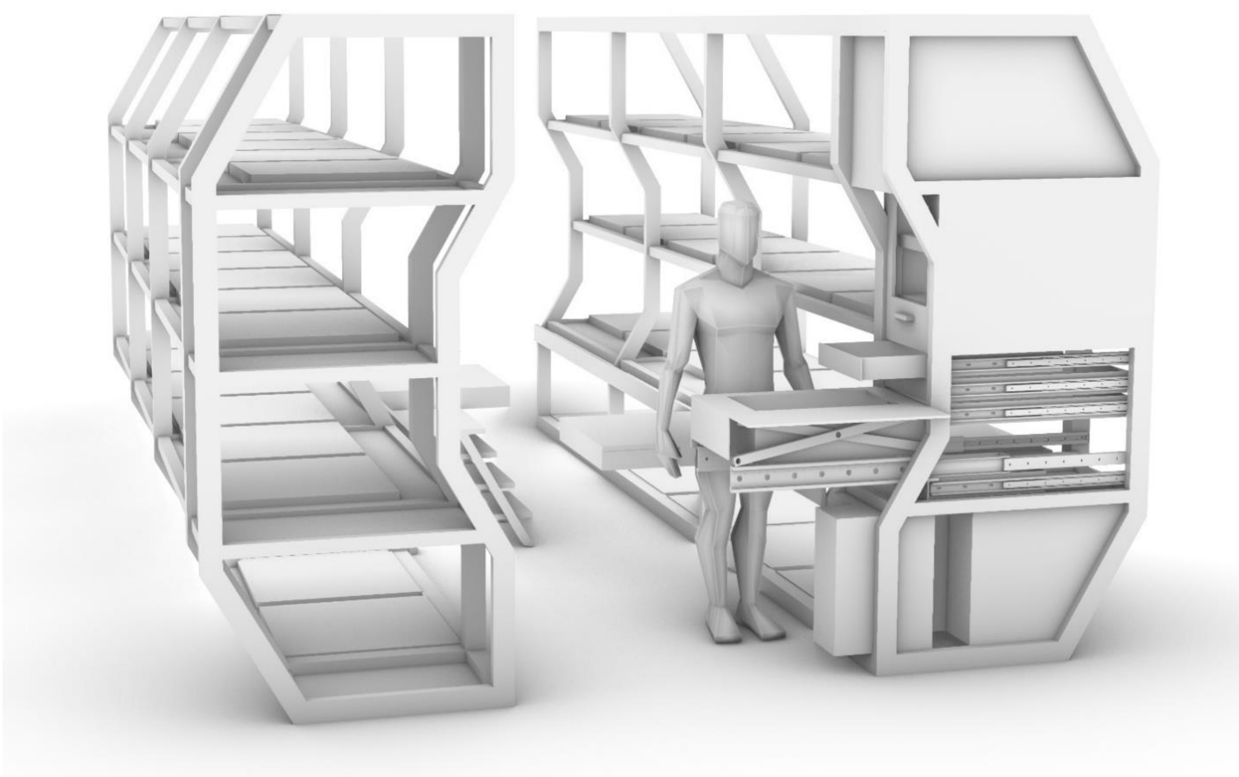


Figure 33: Conceptual render of the workstation in its context.

5. Conclusion and recommendations

5.1. Conclusion

The aim of this thesis was to develop a human-centered design of a workstation supporting agricultural activities within LAM-GTD. The methodology was derived and adapted from NASA's Human Design Integration Handbook, utilizing an iterative, human-in-the-loop approach focused on optimizing human-system interaction. Insights from heritage projects such as EDEN ISS were collected along with the trade-off analyses conducted with subject matter experts. The final design resulted in a workstation hosting key functionalities identified by users: a deployable workbench with an integrated sink, a waste compartment, a nursery, and storage. The proposed workstation focuses on user-system interaction, prioritizing functionality, efficiency and practicality.

While the usability test procedure was fully developed, its execution was deferred as future work, where it will provide valuable insights for further improvement and refinement. The applied methodology is an initial step towards integrating human factors into the overall design of LAM-GTD. Consideration for human-system interaction should extend beyond this thesis to the final development stages of LAM-GTD.

Beyond addressing LAM-GTD's requirements, this project offers one answer to the development of supporting systems for space agricultural activity. Overall, the workstation's design serves as a steppingstone for the future of planetary workstations, particularly within the context of lunar agriculture modules, setting a precedent for following innovations in extraterrestrial outpost and habitat design.

5.2. Outlook

This thesis lays foundational work on the design of a human-centered workstation for LAM-GTD, and lunar agricultural activity support. However, due to limitations in time and resources, several areas for further improvement have been identified.

1. Perform a Comprehensive Usability Test

A ready-to-use procedure was developed during this thesis but could not be executed on the low fidelity mockup. The available population was considered not large enough to provide statistically significant conclusions, leading to its postponement. Conducting this test with a larger sample size, ideally at least 25 participants, is recommended to observe trends and directions for refining the design. This test is critical to improving user-system interaction and validating the workstation's design.

2. Subsystems Expansion and Refinement

Certain subsystems require further development to ensure optimal functionality and integration. For example, the nursery subsystem, essential for germinating seeds to be transplanted into cultivation trays, was only partially developed due to its technical complexity. Collaboration with experts is necessary to finalize its design, ensuring both proper functionality and the integration of human factors principles.

3. Automation and Monitoring

Users expressed a strong interest in incorporating automation within LAM-GTD. Adding a control panel, potentially in the form of a tablet, could facilitate monitoring diverse sensors related to cultivation (e.g., light levels, atmosphere conditions, nutrient solution, etc.) and support activities like note-taking and photography. Additionally, automated features for subsystems such as the adjustable-height workbench and the waste compartment would enhance hygiene, practicality, and overall user experience.

4. DEVELOPMENT OF FLEXIBLE SUPPORTING COMPONENTS

The addition of flexible and modular components, such as a lighting system for the workbench and camera attachment were mentioned by users as valuable components. Integrating L-tracks, like those installed on the ISS, would allow for easy reconfiguration of the components and accommodate diverse tasks and user's preferences.

5. DEVELOPMENT OF MOVEABLE COMPONENTS RELATED TO THE WORKSTATION

Further development of moveable components, such as a stepping platform and tool pockets mentioned in the UTA, is recommended. These elements would improve accessibility and organization, enhancing the usability of the workstation.

Addressing these gaps will enhance the design and usability of both the workstation and the entire module. While envisioned since the beginning, these goals were beyond the scope of this thesis. Answering these challenges in future work will improve the readiness of LAM-GTD, while advancing the state-of-the-art in supporting systems for planetary agriculture.

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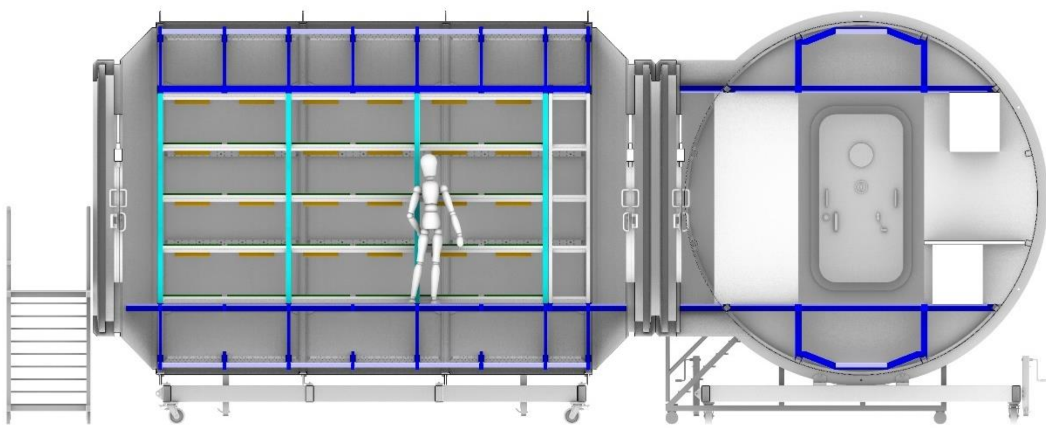
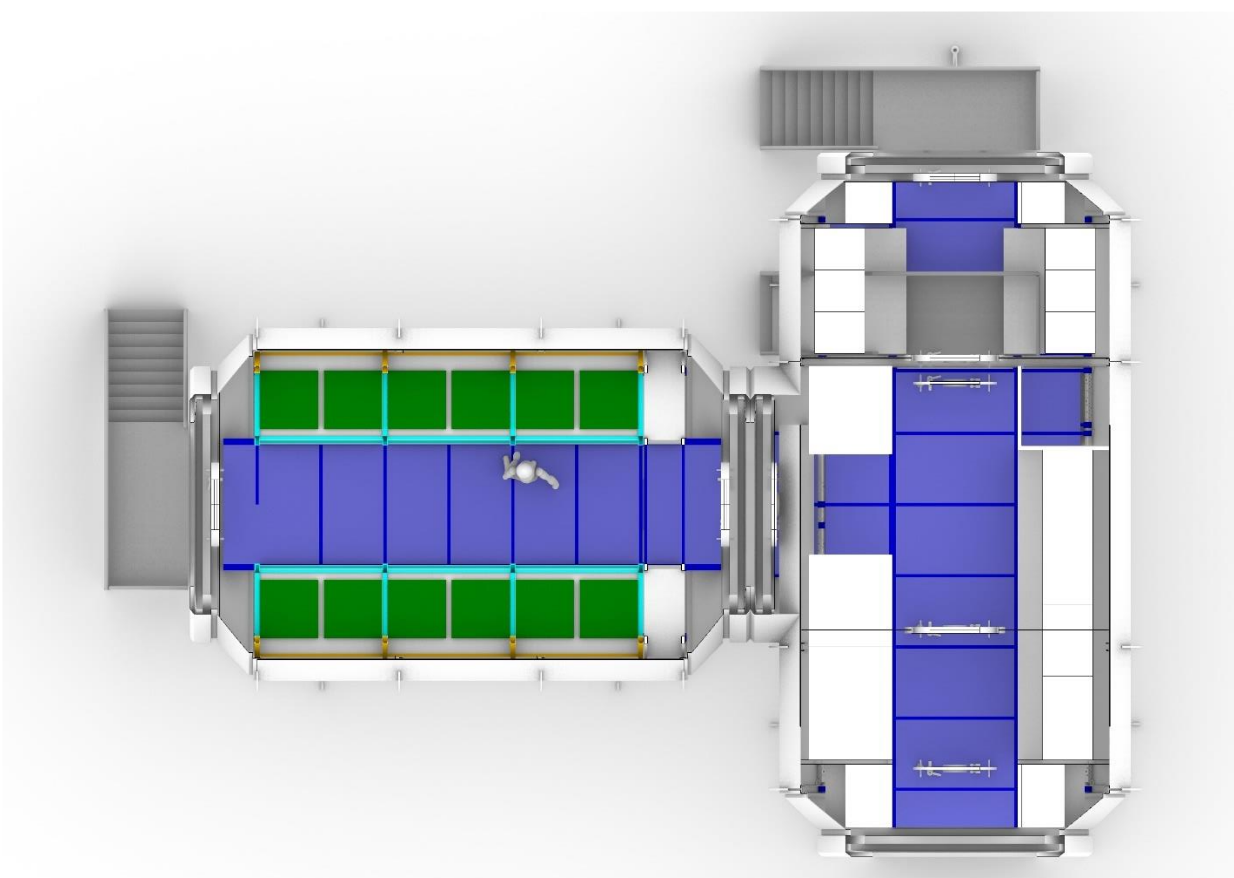
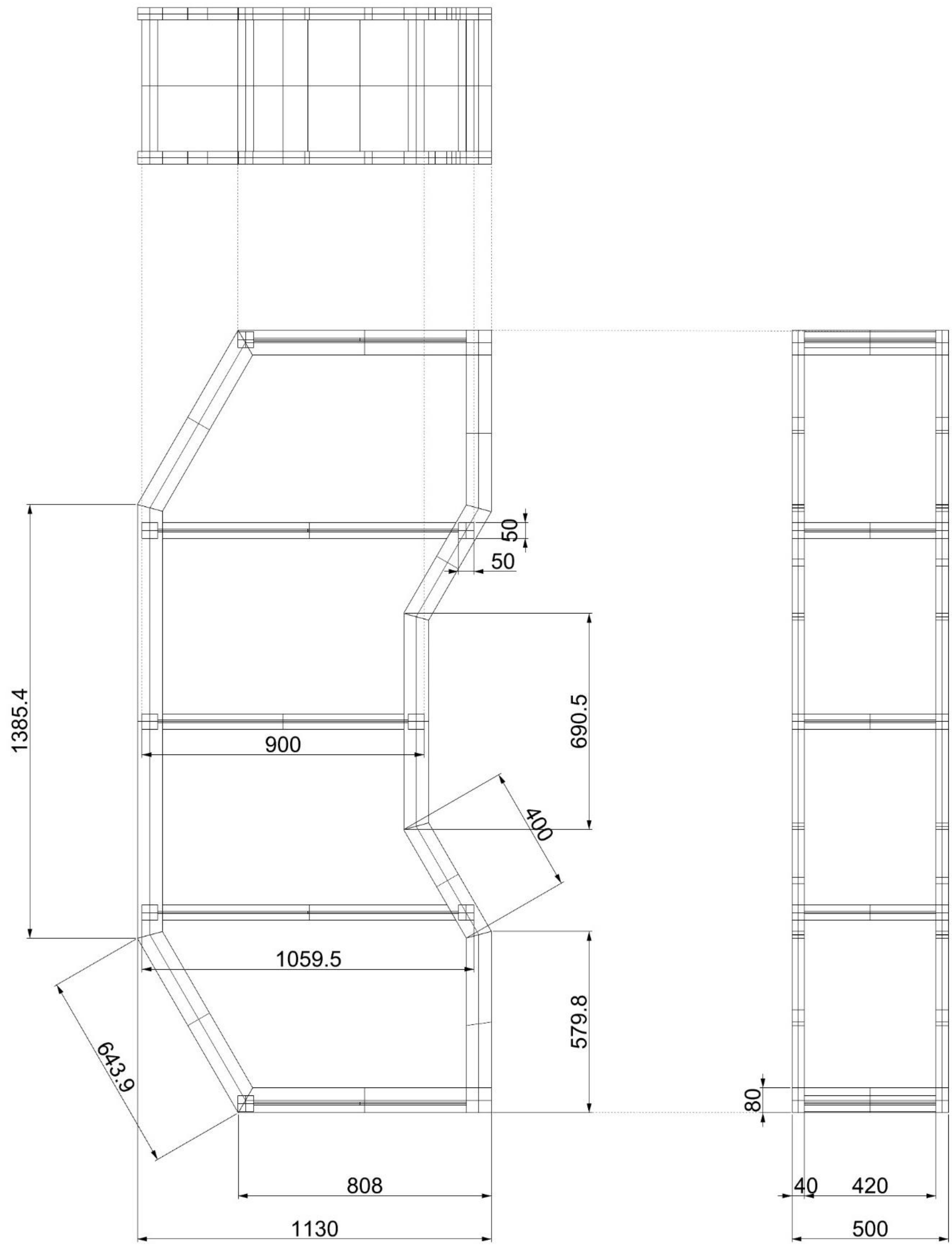
Appendices

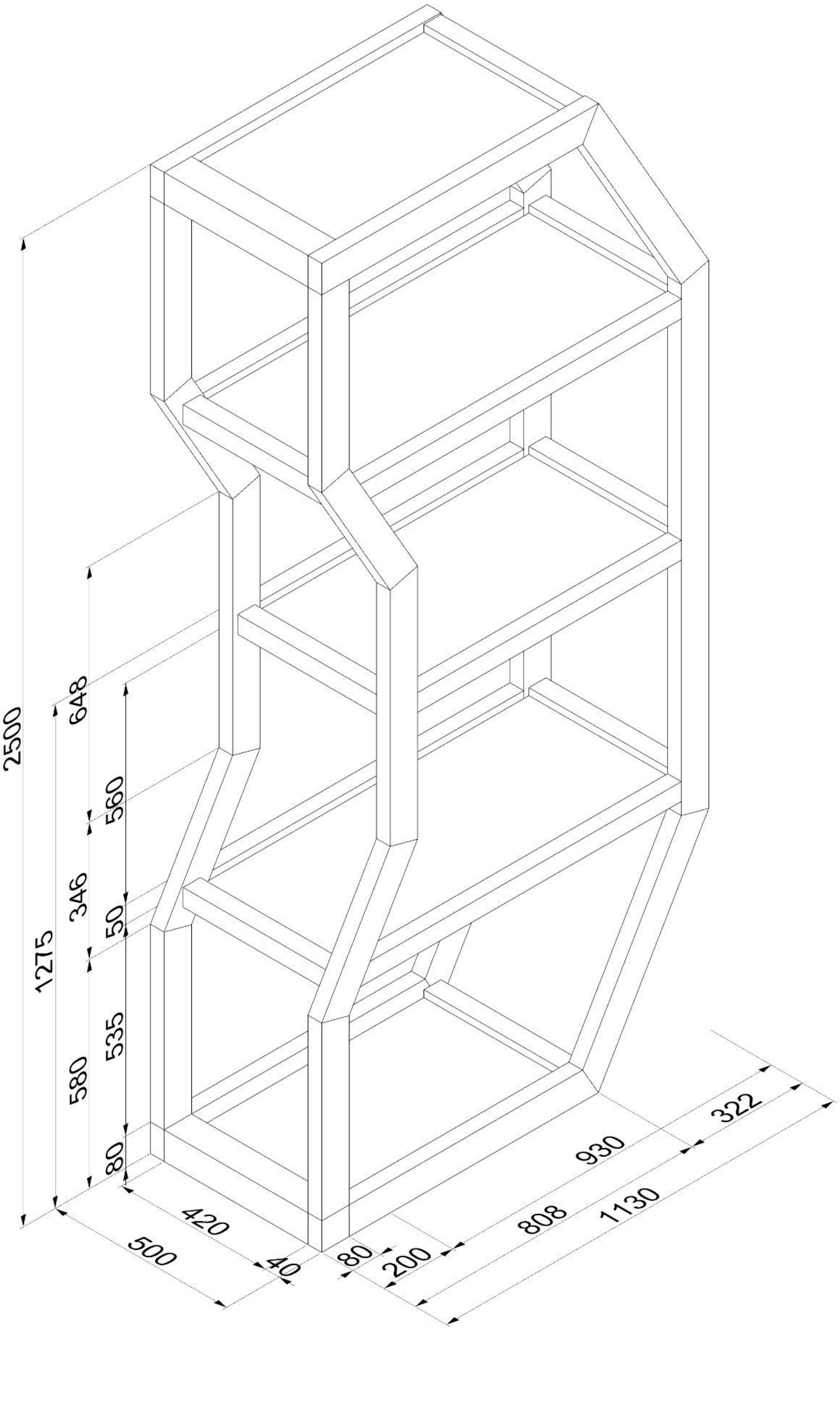
A1. Plan and Section of LAM-GTD





A2. Workstation Rack's Dimensions (in mm)

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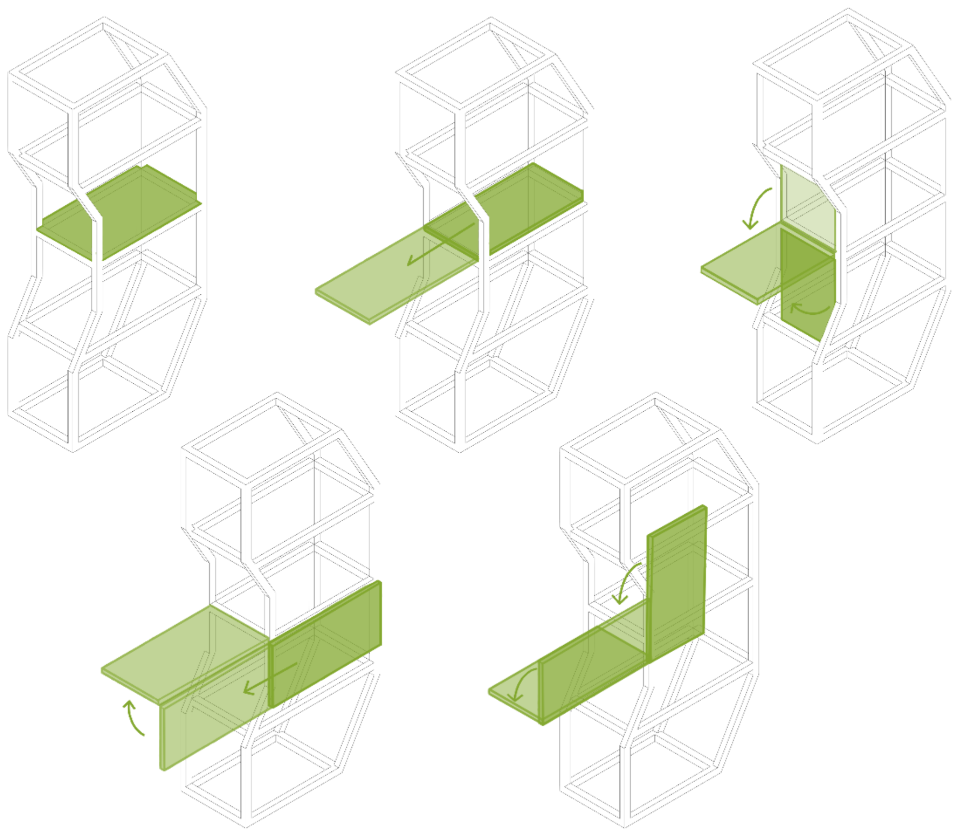
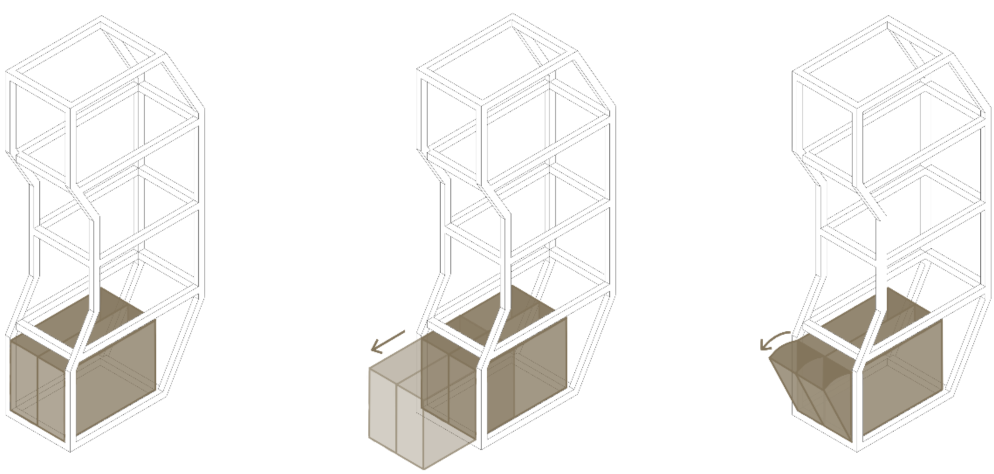
A3. Ideation on Subsystems' Mechanism and Design

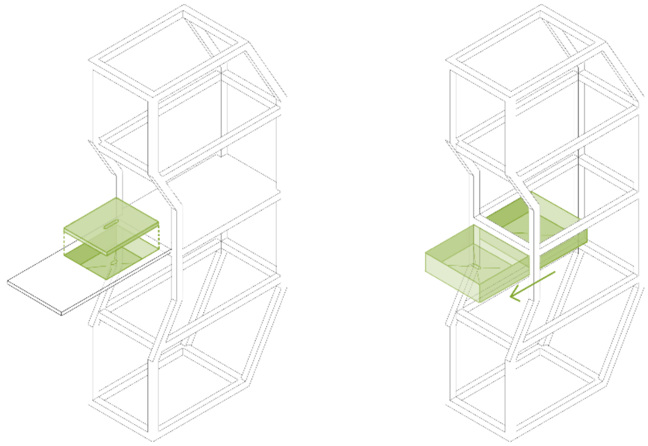
Workbench Ideation



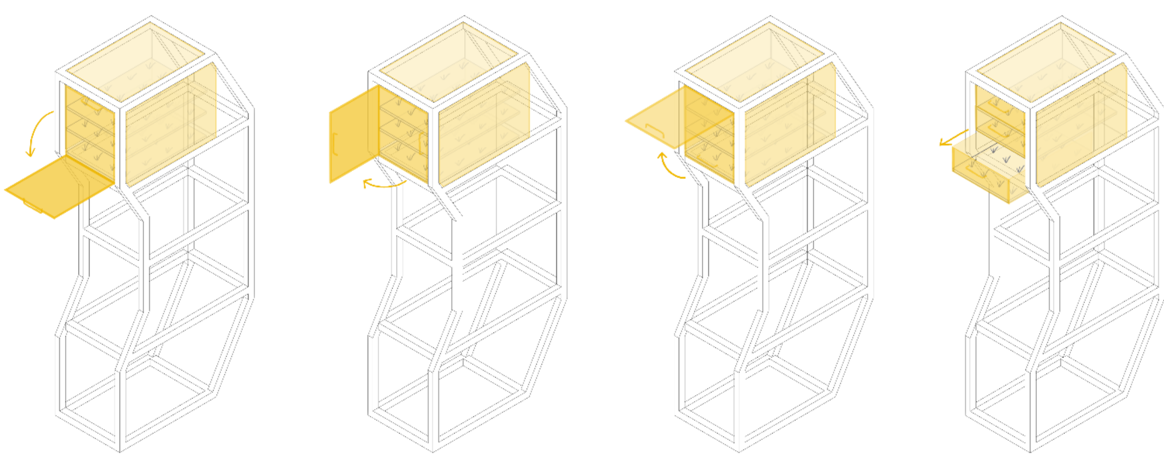
Waste Compartment Ideation



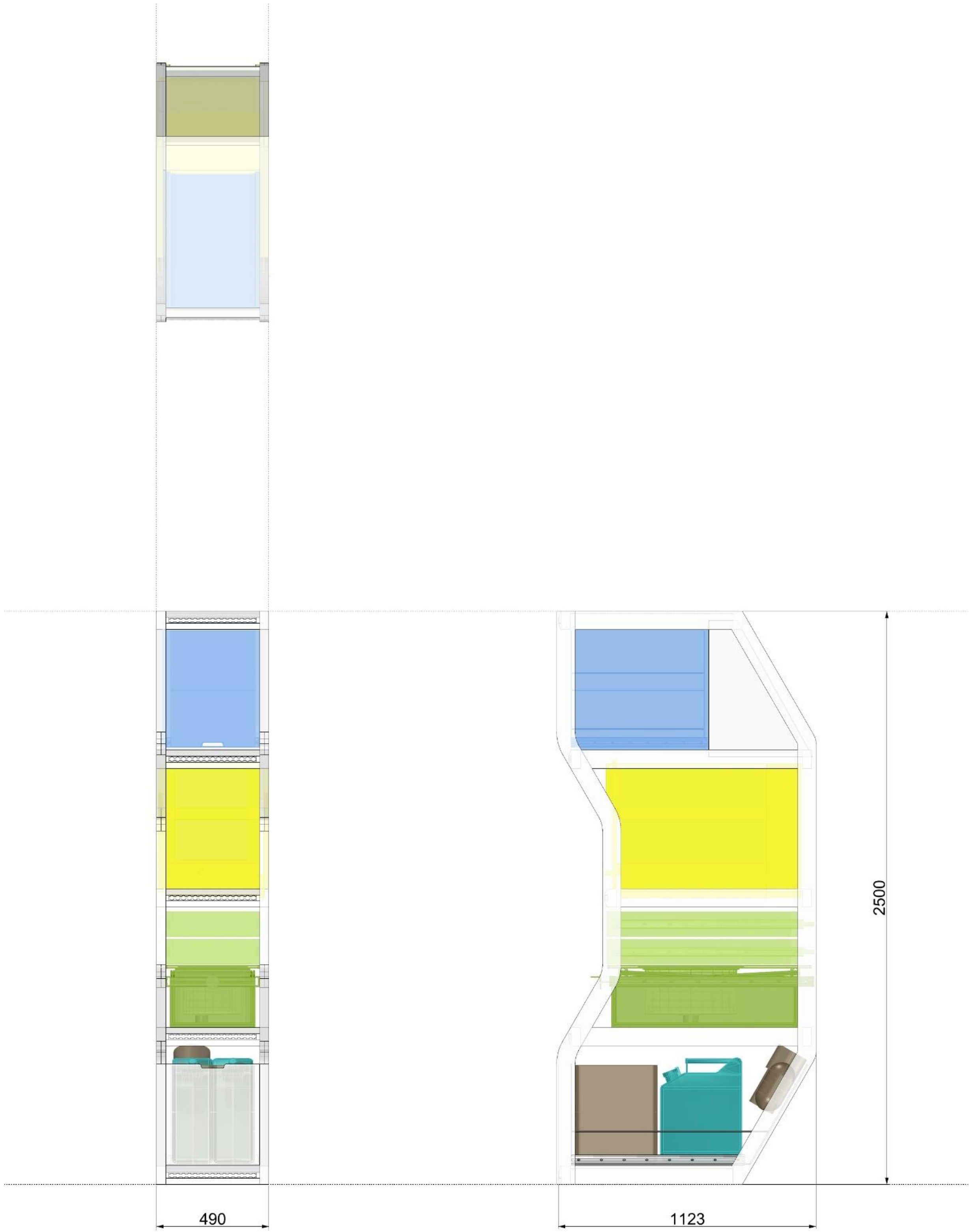
Sink Ideation



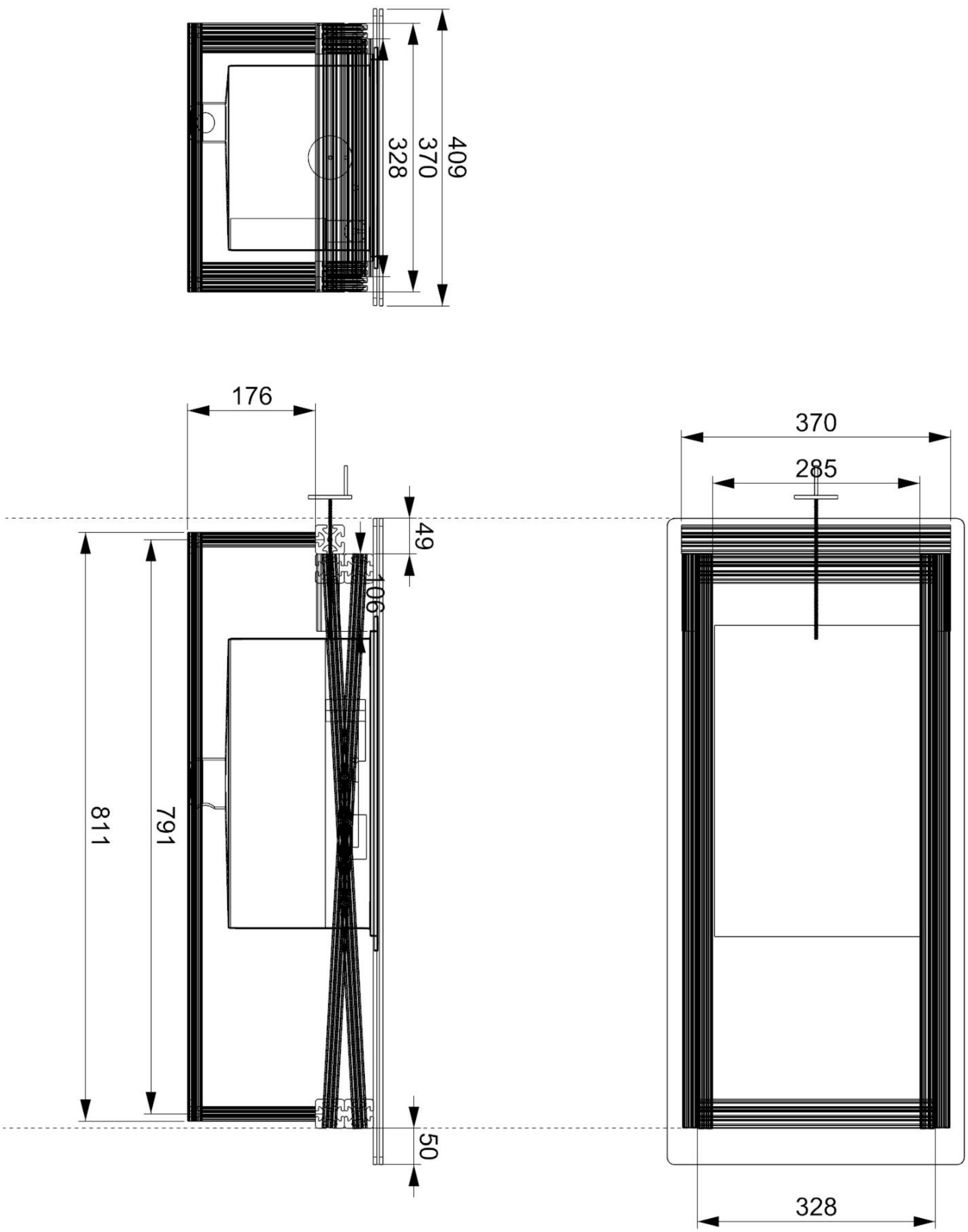
Nursery Ideation



A4. Plan of the Workstation's Final Design



A5. Plan of the Workstation's Workbench and Sink



A6. User Task Analysis Questionnaire

Lunar Agriculture Module (LAM) User Task Analysis

This questionnaire is part of the Task User Analysis of the Lunar Agriculture Module (LAM) by DLR. A workstation has been identified as a requirement but hasn't been defined yet. To configure a coherent design, the input of Subject Matter Experts (SMEs) practical experience is required. **This is why your help is needed!**

The form is compose of 3 sections:

1. Subject Matter Expert's (SME) details (3 Questions)
2. LAM tasks and ranking (6 Questions)
3. LAM equipments and comments (20 Questions)

1. Email address

____

2. Job position and responsabilities.

   Please, describe your responsabilities in one sentence.

____

____

____

____

____

3. Height (in cm)

____

II. LAM Tasks (6 questions)

Answer to the question in your own experience.

Definition of the tasks

Activity	Tasks	Description	Sub-system affected
Harvesting	Crop harvest	Cutting, collecting biomass, waste management	Plant trays
	Data collection	Weighting, dimensions, photos, filming	Plant trays, workbench
	Sampling	sampling, packaging, freezing, ...	Workbench
Crop maintenance	Monitoring	Routine health check-up of the plants (nutrient solution, CO2, pH, lighting, ...)	Plant trays, workbench, monitoring computer
	Data Collection	Weighing, dimensions, color, sampling, packaging, freezing, photos	Plant trays, workbench
	Pruning	Thinning, trellising, waste management	Plant trays, workbench
Nursery	Sowing	Sowing seeds in nursery trays	Plant trays, workbench
	Transplanting	After the plant grow enough they can be transferred to the main trays	Plant trays, workbench
	Monitoring and Maintenance	Thinning, routine health check-up (visual and nutrient solution levels)	Nursery tray and workbench
System maintenance	System monitoring	Routine health check-up of the subsystems	Every subsystem
	Maintenance	Hardware/facility routine maintenance	Every subsystem
	Cleaning	Routine and exceptional cleaning	Every subsystem
	Repair	In case of damage or necessary action required	Every subsystem
Waste management	General waste	Waste from system maintenance and non-biological nor chemicals waste of crop maintenance	Undefined yet
	Liquid waste	General non-concentrated liquids	Undefined yet
	Nutrient-rich liquid waste	Concentrated stock nutrient solution, acid/base solutions, nutrient solution waste	Cultivation racks, NDS, workbench
	Non-hazardous biological wastes	Inedible biomass waste, plant growth substrate	Undefined yet
	Hazardous	Chemicals and bio-hazard wastes	Undefined yet

4. 1. Assess the **tasks' criticality** (in term of impact on the success of the experiment or the mission)

Mark only one oval per row.

	Low	Medium	High	Critical	No answer
Harvesting	◯	◯	◯	◯	◯
Crop Maintenance	◯	◯	◯	◯	◯
Nursery	◯	◯	◯	◯	◯
System Maintenance	◯	◯	◯	◯	◯
Waste Management	◯	◯	◯	◯	◯

5. 2. Assess the **time spent** (%) on each tasks, considering total amount of time spent in the greenhouse.

The sum doesn't have to be accurately 100% but close to it.

Mark only one oval per row.

	0-5%	6 to 25%	26 to 50%	51% to 75%	75 to 100%	Do not know
Harvesting	◯	◯	◯	◯	◯	◯
Crop Maintenance	◯	◯	◯	◯	◯	◯
Nursery	◯	◯	◯	◯	◯	◯
System Maintenance	◯	◯	◯	◯	◯	◯
Waste Management	◯	◯	◯	◯	◯	◯

6. 3. **Occurence / frequency** of each tasks.

You can select multiple answer.

Check all that apply.

	Daily	Weekly	Montly	Less than once a month	Varies on the experiment/ mission	Do not know
Harvesting	☐	☐	☐	☐	☐	☐
Crop Maintenance	☐	☐	☐	☐	☐	☐
Nursery	☐	☐	☐	☐	☐	☐
System Maintenance	☐	☐	☐	☐	☐	☐
Waste Management	☐	☐	☐	☐	☐	☐

7. 4. Assess the **physical load** associated with a task (1 being the lowest).

Mark only one oval per row.

	1	2	3	4	5	6	Do not know
Harvesting	◯	◯	◯	◯	◯	◯	◯
Crop Maintenance	◯	◯	◯	◯	◯	◯	◯
Nursery	◯	◯	◯	◯	◯	◯	◯
System Maintenance	◯	◯	◯	◯	◯	◯	◯
Waste Management	◯	◯	◯	◯	◯	◯	◯

8. 5. Assess the **mental load** associated with a task (1 being the lowest).
Mental load refers to the cognitive and emotional work needed to manage a task.

Mark only one oval per row.

	1	2	3	4	5	6	Do not know
Harvesting	◯	◯	◯	◯	◯	◯	◯
Crop Maintenance	◯	◯	◯	◯	◯	◯	◯
Nursery	◯	◯	◯	◯	◯	◯	◯
System Maintenance	◯	◯	◯	◯	◯	◯	◯
Waste Management	◯	◯	◯	◯	◯	◯	◯

9. 6. Are there any tasks that have been forgotten? Leave a comment on a tasks or assessment not mentioned in this form.

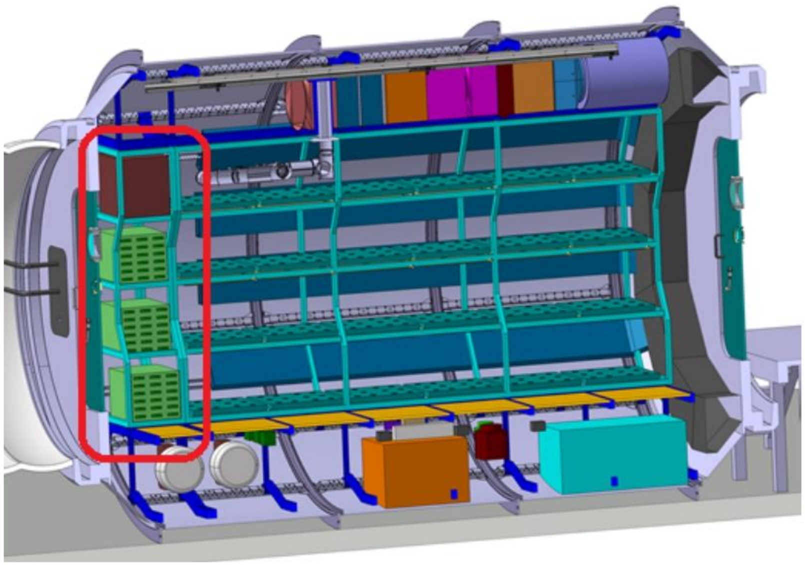
This section is important to us, so please take the time to consider the question.

III. Workstation's equipment valuation

A number of work equipments are planned to be added in order to facilitate the work in the greenhouse, for each element:

1. Collapsible table (6 questions)
2. Toolkit/tool pocket (2 questions)
3. Control panel (2 questions)
4. Stepping platform
   (3 questions)
5. Sink (4 questions)
6. Trash (2 questions)
7. Other
   (1 question)

Section of the Lunar Agriculture Module (LAM)



1. Collapsible table

We consider adding a workbench to perform experiments and routine tasks. The table should be collapsible and easily stored away to save space when not in use.

10. 1.a. Select the task for which you would or wish to use the table for.

Check all that apply.

- [ ] Harvesting
- [ ] Crop Maintenance
- [ ] Nursery
- [ ] System Maintenance
- [ ] Waste Management
- [ ] Other: ____________________

11. 1.b. I consider the addition of a deployable table in the greenhouse to be very **useful/practical**.

Mark only one oval.

	1	2	3	4	5	
Disa	◯	◯	◯	◯	◯	Agree

12. 1.c. I would prefer the **possibility to relocate** the table in the greenhouse.

Mark only one oval.

	1	2	3	4	5	
Disa	◯	◯	◯	◯	◯	Agree

13. 1.d. I would prefer to have **walls on the edges of the table** to prevent items or materials to fall from the table.

Mark only one oval.

	1	2	3	4	5	
Disa	◯	◯	◯	◯	◯	Agree

14. 1.e. What is the **minimum size** of table you would like to have.

Mark only one oval.

- ◯ 0.2 m2 (45x45cm)
- ◯ 0.315m2 (45x70cm)
- ◯ 0.4m2 (45x90cm)
- ◯ 0.81m2 (90x90cm)

15. 1.f. What **features would you particularly like to see added or avoided** in the design of the deployable table?

2. Toolpockets

We consider integrating **toolpockets** that could be worn or could be attached anywhere in the greenhouse.

16. 2.a. Which toolpockets would you use in order of preference.

Check all that apply.

- [ ] Worn tool pocket
- [ ] Tool pockets to attached to the structure of the greenhouse
- [ ] Both
- [ ] None
- [ ] Other: ____________________

17. 2.b. What **features would you particularly like to see added or avoided** in the design of the tool pockets?

3. Control Panel

We consider adding a **control panel** inside the greenhouse, in order to access the technical information (light, nutrient delivery, ...). It could also be used for data collection: photos, notes, etc

18. 3.a. Rate the following statement: **I consider useful/practical adding a control panel in the greenhouse.**

Mark only one oval.

	1	2	3	4	5	
Disa	◯	◯	◯	◯	◯	Agree

19. 3.b. What **features would you particularly like to see added or avoided** in the design of the **control panel**?

____
____
____
____
____

4. Stepping Platform

We consider a stepping platform to access the highest cultivation rack. The design would probably be collapsible to be stored away when not in use.

20. 4.a. Rate the following statement: **I consider useful/practical adding a stepping platform to access the highest cultivation racks.**

Mark only one oval.

	1	2	3	4	5	
Disa	◯	◯	◯	◯	◯	Agree

21. 4.b. Rate the following statement: **I consider a stool sufficient to access the highest cultivation rack.**

Mark only one oval.

	1	2	3	4	5	
Disa	◯	◯	◯	◯	◯	Agree

22. 4.c. What **features would you particularly like to see added or avoided** in the design of the **stepping platform**?

5. Sink

We consider adding a sink to manage the cleaning and liquid wastes.

23. 5.a. Rate the following statement: **I consider useful/practical adding a sink in the greenhouse.**

Mark only one oval.

	1	2	3	4	5	
Disa	◯	◯	◯	◯	◯	Agree

24. 5.b. Rate the following statement: **I would prefer a collapsible sink to save space when not in use.**

Mark only one oval.

	1	2	3	4	5	
Disa	◯	◯	◯	◯	◯	Agree

25. 5.c. Rate the following statement: **I consider critical to have running water in the greenhouse.**

Mark only one oval.

	1	2	3	4	5	
Disa	◯	◯	◯	◯	◯	Agree

26. 5.d. What **features would you particularly like to see added or avoided** in the design of the **sink**?

6. Waste Management

It seems that waste in the lab is an important question and we would like to improve its management.

27. 6.a. In your experience, what are different type of waste necessary inside a lab?

Check all that apply.

- [ ] General waste (non-biological waste such as paper towel, gloves etc)
- [ ] Liquid waste (general non-concentrated liquids)
- [ ] Nutrient-rich liquid waste (concentrated stock nutrient solution, acid/base solutions, nutrient solution waste)
- [ ] Non-hazardous biological wastes (Inedible biomass waste, plant growth substrate)
- [ ] Hazardous (chemicals and bio-hazard wastes)
- [ ] Other: ____________________

28. 6.b. What **features would you particularly like to see added or avoided** in the design of the **waste management**?

____
____
____
____
____

29. 7. In your experience, is there any equipment or design feature not mentioned above that you would like to see added or avoided?

This section is important to us, so please take the time to consider the question. If additional ideas arise later, you can submit again the form answering only this question.

____
____
____
____
____

A7. Usability Test Procedure

Usability Test Procedure

Preparation of the test by the evaluator:

1. Tape the ground to show the accessible zone, locating the surrounding racks
2. Gather the tools required to perform the test:
    a. A ladder, to place easily accessible to the user
    b. Pen and paper, in the tool drawer
    c. A scale, in the upper storage compartment (think about power outlets)
    d. A cultivation tray, with a crop in it, accessible to the user
    e. A valve for the tank
    f. A plastic bag for the waste compartment.
3. Set-up a camera to film the test.
4. Prepare Evaluator form on a computer or tablet.
5. Prepare the questionnaire on another tablet and print the TLX definitions, so that the user can always refer to them.

Preparation of the user:

1. Explain the general goal of the workstation and explain the sub-systems
2. Explain the procedure: 1 Task -> Questionnaire (RTLX + 1 open question) -> x 8
3. Stress that answering open questions is crucial for the analysis phase. It helps to understand the results of the RTLX and to identify further design improvements.

Usability Test

The following tasks are read to the test user who has to perform the steps. The user may ask questions if the purpose of the task is not clear, but is encouraged to use his intuition. The steps are deliberately described without details to test the intuitiveness of the design.

Start the camera.

1. Workbench deployment
    a. Drag out the Workbench
    b. Rotate out the extensions support
    c. Deploy the side panels
    d. If necessary, adjust the height (*evaluator: measure the height*)

The workbench remains deployed to test the interaction between the diverse tasks. The user may modify the configuration of the rack in order to complete the task.

2. Collection of items from the upper storage
    a. Open the upper storage, if necessary use the ladder
    b. Pick-up the scale in the upper storage
    c. Put the scale on the workbench
3. Collection of tools from drawer
    a. Open the drawer
    b. Pick up the pen and paper
    c. Put in on the table
    d. Close the drawer
4. Nominal use of the workbench surface
    a. Lay-out the collected objects
    b. Weight one cucumber
    c. Write the weight down
    d. Measure accessibility (picture?)

The evaluator removes the scale, pen and paper. Installation of the upper storage at the bottom, add the waste container and tank in it.

5. Nominal use of the sink
    a. Prepare the workbench for sink configuration, lower the extension panel by rotating in the supports.
    b. Remove the sink lid
    c. Place the object in the sink
    d. Reach for the tap
6. Change the tanks
    a. Open the lower drawer to access the tanks
    b. Unscrew the valve of the tank
    c. Remove the tank
    d. Place the new tank
    e. Screw the valve back on the new tank
7. Nominal use of the waste compartment
    a. With the workbench deployed, open the lower drawer to have access to the waste compartment
    b. Drop the waste in the waste appropriate compartment
8. Change the waste container
    a. Open the lower drawer to have access to the waste compartment
    b. Change the bag of the waste compartment
    c. Close the waste compartment

A8. User's Questionnaire for Usability Test: Example of Task 1. Workbench Deployment

Usability Form

* Indicates required question

1. Gender

   Mark only one oval.

   - Female
   - Male
   - Prefer not to say

2. Height in cm (eg: 175)

   ____

3. Background / Position

   Mark only one oval.

   - Natural science (biology, physics, cheemistry, etc)
   - Engineering
   - Other: ______________________

4. I have worked in EDEN ISS in Antarctica

   Mark only one oval.

   - Yes
   - No

1. Workbench Deployment

5. Mental Demand *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High

6. Physical Demand

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High

7. Temporal Demand

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High

8. Performance

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Goo	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Poor

9. Effort

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High

10. Frustration Level

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High

11. Comment on your overall experience while using the workstation mock-up. *What stood out to you? What challenges did you encounter while completing the tasks? Which features did you find most helpful or unhelpful during your interaction? If you could change one thing about the workstation design, what would it be and why?*

A9. Moderator's Questionnaire for Usability Test: Example of Task 1. Workbench Deployment

1. Workbench deployment

1. Task Error Rate (number of errors per task)

2. Total number of steps

3. Task Success Rate

   Mark only one oval.

   - Easy
   - Moderate
   - Difficult
   - Failed

4. Completion time (eg: 1.25 for 1min15sec)

5. Observational notes:
   - Table height time adjustment
   - Preffered height
   - Reachability access ...

A10. Summary Table of Usability Test

Task nr	Sub-system tested	Task Name	Steps	Operating envir.	Evaluator metrics	Observations	User questionnaire	Related requir.
1	Workbench	Workbench deployment	1. Drag out the Workbench 2. Rotate out the extensions support 3. Deploy the side panels 4. Adjust the height, if necessary		- Task Error Rate (number of errors per task) - Task Sucess Rate (fail, easy, medium, difficult) - Completion time (and deviation from norm)	- Time taken to adjust height/position/Preferred height - Reachability assessment (ease of access to components)	- RTLX - Do you have any remarks on the design or task? - How useful did you consider the height adjustment feature of the workbench?	WO-01 WO-02 WO-05
	The workbench remains deployed to test the interaction between the diverse tasks. The user may modify the configuration of the rack in order to complete the task							
2	Storage	Collection of items from the upper storage	1. Open the upper storage, if necessary use the ladder 2. Pick-up the scale in the upper storage 3. Put the scale on the workbench	Ladder	- Task Error Rate (number of errors per task) - Task Sucess Rate (fail, easy, medium, difficult) - Completion time (and deviation from norm)	- Number of steps required to retrieve the item	- RTLX - Do you have any remarks on the design or task?	ST-01 ST-02
3	Workbench	Collection of tools from drawer	1. Open the drawer 2. Pick up the pen and paper 3. Put in on the table 4. Close the drawer	Pen and papper	- Task Error Rate (number of errors per task) - Task Sucess Rate (fail, easy, medium, difficult) - Completion time (and deviation from norm)	- Notes on adaptation of rack configuration to perform the task	- RTLX - Do you have any remarks on the design or task?	WO-09
4	Workbench	Nominal use of the workbench surface	1. Lay-out the collected objects 2. Weight one cucumber 3. Write the weight down 4. Measure accessibility		- Task Error Rate (number of errors per task) - Task Sucess Rate (fail, easy, medium, difficult) - Completion time (and deviation from norm)	- Record by a picture or video the reach of the person, or the blind spots	- RTLX - Do you have any remarks on the design or task? - The table was too small (strongly agree to strongly disagree)	WO-03 WO-07
	The evaluator removes the scale, pen and paper. Installation of the upper storage at the bottom, add the waste container and tank in it.							
5	Sink	Nominal use of the sink	1. Prepare the workbench for sink configuration, lower the extension panel by rotating in the supports. 2. Remove the sink lid 3. Place the object in the sink 4. Reach for the tap		- Task Error Rate (number of errors per task) - Task Sucess Rate (fail, easy, medium, difficult) - Completion time (and deviation from norm)		- RTLX - Do you have any remarks on the design or task?	GE-01 GE-02
6	Sink	Water tank swapping	1. Open the lower drawer to access the tanks 2. Unscrew the valve of the tank 3. Remove the tank 4. Place the new tank 5. Screw the valve back on the new tank	Tank valve	- Task Error Rate (number of errors per task) - Task Sucess Rate (fail, easy, medium, difficult) - Completion time (and deviation from norm)		- RTLX - Do you have any remarks on the design or task?	GE-03
7	Waste compartment	Nominal use of the waste compartment	1. With the workbench deployed, open the lower drawer to have access to the waste compartment 2. Drop the waste in the waste appropriate compartment		- Task Error Rate (number of errors per task) - Task Sucess Rate (fail, easy, medium, difficult) - Completion time (and deviation from norm)	- Record if person had to change the configuration of the rack to accomplish the task	- RTLX - Do you have any remarks on the design or task?	WA-01 WA-02 WA-04
8	Waste compartment	Empty and change the waste container	1. Open the lower drawer to have access to the waste compartment 2. Change the bag of the waste compartment 3. Close the waste compartment	Plastic bag	- Task Error Rate (number of errors per task) - Task Sucess Rate (fail, easy, medium, difficult) - Completion time (and deviation from norm)		- RTLX - Do you have any remarks on the design or task?	WA-01 WA-03 WA-04