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Analysis and Design of a Logistic-to-Green Approach for a Lunar Greenhouse Module

Analyse und Design eines Logistic-to-Green Ansatzes für ein Mond Gewächshaus Modul

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Master Thesis

Submitted by

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Declaration of Authorship

I declare that the final thesis “Analysis and Design of a Logistic-to-Green Approach for a Lunar Greenhouse Module” presented to the faculty of Production Engineering is my own unaided work. All direct or indirect sources used are acknowledged as references. This thesis was not previously presented to another examination board.

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Abstract

Today, human space exploration is increasingly moving toward long-term space travel. Various space agencies are developing plans to return first to the Moon and then to the Martian surface. Such an ambitious project requires efforts in areas such as life support systems and locally produced food. This thesis addresses cargo security, which should ensure the safe transfer of equipment to the Moon. It is important for the EDEN NG GTD project, which aims for a dual-use approach. Meaning that it involves using the module first as a transportation carrier and then as a greenhouse.

Extensive research was conducted on various cargo carriers from the past and present to filter out the cargo restraints used. Based on this, different calculations were performed regarding different load arrangements and combinations of transport bags at different positions in the greenhouse section. Furthermore, requirements explicitly for load securing were developed to adapt to the already given greenhouse requirements.

The results show that the packaging material for load securing has a large share in the total mass of the module. Since the racks will contain the plant trays after landing on-site, uses should also be found for the transportation bags and belts. Therefore, developments such as modifying usual transportation bags to achieve more recycling possibilities need to be considered.

Die Erforschung des Weltraums durch den Menschen geht heute verstärkt in Richtung langfristiger Raumfahrt. Verschiedene Raumfahrtagenturen entwickeln Pläne, um zuerst zum Mond und danach zur Marsoberfläche zurückzukehren. Ein solch ehrgeiziges Projekt erfordert Anstrengungen in Bereichen wie Lebenserhaltungssystemen und vor Ort produzierter Nahrung. Diese Arbeit befasst sich mit der Ladungssicherung, die einen sicheren Transfer des Equipments zum Mond gewährleisten soll. Dies ist wichtig für das EDEN NG GTD-Projekt, das auf einen Dual-Use-Ansatz abzielt. Dabei wird das Modul zunächst als Transportträger und anschließend als Gewächshaus genutzt.

Im Rahmen der vorliegenden Arbeit wurde eine umfangreiche Recherche über verschiedene Ladungsträger aus der Vergangenheit und der Gegenwart durchgeführt, um die verwendeten Ladungssicherungen herauszufiltern. Darauf aufbauend wurden verschiedene Berechnungen hinsichtlich unterschiedlicher Ladungsanordnungen und Kombinationen von Transporttaschen an unterschiedlichen Positionen im Gewächshausbereich durchgeführt. Weiterhin wurden explizite Anforderungen für die Ladungssicherung entwickelt, um die bereits bestehenden Gewächshausanforderungen anzupassen.

Die Ergebnisse zeigen, dass das Verpackungsmaterial für die Ladungssicherung einen großen Anteil an der Gesamtmasse des Modules hat. Da die Regale nach der Landung vor Ort die Pflanzenschalen beinhalten werden, sollen auch für die Transporttaschen und -gurte Verwendungszwecke gefunden werden. Daher müssen Entwicklungen wie Änderung der üblichen Transporttaschen in Betracht gezogen werden, um mehr Recyclingmöglichkeiten zu erreichen.

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Abbreviations

AES	Advanced Exploration Systems
AM	Avionics Module
AMS	Air Management System
ASI	Agenzia Spaziale Italiana
ATV	Automated Transfer Vehicle
AVF	Adaptive Vertical Farm
BLSS	Bio-regenerative Life Support System
CAST	Cargo Accommodation Support Tool
CC	Crew Cabin
C-CAST	Columbus-Cargo Accommodation Support Tool
CE	Concurrent Engineering
CEF	Concurrent Engineering Facility
CELSS	Controlled Ecological Life-Support System
CLEP	China Lunar Exploration Program
CNSA	China National Space Administration
COTS	Commercial Orbital Transportation Services
COTS	Components-Off-The-Shelf
C.R.O.P.	Combined Regenerative Organic food Production
CTB	Cargo Transfer Bag
CWC	Contingency Water Container
CWC-I	Contingency Water Container - Iodine
DHCL	Data Handling and Control
DLR	Deutsches Zentrum für Luft- und Raumfahrt
Desert-RATS	Desert - Research And Technology Studies
EDEN NG GTD	Evolution and Design of Environmentally-closed Nutrition-sources Next Generation Ground Test Demonstrator
EDR	European Drawer Rack
EP	Exposed Pallet
ESA	European Space Agency
FEG	Future Exploration Greenhouse
GNC	Guidance Navigation and Control
GTD	Ground Test Demonstrator
HDU	Habitat Demonstration Unit
HTV	H-2 Transfer Vehicle
ICC	Integrated Cargo Carrier
ISIS	International Sub-rack Interface Standard/ Specification
ISPR	International Standard Payload Rack
ISS	International Space Station

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JAXA	Japan Aerospace Exploration Agency
LED	Light Emitting Diode
LEO	Low Earth Orbit
LRR	Logistics Reduction and Repurposing
LSC	Life-Support Cabin
L2L	Logistic-to-Living
M-LGH	Mars-Lunar Greenhouse
MCTB	Multipurpose Cargo Transfer Bag
MPLM	Multi-Purpose Logistics Module
MTF	Mobile Test Facility
NASA	National Aeronautics and Space Administration
NASDA	National Aeronautics and Space Development Agency
NDS	Nutrient Delivery System
NG	Next Generation
ORU	Orbital Replacement Unit
PC	Plant Cabin
PCM	Pressurized Cargo Module
PHM	Plant Health Monitoring
PLC	Pressurized Logistics Carrier
PM	Propulsion Module
RRC	Resource Recycling Cabin
SES	Service Section
SM	Service Module
SSFP	Space Station Freedom Program
TBD	To Be Done
TCS	Thermal Control System
TRL	Technology Readiness Level
ULC	Unpressurized Logistics Carrier
UV	Ultraviolet
VF	Vertical Farming

1 Introduction

This chapter is divided into five parts. The first one is about human long-term space exploration with a focus on the difficulties of developing a habitable space for humans to live on the Moon or Mars. Furthermore, different projects from various space agencies are pointed out which is all explained within Sec 1.1. The following part in Sec 1.2 presents the project which is the basis for this thesis and closes with the term Logistics-to-Living which tries to reuse transportation equipment as much as possible. Subsequently, the underlying methods of how the information for this thesis was collected and processed are presented with additional visualizations in Sec 1.3. Sec 1.4 provides an overview of the processes of how this thesis was approached. Both contributed to information content and possible cargo arrangement solutions to this thesis. Last, the overall structure of this thesis is both described and visualized in Sec 1.5.

1.1 Motivation and Background

The driving curiosity of humanity to explore our universe has led to human space exploration and in particular to the exploration of other planets. But in doing so, the survival of humans in space and on other planets has to be secured due to the extremely harsh environments on-site. To withstand these conditions and to achieve the higher goal of long-duration stays or missions on another planet, closed-loop and life support systems have to be developed and verified beforehand. This means that humans can only be sent on long-duration space missions if the necessary technology can provide a planetary infrastructure with a safe habitat for the astronauts as well as secure food production within a greenhouse. Only then it is possible to guarantee the long-term travel and stay of humans in space.

Since the Moon is the closest celestial body to Earth, it will be the test site for those techniques to investigate and develop reliable, lightweight, and functional habitations. One of the reasons is that the Moon can be reached faster than Mars because of its shorter distance from Earth [1]. Therefore, technologies can be tested in close proximity to Earth before sending humans to Mars for the first time. Furthermore, space conditions such as vacuum, radiation, and different gravitation are challenging areas for constructing a habitable place for humans and growing plants in space. After a test phase on the Moon and an elaboration of all needs and musts, space exploration can be further expanded onto Mars [2]. The planet is of interest because of characteristics such as river-like structures that indicate it may have hosted life at some point. Therefore, in Mars' early history water was presumably liquid. Hence, life could have evolved before the climate cooled down [3]. Although the Moon and Mars share some similarities, a visit to Mars would make the mission's tasks many times more difficult. Just to name some, a journey to Mars can last up to three years resulting in no short-term supply or the possibility of a rescue flight. Furthermore, the stress on the human body concerning isolation and radiation can have serious consequences on mental and physiological health [4].

To catch up with this plan, many demanding tasks such as construction, the growth of plants on other planetary surfaces as well as safe storage for transportation, so that all the interiors will reach their destination safely, have to be considered and guaranteed. Currently, the German aerospace center (DLR) is conceiving, designing, and developing a greenhouse module that shall be operated on the lunar surface. The project is called evolution and design of environmentally-closed nutrition-sources (EDEN) Lunar and evolved from a prototype operated in Antarctica whose goal was to advance agriculture growth technologies in a controlled environment forward [5, 6, 7]. Further ongoing missions to the Moon are the Artemis missions of the National Aeronautics and Space Administration (NASA), whose goal is a long-term presence in orbit and on the Moon [8]. This strategy is complemented by the work of Lockheed Martin and NASA, namely the Lunar Orbiting Platform - Gateway. As a first step, this gateway has to serve as an operational platform for human exploration in the vicinity of the Moon. But for the long run it is envisioned for missions to Mars [9]. Also, the China national space administration (CNSA) started a Moon program, namely the China lunar exploration program (CLEP), also known as the Chang'e project. So far, six missions were successfully flown which all had the goal of orbiting, landing, and bringing a sample back to Earth. The following three planned missions will have the task of surveying and constructing the Moon as well as exploiting the resources on-site [10].

Finally, all these technological developments and improvements are not just for space travel but can moreover be used here on Earth. Since climate change and conflicts such as the one between Ukraine and Russia are affecting life on Earth, those technologies could be used there as well. This would allow quick help for countries in need to increase rapid help for shortages or to be able to grow plants in dry regions like deserts. Where the usual growth techniques do not work after such catastrophes, a quick and independent growth environment could be placed anywhere in a short time. Thus, many lives could be saved by providing food quickly [11, 12].

1.2 Problem Statement

The foundation of this work is the mobile test facility (MTF) which is part of the (EDEN) international space station (ISS) project. In the following, it is shortly called EDEN ISS MTF. This project is part of the Horizon 2020 program, a European Union's Research and Innovation Action program. During its operation time, the MTF was located close to the Neumayer Station III in Antarctica. It consists of two containers, one hosts a service section (SES) while the other one is the actual greenhouse, labeled as future exploration greenhouse (FEG). Its goal was to develop an efficient greenhouse with advanced agriculture technologies [13, 5]. With lessons learned from the MTF prototype from Antarctica, a new facility designed for the Moon was created which is called EDEN Lunar. In order to change and test all lessons learned from the MTF before directly going to the Moon, the EDEN next generation (NG) ground test demonstrator (GTD) project will be used for ground testing as its name indicates [14]. It aims at developing a fully functional bio-regenerative life support system (BLSS) for a greenhouse with the tendency towards supplying further biological systems. This is a complex task since all naturally occurring processes on Earth such as generating oxygen or water handling must be handled artificially [14]. The corresponding mission scenario roughly depicts a long-term mission with a Moon or Mars base, on which the greenhouse module should be placed. It shows two scenarios depending on whether an orbit infrastructure is available at the time of launch or not, which can be seen on the right and left sides, respectively. A visualization can be found in the following Fig 1.1.

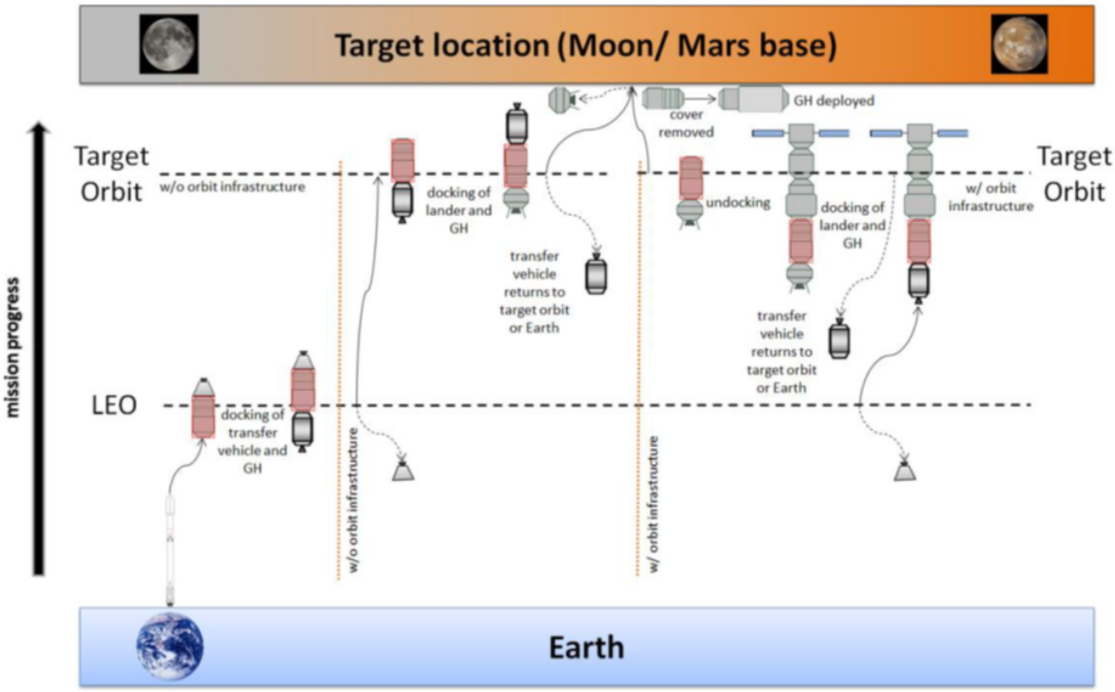


Figure 1.1: Possible mission scenario with (right) and without (left) orbital infrastructure. [5]

In the field of space greenhouses, the term Logistics-to-Living plays an important role. It covers the re-usage procedure of logistical items such as bags, containers, or foams so that they can be transformed into crew items or system components that can further be used. The importance of this term is that by re-purposing parts which were originally needed for transportation, they can be later on used as well which decreases the overall launch mass. [15]

Similar research is done by DLR but with an individual term based on their project, namely the Logistic-to-Green approach. It indicates the important function of the EDEN NG GTD and later EDEN Lunar which is the ability to first serve as a cargo transportation system to the lunar surface with a merged transition into the agricultural mode. After the transition, it can comprise its key function as a greenhouse with just a few working steps in between. This dual-use shall reduce the launch to a single one which means that the entire greenhouse will compactly take off along with diminished revision on the Moon to assure quick plant growth.

This thesis aims to support the Institute of Space Systems of DLR in specifying the design elements which are required to allow such a dual-use approach of a cargo transfer module into a greenhouse module. It contributes a collection and comparison of the storage systems of the different existing cargo transfer modules, deriving lessons learned. Furthermore, the development of requirements typically applied for cargo modules including cargo storage and its securing is done. Additionally, the greenhouse module requirements are going to be analyzed, adapted, and modified to the cargo usage. The aforementioned points will be underlined with flowcharts for the individual requirements. Furthermore, different trade-offs are going to be made concerning various bag arrangements at different positions within the greenhouse. This includes different bag combinations to result in the most efficient one with respect to the internal storage volume the bags can provide against their empty bag masses.

1.3 Method

This thesis is based on extensive literature research in the field of cargo storage of different transportation systems. The main focus lies on the multi-purpose logistics module (MPLM) built by the Italian Space Agency, the H-2 transfer vehicle (HTV) developed by JAXA, the automated transfer vehicle (ATV) designed by the European space agency (ESA), and Cygnus which is part of a NASA project. Knowledge that is gained from this research will then contribute to various trade-off calculations for bag arrangements.

This research started with the study of the existing cargo carrier to gather information about their interior. The focus of this thesis is set on the four cargo carriers ATV, Cygnus, HTV, and MPLM since they provided the most information. Additionally, the storage system on board the ISS is also taken into account. Having all this information together, comparisons, as well as commonalities, were drawn. In the next step, the interior and storage systems were investigated for each module individually. Beginning with the ATV, three sub-classes were found, namely outgassing of materials, cleaning procedures of the module before launch, and the storage solution and used stowage systems. For Cygnus, HTV, and MPLM the gathered information only provided details about their interior and storage designs. Finally, a closer look was taken at the ISS and its interior. One specialty is the development of the CAST tool, which is a software tool used for cargo accommodation inside the ISS. The approach of judging the collected information is represented in the following Fig 1.2 to underline the previous explanation.

The research was then followed by a detailed bag calculation for different positions within the greenhouse section. Starting with the rack compartments, it was first searched for those bag types that fit in there. Afterwards, the empty bag masses and their provided storage volumes were calculated for if only one bag type is used for every rack compartment. Next, different bag combinations, as well as arrangements, were calculated for the subfloor which is the area beneath the floor the crew will walk on. Finally, a last bag calculation was done for the floor and ceiling areas. Those computations were then closed by an estimation of the belts that will be needed to fixate all the bags inside the module. The detailed method process for those calculations can be seen in Fig 1.3.

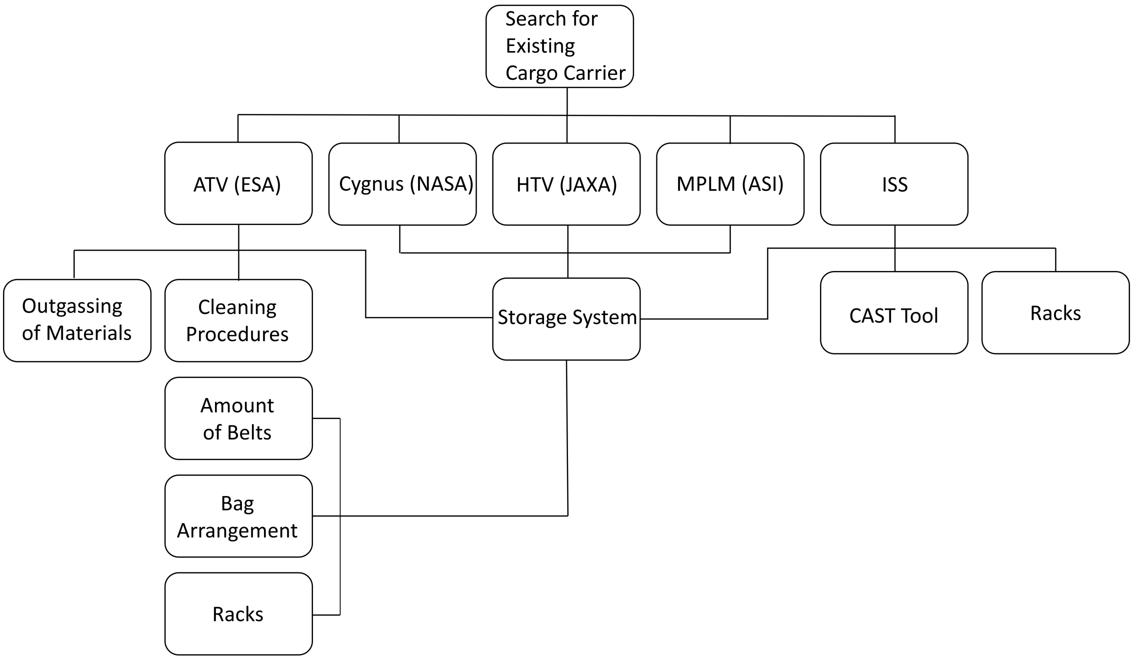


Figure 1.2: Research method for this thesis.

1.4 Concurrent Engineering Study

One development part of this thesis was conducted during the participation in the concurrent engineering (CE) process which was done in the concurrent engineering facility (CEF) at DLR in Bremen. CE is an iterative process meaning the development takes place simultaneously including all relevant disciplines. This means all responsible people for each subsystem are present in one room while executing the emerging tasks in parallel. By that, the development time, mistakes, and cost due to fewer re-works can be reduced. Furthermore, the time in which a decision is awaited is reduced while increasing quality, customer satisfaction, and consistency since all present people are on the same page regarding the development status. Additionally, this leads to better communication since related questions can be addressed immediately with the responsible person or the project group in total because they are all present at one place at the same time. The iterative CE process differs from an incremental, traditional one in which the development is done step-wise. [16]

The development changes beginning with the design before the study and following with the changes towards the results after the study are explained in more detail in Sec 3.1.

1.5 Structure of the Thesis

This thesis is structured in six parts, beginning with an introduction of existing cargo transfer modules in Sec 2. The focus of this section lies on the following carrier, namely

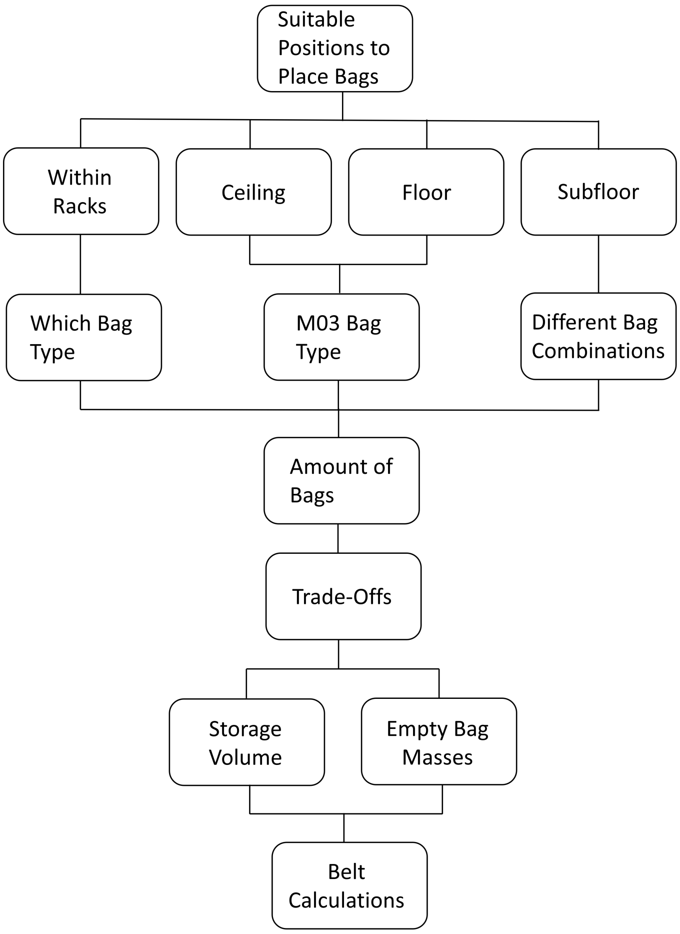
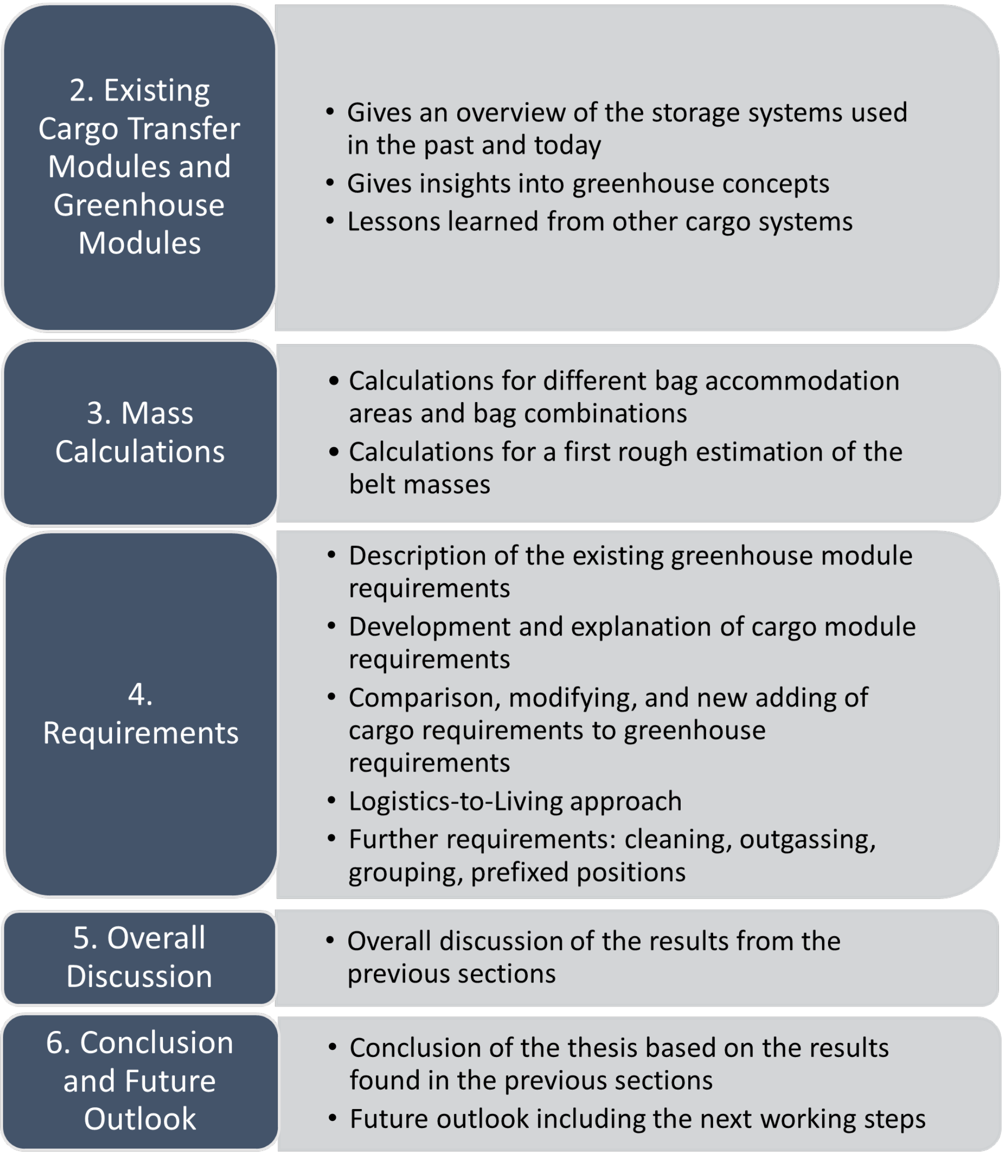


Figure 1.3: Bag calculation method for this thesis.

ATV, Cygnus, HTV, and the MPLM. Furthermore, it provides an introduction to storing systems in form of bags and racks which are already used in those mentioned cargo carriers. The chapter introduces space greenhouses with a special emphasis on the EDEN ISS MTF and closes with lessons learned. The next chapter in Sec 3 is about mass calculations and accommodation arrangements in which also trade-offs are being done to come up with the most efficient accommodation solution for the storing system. Some of those calculations were done within the CE process which is explained in more detail in Sec 3.1. The fourth chapter in Sec 4 is about the requirements for both the greenhouse module in total as well as for the cargo section itself. Furthermore, it deals with a comparison and adaption of the overall greenhouse module requirements to the cargo ones. Additionally, requirements regarding cleaning and outgassing procedures are explained as well. Afterwards, an overall discussion about the results from the previous chapters is conducted in Sec 5. Finally, this thesis is closed by an overall conclusion in Sec 6 regarding problems that occurred during the development time of this thesis. In addition, a future outlook with the next steps that need to be done are presented.

A more compact structure of the following chapters with the overall topics on the left side and their corresponding contents on the right side of this thesis is shown in Fig 1.4.



2. Existing Cargo Transfer Modules and Greenhouse Modules	• Gives an overview of the storage systems used in the past and today • Gives insights into greenhouse concepts • Lessons learned from other cargo systems
3. Mass Calculations	• Calculations for different bag accommodation areas and bag combinations • Calculations for a first rough estimation of the belt masses
4. Requirements	• Description of the existing greenhouse module requirements • Development and explanation of cargo module requirements • Comparison, modifying, and new adding of cargo requirements to greenhouse requirements • Logistics-to-Living approach • Further requirements: cleaning, outgassing, grouping, prefixed positions
5. Overall Discussion	• Overall discussion of the results from the previous sections
6. Conclusion and Future Outlook	• Conclusion of the thesis based on the results found in the previous sections • Future outlook including the next working steps

Figure 1.4: Structure of this thesis.

2 Existing Cargo Transfer Modules and Greenhouse Modules

This section investigates existing cargo transfer modules regarding their storage systems. First, a short overview of the current state of the art is taken in Sec 2.1. Subsequently, a closer look is taken into the five chosen cargo systems and the ISS itself since they provided the most information. They are all noted down in Sec 2.2. In more detail, the ATV can be found in Sec 2.2.1, Cygnus in Sec 2.2.2, the HTV in Sec 2.2.3, the MPLM in Sec 2.2.4 and last but not least the ISS in Sec 2.2.5. Detailed attention is thereby drawn to used storage possibilities inside these cargo modules which were and still are presently used. Next, a closer look was taken at the storage systems themselves in Sec 2.3. These are various kinds of transportation bags in Sec 2.3.1 and multiple racks with different functions in Sec 2.3.2. After that, Sec 2.4 deals with existing greenhouse systems with a space application. Among them is the EDEN ISS MTF which is the pioneer of the EDEN NG GTD for which this thesis is about. This chapter will then be closed by lessons learned in Sec 2.5 of this entire chapter regarding the analyzed cargo modules and storage possibilities as well as lessons learned from the EDEN ISS MTF.

2.1 State-of-the-Art

The state-of-the-art deals with questions concerning equipment for potential planetary bases, in particular regarding bio-regenerative life support systems (BLSS) and how to properly test them on selected test sites. BLSS is the overall application for processes on a biological basis to support a space crew on its mission. These processes include regeneration of the air, recycling of the water and organic waste as well as food production on-site [17]. Therefore, a lot of effort is undertaken to simulate different habitats in similar environmental conditions to evaluate the important steps needed to reach the goal of making another planet viable. Thereby, the habitats including greenhouses are ranging from positions hostile to life, such as Antarctica [5], to desert-like regions, such as the high deserts in Arizona where different hardware and operations are tested [18].

One such test facility is EDEN ISS MTF, a greenhouse located in Antarctica. The reason behind this greenhouse test demonstrator is to find ways of providing edible and fresh food such as vegetables which will be planted in situ under extreme climates. This project is important for a future crew on another planet. First, it has to face a long space flight and second, the actual daily living has to be secured. The reasons are that it will not be possible to get a constant resupply of food and water from Earth. Furthermore, it will not work to grow plants in the same manner as it is done on Earth. Those are some points for why Antarctica was chosen as the test site because this place is also rarely supplied. That is why the crew in Antarctica would be similarly dependent on food production on-site if it would not get one huge resupply once a year [7]. The main difference between growing plants on Earth and in space is that the crops will grow without having their roots in the soil and with an artificial light source. The reason for the former is that for example a hydroponic system has a higher growth rate while also needing fewer chemicals for growing [19]. The latter one, for which light emitting diodes (LEDs) are used, is chosen because of, among other things, their small size and near monochromatic emission. This specific emission allows the adjusted setting of the light emission spectra to the individual absorption spectra of each plant [7].

While Antarctica is used as a test site for a harsh and cold environment, NASA's desert research and technology studies (Desert RATS) are conducted at various test sites around the city of Flagstaff in Arizona. The reason for this location is the resemblance to possible future planetary terrains and their features. Some of the test areas are conducted at the Cinder Lake which is a volcanic area. There, it was possible to simulate craters during the Apollo training. Another test site for loose Lunar regolith is the one close to Joseph City. Its terrain is hilly and sandy and was therefore used as a representative of the Martian dunes. In those locations, a variety of applications for space missions were tested based on the composition of the test area itself. Some of those tests were procedures for the collection of geological and biological samples or surface missions including a rover. An advantage of this place is the accessibility because one can get there quickly and quite easily compared to a test site directly on the Moon for example. [20]

Another greenhouse designed for a Moon or Mars application is the Mars-Lunar greenhouse (M-LGH) funded by NASA Ralph Steckler Program. It has a hydroponic system meaning that it uses nutrient-rich water instead of soil in which the plants for food production are growing. Furthermore, it contains air revitalization and recycled water which is all part of the BLSS and will secure a future planetary outpost. [21]

2.2 Existing Cargo Carrier and the ISS

The origin of a cargo carrier lies in the need for a resupply system for the ISS. The station is dependent on regular delivery for the experiments run onboard the ISS as well as for the daily needs of the astronauts such as water and food [22]. The baseline for this thesis, which will be presented in more detail in the following, is therefore a set of the cargo carrier. These are the ATV, Cygnus, HTV, and the MPLM. In general, these cargo carriers are similar regarding their construction and are only differing in their values and fine differences. Therefore, the Tab 2.1 at the end of this sub-chapter contains a summarized list of all the technical details of each carrier to simplify the comparison among them. Apart from those four cargo carriers, a closer look is taken at the ISS and its storage system along with an introduction to the CAST tool. This is used to simulate the cargo accommodation inside the Columbus laboratory within the ISS configuration.

2.2.1 ATV

The first cargo carrier to be investigated is the ATV, built by ESA, and launched atop an Ariane 5 rocket. Since it was not a reusable cargo carrier, the ATV consisted of a series of total five carriers. They lasted over the period beginning in 2008 until 2014. Although it was not continued, it can still serve as a source from which conclusions can be drawn as is the case for this thesis. [23]

Its duty, as it counts for all the following resupply cargo carriers, was the delivery of all its necessities required to guarantee unrestricted daily work on board the ISS. This meant on the one hand providing equipment and spare parts to run all the experiments located on board the ISS. On the other hand, it took care of the availability of nutrition, water, and air for the astronauts [24]. Since the ATV remained attached to the ISS for up to six months, the crew had time to unload the delivered goods and also to refill the carrier again with accumulated waste from the station. This process is similar to the needs of the EDEN NG GTD since all the transported equipment needs to be first stored for launch and flight and requires an unpacking once the final destination on the Moon is reached. For both scenarios, this unpacking has to be as quick as possible to have more time for the relevant actions such as running the experiments on the ISS or starting the growing process inside the EDEN NG GTD greenhouse. Besides the two resupply needs mentioned before, the ISS also needs regular refueling of its propellant tanks to be able to lift its orbit. The reason for the gradual decay of the orbit is due to the gravitational pull of Earth combined with an atmospheric drag which requires a periodical adjustment [25]. Therefore, the ATV was also carrying propellant on board to refill the stores of the ISS [26]. A sketch of an ATV is shown in Fig 2.1.

Figure 2.1: Cutaway model of the ATV carrier. Image adapted from [27].

It was further divided into a service module (SM) and the so-called integrated cargo carrier (ICC). The former was the non-pressurized part and hosted all the equipment necessary for guiding the ATV directly to the ISS. That included batteries, computers, and the propulsion to do the maneuvers in space. However, with 40% of the total volume, it only represented the minority of the total volume of the ATV [28]. The pressurized latter, based on the MPLM, was powered by the SM and insofar important as for the storage of the cargo to be transported. This module part was further divided inside into dry and fluid cargo. The dry cargo compartment hosted critical equipment which was stored inside the cargo carrier for launch and was later accessed via the crew. The critical hardware varied from personal belongings for the astronauts, new experiments or spare parts for a stay on the ISS to a resupply of food [29]. In contrast, the fluid cargo stored the propellant for refueling the station [26]. As its main task was to supply the ISS, it was able to transport 7500 kg of cargo upload capacity. In detail, it consisted of 5500 kg of dry supplies, 840 kg of drinking water, and 100 kg of oxygen and nitrogen. For the fluid part, it transported 4700 kg of re-boost and attitude control propellant with additional 860 kg of refueling propellant. Although the ATV was not able to reuse, it was still able to host 6400 kg of station waste which then burned up in the atmosphere during its re-entry. [24]

Figure 2.2: Interior of the ATV 5 carrier. Image adapted from [27].

A summarized list of the technical details regarding the ATV can be found in Tab 2.1. In the following, an x marks that the carrier did not possess the ability while a hook marks that it had the ability.

2.2.2 Cygnus

The next cargo carrier being analyzed is the Cygnus spacecraft which was developed within NASA's commercial orbital transportation services (COTS) program. It was a joint work together with Northrop Grumman, former Orbital Sciences, and SpaceX [30]. Cygnus is an unmanned spacecraft and gets transported on top of the Orbital's Antares rocket. However, it can only be used once since it is burning up in the atmosphere when returning to Earth, which concludes that there exists a series of Cygnus modules, all varying in their payload mass [31].

The Cygnus carrier consists, same as for the ATV, of two domains. The one domain is the SM and it is attached to the other domain, the pressurized cargo module (PCM). The latter evolved from the MPLM. A closer look at the MPLM will be taken in Section 2.2.4. The PCM was constructed by Thales Alenia Space and is used for storing the cargo which is going to be transported to the ISS. After unloading the interior into the station, the PCM is filled again but this time with equipment that is no longer used. The additional waste that arose through the daily living of the astronauts will be stored inside Cygnus afterwards as well. Everything that is packed into the pressurized segment of Cygnus is going to be burned into the atmosphere since it is not intended for this carrier to be used again. The SM is alike the one in the ATV by means of its responsibility for the supply of power, propulsion, and orbit control for the pressurized module. The overall exterior appearance of Cygnus can be seen in Fig 2.3.

Figure 2.3: Exterior look of the Cygnus carrier. Image adapted from [31].

Getting more specific, the PCM exists in two versions, a standard and an enhanced one differing in their size. The standard module is able to carry 2000 kg of cargo whereas the enhanced version is capable of hosting 1500 kg more resulting in a total of 3500 kg cargo capacity. While the enhanced module is capable of carrying the same amount of waste as it can carry cargo, the standard version can host less, speaking in numbers of 1200 kg. Regarding the amount of time in which they can stay attached to the ISS, it is quite similar for both modules: 60 d for the standard and 66 d for the enhanced one. Overall, these two versions have a similar set-up which is shown in Fig 2.4. [31]

Figure 2.4: Interior of the Cygnus carrier. Image adapted from [32].

A detailed distinction between the two versions can be found at one glance in the following Tab 2.1.

2.2.3 HTV

Next, a closer look is taken at the HTV carrier, also known as H-II Transfer Vehicle. It consisted of a series of HTV vehicles, ranging from HTV-1 to HTV-9 with the newest developments on the HTV-X. Nevertheless, all were built by JAXA itself and Mitsubishi Heavy Industries. While HTV-1 to HTV-9 were flown on board the H-IIB rocket, HTV-X will be launched aboard the new H3 rocket. The exterior view of the HTV-9 is shown in Fig 2.5. [33, 34]

In the following, the description of the HTV's details is based on the previously flown HTV-1 to HTV-9, since the launch of HTV-X is indicated for January 2024 [36].

In general, the HTV was divided into four sections, namely the pressurized logistics carrier (PLC), the unpressurized logistics carrier (ULC), the avionics module (AM), and the propulsion module (PM). The first pressurized section (PLC) hosted all the cargo for

Figure 2.5: Exterior of the HTV-9 carrier. Image adapted from [35].

utilization onboard, i.e. clothes, food, and experimental racks. A picture from the inside of it can be seen in Fig 2.6.

The unpressurized section (ULC) contained an exposed pallet (EP) and both were used to transport external experiments and the so-called orbital replacement units (ORUs). The entire setup and how both combined looked can be seen in Fig 2.7. The avionics section (AM) and the propulsion section (PM) were necessary for guidance navigation and control (GNC) and orbital maneuvers, respectively. [33]

All in all, the HTV series was an uncrewed cargo carrier [34]. It stayed attached to the station for about one month during which the carrier was unloaded from all items inside and afterwards refilled with trash and items, which were no longer used onboard. After that, it detached and made its destructive re-entry into Earth's atmosphere. To name those amounts of cargo, the HTV was able to transport 5200 kg of pressurized cargo inside the PLC and 1500 kg of unpressurized cargo in the ULC with the EP. Furthermore, it was able to load 6000 kg of waste from the station for disposal. All the details as well as the one from the other cargo carrier can be found in Tab 2.1.

The HTV-X, which is currently under development, will be the successor of the former HTV series. It will heritage two important points. First, the cargo transportation aspect is still able to resupply the ISS. This includes a reconfiguration of the inside of the carrier as well as the outside to be able to carry more payload. Additionally, late access will be possible meaning that cargo can be mounted until 24 hours before launch. The first point, the cargo transportation, will also include support of the gateway, which is currently, as well, under development. The Lunar Orbiting Platform - Gateway is similar to the ISS just with the difference that it will offer humans a lunar presence in the beginning. Later on, this concept shall be transferred to Mars to support human explorations to both, the Moon and Mars [37]. Second, after separating from the ISS, the HTV-X will further stay in space for up to 18 months. Then, it will provide a platform for users for technical

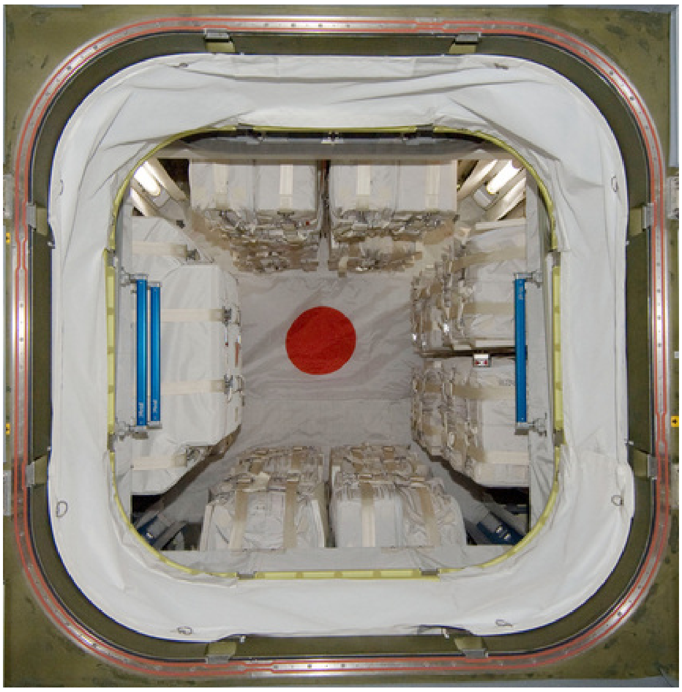


Figure 2.6: Interior of the HTV carrier. Image adapted from [33].

Figure 2.7: Exposed pallet inside the unpressurized logistics carrier of the HTV carrier. Image adapted from [33].

demonstrations. [38]

2.2.4 MPLM

The last cargo carrier to be looked at is the MPLM built by the Italian space agency (ASI). In total, it was a series of three modules of which, however, only two were used in the end, namely Leonardo and Raffaello. The two MPLMs, respectively, were transported to the ISS on board the Space Shuttle which was formally in operation until 2011. Integration of the Leonardo module inside the Space Shuttle can be seen in Fig 2.8. [39]

Figure 2.8: Integration of the Leonardo MPLM inside the Space Shuttle. Image adapted from [40].

The MPLM differs from the before mentioned other three cargo carriers that were describe before in several points. First, the module is not subdivided into a pressurized and an unpressurized section but just consists of a completely pressurized interior. Second, it not only fulfilled the function of a cargo carrier but also as a space station module while being attached to it. During the coupling, it was possible to unload the MPLM's stored racks and equipment as well as reload ISS racks back into the MPLM. Third, it was reusable due to the fact that it was transported inside the Space Shuttle bay which protected the module from burning up in the atmosphere during re-entry. [39]

Besides the three mentioned deviating facts, the MPLM was able to transport up to 10 000 kg of cargo, all being stored within 16 racks mounted inside the module. Five of those racks were additionally able to provide power, data, and fluids which were necessary to maintain a refrigerator freezer to be able to store experiment samples and food during the flight. The following Fig 2.9 shows the interior of Leonardo, the first MPLM to carry supplies to the ISS. A compact list of the MPLM as well as a comparison to the other cargo carrier can be found in Tab 2.1. [39]

Figure 2.9: Interior of the MPLM Leonardo. Image adapted from [41].

Technical details	ATV [24, 42]	Cygnus [31] standard/enhanced	HTV [33, 43]	MPLM [44, 39]
Length [m]	10.30	5.14 / 6.39	10.00	6.60
Diameter [m]	4.50	3.07 / 3.07	4.40	4.20
Pressurized Volume [m^3]	48.0	18.9 / 27.0	14.0	31.0
Cargo Mass [kg]	7500	2000 / 3500	6700	9400
Disposal Volume [kg]	6400	1200 / 3500	6000	6000
Endurance [month]	up to 6	60 days / 66 days	~ 1	1
Reusable?	x	x / x	x	✓
Crewed?	x	x / x	x	x

Table 2.1: Technical details of the four cargo carriers ATV, Cygnus, HTV, and MPLM (yes=✓, no=x).

2.2.5 ISS

Finally, a more detailed investigation is going to be done on the ISS. Although it is not a cargo carrier such as the modules mentioned before, it still needs to store all the equipment and supplies on board. Therefore, the ISS contains equal storage systems as well. The reason behind a well-organized storage system on board is the requirement for safety, crew productivity, and habitability [45]. The first point, safety, plays an important role for the astronauts in the first place, but also for the stored equipment. Both have to be protected to ensure a successful mission operation at any time. The second point refers to a well-organized system on board. The better the storage coordination inside the less time the crew members need to search for pieces resulting in more time for maintenance and experiment implementations. Additionally, the volume has to be used most efficiently since the ISS only has a limited amount of space. And last but not least, habitability is important for the psychological well-being of the crew since they are staying on board for multiple months.

One large contribution of ESA to the ISS is the Columbus laboratory which offers scientists a platform in a weightless environment. A cut-away picture of the laboratory can be seen in Fig 2.10. To provide space for storing all the experiment equipment inside, Columbus is containing ten internationally standardized racks [46]. Each of these racks can support the equipment with a power and cooling system as well as video and data links to send the results back to Earth.

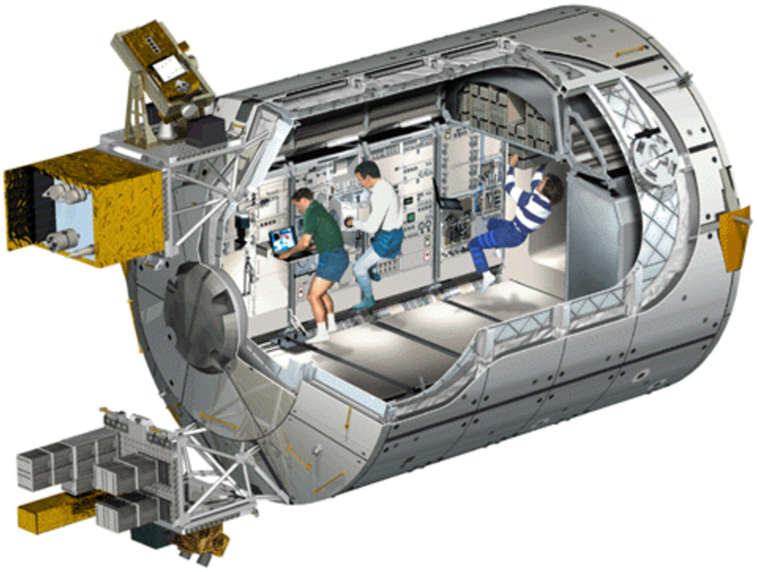


Figure 2.10: Cut-away view of the Columbus laboratory of the ISS. Image adapted from [47].

Within these ten racks, the laboratory contains five payload racks, each with an individual purpose. The first one is called the Biolab and hosts experiments with all kinds of microorganisms, plants, and insects. The second rack is the European Physiology Modules Facility and is analyzing a long stay in space. Fluid Science Laboratory is the third rack and investigates how liquids are behaving in micro-gravity. The fourth rack is called the European Drawer Rack and can be used to store different types of scientific experiments. The last one is the European Transport Carrier which is used for transporting and storing components. A figure with all five payload racks can be seen in Fig 2.11. [46]

Figure 2.11: Five payload racks inside the Columbus laboratory on board the ISS. Image adapted from [45].

To come up with quick re-adaptions for the accommodation of equipment inside the Columbus laboratory, a fast computation is needed. However, the abilities of a stowage engineer are more time-consuming when doing these calculations and are more prone to errors. In addition, there is no guarantee of getting the best solution compared to computer computations. Therefore, a new tool named CAST was created to take over that kind of task. CAST stands for cargo accommodation support tool and was developed by Thales Alenia Space Italia. The reason for the CAST development was to be able to provide a quick and solid solution for the cargo accommodation on board of the ATV on which CAST was developed. Later, this tool was also used for the stowage inside the Columbus laboratory (C-CAST). The general procedure for accommodation equipment is first to generate an optimal solution for how to accommodate the parts best inside a rack. Afterwards, a reallocating process is started in which the residual volume of one sector is minimized. With that, empty sectors can be identified and filled with items that could properly fit in there. Due to the tools, the time needed to find a suitable accommodation solution can be reduced significantly from two to three days to one hour while increasing the filling coefficient inside the sectors by more than 20%. The following Fig 2.12 shows such a comparison between a handmade solution on the left side and a solution created by the C-CAST tool on the right side. What can be seen is that in the solution on the right side from the C-CAST tool, the arrangement is more compact. Through that, the four red boxes identified which space is still unused. [45]

2.3 Cargo Storage

The ISS is getting a regular resupply from Earth meaning that these goods have to be additionally stored on board while other parts from the station will be packed back into the cargo carrier for removal. Therefore, a quick stowage adaption is required each time.

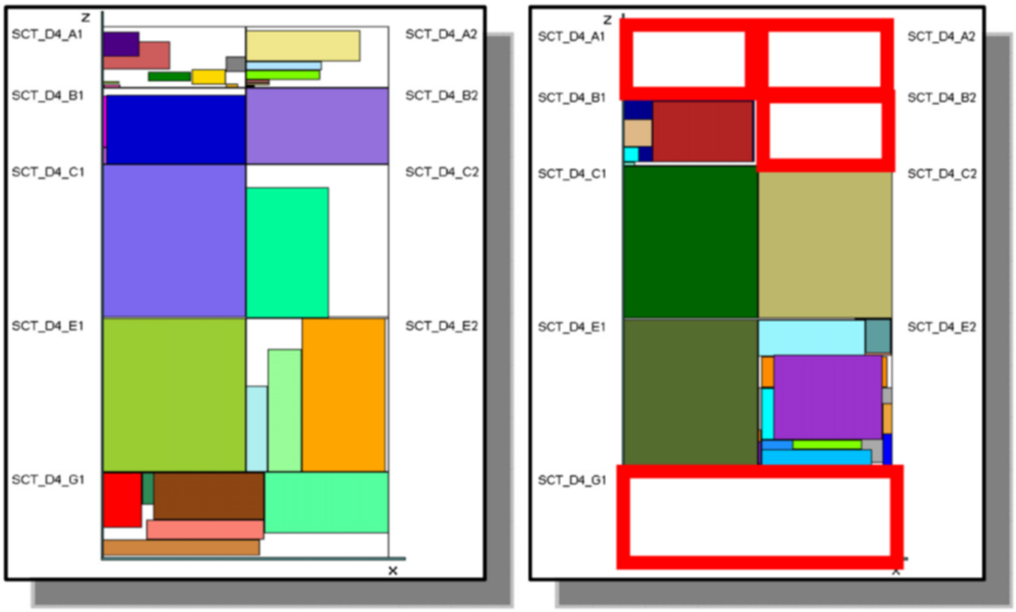


Figure 2.12: Comparison of a re-allocation inside a sector between a handmade (left) and C-CAST (right) solution. C-CAST solution shows empty areas as red boxes. Image adapted from [45].

However, the cargo which shall be transported can be changed and updated in the short-term, which results in a quick re-adaption of the item accommodation. This readjustment concerns both the cargo transportation module on the ground as well as the destination module in space, in this case, the ISS.

In this context, the available volume is limited which requires efficient exploitation of the given space on board, especially when having difficult geometries of equipment. This exploitation is tightly bound to balancing constraints to meet the spacecraft's dynamic control. Furthermore, some accommodation requirements demand the grouping of items together due to operational aspects. However, there are also cases in which it is forbidden to group specific items together which are not compatible when getting stored nearby. Additionally, there are forbidden positions where no equipment is allowed to be stored such as in the path of emergency exits. Some of those forbidden positions and further specific stowage constraints arose for the space station to guarantee a safe, ergonomic suitable, and operationally feasible stowage. Here, just some of those constraints are mentioned in the following: [45]

- Keeping, in general, a minimum distance towards any light assembly.
- Avoid interfering with safety critical equipment.
- Avoid interfering and therefore reduce the usability of equipment.
- Avoid the connection with heater elements or electrical power cables.
- Do not block the inlets or outlets of the air circulation.

The overall accommodation of equipment is one task to solve, the other one is how to store the individual equipment parts. First, one can distinguish between fluids and the so-called dry cargo that is going to be transported. The former is stored in tanks while the latter includes a huge variety of different parts which is why there exist different levels of how to store them. The hierarchy starts with putting small items into bags. Those bags along with large items are further placed into sectors which are then accommodated inside the racks. The last level, the racks, are then placed at their intended position inside the module. In addition, the overall hierarchy is fixed regarding the limitations towards mass, volume capacity, and positioning rules along with balancing rules. [45]

2.3.1 Bags

CTBs The mostly used storage bags in cargo transfer modules are the so-called standard cargo transfer bags (CTBs). In total, there are four different ones, namely half, single, double, and triple CTBs which can all be seen in Fig 2.13. Those bags vary in their main features which are, among other things, their maximum cargo mass accommodation. Here, it is differentiated between a general, normal storage and a fully packed bag. The last one refers to if the bag is packed in a way such that on the one hand, no hardware inside can translate around when it is already in a stowed position and on the other hand the bag is already restrained by other cargo or by the locker itself. Furthermore, the four standard CTBs can be distinguished between their volume which they can accommodate and are related to the internal and external dimensions of the respective bag. In the following, the dimensions are listed in the following order: $depth \times width \times height$ and shortened to $D \times W \times H$. And last but not least, the individual empty bag masses are also a feature that is different among all four bags. Nevertheless, these bags have two points in common, namely that they all transfer cargo at the sub-rack level and have two pocket labels on the inside and four on the outside for better organization. Additional features, which are the same for all four bags, are external handles which are mounted on the bags as well as a bar code attached on the outside of each bag. This ensures the identification of every bag at any time. On top of the bar code, the bags are also having exterior pockets to place labels that show what content is stowed inside which bag. Finally, all the bags are having straps with which it is possible to attach the bags on-orbit either inside the racks or outside attached to them. A combined representation of all the individual features of the bags can be gained from Tab 2.2. [48]

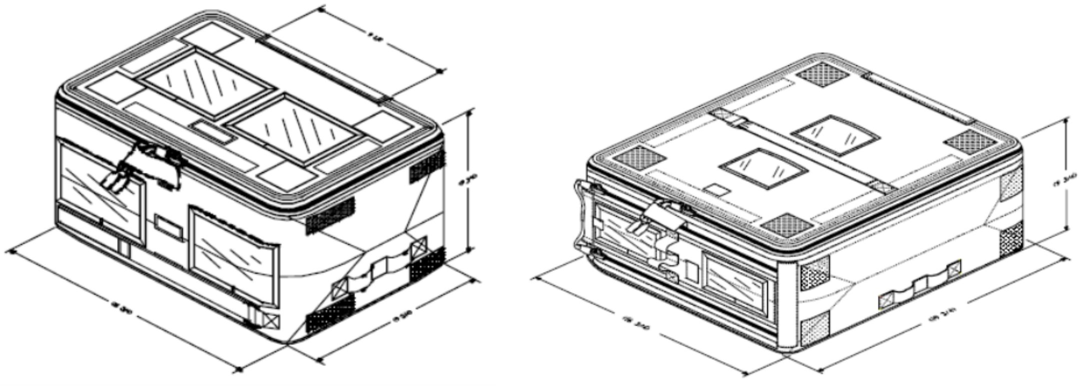
The first bag which is going to be presented is the half CTB which is the smallest of the four CTBs. Its external dimensions are $24.8 \times 42.5 \times 23.5cm$ which are important for the integration of the bag in its final destination inside the module. The internal dimensions are a bit lower, namely $24.13 \times 41.28 \times 22.86cm$ which are important for the internal capacity volume in which the equipment will be stored. The bag dimensions result in the least accommodation capacity of all four bags. The external volume of the half CTB is $0.025\,\mathrm{m}^3$ and the internal one is $0.023\,\mathrm{m}^3$. Because of its small dimension, the bag has the lowest bag mass of $1\,\mathrm{kg}^3$ when it is empty. Regarding the amount of cargo, the bag can take, in total, the half CTB can store 13.62 kg of cargo if it is normally packed. If it is fully packed, it can accommodate almost twice as much, namely 27.22 kg. Fig 2.13a shows a schematic of the half CTB from the outside in comparison to the other three CTBs of Fig 2.13. At the end of this sub-chapter, in Tab 2.2, there is a compact representation of all the features from all CTBs. [48]

The next bigger bag is the single CTB which can be seen in Fig 2.13b. It is larger compared to the half CTB which was mentioned before. Speaking in more detail, its dimensions are externally $50.2 \times 42.5 \times 24.8cm$ and internally $49.53 \times 41.28 \times 24.13cm$. This results in an external volume of $0.053\,\mathrm{m}^3$ and an internal volume capacity of $0.051\,\mathrm{m}^3$ for storing equipment. The bag mass of the empty bag itself is 1.81 kg. Furthermore, 27.24 kg can be accommodated inside the bag if it is normally packed. In comparison, a maximum of 45.36 kg can be stored in the bag if it is fully packed so that every corner of the bag is exploited. A compact overview of all the details of the bag can be found in Tab 2.2. [48]

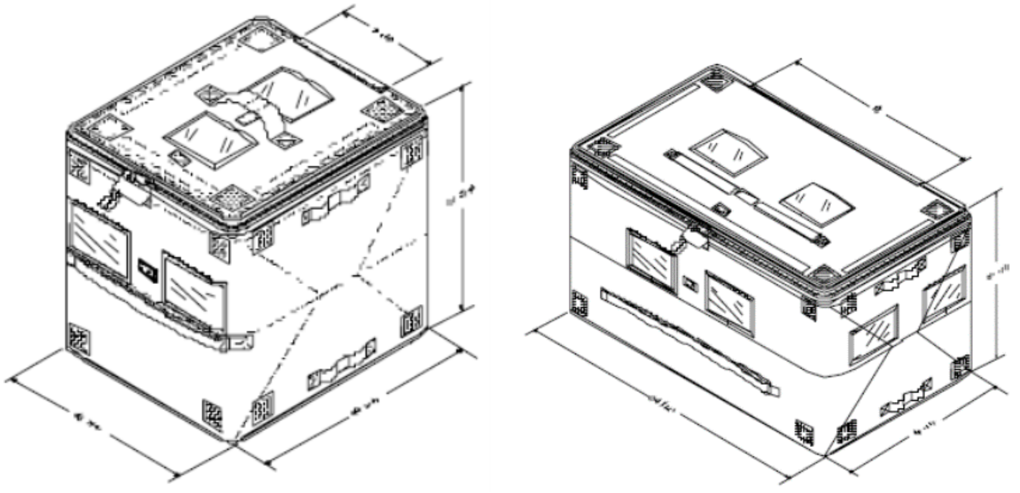
The third bag to be mentioned is the double CTB. It is the second largest bag with external dimensions of $50.2 \times 42.5 \times 50.2cm$. The internal dimensions are $48.26 \times 41.28 \times 46.99cm$ which leads to an internal volume of $0.096\,\mathrm{m}^3$. Compared to that, the external volume is $0.106\,\mathrm{m}^3$ which is important to mention as well since it needs to be stored appropriately inside the module. A schematic of the double CTB can be seen in Fig 2.13c. The bag itself weighs 2.04 kg if no cargo is placed inside the bag. If it is normally filled, it can accommodate 54.48 kg. Completely filled, it can store 81.65 kg of cargo. All the mentioned details about the double CTB can be compactly found in Tab 2.2. [48]

The last bag which is going to be presented is the triple CTB. A first overview of the bag can be gained from Fig 2.13d. The bag's dimensions on the outside are $74.9 \times 42.5 \times 50.2cm$ and $72.39 \times 41.28 \times 46.99cm$ on the inside. This leads to first an external volume of $0.159\,\mathrm{m}^3$ and second to an internal volume of $0.144\,\mathrm{m}^3$. The empty triple CTB itself weighs 2.81 kg. Regarding the maximum cargo mass accommodation, this bag has space to store 81.72 kg for general stowage applications. The packing of the bag, however, is independent of the used storage method. Therefore, the 81.72 kg is the maximum storage accommodation in total for the bag no matter if it is normally or fully packed. A compact list of all the features of the triple CTB as well as from the other bags can be found in Tab 2.2. [48]

M01, M02, M03 In the case that some equipment parts may not fit within the standard CTBs from the previous sub-chapter, there exist custom containers. These can be used for parts that are larger than the CTB itself or that have an asymmetric shape that also exceeds the dimensions of the standard CTBs. Other more standardized solutions besides the custom containers are the so-called M01, M02, and M03 bags. These are bigger compared to the standard CTBs and vary among themselves in their size. Fig 2.14 shows the M01 and M02 bags in comparison. In the following, the term Mxx is used to refer to all three M01, M02, and M03 bags in general. An advantage of the Mxx bags as well as for the standard CTBs is that they are already flight proven meaning that they were already used in various space missions before. However, not every vehicle can accommodate the Mxx bags because they need to fit through the front hatch of the space vehicle. This needs to be checked beforehand. What types of bags the ATV and HTV can host will be described later in Sec 2.3.1. A further advantage of the Mxx bags is that



(a) Half CTB. (b) Single CTB.



(c) Double CTB. (d) Triple CTB.

Figure 2.13: Schematics of the four different cargo transfer bags (CTBs). Image adapted from [48].

they can store standard CTBs as well which might not be properly fixed onto some rack. At the end of this sub-chapter, Tab 2.3 lists all the individual sizes of each Mxx bag. [48]

The first one of the bigger bags is the M01 bag. It is the second largest bag with external dimensions of $90.2 \times 53.3 \times 81.8cm$. Furthermore, it can store equipment up to 136.2 kg. The mass of the bag itself is 4.826 kg [49]. A first impression of the M01 bag can be gained from Fig 2.14a. It further shows that standard CTBs can be placed and stored as well within the M01 bag. A compact representation of all the features of the M01 bag as well as from the other Mxx bags can be found in Tab 2.3. [48]

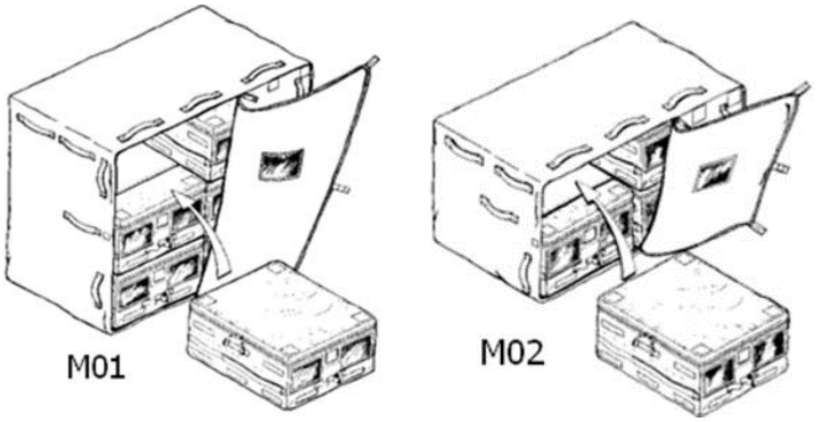
The next bag which is going to be presented is the M02 bag. Its external dimensions are $90.2 \times 53.3 \times 50.7cm$. Therefore, it is the smallest bag compared to the M01 and M03 bags. That is why this bag can store the least amount of equipment, namely 90.8 kg.

CTB Features	Packing [kg]:	Dimensions [cm^3]:	Volume [m^3]:	Empty Bag Mass [kg]:
	Normally	External	External	
	Fully	Internal	Internal	
Half [48]	13.62	24.80, 42.50, 23.50	0.025	1.00
	27.22	24.13, 41.28, 22.86	0.023	
Single [48]	27.24	50.20, 42.50, 24.80	0.053	1.81
	45.36	49.53, 41.28, 24.13	0.051	
Double [48]	54.48	50.20, 42.50, 50.20	0.106	2.04
	81.65	48.26, 41.28, 46.99	0.096	
Triple [48]	81.72	74.90, 42.50, 50.20	0.159	2.81
	/	72.39, 41.28, 46.99	0.144	

Table 2.2: Main features of the cargo transfer bags (CTBs).

Furthermore, the bag itself weighs 3.098 kg if no equipment is stored inside the bag [49]. Fig 2.14b shows a schematic of the M02 bag with again a possible accommodation solution if single CTBs would be stored within the M02 bag. A final table with all the information about the bag can be found in Tab 2.3. [48]

The last bag, the M03 bag, is the largest one of them. Its external dimensions are $90.2 \times 53.3 \times 133.4cm$ with an accommodation capacity of 227.0 kg. The M03 bag itself weighs 7.484 kg if it is empty [49]. The following Tab 2.3 shows a compact representation of the main features of the M03 bags compared to the features of the other two Mxx bags. [48]



(a) M01 bag.

(b) M02 bag.

Figure 2.14: Schematics of the M01 and M02 bag if six or four single CTBs, respectively, would be stored inside. Image adapted from [48].

Main features	M01 [48, 49]	M02 [48, 49]	M03 [48, 49]
Dimensions (external) [cm^3]	90.2, 53.3, 81.8	90.2, 53.3, 50.7	90.2, 53.3, 133.4
Volume [m^3]	0.393	0.243	0.641
Accommodation Mass [kg]	136.2	90.8	227.0
Empty Bag Mass [kg]	4.826	3.098	7.484

Table 2.3: Main features of the Mxx bags.

NS CTBs Another bag type that is going to be presented here is the so-called Non-Standard CTB Types (NS CTB Types) which are used inside the ATV transportation racks. In total, there exist three types, namely type A, B, and C, and they are designed to fill out the unused space inside the ATV rack at the back. They differ, as well, in their dimensions and total allowable mass which they can accommodate. It is best explained with the following Fig 2.15. This figure shows two standard CTBs, namely the single and triple CTB which are marked with an S and T in the picture, respectively. At the back of the transportation rack, the three NS CTB Types A-C are accommodated. They are differing in their shape since they have rounded edges or asymmetric shapes which can be used because of the NS CTBs. Fig 2.16 shows these NS CTBs with a more detailed breakdown into type A in Fig 2.16a, type B in Fig 2.16b, and type C in Fig 2.16c. The following Tab 2.4 provides an overview of the dimensions and allowable cargo mass accommodation of the three NS CTB Types. [48]

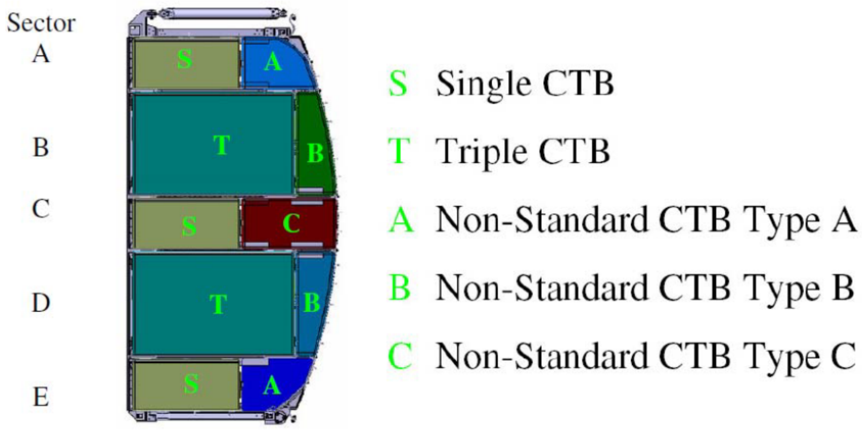
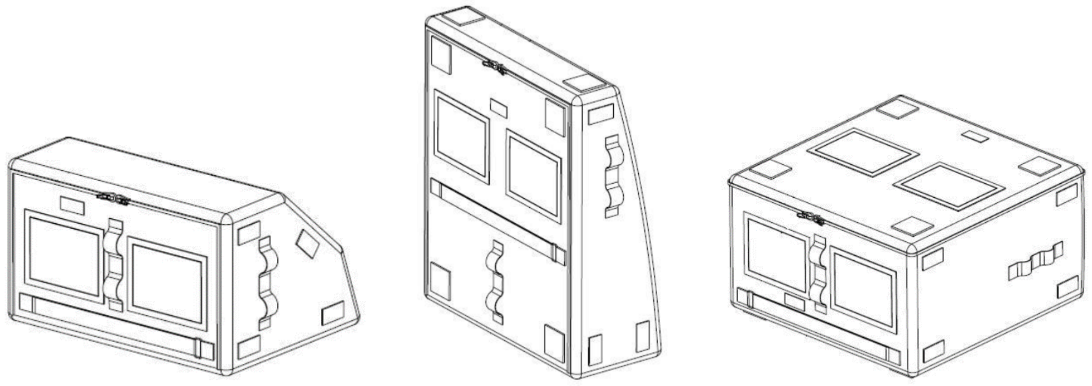


Figure 2.15: Non-Standard CTB Types A-C. Image adapted from [48].

Bags that can be Stored within ATV and HTV As examples of what other cargo carriers were able to accommodate, the ATV and HTV are chosen and the bags which were used inside are introduced. Beginning with the ATV, it mainly had payloads that were stored in primarily racks. Therefore, standard and non-standard CTBs were used. Additionally to those two bag types, triple CTBs, M01, and M02 bags were used and



(a) NS CTB Type A. (b) NS CTB Type B. (c) NS CTB Type C.

Figure 2.16: NS CTBs Types A-C. Image adapted from [50].

NS CTB	Max. Cargo Mass [kg]	Dimensions [cm^3]: External Internal
Type A	16.27	23.50, 42.00, 33.78
		21.00, 39.00, 33.78
Type B	17.85	49.00, 42.00, 18.18
		47.50, 39.00, 18.18
Type C	24.15	23.50, 42.00, 43.34
		21.00, 39.00, 43.34

Table 2.4: Dimensions and accommodation masses of the NS CTB Types. [48]

attached in front of the transportation racks using belts. Compared to that, the HTV was able to accommodate all standard CTBs as well as M01 and M02 bags. These bags were mounted inside the HTV racks or, for some equipment that was too large, in front of the racks. In general, there was a certain amount of volume available for non-standard equipment, namely $78.5 \times 44.0 \times 51.7cm$. Nevertheless, all bags inside the HTV were fastened with straps or belts. An example accommodation of the HTV rack can be seen in Fig 2.17. [48]

Containers to Store Fluids The final types of containers used for transportation in space are those used for transporting fluids. There is the contingency water container (CWC) on the one and the contingency water container - iodine (CWC-I) on the other hand. The first one, the CWC, is a soft goods container that can accommodate a broad variety of water types such as potable, technical, condensate, and wastewater. A picture of the CWC container can be found in Fig 2.18. The CWC-I, however, can hold the same types of water but additionally can store iodinated water. [51]

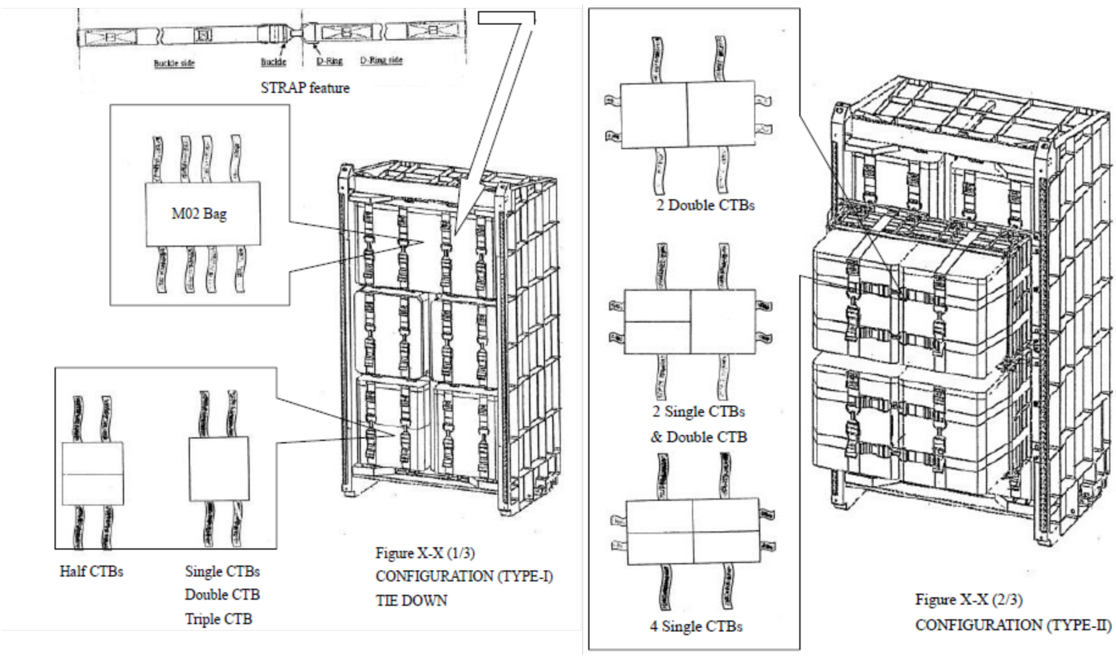


Figure 2.17: Exemplary rack accommodation of the HTV. Image adapted from [48].

2.3.2 Racks

One important part of cargo securing is the safety of the equipment itself which is done with the previously presented different types of bags. However, these bags need to be secured as well. This is done with racks that are mounted inside the module. As for the bags, there exist different kinds of racks that can provide different functions to the equipment itself such as power or different kinds of cooling. In the following, different types of racks will be presented.

ISPRs The first rack which is going to be introduced is the international standard payload rack (ISPR). A schematic of it can be seen in Fig 2.19. It all started with the space station freedom program (SSFP) which aimed at building an on-orbit laboratory facility in which international partners could conduct their experiments. Finally, the space agencies of NASA, ESA, and the national aeronautics and space development agency of Japan (NASDA), which later united in JAXA, provided each a laboratory module for the ISS. Thereby, it is more efficient to provide a standardized accommodation system in all three laboratory modules for the experiments which the scientists want to conduct. The reason for that is that the scientists do not need to redesign their system depending on the module in which their experiment is going to be placed since they all are going to be interchangeable. Therefore, it is possible to rearrange entire racks between the modules since every rack can be installed inside the standardized ISPRs in every module. This results in less work effort for the crew because experiment racks can be moved and installed

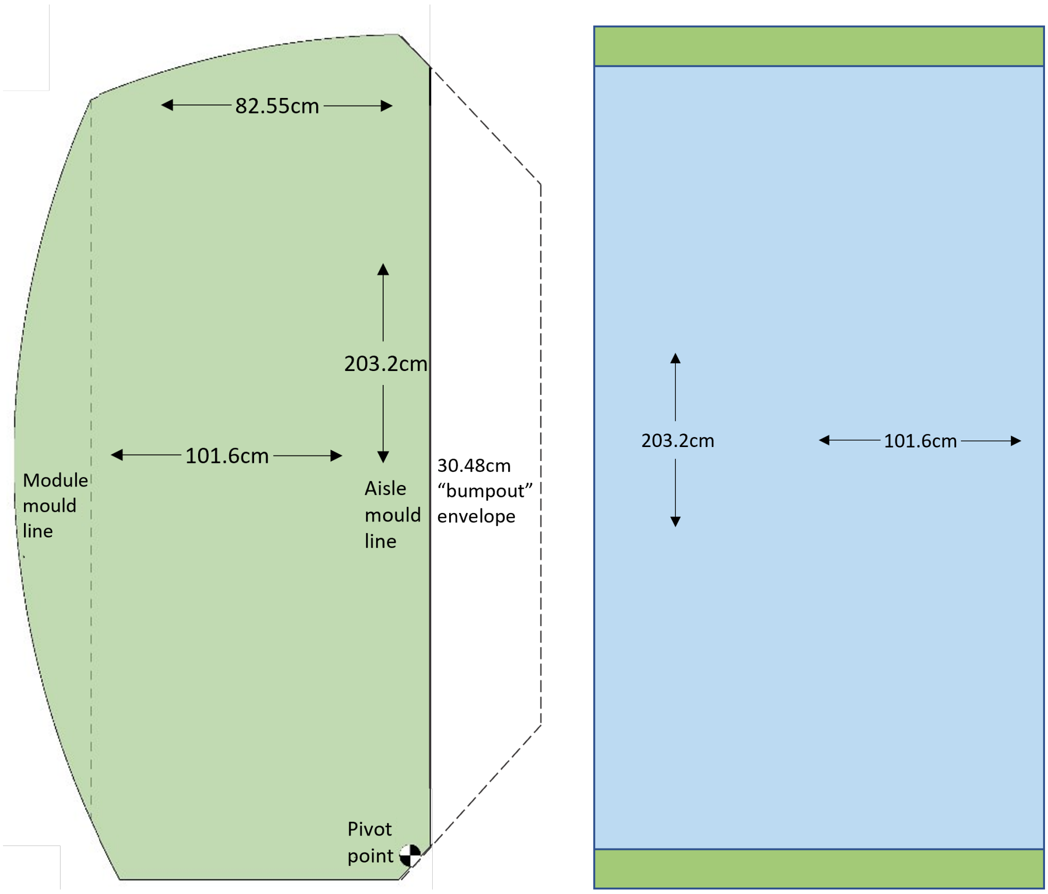
Figure 2.18: View of a contingency water container (CWC). Image adapted from [51].

close to each other to reduce the crew member movement between the individual modules as well as the complexity since the crew just has to get used to one rack mechanism. [52]

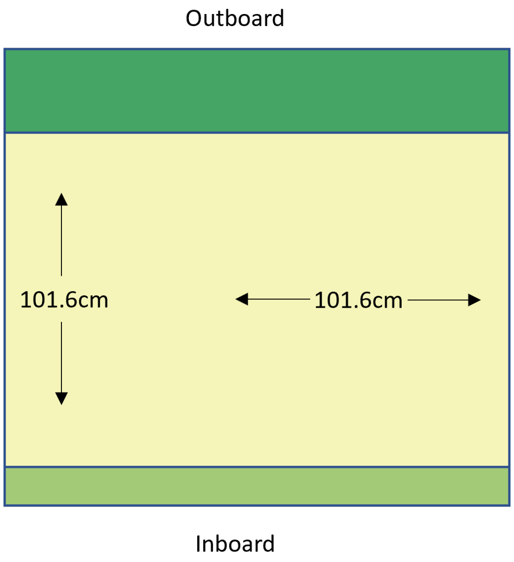
Since the ISPR is a compromise between the three space agencies, the possibilities of the ISS and the needs of international partners resulted in not every feature being able to get implemented. To mention some of the standard interfaces which were provided, these are mechanical fixations for on-orbit, air ducts for cooling, and power supply. [52]

EDRs The next type of rack, the European drawer rack (EDR), has the purpose of accommodating medium-sized equipment for space research experiments while simultaneously reducing the costs for this research and its development times [54]. With the EDR, on behalf of the ESA, there is an experiment carrier suitable for this kind of task. To accommodate all the experiments inside the EDR with a decent supply, for example, air cooling and power supply, there are two ways of storing the experiments: first, the international sub-rack interface standard (ISIS) drawer and second, the ISS locker [54]. Fig 2.20a on the left side shows the ISS locker and Fig 2.22b on the right side depicts the ISIS drawer. In general, the EDR can accommodate up to three ISIS drawers, with a volume of 27 L per drawer and dimensions of $57.4 \times 38.7 \times 32.7cm$, and four ISS lockers, each with a volume of 57 L per locker and dimensions of $51.6 \times 44.0 \times 25.3cm$ [55]. Those two storage possibilities, the drawer and the locker, allow for easy accommodation as well as quick operational readiness since they can be stored at multiple positions leading to an increased number of opportunities for the users to conduct their experiment. This is because most of them do not need the full rack for themselves so they can share one rack with others. [56]

Space Qualified Racks The last type of racks that is going to be presented are the ones used inside the ATV which were produced by the Swiss company Ruag space. An overall



(a) ISPR from the side. (b) ISPR from the front.



(c) ISPR from overhead.

Figure 2.19: Schematic of an ISPR. Image adapted from [53].

(a) ISS locker.

(b) ISIS drawer.

Figure 2.20: Sub-rack payloads of the EDR. Image adapted from [56].

view of the racks inside the ATV can be inferred from Fig 2.2. One main design driver was their weight since every additional mass leads to higher costs of the entire mission since more fuel is needed to bring everything into orbit. These space-qualified racks are made of aluminum and weigh 92 kg but can still withstand an acceleration of more than 12.5 g. Furthermore, they are designed in compliance with NASA's standard sizes for the ISIS drawer and Mid Deck locker and can hold up to 750 kg of equipment. A closer look inside the rack system can be seen in Fig 2.21. [57]

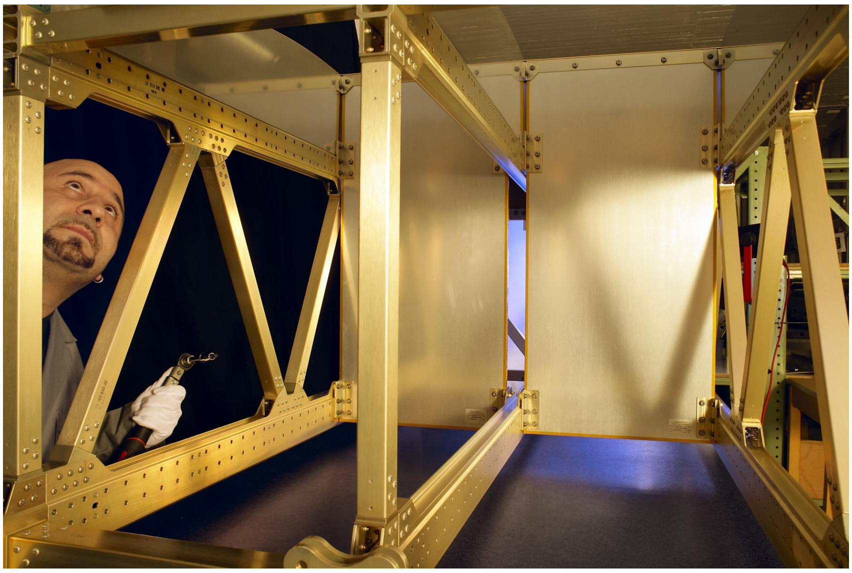


Figure 2.21: ATV cargo rack built by Beyond Gravity Schweiz AG. Image adapted from [57].

2.4 Existing Greenhouse Modules

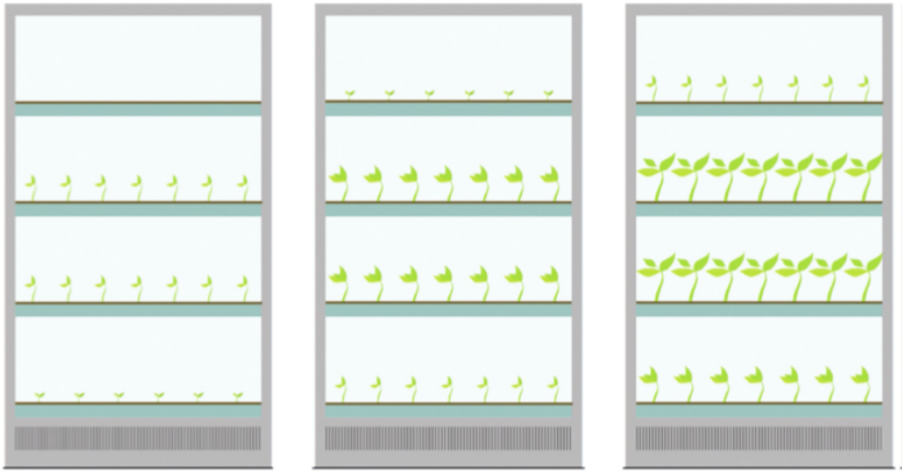
After a detailed introduction to different cargo transfer modules and their logistics on how to transport equipment, it also needs to be looked at the main part of the EDEN NG GTD since the greenhouse will be the main purpose of this whole mission.

2.4.1 Space Greenhouse Systems

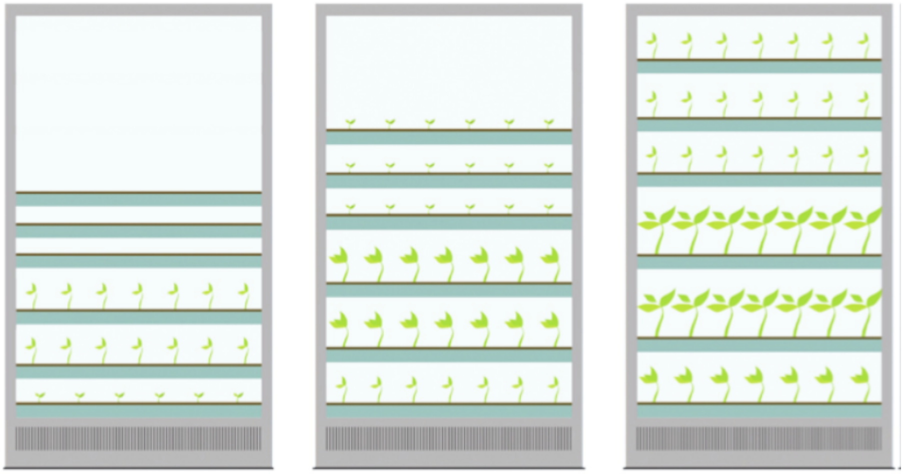
Before going into examples of space greenhouse test facilities, it is important to mention that all the test modules need to be scalable as well as adaptable to the space application. This flexibility is needed to be able to adapt the module depending on the respective environmental conditions on-site. For instance, there are different gravitational situations, for example on Moon or Mars, on the one and the usage of additional robotics to make the overall system more autonomous on the other side. However, those different environmental conditions lead to the necessity of doing trade-offs between the individual designs. For the more autonomous option, the trade-off could be, for example, between going into reduced crew operations while adding more infrastructure due to the robotic arm. [58]

Vertical farming gets more and more of a field of interest since the population on Earth increased over the last few years and is still growing. This demands both more food but also more cultivation land for growth. A possible solution to this end is vertical farming which arranges the growing trays not horizontally but upwards [59]. However, the space in vertical farming is not used wisely since at the beginning of the growth the plants are smaller compared to when they get harvested. Therefore, the adaptive vertical farm (AVF) was proposed. Its objective is to improve the vertical farm (VF) concept through an adaptable growth structure. A visual representation of the differences between VF at the top and AVF at the bottom can be seen in Fig 2.22. With the adaptive version, it is possible to save energy since no unused space needs to be illuminated because the relevant space is reduced which in return has a direct impact on the mission costs. Furthermore, the available space can be exploited more effectively when comparing an AVF with a VF, both with the same height. Moreover, this additional usable space will lead to an increased production rate since more food can be planted. However, such an AVF concept would require a predefined sowing schedule since it is not possible to plant simultaneously as it is the case for the VF. This is because it would result in all plants reaching their maximum height at the same time meaning in the case of the AVF that fewer plant trays can be fit into one rack. [60]

Another greenhouse design designated for Moon or Mars is the M-LGH. It is a cylindrical tube with the dimensions of 5.5 m in length and 2.1 m in diameter. Furthermore, it is an inflatable module meaning it will reach its full dimensions after reaching its final destination. A visual representation between the collapsed and deployed module can be seen in Fig 2.23. It contains a BLSS since this greenhouse is designed for a permanent outpost in space, meaning it has a duration longer than six months. It is a module to test a poly-cultivation hydroponic system in a semi-closed environment. Poly-cultivation means having diverse plant cultivation which would result in a rich diet for the crew. Such a balanced diet could be a combination of, for example, sweet potatoes, beans, berries,



(a) Vertical Farm.



(b) Adaptive vertical farm.

Figure 2.22: Comparison between the vertical farm and the adaptive vertical farm. Image adapted from [60].

and tomatoes. The roots of a plant in a hydroponic system, compared to a soil-based one, grow in nutrient-rich water. This has the advantage of cultivating plants in places where it is not possible for soil-based systems. Additionally, it is cost-effective while simultaneously having a larger harvest [19]. The cultivation area of this module varies between 28-40 m^2. This strongly depends on the plants themselves, since they can grow both horizontally and vertically. It is achieved by letting tall plants grow upwards along the side walls of the greenhouse. Overall, the goal of this greenhouse is to produce food, recycle water, and revitalize the air. [21]

The last greenhouse which is going to be presented is the controlled ecological life-support system (CELSS) experimental platform suitable for a maximum of six astronauts.

(a) Collapsed view of the M-LGH.

(b) Deployed view of the M-LGH.

Figure 2.23: Comparison between the collapsed and deployed M-LGH. Image adapted from [21].

The platform was further divided into four cabins, namely crew cabin (CC), plant cabin (PC), life-support cabin (LSC), and resource recycling cabin (RRC). A schematic diagram of the four cabins can be seen in Fig 2.24. The CC offered places for the crew such as a kitchen, lavatory, and medical monitoring. The PC was the area for food production but also provided O_2 and water. The LCS was there to support the plants if they can not intake the amount of CO_2 and therefore provided O_2 in case of an emergency. The last cabin, the RCC, was used for recycling biodegradable wastes as well as wastewater. In total, a plant cultivation area of $206.6\,\mathrm{m}^2$ could be provided. The goal of this greenhouse platform was to verify that air, food, and water could be recovered with a physicochemical and biological technique, which was confirmed in the end. In this context, the platform starts with zero biomass. Therefore, the physicochemical techniques and transfers afterwards are for an independent and efficient biological technique because the greenhouse will host plants for food production after some time which will additionally require an air and water regeneration. [61]

2.4.2 EDEN ISS MTF Prototype

The last project including a greenhouse system is part of the EDEN ISS project. It is important for this thesis since within the EDEN ISS project the MTF was developed which is the pioneer and origin of the EDEN NG GTD. The development of the MTF started in March 2015 with funding from the EU and went into operation in February 2018. Its goal was to develop and test a first model of a greenhouse that could be operated in space. However, since this prototype was not intended to be deployed directly to a space mission, it still provides a baseline on which further developments, such as for the EDEN NG GTD, can be taken towards a space greenhouse. The reason for such a greenhouse type is, as mentioned at the beginning of this thesis, that long-term space missions on Moon or Mars would be independent of resupplies coming from Earth. [5]

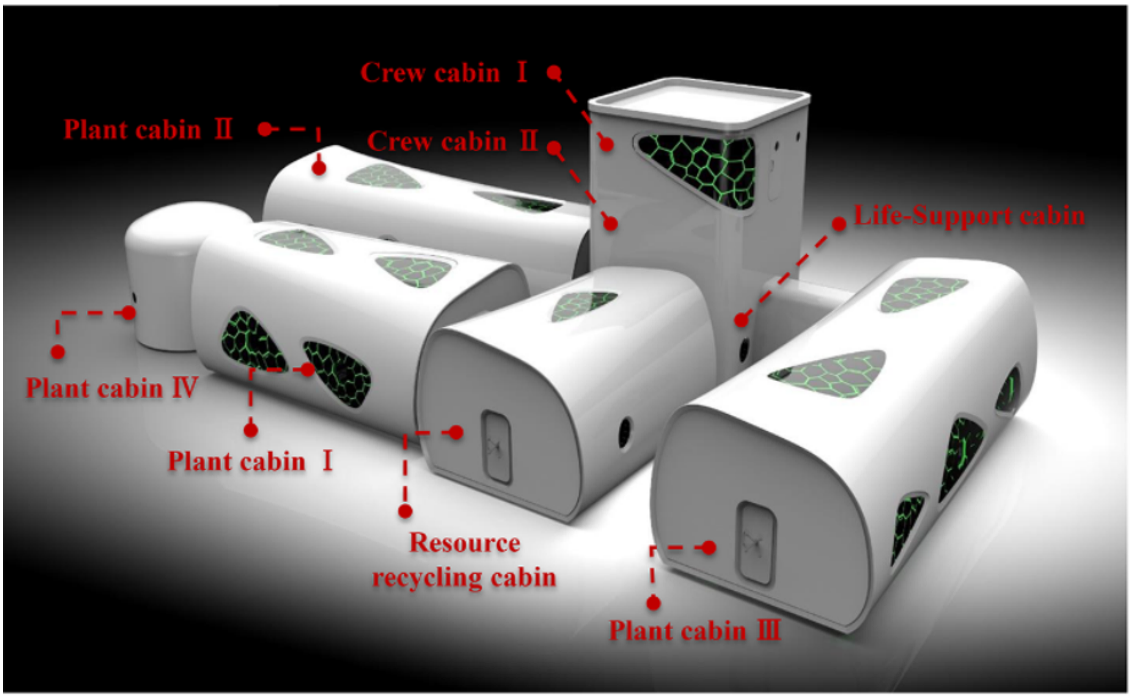


Figure 2.24: Schematic diagram of the four cabins of the CELSS greenhouse platform. Image adapted from [61].

The choice of the test location, Antarctica, was not done randomly. It was chosen because both, Antarctica and solar system bodies, have things in common, such as the protection of the place and the accessibility itself. For Antarctica, there exists the Madrid protocol for the protection of the Antarctic environment. For instance, this protocol regulates that all proposed activities need to clarify the environmental impacts on Antarctica beforehand [62]. A similar regulation, called planetary protection, exists for solar system bodies which shall be protected from contamination by Earth life but also vice versa to protect the Earth from any kind of contaminants which may return from solar system missions [63]. Furthermore, the accessibility is similar for both places. While it is intuitive for Moon and Mars, it is not for Antarctica. There, it is only possible to travel to the Antarctic during the summer season, meaning from November to March. As a consequence, missions in the Antarctic as well as on the Moon or Mars need to be as less prone to failures as possible since a resupply is only rare. Additionally, the crew which is staying at the Neumayer III Station in Antarctica during winter consists of nine people: four researchers, three engineers, a cook, and a doctor [64]. This crew size is comparable to that of a space crew which again is suitable as a test environment for a space mission. And eventually, the environmental conditions on Antarctica and Moon or Mars are similar: Both are rare in their biodiversity and are isolated from other human beings except their crew on-site. All these points make Antarctica a suitable place for testing modules and habitations for long-term space missions. [5]

The redesign of the EDEN ISS MTF module towards the EDEN NG GTD resulted in a cylindrical shape with a total mass of 19000kg already including a 20% margin. The total mass contains the equipment for launch, transfer, and landing. Therefore, the greenhouse fits into the Falcon 9 launcher from SpaceX, which has a launch mass capability of 22 800 kg [65]. The transformation from the container shape of EDEN ISS MTF to a cylindrical EDEN NG GTD was performed to better fit into a launcher but also to be able to withstand the pressure loads on Moon or Mars. In general, both project modules are divided into a SES and a FEG. The first one contains parts such as power distribution, the nutrient delivery system (NDS), and the air management system (AMS). The latter one hosts the growth area with plant cultivation trays and air ducts to name some equipment parts inside. Both, the SES on the left side and the FEG on the right side can be seen from the side in Fig 2.25. In this CAD model, one can see the air ducts of the AMS at the top of the module in dark blue as well as its pipes on the side walls in light blue which will be responsible for airflow. Inside the FEG on the right side, one can see horizontally arranged green parts which are the plant trays mounted inside the racks. The purple blocks below the plant trays represent the illumination sources and the red tubes next to the light blue air pipes will supply feeds for the nutrient solution for the plants. On the left side inside the SES, one can see one and a half ISPRs as well as containers and electrical parts for the individual subsystems such as for the illumination and AMS. [5]

The importance of the greenhouse section itself differs from other, more traditional greenhouses since it plays an important role with regard to the mental health of the crew. On Earth, people are able to go out into nature or just change their environmental setting. In a space habitation, such a change is not possible due to the different environmental conditions and that can lead to stress on the body but also on the mind. Therefore, having an area where plants can grow and where astronauts can do calming activities will contribute to better living conditions [66]. Another point in which a space greenhouse differs from a traditional one is that more equipment is installed for monitoring and controlling the greenhouse remotely due to the different conditions outside and the distance to Earth. [5]

In the beginning and through the insights gained during the project, requirements and lessons learned for the greenhouse have arisen. In the following, only some requirements are going to be mentioned. First, the entire module shall be launched within a single launch. The reason for that is to limit the launch costs but also the complexity of the overall system since multiple launches would result in the reassembly of the different interfaces on-site. Furthermore, as mentioned before, the module is designed in such a way that it shall fit into the envelope of the Falcon 9 with a 4.0 m diameter and a 6.6 m length with a maximal launch mass of 22 800 kg. Some lesson learned that arose from the EDEN ISS MTF project was to adopt three plant cultivation racks into the design. Meaning one on each side and an additional one in the middle intended for tall growing plants such as tomatoes. However, it is important to mention that this concept of further development is not adjusted so far to the desired environmental conditions which prevail on the Moon or Mars. [5]

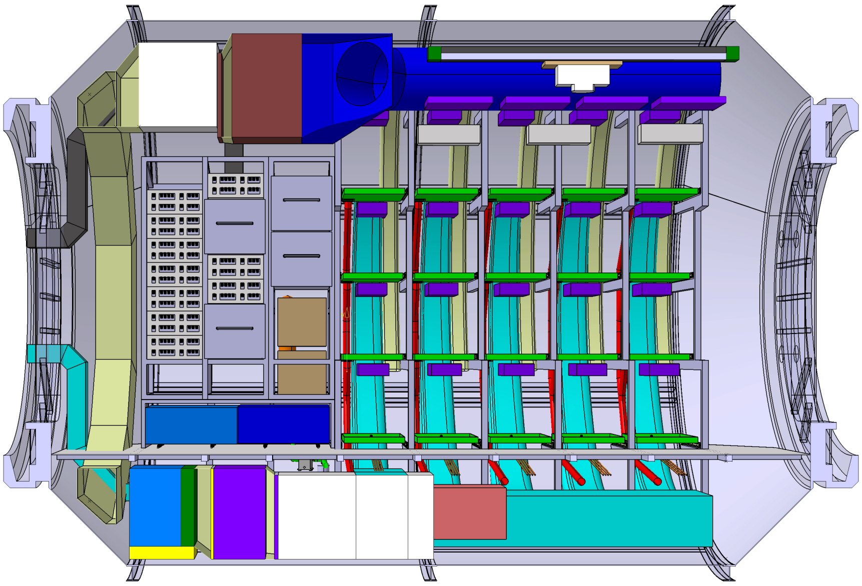


Figure 2.25: CAD model of the current EDEN NG GTD with the SES (left) and FEG (right). Image source: DLR, Vincent Vrakking.

2.5 Lessons Learned

To conclude this chapter, all the main takeaways and key facts for this thesis are going to be summarized.

The overall design for the EDEN NG GTD was chosen to be cylindrical since this form better fits into a launcher's envelope. As a baseline launcher, the Falcon 9 was chosen. Thereby, the module has a fixed size which is 4.2 m in its width and 6.6 m in its length to still fit into the Falcon 9 launcher. Another specification given by the launcher is the maximum launch mass into low Earth orbit (LEO) of 22 800 kg. With this limitation, the total mass of the EDEN NG GTD resulted in 19 000 kg. Another reason for this shape was to better withstand pressure loads that prevail on the Moon or Mars. Furthermore, the overall structure of the module was set to be fixed meaning that it has no inflatable part which would be compressed during launch to reduce the complexity of the system. Lastly, the module was designed to get launched in one take since this limits the launch costs on the one hand but also reduces the complexity of the entire system on the other hand. The reason for the reduced complexity is that there will be fewer interfaces that would need to get connected because it will only be one module in which all the necessities are preinstalled as far as possible.

Through the evaluation of the different cargo transfer modules at the beginning of this section, an idea of the transportation possibilities could be gained. Overall, it can be said that all of these cargo carriers have their features as well as specific advantages and disadvantages. One detail that immediately stands out is that only the MPLM was a reusable module. However, that was only given through the Space Shuttle which flew the module safely back to Earth every time. Regarding endurance, the ATV stands out with up to six months which it can stay attached to the ISS. Furthermore, the cargo and disposal masses of the ATV and HTV are in the same range, namely around 6000 to 7500 kg. The Cygnus module can only carry the least amount of mass which is between 1200 to 3500 kg depending on the standard or enhanced version. The most could be transported by the MPLM which was 9400 kg for the cargo mass and 6000 kg for the disposal mass. Last, the pressurized volume differed greatly among the modules. Here, the HTV had the lowest volume with $14.0\,\mathrm{m}^3$ followed by the Cygnus with $18.9\,\mathrm{m}^3$ in standard and $27.0\,\mathrm{m}^3$ in enhanced version. The most volume was possible in the MPLM and ATV with $31.0\,\mathrm{m}^3$ and $48.0\,\mathrm{m}^3$, respectively. The message to take away from this evaluation is that each module for itself had advantages and disadvantages in specific features and none was superior to the others.

Another lesson learned which was consolidated through the EDEN ISS MTF project was to have a plant tray for tall growing plants in the middle corridor of the greenhouse section. Furthermore, one and a half ISPRs will be used on each side inside the SES.

All the equipment on board the EDEN NG GTD needs to be stored during launch. Therefore, the interior accommodation will be done with the different-sized bags which were presented in Sec 2.3.1. Beginning with the standard CTBs, there exist four different bags. The smallest one is the half CTB, going over to the single and double CTB to the largest triple CTB. Those standard CTBs are usually used to be stored inside a rack. The next bigger-sized bags are the Mxx bags of which three types exist, namely the M01, M02, and M03 bags. However, those are usually attached to the front of the racks and not inside since they are too big to fit into the rack compartments. All of these bag types are already flown on different cargo transfer modules to resupply the ISS and were tested accordingly. Some advantages which all of these mentioned bags have are external handles for easy handling of the bags both on Earth and in orbit but also for fastening the bags to the racks. Additionally, Velcro straps are placed on each bag to make an on-orbit attachment easier for intermediate fastening. Furthermore, they all have a permanent bar code for identification on their outside as well as additional exterior pockets to place labels telling the content of the bag.

3 Mass Calculations

The mass calculation section deals with different trade-offs that were made during the work of this thesis. Beginning with the CE study in Sec 3.1, every developing step is explained. Furthermore, the first trade-offs which were made are pointed out. They laid the foundation for the following calculations. In detail, different bag combinations at different positions within the module were determined. The next calculations in Sec 3.1.1 are referring to placing different bag types within the rack system. Afterwards, another mass calculation is done in Sec 3.1.2, specifically for the subfloor area. Following with calculations for the floor and ceiling within the module which are described in Sec 3.1.3. Then, in Sec 3.1.4, a separate look is taken at the belts with which all bags are fastened. In the next Sec 3.1.5, it is explained in which case additional equipment can be stored there and when it is forbidden. After that, a closer look is taken at the ATV racks in Sec 3.2. Furthermore, possible design options are considered and explained. Afterwards, it is shortly looked at the belts to secure all transportation bags. Since those belts bring additional mass to the system, it is important to consider them which is done in Sec 3.1.4. Finally, Sec 3.3 summarizes all calculations that were made and discusses them shortly. An extensive discussion follows in Sec 5.

3.1 Developments During the CE Study

One part of this thesis was the opportunity to participate in the CE study, of which the concept was already explained in Sec 1.4. It took part in the CEF at the DLR located in Bremen and lasted from the 12^{th} to 15^{th} of September 2022. The corresponding subsystems present during the study were:

- AI risk mitigation
- Air management system (AMS)
- Combined regenerative organic food production (C.R.O.P.)
- Data handling & control (DHCL)
- Human factors
- Illumination
- Nutrient delivery system (NDS)
- Plant health and cultivation
- Power & thermal
- Robotics
- Structure & configuration
- Systems

During that study, the required information about structural parts could be clarified to be able to determine how much space is left to position storing bags. The clarification concerned the plant trays inside the racks, a possible tray configuration in the middle of the module for tall growing plants as well as the positioning of the air ducts and the sump tank for the nutrients in the subfloor.

Beginning with the plant trays, their dimensions were set to $70 \times 50 \times 60\,\mathrm{cm}^3$ (status: September 2022) so that they can fit inside the compartments of the rack system. Those measurements can be checked in Fig 3.1. However, not every transfer bag mentioned in Sec 2.3.1 can be put inside the racks since the rack compartments have the mentioned fixed size. As a result, the half, single, and double CTB fit into the rack compartments. For the triple CTB, it has to be looked at in detail if the bag can stand out off the shelf since the depth of this bag is 74.9 cm which is longer than the plant tray itself. Furthermore, non of the Mxx bags fit into those slots since they are too big.

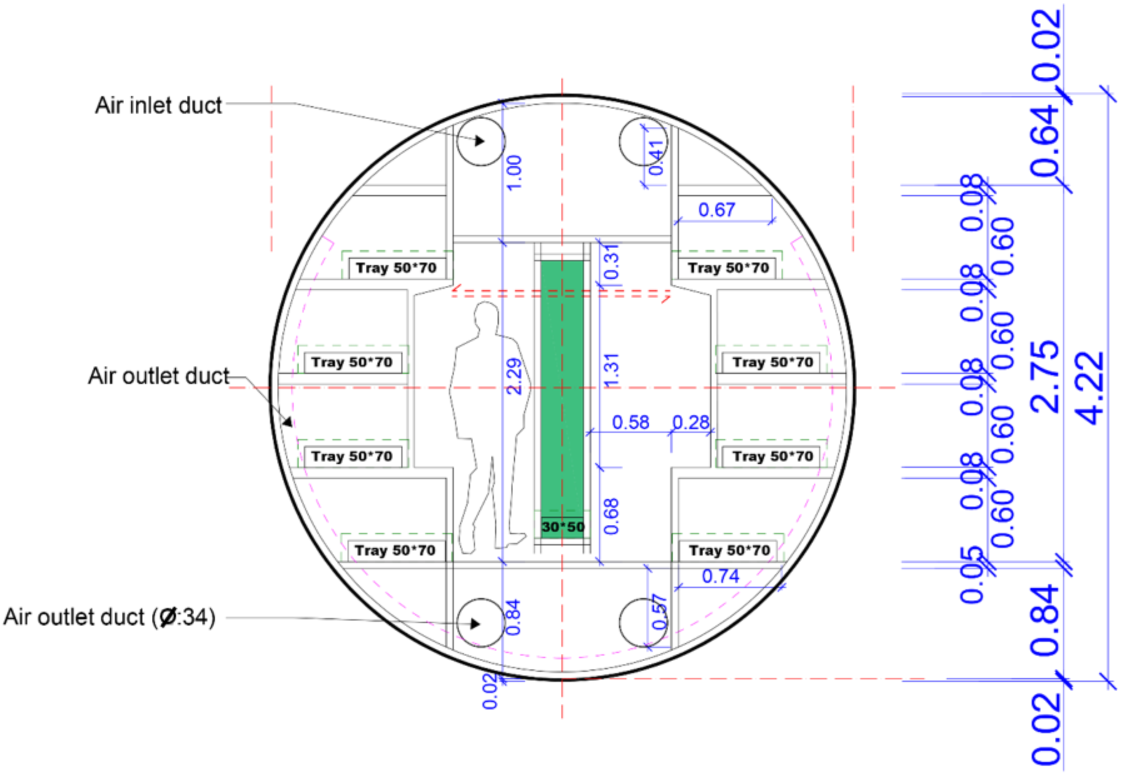


Figure 3.1: Cross section of the greenhouse compartment with its dimensions. Image adapted from: DLR, Kim Kyunghwan.

Moreover, the mass distribution requirements of the launcher need to be considered. Therefore, storage bags also need to be mounted on the top and bottom of the module to counteract the weight of the racks which are filled with the transportation bags. Since a tray for tall growing plants is foreseen in the middle corridor and two air inlets shall be mounted at the top of the module as well, it was important to clarify how much space is left for transportation bags to be mounted at those two positions. The result was that the middle tray for tall growing plants is going to be installed when the module is landed on the surface (status: September 2022). As a consequence, there are no restrictions for the transport besides the two air ducts but they will be compressible so that they can be stored tightly in a small area at the top.

The last point which had to be clarified was the free volume in the subfloor. In there, the sump tanks for the nutrient solution need to be stored as well as the air outlets. Before the study had started, the two air ducts were placed in the middle of the subfloor as it is indicated in Fig 3.1. Since they are planned to be compressible, the first design was such that the air ducts would be compressed during launch. The assumption was made that the compressed air ducts would have a width of 10 cm in order to be able to estimate the space left in the subfloor. In the course of the study, another design emerged in which the two air ducts were placed inside the corners on the left and right side next to the subfloor. This design can be seen in Fig 3.2 and it is also the design that is considered in this thesis. However, during the CE study, it was not possible to define the sizes of the two sump tanks. This is still in progress which is why all calculations for the subfloor area are not considering any additional tank there. As soon as the sump tank will be defined those dimensions can be considered and accommodation bags can be reduced accordingly. Detailed calculations and trade-offs regarding the bags inside the racks, at the bottom and top of the module, as well as in the subfloor are conducted later on.

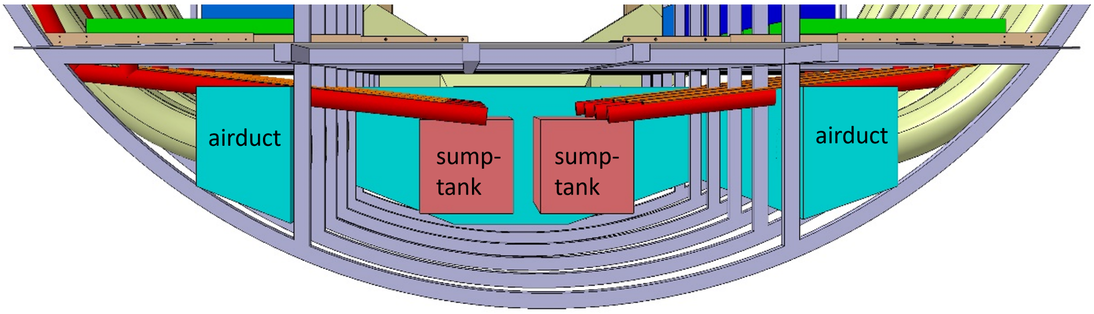


Figure 3.2: Subfloor of the greenhouse section containing the two sump tanks as well as the two air ducts. Adapted image source: DLR, Vincent Vrakking.

During the study, a mass budget calculation was started in which every responsible person for its respective subsystem noted down every equipment piece their subsystem needs so far. Through that, a rough mass budget calculation was done to see if the overall mass does not exceed the maximum the Falcon 9 launcher can lift. Additionally, it also provided a first equipment list of parts that need to be transported inside the module. Tab 3.1 shows the overall picture of every individual mass corresponding to its respective subsystem. The row containing the thermal control system (TCS) details has no mass inputs which is indicated with zero kilograms for both the total mass and the mass with margins (second and third column, respectively). That is because no expert for this subsystem was present during the CE study resulting that it still needs to be edited. Same counts for the habitat interface in the third row from above. The last subsystem, which shows the mass of the cargo section, contains a first rough list of components that are needed to transport the equipment safely.

A more detailed listing regarding the cargo section can be seen in Tab 3.2. In the first column of this table, the properties of each equipment piece are listed. The only component of the cargo section are the racks and it was set to 92 kg for each one. This mass was oriented on the ATV racks which were explained in Sec 2.3.2. It results in a total of 920 kg solely for the rack system. The belts and different transportation bags are listed under assembly parts. During the CE study, a first estimation of the necessary belts and their respective mass were made resulting in 50 pieces with a mass of 1 kg. It is important to note that the mass of the belts was estimated to 1 kg. Next, only single CTBs were chosen to be accommodated within the racks, leading to 40 pieces of them each with an empty bag mass of 1.81 kg. Eventually, the rack system closes with two M03 bags, each weighing 7.484 kg, which shall be accommodated in the subfloor area. Added all up, these parts for the cargo section are contributing to the final mass further 1058 kg. The sixth row depicts the status of the respective components and assembly parts which can vary between off the shelf, to be modified, or to be developed. For the cargo part, the racks are set to be modified since the ATV racks were custom-made and so will the racks for the greenhouse section. The other three parts are all set to off the self since the belts as well as both transfer bag types can be chosen depending on their size. The fifth and seventh rows contain both the total mass, just with the difference that a margin is added on top in the seventh row. This margin depends on what status was chosen in the sixth row. The least margin will be added to off-the-shelf parts, namely 5 %. Followed by pieces that need to be modified, for them, a margin of 10 % is added. The most margin that is going to be summed on top are parts that need to be developed. Since for these parts the entire development process has to be done further 20 % are added.

Besides the cargo section, 13 other subsystems contribute to the total mass of the EDEN NG GTD. As mentioned before, each subsystem noted down its needed parts during the CE study. This list, however, serves not only as a first total mass reference value but also as an equipment list. This will be useful to plan the accommodation of every piece later on. Furthermore, it serves as a baseline for additional considerations regarding prefixed positions in Sec 4.4.4 and grouping of those items in Sec 4.4.3.

In the following subsections, the calculations, which started during the CE study, are going to be explained. However, the following computations have been supplemented during the work of this thesis. Therefore, a hard cut between what is calculated at which time can not be made. In general, all made calculations were conducted because the equipment of the module has to be transported safely to the Moon. This will be done with a variety of transportation bags. But these, in turn, must also be fastened to ensure the safe transport of all equipment. In addition, these bags can only be fixated at certain positions within the module, as they can only be well fastened there. This is why trade-offs were done for the 40 rack compartments, the subfloor area as well as for the floor and ceiling inside the greenhouse section. Furthermore, only the half, single, double, and

Subsystem	Total Mass of Subsystem [kg]	Mass /w Margin of Subsystem [kg]
AMS	643	695, 05
DHCS	13	15.3
Hab Interface	0	0
ICS	360	432
NDS	139.97	153.967
PDCS	200	240
PHM	3	3.15
Primary Structure	4750	5700
Robotics	59.09	62.977
Secondary Payload (CROP)	97.52	104.264
Secondary Structure	1107.6	1208.83
TCS	0	0
Safety	64.25	68.1875
Cargo	1057.368	1156.2364
Total [kg]	8494.798	9839.9619
System Margin [%]	20	11807.95428
Harness [%]	10	1180.795428
Sum [kg]		**12988.74971**

Table 3.1: Overall mass budget calculations for the individual subsystems. Excel source: DLR, Volker Maiwald.

Properties	Racks	Belts	Single CTBs	M03 Bag
Component	x			
Assembly		x	x	x
Amount	10	50	40	2
Mass/Unit [kg]	92	1	1.81	7.484
Total Mass [kg]	920	50	72.4	14.968
Status	To be modified	Off the shelf	Off the shelf	Off the shelf
Margin [%]	10	5	5	5
Mass /w Margin [kg]	1012	52.5	76.02	15.7164

Table 3.2: Mass budget of the cargo section containing the equipment needed for the launch. Edited Excel source: DLR, Volker Maiwald.

triple CTBs were considered for the rack compartments whereas only the M03 bag was considered for the floor and ceiling areas. A combination of all Mxx and half and single CTBs were taken for the subfloor area. By that, different bag type combinations were analyzed to find the best result of a high storage volume while keeping the bag masses as low as possible. Positions within the SES were not considered for the trade-offs since this area already hosts a variety of subsystem equipment.

3.1.1 Mass Calculation for Transfer Bags Inside the Racks

The mass calculations for the transfer bags were first conducted for the shelf compartments inside the racks. Since there are five racks per side each with four compartments, resulting in ten racks in total for the greenhouse section, this leads to 40 places where bags can be put into racks. Each of the compartments has the dimensions of $70 \times 50 \times 60\,\mathrm{cm}^3$ as it was stated in Sec 3.1. Within these dimensions, it is possible to place half, single, and double CTBs. However, the triple CTB was calculated as well in case it can be positioned within the racks too. The first calculation was dealing with the question if only one sort of the mentioned four CTBs would be taken for all the compartments inside the racks. As a result, the half CTBs provide the least internal storage volume with $0.91\,\mathrm{m}^3$. However, since it is the smallest bag, it also contributes the least mass to the overall system, namely 40 kg. In contrast to the half CTB, the double CTB would add more than the double amount of mass to the overall system which is 81.6 kg. Thus, the maximum internal storage volume of $3.74\,\mathrm{m}^3$ is reached with these bags. The single CTB option is the golden course between the two other options mentioned before. A result of the chosen option is drawn in Sec 3.3. Lastly, a compact representation of all calculated values can be seen in Tab 3.3.

CTB Type	Empty Bag Mass [kg]	Storage Volume (internal) [m^3]	Storage Volume (external) [m^3]
Half CTB	40.00	0.91	0.99
Single CTB	72.40	1.97	2.12
Double CTB	81.60	3.74	4.28
Triple CTB*	112.40	5.62	6.39

Table 3.3: Trade-off between the mass of the empty bags versus the storage capability they provide if only one CTB type for every rack compartment is used.
*The triple CTB is calculated as well for the case it can be positioned within the racks.

3.1.2 Mass Calculation for Transfer Bags in the Subfloor Area

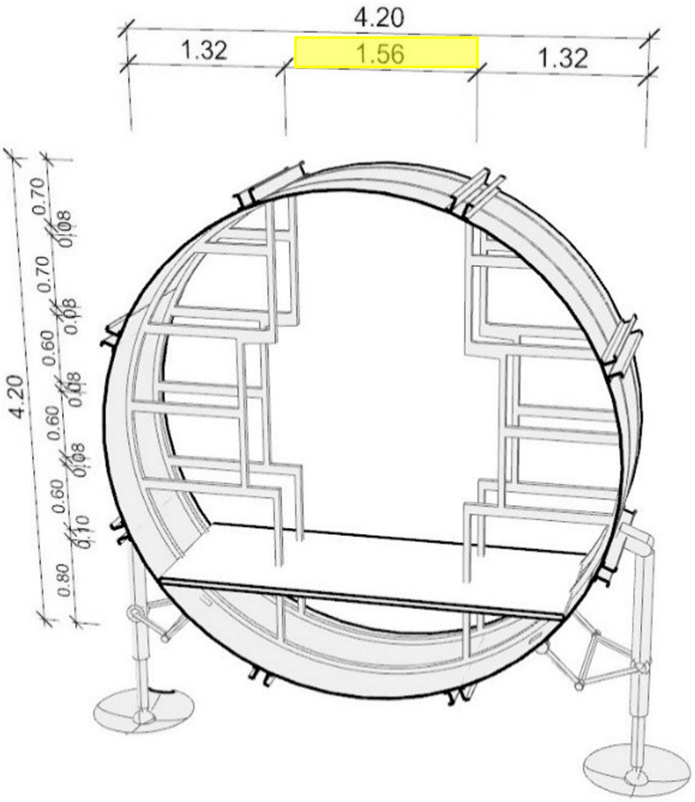
The next calculations were conducted for the subfloor of the greenhouse module. However, it is important to mention that these calculations which are presented in this thesis just reflect a fraction of all possibilities for how to position different bags with one another. Since this bag accommodation is a combinatorics problem, there is no easy way for computing the best storage option. Therefore, the presented options reflect only the beginning in order to deliver the first mass and storing volume results to get a taste of where the final values go.

The following calculations are based on the design and dimensions of the greenhouse and how it was during the CE study in September 2022, meaning without any tanks placed in the subfloor area since their dimensions were not fixed by then. Therefore, the following accommodations are proposals for the configuration from September 2022. During the

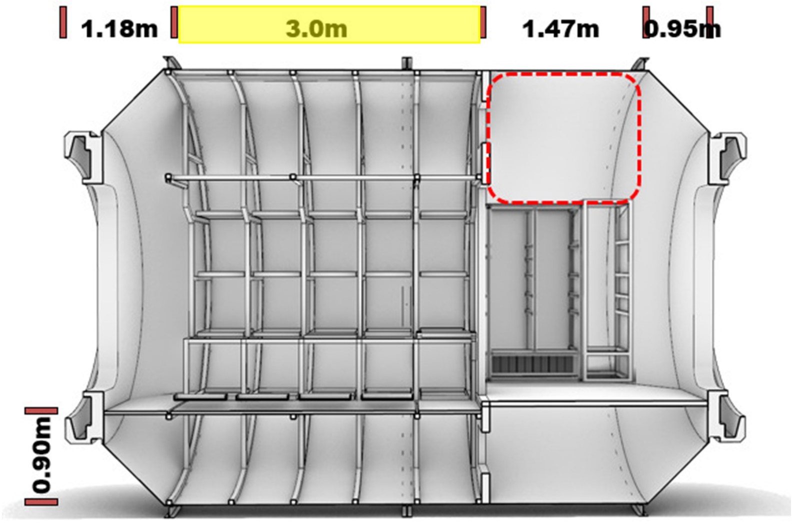
CE study, it was started with a rough estimation of how many Mxx bags can be fit in the subfloor area. For that, the empty bag masses as well as their corresponding storage capacities are calculated. The result was that, depending on the sump tank dimensions which are still not defined, it is possible to store two to three M03 bags. If two M03 bags would be stored, it would result in $1.28\,\mathrm{m}^3$ of storage volume with a bag mass of 14.97 kg. Compared to that, if three instead of two bags are used, it results in $1.92\,\mathrm{m}^3$ volume with 22.56 kg of the bag mass. During the work of this thesis, those calculations were further revised and extended to exploit the space below the floor even more. There, an extensive analysis of the different arrangements of the varying bag sides was made. This analysis was conducted by placing the bags first along the width of the greenhouse which is 1.56 m long and which can be seen in Fig 3.3a. In the following, this point of view will be named width view. Afterwards, it was analyzed how many bags can be placed in a row one after another exploiting the full length of 3.00 m. This view will be further called length view and can be seen in Fig 3.3b.

In the following, the different trade-offs which were made are going to be explained. However, only the best solution for each trade-off option is shown in the picture here. A full visual representation of each accommodation trade-off can be seen in the Appendix 6.1. First, it was started with placing Mxx bags of the same type inside the entire subfloor area. Simultaneously, it was looked at how the individual bags need to be positioned in order to reach the maximum amount of bags inside the subfloor area. The option in which the maximum amount of M01 bags can be stored leads to in total of two rows next to each other. This results in a total of eight M01 bags. Furthermore, a storing volume of $3.144\,\mathrm{m}^3$ is reached with an empty bag mass of in total 38.608 kg. This option is marked as $a_{1,1}$. The best configuration for the M02 bags results in two rows with four bags per row as well. The option is marked with $a_{1,2}$ and reaches a storing volume of $1.944\,\mathrm{m}^3$ with bag masses of 24.784 kg. And last, a maximum of three bags in option $a_{1,3}$ can be placed if only M03 bags are positioned. This option provides a storing volume of $1.923\,\mathrm{m}^3$ and results in an empty bag mass of 22.452 kg. This last arrangement for the M03 bags is the same as the one which was already calculated during the CE study. A graphical representation of the accommodation options of Mxx bags can be seen in Fig 3.4.

These computations were then followed by a further analysis in which a mixture of the Mxx bag types is placed in the subfloor area. The corresponding visualizations of the accommodations can be seen in Fig 3.5. For the M01 bag, it remains that the best solution for exploiting the volume is reached if it is combined with itself. This option was already presented in the previous paragraph. For the case, if M02 bags were at least placed on the subfloor, the best option would be combining this bag type with M01 bags. For this combination, two options were looked at. Option $a_{2,1}$ arranges the bags such that the M01 bag side $81.8 \times 90.2\,\mathrm{cm}^2$ and the M02 bag side $50.7 \times 53.3\,\mathrm{cm}^2$ are facing the width view. This leads to a total of eight bags which can be placed in two rows. However, this bag combination reaches a lower storing volume of $2.694\,\mathrm{m}^3$ but also a smaller bag mass of 33.424 kg. Lastly, if M03 bags were certainly used in the subfloor area, the option providing the most accommodation volume would be to combine those bags as well with M01 bags. Then, the storage accommodation would lead to $2.461\,\mathrm{m}^3$ with an empty bag

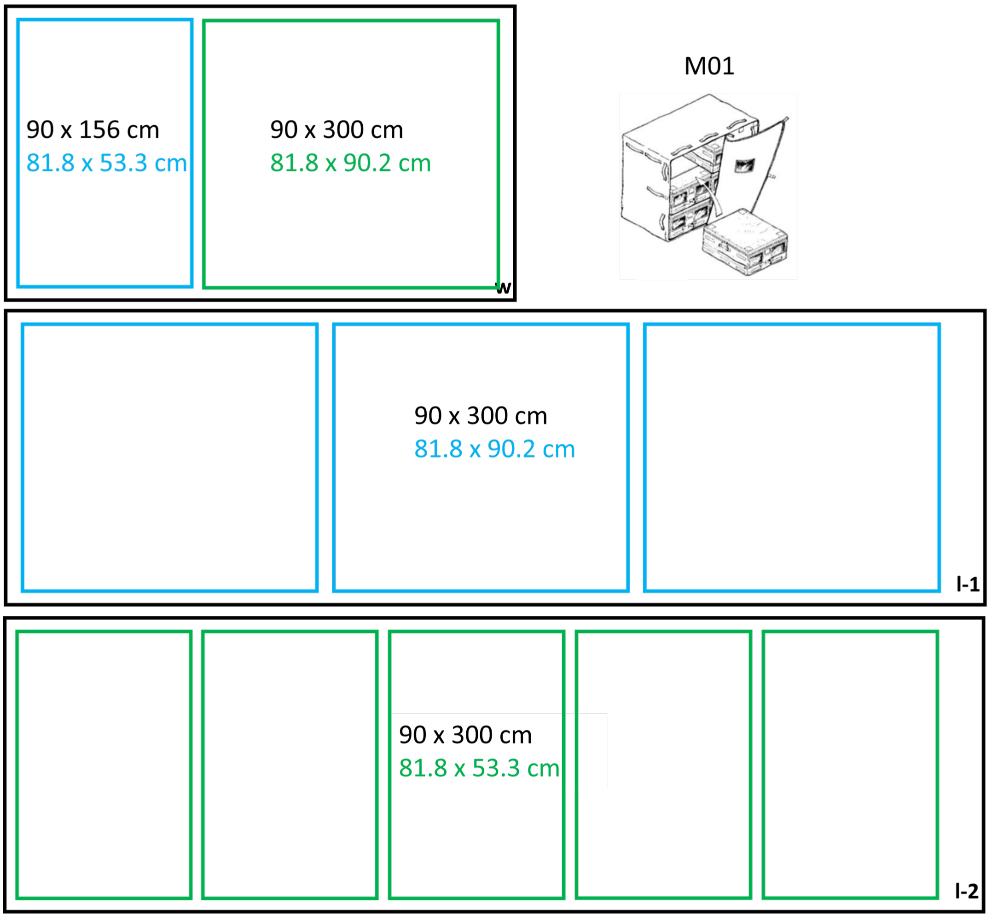


(a) Front view of the greenhouse with its corresponding width of 1.56 m.



(b) Side view of the greenhouse with its corresponding length of 3.00 m.

Figure 3.3: Different viewing angles of the module to highlight the width and length sizes. Adopted image from: DLR, Kim Kyunghwan.

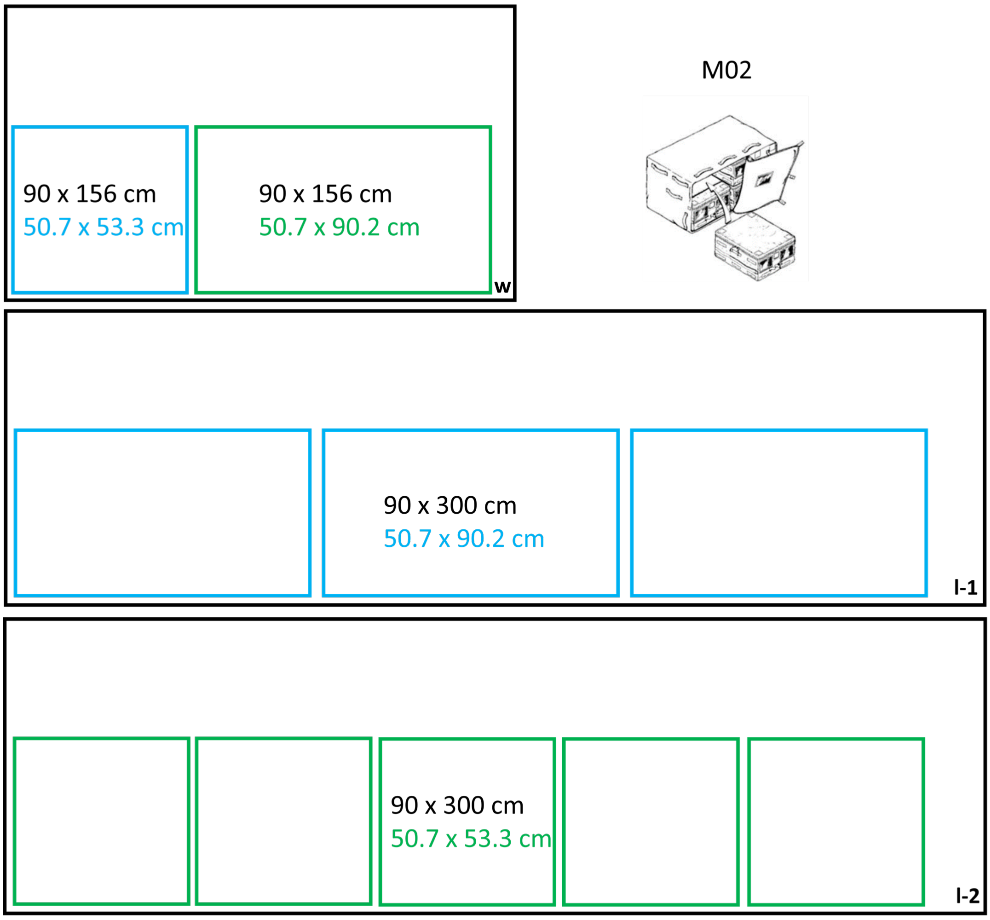


(a) Subfloor accommodation if only M01 bags are used.

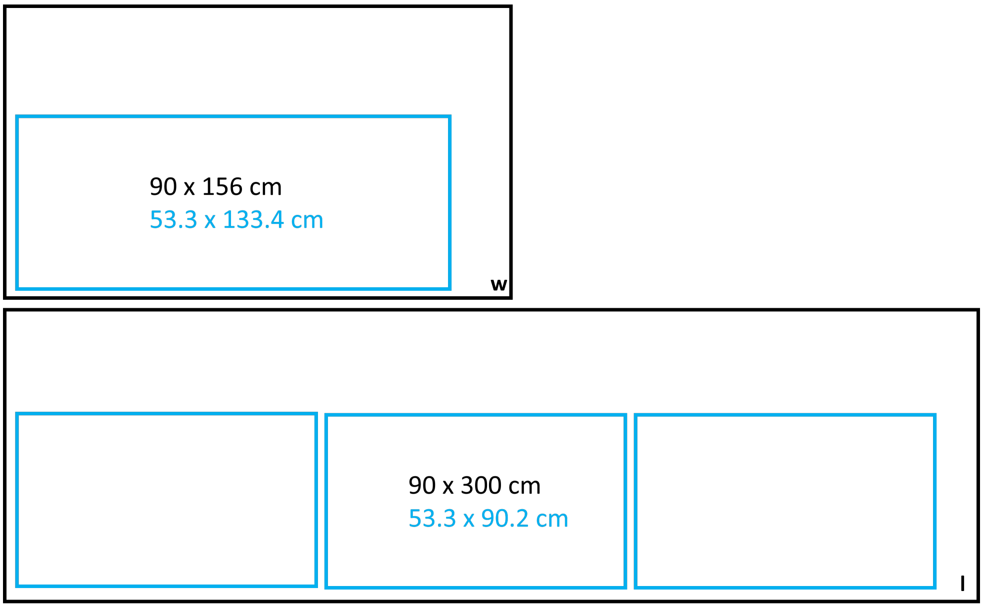
Figure 3.4: Maximum amount of storage bags inside the subfloor area (black box) if the same bag type (blue boxes) is used.

mass of 29.446 kg and is marked as $a_{2,3}$. The combination of M02 and M03 bags in the subfloor area is not going to be mentioned here since the combinations M02 with M01 as well as M03 with M01 are providing a higher storage volume than combining M02 with M03 bags. However, it is still listed in the overall Tab 3.4 under option $a_{2,4}$ and can be found in the Appendix 6.1 as well.

Finally, after doing the trade-offs for the subfloor area for first equal bag types and second for mixed bag types, some empty spaces are still left in those calculations. These empty volumes can not be filled with Mxx bags since they are too large. However, it is possible to fill those holes with standard CTBs if some storing units are still needed later on. Since all empty volume compartments have one side length smaller than 0.4 cm, only the half and single CTB can be taken into account since these two bags have one side smaller than the available height of 0.4 cm which makes it possible to place those into the

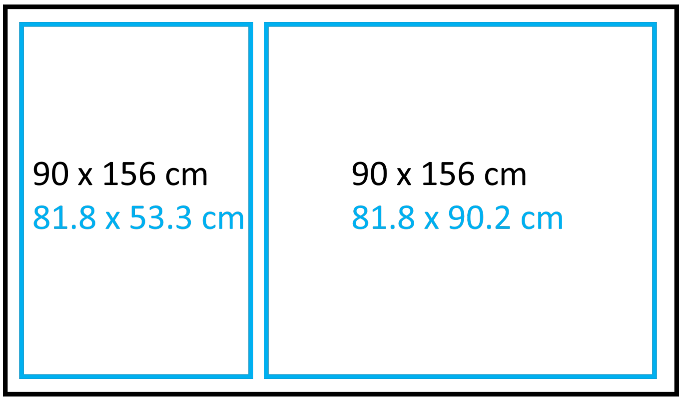


(b) Subfloor accommodation if only M02 bags are used.

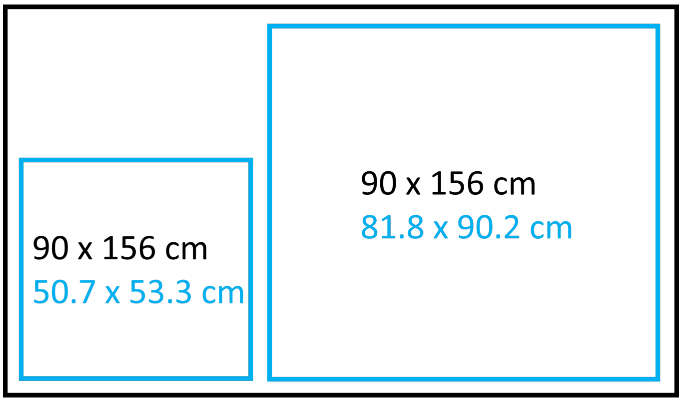


(c) Subfloor accommodation if only M03 bags are used.

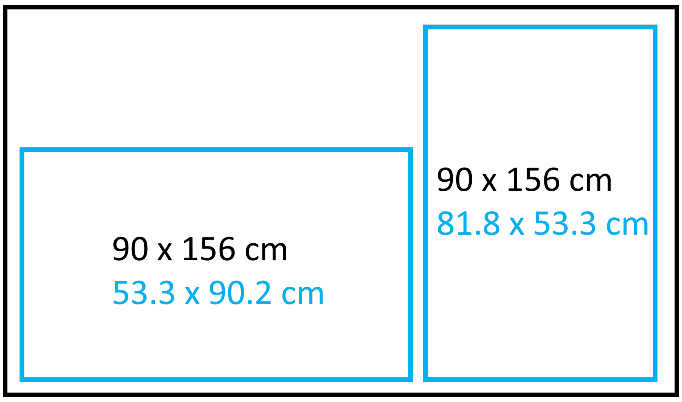
Figure 3.4: Maximum amount of storage bags inside the subfloor area (black box) if the same bag type (blue boxes) is used (continued).



(a) Maximum amount of storage bags inside the subfloor area (black box) if the M01 bag type is mixed with other M01 bag types (blue boxes).



(b) Maximum amount of storage bags inside the subfloor area (black box) if the M02 bag type is mixed with M01 bag types (blue boxes).



(c) Maximum amount of storage bags inside the subfloor area (black box) if the M03 bag type is mixed with M01 bag types (blue boxes).

Figure 3.5: Maximum amount of storage bags inside the subfloor area (black box) if a mixture of Mxx bag types (blue boxes) is used.

remaining gaps. Therefore, another trade-off was done for each of the five cases, namely using the same type of bags (only M01, M02, or M03) or a mixture of bag types (M01 with M02 and M01 with M03).

In the beginning, the first option of just using M01 bags for the subfloor is outlined. There, an empty space of $36.7 \times 102.7\,\mathrm{cm}^2$ is still unused. First, option $a_{3,1}$, only half CTBs were placed, for which two options were looked at. Beginning with placing the half CTBs with the dimensions of $24.8 \times 42.5\,\mathrm{cm}^2$ along the width view, this leads to two rows. With each row containing 11 bags, this option results in 22 half CTBs which can be placed. Thus, a total of $2.864\,\mathrm{m}^3$ can be stored while also adding 50.956 kg to the total mass of the module. The other possibility, option $a_{3,2}$, is to place the bag side $24.8 \times 23.5\,\mathrm{cm}^2$ along the width view. Thereby, three rows with each six half CTBs can be placed. Furthermore, two additional half CTBs can be placed since there is space left again. Overall, this option leads to a total storing volume of $2.818\,\mathrm{m}^3$ with 48.956 kg of bag mass due to the in total 20 half CTB and six M01 bags.

Another way of exploiting this empty space is by filling it with single CTBs, for which the dimensions $24.8 \times 42.5\,\mathrm{cm}^2$ are facing the width view. Resulting in two rows with each five single bags there is still some unused space which can not be filled with further single CTBs but with two half CTBs. This option $a_{3,3}$ leads to an accommodation volume of $2.914\,\mathrm{m}^3$ with 49.056 kg of mass due to the bags itself. The other option for this accommodation case places the single CTBs with the dimensions $24.8 \times 50.2\,\mathrm{cm}^2$ along the width view resulting in one row with five bags for each row. Next to this row, a second row can be placed either with further single (option $a_{3,4}$) or half (option $a_{3,5}$) CTBs. For option $a_{3,4}$ which has a second row with single CTBs as well, five additional bags can be placed. Again, two half CTBs can be placed behind the two rows since a single CTB would be too big for the left space. For option $a_{3,5}$, a second row with half CTBs would lead to 11 half CTBs in the second row with an additional half CTB behind the single CTB row. As a result, option $a_{3,4}$ provides a storing volume of $2.914\,\mathrm{m}^3$ while option $a_{3,5}$ offers a storing volume of $2.889\,\mathrm{m}^3$. Regarding the masses of the bags themselves, option $a_{3,4}$ adds further 49.056 kg and option $a_{3,5}$ adds 50.006 kg to the overall system. The best solution of all four mentioned possibilities can be seen in Fig 3.6.

Next, a trade-off is done for the unused space in the subfloor area when only M02 bags are placed. This unused space has the dimensions of $39.3 \times 156.0\,\mathrm{cm}^2$. Again, it was started with placing half CTBs with the dimensions of $24.8 \times 23.5\,\mathrm{cm}^2$ along the width view for option $a_{3,6}$. This results in five rows with each six bags per row resulting in 30 half CTBs in total. Additionally, further three differently arranged half CTBs can be placed in the subfloor area leading to in total 33 half CTBs. This option offers $2.703\,\mathrm{m}^3$ of storing volume while adding 57.784 kg of mass. When placing the half CTBs differently along the width view, namely with the dimension of $24.8 \times 42.5\,\mathrm{cm}^2$, three rows with 11 bags per row can be achieved leading to 33 half CTBs in total for option $a_{3,7}$. This results in an accommodation volume of $2.703\,\mathrm{m}^3$ with empty bag masses of 57.784 kg. However, if not purely half CTBs but a mixture of half and single CTBs is used, it is possible to place three rows with five bags in each row in the subfloor area. Another three half CTBs can fill the remaining gap leading to in total 15 single and three half CTBs for option

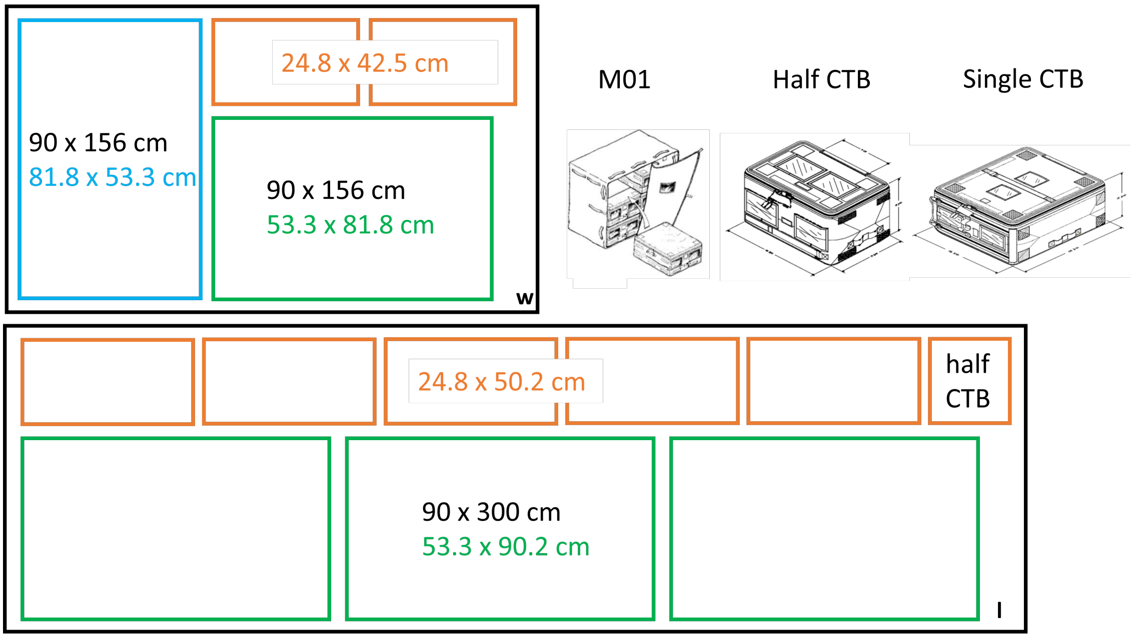


Figure 3.6: Best solution by placing half and single CTBs (orange) in the empty spaces in the subfloor along with M01 bags.

$a_{3,8}$. All together, they provide a storing volume of 2.778 m^3 with bag masses of 54.934 kg. Another way of placing single CTBs is by positioning two rows of single CTBs with the dimensions of $24.8 \times 50.2\,\mathrm{cm}^2$ along the width view while the third row is positioned with $24.8 \times 42.5\,\mathrm{cm}^2$ along that view. This option $a_{3,9}$ results in having 12 single CTBs for the first two rows with additional two half CTBs and five single CTBs for the third row with one further half CTB at the end. In total, a storing volume of 2.880 m^3 can be achieved with the empty bag masses of 58.554 kg. As a result, the best solution from these four presented versions can be seen in Fig 3.7. These results for the case that M02 bags are used for the entire subfloor are the same as if purely M03 bags are used since both options have an unused space of $39.3 \times 156.0\,\mathrm{cm}^2$. That is why no explanation of the arrangements is shown here for the constellation that only M03 bags are used. However, the results are still noted down in the Tab 3.4 under options $a_{3,10}$-$a_{3,13}$.

The next trade-offs are done for a mixed bag type accommodation in the subfloor area. Beginning with if M01 and M02 bags are placed there, an unused space of $39.3 \times 65.8\,\mathrm{cm}^2$ exists. In option $a_{4,1}$, it is filled with half CTBs. In this way, it is possible to place one row with 11 bags resulting in a total accommodation volume of 2.947 m^3 with bag masses of 44.424 kg. By placing the half CTBs differently in option $a_{4,2}$, it is possible to position two rows of half CTBs, each with six bags per row. One additional half CTB can be placed, leading to a total storing volume of 2.993 m^3 and empty bag masses of 46.424 kg. On the other hand, if a mixture of half and single CTBs is used for filling the gap, two other possibilities for placing those bags were analyzed. The first option

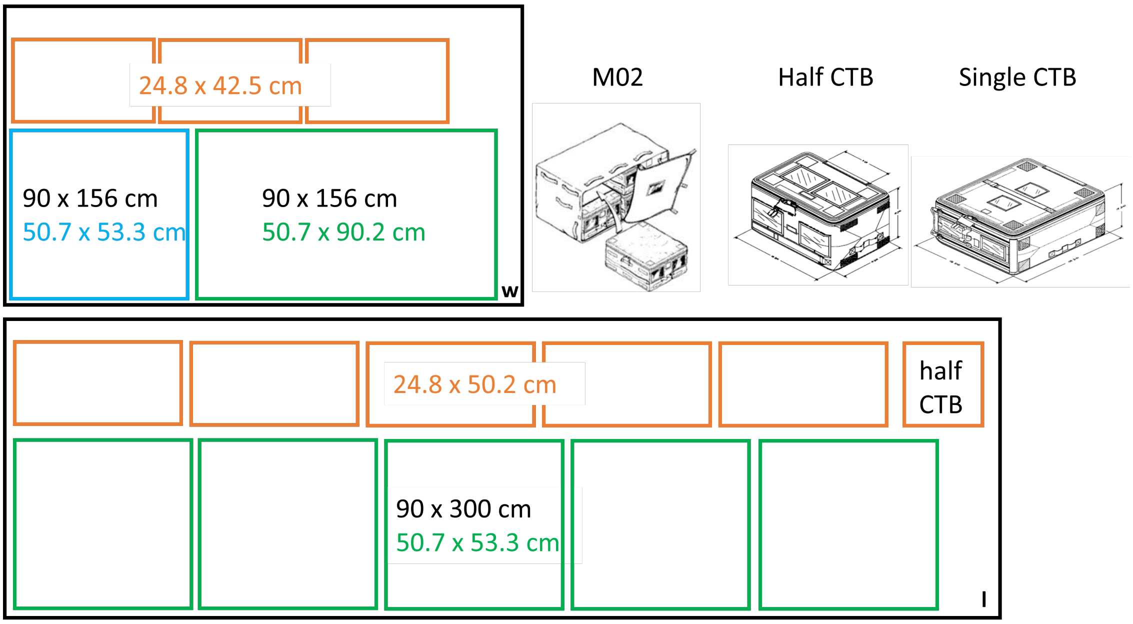
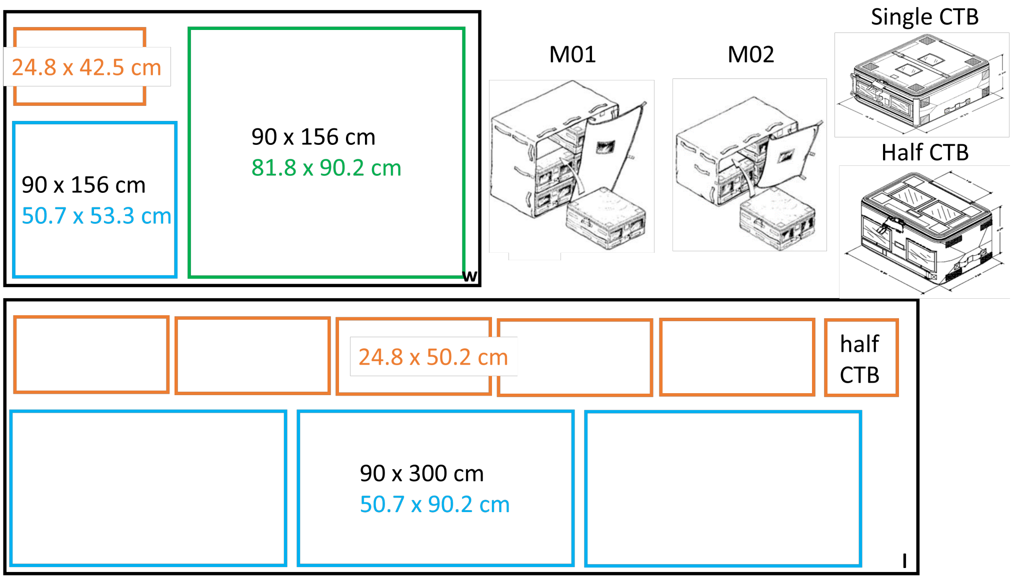


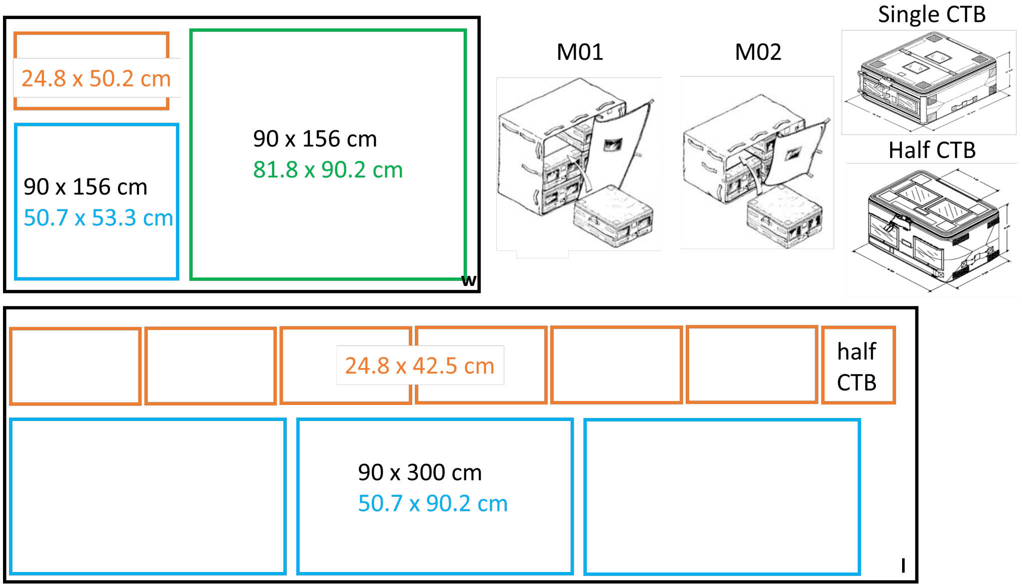
Figure 3.7: Best solution by placing half and single CTBs (orange) in the empty spaces in the subfloor along with M02 bags.

$a_{4,3}$ placed single CTBs in the empty spaces, leading to one row containing five single CTBs. Additionally, one half CTB can be placed in such a way that an accommodation volume of in total 2.972 m^3 with bag masses of 43.474 kg are reached. The other option $a_{4,4}$ containing half and single CTBs arranges the bag sides differently but leads to the same storage volume and empty bag masses. The best solutions, since both provided the same amount of storing volume as well as empty bag masses out of those four mentioned possibilities, can be seen in Fig 3.8a and 3.8b.

The last trade-off of CTBs for the gaps left in the subfloor area was done if M01 and M03 bags are positioned there. Again, four options were looked at beginning with filling the space with only half CTBs in option $a_{4,5}$. They can be positioned in such a way that there will be two rows with each 11 bags resulting in 22 half CTBs in total. Altogether, they would provide a storing volume of 2.967 m^3 while adding bag masses of 51.446 kg. If the half CTBs are positioned differently, three rows can be placed with each six bags in a row resulting in option $a_{4,6}$. Additionally, two further differently arranged half CTBs can be placed as well. This leads to 20 bags that can be positioned resulting in an overall storing volume of 2.921 m^3 with empty bag masses of 49.446 kg. The last two options represent a mixture of half and single CTBs. The first option $a_{4,7}$ for this combination is to place the single CTBs in two rows with five bags each resulting in ten bags in total. Additionally, two half CTBs can be placed as well in this combination resulting in an accommodation volume of 3.017 m^3 and bag masses of 49.546 kg. The other option $a_{4,8}$ is to place the single CTB differently, leading to only one row but this time with six bags in this row. Next to it, a row with half CTBs can be placed with six bags as well in this



(a) Accommodation option 1: Filling the empty space with half and single CTBs (orange) along with M01 and M02 bags.



(b) Accommodation option 2: Filling the empty space with half and single CTBs (orange) along with M01 and M02 bags.

Figure 3.8: Best solutions by placing half and single CTBs (orange) in the empty spaces in the subfloor along with M01 and M02 bags.

row. Also, further two half CTBs can be placed leading to in total eight half CTBs and six single CTBs. This bag mixture provides a storing volume of 2.951 m^3 with bag masses of 48.306 kg. Again, the best option out of these four mentioned ones can be seen in Fig 3.9.

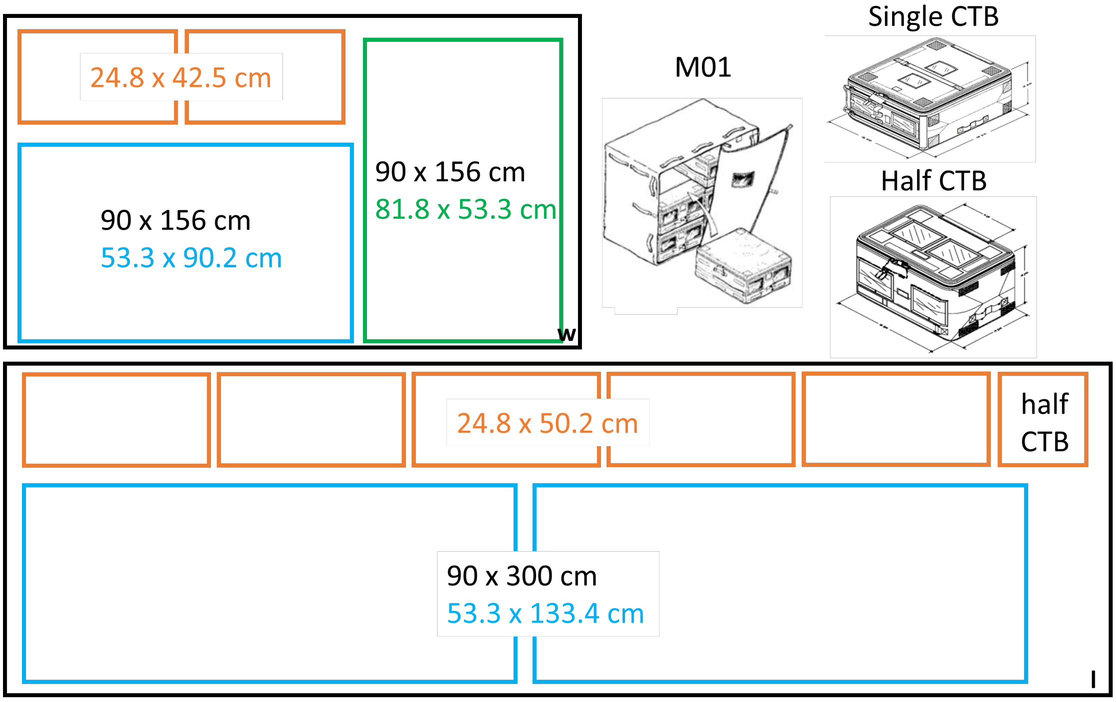


Figure 3.9: Best solution by placing half and single CTBs (orange) in the empty spaces in the subfloor along with M01 and M03 bags.

The trade-off for the bag combination of M02 with M03 can be seen in Tab 3.4 with the corresponding options $a_{4,9} - a_{4,12}$.

An overall table including all trade-offs made between storage volume and empty bag masses with their corresponding amount of bags for the subfloor area can be seen in Tab 3.4. A first analysis of the trade-off results will be discussed in Sec 3.3 with a following detailed evaluation in Sec 5.

3.1.3 Mass Calculation for Transfer Bags at the Floor and Ceiling

As an additional storage place, the floor and ceiling inside the greenhouse section are considered. It may be necessary either because further transportation bags are needed or, more likely, to balance out the module concerning the mass distribution. Resulting from the greenhouse dimensions, which can be seen in Fig 3.3, bags can be placed within the dimensions $300 \times 156\,\text{cm}^2$ inside the middle corridor. For this, a mass calculation with the biggest M03 bags was done in order to get the mass that those additional bags would

Bag Type Config.	Options	Amount of Bags					Storage	Empty Bag
single=s; half=h		h	s	M01	M02	M03	Volume [m^3]	Mass [kg]
pure M01	$a_{1,1}$	-	-	8	-	-	3.144	38.608
pure M02	$a_{1,2}$	-	-	-	8	-	1.944	24.784
pure M03	$a_{1,3}$	-	-	-	-	3	1.923	22.452
M01+M02	$a_{2,1}$	-	-	5	3	-	2.694	33.424
	$a_{2,2}$	-	-	3	5	-	2.394	29.968
M01+M03	$a_{2,3}$	-	-	3	-	2	2.461	29.446
M02+M03	$a_{2,4}$	-	-	-	3	2	2.011	24.262
M01, h	$a_{3,1}$	22	-	6	-	-	2.864	50.956
	$a_{3,2}$	20	-	6	-	-	2.818	48.956
M01, s+h	$a_{3,3}$	2	10	6	-	-	2.914	49.056
	$a_{3,4}$	2	10	6	-	-	2.914	49.056
	$a_{3,5}$	12	5	6	-	-	2.889	50.006
M02, h	$a_{3,6}$	33	-	-	8	-	2.703	57.784
	$a_{3,7}$	33	-	-	8	-	2.703	57.784
M02, s+h	$a_{3,8}$	3	15	-	8	-	2.778	54.934
	$a_{3,9}$	3	17	-	8	-	2.880	58.554
M03, h	$a_{3,10}$	33	-	-	-	3	2.682	55.452
	$a_{3,11}$	33	-	-	-	3	2.682	55.452
M03, s+h	$a_{3,12}$	3	15	-	-	3	2.757	52.602
	$a_{3,13}$	3	17	-	-	3	2.859	56.222
M01+M02, h	$a_{4,1}$	11	-	5	3	-	2.947	44.424
	$a_{4,2}$	13	-	5	3	-	2.993	46.424
M01+M02, s+h	$a_{4,3}$	1	5	5	3	-	2.972	43.474
	$a_{4,4}$	1	5	5	3	-	2.972	43.474
M01+M03, h	$a_{4,5}$	22	-	3	-	2	2.967	51.446
	$a_{4,6}$	20	-	3	-	2	2.921	49.446
M01+M03, s+h	$a_{4,7}$	2	10	3	-	2	3.017	49.546
	$a_{4,8}$	8	6	3	-	2	2.951	48.306
M02+M03, h	$a_{4,9}$	33	-	-	3	2	2.770	57.262
	$a_{4,10}$	33	-	-	3	2	2.770	57.262
M02+M03, s+h	$a_{4,11}$	3	15	-	3	2	2.845	54.412
	$a_{4,12}$	3	17	-	3	2	2.947	58.032

Table 3.4: Different accommodation options if the same or mixed Mxx bag types are used inside the subfloor area.

add to the overall module mass. The reason for the choice of the M03 bag type is that this is the bag with the largest dimensions. With those bags bigger or heavier equipment pieces can be stored safely while simultaneously counteracting the masses of the racks and bags at the sides to reach a balanced mass distribution for launch. Also, since only the smaller CTBs can be accommodated within the racks there are so far not many bigger transportation bags foreseen in the module which are potentially necessary.

The corresponding graphical representations of all four options which are going to be explained in the following can be found in the Appendix 6.1. Depending on the height to which M03 bags are going to be arranged at the ceiling or floor, four options are possible. In this context, the floor is meant the area above the subfloor. The first two, $b_{1,1}$ and $b_{1,2}$, are designed for a height of 156 cm while options $b_{1,3}$ and $b_{1,4}$ are calculated for a height of 78 cm. Therefore, the first two options for the larger height can accommodate four to six bags while the latter ones can position two to three bags. All possibilities lead to different accommodation volumes as well as empty bag masses. The most can be stored in option $b_{1,1}$ which is 3.846 m^3. However, this also means the highest bag masses of 44.904 kg. Compared to that, the lowest bag mass is reached with option $b_{1,4}$. There, only two bags can be stored which would result in a weight of the bags of 14.968 kg. However, since the least amount of bags is used, this results in the lowest storing volume of 1.282 kg. The option which is going to be chosen depends strongly on the equipment which needs to be stored for transportation. If more storage possibilities are required, the options which provide the most storing volume are then preferred. However, if the overall mass of the module exceeds the mass capabilities of the launcher, options with a reduced empty bag mass are preferred which would also lead to a reduced storage volume. The following Tab 3.5 contains all results for the floor and ceiling calculations for a better overview.

	either for Ceiling or Floor			
Options	$b_{1,1}$	$b_{1,2}$	$b_{1,3}$	$b_{1,4}$
Amount of Bags	6	4	3	2
Storage Volume [m^3]	3.846	2.564	1.923	1.282
Empty Bag Mass [kg]	44.904	29.936	22.452	14.968

Table 3.5: Different accommodation options of M03 bags for the floor and ceiling areas of the greenhouse module.

3.1.4 Mass Calculations for the Safety Belts

Another important point to consider is the belts for fastening the bags. Their weight adds up since multiple belts are needed for a single bag to fixate it properly. In addition, the following applies that bigger bags such as the Mxx ones need more belts than the smaller CBT bags. The reason is due to the different sizes of the bags and therefore the different masses which need to be held by the belts. And since multiple bags are going to be used within the system the belts make an important part that should not be underestimated.

Since no information during the search was found regarding the used belts in cargo transfer modules, the following assumptions were made. From the ATV configuration inside, it can be derived and assumed that the half, double, and triple CTBs are fastened by two belts whereas the single CTBs are fixed by one belt. The assumption is based on Fig 2.2. For the bigger Mxx bags, more belts are required. Here, five belts are assumed to be needed to fasten them. The reference for that is the following Fig 3.10.

Figure 3.10: Fastening of Mxx bags inside the ATV 5 carrier. Image adapted from [67].

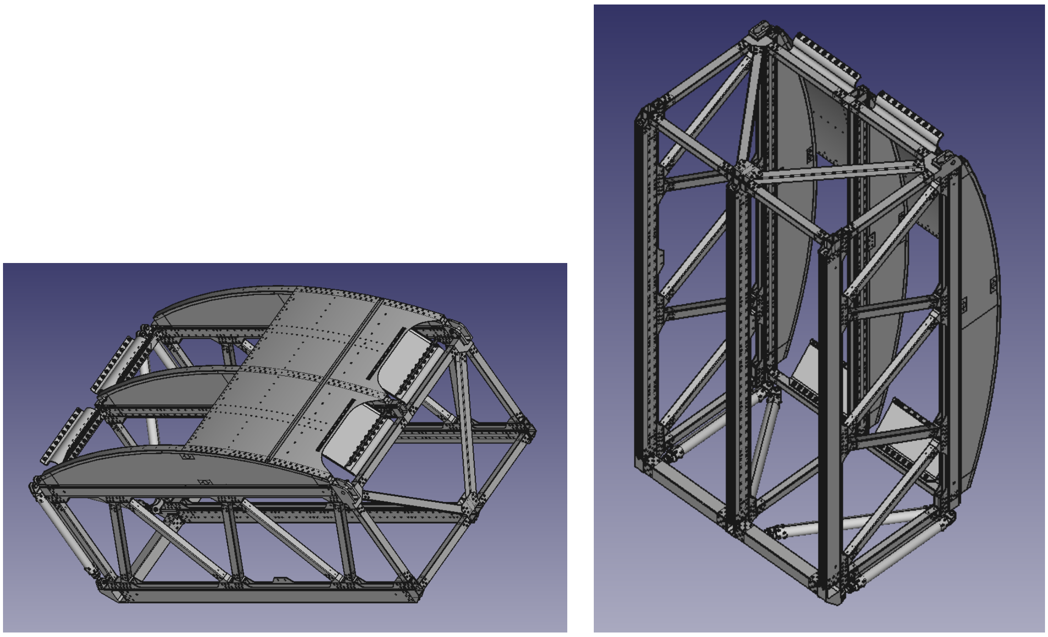
As a first estimation, the following transportation bag combinations are chosen. The selection here does not necessarily match with the final chosen bag combination from Sec 5. The reason is that for the belt calculation, a higher margin is taken meaning more belts are taken into account than may be necessary. For the rack compartments, double CTBs are chosen leading to 40 double CTBs (see Sec 3.1.1). Since two belts are assumed to be required to fasten the double CTBs accordingly this leads to 80 belts solely for the rack compartments. Next, two options are considered for the subfloor area (see Tab 3.4). The first option $a_{1,1}$ contains eight M01 bags. This results in 40 belts necessary to ensure the safe transport of these bags. The second option which is going to be considered is $a_{4,4}$. There, one half CTB, five single CTBs, five M01 bags, and three M02 bags need to be fastened. Since the half CTB requires two belts, the single CTBs one belt, and both the M01 and M02 bags require each five belts, there will be a total of 47 belts needed for the subfloor area. By also choosing the highest amount of bags for the ceiling and floor, there 12 M03 bags are need to get fixed in that section (see Tab 3.5). This leads to 60 belts for the ceiling and floor bags. As a result, there are in total 180-187 belts required (here depending on the option for the subfloor area). Next, the mass of one belt is required. Since this strongly depends on the individual properties of the belt, the mass was again estimated. Features of the belts that need to be considered are the material of the belt itself and all its possible hooks or ratchets. Furthermore, the thickness and width of the strap has to be considered to not cut into the bags. Last, the overall length of the belt needs to be considered as well to make sure that it fits at least once around the bag. The most important property, however, is that the belts withstand heavy loads. As a first guess it was assumed that they need to withstand at least 2000 kg. For this purpose, two belts were chosen for a guideline and their corresponding data-sheet can be seen in the Appendix 6.1. One of them weighs 2.14 kg, the other one 3.20 kg. Therefore, the average of both was taken which leads to the assumed mass of 2.7 kg per belt. Thus, the belt mass amounts to 504.9 kg for those 187 required belts.

3.1.5 Considerations for Placing Transfer Bags Inside the SES

A further location that can be considered for placing transportation bags in case more storage opportunities are needed is the other part of the module, namely the SES. The dimensions of the corridor of this module part, which can be seen in Fig 3.3, are $242 \times 156 \times 352\,\text{cm}^3$. In the case that bags will be stored in the corridor of the SES it is immensely important to stow the equipment inside the bags in an ordered sequence. Therefore, equipment pieces that are needed first have to be within the first bag directly in front of the entrance door such that the astronauts will be able to unpack it in the beginning. A packing order is important because once everything is stored it will not be possible to reach bags inside the module since the corridor will be blocked by other transportation bags. At the same time, the overall module has to be balanced out regarding its mass distribution. One and a half ISPRs are already placed at each side of the SES containing subsystem parts and electronics. To mention some, the power, onboard computer, a worktable, and all the tanks and pumps for the NDS will be preinstalled and stored there. Therefore, if the SES is already quite heavy meaning that the greenhouse section is lighter, it will not be possible to put further equipment in there. And again, it strongly depends if further storage possibilities are needed when it is not possible to store every piece in bags in the greenhouse section.

3.2 ATV Rack System

The rack system for the greenhouse section first contains the transportation bags and later hosts the plant trays. The racks are inspired by other rack systems inside transportation modules such as the ones mentioned in Sec 2. One of those systems was taken as the base for the greenhouse section, namely the one from the ATV module called space-approved racks. It was built by the Beyond Gravity Schweiz AG company in Zurich, which was formally known as RUAG Space. All racks inside the ATV were made out of aluminum with an empty rack mass of 120 kg. This mass differs from the 90 kg [68] which were estimated during the CE study. This is due to the fact that more recent information was gained during the work of this thesis. The weight of the racks resulted from the need of withstanding the internal loading of 511 kg and the external loading of 180 kg. Through that, it had to be built quite massively which is also reflected in the end mass of each rack. The corresponding CAD model for the ATV racks can be seen in the following Fig 3.11. (source: personal correspondence with Beyond Gravity Schweiz AG)



(a) Back view of the ATV rack. (b) Front view of the ATV rack.

Figure 3.11: CAD model of the ATV racks built by the Beyond Gravity Schweiz AG. Image source: personal correspondence with Beyond Gravity Schweiz AG.

To withstand internal and external loads is also important for the EDEN NG GTD since these racks need to first accommodate all transportation bags during flight as well as host the illumination installations and plant nutrition suppliers afterwards. Additionally, the racks will contain the plants inside the trays which will contribute to the internal loading of the racks once on-site. This rack system was chosen for the EDEN NG GTD application because they are still lightweight while simultaneously being able to accommodate a heavy amount of equipment inside and attached to it. Furthermore, those racks have already reached a high technology readiness level (TRL) meaning that they are already flight-proven due to their multiple uses on board the ATV.

Since there will be five racks per side with one weighing 120 kg, leading to ten racks in total, those will add further 1200 kg to the overall system mass.

One consideration for the rack system was to place all the cables from the illumination and nutrition system inside the struts of the racks. This would have the advantage of having the supply inlets preinstalled and protected from external influences. Although the struts of the ATV racks were hollow, this option was still discarded since this would pose too great a risk for the cables and pipes. The reasons for this decision were on the one hand that the plugs from the cables and the flanges of pipes have oftentimes a larger diameter than the cables and pipes themselves. This makes it difficult to pull them through the tight hollow spaces inside the struts during mounting. The plugs and flanges could be installed after pulling the cables and pipes through the struts solely.

However, this is not practical and makes the maintenance even more aggravated. On the other hand, the cables and pipes would not be protected mechanically although they would be placed inside the struts. The problems are vibrations during launch which can lead to chafing points resulting in short circuits or leakage of the pipes (source: personal correspondence with Beyond Gravity Schweiz AG). One possible solution to improve this point can be to either make the struts of the racks thicker. Through that, the loads could be withstand better. A further solution could be to manufacture the struts such that one of the four sides is open, so u-shaped. The advantage would be that the opening could be positioned towards the corridor making it easier for maintenance. Nevertheless, both options require further consideration as well as a profound test phase.

3.3 Lessons Learned

This chapter will sum up all the important points of chapter three as well as draw a result from the calculations made. First, it was looked at the compartments inside the racks. There, it is only possible to accommodate half, single, and double CTBs. The triple CTB does not fit into that space since one side length (74.9 cm) exceeds one side length (70 cm) of the rack compartment. Furthermore, all Mxx bags are too large as well and therefore cannot be placed inside the racks. What can be seen from Tab 3.3 is that the single and double CTBs are not varying that much from each other regarding their bag masses for 40 bags. However, the double CTBs can provide almost double the amount of internal storage compared to the single CTBs by just weighing less than 10 kg. The double CTBs also provide more storage volume compared to the half CTB. When doubling the volume of the half CTBs it is still more than half of what the double CTBs can provide while the mass for the two bags would be the same.

Next, different accommodation options and calculations were done for the arrangements in the subfloor area. They were first conducted for the case that only Mxx bags are used. In the next step, empty spaces that were still left were filled with different CTBs. All calculated results can be seen again in Tab 3.4. By analyzing the obtained results, it can be seen that the highest storage volume is gained when purely M01 bags are placed inside the subfloor area (first row in the table). Then, the highest storing volume of $3.144\,\mathrm{m}^3$ can be achieved. The corresponding bag masses are 38.608 kg. These are compared to the other results in the middle field. However, when looking at the following two results in the next rows, these options provide roughly $1\,\mathrm{m}^3$ less storing volume but are also weighing less than 10 kg compared to the first option. All following results in this table provide around the same storage volume which is on average $2.796\,\mathrm{m}^3$. Nevertheless, the corresponding empty bag masses of options $a_{2,1}$ to $a_{4,12}$ of each option vary more clearly. While the heaviest option weighs 58.551 kg the lightest option weighs 24.262 kg.

After a close look at the subfloor area, it was then looked at the ceiling and floor of the greenhouse section. There, a small trade-off was done but only with M03 bags. The reason for this decision was that larger and/or heavier equipment pieces can be stored within those bags. Furthermore, those bags can act as counter masses to reach a balanced mass distribution for the overall module. In total, four options were looked at for both the ceiling and the floor. Two possibilities are designed for a height of 78 cm and the other two for 156 cm, respectively. All in all, the decision for one option strongly depends on the equipment itself. If parts can not be accommodated within the smaller CTBs, it is necessary to have storing possibilities within the larger Mxx bags. Furthermore, the overall storing situation needs to satisfy the mass balancing conditions of the launcher. Moreover, the option to go with strongly depends on if the module mass tends to exceed the mass capabilities of the launcher. If that is the case, an option with a lower empty bag mass is preferable. As a consequence, a lower storage volume must be accepted.

Further considerations were done regarding the belts which will secure the bags during transportation. Since no specific information on used belts was found during the research, the mass for one belt was assumed to be 2.7 kg. In a next step, the amount of belts per bag was set. Through the evaluation of pictures from inside the ATV, the following assumptions were made. Therefore, half, double, and triple CTBs are fastened by two belts while single CTBs are fixed by one belt. Since the Mxx bags are bigger compared to the CTBs, they require five belts. Afterwards, the number of needed belts in total was calculated based on specifically chosen bag accommodation options. As a result, 180-187 belts are required to fix all bags inside the module. By multiplying this amount by the mass of one belt, further 504.9 kg will be added on top of the overall system mass.

Then, it was looked at the other half of the module, namely the SES. There, considerations were done regarding the packing order of the equipment. If further transportation bags are needed, they can be placed in the SES corridor. There, the first bag in front of the entrance door needs to contain all parts which are needed first. Only this strategy allows for a coordinated unpacking of the entire module. However, considerations regarding bag positioning is not done further for the SES since all storing units are intended for the greenhouse section in the first place.

The last point that was looked at was the rack system of the ATV. They were custom-made by the RUAG Space company and had a mass of 120 kg when they were mounted inside the ATV module. The reason for building them so massively was to be able to withstand the internal and external loads. Further considerations were done on how to properly store the cables from illumination and nutrition within the greenhouse module. The first idea was to place them within the struts. However, this solution was discarded since the cables would not be protected mechanically against the vibrations during launch. This was then followed by two more ideas, namely making the struts thicker or designing the struts in an u-shape. The latter would allow for an easier access and maintenance. To conclude, it must be noted that independent of the selected solutions further profound tests are required to identify the best working option.

4 Requirements

This chapter deals with the different requirements for the module. First, some already existing requirements for the greenhouse module are going to be mentioned in Sec 4.1. The following chapter in Sec 4.2 is more detailed about the requirements related to the cargo system. Afterwards, it is looked at further requirements for the overall module which are all listed under Sec 4.4. There, cleaning of surfaces in Sec 4.4.1 and material outgassing in Sec 4.4.2 are explained in more detail. Within these two sub-chapters flow charts will demonstrate certain actions that need to be done beforehand in order to guarantee a safe mission conduction. Then, the equipment list from the CE study is investigated to conclude the grouping of items in Sec 4.4.3 and the necessary prefixed positions of specific items in Sec 4.4.4. This chapter is closed by a summary of the gained results from the previous chapters from Sec 4.5.

4.1 Greenhouse Module Requirements

During the course of the EDEN NG GTD project, different requirements were set. In total, there are requirements for individual subsystems such as the AMS, NDS, or the structure. Additionally, requirements are set for the overall system which are further divided into level zero and one requirements. The former are related to the overall system and marked as parent requirements. The latter ones are one step more detailed and therefore marked as children since some parent requirements are further specified in their children's requirements. In total, there are 23 level zero requirements and 76 level one requirements (status: August 2022). However, only the most relevant ones related to the transportation of equipment are mentioned here.

Beginning with the level zero requirements, there are three relevant ones worth mentioning. The first one, labeled as P-01, concerns the launch object which will be the Falcon 9 (status: December 2022). Since this launcher has a specific launch capacity, the module can not cross this capacity because the entire system shall be launched at once to reduce system and mission complexity along with the cost. Next, the module will also be used for transporting the logistics and not only serve as a greenhouse. This requirement P-02 is going to increase usability and shall save room in general. Last, requirement P-03 demands that all mission elements shall be interchangeable in order to reduce the mission cost while improving reliability and availability. The reason is that parts can be exchanged and replaced more quickly. The now following requirements which are going to be mentioned are all part of the level one requirements. The first one, C-01, is the child of the first mentioned requirement of level zero. Consequently, the overall module mass shall not exceed 18 800 kg including service vehicle, radiation, and debris shield. The next relevant requirement for this thesis is C-02 and the one specifying that the repair and maintenance of the system need to be able without the removal of other subsystems which are necessary for operation. Along with that C-03 is stating that the piping and harness diameters shall be similar to limit the number of interfaces in total. The fourth requirement, C-04, concerns the overall system including all pre-installed equipment. Everything needs to withstand launch loads, loads during transfer, and the landing on the planetary surface. The penultimate requirement C-05 deals with the equipment used for the design. With this condition, it can be ensured that the module will be ready by 2025 to keep the launch date. Finally, C-06 is the child of the second level zero requirement. There, it is defined that the system shall be used once as a cargo module to transport all equipment inside safely without any damage to them. All mentioned level zero and one requirements can be compactly seen in the following Tab 4.1.

Level	Label	Greenhouse Requirements
Level 0	P-01	The launch capability of the Falcon 9 shall not be crossed to allow launching the entire module within a single launch.
	P-02	The module shall be additionally used for carrying logistics besides the usage as greenhouse.
	P-03	All mission elements shall be interchangeable where possible.
Level 1	C-01	The launch mass shall not exceed 18 800 kg, including service vehicle and radiation and debris shield.
	C-02	The system shall allow repair and maintenance without the removal of subsystems required for operation.
	C-03	Piping and harness diameters shall to similar among parts.
	C-04	The system shall withstand launch loads, including all pre-installed equipment, and loads during transfer and landing on the planetary surface.
	C-05	Only equipment ready by 2025 shall be used for the design.
	C-06	The system shall allow single use as cargo module during transfer so that no pre-installed equipment is damaged.

Table 4.1: A few selected requirements from level zero and one related to the greenhouse.

4.2 Cargo Module Requirements

The requirements solely for the cargo module were first developed during the CE study and then further evolved during this work. In total, 21 requirements have been set up of which a few were considered in the previous chapters. In order to get a first impression of the developed requirements, the compact Tab 4.2 is shown directly at the beginning.

T-01 is the first requirement describing that all cables need to be pre-installed inside the greenhouse section. By this, the cables of the illumination and nutrition system are meant which are going to supply the plant tray inside the racks. This requirement will secure that the crew's work effort after landing on the planetary surface is minimized as much as possible. The following two requirements are both important to do before launch. There, T-02 requires that all staff working inside the module must wear a full-body suit together with a breathing mask. This is necessary to ensure that no contamination through human interaction is triggered. T-03 supports the previous requirement by additionally cleaning all surfaces with hydrogen peroxide after integration. This action will eliminate the risk of contaminating the plants and prevents the astronauts from getting serious health issues.

Label	Cargo Requirements
T-01	Supply cables for the illumination and nutrition system shall be pre-installed before launch.
T-02	The staff working inside the module shall wear a full-body suit along with a breathing mask.
T-03	The overall system including all surfaces shall be cleaned with hydrogen peroxide before launch.
T-04	The crew work effort for the transition from the cargo to the greenhouse module shall be done in TBD h.
T-05	The system shall allow any assembly without repacking or the removal of other subsystems or parts.
T-06	The stowage systems mass shall not exceed TBD kg, including racks, bags, and belts.
T-07	The system shall be realized with COTS parts where possible.
T-08	Stowage components (bags) shall be interchangeable where possible.
T-09	Stowage components (e.g. bags, belts) used for the transportation during flight shall be further used later on inside the module.
T-10	The equipment on board shall fit into the standardized CTBs, Mxx, and NS CTBs.
T-11	All loose parts shall be packed within a bag to ensure safe transportation.
T-12	Compatible items shall be grouped.
T-13	The equipment shall be organized, grouped, and accordingly packed depending on if it belongs to the service or greenhouse section.
T-14	Forbidden positions for items to be stored shall be identified beforehand.
T-15	The bags shall be fixed with belts inside and outside the racks to ensure that no bag gets loose during launch.
T-16	The storing volume of each bag shall be maximally utilized.
T-17	The accommodation within each rack shall be re-allocated to minimize the residual volume of the sectors.
T-18	Free spaces inside the bags shall be identified and filled with suitable components.
T-19	The maximum mass capability of each bag shall not be crossed.
T-20	The belts shall withstand the weight of TBD kg of the bags to keep them in place.
T-21	The belts shall withstand the vibrations during the launch and landing of TBD daN.

Table 4.2: Requirements solely for the system as cargo module for transportation.

Like the T-01, the next T-04 requirement aims at reducing the crew work effort. Here, the transition from the cargo to the greenhouse module shall be done in TBD (to be done) hours. A specific value was not fixed yet and requires further investigations. T-05 secures that any assembly or access within the system has to be done without repacking or removing other systems or pieces. Through that, easier access to the equipment will be allowed while reducing the crew work time as well as decreasing the need for additional disassembly tools.

Since all transportation bags are adding to the overall module mass, T-06 guarantees that the stowage equipment is not exceeding a certain amount of kilogram which still has to be determined. This stowage equipment includes racks, bags, and belts. To decrease the overall cost while increasing the interchangeability, T-07 represents the requirement of realizing the system with components-off-the-shelf (COTS) parts where possible. This requirement is supported by the advantage of using already flight-proven hardware such as bags or racks since this equipment was already tested within other projects and has proven to work properly. T-08 underlines the requirement from before because COTS parts will allow a quick reordering which results in high interchangeability. This is especially useful in case any bags are getting damaged during loading. The question arises what to do with the belts and bags after transportation. Therefore, T-09 demands that those bags and belts which were used during transport shall be further used inside the module. This requirement with possible uses is explained in more detail in Sec 4.2.1.

Regarding the equipment which needs to be accommodated, T-10 requires that all the hardware needs to fit into the standard CTBs, Mxx, or NS CTB bags. Along with the T-09 requirement the next one deals with all loose parts. T-11 requires that all loose parts within the module must be packed in a storage bag to ensure a safe transport. Within the bags themselves, it is important to only store equipment together which is compatible with one another. This point is set under the requirement T-12. Along with the check for compatibility also a packing order needs to be considered as well. Therefore, T-13 is the requirement for the organization of the entire equipment. By having an accommodation order it is possible to store the same equipment which all belongs to the greenhouse or SES in the same bag, respectively. This facilitates the unpacking later on. While storing the equipment within the bags it is important to consider forbidden positions for the bags themselves inside the greenhouse section. Therefore, T-14 requires to identify of forbidden positions beforehand. Those can be positions in which it is not possible to fasten the bags properly or where the overall mass distribution can not be fulfilled. Next, the bags need to be fixed inside the greenhouse to not get loose during launch, flight, and landing. This is going to be done with proper belts to fasten the bags both inside and outside the rack systems and is written down under T-15.

To limit the amount of required bags for transportation, T-16 demands to maximally use the storing volume of each bag. Through that, empty spaces inside bags can be identified, filled with equipment, and may lead to discard superfluous bags leading to a reduced module mass in total. This space search shall be expanded onto the racks. Therefore, T-17 says that the accommodation will be reallocated to minimize the residual volume of each rack sector. Along with T-15, T-18 says that free spaces within the bags shall be identified and filled with suitable components. By that, every bag's storage capacity can be fully exploited. Another point of securing the bags is to take into account the maximum storing volume of each bag. T-19 prevents the overloading of the bags by demanding that the maximum mass capability of each bag shall not be crossed. Additionally, it needs to be secured that the belts which fixate the bags are capable of withstanding the weight of TBD kilogram of the bags plus their content. This requirement is set under T-20. The last requirement, T-21, further specifies that the belts need to withstand the vibrations of the launch which is yet to be determined. Later, a comparison and adaption of the greenhouse requirements with the cargo requirements are done in Sec 4.3. All mentioned requirements for the system as a cargo module can be compactly found in Tab 4.2.

4.2.1 Logistics-to-Living Approach

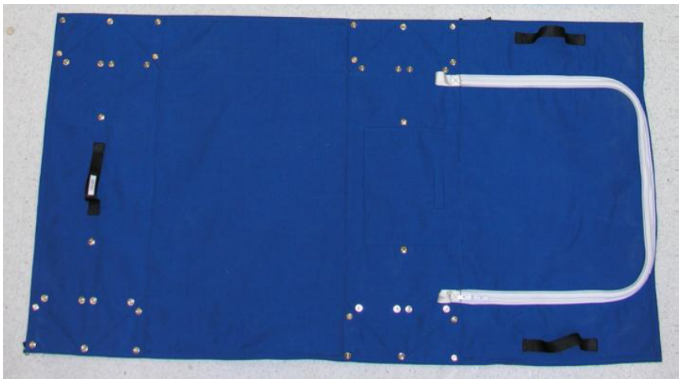
In space travel, every additional mass equals more launch cost. Unfortunately, a major part of logistic items is just packaging mass. To name a value, for four astronauts on a six-month mission, around 100 CTBs are necessary [69]. And if those bags are purely used for transfer and storage they will become waste afterwards. However, not all of the waste can be transported back to Earth since the down mass is limited. This results in unused waste that has to stay and needs to be stored in orbit for further time. Therefore, the Logistics-to-Living (L2L) approach was created to re-purpose components that are used for the logistics as much as possible after the transport. The term includes bags, belts, containers, foam, and components. But many more equipment pieces can be comprised within this strategy, namely everything that originally fulfills only one task such as just being there for the transportation. And this L2L approach is exactly what the requirement T-09 from Sec 4.2 is demanding.

In today's world, the demand for sustainability has a high priority. Therefore, it would be better to give those objects, especially transfer bags, a second life. Out of that need, the multipurpose cargo transfer bags (MCTB) were innovated by NASA under the advanced exploration systems (AES) logistics reduction and repurposing (LRR) project. Those were built on the L2L work by Howe and Howard which started in 2009 [70]. Those MCTBs arose from the already mentioned single CTBs but with the advantage of being able to unfold them to flat sheets. This flattened bag can be seen in Fig 4.1b. But to make this possible, additional zippers and snaps at the bag had to be mounted. Furthermore, extra fabric in the corners of the bags had to be added which is overlapping when it is a bag but resulting in the possibility of unfolding it entirely. Thereby, the MCTB does not weigh much more than the CTB which is 1.09 kg and 1.81 kg, respectively.

Due to the possibility of deploying the bag to a flat sheet, it can be transformed into a variety of other options. The more obvious once that were figured out during the AES LRR project were the transition into partitions, doors or dividers or as trash bags [69]. In Fig 4.2, such a partition can be seen which was used in the HDU hygiene module for testing. Regarding the trash bags, not only waste such as non-edible plant residues could be stored within them. Further ideas on how to use the bags could be to continue to use them as stowage options for clothes from the crew, harvested food, tools, or collected material from the Moon.

Some more unintuitive ideas were to use those bags as sleeping bags, window shades, or furniture. Since CTBs are the baseline for the development of the modified bags, their metal inserts could be used to make furniture from them. An example of such furniture could be a desk [70]. And last, the most brilliant ideas resulting from the project were

(a) MCTB as a bag.



(b) MCTB unfolded.

Figure 4.1: The multipurpose cargo transfer bag (MCTB) in bag (left) and unfolded (right) configuration. Image adopted from [69].

passive clothes dryers, clothing, or life support augmentation [69]. For the wearable clothing idea, there exist two concepts. One would contain water and the other one polyethylene. The first concept would contain membranes or bladders inside the unfolded bags in which wastewater could be processed or stored. Through that and due to the fact that multiple bags can be connected with each other it can be worn as a radiation shield [71]. The second concept would contain polyethylene in form of tiles. Those tiles would be made out of the trash that accrues at the station in combination with a heat melter which is developed at NASA as well [72]. Those tiles could then be used as a layered shielding against radiation [69].

Finally, a few ideas for possible uses of the belts are presented since they are also no longer needed after transport. They could be used to hang up other components or tools which are required inside the greenhouse. Those tools could be tools for the care and harvesting of the plants growing inside. Furthermore, the belts could be used to stabilize the stem of tall growing plants in order to avoid that they do not snap off. Another idea

Figure 4.2: A privacy partition out of multipurpose cargo transfer bags (MCTB) used inside the habitat demonstration unit (HDU) for testing. Image adapted from [69].

on how to use the belts further on is to fasten or attach different components. This can refer to both pieces inside and outside the module.

4.3 Transition from Cargo to Greenhouse Module

This chapter combines the already existing greenhouse module requirements with the own developed ones for the cargo section. In detail, this means evaluating the greenhouse module requirements with respect to the cargo usage and supplementing or modifying the related greenhouse requirements.

During that evaluation, one developed requirement exists in both requirement lists. It is the T-07 requirement demanding that the system shall be realized with COTS parts where possible. It is equivalent to the greenhouse requirement with the designation SY-0056 within the level 1 requirements. Therefore, no further modification needs to be done.

Next, similarities were found for three cargo requirements in the greenhouse requirements list. Here, only the cargo requirements with their respective similar greenhouse requirement are mentioned. In the next subsection 4.3.1, the detailed modification of the respective greenhouse requirement is explained. The first of them is the T-01 requirement saying that all supply cables for the illumination and nutrition system must be pre-installed before launch. The related greenhouse requirement is the SY-0001 within the level 1 requirements. It says that all SES subsystems must be pre-installed before launch to allow operation. The next requirement is the T-05 demanding that the system shall allow any assembly without repacking or the removal of other subsystems or parts. It is similar to the SY-0013 requirement within the level 1 greenhouse requirements. This is because SY-0013 demands a system that allows repair and maintenance without the removal of subsystems required for operation. And the final one is the cargo requirement T-08 which is about the interchangeability of stowage components such as the bags. The corresponding similar greenhouse requirement is the SY-0059 within level 1 saying that the system components, such as vents, must be interchangeable where possible.

4.3.1 Greenhouse Requirement Adaption to Cargo Aspect

For the further course of the EDEN NG GTD project, the developed cargo requirements need to be taken into consideration as well in the overall requirements list for the greenhouse section. This requirements list is a DLR internal Excel document out of which only the relevant pieces are displayed in this thesis. Therefore, 13 of the cargo requirements were added to the greenhouse requirements list under a new sub-folder called LVL2 - Cargo without any modification. Hence, only cargo-related requirements are listed in this sub-folder. Here, they are not further explained since this was already done in Sec 4.2. The remaining seven cargo requirements were then either added within other sub-folders or existing greenhouse requirements were modified to consider the cargo aspect. All those requirements can be seen in Tab 4.3 along with their new corresponding sub-folder and label. Furthermore, their parent requirement specified the meaning from which requirement they are derived.

T-02 which requires the wearing of a full-body suit and a breathing mask was noted down unchanged under the sub-folder LVL1 and has the new name SY-0071. Same counts for the further three requirements. Beginning with the formerly T-03 now SY-0072 requirement demanding that all surfaces must be cleaned with hydrogen peroxide before launch. Next, requirement T-04 says that the crew work effort for the cargo to greenhouse transition has to be done in a specific time changed to SY-0073. Last, the demand to pack all loose parts within a bag changed from the name T-11 to SY-0075 to fit into the greenhouse requirement labeling.

In the last step, the three remaining cargo requirements were evaluated with respect to their similarity to some greenhouse requirements. Since every requirement needs to be unique, it had to be checked on how the related requirement needs to be modified or if a completely new one should be included. Beginning with the T-01 cargo requirement which says that all supply cables for the illumination and nutrition system must be pre-installed before launch. A similar greenhouse requirement is the SY-0001 which says that all SES subsystems must be pre-installed before launch to allow operation. However, as the SY-0001 refers to the SES while the T-01 relates to the greenhouse section, it was decided to add the T-01 requirement as a new one. Therefore, it was included in the level 1 requirements and can be found under the name SY-0074. Next, the T-05 requirement demands for a system that allows any assembly without repacking or removing of other subsystems or parts. It is similar to the SY-0013 greenhouse requirement within the level 1 sub-folder. Therefore, it was modified from 'The system shall allow repair and maintenance without removal of subsystems required for operation' towards 'The system shall allow assembly, repair, and maintenance without removal of subsystems required for operation'. The last cargo requirement having similarities to the greenhouse ones is the T-08. It says that all stowage components such as the bags must be interchangeable where possible. Moreover, it is similar to the SY-0059 requirement which says that system components such as vents must be interchangeable where possible. Due to the resemblance of both requirements, the SY-0059 was changed to additionally contain the cargo aspect. Therefore, the requirement was changed from 'System components (e.g. vents) shall be interchangeable where possible' towards 'System components (e.g. vents, stowage components) shall be interchangeable where possible'. Furthermore, the rationale was extended by the remark of a quick adaption to updated versions.

Sub-folder	ID	Description	Parents
LVL1 (modified)	SY-0013	The system shall allow assembly, repair, and maintenance without removal of subsystems required for operation.	MI-0011
	SY-0059	System components (e.g. vents, stowage components) shall be interchangeable where possible.	MI-0018
LVL1 (new)	SY-0071	The staff working inside the module shall wear a full body suit along with a breathing mask.	MI-0011
	SY-0072	The overall system including all surfaces shall be cleaned with hydrogen peroxide before launch.	MI-0011
	SY-0073	The crew work effort for the transition from the cargo to the greenhouse module shall be done in TBD h.	/
	SY-0074	Supply cables for the illumination and nutrition system shall be pre-installed before launch.	MI-0008
	SY-0075	All loose parts shall be packed within a bag to ensure safe transportation.	/
LVL2 - Cargo	Ca-0001	The stowage systems mass shall not exceed TBD kg, including racks, bags, and belts.	SY-0006
	Ca-0002	Stowage components (bags) shall be interchangeable where possible.	MI-0018
	Ca-0003	The equipment on board shall fit into the standardized CTBs, Mxx, and NS CTBs.	/
	Ca-0004	The bags shall be fixed with belts inside and outside the racks to ensure that no bag gets loose during launch.	/ /
	Ca-0005	The storing volume of each bag shall be maximally utilized.	/

LVL2 - Cargo	Ca-0006	The accommodation within each rack shall be re-allocated to minimize the residual volume of the sectors.	/
	Ca-0007	Free spaces inside the bags shall be identified and filled with suitable components.	/
	Ca-0008	The maximum mass capability of each bag shall not be crossed.	/
	Ca-0009	The belts shall withstand the weight of TBD kg of the bags to keep them in place.	/
	Ca-0010	The belts shall withstand the vibrations during launch and landing of TBD daN.	/
	Ca-0011	Compatible items shall be grouped.	/
	Ca-0012	The equipment shall be organized, grouped, and accordingly packed depending on if it belongs to the service or greenhouse section.	/
	Ca-0013	Forbidden positions for items to be stored shall be identified beforehand.	/

Table 4.3: Greenhouse requirements modified by cargo requirements (LVL1 modified), added cargo requirements to the greenhouse ones (LVL1 new) or added cargo requirements to new sub-folder (LVL2 - Cargo). Additional information about their label (ID) and requirement from which they were derived (parents).

4.4 Further Requirements

A further requirement that emerged during the work of this thesis is the outgassing of materials. Since this can be hazardous for the crew when getting inhaled a procedure of what to do before the first entering was developed. The same is done for cleaning surfaces before launch to ensure that no pathogens get into the module. The following two requirements are analyzed, namely the grouping and prefixed positions of items. The former ensures that only compatible items are grouped in order to damage none of the equipment pieces. The latter deals with equipment that might require a constant power supply or a cooling system.

4.4.1 Cleaning of Surfaces

An important step that needs to be done before launch as well as during the mission is to clean all surfaces inside the module. This will prevent both the astronauts and the materials inside from getting damaged. It is because individual microorganisms may not be harmful on their own to humans and materials but their end products can be toxic [73]. Through that, astronauts have an increased risk of getting sick since they are working and living in the same closed environment. This is one of the differences compared to Earth, the limited space available in which the crew can stay. Another one is the lack of gravitational forces in space. The human body is designed for the environment on Earth but not for space. As a result, astronauts are affected by pathological conditions such as an impaired immune system [74]. Those microorganisms on board can be bacteria and/or fungi species and among others also pathogens. They can be harmful to humans and can cause respiratory infections or poison food. As a result, this can have dramatic effects on the crew since their immune system is already weakened under microgravity conditions. Thus, microbial populations need to be controllable in a long-duration space mission in the future [73].

One way of preventing surfaces from getting contaminated is to dress the workers who are preparing the module accordingly. This includes a full-body suit together with breathing filters. Those actions protect the module from various contamination carriers. To name a few of those carriers, it can be through human interactions by means of human sweat and skin cells. A further source of risk arises from screwing equipment inside the module. By that, larger particles can get loose and, especially under microgravity, float around randomly. This poses the risk of inhaling those particles or getting serious damage to the crew's eyes. To prevent larger floating particles to spread inside the module, there are further actions to remove those particles. It is possible to do small-scale wiping, vacuuming, or exchanging the air inside the module. [67]

After accommodating all transportation bags and equipment pieces inside the module, it is important to make sure that every surface is free from any fungi or bacteria. This can be assured by cleaning all the external sides of the pieces with hydrogen peroxide [67]. The advantage of it is the quick breakdown into hydrogen and water. However, it is important to ensure that none of the cleaning agents and methods damage the equipment itself or its function to the worse [75]. Through this caution, the surfaces are not going to get damaged due to any taken action. Hydrogen peroxide is used since it has already its application in hospitals which requires equal importance of cleanliness inside [67]. Still, after cleaning, it is necessary to check again the cleanliness of the surfaces. For that, follow-up samples must be taken to make sure that the cleaning process was effective. Nevertheless, the results of the samples strongly depend on the satisfactory level that should get achieved. If that is the case, all surfaces are proven to be clean from any contamination such as dirt [75]. A list with different surface materials and the corresponding cleaner was published by NASA and can be found in the Appendix 6.1 [76]. Another way to protect surfaces from corrosion is by explicit design features. Those can be rounded edges for all metals or drain holes [75]. The former is to ensure that an adequate protective coating can be applied. However, this is rather important for exterior surfaces. The latter should prevent the interior from unwanted fluids that may be spilled accidentally to the ground. Another useful compound with respect to clean surfaces is titanium oxide. Its useful property is that it decays the water vapor in the surrounding air into free oxygen radicals if it is exposed to UV light [73] and those free oxygen radicals eliminate everything that is on the surface. Therefore, by exposing titanium oxide surfaces to UV light, the surfaces are cleaning themselves.

Lastly, a flow chart is shown in Fig 4.3. This presented process should serve as a guide to what must be thought of before launch. The main box of this process is the green one in the middle. It defines that all surfaces suitable for cleaning shall be cleaned.

Furthermore, three preconditions lead to this green main box. Continuing with the two orange ones on the left side: First, it needs to get checked what materials are used inside the module that can be cleansed with what cleaning agent. After that is clarified, it needs to be checked what surfaces can be sanitized with hydrogen peroxide since this is gentle on surfaces. Next, the two red boxes at the top have effects on the main green box. Those define that all workers, who are operating inside the module, need to wear a full-body suit and breathing filters. Through this action, it can be prevented that human impurities can enter the module. In the case of screw work, the direct air or the entire air inside the module needs to get exchanged to get rid of larger particles that may be chipped off. Additionally, small-scale wiping can be done after screwing work is done. Last, the single blue box on the right side: Design features can be implemented to prevent the surfaces from corrosion. This can be rounded edges to name one possibility. Concluding, this flow chart ends with the two black boxes at the bottom. Those actions are follow-up samplings to secure if the previous cleaning measures were effective. The guideline for this decision depends on the previously set satisfactory level which shall be reached with the cleaning actions.

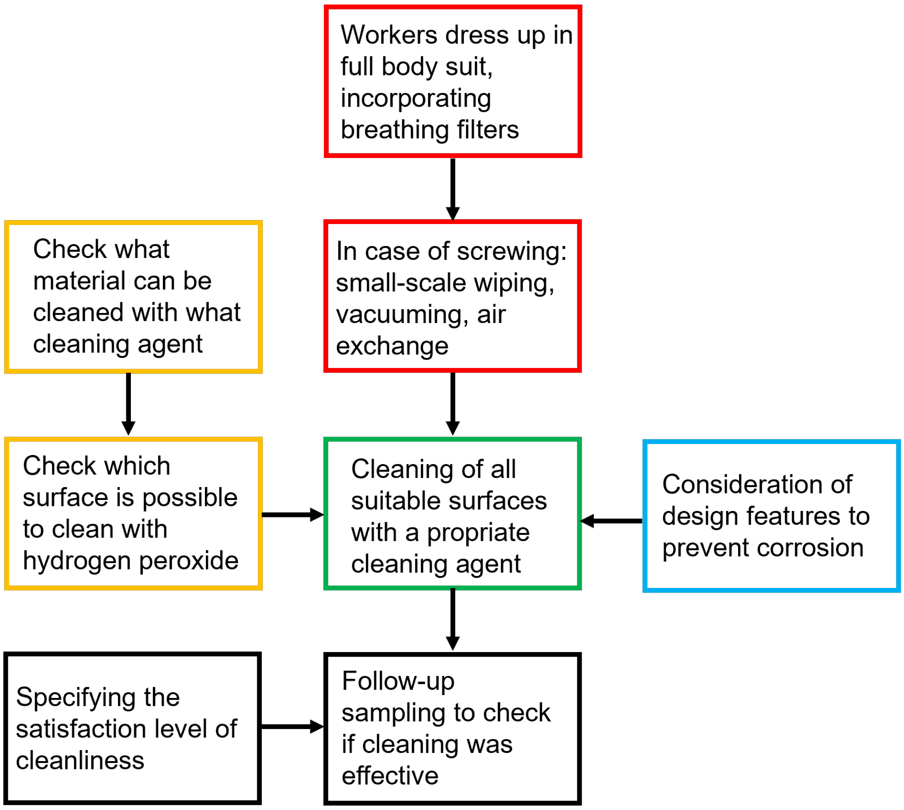


Figure 4.3: Cleaning procedure before loading the module with all required equipment pieces.

4.4.2 Outgassing of Materials

Another point that needs to be considered is the outgassing of materials. Since the module represents a closed environment in which no exchange of air molecules can happen, the materials inside are slowly dispersing. This process depends on the outgassing properties of each material as well as on the installed ventilation system [77]. As a first rough estimation, it can be said that the outgassing is accompanied by a material loss which needs to be considered as well. Therefore, light alloys which are made of aluminum are the chosen metals for spacecraft structures. Additionally, titanium as an alloy can be chosen as well but less often than aluminum. The reason for those alloy metals is that they do not have a vacuum performance problem but more a stress corrosion cracking one [78]. Overall, how much the individual materials are outgassing strongly depends on the type of mission along with the target orbit properties, i.e., altitude. To just name a few environmental factors that have effects on the outgassing, these are: vacuum, ultraviolet (UV) radiation/solar exposure, micrometeoroid and debris, bacteria, and fungus [79]. The last factor, the bacteria and fungus are an important point to pay attention to since the main task of the EDEN NG GTD will be to grow plants inside to provide the crew with fresh food. Therefore, growing a microbial flora in a closed system as it is the case for the module, the recycled atmosphere inside leans towards producing unintentional chemical contaminants. Thus, predicting the impact as well as controlling such growth of microflora is important for a human habitat [80]. The risks that can occur related to material outgassing are adverse effects resulting in harmful impacts. Those can be chronic toxicity such as cancer or reproduction. The performance of astronauts can be endangered as well which would have a direct impact on the mission's success [80].

Due to the mentioned factors which can influence material outgassing, it is proactive to already select materials based on different criteria. First of all, the chosen materials need to be lightweight while being strong enough at the same time. By that, the launch mass can be limited resulting in a lower cost for the overall mission while maximizing the payload mass which can be used. Additionally, it can be ensured that the structure is able to withstand the loads during the transfer [78, 79]. Besides that, the materials should have a low tendency towards contaminating other critical surfaces. This reduces the overall probability that impurities arise in the first place. Additionally, materials should be chosen which are resistant to radiation as well as having a low outgassing [78]. In the same case as for the EDEN NG GTD, if humans are present in the system, it is moreover important to check the materials for flammability and toxicity. This involves materials of which the spacecraft consists, storing equipment, and possible experiments inside [78, 81]. The second important requirements for used materials in space are low magnetic properties and no tendency towards corrosion [78]. Last, all decisions made should ideally be based on the experience of already flown materials. The reason is that the materials are then already proven to meet the criteria in the environment they will be in later on [81].

To conclude this chapter, a flow chart is shown in Fig 4.4. It represents actions to do beforehand due to the fact that different materials are off-gassing. The vertical process steps are intended to support the astronauts for the time before they will enter the module for the first time. By that, the crew shall be protected from getting harmed by possible fumes that were emitted from different materials during the flight. While the gas which is emitted by one material alone may not be harmful to the astronauts, the combination of multiple gases from different materials can be. Therefore, a simulation shall be done beforehand. With that, microparticles due to off-gassing are going to be simulated. From this, it should be clarified what gases may be harmful to humans if they get mixed during flight. As a result, a decision should be drawn regarding the material selection for the interior of the module. The simulations may reveal material combinations that contain a lower toxic mixture than other combinations. Nevertheless, it is important to exchange the air for multiple hours to ensure clean air so that the astronauts can enter the module to prepare it for work. Therefore, the first three boxes of the flow chart concern the simulation of mixed gases that are going to get secreted during flight.

To choose materials for the interior design it needs to be decided what level of mixed gases poses a risk for the crew and what mixture is still fine. The following boxes are then concerning the crew before they enter the module for the first time. There, the first step is to activate the air system. Afterwards, the composition of the air inside the module is measured. By that, the individual parts of the air can be identified and classified. The step is important to determine if the air composition has crossed a predefined level that is then hazardous for astronauts to breathe. The next step is to distinguish between high and low air pollutants. The branch which is going to be chosen next depends on the measurement from the step before. Depending on whether the pollutants are high the air ventilation needs to get increased or decreased if the pollutants are low. Next, the air composition is measured again. This step is necessary to decide whether the air circulation and exchange were already enough or if they need to be activated longer. In the case that the air composition is in an acceptable range this means that the air is no longer dangerous for the crew. Therefore, the astronauts can enter the module. In the other case, if the composition is not in an acceptable range, the previous steps must be repeated. Then, the process starts again depending on the number of pollutants in the air for which the air circulation flow will be adjusted.

4.4.3 Grouping of Items

During the CE study in September 2022, each subsystem on-site noted their respective equipment list. As a next step, equipment that is not fixed preinstalled inside the module needs to be properly stored for flight. The accommodation can be done under different accommodating criteria. While this chapter deals with possible groupings of items inside the same bags by means of their properties, the next chapter 4.4.4 is about the individual needs of each piece of equipment itself. However, it is important to mention that the list of equipment pieces from the CE study is not complete. In the following course of this project, more parts will need to be stowed inside the bags resulting in a modified list.

One criterion for grouping items is to look for fragile pieces. For those, it is important to store them accordingly by means of enough padding. Furthermore, it can be advantageous to look for a solid caging for the individual piece so that they are not deformed by the weight of the other objects placed in the same bag. At the same time, it must be ensured

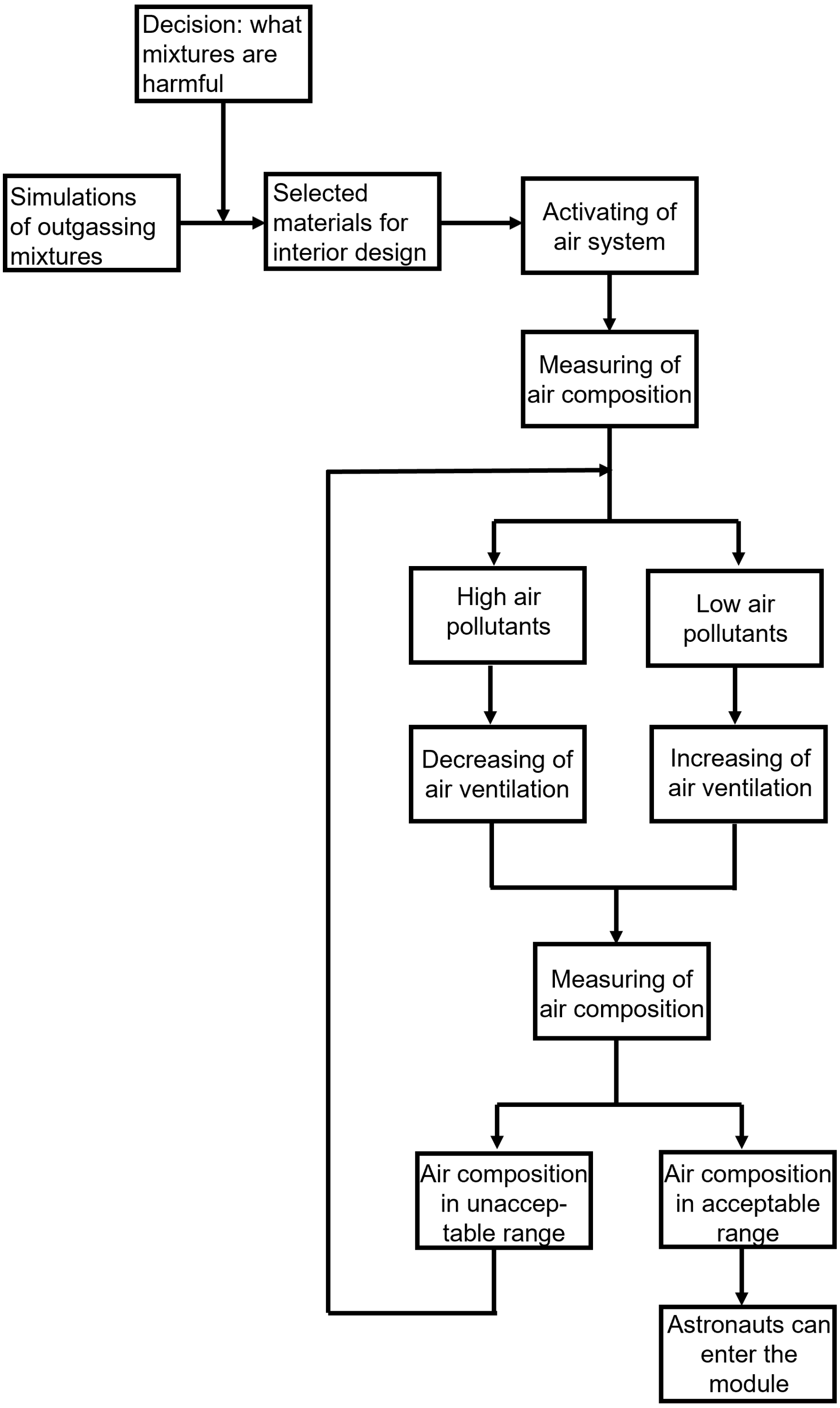


Figure 4.4: Outgassing procedure after landing on-site before letting astronauts enter the module.

that each piece inside the bag is stowed such that it is not moving around which may pose a risk to the object itself.

Another important criterion is the storing of similar components that need to stay all dry. Therefore, those pieces are not going to be stored along with fluids or pieces that tend to excrete water. For example, the seeds for the plants need to be stowed in a dry environment. In this context, to stick with the example of the seed, they also need to be stored in a dark environment to guarantee their germination afterwards.

Liquids that need to get transported are best placed in containers that are designed for liquids. Those were already explained in Sec 2.3.1. With that, it can be guaranteed that no liquids leak out during flight which may make other equipment inoperable. Another advantage of those fluid containers is their flexibility which allows them to be moved.

Oversized equipment pieces may need to be stored individually in a bigger bag such as the Mxx bags. Another possibility is to store multiple oversized equipment pieces together in an Mxx bag. It is important that no piece gets damaged which is why smaller components should not be stored along with oversized ones.

Last, the packing order needs to be in such a way that it is optimal for the unpacking sequence. This means that the storing bags closest to the entrance contain pieces that are needed and installed first. The aforementioned point also includes all tools which are needed for the installation. By that, it is guaranteed that the unpacking can happen as fast and organized as possible. Furthermore, there will be no need of browsing for other bags since all needed equipment is already available in the first bag.

4.4.4 Prefixed Positions of Items

As previously mentioned, this sub-chapter deals with the needs of the individual components themselves. The reason is that each equipment piece is best stowed in a specific environment tailored to each component. Therefore, it is important to check beforehand if and which objects are affected to consider their needs in the accommodation plan. Overall, there can be many different demands by the equipment itself. In the following, a few are going to be mentioned.

Beginning with the temperature of the environment in which the equipment needs to be stowed, every temperature from cold to warm is possible. Thus, the preferred temperature needs to be figured out for each object. Afterwards, it can be checked if multiple pieces of equipment requiring the same temperature environment can be placed together in one bag as it was described in Sec 4.4.3. Furthermore, this is important to ascertain the environment around the object since this action requires a constant power supply for cooling or heating. And this supply may only be available at specific positions inside the module because power accesses are only placed at certain positions.

Related to the point mentioned before, another requirement can be a constant power supply. This may be required to ensure that the object is working properly all the time. A constant power supply can be required for different applications such as keeping a specific temperature or taking measurements during flight.

A further requirement for a defined position can be the quick or direct access after landing, meaning if some equipment may be installed first. Therefore, it needs to be stored close to the entrance through which the crew enters the module.

The mass distribution of the entire module influences the prefixed positions of bags as well. There, it may be necessary to arrange the individual equipment bags in such a way that each side of the module is balanced out. This is important for the flight dynamics and also a requirement of the launcher itself. Also, oversized pieces may need to be stowed in bigger bags and therefore cannot be accommodated within the racks. As a result, those have to be stored inside the module which needs to be considered with respect to the unpacking order.

4.5 Lessons Learned

This chapter concludes with a summary of the most important points since they bring an advantage to the project. Here, only the further four requirements from this chapter are dealt with. In contrast, the requirements which were developed for the cargo section are further discussed and compared with the existing greenhouse requirements in the next Sec 4.3.

Beginning with the L2L approach with which it is attempted to reuse ideally all of the transfer bags. Since their only purpose is to carry all the equipment safely towards the destination, all bags would become waste once arrived on-site. Therefore, efforts have been made to solve this problem in the best possible way. In order to tackle this problem the MCTBs are created which originate from the single CTBs. The advantage of the MCTB is that they can be unfolded completely so that they are only a flat sheet. This was made possible by adding zippers, snaps, and additional fabric in the corners of the bags. Through this possibility of fully unfolding the bag, it can be further used as partitions, doors, or dividers for example in a future hygiene compartment. In addition, the bags can still be used as storage space for example for the clothes of the crew, the harvested food, and its non-edible plant residues, tools, or material that will be collected on the Moon. Another possible way of using transportation bags is as sleeping bags, window shades, or furniture. There, the metal inlets of the bags could be used for re-configuring it into a desk or other outfittings for the module. Through that, equipment such as a desk is not needed to be transported in the beginning since they will be built on-site.

The most advanced ideas for repurposing transportation bags with respect to an L2L approach were to convert them into clothing for the crew or life support augmentation. For the former one, multiple MCTBs could be connected via the snaps. And by a redesign of the bag itself, bladders or a membrane could be added to the bag through which wastewater could be processed or water stored. And since water can block radiation well this piece of clothing could contribute to the crew's safety. Furthermore, these sheets filled with water could also be mounted on the outer shell of the module to achieve the same effect of blocking radiation. In another case in which no water but polyethylene is used within the bags, tiles made out of trash from the module could further be used as shielding against radiation. All of these approaches could lead to a decrease of additional waste due to unused transportation bags. Furthermore, it contributes to reducing the waste which is produced inside the module while using it effectively as shielding. And last, it could support the wastewater treatment system to provide enough purified water.

The last cargo pieces which have the single purpose of fixating the transportation bags are the belts. For them, it was considered of reusing them to hang up components or tools that are needed within the module. As an example, these could be tools for the care and harvesting of the plants that grow inside the greenhouse section. Additionally, the belts could be used to fixate stems of tall growing plants which would snap off without such support. Finally, the belts could be continued to be used to fasten and attach components, either inside or outside the module.

During a project, it is important to note done requirements for the individual subsystems. Through that, it is easier to define necessary conditions which are important for the overall project. Therefore, it is important as well for the EDEN NG GTD since it has to fulfill the tasks of first serving as cargo transportation and second the main task as a greenhouse. Thus, the cargo aspect plays an important role in this project. And since this aspect was not considered so far it has to be included in the greenhouse requirements list as well. Because of that, an individual sub-folder within the greenhouse requirements list was created called LVL2 - Cargo. In there, most of the requirements that were explained in Sec 4.2 have been taken over. In detail, the cargo requirements T-06, T-09, T-10, and T-12 to T-21, so in total 13 requirements. Furthermore, they were not changed but taken as they were because no cargo requirements were written down in the overall greenhouse requirements list so far.

The cargo requirements T-01 to T-04 and T-11 were added to an already existing sub-folder, namely LVL1. The reason why these were not added to the specific cargo sub-folder LVL2 - Cargo is that they do not specifically concern a cargo aspect. They demand more of a general necessity concerning the whole module. For example, the staff working inside the module must wear a full-body suit and a breathing mask to make sure the module stays as free from impurities as possible. Another reason why those five cargo requirements were added unchanged to this sub-folder is that there did not exist any similar requirements beforehand. In contrast to this, some of the content of the cargo requirements T-05 and T-08 were added to other greenhouse requirements. For example, the previous SY-0059 requirement only mentioned vents as an example of system components that must be interchangeable. Therefore, stowage equipment was added to the example to consider the storing aspect as well. And last, the cargo requirement T-07 was not taken over since this requirement already existed in the SY-0056 requirement.

Next, the cleaning of all surfaces inside the module before launch was explained. This is an essential step to take beforehand to protect both the astronauts and materials from getting serious damage. Considering the fact that the interior already passed through several hands before finally being mounted inside the module poses a high risk of bringing contaminants inside the module. Also, the bags contribute to that risk because they are going to be filled with equipment as well as being positioned within the module. Furthermore, every component such as the racks which are going to be produced externally brings in different microbacteria themselves. Therefore, one preventive step is that the staff working inside the module needs to wear a full-body suit together with a breathing mask. By that, impurities emanating from humans can be prevented in the first step. To additionally ensure to get rid of any kind of contamination, all surfaces need to get cleaned after integration. Here, it is important to check beforehand which surfaces can be cleaned with what cleaning agent. Only then it can be guaranteed that the cleaning has no negative impact on the surfaces and functions of items. As a third action, samples of the surfaces are made. Based on a predefined limit it can be decided if the respective surface is cleaned sufficiently or if it needs to be re-cleaned. However, it is important to mention that it is not possible to have a fully sterile module since all actions themselves are not germ-free. A further preventive action against contamination is to already consider designs that are more resistant to contamination. One example which was mentioned was rounded edges.

Last, it is important to exchange the air within the module before the crew enters it. The reason is that the module is a closed system during flight. Therefore, any left small particles due to screwing or cleaning which were not caught are still within the system and can harm the astronauts when they enter. That is why exchanging the air can diminish the risk. Added to this, a mixture of released gases from all materials inside the module can transform into toxic air. This air composition arises during flight since various materials behave differently in a vacuum. And as mentioned before, the module is a closed system meaning that no gas can escape. Therefore, it is advantageous if light alloys made out of aluminum are chosen in the first place. The reason is that those do not have a vacuum problem resulting in less outgassing. On top of that, the chosen materials have to fulfill further requirements. One of those is to be lightweight. By that, the launch cost can be reduced while simultaneously increasing the launch mass. Since less mass is needed for the overall structure this "unused" available mass can be equivalently used for the payload. At the same time, the chosen materials need to be strong enough to endure the launch and then be fully functional afterwards. The fact that people will be working inside the module the used materials need to be further checked regarding their flammability and toxicity. The last one is explained by the general outgassing of materials which can have a risk to human health. The first one, however, is important to consider as well. The reason is that it will not be as easy for the crew to just leave the module in case of a fire as it is the case here on Earth. The procedure would take too long to first put on a spacesuit before being able to leave. Therefore, the property of low flammability of materials is preferable. Last, all used materials for the module need to have a low tendency towards corrosion. This is an important property since the entire system will be exposed to vacuum and radiation at any time. In conclusion, one can say that it would be an advantage if all decisions regarding material selection are based on experience reports. In that case, if certain materials were chosen in several past missions they were tested for this purpose and considered appropriate. However, the air needs to be exchanged after landing in order to be on the safe side. This can be done by letting the AMS run some hours before the crew enters the module for the first time. To be able to specify the minimum time that the AMS has to run beforehand, simulations are beneficial. But simulations are not solely important to predict air mixtures. It is further important to forecast the potential growth of microflora to be able to control it in case it occurs. Nevertheless, these simulations are difficult to do because several factors play a role. These are all the individual materials but also the internal airflow under different circumstances during flight.

Further considerations were done regarding prefixed positions for individual items along with possible groupings among them. First, the project is still at the beginning which is why the equipment list will be further changed. This means equipment pieces may be added or removed during the project. And because of that the grouping can still change. Nevertheless, in any case, the individual needs of each equipment piece need to be figured out. This is because some demands may only be provided at specific positions within the module. One such a requirement can be a specific temperature environment. That can be either more cold or warm conditions. However, independent of the temperature itself, power access is required in order to regulate the environment accordingly. Therefore, the second need for equipment can be constant power access. And this may only be available at specific positions within the module. Quick access after landing can also be a condition of some components. That is why they need to be placed in an area that the astronauts will reach as one of the first places. Last, the entire accommodation must fulfill the mass distribution requirements of the launcher. Thus, some equipment may be placed in positions to counteract other masses to reach an even mass distribution.

Contemporaneously, it can be considered if certain items can be grouped and placed together. However, there must be paid special attention to fragile pieces. These require special padding and maybe an additional caging to be protected from other equipment. The reason is that they can not withstand pressure loads by other objects themselves. Furthermore, equipment needs to be separated depending on if it must stay dry or if it is a liquid. The way of storage depends on this differentiation since there exist special containers to store fluids. Through that, leakage can be prevented. And components that need to stay dry may only be stowed with other equipment that does not emit water under any circumstances. Next, oversized equipment must be stored in a proper bag such as the Mxx bags. Special attention needs to be drawn to the fact that the piece does not pierce through the bag itself resulting in damaging other bags and objects. This can also mean storing every oversized component individually resulting in a higher mass for the cargo. And besides all these conditions, it needs to be thought of a proper unpacking order. Ideally, the transportation bags which are closest to the entrance should contain the equipment which is needed first. Afterwards, the following bags can be unpacked, and so on. Through that, the unpacking is not messy and reduces the transition and working time of the crew. The downside of all these requirements is that there will be no ideal solution since some needs are contradictory to each other. To mention one example, if a component needs to be cooled down to a specific temperature, it requires a constant power supply. Therefore, it has to be positioned close to one power supply. However, if this component also needs to be unpacked first but there is no power supply close to the entrance, a good middle ground has to be found.

5 Overall Discussion

This chapter discusses all the important knowledge gains. Furthermore, important decisions regarding bag accommodation arrangement are taken.

The racks inside the greenhouse section provide the first part of the discussion. For the accommodation problem of the EDEN NG GTD project, different cargo carriers were looked at. This approach was taken because they all face the same difficulties such as a limited storage volume and specific flight constraints of the launcher. From this pool of cargo carriers, the racks inside the ATV were taken as a reference for this project because most information was found in this regard. Furthermore, those racks also accommodated transportation bags of various sizes as it will be the case for the EDEN NG GTD project. Inside the greenhouse section, five racks will be placed on each side. In total, this leads to ten racks for the entire greenhouse section since one rack weighs 120 kg all add up to 1200 kg. Because of the solid design, the racks are able to withstand 511 kg of internal loading as well as 180 kg of external loading. For the project, CTBs will be placed inside the racks and Mxx bags will be attached to the rack fronts. Withstanding those loads is important since all the equipment needs to be transported first while still being solid to host the plant trays afterwards. Another important criterion for the design of the racks is the implementation of the cables of the illumination and nutrition supplies. A requirement related to this is that all cables should be pre-installed inside the rack struts to reduce the crew work effort on-site. However, this means that they need to be resistant to damage due to e.g. friction points during the flight. For that reason, two ideas on how to solve this the best way were mentioned. First, make the struts thicker to be better protected against mechanical loads. Second, design the struts in a u-shape in which the cables can be pinched. The latter solution has the advantage of simpler maintenance once the greenhouse is being operated. However, so far no solution can be chosen since this requires additional tests and simulations to make a decision based on solid proof. What can be concluded is that the EDEN NG GTD module will contain its own construction because that system does not have to be transported within a rocket since it is a ground test demonstrator for here on Earth. Hence, no expensive shelves need to be installed in the module. In the follow-up project EDEN Lunar, which will be sent to the Moon, such launch-secured racks will be of great importance. Therefore, custom-made racks will be bought for this in which all needed design requirements will already be considered.

As mentioned before, ten racks will be installed inside the greenhouse section of the module. Since each rack has four compartments, this leads to 40 compartments in which transportation bags can be stored. There, an accommodation space of $70 \times 50 \times 60\,\mathrm{cm}^3$ (status: September 2022) is available. However, only half, single, and double CTBs can be placed in there. For the triple CTB, one side length exceeds the rack compartment which is 74.9 cm. This means if the triple CTB should be taken inside the compartments, it further has to be checked if it is acceptable when the bag stands out of the shelf. Therefore, it has to be clarified if they can be fastened properly. Due to the outlined explanation, the triple CTB is not taken into account because of the justification mentioned. The upcoming bag selection depends on how much storage volume is required to accommodate all equipment safely. Furthermore, it also involves how much mass can be added to the overall module mass. The most storing volume can be provided with the double CTBs which is 3.74 m^3 for the 40 compartments. However, that would also mean leading to the most mass which is 81.60 kg. Although 40 half CTBs weigh the least it is still not recommended because of their low storing volume of 0.91 m^3. The last option is using single CTBs. Their provided storage volume is approximately in the middle range. However, their empty bag mass of 72.40 kg only differs by 9.20 kg from using double CTBs. When viewed over the entire module launch mass of 19 000 kg, this does not make much of a difference. Thus, the double CTBs are the bags recommended for the compartments inside the racks since they provide the most storing volume of all suitable transportation bags.

A further place for storing transportation bags is the subfloor area beneath the floor on which the crew will walk. In this area, sump tanks will be placed as well. However, since their dimensions have not yet been set (status: September 2022) the calculations made were based on no tank in the subfloor at all. Once the dimensions of the sump tanks are set, the corresponding transportation bags within the calculations can be reduced accordingly. In total, 32 different accommodation variations were calculated. What can be concluded from the results is that the first calculation with purely M01 bags results in the most storing volume, namely 3.144 m^3. In this option, eight M01 bags are placed which add further 38.608 kg to the overall system mass. Compared to the other results, this is in the middle range. Comparing those results to the next two calculations in which purely M02 and M03 bags are placed, respectively, it can be seen that both options can provide around 1.2 m^3 less storage volume but are also weighing significantly less. In detail, placing purely M02 bags results in a mass of 24.784 kg and for purely M03 bags it is 22.452 kg. Four further options are around the same empty bag mass as the two mentioned before, namely placing M01 with M02 bags. This results in a storing volume of either 2.694 m^3 or 2.394 m^3 with the corresponding bag masses of 33.424 kg and 29.968 kg, respectively. The result depends on how to arrange the bags within the subfloor area. The next option is when placing M01 bags with M03 bags. Then, a storing volume of 2.461 m^3 is achieved with bag masses of 29.446 kg. And last, accommodating M02 and M03 bags together leads to a storing volume of 2.011 m^3 with bag masses of 24.262 kg. All four options provide more storage volume than the ones if only M02 or M03 bags are placed. Regarding their masses, they only vary by a maximum of around 10 kg. All further calculations which were done and not mentioned so far vary between a storing volume of 2.394 m^3 to 2.993 m^3. However, their corresponding empty bag masses are significantly increased beginning with 43.474 kg up to 58.554 kg. The reason for this is that these options all contain single or both single and half CTBs for filling the empty spaces that are left in the subfloor. The option which will be chosen in the end strongly depends on the amount of equipment and therefore on how many storage opportunities are needed. It can be started by only placing Mxx bags in the subfloor area. When it is then determined that more possibilities are needed, further CTBs can be placed within the subfloor in the same way as the calculations were set up. Therefore, the recommended option is $a_{2,3}$ which places three M01 bags and two M03 bags in the subfloor area. By that, 2.461 m^3 can be accommodated which lies in the average of all calculations. The corresponding empty bag masses are 29.446 kg which is one of the lightest options that was calculated. Additionally, if further storage space is needed more CTBs can be placed in the empty spaces that are left. However, this also results in an increased mass since every additional CTB needs to be fastened with at least one, more likely two, belts.

The last bag accommodation places that are considered are the floor above the subfloor and the ceiling. There, calculations were done solely using M03 bags. The reason for that is that the overall system needs to be balanced out with respect to its mass. Hence, the two sides containing the racks with bags need to be counteracted which will be done by placing bags on the floor and ceiling in the greenhouse section. Since the same space is available for both positions four options were calculated. These range from two to six bags per position. For two M03 bags, a storage volume of 1.282 m^3 is achieved with corresponding empty bag masses of 14.968 kg. In comparison to that, if six M03 bags are used, a storing volume of 3.846 m^3 with empty bag masses of 44.904 kg are reached. Unfortunately, no recommendation can be made for this accommodation area because it strongly depends on how much equipment needs to be stored as well as on the size of the pieces e.g. if they are oversized. Furthermore, the decision depends on the weight of both rack sides with their containing and attached bags because the overall module needs to be balanced out to meet the launcher's flight constraints. However, in order to get a first estimation for the overall mass of the pure packaging material, option $b_{1,3}$ with three M03 bags is chosen because it is the mean value of those floor and ceiling computations.

The last pieces that contribute to the overall packaging material mass are the belts for fastening the bags inside the module. Since no further information was found on the properties of the belts that were used on different cargo carriers, a belt mass of 2.7 kg was assumed. This value arose from the average of two commercial belts. Furthermore, due to a lack of information, it was assumed that half, double, and triple CTBs are fixed by two belts whereas single CTBs only require one belt. For the Mxx bags, five belts are required to fasten them properly. Combining all the evaluated bag arrangements discussed before with the needed amount of belts, a first assumption regarding the mass for the overall packaging material can be done. This packaging material contains racks, used bags, and belts. As mentioned above, the ten racks themselves weigh 1200 kg. Inside those racks, 40 double CTBs will be placed contributing further 81.60 kg to the overall module mass. The option for the subfloor adds another 29.446 kg. And last, the bags at the floor and ceiling add 44.904 kg. Regarding the belts, the 40 double CTBs require 80 belts. For the subfloor, 25 belts are required since there will be three M01 and two M03 bags placed. Eventually, 30 belts are required for the floor and ceiling because three M03 bags are placed at the floor and ceiling, respectively. In total, this will be 135 belts resulting in a belt mass of 364.5 kg. In total, the packaging materials alone will add 1720.45 kg to the overall module mass. Finally, it is important to mention that this packaging mass can still easily increase if other arrangement options will be chosen or if additional CTBs are placed which require for themselves further belts for fixation. Furthermore, if CTBs will be placed within Mxx bags, the cargo storing mass can increase as well.

Next, some requirements are discussed based on various points in which the importance of the project is outlined as well. Since humans will work inside the module and plants will be grown in there, it is extremely important to protect both from any microbacteria. Therefore, it is crucial to take measures before the launch in form of appropriately dressed workers. This action can be supported by additional cleaning of all surfaces inside the module. To test both measurements, samples can be taken before and afterwards to check whether the situation inside the module has improved. Furthermore, previous test runs for the unpacking of the materials can already be done. By that, it can be checked if the accommodation distribution and the developed unpacking order are suitable and lead to a quick unpacking. If not, lessons learned can be drawn from this test run and implemented into a better procedure. Through a first test run in which all equipment pieces will be stored, it can also be evaluated if the assumed amount of transportation bags is enough or if further ones are needed. For the transportation bags themselves, it has to be ensured that their maximum storage volume will not be crossed. To further guarantee that the bags do not break they can be tested in a filled state on top of a shaker to simulate the launch conditions. A potentially critical issue in the process is the possibility that the bags can get damaged due to overload. As a possible result, the equipment inside could be distributed among multiple bags which would also mean a potentially increased module mass since more bags are required for storing. The filled bags can also be attached to the racks with the chosen belts. By that, it can be checked if the racks can withstand the masses that are forced onto them and if the bags are capable of holding the bags tight to their position they are at. In case one or both tested objects fail, the results could be drawn to amplify the racks or to choose stronger belts that can endure higher loads.

One major demand of the EDEN NG GTD project is dual use. This is to first utilize it as a cargo module and then transfer it to second a greenhouse system. However, since a lot of system mass comes from packaging material, to transport all the equipment the sustainability aspect gets a high priority in there. Through that, the term L2L was initiated to develop solutions for re-purposing equipment pieces that otherwise would only serve in the transportation phase. Within the L2L approach, it was started to modify the single CTBs. As a result, the MCTBs were created which differ from the original single CTBs in their unfolding. Due to added zippers, snaps, and fabric, they are able to get unfolded to a flat sheet. By that, many more applications are possible which range from simple partitions and trash or storing bags over to furniture and sleeping bags towards clothing and life support augmentation. Through their usage, it would be possible to reduce the launching mass since specific pieces do not need to get launched. This is because those components could be built up directly on-site such as a chair. The downside might be that if those components can not be built up because they got damaged during transport there will also be no other option on how to produce it in another way. However, this risk is limited by the fact that there will not only be one transportation bag. Hence, the probability that this building on-site will be possible is high. Furthermore, within those unzipped bags bladders or membranes could be integrated beforehand. This would have the advantage of processing wastewater from the module while also being able to store it. Additionally, those sheets containing bladders could be combined to create clothing for the crew. And because water is a good radiation shield they could act as wearable radiation protections for the crew. Additionally, they could be mounted outside to the module to add a further radiation protection layer. Another area of research on these reusable transportation bags is to heat station food wastes to create tiles. Those tiles could be placed within the sheets to also use them as station radiation shields outside. Both applications could contribute to the safety of the astronauts as well as help to reduce the waste products that emerge during daily living inside the module. Since these MCTBs are still under development they require further analysis and testing phase. A possible solution, if MCTBs are available, could be to mix the transportation bags to test out the MCTB within the EDEN NG GTD to verify them for the final EDEN Lunar module.

6 Conclusion and Future Outlook

This thesis aimed to fulfill the Logistic-to-Green approach to first use the module as a transportation system and be able afterwards to transform it into a greenhouse system. To achieve this, extensive research on previously and currently used cargo transportation modules for the ISS was done in which the general storing possibilities were identified. This analysis dealt with issues such as how the cargo is stored and secured as well as requirements for specific cargo usage. Moreover, requirements specifically for cargo usage were developed. Since this aspect was not considered in the overall greenhouse requirements so far, they were reviewed concerning the cargo section and modified where necessary. One of the major changes was to take the specific needs of the bags and belts into consideration. Since they need to withstand the loads they are going to carry, it has to be taken into account to pack them appropriately. Furthermore, it was outlined that the staff working inside the module must be dressed properly to not contaminate the equipment inside even more.

Most information regarding internal storage was gained from the ATV cargo module. Therefore, it was set as the baseline, particularly for the rack system that is going to be used inside the EDEN NG GTD. As a reference value, the mass of 120 kg for each rack was assumed. Furthermore, the number of belts that will fasten the bags inside the module was estimated based on configurations inside the ATV. Depending on the type of bag, it varies from one belt for single CTBs, over two belts for half, double, and triple CTBs to five belts for all Mxx bags. Therefore, the belts are not a negligible factor in the determination of the overall packaging mass for the accommodation. To conclude the storing chapter, various bag combinations were looked at for different positions within the module. Thereby, all calculations were done based on the trade-off between the provided storing volume versus the empty bag masses without any equipment stored inside the bags. The limiting factor for the compartments inside the racks are their dimensions in which only the CTBs except for the triple CTB fit. Further storing positions are the floor and ceiling and the subfloor area beneath the floor on which the crew will walk. The reason for positioning bags on all four module walls is to reach a mass balance of the overall module. This is important since the launcher constraints have to be satisfied. All those calculations resulted in 1200 kg for the rack systems, 155.95 kg for all 51 bags, and 364.5 kg for all 135 belts. In total, this leads to 1720.45 kg purely resulting from packaging material for storing all equipment pieces.

Because of this high amount of stored material, the next step was to looked at on how to re-purpose the equipment so that the material does not become useless afterwards. For that, a project within the L2L approach modified the single CTBs to offer a wider range of possibilities after transportation. These so-called MCTBs have additional zippers, snaps, and fabric to be able to unfold the bags to a flat sheet. In this way, they can be used as partitions, storing bags for waste or harvested vegetables, and furniture. It should be emphasized that the greatest advantage can be achieved by integrating bladders or membranes into the sidewalls of the bags. Through that, it is possible to filter or store water as well as process food waste. On the one hand, this supports the waste management inside the module. On the other hand, these sheets filled with water or tiles made out of waste can be used as a protective layer on the outside of the module to shield against radiation. Since the flat sheets can be combined, they could also be transformed into wearable clothes for the astronauts working as a radiation shield as well. However, it is important to note that the MCTBs are still in development and were therefore never tested in space.

The limitation of this work was the challenge to find specific information on the individual cargo carrier, e.g. cargo handbooks. Only a few publications and developments were found on the topic which is why a lot of assumptions were made. Those assumptions were the way to deal with the lack of information to still be able to make an initial assessment regarding the overall packaging material mass. One further solution to deal with the lack of information found were the employees of the DLR that shared information about cargo equipment during the CE study. Furthermore, a contact with an employee of the Beyond Gravity company was established at the Space Tech Expo which took place in Bremen in November 2022. With both supportive solutions it was possible to gain some detailed information about the cargo equipment as well as to make more informed decisions about the packaging material mass for the overall module.

6.1 Outlook

The results of this thesis show the high contribution of packaging material solely for cargo accommodation. In order to further improve this issue, the developments of the MCTB should be kept in mind as well as similar advancements that aim at re-purposing transportation material. Additional calculations and different bag arrangements should be done, especially for the trade-off of using fewer Mxx bags which require more belts versus using more smaller CTBs while using less belts. Further considerations should be taken towards the mass distribution both within the bags themselves and within the overall greenhouse section. This is important for the launcher requirements and its dynamics since a balanced mass distribution of the entire system needs to be achieved.

Further working steps concern the sorting and distribution of the equipment inside the bags that have to be brought to the Moon. The number of transportation bags strongly depends on the equipment since oversized pieces require a larger bag than smaller components. Also, the grouping of items can lead to a reduced amount of bags since they can be arranged more efficiently. This task also has effects on the mass distributions and therefore on the launcher, respectively, which is why it is also important to test some filled bags on a shaker to simulate the launch conditions. Using this method, insights can be gained for the general loading of the bags so that they will not be packed too crowded. A further point that is important to test beforehand is the design of the rack struts. Since the cables of the illumination and nutrition supply have to be placed within the struts, the best solution has to be identified. For that, thicker and u-shaped struts should be tested to identify possible weak points that could damage the cables during transportation. Those results will be valuable for the EDEN Lunar module for which the rack systems will be customized.

Another point for future work is the development of a rail system inside the module.

Within the L2L approach, such a system was investigated to increase the interchangeability of the stowage architecture. Through that, the rack compartments could be deeper to offer more storage volume. Since the shelves can be moved easily, the astronauts could turn the entire rack so that they can reach the back easier [69]. Further considerations on this idea have to be taken to decide if such a rail system would bring the interior forwards to a more flexible one. Additional research should be conducted to gain additional insights on the cargo systems of the mentioned transportation modules. By that, individual details of the utilized belts used inside the modules could be identified. Eventually, specific accommodation constraints and rules on how the different agencies load their cargo carrier could be found out and transferred to the EDEN NG GTD or EDEN Lunar project.

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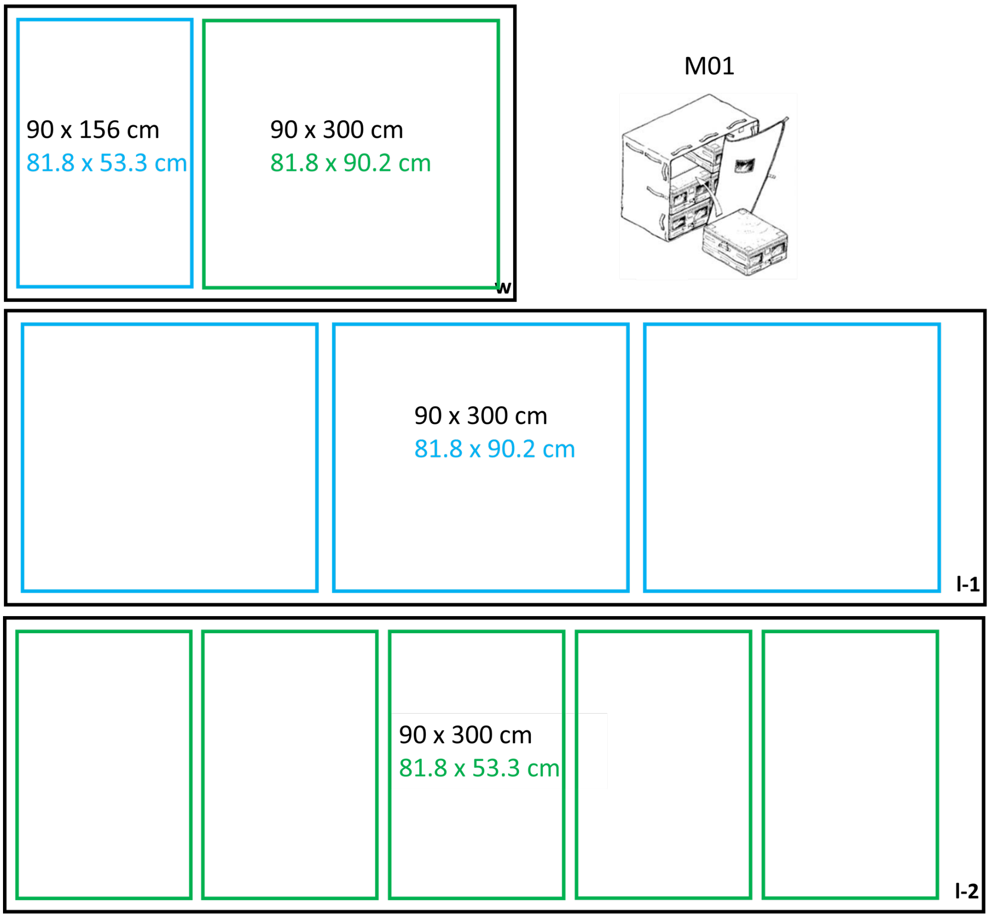
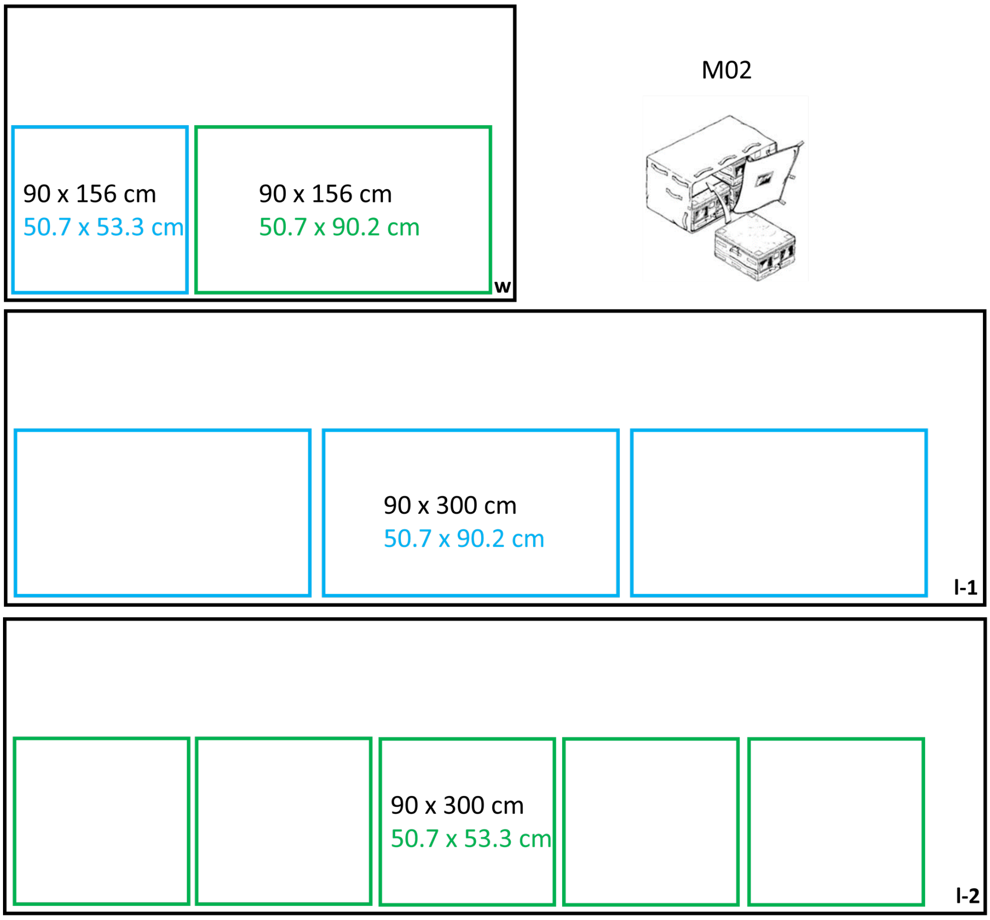
Appendix

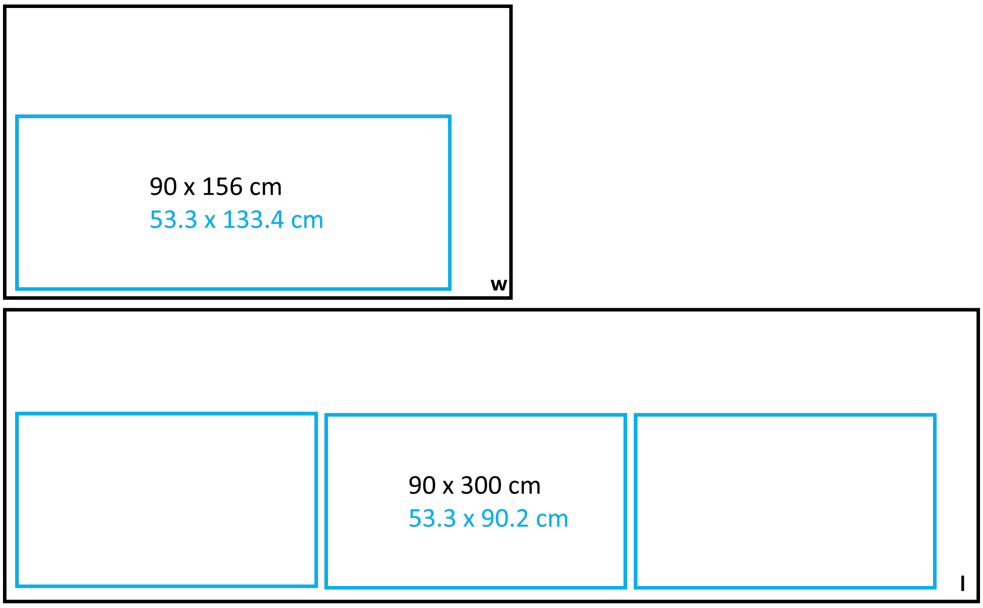


(a) Sub-floor accommodation if only M01 bags are used.

Figure A.1: Maximum amount of storage bags inside the sub-floor area (black box) if the same bag type (blue and green boxes) is used.

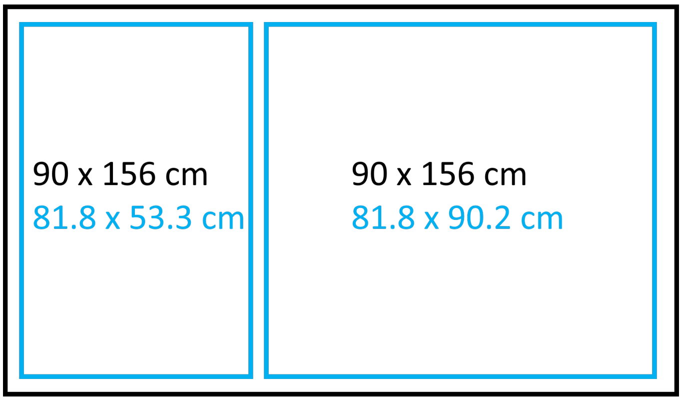


(b) Sub-floor accommodation if only M02 bags are used.

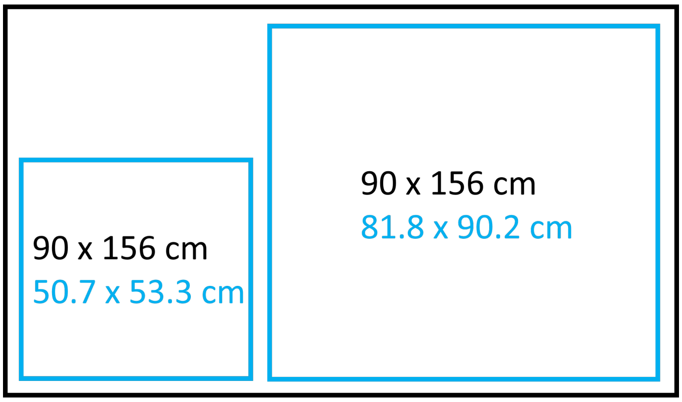


(c) Sub-floor accommodation if only M03 bags are used.

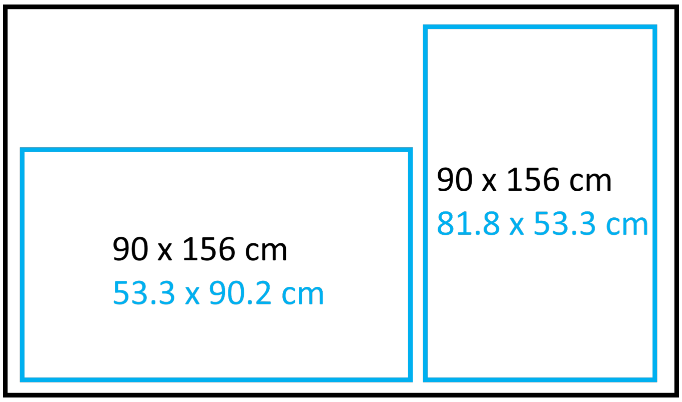
Figure A.1: Maximum amount of storage bags inside the sub-floor area (black box) if the same bag type (blue and green boxes) is used (continued).



(a) Maximum amount of storage bags inside the sub-floor area (black box) if the M01 bag type is mixed with other M01 bag types (blue boxes).

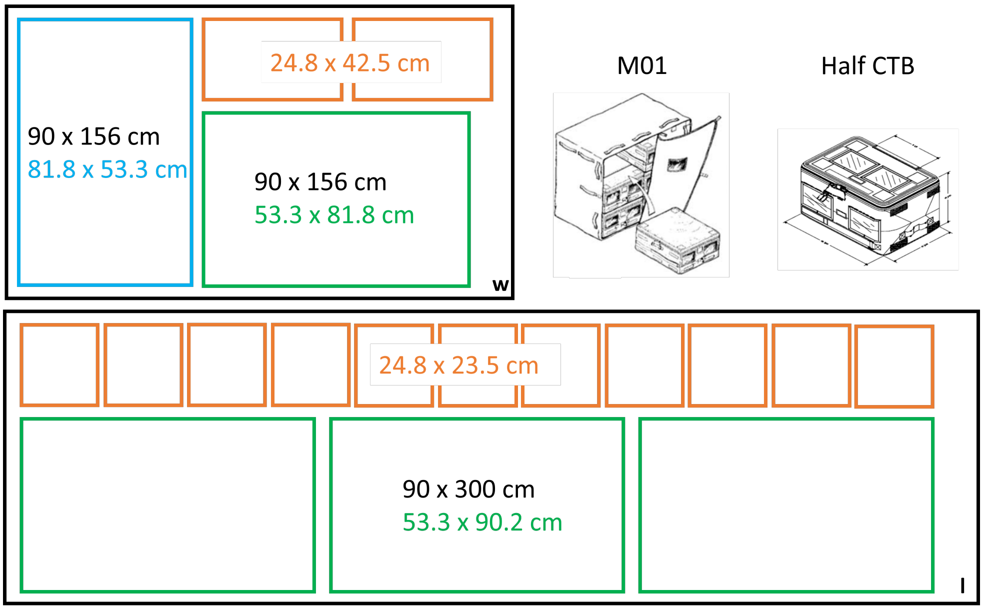


(b) Maximum amount of storage bags inside the sub-floor area (black box) if the M02 bag type is mixed with M01 bag types (blue boxes).

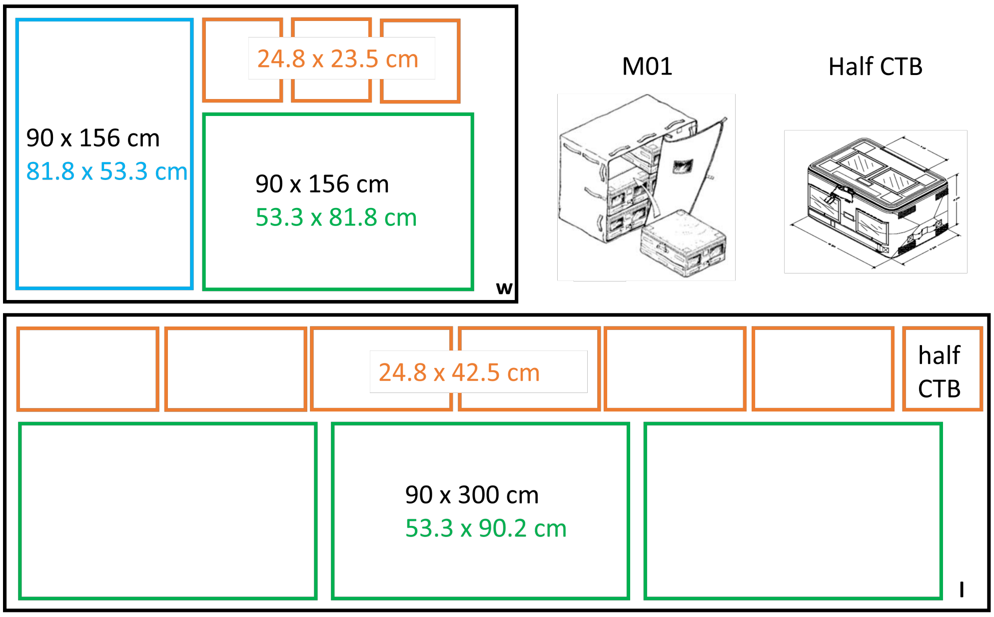


(c) Maximum amount of storage bags inside the sub-floor area (black box) if the M03 bag type is mixed with M01 bag types (blue boxes).

Figure A.2: Maximum amount of storage bags inside the sub-floor area (black box) if a mixture of Mxx bag types (blue boxes) is used.

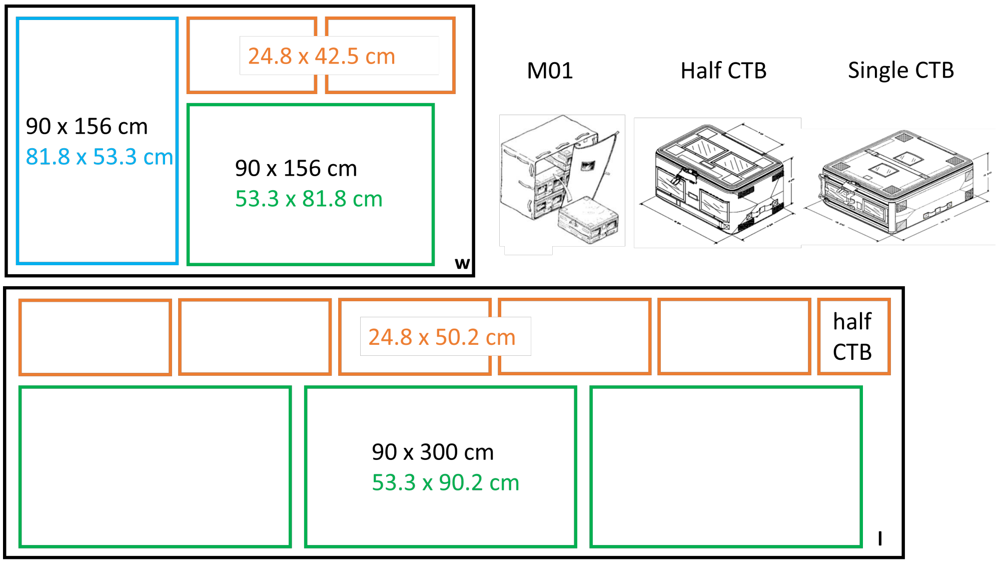


(a) Option a - Maximum amount of half CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M01 bags (blue and green boxes).

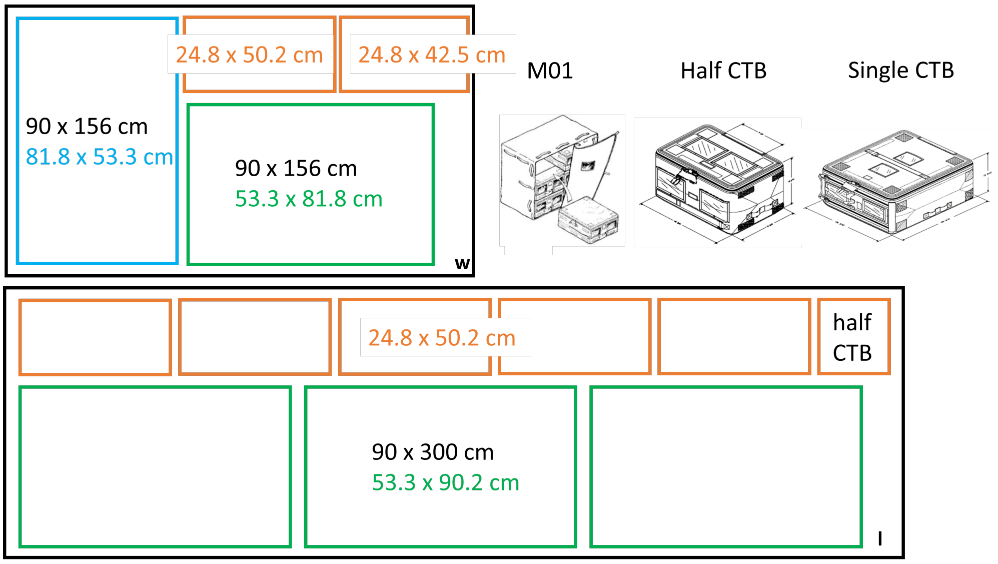


(b) Option b - Maximum amount of half CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M01 bags (blue and green boxes).

Figure A.3: Filling the empty spaces in the sub-floor area (black box) with half and/or single CTBs (orange boxes) along with M01 bags (blue and green boxes).

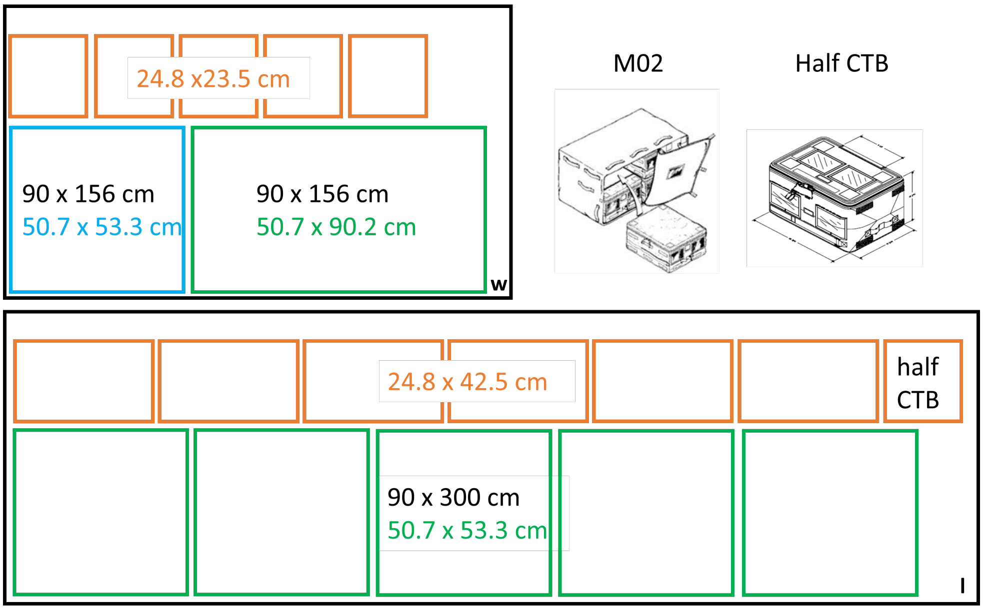


(c) Option a - Maximum amount of half and single CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M01 bags (blue and green boxes).

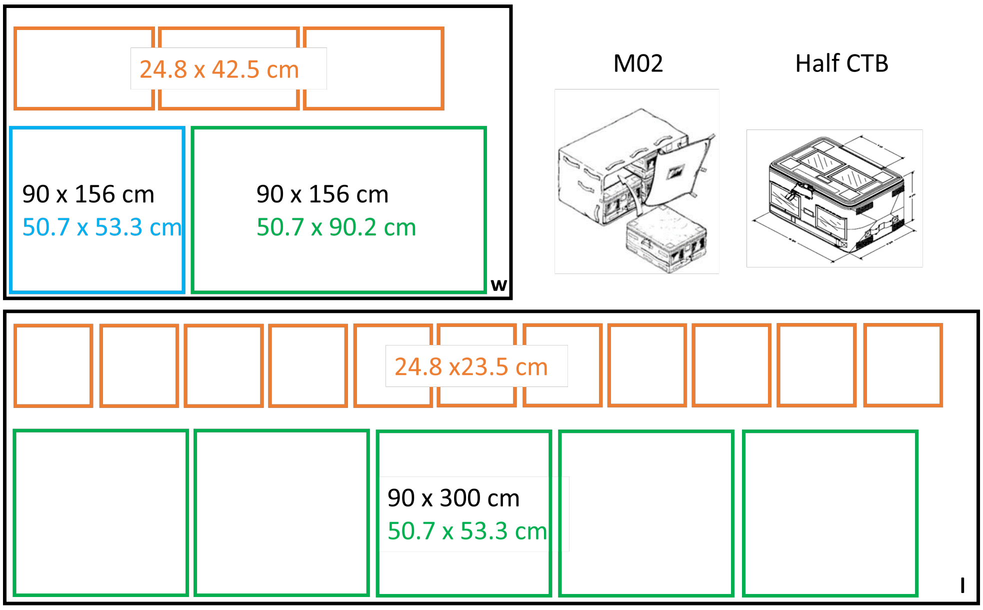


(d) Option b - Maximum amount of half and single CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M01 bags (blue and green boxes).

Figure A.3: Filling the empty spaces in the sub-floor area (black box) with half and/or single CTBs (orange boxes) along with M01 bags (blue and green boxes) (continued).

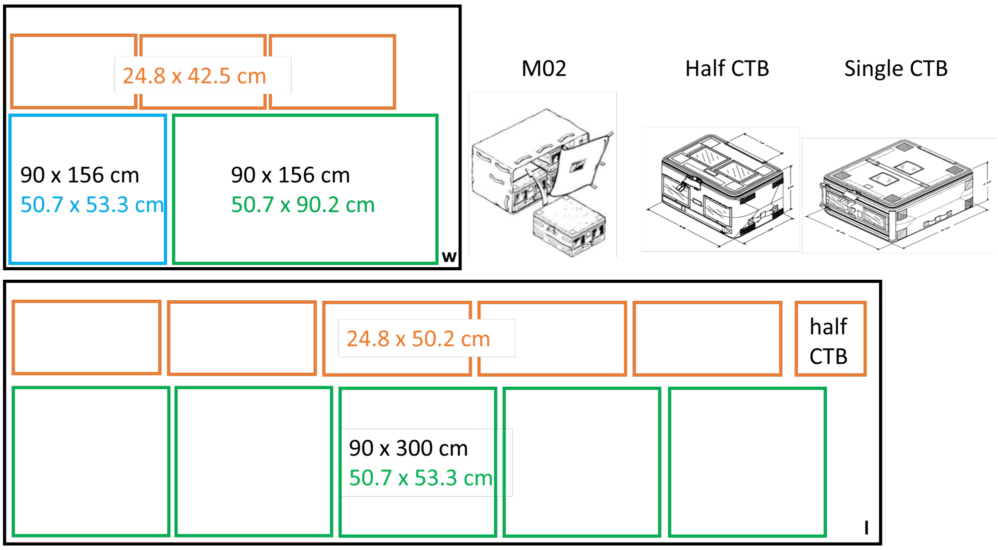


(a) Option a - Maximum amount of half CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M02 bags (blue and green boxes).

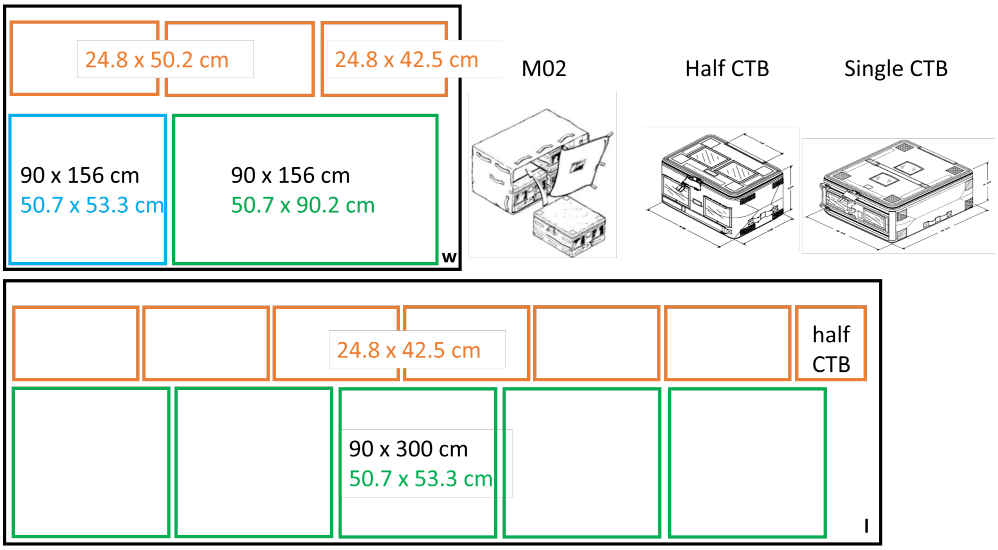


(b) Option b - Maximum amount of half CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M02 bags (blue and green boxes).

Figure A.4: Filling the empty spaces in the sub-floor area (black box) with half and/or single CTBs (orange boxes) along with M02 bags (blue and green boxes).

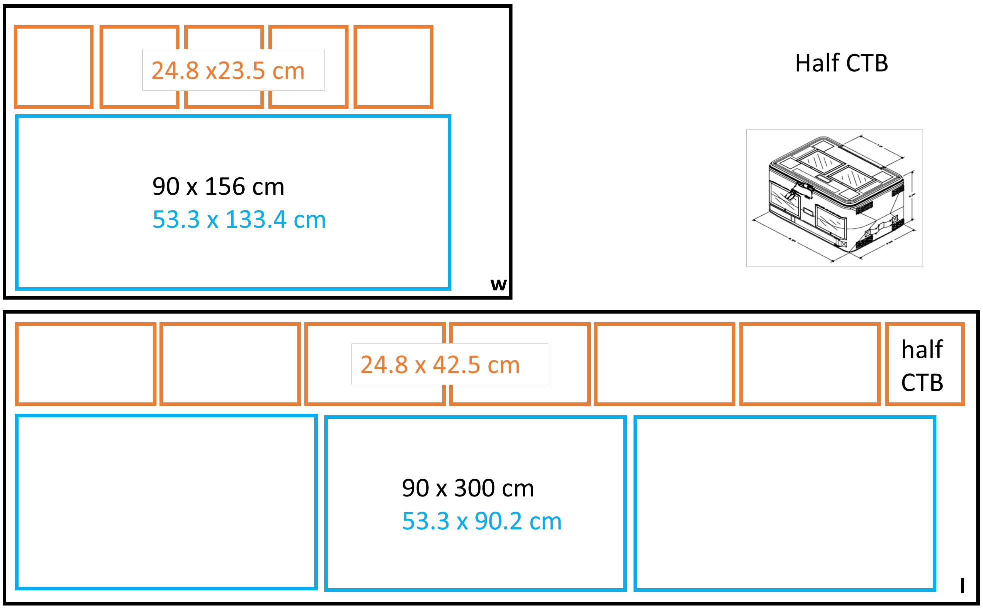


(c) Option a - Maximum amount of half and single CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M02 bags (blue and green boxes).

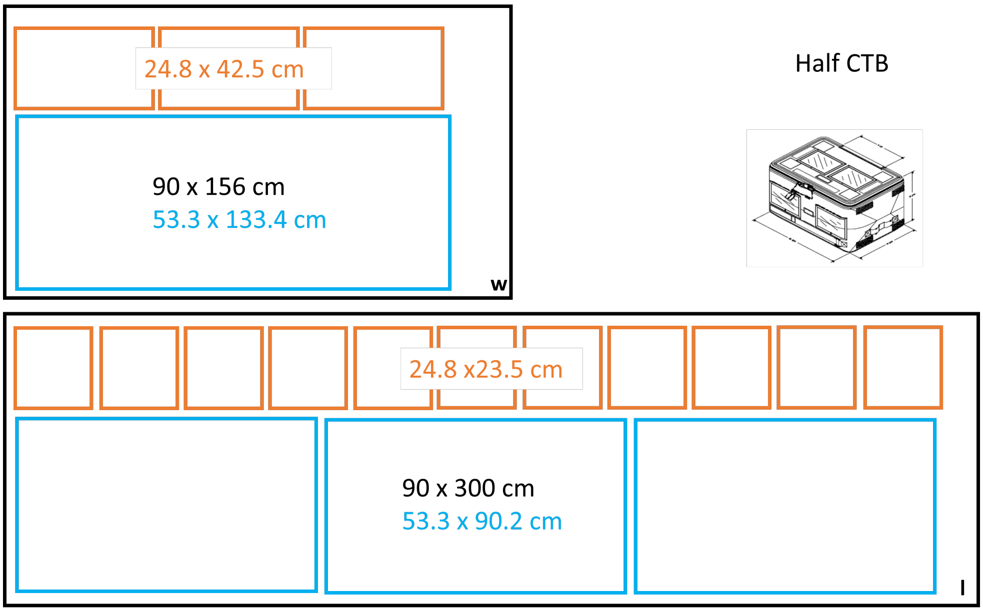


(d) Option b - Maximum amount of half and single CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M02 bags (blue and green boxes).

Figure A.4: Filling the empty spaces in the sub-floor area (black box) with half and/or single CTBs (orange boxes) along with M02 bags (blue and green boxes) (continued).

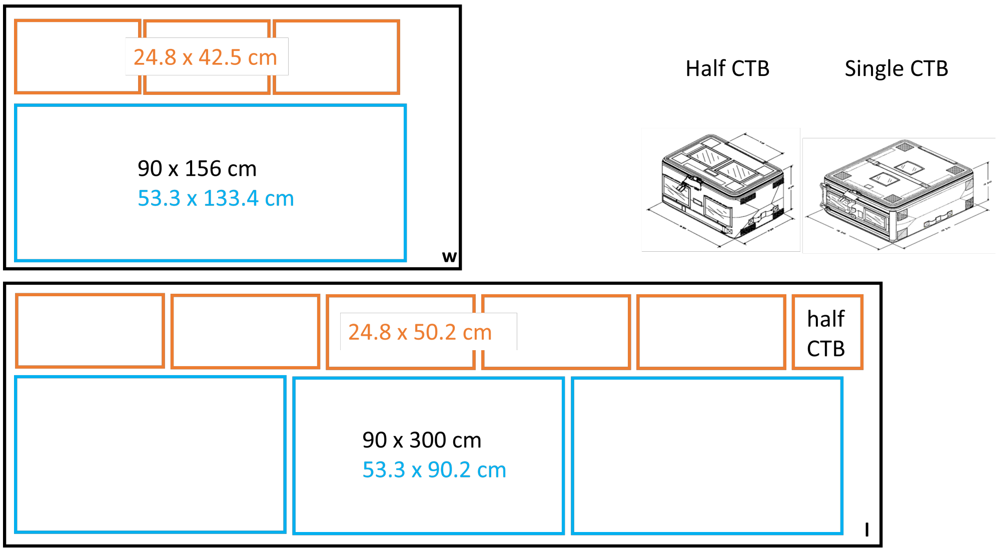


(a) Option a - Maximum amount of half CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M03 bags (blue and green boxes).

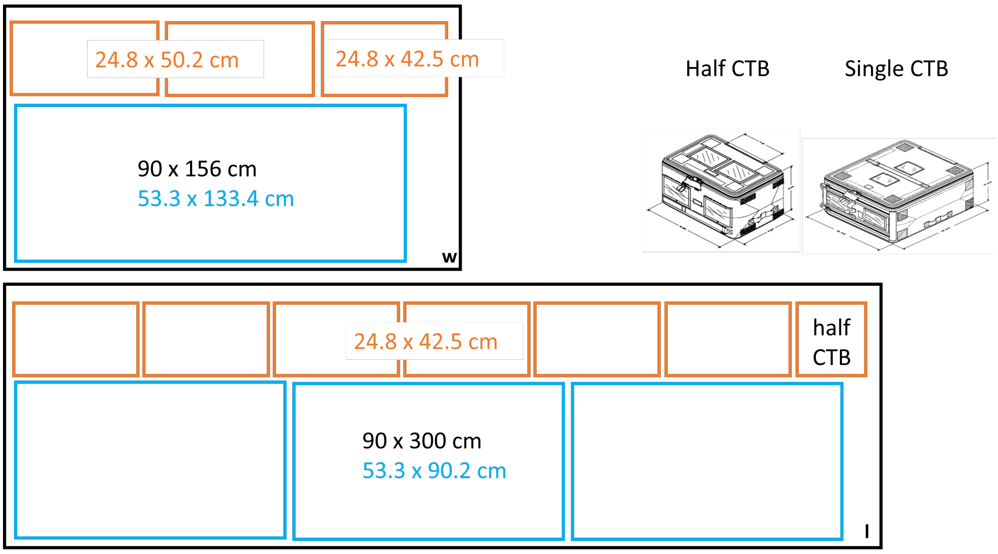


(b) Option b - Maximum amount of half CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M03 bags (blue and green boxes).

Figure A.5: Filling the empty spaces in the sub-floor area (black box) with half and/or single CTBs (orange boxes) along with M03 bags (blue and green boxes).

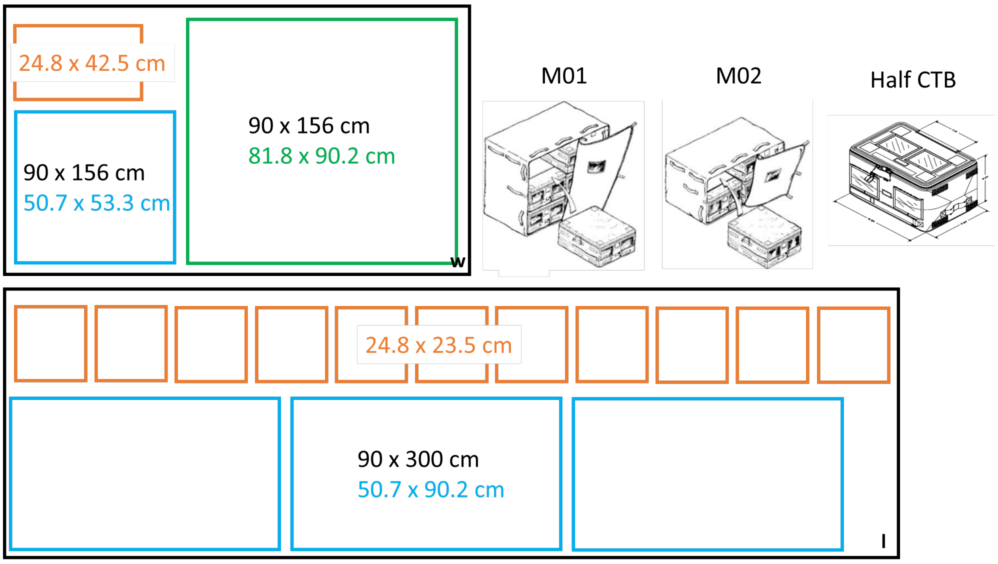


(c) Option a - Maximum amount of half and single CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M03 bags (blue and green boxes).

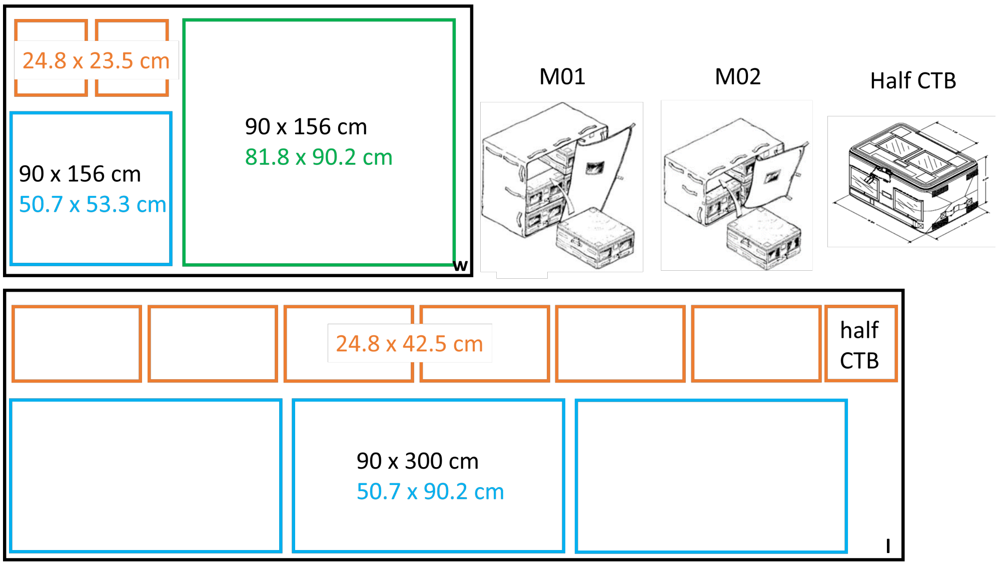


(d) Option b - Maximum amount of half and single CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M03 bags (blue and green boxes).

Figure A.5: Filling the empty spaces in the sub-floor area (black box) with half and/or single CTBs (orange boxes) along with M03 bags (blue and green boxes) (continued).

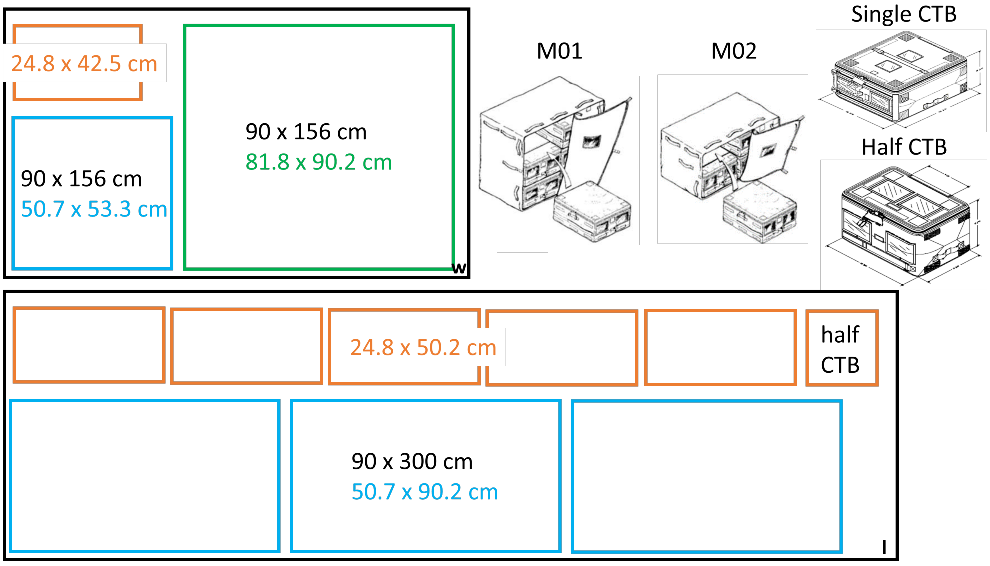


(a) Option a - Maximum amount of half CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M01 (green boxes) and M02 bags (blue boxes).

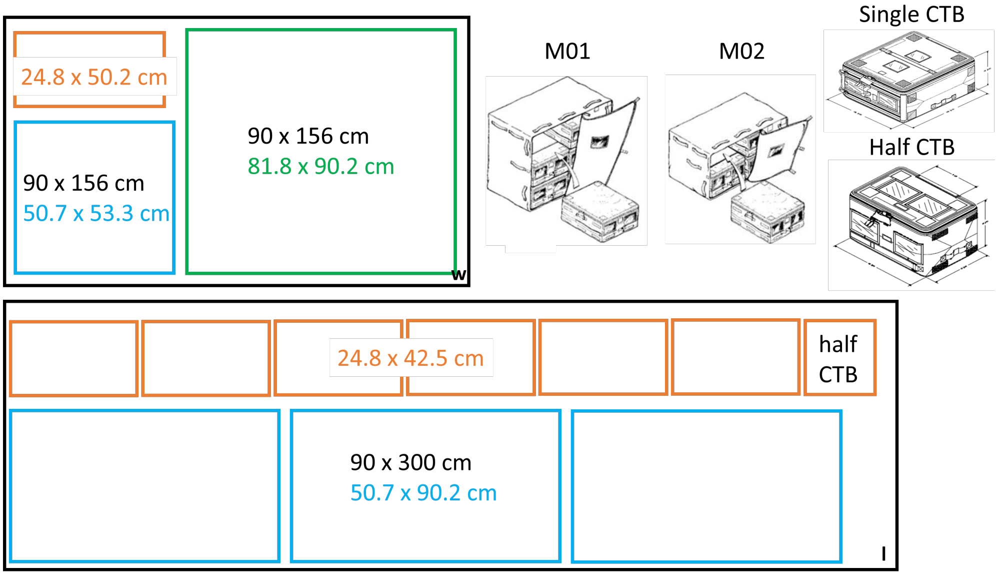


(b) Option b - Maximum amount of half CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M01 (green boxes) and M02 bags (blue boxes).

Figure A.6: Filling the empty spaces in the sub-floor area (black box) with half and/or single CTBs (orange boxes) along with M01 (green boxes) and M02 bags (blue boxes).

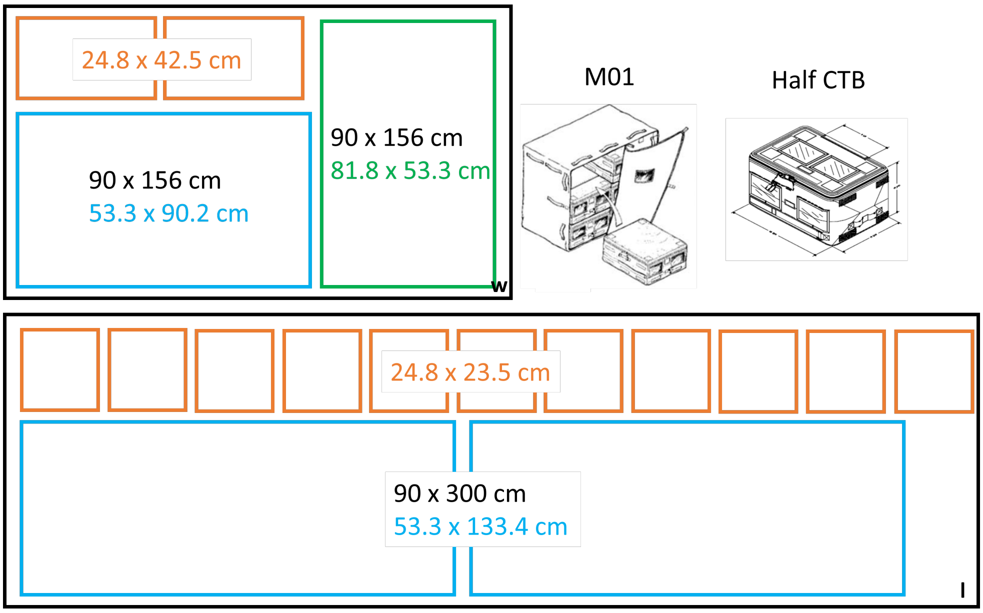


(c) Option a - Maximum amount of half and single CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M01 (green boxes) and M02 bags (blue boxes).

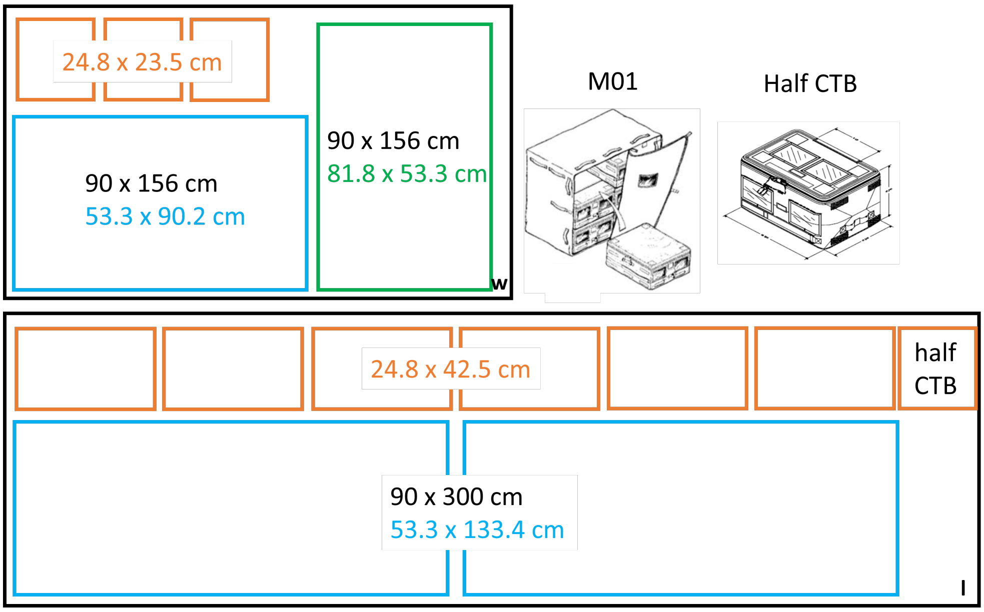


(d) Option b - Maximum amount of half and single CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M01 (green boxes) and M02 bags (blue boxes).

Figure A.6: Filling the empty spaces in the sub-floor area (black box) with half and/or single CTBs (orange boxes) along with M01 (green boxes) and M02 bags (blue boxes) (continued).

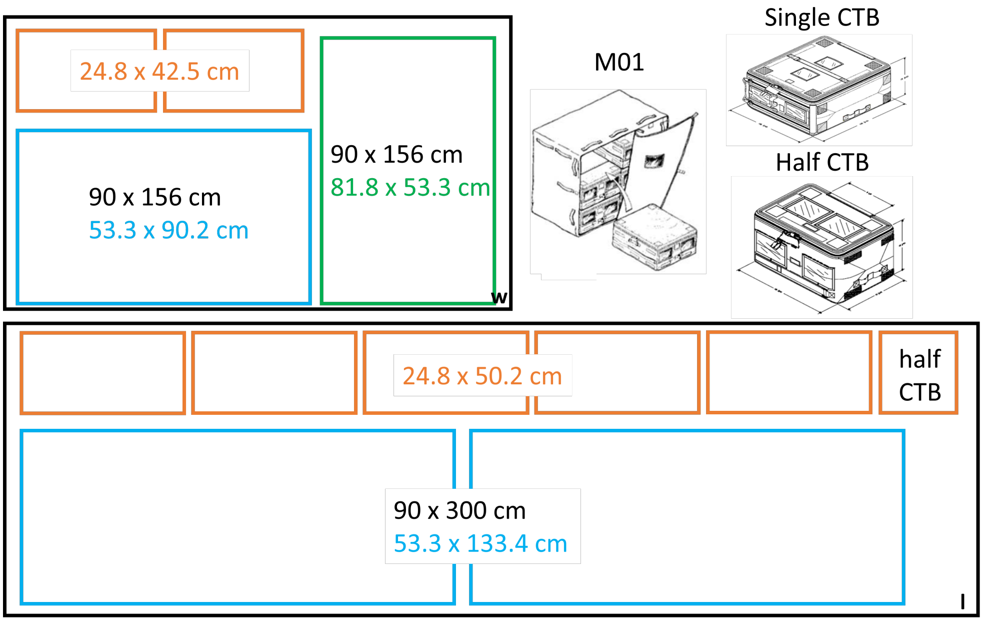


(a) Option a - Maximum amount of half CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M01 (green boxes) and M03 bags (blue boxes).

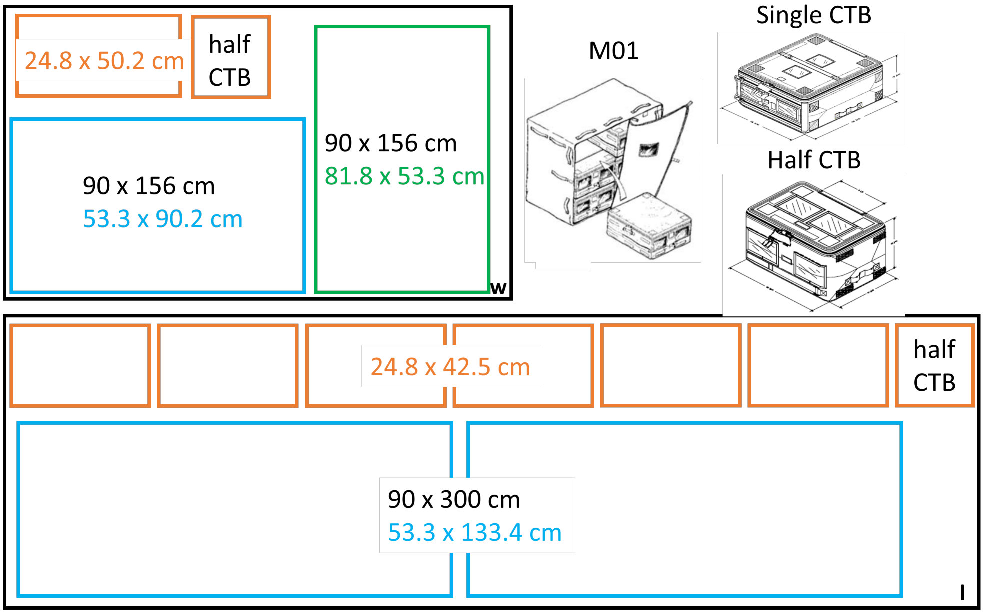


(b) Option b - Maximum amount of half CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M01 (green boxes) and M03 bags (blue boxes).

Figure A.7: Filling the empty spaces in the sub-floor area (black box) with half and/or single CTBs (orange boxes) along with M01 (green boxes) and M03 bags (blue boxes).

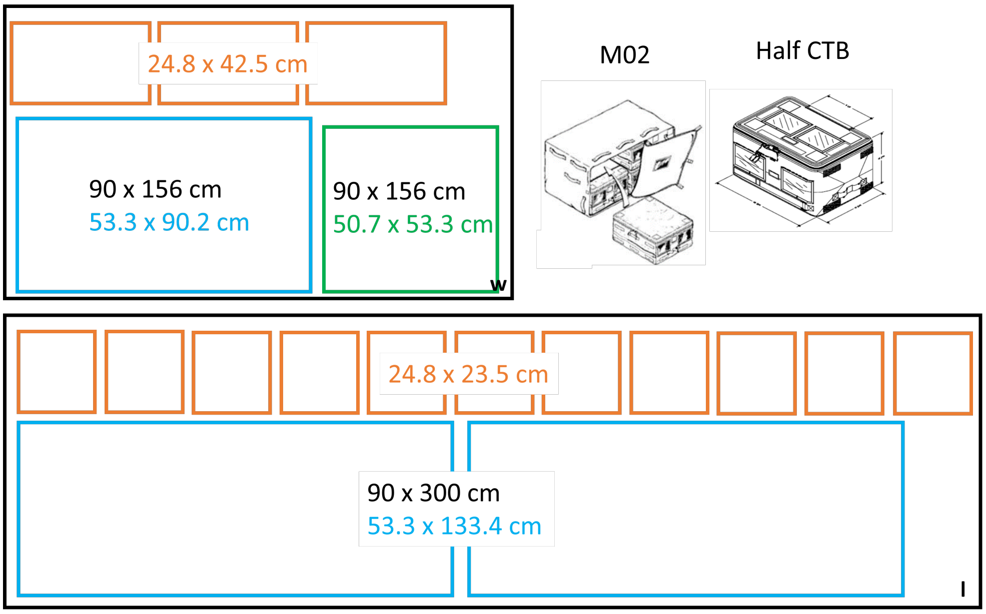


(c) Option a - Maximum amount of half and single CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M01 (green boxes) and M03 bags (blue boxes).

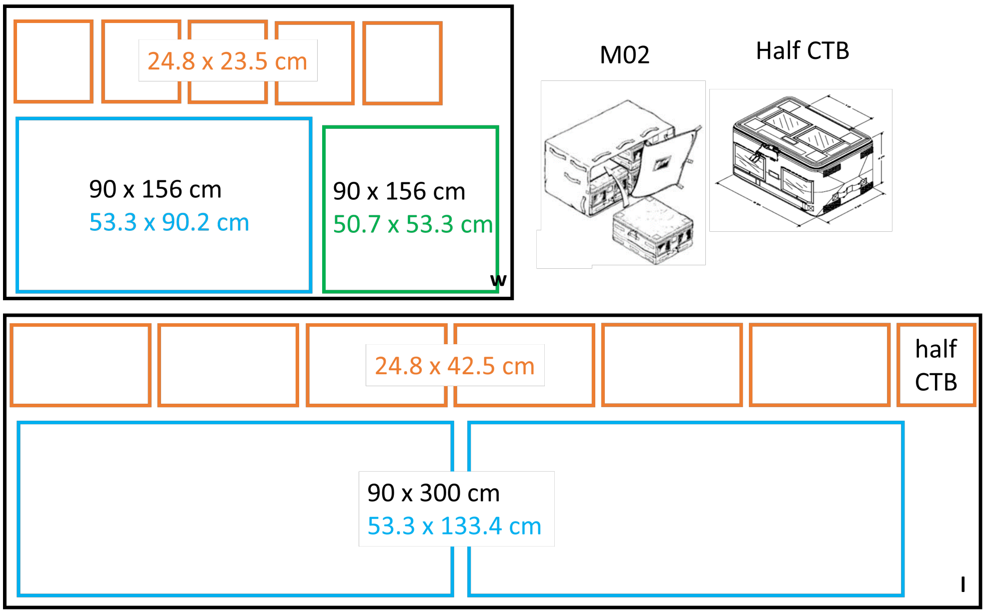


(d) Option b - Maximum amount of half and single CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M01 (green boxes) and M03 bags (blue boxes).

Figure A.7: Filling the empty spaces in the sub-floor area (black box) with half and/or single CTBs (orange boxes) along with M01 (green boxes) and M03 bags (blue boxes) (continued).

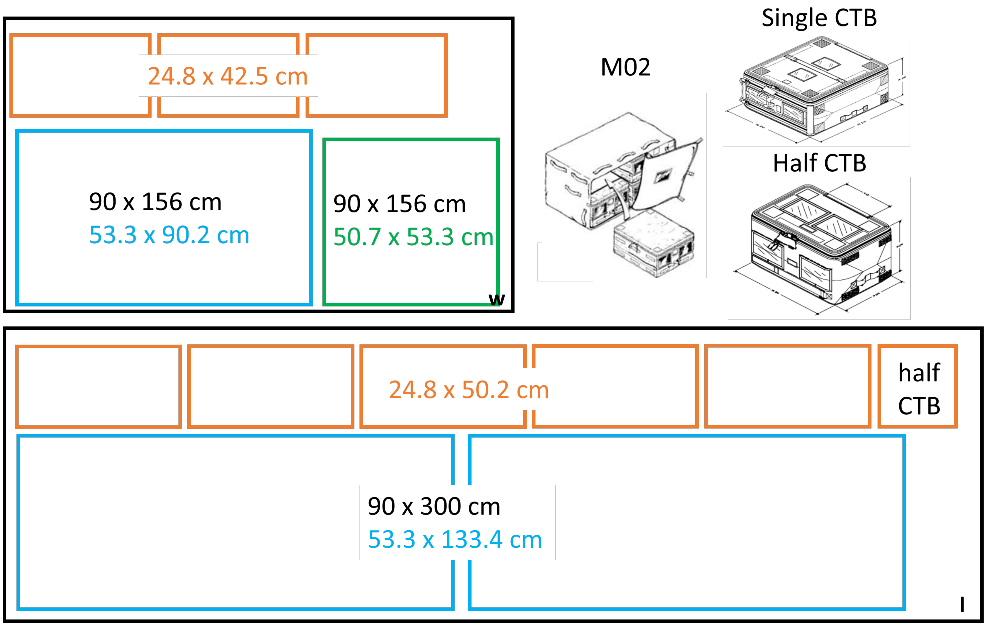


(a) Option a - Maximum amount of half CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M02 (green boxes) and M03 bags (blue boxes).

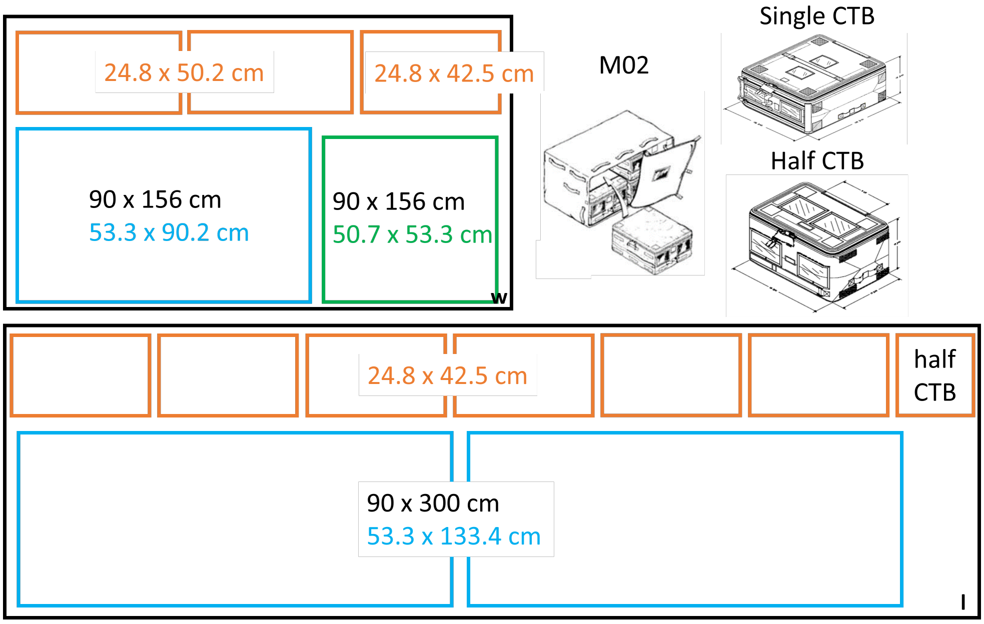


(b) Option b - Maximum amount of half CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M02 (green boxes) and M03 bags (blue boxes).

Figure A.8: Filling the empty spaces in the sub-floor area (black box) with half and/or single CTBs (orange boxes) along with M02 (green boxes) and M03 bags (blue boxes).

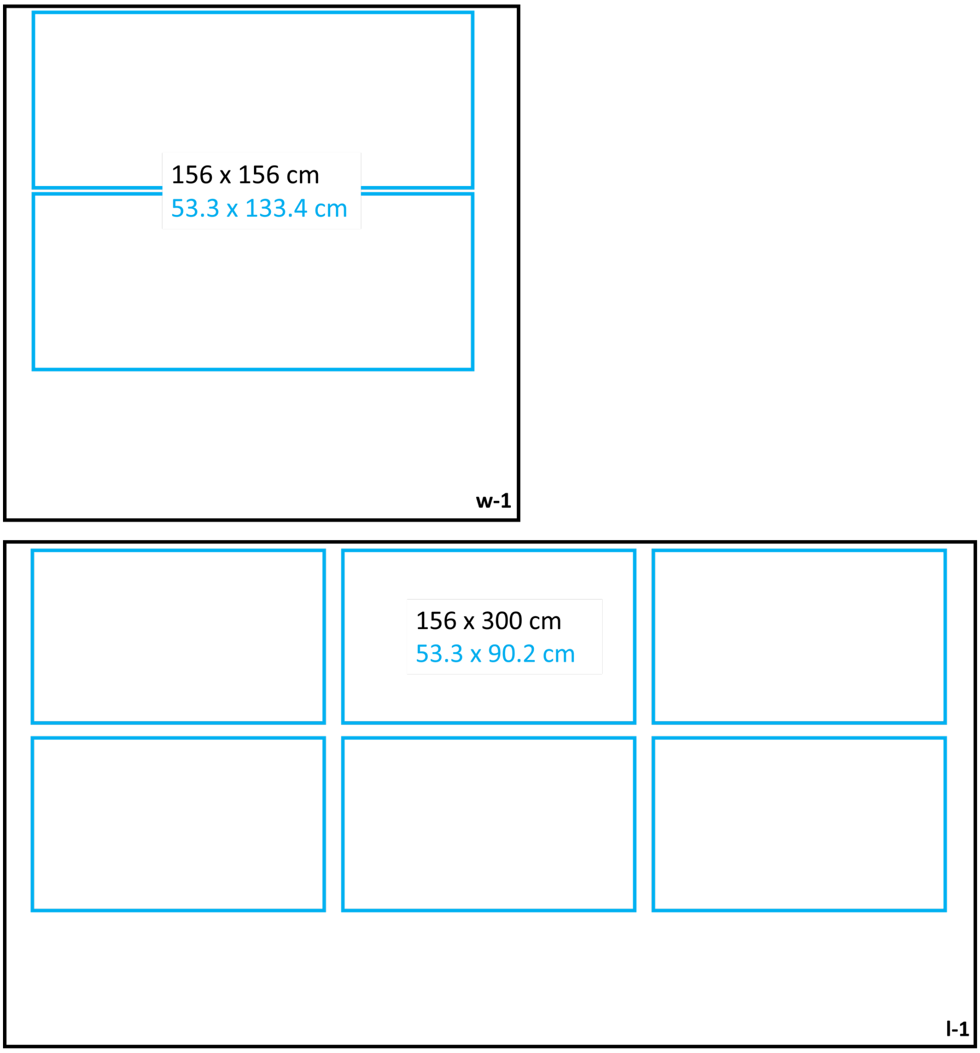


(c) Option a - Maximum amount of half and single CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M02 (green boxes) and M03 bags (blue boxes).



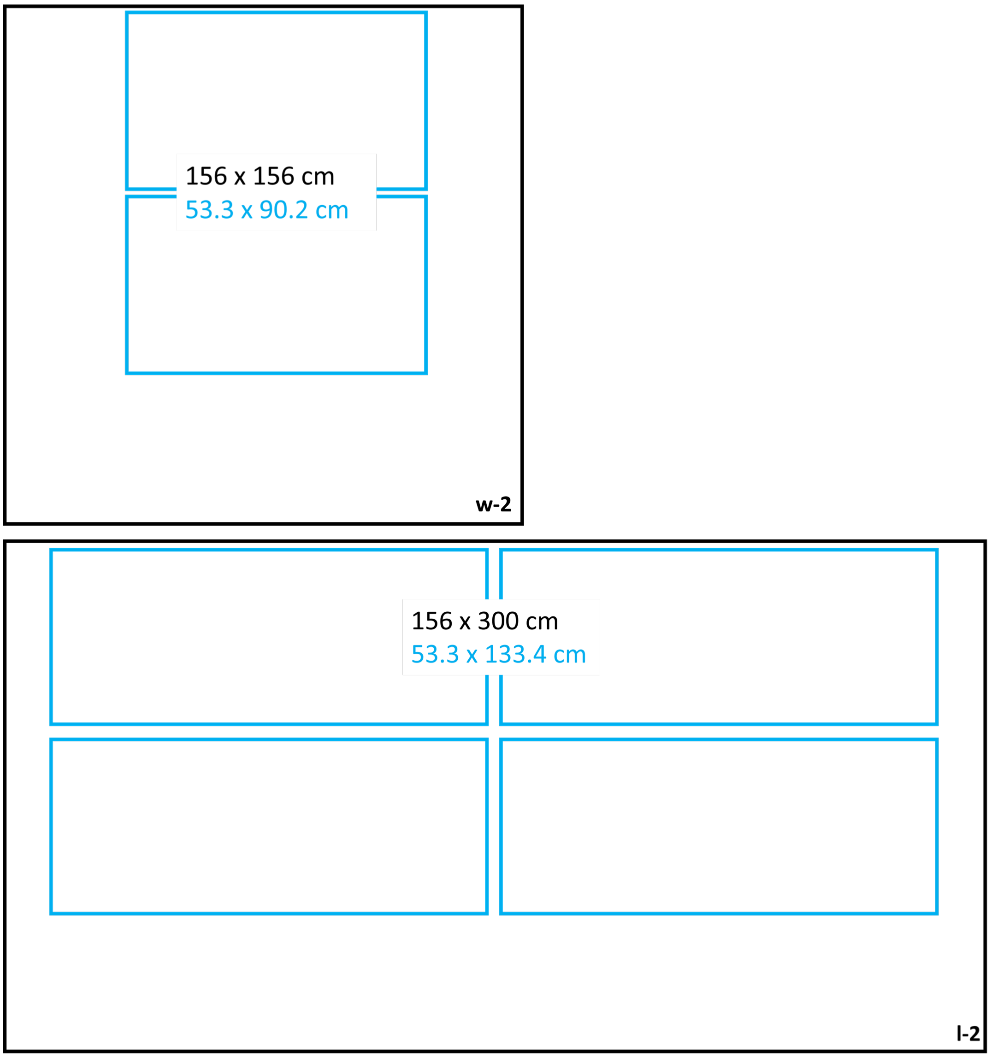
(d) Option b - Maximum amount of half and single CTB bags (orange boxes) inside the empty spaces in the sub-floor area (black box) along with M02 (green boxes) and M03 bags (blue boxes).

Figure A.8: Filling the empty spaces in the sub-floor area (black box) with half and/or single CTBs (orange boxes) along with M02 (green boxes) and M03 bags (blue boxes) (continued).



(a) Option a - Placing M03 bags (blue boxes) at the ceiling of the greenhouse module.

Figure A.9: Two options of placing M03 bags at the ceiling of the greenhouse module.



(b) Option b - Placing M03 bags (blue boxes) at the ceiling of the greenhouse module.

Figure A.9: Two options of placing M03 bags at the ceiling of the greenhouse module (continued).

Technical Data

PRODUKTMERKMALE	PRODUCT FEATURES		
Artikeltyp	Article type	Zubehör für Seilhebezüge	accessories for wire rope hoists
Ausführung	Execution	Zubehör für Seilhebezüge	accessories for wire rope hoists
Material	Material	Polyester	Polyester
Oberfläche	Surface	Galvanisch verzinkt	electrogalvanized
Materialstärke	Material thickness	2.3mm	2.3mm
Gliederbreite	Limb width	50mm	50mm
Max. Tragkraft	Max. load capacity	2500kg	2500kg
Norm	Norm	EN12195-2	EN12195-2
Gesamtlänge	Total length	10m	10m
Einsatzbereich	Application area	Außen	Outside

MAßE UND GEWICHT	DIMENSIONS AND WEIGHT		
Gewicht	Weight	3.20kg	3.20kg
Höhe	Height	10.0cm	10.0cm
Breite	Wide	13.0cm	13.0cm
Tiefe	Depth	34.0cm	34.0cm

Technical Data

PRODUKTMERKMALE	PRODUCT FEATURES		
Artikeltyp	Article type	Zubehör für Seilhebezüge	accessories for wire rope hoists
Ausführung	Execution	Zubehör für Seilhebezüge	accessories for wire rope hoists
Material	Material	Polyester	Polyester
Oberfläche	Surface	Galvanisch verzinkt	electrogalvanized
Materialstärke	Material thickness	2.2mm	2.2mm
Gliederbreite	Limb width	50mm	50mm
Max. Tragkraft	Max. load capacity	2000kg	2000kg
Norm	Norm	EN12195-2	EN12195-2
Gesamtlänge	Total length	8m	8m
Einsatzbereich	Application area	Außen	Outside

MAßE UND GEWICHT	DIMENSIONS AND WEIGHT		
Gewicht	Weight	2.14kg	2.14kg
Höhe	Height	8.5cm	8.5cm
Breite	Wide	11.0cm	11.0cm
Tiefe	Depth	37.0cm	37.0cm