FLEXhab working module

Architectural requirements and prototyping for a lunar base analogue

TECHNISCHE UNIVERSITÄT WIEN
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DIPLOMARBEIT

FLEXHAB WORKING MODULE

ARCHITECTURAL REQUIREMENTS AND PROTOTYPING FOR A LUNAR BASE ANALOGUE

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Diplom-Ingenieurs unter der Leitung von

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Kurzbeschreibung

In der Erforschung des Weltraums spielen Simulationshabitate eine wichtige Rolle. Sie erlauben uns, Experimente vorab zu testen, Gegenmaßnahmen für die besonderen Bedingungen zu entwickeln oder menschliches Verhalten in ähnlichen Umgebungen zu untersuchen. Das sogenannte FLEXhab, Future Lunar Exploration Habitat, wird als Simulation einer Mondbasis dienen, um Training und Simulationen am Europäischen Astronautenzentrum (EAC) zu ermöglichen.

Besonders die spezifischen Umweltbedingungen wirken sich auf das Design einer potentiellen Mondbasis aus. Diese werden analysiert, um die Effekte in die Simulation zu implementieren mit dem Ziel, das selbe Interieur zu schaffen. Darüber hinaus bietet dies die Möglichkeit, Gegenmaßnahmen zu testen.

Auch die Nutzer und ihre Aktivitäten innerhalb der Mondbasis werden analysiert, da auch diese das Design des Habitats wesentlich beeinflussen.

Die Arbeit präsentiert anschließend ein Innenraumdesign für das FLEXhab-Arbeitsmoduls, basierend auf einem zuvor entwickelten Konzept. (O. Punch, T. Dijkshoorn, Spaceship EAC, 2016)

Des Weiteren wird das so genannte FLEXrack implementiert, ein im zuvor erwähnten Konzept entwickeltes, bewegliches Rack-System. Dieses erhöht die Flexibilität in Explorationsmodulen und steigert den verfügbaren Platz für Aktivitäten und Experimente innerhalb des Moduls. Um einen ersten Eindruck vom Design und dem FLEXrack-Konzept zu erhalten, wird am EAC ein Prototyp errichtet und evaluiert. Abschließend werden Designanforderungen für das endgültige Design von FLEXhab, die Integration von FLEXrack in FLEXhab sowie für Simulationshabitate im Allgemeinen präsentiert.

Abstract

Analogues and simulations play an important role in preparation for space exploration. They allow us to test experiments before sending them into space, develop countermeasures for the special conditions, or study human behaviour in similar environments. The so called FLEXhab, Future Lunar Exploration Habitat, will serve as a lunar base analogue in order to create a training and experimental environment at the European Astronaut Center, EAC.

The design of a potential lunar base is very much affected by the specific environmental conditions. Therefore, these will be analysed to implement the effects into the analogue, with the goal to create a similar interior and to test countermeasures for specific challenges.

Additionally, an overview is given on the potential tasks carried out inside a lunar base, as well as the analogue, as they influence the habitat design as well.

This thesis presents a design for the interior of the FLEXhab working module, based on a previously developed concept. (O. Punch, T. Dijkshoorn, Spaceship EAC, 2016)

Furthermore, the so called FLEXrack will be presented, a recently developed movable rack system. The concept will increase flexibility for the exploration module design and increase the available space for tasks and experiments inside the module. To give a first impression of the design and the FLEXrack concept operationally, a prototype is built and evaluated at the EAC. Finally, design requirements for the final design of FLEXhab, the integration of FLEXrack within FLEXhab, as well as for analogues in general are presented.

A lot of people have contributed to this thesis in one way or the other...

The EAC team, by sharing their knowledge and experience, giving important input and feedback, and providing such a pleasant working environment:

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All my friends, by giving me such a warm welcome 'back on Earth'

My best friend

My family

Thank you

Abbreviations

ISRU: In situ recource utilization

EMU: Extravehicular mobility unit

EVA: Extravehicular activity

CROP: Combined Regenerative Organic-food Production

PBR: Photobioreactor

ESA: European Space Agency

EAC: European Astronaut Center

ISS: International Space Station

ECLS: Environmental control and life support system

GCR: Galactic cosmic rays

SCR: Solar cosmic rays

RAF: Random Access Frame

DPC: Daily planning conference

ISPR: International standard payload rack

EDR: European Drawer Rack

ICE: Isolated confined environment

Content

1. Introduction

The human race always tended to explore. In the past we explored different continents, during the cold war space exploration lead us to the Moon, and international cooperation finally allowed us to maintain a space station orbiting the Earth for almost 20 years now. It allows us not only to look back on Earth but also to take a further glance at new bodies to discover in the distance.

Before going on a long journey, for example to Mars, several challenges need to be accomplished. In order to do so, our nearest body in the solar system, the Moon, can serve as a test bed. Reachable within 2-3 days (Eckart, 1999: 100) it provides plenty of possibilities for research of itself and the universe.

As the International Space Station (ISS) will finally reach the end of its lifespan within the next decade, the goal of several space agencies around the world is to go back to the Moon. Different approaches have been developed so far. The so called deep space gateway, as its name already implies, shall serve as a gateway to move further into space but also allow access to the Moon. (ISECG, 2018)

Apart from that, the so called moon village has been announced by the European Space Agency as an international project similar to the ISS. A permanent lunar base, possibly located in the polar regions of the Moon will serve further research or even allow construction of radio telescopes on the far side. Once we learn how to sustain habitation on the Moon through developing technologies to use local resources such as regolith or water ice, we will be able to go further and settle on other planets, such as Mars. The Moon therefore is the essential stepping stone to reach our further goals. (Wörner, 2016)

1.1 Lunar base analogue

The very special conditions in space require even more special adaptions to allow human existence. Different kinds of technologies need to be developed, the impact on human behaviour needs to be studied, and countermeasures for upcoming challenges need to be investigated. Terrestrial conditions usually do not allow for testing all those things at the same time. Nevertheless, solutions need to be found to create at least similar conditions for certain experiments before the actual space mission.

Analogue missions create an environment or situation similar – or in best case identical – to those appearing in space. Reaching from similar environmental conditions, such as reduced gravity during a parabolic flight, to procedures in remote operations for e.g. controlling a lunar rover. (NASA [Analogue], 2017)

Those missions can prove the feasibility of technologies and operations as well as improve them. They also serve as a training possibility for future astronauts, which is of essential importance as time in space is very limited. Furthermore, the number of people going into space is limited as well. Therefore, analogue simulations also increase the number of test subjects for specific studies. For example: the socio-psychological aspect of a crew living isolated in a confined space does not have to take place in space. A similar confined environment can also be located on Earth to investigate upcoming problems or ideal composition of a crew on a larger number of subjects to create more relevant data. (Häuplik-Meusburger et al., 2017)

With the goal of sustaining a permanent lunar base, it seems obvious to create an analogue for simulations on Earth in advance. As terrestrial conditions do not allow simulation of everything at the same time as it will be on the Moon, different analogues exist for different purposes. Hence, for the design of a lunar base analogue it is necessary to first define the goals of the analogue. This requires consideration of the expected conditions as well as the capability to test them on Earth. Chapter 2 explains those conditions and their effects of a lunar base.

1.2 Personal motivation

Throughout all kind of architectural design tasks, a lot of different parameters are relevant. Depending on function, budget, context, resources and many more, a design is created that deals with those parameters in the most suitable way, always referring to the user's needs.

But some of the factors influencing our designs, our buildings and even the way we live, are never changing and therefore taken for granted. Standards and regulations have been developed throughout history for those conditions, resulting in standardised solutions, often similar and again, taken for granted.

Once removing or changing these constant conditions, our known standards are often not applicable any more. Suddenly gone, a design task does not start with defining a room program, it more starts with the definition of the overall purpose of a habitat, tasks that shall be carried out and the space needed for those. In other words, we need to start from scratch.

The completely different conditions, their effects on the design, and the different approach to a design task is what personally interested me the most when I first came in contact with space architecture during a course at the Vienna University of Technology. Planning for space, i.e. the Moon, allows one to look at terrestrial tasks in a different way and encourages us to question the common standards and to find individual solutions for what is really necessary.

Before starting this thesis I was part of a project where an office building was transformed into a home for students and refugees – the gap to space architecture appeared to be a big one. Looking a bit closer, the basic goal nevertheless is still the same: the design of an environment for human beings, according to their needs. Of course, on the Moon a building needs to provide much more, just to keep the inhabitants alive. But in the end, the environment is just one aspect of many, that together lead to different solutions.

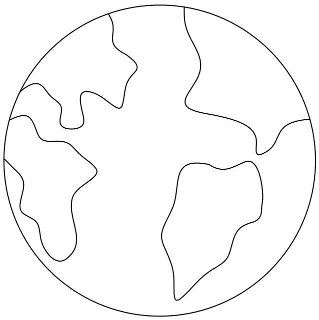
This is what makes architecture so interesting to myself. It is a tool that allows us to develop ideas, concepts, and solutions for so many different challenges.

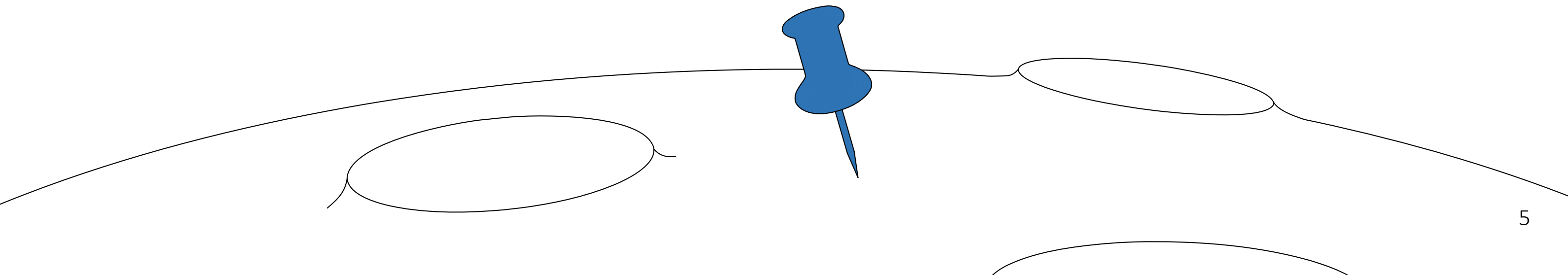
With missions to Mars, the periods of isolation in future space habitats will further increase, making their design, and therefore habitability, even more important. During six months at the EAC, as part of the Spaceship EAC initiative, and the design of a lunar base analogue facility, a contribution to increase habitability of future space habitat design was possible.

2. Lunar base interior design

For designing a simulation habitat, it is necessary to consider the design requirements for the actual habitat. The simulation should get as close as possible to the real constraints - according to its purpose. That means, for example, to study human behaviour in an isolated confined environment, the simulation has to take place in a similar sized space to a real lunar habitat. In that case, other things like the provision of air and water may not have to work in the same way because it is not relevant for the study.

Therefore, the purpose of the analogue needs to be defined, according to which aspects of the lunar base will be simulated.





2.1 Simulating the Moon

One of the major influences on a lunar base, is the environmental conditions of the Moon. These conditions will be analysed and evaluated in terms of possible simulations on Earth.

Some of the upcoming topics may be not as relevant for the analogue as for the lunar base, some conditions are even not possible to simulate at all.

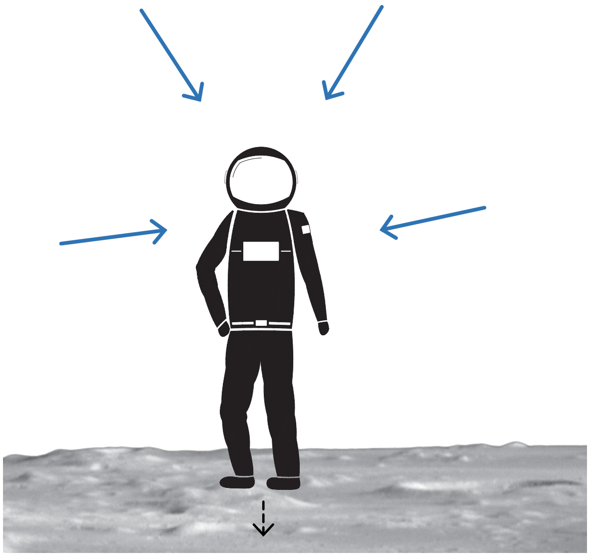
Apart from that, priority is given to the interior design. So some of the special conditions may create also other challenges such as technical or structural ones which are not discussed in detail.

Environment

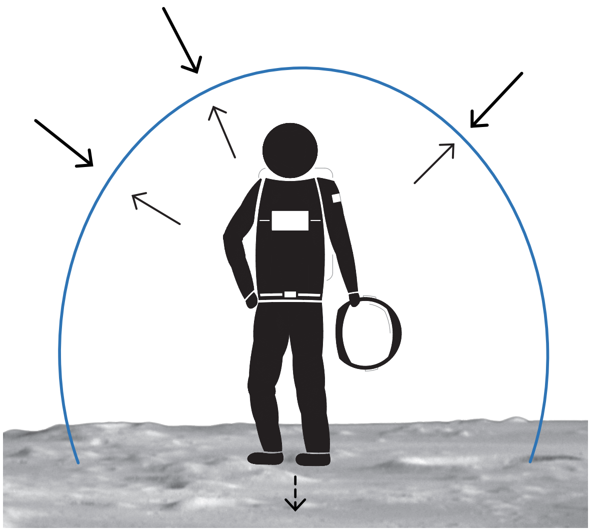
The harsh lunar environment needs to be analysed in order to create a lunar base that not just withstands but also protects.

Impact

Creating such a lunar base requires design and technologies that are adapted to all the challenges arising - not only from a technical perspective but also the effects on the humans living inside.



2.1 Influence of the lunar ennvironment

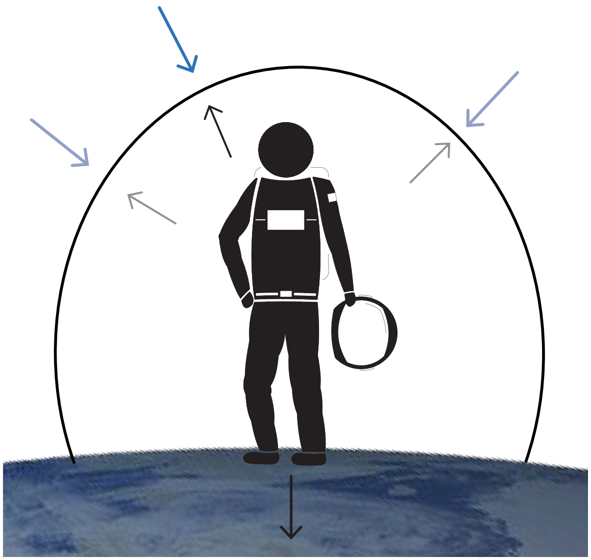


2.2 Impact on the habitat

Simulation

On Earth, the different environment only allows for simulation of some of the lunar challenges. The purpose of the lunar analogue finally decides which of those will be implemented and tested.

The relevant aspects for the later designed FLEXhab working module are highlighted.



2.3 Simulation of impacts on Earth

Environment

Gravity

Due to different masses of Earth and Moon, different levels of gravity apply. While on Earth, the so defined 1g, which means 9,807 m/s^2 prevails, on the Moon it is only about 1/6, i.e. 1,622 m/s^2. (Schrunk et al. 2008: 4)

Impact

This circumstance causes several issues that can be separated into technical- and human-related. On the one hand, less gravity for example means less structure needed for construction for vertical loads, which at first thought seems to be an advantage. But on the other hand, even though jumping sounds very tempting, the physiological effects on humans are, so far, more or less unknown. Less Gravity means less impact on the human body, resulting in loss of muscles as well as bone density, which is crucial especially when going back to Earth. (Eckart, 1999: 389ff.)

Even though it can be assumed that similar effects like in microgravity may apply (but less intense), we do not know about the long term effects. Apart from that, moving on the lunar surface can be quite challenging as we are not used to that level of gravity. Inside the lunar base, we may be confronted with different ways of movement, which could result in different ergonomics and different spatial requirements.

Atmosphere

The Moon has essentially no atmosphere (Eckart, 1999: 143). Therefore, additional difficulties arise.

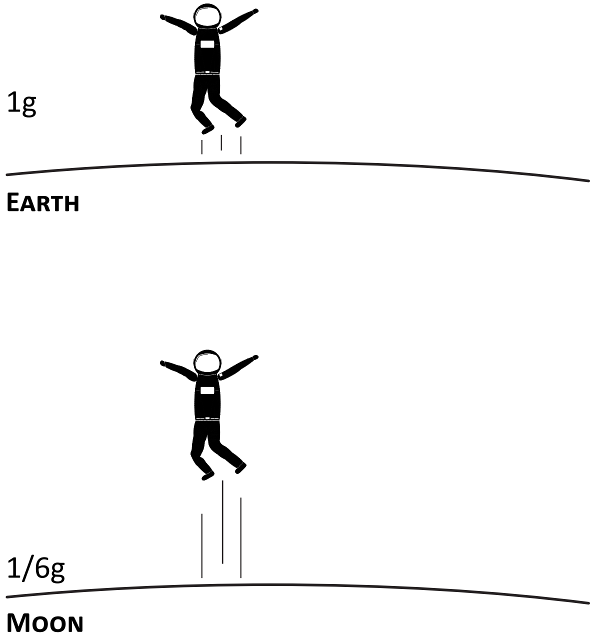
Humanity is adapted to Earth's atmosphere, which provides oxygen we can breathe, a pressure we can live in, and shielding against radiation (together with the magnetic field). Additionally, the lack of an atmosphere results in high variations of temperature and also affects the way light behaves before it reaches our eyes. (Schrunk et al, 2008: 4)

To survive without this atmosphere we need to create our own artificial environment that provides at least similar conditions to those on Earth. The lunar base, therefore, in any case has to be a pressurized volume, providing radiation shielding, thermal insulation, and oxygen. The latter can be added through a so called `environmental control and life support system' (ECLS) and does not much influence the design. The other topics related to the atmosphere will be discussed in more detail below.

Simulation

Reduced gravity and the aspect of moving are highly relevant for future lunar missions and may influence the design of a lunar base significantly. Unfortunately, on the surface of Earth we simply cannot create an environment with less gravity. Therefore, this aspect can only be simulated by creating at least similar conditions for example under water for the training of EVA`s (ESA [NBF], 2006), or in parabolic flights. (ESA [Zero-G], 2015)

Apart from that, reduced gravity is relevant in case of implementation of training tools for physical countermeasures. As exercise is a very important part of the daily schedule, for instance on the ISS, for simulating lunar missions it can be integrated even though it will not be exactly the same as on the Moon.



2.4 Different gravity levels of Earth and Moon

Even though the Earth's atmosphere gives us all we need, inside a closed volume we can still provide an artificial atmosphere if relevant for the simulation. Different kinds of compositions could be tested before using them in space as they have different effects on humans or, for example, sound transmission and even the choice of materials. (NASA [HIDH], 2014)

FLEXhab will be equipped with an ECLS, allowing for tests with different atmosphere environments.

2.5 The very thin atmosphere inside Skylab caused low transmission of sound, which made unaided communication very difficult
Credit: NASA

Environment

Impact

Pressurisation

As essential as the oxygen to breathe, is the right pressure. The absence of an atmosphere also requires artificial pressurisation of any space that shall allow human presence. (Eckart, 1999: 379ff.)

Pressurisation is probably the most influencing aspect for a lunar base in terms of construction. Creating a pressurised volume adds several constraints, which are unusual compared to terrestrial buildings. The hull has to be completely sealed. As leakage is critical, a modular layout is preferred and additionally, entering and exiting the habitat requires the implementation of an airlock or similar. (Eckart, 1999: 284)

Besides the technical challenges, the need of pressurisation also affects the interior of a lunar habitat. Contrary to Earth, the envelope has to take pressure from the inside, requiring a different structural approach than usual. The additional limitation of interior space due to launch systems often results in neglection of the architectural and sociological zoning of the habitat. (Vogler/ Jørgensen, 2004)

Temperature

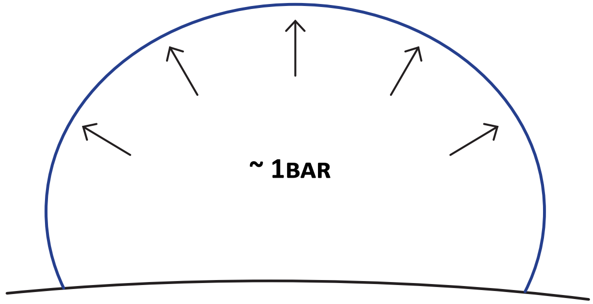
Related to the absence of an appreciable atmosphere are the high fluctuations in temperature. Depending on the presence of sunlight, the temperature varies from +127 °C to -173 °C at the equator. In permanently shadowed craters in the Polar Regions it may be as low as -230 °C. (Schrunk et al. 2008: 54)

To create an environment suitable for human life, insulation is required, supported by an ECLS for heating or cooling the habitat. Additionally, the temperature fluctuation will cause internal stresses of the stucture´s material that need to be considered.

Simulation

For a habitat on Earth, pressurisation is not necessary, but for creating a similar environment, especially for entering and exiting procedures and the test of closed loop technologies, it can be implemented. The pressure differential between the inside and outside of the analogue will be significantly smaller than on the Moon. This allows design of the habitat´s structure and layout according to the purpose of the analogue or other requirements such as parameters given by the building site.

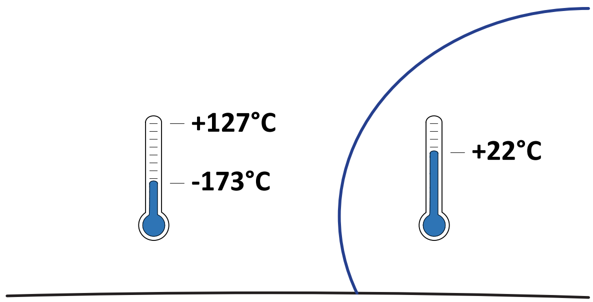
FLEXhab will be constructed as a pressure vessel to allow for an internal pressure for simulations.



2.6 Pressurisation resulting in different ideal forms for habitats

Focusing on the interior design, the technical challenges in that case are not as relevant in the simulation. Usual building technologies can be used. Only for the use in areas like Antarctica or in deserts, special requirements apply, which again do not really influence the interior design.

If the habitat is equipped with an ECLS, either for environmental or simulation reasons, maintenance work has to be considered, which means that accessibility has to be ensured. Floor, wall and ceiling can be designed as removable elements to provide easy maintenance.



2.7 Extreme temperature variations

Environment

Radiation

The atmosphere, as well as the magnetic field of the Earth protect us against almost all harmful rays. Without these, humans on the Moon are exposed to several types of radiation. Electromagnetic radiation from the Sun, which can actually be used for solar arrays as an energy supply. Ionising radiation though, in forms of solar cosmic rays (SCR) and galactic cosmic rays (GCR), is potentially lethal and therefore requires shielding. (Eckart, 1999: 144) In particular, galactic cosmic rays present a hazard as it is nearly impossible to shield against and their biological effects are not well understood. (Häuplik-Meusburger/Bannova, 2016)

Impact

The possibilities of radiation shielding with different kind of materials for a lunar base are still under research. As the effects of radiation can be critical, especially for long duration missions, a solution is indispensable.

Current studies for example evaluate the capability of lunar regolith[1] as radiation shielding using an ISRU[2] approach. (Spaceship EAC, 2018) Besides that, the chosen material for radiation shielding may influence the structure and, therefore, the interior of the habitat.

Furthermore, radiation shielding is even harder to achieve with glass, which limits the possibility of windows. Apart from natural light coming in, the view to the outside is of high psychological importance. (Vogler/ Jørgensen, 2004)

The psychological effects of having no direct view of your surrounding have been tested in several simulations before (e.g. Mars 500, p.50). No possibility to look outside, especially while being on the Moon, might be even more depressing and influencing the mood of the crew members.

[1] **Regolith:** The term was first proposed by Merrill, 1897 as *"[…] the layer or mantle of fragmental and unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface of the land and overlies or covers the bedrock. It includes rock debris of all kinds […]"* (Heiken et al, 1991) Originally a terrestrial term, now commonly used for material covering the lunar surface as 'lunar regolith'.
[2] **ISRU:** In-situ resource utilisation; use of local resources. e.g. using lunar regolith as building material instead of bringing materials from Earth.

Radiation protection is not necessary for an analogue as shielding is naturally provided. Therefore, it is also not affecting the design.

Nevertheless, whether or not windows are integrated in either a Moon base or a simulation habitat makes a big difference. For the simulation additional constraints arise. As the habitat should serve as a Moon base, a window should show the lunar surface. Based on Earth, that implies some kind of simulated window, either digital or analog. Several approaches for the implementation of virtual windows can be tested in the simulation, such as images or screens. Additionally, the view to a greenhouse or plants in general can create a similar positive effect. (Häuplik-Meusburger/Peldszus/Holzgethan, 2010)

2.8 Cupola, ISS. Looking outside as one of the favourite activities on the ISS (Häuplik-Meusburger, 2011)
Credit: NASA

Environment

Meteoroids

Without any natural protection, the lunar surface is not only hit by all kind of rays but also by solid bodies, the so called meteoroids. Smaller than asteroids or comets they hit the lunar surface at 13-18 km/s. Their impact has formed the lunar surface over the past million years and still represents a hazard for all elements on the lunar surface. (Eckart, 1999: 148)

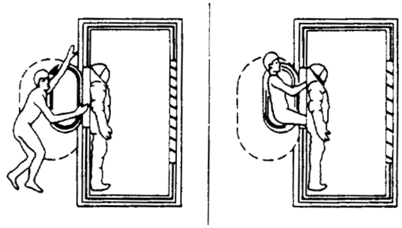
Impact

A lunar base needs to be shielded against meteoroid impact, either by natural features such as a cave, or by its structure. Similar to radiation shielding, this is especially relevant for the implementation of windows.

Dust / regolith

The lunar surface is covered by a 4 to 15 m (depending on the location) thick layer of regolith. This very fine grained rock material can cause serious issues for future lunar missions, as it is also highly adhesive. Equipment, EMU[3] and tools get covered very quickly, which can lead to failures. Very fine particles may even get into people's lungs. (Eckart, 1999: 122ff.)

Astronauts entering the habitat from the lunar surface are bringing regolith inside the habitat. Solutions for dust mitigation therefore need to be implemented into the airlock. A concept to avoid regolith inside the habitat is the 'suitport' which allows the astronauts to doff the suits without contaminating the habitat (Cohen, 1995).



2.9 Access to suitport. (Cohen, 1995)

[3] EMU: Extravehicular mobility unit; 'Space suit'

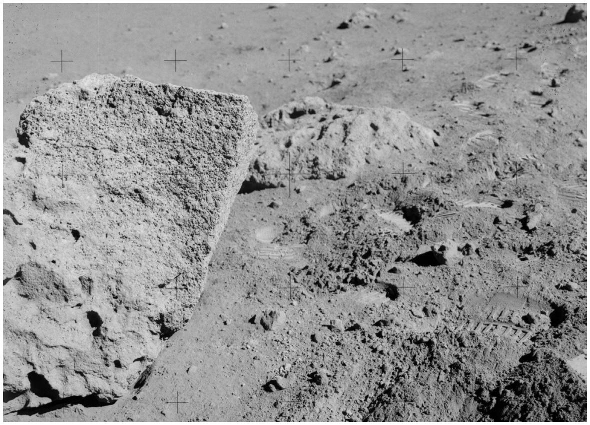
Simulation

Meteoroid impact is not relevant for an analogue on Earth. Only in case of special simulations, for example structural tests, the habitat needs to provide appropriate shielding.

2.10 Impact of meteoroids on lunar surface. View from lunar orbit
Credit: NASA

Simulating those conditions requires an environment with similar material to the lunar surface. The so called regolith simulants, such as the EAC-1, are commonly used for tests and simulations on Earth and can also be used for simulating a lunar surface environment. (Spaceship EAC, 2018) Together with a Lunar base analogue, simulations would allow investigation of technologies for dust mitigation. Apart from that, simulations are often done in deserts for similar environmental conditions. (HI-SEAS, p.50)

FLEXhab will be located next to a simulated lunar environment to allow for simulation of EVAs[4] and dust mitigation.



2.11 Lunar Regolith layer
Credit: NASA

[4] **EVA**: Extra vehicular activity, leaving the space habitat, such as the ISS or a lunar base, requires EMU

Environment

Light

The Moon as a natural satellite, takes about 27 days for one rotation around the Earth. As the Earth is orbiting the sun, it takes 2.5 days more until the same alignment of Earth, Moon and Sun is achieved again. This is described as one synodic month or one lunar day. (Eckart, 1999: 110)

Those orbital parameters result in a 14-day-night-14-day-light cycle at the equator. On the poles, they lead to a cycle of ½ year light, ½ year night. Some craters are even in constant shadow. (Eckart, 1999: 114)

Therefore, depending on the location, different lighting conditions can be found, which is particularly relevant for the selection of a lunar base site. Nevertheless, all places on the Moon have completely different timespans of sunlight than on Earth, which on the one hand creates technical difficulties, especially the provision of energy through solar arrays. On the other hand, the circadian rhythm of 24 hours that humanity is adapted to is no longer sustained.

Due to the harsh environment, in particular radiation, direct sunlight for humans on the Moon is impossible. The lack of sunlight does not only result in psychological but also physiological effects. (Kolodziejczyk/Orzechowski, 2016) Countermeasures in forms of artificial light are therefore indispensable.

Additionally, no atmosphere results in no particles to scatter light, which further resuls in a high contrast environment due to almost no ambient light. This in turn results in extremely difficult light situations, caused by different inclination angles of the sun and the extremely dark shadows. (Eckart, 1999: 142)

Impact

The absence of natural light is one key factor causing difficulties in maintaining a stable circadian rhythm.

Without the Sun, providing different light situations on a 24 hour cycle, astronauts experienced disruptions in sleep-wake cycles. (NASA [HIDH], 2014: 772) This generally reduces performance and can also result in different cycles within the crew, causing social tension. For sustaining a healthy and pleasant environment for longer stays at a lunar base, an appropriate simulation of natural lighting is therefore required.

The absence of ambient light is not relevant for the interior, as Earth-like conditions in terms of atmosphere have to be provided anyway.

Simulation

A simulation habitat can basically have two different purposes in terms of light:

1. Providing the same conditions as on the Moon to study their impact.
2. Test artificial lighting systems acting as countermeasures, such as Earth-like lighting.

Both cases require a closed environment. That matches with the idea of virtual windows due to the limited openings caused by radiation and meteoroid shielding.

The habitat needs to provide ambient lighting that compensates the missing natural light. Additionally, specific lighting is required for activities, such as repair work that requires brighter illumination.

Apart from that, terrestrial Polar Regions can serve as natural simulations for different day-night-cycles.

The closed environment of FLEXhab will allow for tests on the effects as well as countermeasures to the lunar environment.

2.12 High contrast environment due to missing ambient light
Credit: NASA

Conclusion

For creating a realistic analogue of a lunar base, the real conditions need to be considered. As not all of these topics are relevant for all kinds of simulations, the goal of the analogue has to be defined in order to get the relevant requirements.

The previous analysis shows that the lunar environment mostly influences form and shape of the habitat. The construction technology will affect the interior shape of the habitat and therefore cause different constraints.

Regardless of weather materials are sent completely from Earth or build by ISRU technologies, a lunar base will (at least for the near future) always have to deal with limited space, isolation and confinement. Apart from the environmental aspects, the main driving factor is the capability of the launch system. As an example, the Falcon Heavy is shown in image 2.13. (SpaceX, 2015)

On Earth the environmental aspects of the Moon have no direct influence on habitat design. That means that the shape of the habitat can be chosen, for example, referring to a specific lunar base concept. Additionally, Earth based requirements such as transport or location may be the driving factors. Also some of the environmental factors on Earth need to be considered for the analogue as well. In a high fidelity simulation of a lunar base, the sound of rain on the habitat´s roof for example, needs to be avoided.

One of the biggest challenges of the lunar environment is the lighting situation. Appropriate solutions shall be tested to create an Earth like environment inside the volume. Not only because of the limitation of windows in a lunar base, but also due to the different day-night-cycle.

Isolation and confinement can not only cause social tensions within the crew but also physical effects such as myopia due to no possibility of looking into distance (Benaroya, 2010: 182). The so called sensory monotony caused by the everyday same small environment (Schlacht, 2012: 30) may decrease the crew’s performance, which is why countermeasures should be established.

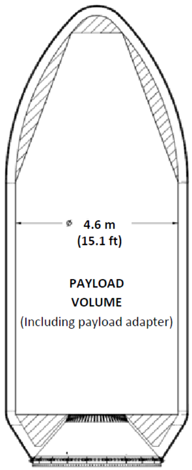
Further requirements will be added by the tasks that should be carried out during the simulations. Those will be analysed in the following chapter.

Applicable in FLEXhab:

- Light
- Dust mitigation
- Atmosphere
- Pressure

Falcon Heavy payload:

- 4.6 m diameter
- 11 m total height
- 8,300 kg into geosynchronous transfer orbit



2.13 Falcon Heavy+
Payload capability
Credit: SpaceX

2.2 Simulating activities

Similar to terrestrial buildings, the design is not only influenced by the environment, but also, and maybe even more importantly, the function of the building. The user and their requirements add a lot of constraints to the space they live in. Starting with the basic functions such as sleeping, eating, hygiene and exercise, the main purpose of a lunar base will definitely be science. Therefore, it is not only a space for accommodation, but also a workspace and laboratory.

Future lunar missions are by now not defined in detail. Any concept of a lunar base proposed now has to be flexible enough to integrate a variation of functions or experiments. In the following, tasks relevant for a lunar base will be described, according to their challenges and requirements. Similar to the last chapter, those will be, if possible, transformed into the simulation on Earth. In this thesis, the focus will be on working activities, referring to the later designed working module.

For the FLEXhab working module, mostly working activities will be relevant. Those tasks will be highlighted.

Activities

Movement

Getting from one point to another in the reduced gravity of the Moon requires adaption. Not only the way people move needs to adapt, also the environment around the people must adapt to whatever kind of movement they perform.

Spatial requirements

The possibilities of testing and analysing human movement in lunar gravity are still limited. The Apollo astronauts on the lunar surface had the additional restriction of the EMU, which made moving even harder. Inside a lunar base it is still unknown if and in which way the habitat needs to be adapted to the gravity condition.

Simulation

Unfortunately, lunar gravity can only be simulated through parabolic flights, allowing people to experience that special conditions for about 23 seconds in a row of 31 parabolas. (ESA [Zero-G], 2015) Therefore, tests and outcomes are very limited. A similar effect can be achieved through under water training in a neutral buoyncy facility. (ESA [NBF], 2006) Analogues on the surface cannot simulate lunar conditions and adhere to Earth standards. Dimensions and volume required for moving and activities in partial gravity are given by Adams (1999).

2.14 Apollo 12 astronaut on lunar surface
Credit: NASA

Activities

Spatial requirements

Sleeping, privacy and personal space

Missions to the lunar surface, especially when speaking of sustaining a permanent lunar base, will go on for several days or even months. Therefore, astronauts need a place to sleep as well as a place for privacy.

The length of the mission has a big influence on the requirements of such a space. For short time stays of several days it could be kept at a minimum, while for longer periods it is essential for the astronaut's wellbeing to have a room for privacy, personal equipment or just a place to retreat. *"If humans can't retreat spatially, they will retreat socially."* (Hagner, 2016, lecture)

According to Adams (1999) the space for sleeping in partial gravity requires 85x215x85 cm (HxLxW). Additional space is required for stowage, dressing or personal work. The longer the mission, the more volume is required for each crew member.

Apart from that, electricity, light, and data connection need to be provided, as well as acoustic isolation.

History of space flight has shown that the crews often had problems with sleeping due to the light environment as well as noise and medication was often necessary. (Kolodziejczyk, 2016) On the Moon, with the absence of natural light, similar problems are very likely.

Exercise

The effects of partial gravity are still under research, for example through bed rest studies done at Envihab, Cologne (Clément, 2017: 29). Similar effects than in microgravity will appear, but less intense. Therefore, physical exercise is required to reduce the effects on the human body. Apart from that, physical exercise can serve as a stress relief and is therefore often used as a leisure activity.

Considering that all crew members will have to exercise every day (based on ISS experience) these kind of activities will occupy a significant area within the habitat. Additionally, sound or visual separation needs to be considered, depending on the layout of the base. Space needs to be adapted to the equipment used, such as a treadmill or a cycle ergometer, as well as the volume needed for people moving. Spatial arrangements should be achieved to not disturb other crew members while exercising through sound and vibration.

SIMULATION

For the simulation, the same requirements apply as for the lunar base. Little differences may only occur due to different movement according to gravity levels. The duration of the simulation therefore defines the spatial requirements.

As an example, the personal compartment on the Mars 500 missions have been equipped with a bed, a little desk and some storage space, as shown in image 2.15. Even though very limited, according to Romain Charles, participant of the 520-day mission, it contained everything needed and could have even been smaller. Nevertheless, taller people had issues with the length of the bed. (Charles, 2017, personal converstaion)

2.15 Romain Charles inside his private compartment during the Mars 500 mission
Credit: IBMP

As physical exercise plays such an important role, it should be part of the daily schedule in a simulation as well. Different equipment might be tested, size and location of the designated area need to be adapted to the size of the crew and equipment. The test of a variation of equipment may require easy replacement of these. Additionally, an attractive design of the space for exercise can help against arising laziness during long duration simulations.

2.16 ESA Astronaut Frank de Winne during exercise on the ISS treadmill
Credit: NASA

Activities

Spatial requirements

Eating / Food

On a lunar base, due to high costs and limited payloads food supply needs to be as efficient as possible. Additionally, things have to be stored over longer periods of time. That, firstly, means storage space needs to be available, and secondly, fresh food is more or less impossible, apart from things grown in-situ.

For example, food supply for the ISS is mainly pre-cooked on Earth and packed while increasing shelf life. Preparation is done through heating and/or rehydrating. (NASA [HIDH], 2014: 593ff.)

Lunar conditions make cooking much more likely, even though there are still a lot of other constraints, from the creation of steam, up to additional safety issues.

Nevertheless, cooking and good meals are things missed the most on previous space missions or analogues (Romain, 2017, personal conversation). Not just the improvement of the meals is very important to the crew, also the social part of having meals together is a very important aspect for the social interaction. Having at least one meal per day, attended by all crew members, has proven to be of vital importance in several analogues as well as on the ISS (Häuplik-Meusburger, 2011: 218). Therefore a lunar base needs to provide a table for all crew members having a meal together, as well as space for storing and preparation. The latter may improve in the future, which will make the implementation of a kitchen necessary.

Hygiene and housekeeping

To cover the basic human needs, a Lunar base requires a toilet and waste management system. Contrary to the very difficult condition in current space habitats due to microgravity, the toilet on a lunar base can potentially be a bit more Earth-like. Unlike uncomfortable showers in microgravity, like in Skylab (NASA [HIDH], 2012: 599), comfort in personal hygiene can be added through more Earth-like devices.

For sustaining a clean, hygienic environment, also housekeeping has to be considered. (Häuplik-Meusburger, 2011: 130ff.)

Toilet, shower and a sink is probably what can be seen as the basic features in a bathroom with similar spatial requirements as on Earth. Visual separation is necessary. Humidity and odour may require seals. Humidity may also affect the use of materials as well as cleanability. For housekeeping, dust mitigation plays an important role, due to regolith, as explained in chapter 2.1.

Simulation

Within an analogue, depending on the simulation, the technical difficulties may not be relevant.

The reduced capabilities in food supply can easily be simulated in case it is relevant for the simulation. Considering long duration mission scenarios, the same capacities for storing food have to be taken into account.

Studies can be done on the required space according to types of food consumed. For example, if more food is prepared fresh, requirements for the space as well as for equipment will change. An evaluation for future lunar missions can be done on Earth.

2.17 Crew having breakfast at Mars 500 analogue
Credit: IBMP

Dust mitigation plays an important role inside a lunar base. Therefore, tests and simulations are highly relevant for an analogue as well. Those simulations require space to test different equipment as well as procedures for entering the habitat, mostly affecting the airlock of an analogue.

The spatial requirements for hygienic activities do not differ from conventional terrestrial ones.

The FLEXhab working module will only be equipped with a toilet.

2.18 Shower on Skylab
Credit: NASA

Activities

Leisure

Some time within the astronauts´ schedule is also reserved for leisure activities. Common activities are physical exercise, reading, watching films and series, and group activities. In particular, social interaction with other crew members is not just relaxing but also important for the performance of the crew. Watching movies, play games, or work on personal projects together are just a view possibilities. (Häuplik-Meusburger, 2011: 264ff. / Charles, 2017, personal conversation)

Spatial requirements

While other tasks are often allocated to specific areas of the habitat, the free time can be spent wherever preferred. Therefore it is important that areas of different qualities exist. In particular different levels of privacy are necessary. Apart from the possibility of private retreat, also smaller group gatherings should be possible without disturbing others, as well as a space to comfortably accommodate all crew members for common activities. Most important is the possibility of personal choice which activities to attend and which not, to avoid social tension or give room for relief in case of those. For example, doors or windows between private and common areas can allow or limit visual and acoustic connections, according to current personal preference. (Vogler/ Jørgensen, 2004)

Storage

All of the previous mentioned activities basically require some sort of storage for food, tools, equipment, personal belongings, waste and many more. Enough and well organized storage is essential for an efficient workspace.

Depending on the mission duration and re-supply capabilities, space for storage needs to be included. The challenge is not just to provide enough space but also to allow easy access for the crew.

Communication

During isolation on a different planet with a very limited amount of people, connection to friends and family proved to be of vital importance for the psycho-social well-being of the crew members. (NASA [HIDH], 2012: 650ff.) The possibility to interact visually via video conference, audio or at least emails can therefore be seen as a basic need within a lunar base.

Apart from private communication, also interaction with ground control is necessary to define tasks, or simply keep everyone updated.

Private communication should definitely take place in a separated area, ideally a private compartment, separated visually and acoustically.

Work related communication might require the attendance of all crew members and therefore requires a place which allows appropriate communication as well as the necessary equipment, such as screens, microphones etc., usually already covered by a laptop.

Simulation

Within recent simulations, lots of studies have been done on the psycho-sociological aspects of isolation. As the built environment also influences the life of its inhabitants, a well-designed habitat can contribute either in a positive or negative way. Before going into space, those aspects are highly relevant as social tensions can represent a serious risk of mission failure. (Häuplik-Meusburger, 2017) Different spatial layouts or designs in general can be tested to develop solutions supporting a mission.

"[...] You just took the vacuum cleaner between the legs, turned it on and then you flew like a rocket inside the station."

(Prunariu, 2011, cited after Häuplik-Meusburger, 2011: 267)

In simulations, re-supply is much easier and depending on the fidelity of the study, storage space within the habitat can be reduced through additional external storage. Nevertheless, the same conditions can be provided as on the Moon if required for the simulation.

"[...] Sometimes a prayer to St. Anthony, patron saint of lost articles, is more effective"

(Jones, 2010, about disappearing stuff at the ISS)

Communication during a simulation can be artificially provided in the same way as it would be on the Moon. Delays can be added and transfer of data can be limited. Apart from testing the psycho-sociological impact of communication, also upcoming technologies such as virtual reality can be tested for communication purposes (Häuplik-Meusburger et al., 2017).

FLEXhab can simulate delays in communication with ground control according to the simulation.

2.19 Video conference with the ISS
Credit: NASA/Carla Cioffi

WORK

The main purpose of a lunar base, as well as the later designed FLEXhab, is the scientific work, either on the lunar surface or on specific experiments. As no specific mission scenarios are defined so far, only assumptions can be made on what work related tasks the crew of a lunar base would have to carry out. An additional necessity is maintenance to sustain the habitat.

Activities	Spatial requirements
EVA	
Exploring the Moon is one of the main reasons for building a lunar base. Going outside to investigate the lunar surface, as well as to take samples and test technologies, will therefore be one of the main tasks for astronauts. EVAs generally require intensive preparation and support. The astronauts conducting an EVA need to perform the pre-breathing or also called 'Campout' to prevent decompression sickness. During the EVA, support will be given by the crew inside the base through audio and video. Additionally, for future mission scenarios, the astronauts on the lunar surface might be assisted by a lunar rover or robot. (NASA [ISS], 1998: 238ff.)	For exiting and entering a pressurized volume, an airlock is necessary which allows for decompression. During preparation for the EVA it needs to be big enough for the number of crew members conducting an EVA, including space to put on the EMU and doing physical exercises throughout the pre-breathing protocol. (NASA [ISS], 1998: 238ff.) For support from the inside, a computer workstation is required, allowing communication, visual connection, or even control of robotics.
Robotic- and remote operations	
Rovers and robots will assist astronauts during EVAs, but can also be used independently for remote exploration of the lunar surface.	For the control of rovers or other kinds of robotic operations, a workstation is required containing the necessary controls, such as joysticks, depending on the tasks. Additional screens compared to a normal workstation might be necessary to allow different views from the outside (helmet camera of the astronaut, view from rover, etc.) as well as for indicators of sensors or vital data of the astronaut. (Spaceship EAC, 2017)

[5] **Canadarm**: Robitic arm of the ISS to move objects and assist docking

Simulation

For an analogue, the same procedures are applicable as preparation for EVAs is a very important aspect in the training of astronauts. (ESA [NBF], 2006) Lunar gravity compared to Earth gravity might result in different requirements of space needed, but nevertheless, the simulation should allow the same tasks to be carried out.

FLEXhab will be attached to a lunar surface environment to simulate EVAs.


2.20 EVA preparation on the ISS
Credit: NASA

The simulation allows testing of a variety of elements for those operations. Procedures in interaction and controls can be evaluated, the workstations and controls as well as their layout can be adjusted. If several people are involved in the operation, the configuration of workstations could either support or impede the communication between crew members. Easy adaptations on the workstations themselves as well as their location should therefore be possible.

FLEXhab will allow for robotic operations


2.21 Operation of Canadarm[5] on the ISS. Credit: NASA

Activities

Spatial requirements

Experiments

Apart from the exploration of the Moon itself, a variety of scientific experiments will be executed inside the lunar base. For example, from the previous described EVAs, samples will be analysed, tests for in-situ resource utilisation will be carried out, and also studies on the impact of reduced gravity on the human body are very likely.

For sample analysis a geology workstation and specifically a glove box, possibly similar to the one on the ISS, has to be integrated.

It can also be assumed that experiments need a certain amount of infrastructure, such as electricity, water, data, or even gas. Wherever experiments shall be located, sufficient provision of those needs to be provided. Apart from that, certain tasks may require special light, visual or acoustic separation, or even to be sealed, which has to be considered in the habitat design. Specific requirements have to be evaluated for each task once defined.

Maintenance

Maintainability is a very important aspect for space habitat design. Preventive and corrective maintenance occupied a lot of time in past and present space missions and should be kept at a minimum. (NASA [HIDH], 2014: 806ff.)

Clearly stated in NASA´s HIDH (2014, 806ff.) accessibility for inspecting, removing, or replacing equipment needs to be provided, considering also potential protective clothing worn by individuals.

This accessibility not just affects the visual appearance of the habitat due to gaps, handles, and seams, but also the interior layout. Space for these tasks needs to be provided. For example, access to the floor may require movement of furniture and equipment. Therefore, the location of frequently accessible elements needs to be optimised as well as the space that is required for certain tasks. Removing a panel of the wall, for example, needs to provide a space next to the wall with at least the dimensions of the panel with additional space for the astronaut to grab it.

Simulation

Scientific tasks and experiments should also be implemented into the habitat as they are not only essential for the daily life of a lunar base but also provide a possibility for training. Definition of the purpose of the analogue, and further the experiments done, will allow specification of the spatial requirements.

FLEXhab will host a variety of experiments.

2.22 Glove-box on the ISS
Credit: NASA

The simulation allows for testing of the most suitable solutions for maintenance, optimisation of the location of certain systems, and even application of different designs for a comfortable interior. Apart from that, procedures for different tasks can be evaluated as well as the required space within the habitat.

Maintaining the habitat itself, as well as simulating maintenance activities are relevant for FLEXrack.

2.23 New rack on the ISS
Credit: NASA

Conclusion

Simulating the activities of a lunar base is technically not a problem. Different levels of gravity, nevertheless, do not allow for simulation of the same spatial requirements. The interior design of an analogue therefore adheres to spatial conditions of the Earth. However, especially the aspect of maintainability of the habitat adds additional constraints to the overall interior design. Solutions to meet the technical requirements as well as a pleasant interior environment need to be developed.

Overall, the variety of tasks and their different requirements, in particular the different levels of privacy, require special attention and individual solutions to increase crew comfort in future space missions.

Testing different spatial configurations and designs of a habitat may allow definition of requirements for future space habitats.

Tasks relevant for FLEXhab:

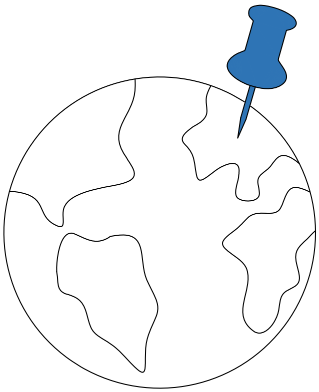
- \+ **Maintenance**
- \+ **EVA**
- \+ **Robotic operations**
- \+ **Experiments**
- o **Hygiene**

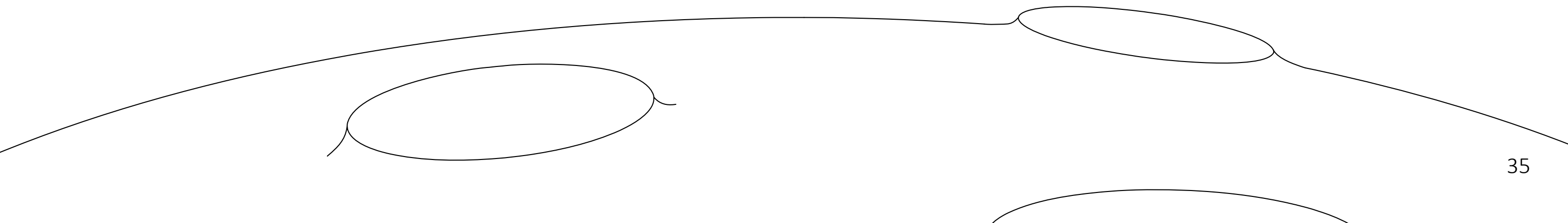
3. Lunar base analogue

This chapter focuses on the design of one specific lunar base analogue: the so called FLEXhab, Future Lunar Exploration Habitat, developed by the European Space Agency at the European Astronaut Center.

From the former described environmental aspects and activities inside a lunar base, the relevant ones will be chosen regarding the planned purpose and capabilities of the analogue. Some things may be more important than others, some may be even irrelevant.

Before doing that, the concept and previous work by the EAC will be described, as well as the requirements given for the design of the interior.





The European Space Agency and the EAC

More than 45 years ago, on December, 14, 1972 Eugene Cernan left the Moon at the end of the Apollo 17 mission. Since that moment, no human has made a step on the lunar surface again. But in all those years, another project in space has been carried out: the International Space Station, ISS. Starting its construction in 1998, the ISS may reach the end of its lifespan in the next decade (ESA, 2013 / ISECG, 2018: 12).

Therefore, new targets need to be set, so done recently by ESA director general Jan Wörner: the establishment of a permanent lunar base, called `moonvillage'. Similar to the ISS, international cooperation should make this ambitious project reality. (Wörner, 2016)

ESA therefore has clearly set its focus of the next decades on going back to the Moon. That also means that future astronauts must be trained for lunar missions as they are now trained for their missions to the ISS.

This is where the European Astronaut Center (EAC) comes into play. As the training facility especially for European Astronauts, but also for others training on all European contributions for the ISS, it needs to extend its capabilities for the upcoming tasks (Spaceship EAC, 2017).

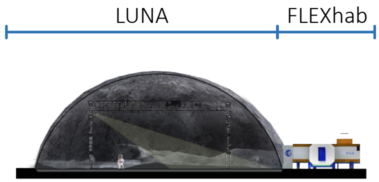
As one first step, the LUNA project was already established and will soon start its construction. A dome with a diameter of 35 m will simulate the lunar surface to train astronauts, as well as test new technologies.

Furthermore, the Spaceship EAC initiative was created in 2012 to focus on many different fields *“to investigate innovative technologies and operational concepts in support of ESA’s exploration strategy.”*(Cristoforetti, 2016). The author had the chance to be part of the initiative for six months.

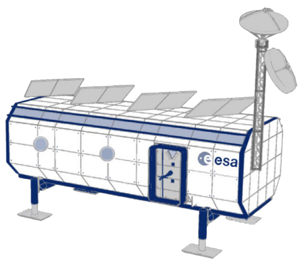
As one of many projects within Spaceship EAC, the FLEXhab simulation habitat will extend the training capabilities of EAC. It will provide the lunar base from which the lunar surface inside the LUNA dome can be accessed. Additionally, all kinds of tasks can be simulated and tested in the analogue environment, from experiments over design approaches to the control of robots inside LUNA.

The FLEXhab

To create a lunar base analogue, several parameters have been defined for FLEXhab, which will be listed in chapter 3.2. The general approach was to create a habitat, which, as based on Earth, can be built without the cost driving factors of usual spacefaring habitats. Apart from that, the habitat should be equipped with commercial off the shelf (COTS) products to save time and costs, but also as a general approach of testing and improving



3.1 LUNA and FLEXhab.
Credit: Orla Punch



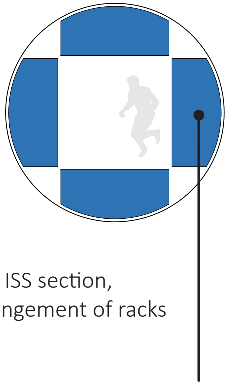
3.2 Flexhab working module
Credit: Orla Punch

COTS parts and technologies for space applications.

Based on the requirements as listed below, a first 3D-model has already been created as a basis for the final design. But so far, only concerning the envelope and technical infrastructure of the habitat.

At the time this thesis is written, the final design of FLEXhab's envelope and structure was still in progress, but defined by technical requirements with input from the EAC team.

The concept of the habitat should provide a lunar base environment in which not yet defined tasks can be carried out. Therefore, a high amount of flexibility is required for the internal space. According to that, the so called FLEXrack concept was developed. (Orla Punch, 2016)



3.3 ISS section,
arrangement of racks

3.4 ISPR - European Drawer Rack
Credit: ESA/D.Ducros

3.5 Archive storage
Credit: DRs Kulturarvsprojekt

The FLEXrack

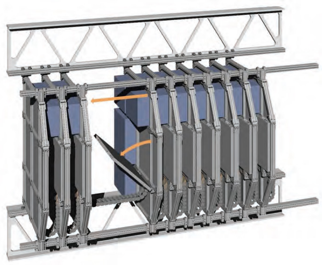
A rack system basically provides a modular layout of components, such as experiments, furniture, or storage, to allow exchangeability as well as replaceability of those modules. Taking the ISS as an example, the international standard payload racks (ISPR) can be placed on floor, walls, and ceiling due to microgravity (image 3.3). Furthermore, new experiments can replace old ones by exchanging the racks as a whole, or in part, due to the standardised size and infrastructure. Different arrangements are possible during the lifetime of the space station, which was not only necessary due to the modular assembling over several years, but also due to the previously unknown experiments that are now placed there. (NASA [ISS], 2000)

Microgravity in that case has a big advantage. The racks on the ISS, such as the European drawer rack shown in image 3.4, are quite bulky (1046x850x1836mm) and heavy (about 500 kg at launch) without that being a problem. (ESA [EDR1], no date; ESA [EDR2], 2001)

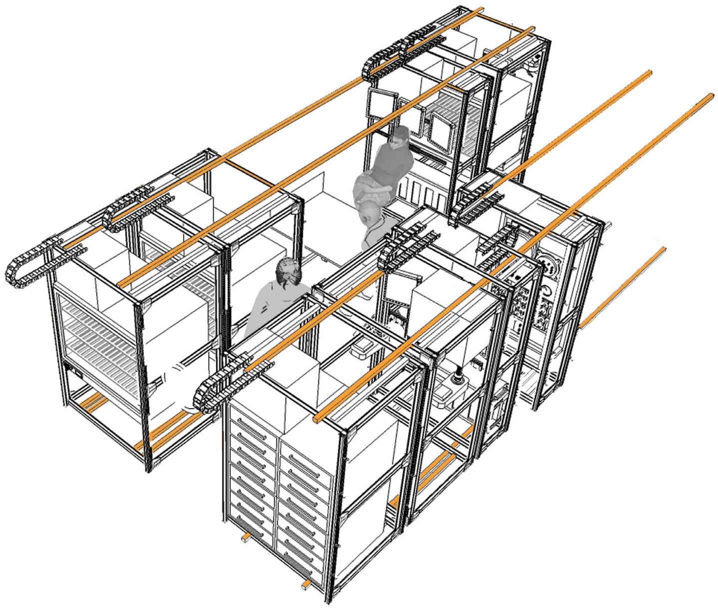
On Earth at least a similar, if not even higher level of flexibility is required, due to the unknown upcoming tasks as well as the possibility of cooperation with other agencies or industry as well as different types of trainings. Therefore, a rack system was developed, adapted to Earth's conditions and FLEXhab requirements. All this should be achieved by a sliding system, in which the racks are integrated. Racks can then not only be rearranged by replacing them, but also for different mission scenarios or even different activities. Racks currently not in use should be moved to the side to open up space for things that need to be accessible. Comparable to storage systems in libraries or archives where corridors are only opened up when needed (image 3.5). Supported by folding mechanisms to create different situations, the use of the interior space of the habitat will be as efficient as possible, while sustaining a high level of flexibility.

A similar approach has been developed by NASA´s JPL (Jet Propulsion Laboratory; Howe / Polit-Casillas, 2014), the so called Random Access Frame, RAF. Located on a sliding system, standardised frames can be used to attach all kind of things like experiments and containers. Moving them on the slides allows different configurations for different purposes. Unlike needed for FLEXhab, the RAF concept was developed for microgravity.

Nevertheless, FLEXrack will follow a similar approach adapted to the requirements of FLEXhab with the use of COTS products to allow easy reconfiguration of the habitat.



3.7 Random Access Frame
Credt: Howe, A. Scott / Casillas, Raul



3.6 FLEXrack concept, previous work
Credit: Orla Punch

3.2 Requirements

Several requirements apply to the design of the habitat defined by the EAC through previous work by Orla Punch, Thomas Dijkshoorn and Victoria Nash (Spaceship EAC, 2017). Those will be explained in the following.

FLEXhab is considered as a modular habitat. Starting with the working module, habitation and greenhouse modules are meant to be added at a later stage.

Furthermore, in this thesis priority is given to requirements relevant for the interior design. Specific technical requirements relevant e.g. for external support structure or ECLS subsystem are therefore only mentioned if affecting FLEXhab's internal space in some way.

Even though the later phases will be kept in mind during the design process, priority is given to the first stage of the project because the main purpose of the first module will not change a lot afterwards but will get extended.

The primary objectives of FLEXhab have been defined as following:

1. Develop and validate future crew operations concepts
2. Develop and validate new training methods for both ground personnel and crew
3. Technology demonstration platform

Further, secondary objectives are defined as:

1. Provide human analogue habitat capabilities and technology demonstration platform to external partners
2. A test-bed for experiments and concepts relevant to EAC

Additionally, requirements for the design apply:

1. Simulating the interior of a lunar habitat at an affordable rate
2. Directly connected to LUNA
3. Transportable
4. Fully functional within a range of climates
5. Lifetime >10 years
6. Construction based on ship building expertise

(Nash, Spaceship EAC, 2017, internal document)

Based on that, technical requirements as well as the structure shown in images 3.11 and 3.12 have been developed previously. The list and plans below are serving as the envelope on which the following studies are based. Apart from adding an interior design and integrating the FLEXrack concept, the goal is also to evaluate for further definition of architectural requirements for FLEXhab.

Layout and construction

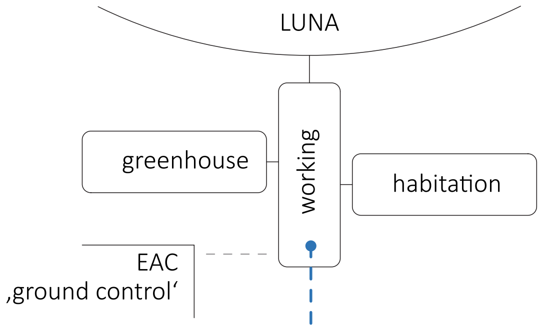
Modular layout in 3 phases:	1) **working module** 2) habitation module 3) greenhouse
Module design:	Transportable through european roads (EU Directive, 2015)
Dimensions:	Outside: 3.50 x 10.54m Inside: 3.26 x 10.32m
Interior Layout:	Engineering compartment Airlock Main compartment
Hatches:	Airlock for access to LUNA Access to modules 2 and 3 Emergency exits Supply opening

Technical

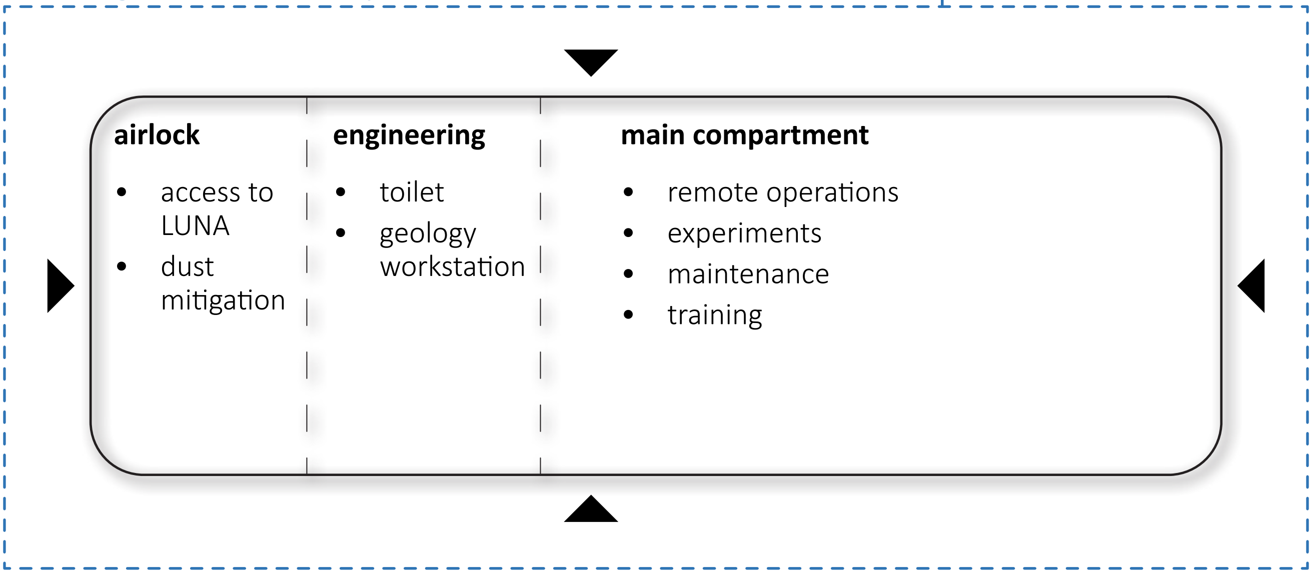
Pressurisation	Internal pressure of 1.3 bar
ECLS	Temperature control Air conditioning Energy provision through solar arrays
Maintenance	Removable wall panels Removable false floor Easy accessibilty

FLEXhab overview

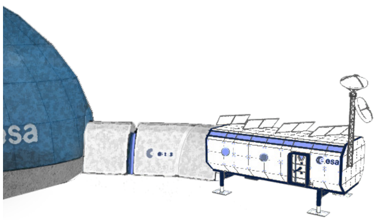
3.8 FLEXhab final stage
Credit: Orla Punch



Working module - floor plan scheme



3.9 FLEXhab working module, floor plan scheme



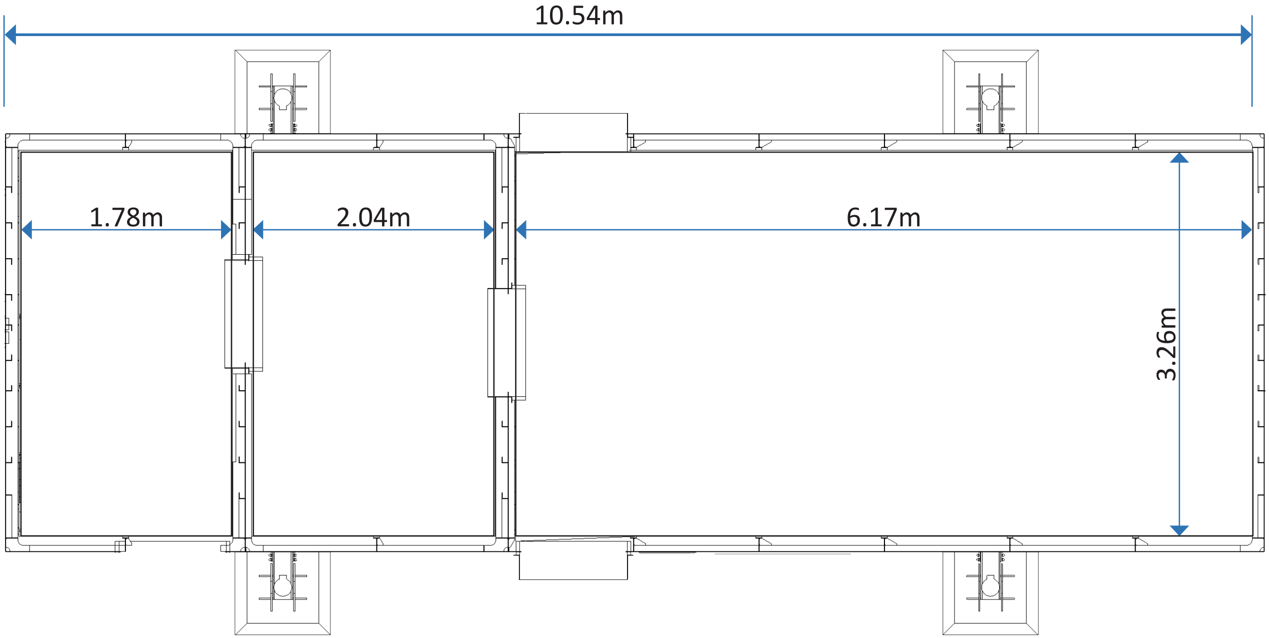
3.10 FLEXhab working module attached to LUNA
Credit: Orla Punch

Simulation and training

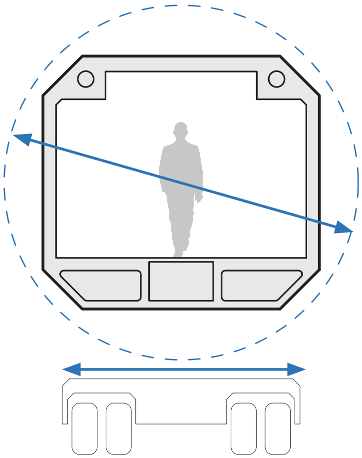
Crew	2-4 people
Duration	First phase: 1 day Later phases: up to 4 weeks
Organisational Structure	Open platform for use also by externals
Types of simulations	Laboratory for different experiments
	Provide lunar base design
	EVA´s to LUNA
	Robotic operations
	Astronaut training
	Technology demonstration

Payload/Racks

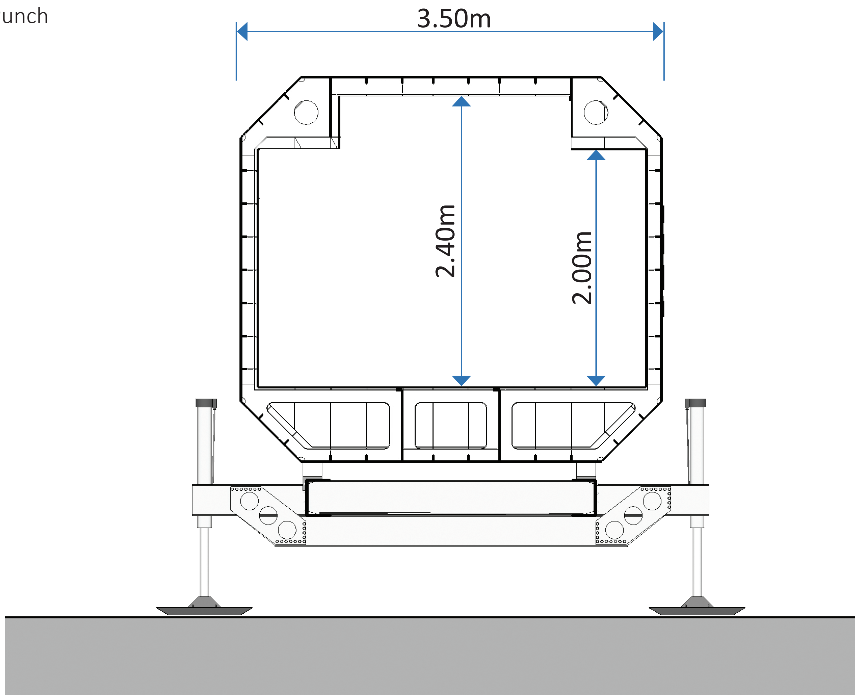
FLEXrack	Robotics General maintanance Communication EVA support Experiments Storage
Non-FLEXrack	Toilet Geology EVA-suit storage



3.11 Floor plan. Credit: T. Dijkshoorn / O. Punch



3.12 Dimensions depending on launch system and/or transportation limits.



3.13 Module structure, section. Credit: T. Dijkshoorn / O. Punch

Apart from project specific requirements, common and legal standards need to be considered for the design as well. Those are summed up in the following.

Legal

As it is mainly a workspace, regulations for workspaces shall be met as a requirement by the EAC. Generally speaking, for such a specialised research facility it is hard to simply apply legal regulations. First of all, the goal is to develop individual solutions for a special environment on a very limited space. The absence of daylight for example would already interfere with usual regulations for working environments. Standards in room dimensions might be hard to achieve while staying in a realistic lunar base scenario. Therefore, special approval or permissions are very likely inevitable.

Apart from that, the habitat is meant to be relocated, which means that at each individual location different regulations would apply according to national law.

Nevertheless, in order to meet certain health and safety standards for the habitat and its users, the legal framework needs to be considered and if not applicable taken as a guideline in order to create at least a similar level of safety and health care through individual solutions.

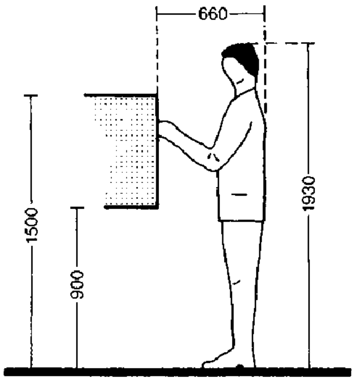
Located in Germany, the German workplace ordinance (Verordnung über Arbeitsstätten, ArbStättV, 2004) is the most relevant document for work space requirements. It describes the basic environment of different types of work spaces but also more specifically describes requirements for e.g. computer workstations. Basically, the target of this regulation is to create a workspace as comfortable and safe as possible for the workers. Further details are described in the more detailed technical rules (Technische Regeln für Arbeitsstätten, ASR). There, everything from minimal space of an office desk to requirements of lighting in circulation areas is described and stated as the current state of the art. In case of deviations or different solutions, it has to be individually proven that at least the same level of safety and healthcare is reached.

During the design studies (chapter 4.1), the relevant and applied legal regulations will be mentioned as well as nonconformities.

Ergonomics/Anthropometry

As for any other human related design task, the human body itself defines several parameters according to the task that has to be carried out. Especially when having a very limited available space, mostly the

3.14 Minimum dimensions for office workspace as stated in ArbStättV ASR A1.2.
Credit: VBG Hamburg



3.15 Human dimensions for basic tasks. Credit: Neufert (2002)

minimum dimensions needed are taken into account. The very common "Neufert Bauentwurfslehre" (Neufert et al., 2002) gives dimensions as a first guideline for many different cases related to architectural design. Apart from that, as mentioned above, the legal requirements also serve as guidelines, as they are based on human ergonomics to meet the most suitable solution for the user's health and safety. Additional requirements might be necessary due to the special conditions.

Besides literature for terrestrial design tasks, throughout history of space travel, specific standards and guidelines have been developed for the very special conditions in space. A comprehensive reference work is the Human Integration Design Handbook (NASA [HIDH], 2014). It is giving requirements on a huge variety of human related design aspects. Similar to that, the man system integration standards (NASA [MSIS], 1995) provide similar requirements as well as design examples for space craft design.

For precise design, a definition of the user population would be necessary, as human anthropometry varies a lot. In ergonomics, different models exist for that reason. Those models are usually based on a distribution of people from a certain population. The minima and maxima are then defined through percentiles. For example, the user population defined for the ISS by NASA was involving people with international background. For the minima, the 5th percentile Japanese female, while for maxima the 95th percentile American male had been defined. That means, that 5% of Japanese females would be smaller than the minima, while 5% of American male would be taller than the maxima. However, it turned out that lots of past crew members exceeded those values, which means that for similar projects, like the moonvillage and therefore the FLEXhab, a new user population has to be defined. (NASA [HIDH], 2014: 40 ff.)

That very precise approach of anthropometric values, becomes especially necessary and complex when designing specific tools or applications where many different values such as arm length, crushing grip, pinching etc. have to be taken into account. For example, the design of a workstation with all its handles and controls has to be designed for a specific task with all its requirements, suitable for as many possible users as possible, or adjustable to those.

The overall design of the interior nevertheless will be designed in a way to fit human anthropometry. The applicable dimensions, referring to human scale will be described during the design process in chapter 4.1.

Safety

Apart from all the requirements referring to the comfort of the crew, also safety issues need to be considered.

According to the regulations for working places within Germany, the applicable dimensions especially for escape routes in case of fire will be implemented as well as the requirements for lighting in case of an emergency. Through the previously defined requirements there is already an adequate supply of openings for exiting the module. Special attention needs to be given to FLEXrack as throughout different configurations the escape routes and their dimensions need to be fulfilled.

Apart from this, methods of preventing and recognising a fire have to be set. As the analogue facility will be equipped with a variety of sensors due to the ECLS, that will be achieved without additional effort. Apart from that, ongoing simulations will be monitored through the external ‘ground control’, which means that any special occurrences will be noticed immediately.

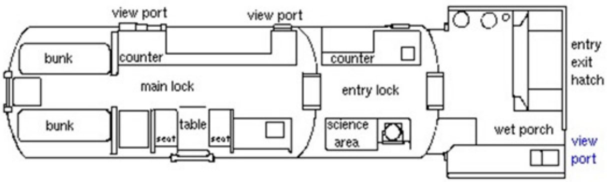
The use of different materials needs to be considered regarding flammability, but also with respect of the monitoring of the habitat.

Existing analogues, as well as actual space missions and habitats, obviously serve as an important reference. On the one hand, their design can be evaluated to define certain requirements. On the other hand, the impact of isolated, confined, and extreme environments from a psychological and physiological point of view can be analysed in order to develop solutions for countermeasures that can be tested in future analogues. As summarised in Häuplik-Meusburger et al. (2017) examples of relevant analogues are given in the following.

NEEMO / Aquarius

The Aquarius underwater facility within the NASA Extreme Environment Mission Operations (NEEMO) is located off the coast of Florida and allows simulations of up to 3 weeks, while testing equipment, tools or operations within the habitat. Furthermore, the underwater location allows simulation of EVAs with different levels of gravity. (NASA [NEEMO], 2011)

Especially relevant for the design of future analogues is the Habitability Assessment, done on Missions NEEMO 1 to 5 (2001-2003). This evaluation of human factors inside the habitat gives important input. For example, the analysis has shown that the table designed was too small to accommodate the crew of 4 and especially in cases with 6 crew members. (NASA [NEEMO-HABITABILITY], 2004) As the table was used quite often for different kind of tasks, a more appropriate size would improve the comfort of the crew members as well as social interaction. Even though, the habitability studies bring some relevant insights for analogue design, the main purpose of NEEMO was never meant to be research in human factors or habitability. Therefore, the interior is obviously improvable to increase crew comfort.



3.16 Floorplan of Aquarius/NEEMO. Credit: NOAA

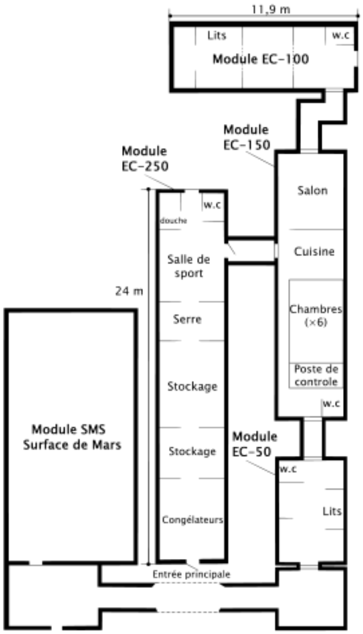
3.17 Interior of Aquarius/NEEMO. Credit: NASA

Mars 500

The Mars 500 analogue allows simulation of long term missions, in particular a simulated trip to Mars with a crew of six. Lasting 520 days, this was the longest simulation carried out which led to a series of results about the effect of long term isolation. For example, it was observed, that two crew members lost the 24 hour day-night-cycle, due to isolation. (Charles, 2017: personal conversation)

Apart from the studies throughout the simulation, personal feedback and input was given by Romain Charles, attendee of the 520 days mission. His insights from the mission have been implemented into the design as well as the final requirements.

3.18 Living room in Mars 500. Credit: IBMP



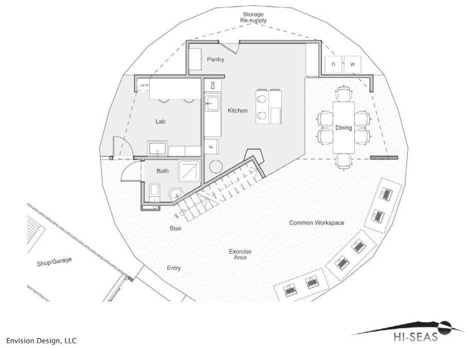
3.19 Floor plan, Mars 500
Credit: Armael

Mars 500 and NEEMO in particular follow a similar spatial approach as FLEXhab. Consisting of either one or several modules with similar dimensions, feedback and evaluation of the spatial design can serve as an important input.

HI-SEAS

The ‘Hawai’i Space Exploration Analog and Simulation’ has so far accomplished five missions, lasting from 4 to 12 months. Even though it follows a different spacial concept than other analogues, various long duration simulation studies on analogue habitability have been done and are therefore particularly relevant.

Within a dome with a diameter of 11 m, two levels are located. The ground floor accommodating the communal areas, such as kitchen, dining room, work space, and exercise area as well as a bathroom with shower and toilet. The upper floor consists of the six bedrooms for the crew members. All conditions of the simulation, including the habitat, are designed to be similar to those of a planetary surface exploration mission. (HI-SEAS [MediaKit] 2016). Due to the dome structure, different interior heights are achieved as well as a visual connection from the ground floor to the upper floor. As this is a different interior situation than most other analogue facilities, the outcomes of the habitability studies are of particular interest. Nevertheless, the study is still in progress, preliminary results already give some insight on the relation of social and psychological aspects in relation to the habitat. (Häuplik-Meusburger et.al. 2017)



3.20 Ground floor HI-SEAS
Credit: HI-SEAS, edited by the author

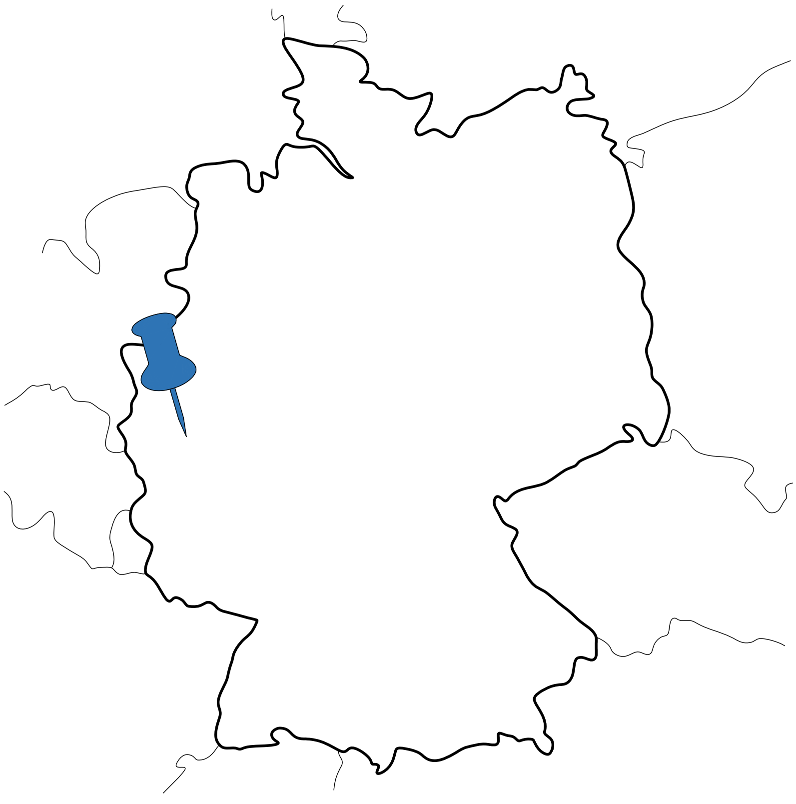
3.21 HI-SEAS interior. Credit: HI-SEAS

In general it is fair to say, that most analogues nowadays investigate the effect of ICEs (isolated confined environments) on humans social behaviour, more and more with the awareness of the impact of the built environment.

As a next logical step, not just the impact of a common situation needs to be studied, but also countermeasures for the observed social and psychological phenomena need to be developed and tested in an analogue. According to the achieved knowledge, improvements in habitat design can further be used for space applications to reduce the upcoming impact of isolation and confinement.

4. Prototype development

In the following chapter a design for the FLEXhab working module is developed, which will then be transformed into a prototype. Based on the analysis of the lunar conditions and activities, the given requirements will be transformed into an interior environment, specifically adapted to the FLEXrack concept.



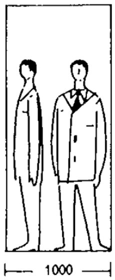
The previously described concept and requirements have been developed at EAC (Spaceship EAC, 2017). The purpose of this thesis therefore is not only designing the interior with the given situation, but also evaluating it.

The existing 3D-model of the module, including the structure which defines the maximum interior volume, the general layout of the three compartments, as well as the general and technical requirements given by ESA are considered as defined for the following studies.

While considering the legal, ergonomic and safety standards, that concept will now be complemented by functional and visual elements in order to meet the given requirements and to create a lunar base simulation.

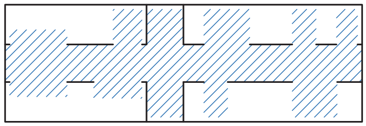
4.1.1 Access and internal translation

As described in chapter 3.2, the developed structure of the module allows an interior width of 3.26 meters. First of all the width of the translation path needs to be defined. It has to be considered, that this dimension defines the available usable space of the module and therefore needs to be chosen carefully. According to Neufert (et al., 2002: 31), at least 1 m is required for two people standing next to each other, as shown in image 4.1. Additionally, in case of movement, 10% need to be added, resulting in 1.1 m.



4.1 Dimensions according to Neufert (2002, 31)

According to Adams (1999) translation between activities for one person requires at least a space of 215 x 82.5 cm. Depending on the configuration of the racks, the actual limitation of the translation area can reach from several meters to only parts of one meter, depending on rack size. An example is given in image 4.2.



4.2 Limitation of corridor width

Furthermore, transition of equipment and even racks needs to be considered. Limitation is already given by the supply opening. That is by now referred to the ISPR racks and might be adapted to the actual size of FLEXrack dimensions. As those haven't been defined yet, adaptations might be necessary in a later stage.

Safety regulations require a minimum width of 87.5 cm for escape corridors for up to five people in the habitat. Doors can be smaller as they are only partially reduce the width. (Verordnung über Arbeitsstätten, 2004, ASR A2.3)

To create a corridor that still allows passing of crew members according to tests in a similar environment with several dimensions, a minimum width of 1 m is chosen, which also allows carrying bulkier equipment such as parts of racks.

The interior layout is highly influenced by the given requirements of access points. With the airlock, the main access point for EVA simulations is defined. Furthermore, an additional supply opening on the opposite side of the module requires a translation area through the whole module, as well as for safety regulations. The addition of other modules, connected through the main compartment, requires another two access points. By connecting these access points, two different solutions can be created:

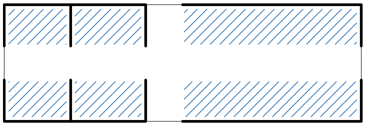
1. **Central corridor:** a corridor in the centre along the longitudinal axis and an orthogonal addition to access the other modules. In doing so, a space on each side of the corridor is created as the actual usable area.
2. **Side corridor:** an eccentric translation path on one of the long sides of the module. Instead of two separated areas, one bigger area is created in each compartment.

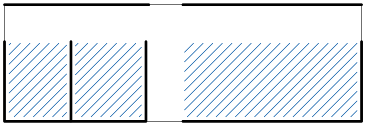
In both variations, the access to future modules are placed opposite each other to create short ways as well as to avoid transit through the working area. For the same reason they are located next to the engineering compartment.

Due to the later integrated FLEXrack system, which requires a railing system, hybrid solutions are not considered to keep the racks within as little lines as possible. To evaluate the best solution, a trade off displays the differences.

Trade-off

Available space:

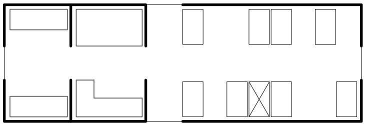


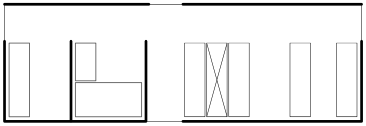


4.3 Corridor in the centre
4.4 Corridor on the side

• Main compartment: **500 x 110 cm (x2)**	**500 x 220 cm**
• Engineering compartment: **200 x 110 cm (x2)**	**200 x 220 cm**
• Airlock: **170 x 110 cm (x2)**	**170 x 220 cm**

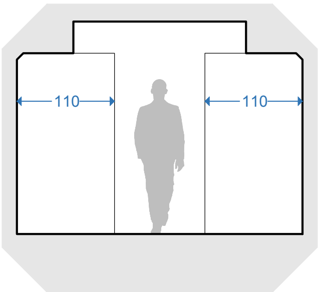
Racks (main compartment)

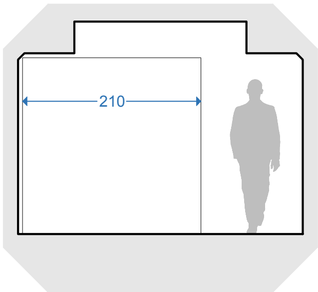




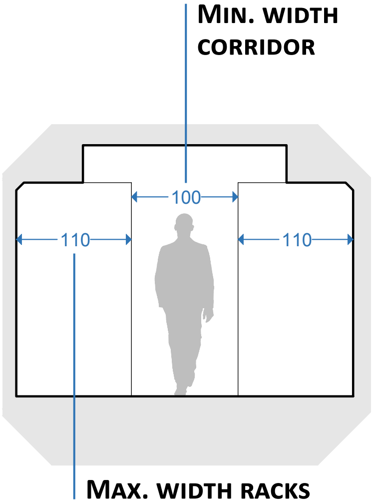
4.5 Rack size corridor centre
4.6 Rack size corridor side

• **Amount: 9** (same depth for both cases)	**5**
• **Max. dimensions: 110 x 200 cm** (W x H, depth variable)	**210 x 200 cm**

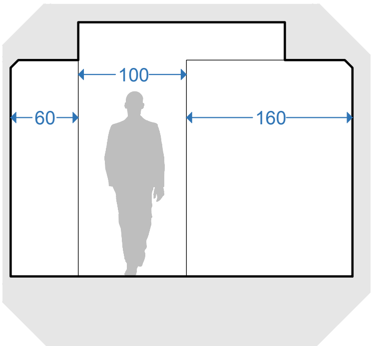




4.7 Section corridor centre
4.8 Section corridor side



4.9 Division of translation and accommodation area



4.10 Eccentric corridor creating different sized racks.

The solution with a central corridor is preferred for the following reasons:

1. **Interior shape:** the specific symmetrical shape of the interior rather suggest an also symmetrical layout, especially due to the lower ceiling on the sides. (image 4.7 and 4.8)

2. **Light:** the later described interventions in case of light also support that layout. (Chapter 4.1.3)

3. **Rack size:** a large variety of smaller racks (size of about 100 x 80cm) is expected. For an arrangement that allows easy access to individual racks, the corridor in the middle seems to be more appropriate, especially in the main compartment, where the application of movable racks is planned. (Image 4.5)

4. **Engineering compartment:** separation of areas within the engineering compartment is done already by the corridor. With a side corridor, dividing it into two zones for the required toilet and geology workstation would be hard to achieve.

The actual usable space for racks, equipment, workstations, and experiments in a symmetric layout is therefore limited to a width of about 110cm, not considering any separation or structure in-between. Further development such as the integration of rails for movement, panels for walls, or lighting will additionally reduce the available space to about 1 m.

Based on previous concepts as well as current rack systems, the available maximum width allows an appropriate dimension of the racks. Also many of the experiments within Spaceship EAC would be suitable. One reference is the so called CROP and PBR[6] system, which is planned to be one of the payloads of FLEXhab. It is currently operated within a rack of 94x78x180cm. As one of the bigger experiments now known to become part of the FLEXhab, it can be taken as a guideline for rack dimensions.

Shifting the corridor to one of the sides as shown in image 4.10 would create different sized areas and racks. As this would reduce the exchangeability of racks between the two sides, a symmetrical layout is preferred.

The integration of different functions into the racks, as well as their design will be discussed in chapter 4.2.

[6] C.R.O.P: Combined Regenerative Organic-food Production; a biofilter system developed by DLR in Cologne, which is capable of providing fertiliser solution for the cultivation of plants using human urin. The solution is used to feed algae in a photobioreactor (PBR). The so achieved bio-regenerative life support system uses human waste to help cleaning the air of a habitat while the algae serve as a source of protein, lipids, minerals, and vitamins for the astronauts. (Just, Spaceship EAC, 2018, personal communication)

4.1.2 Interior volume

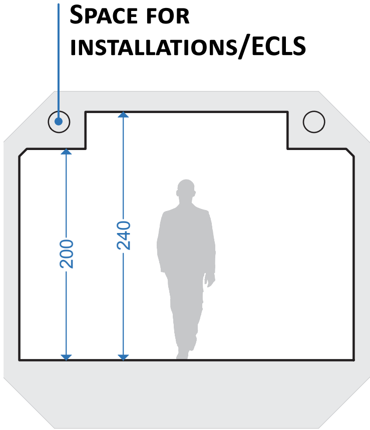
The interior height requires special attention as it is very limited in the current structure. The functional shape as shown in image 4.11 reduces the available height on the sides from 2.4 m to 2.0 m. As already mentioned, this symmetrical shape supports the chosen layout and additionally defines the side zones as the more accommodating zones due to the reduced height. It implies, especially for tall people, that tasks are carried out while sitting, which vice versa would shift tasks for standing and walking more in direction of the corridor.

In general it is to say, that the available volume, especially once equipped with racks and workstations, becomes a very confined space. Therefore, the goal is to set actions to visually increase the perceived volume. In the following, these design actions are explained.

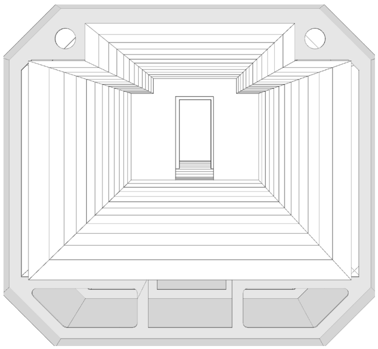
First of all, as stated in the technical requirements (chapter 3.2), the wall panels need to be removable, resulting in some kind of grid due to seams. Depending on material, colour, and mounting, those can be more or less visible, but in any case will influence the visual appearance of the module. Based on the grid of the construction and a distinction of the translation and accommodation area, dimensions of the panels are defined with the goal to create balance between panel format and the amount of visible joints for the visual appearance.

An additional element is added by the later introduced FLEXrack, which requires some kind of rails in order to allow for the movement of racks. Those rails add a strong visual element to the longitudinal axis of the module, which will be balanced by the grid of the wall and floor panels.

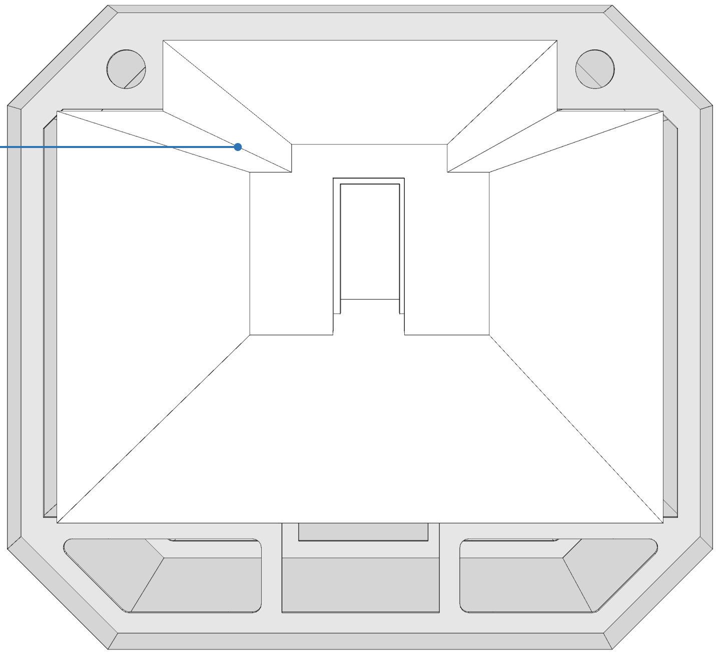
To strengthen the distinction between the two zones in the module even further, the top and bottom edges of the room will be cut off by a 45 degree angle in order to create space for cable management and other infrastructure needed for the racks. (Image 4.14) The so achieved shape is associated with current modules of the ISS, which could even be pushed further with similar lighting coming from the edges on the top (see following chapter light) to create a familiar environment for current astronauts. Besides that, removing the 90 degree edges, especially in that area with reduced height, the envelope appears more accommodating.



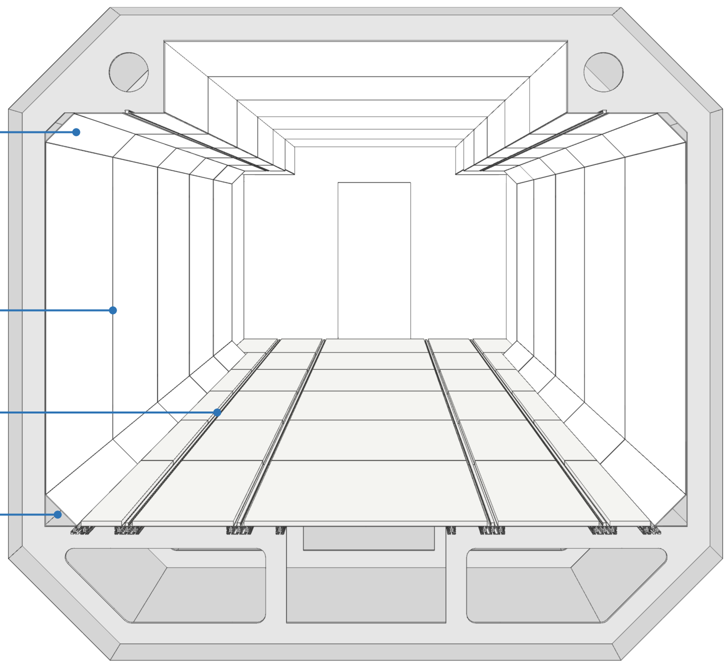
4.11 Interior heights



4.12 Example for visual appearance of panel dimensions



4.13 Main compartment interior



4.14 Gaps and rails influence visual appearance

4.1.3 Lighting

Through the implementation of indirect or diffuse lighting of the ceiling, the perceived interior height will increase. (Image 4.17) Additionally, more advanced concepts are necessary to compensate the absence of natural light, as already mentioned in chapter 2.1. Lamps allowing different light temperature provide simulation of different times of the day, similar to Earth-conditions. Also the effect of different cycles can be studied and evaluated in order to find the most suitable one for future missions. Those measures are in particular relevant in the later stages of the project where the duration of missions will be increased by a habitation module. (Kolodziejczyk/Orzechowski, 2016)

To not only open up the space vertically but also horizontally, a similar approach will be applied to the walls; several other aspects also lead to the introduction of the concept henceforth described as ‘window reveal’.

Within terrestrial buildings, especially when it comes to office and workspaces, the most commonly found situation of natural light are windows, providing light from the side. Apart from light coming inside, people also have a view to the outside, which not only allows them to look into the distance and have a view of their surroundings, but also widens the interior space as illustrated in image 4.16.

In chapter 2.1 the integration of windows into a lunar base simulation has already been evaluated as generally counterproductive. A solution has to be worked out which is more of a simulation than a real window, especially due to the two different scenarios: simulating the Moon and testing countermeasures.

To create a similar physical space compared to a real window, a partial setback creates a window reveal. This setback not only serves as a visual element, it will also serve as rails for the FLEXrack system and further allows the implementation of a secondary rail system that will be described in 4.2.

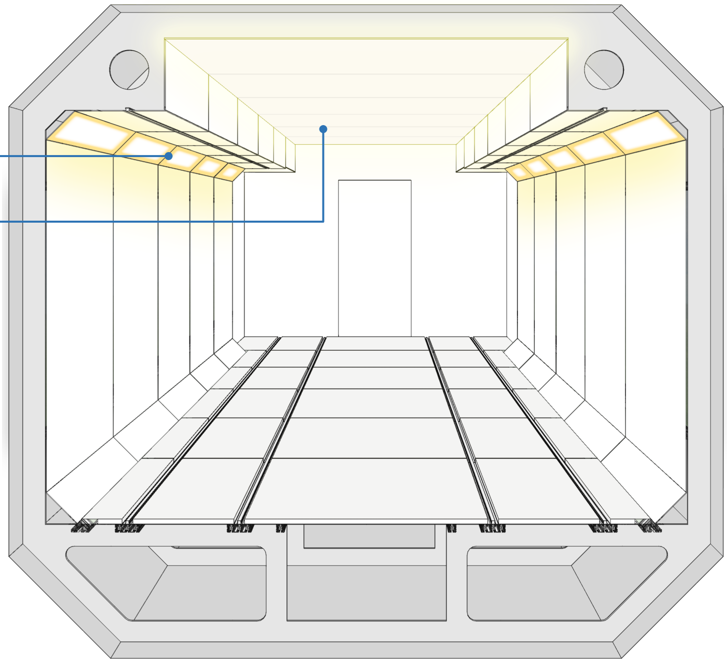
The area within the window reveal will serve as a light source through the use of backlit translucent glass, acrylic glass or similar. Size and position are adapted to the available height, which implies tasks mostly be carried out while sitting.

Together with illumination of the ceiling ambient light is provided for the whole module. Lamps within the edges provide illumination of certain areas and can be seen as task light. More specific solutions need to be implemented as well, according to special tasks. As most of the functions take place in racks, additional light will primarily be implemented in those.

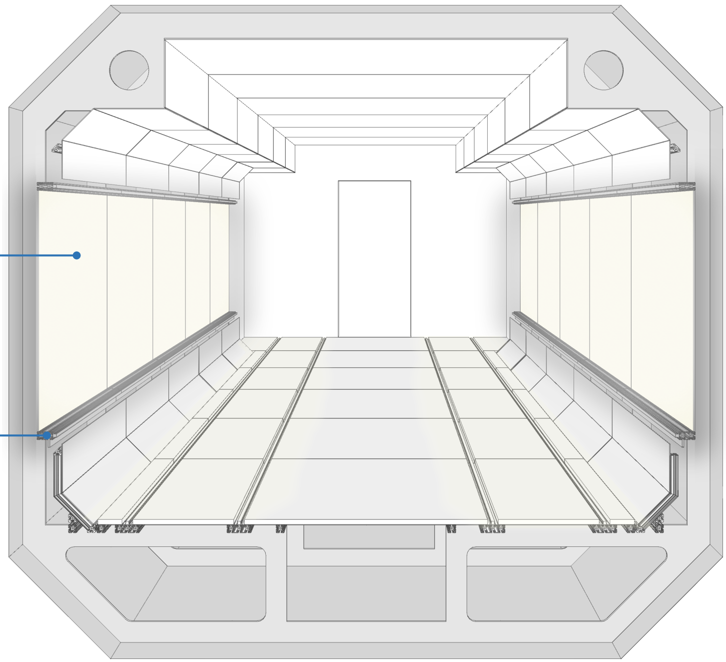
4.15 ISS interior. Credit: NASA

4.16 Windows providing light and extend the space visually

4.17 Ambient skylight and additional light through edges similar to ISS



4.18 Window reveal as ambient light source and simulation of surrounding



4.1.4 Materials and colours

The use of colours and materials has a strong impact on the interior space, especially in isolated, confined environments. So far, space habitats such as the ISS mostly have or had a quite sterile environment. Even tough, designs have been developed starting in the 70’s by Galina Balashova, whose design is essentially still in orbit on the Russian Svezda module of the ISS (Meuser, 2014).

4.19 Design for workspace of the Russian space station Mir (Meuser, 2014)
Credit: Archiv Balaschowa

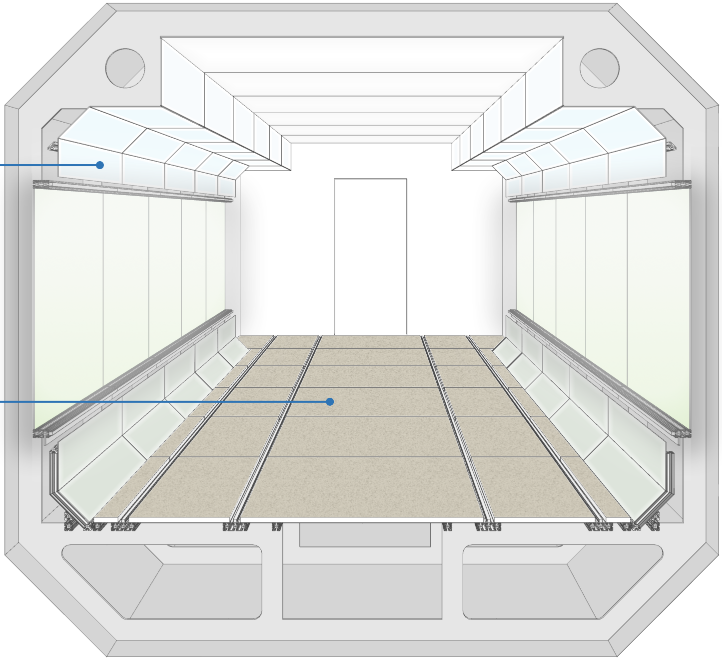
The more recent work of Maria Durao evaluates different colour schemes for the ISS as well as the influence of colours on space habitat design in respect of the International Space Station Interior Color Scheme’ (NASA, 2001). Even though, the current design does not use a lot of colours and appears quite monotonous, a richer variation in colours is desired by astronauts. (Durao, 2002). The microgravity environment on the ISS adds additional constraints through the necessity of orientation. Nevertheless, the studies show the basic effect of the different colour schemes on the perception of interior space. It is stated, that *“Whereas contrast of chromatic values and intensities tend to break down the visual space, hues with similar chromatic value do not. Instead, they guarantee continuity allowing for the interior space to expand visually.”* (Durao, 2002: 9)

Especially, in a confined environment of FLEXhab, measures to increase the perceived space are preferred, a colour scheme shall be applied in a similar approach. Light or pastel colours will be used for the overall interior, i.e. walls, floor, and ceiling. Darker colours are applied to the ground, in relation to a natural environment, while colours on the top are brighter to simulate the sky.

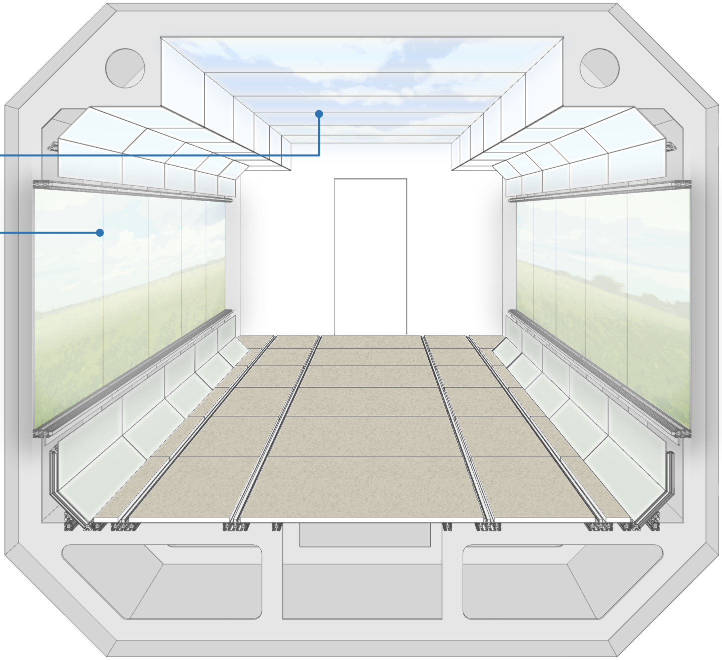
Similar to the simulation of light, the habitat can either serve as a simulation of specific conditions to study their impact, or allow for tests of different approaches as countermeasures. FLEXhab is generally designed to allow easy replacement and adaption of elements. Therefore, also different colour schemes and materials could be applied and tested.

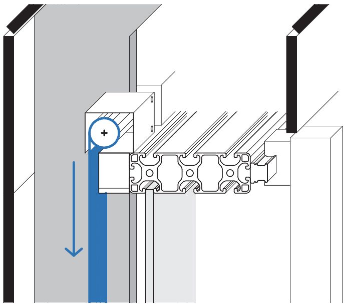
To quickly achieve different colour situations, also light could be used and in particular the former described window reveal, which allows for integration of background images or colours. (Image 4.21) The wall and ceiling panels are therefore designed in a monochrome way, to not interfere with the applied colours of the window reveal or light. With the addition of further modules and increased simulation duration, those elements add the possibility of individual adaption to FLEXhab. Furthermore, they serve as a countermeasure to visual monotony.

4.20 Application of colours and materials



4.21 Images supporting the simulation of a natural environment





4.22 Application of background images or colours though a roller blind

The interior space is not just perceived visually, but also by listening, touching, and even smelling. Materials provide an additional design element within the habitat. Limitations in payload capacities as well as safety issues limit their variety in current space habitats. Restrictions according to outgassing and flammability, as well as the higher weight, make the use of wood for example almost impossible. (NASA [Materials], 1998]

Nevertheless, the positive effect of different materials is indisputable. Especially, in isolated, confined environments, the goal is to get as close as possible to a natural environment. As an example, at the Halley VI station in Antarctica, cedar panels are used as they *"give off a pleasant smell in a place where there are no plants"* (Broughton, 2016: 4) Apart from colours, the haptic properties as well as the texture, or even smell of materials help reducing the effects of isolation.

The Mars 500 habitat was almost entirely using wood for panels and surfaces, as well as furniture. Feedback on the habitat design according to the use of material was generally positive. The wooden floor and wall panels allowed the crew to sit and lean onto, which would have not been as comfortable with metal, for example. (Charles, 2017: personal conversation)

Nevertheless, the overall use of the same material may result in a monotone environment. Additionally, certain materials may be associated with specific tasks or vice versa, a task can simply require specific materials. Different approaches can be applied for specific simulation or in specific areas, such as a common place where wooden panels create a more comfortable environment.

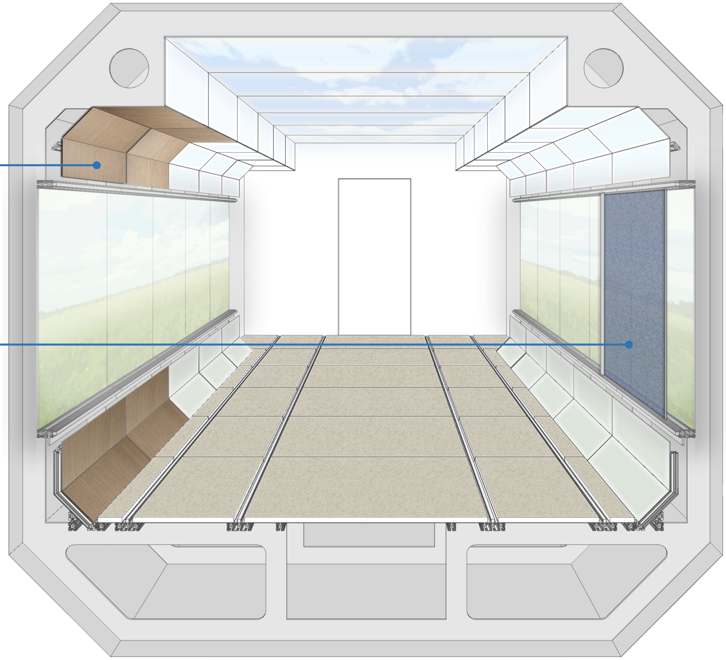
Textures of materials can be relevant in terms of housekeeping, as surfaces next to experiments should be easy to clean. Specific requirements such as these need to be evaluated once the tasks are specifically defined.

For the choice of materials also acoustic properties are relevant. Especially in the main compartment, where several people will work at the same time. For example, the wall or ceiling could be equipped with special acoustic panels. Also the integration of absorbing materials into the racks where needed is possible. Even the integration of specific elements for acoustic and also visual separation into the sliding system can be considered.

For the overall interior of FLEXhab, similar to the application of colours, a discrete approach is chosen, as more specific elements will be added according to specific tasks, which are integrated into the racks. Those are defined in chapter 4.2.

4.23 Materials in Mars500 analogue.
Credit: IBMP

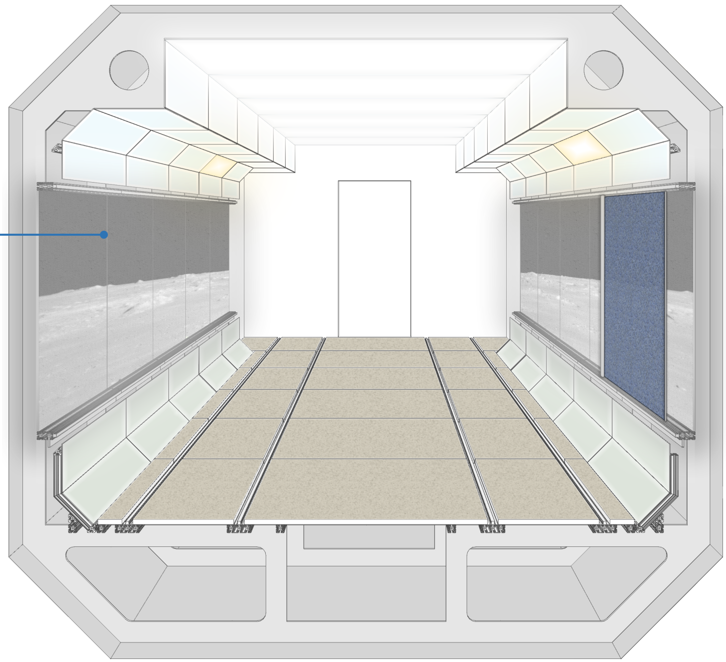
4.24 Application of materials



Wooden panels for relaxation areas

Textiles for individualisation and acoustics

4.25 Simulation of lunar environment



Background supporting the simulation

4.2 FLEXrack

For the integration of payloads and workstations into the main compartment of the FLEXhab working module, a flexible and reconfigurable rack system should be integrated – the previously developed FLEXrack concept.

Three different requirements for FLEXhab lead to that concept:

1. Not yet defined and changing simulation scenarios, therefore flexible interior configuration

2. Not yet defined experiments and tasks due to open platform leading to modular configuration and replacement (rack system)

3. Efficient use of the limited space to increase the possibilities of different simulations and experiments.

Assuming that

- different racks are used for different simulations/trainings
- different workstation are used for different tasks,
- different experiments require different amount of 'attention' and
- the same payloads require different amount of space during their life cycle,

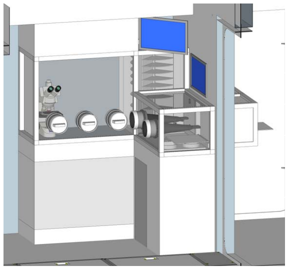
the conclusion can be drawn that not all of the equipment is used simultaneously. Therefore, racks not in use can be stored to make place for others, allowing more payloads inside the habitat at the same time and reducing time for reconfiguration.

4.2.1 Functions

Even though the exact payloads and their design are not defined in the current state, an assumption can be made by the given requirements, previous concept, as well as reference projects and input from experts at EAC.

The engineering compartment should host a geology workstation for analysing samples brought in from LUNA through the airlock. Also located in this compartment is the toilet for the working module.

Those two functions are considered as 'static' payloads – meaning that they are not integrated into the FLEXrack system. The toilet requires infrastructure which would hardly be feasible in a moving rack. Also the size of the compartment does not allow integration of more functions which could be rearranged.



4.26 Geology workstation
Credit: O. Punch / T. Dijkshoorn

Within the main compartment, several tasks will be carried out:

- Robotic operations
- EVA support
- General maintenance
- Experiment maintenance
- Training on experiments
- Experiments in/on:
    - 3D-printing
    - Regolith sintering
    - Dust mitigation
    - C.R.O.P / PBR
- Daily planning conference (DPC)
- Physical exercise
- Meeting and discussion
- Eating

Those tasks are either meant to happen during simulations of a mission or through training for specific tasks.

For each task, different spatial requirements may appear during simulation or training. For example, during a simulation one person can easily operate and maintain a 3D-printer, while for training with an instructor several people may attend and require more space around it. This is also where the strength of the concept lies. It allows practising in the same place as the actual simulation happens through opening up space for one specific task/rack.

4.2.2 Spatial requirements

The tasks are now formed into spatial requirements, also considering multiple use of elements and additional necessities.

Workstations

For the control of a robot, as well as for assisting EVAs from inside the FLEXhab and any other remote operation, a workstation is required similar to a classic computer workstation. This will be quipped with screens and controls, ranging from conventional keyboard and mouse to joysticks and other hand controls.

The exact requirements of the equipment is related to the exact tasks and requires further evaluation.

It can be assumed that several tasks within a mission scenario require a similar workstation, such as writing reports, communication, or digital operation of experiments. Depending on how many people need a workstation it still might be necessary to have several of those inside the habitat. Especially, as the rack size limits the available space, for multiple users an additional workstation will be necessary. In that case it makes sense to create specialised workstations for certain tasks, as additional controls for robotics operation may not be needed on all of them.

Considering long term missions, it might also increase the productivity of crew members if they have their own workstation that can be adapted to individual needs.

According to legal and ergonomic standards, the actual space needed within the compartment is defined as shown in images 4.27 and 4.28 and refers to the legal requirements. (ArbStättV, 2004)

Depending on sitting or working upright, different minimum dimensions are applicable, which are especially relevant for planning arrangements and scenarios for the whole FLEXrack. Further, the potential for multiple users during training or demonstrations has to be considered as well, as more space than the given minimum might be required.

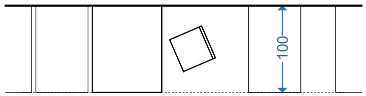
Maintenance

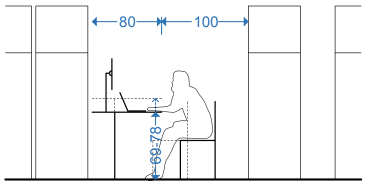
For maintenance work, different scenarios are possible. First of all, maintenance can be either necessary or simulated for the habitat itself. Those two result in the same spatial requirements and can only be defined once the whole integration of subsystems and infrastructure have reached final design to know which parts have to be accessible. As a general approach, the minimum space between two racks that has to be achievable for maintenance is slightly bigger than the size of the panels on the floor, wall, and ceiling as they have to be removable. Additional tasks may require more space, e.g. because of the need of two people working. Further evaluation on that can be done in the prototype.

The second scenario is the maintenance of racks and experiments, again either in simulation/training or in actuality. As those dimensions are related to the racks and experiments, the spatial requirements are

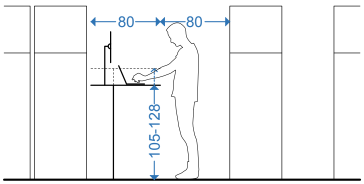
Requirements Workstation

- **Additional light**
- **Electricity**
- **Data**

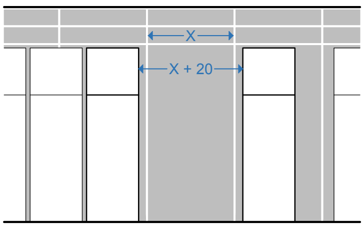




4.27 Space for workstation sitting



4.28 Space for workstation standing



4.29 Space for maintenance- relation of panel dimensions defined with those.

Apart from that, tools, equipment, and parts of the habitat may require repair work. Therefore, a workstation is needed with the ability to do so. That is already covered by the workstation as described above, As those tasks might be more complex and require more precision, additional lamps for proper illumination might be needed.

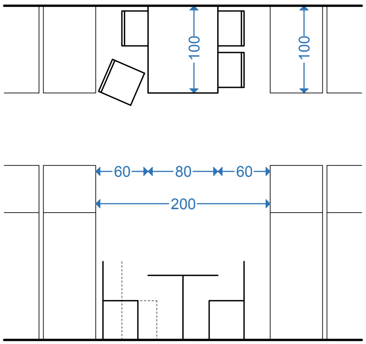
Eating, meeting, communication

During simulation as well as for training purposes, different tasks simply require a gathering of all attendees or crew members. For having a break, lunch, a discussion, or the so called daily planning conference with mission control during simulations, a table is required that allows people to sit and interact.

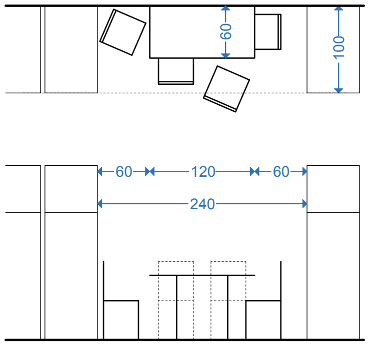
As the maximum size of the crew is defined as four people, that table needs to at least fulfil that requirement. Different arrangements within the module are possible:

REQUIREMENTS TABLE

- **4 PEOPLE**
- **ELECTRICITY**
- **DATA**



4.30 Configuration 1



4.31 Configuration 2

Configuration 1:

- \+ **LITTLE SPACE OCCUPIED IN FLEXRACK**
- – **LIMITED WIDTH**
- o **MORE SPACE ONLY THROUGH FOLDING MECHANISM**

Configuration 2:

- \+ **BIGGER TABLE WITHOUT ADDITIONAL MECHANISMS**
- – **MORE SPACE OCCUPIED IN FLEXRACK**

For maximum efficiency within FLEXrack, configuration one is preferred, as it occupies less space. The limitation in width may be an issue in case of long duration use. As the working module itself only allows for simulations of one day, time spent on the table will be limited. For more extensive use, additional space can be created, for example through folding mechanisms (chapter 4.2.4). Locating the table at one end of the table, or even outside FLEXrack, would also allow more width.

For simulations of several weeks or even longer, the table basically provides a surface also for other tasks, such as working, recreation or common activities. In case it is used frequently, permanent location should be considered as well as increased dimensions for more comfort.

Physical exercise and use of free space

In contrast to all the tasks requiring special rack design, some tasks simply require an open space. A designated area will be implemented for testing tools for physical exercise. The equipment in use defines the actual needed space, as an example already given in chapter 2.2, referring to Adams (1999), a cycle-ergometer needs a space of 101 x 150 cm. Additional space can be related to the human dimensions as shown in image 4.32.

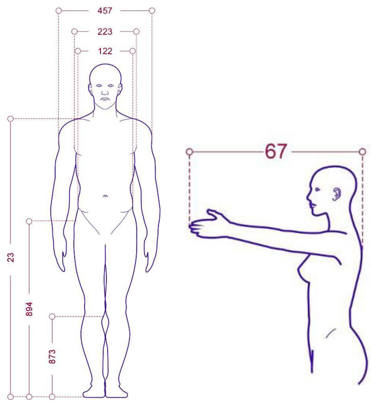
Furthermore, development in virtual reality allows the control of robots or tele-operations, as well as training of basic tasks simulated on the lunar surface. Contrary to conventional workstations, body movement (with the addition of hand controls) is used for operations. Space is therefore needed to allow movement.

The movability and horizontal stacking of racks should allow for an easy creation of a bigger space inside the main compartment. The maximum achievable space is related to the amount and size of racks, an example of the achievable space is given in image 4.33.

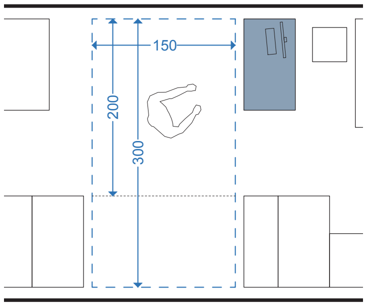
Experiments

The exact experiments going into FLEXhab are not defined, yet some things are assumed to be part of it. Requirements in rack size might be different, nevertheless limited by the maximum dimensions defined before. Some experiments will be a whole rack on their own, like the existent CROP and PBR. The space needed for those can therefore be evaluated on existing experience. For other experiments and tasks, an assumption is made for minimum and maximum dimensions according to known dimensions of equipment, ergonomics, and personal experience. Relevant for the definition of those is in particular the depth of the rack, as bigger equipment placed on them requires more space in front of the racks to handle them. The same applies to drawers that add additional functional area.

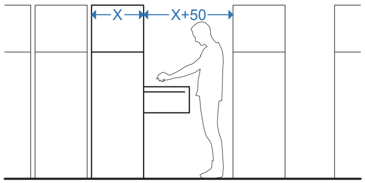
The images 4.34 to 4.36 show the relevant cases for designated areas



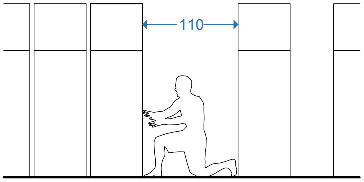
4.32 Human anthropometry, American male and female (NASA [HIDH], 2010)



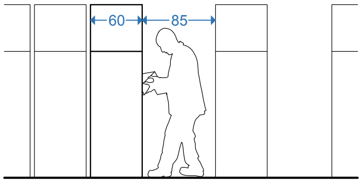
4.33 Space for exercise/VR



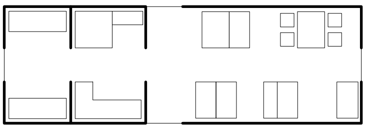
4.34 Access to drawers



4.35 Access to bottom of rack



4.36 Short access to rack



4.37 Case 1- long term arrangement

around the racks. As already mentioned for the other racks, the space can be extended for additional requirements during training or demonstration.

Storage

All of the previously described functions require a certain amount of equipment for operation, tools for maintenance and repair, or consumables. Therefore, last but not least, a reasonable amount of storage needs to be integrated. Especially relevant is the fact that different things have to be stored over different periods of time. Food for example probably has to be stored for a full simulation duration while access has to be provided several times a day by the crew.

The movable rack system is limiting access to some racks depending on the current configuration. Therefore, it has to be well planned where things are stored. Specific tools for experiments should ideally be stored with them. Especially health and safety related equipment must not be covered at any time.

In general, all things that need to be accessible all times, do not have to go into the FLEXrack system as it would be a waste of resources and also limits the possibilities in configuration scenarios. Another possibility would be racks that allow access from the corridor at any time. For spatial requirements, basically the same principles apply as for the experiment racks.

4.2.3 FLEXrack configurations

The configuration of the interior environment is divided into three categories according to the **frequency of changes:**

1. **Rare changes** throughout the lifetime of the habitat
2. Mid-term **changes in between different simulations/trainings**
3. Short-term **changes during simulations/trainings**

Case 1: rare changes

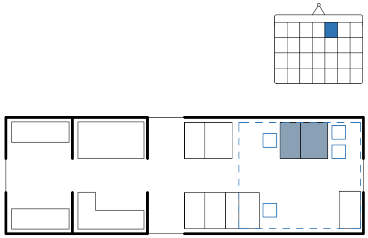
Similar to the ISS approach, the module layout is such that is currently needed, with the modular system allowing exchangeability in later phases. The spatial organisation stays as it is for several weeks or months, maybe even years. In case of different simulations or changing requirements, modules can be rearranged or exchanged.

As those changes do not happen often, the arguable effort for rearrangement is a lot higher than it would be for constant changes.

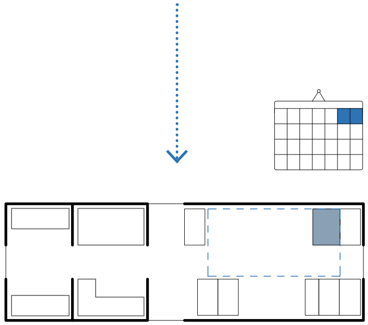
Case 2: changes between simulations and trainings

The more likely case for FLEXhab will be that different simulations and trainings will be carried out on a daily basis. Therefore, changes in configuration, if needed, should be possible faster and with less effort. Depending on the level of difference of the requirements, parts of the habitat, experiments, and workstations should be rearrangeable more easily. Things not needed in the current simulation will be stored, ideally in a compact way to increase the available space for other things. Depending on how often things need to be changed, the level of acceptable effort varies. Several simulations are conceivable:

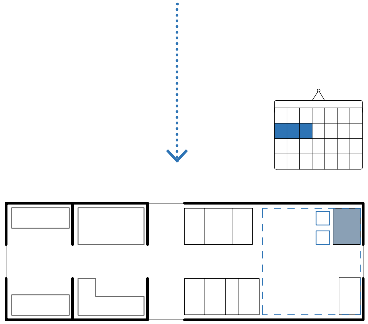
- As FLEXhab serves as the lunar base for LUNA, **EVA**´s will be carried out from inside FLEXhab supported from the main compartment. A workstation will give visual assistance for the crew outside, while also other tasks can be carried out by the rest of the crew. (Image 4.38)
- **Robotic operations**, can be carried out. Probably even at the same time as an EVA, as a current Spaceship EAC project aims to investigate the interaction of robots and astronauts. (Spaceship EAC, 2017) Therefore, more than one workstation might be needed, as well as easy communication and interaction between the crew members inside and outside the habitat. A special spatial configuration could support that task at least inside FLEXhab.
- Technology development will soon also allow the operation of robots through **virtual reality**, meaning that a classic workstation is not needed. However, for controls and movement more space will be needed as the user has to move much more compared to conventional controls. (Image 4.39)
- **Training** on experiments and/or maintaining the habitat will require access to different parts of the floor, the wall, or the ceiling as well as access to different experiment racks. Rearrangement of the different parts allows for easier access to the ECLS system, for example. (Image 4.40)



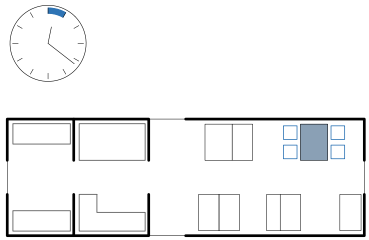
4.38 Case 2. EVA operation



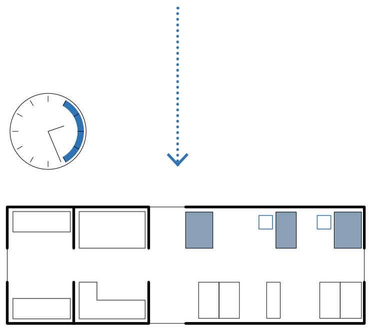
4.39 Case 2. Virtual reality



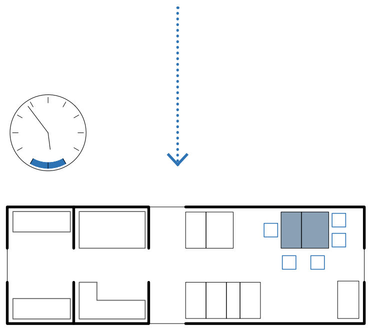
4.40 Case 2. Experiment training



4.41 Case 3. Lunch



4.42 Case 3. Robotic operation



4.43 Case 3. Team meeting

Case 3: changes during simulations and trainings

During a day of simulation or training, different tasks will be carried out. Especially during longer simulations, once the FLEXhab has reached further stages, a variety of tasks and experiments will take place inside the working module. Therefore, it seems obvious that during the everyday schedule, different configurations could allow for additional space as things not in use can make place for things needed. Reconfiguration allows for special arrangements that suit a specific task more than a basic configuration used for everything.

In case things will be moved several times a day, the movement and rearrangement of interior equipment, experiments, or workstation has to be as easy and with the least possible effort. This is crucial for the actual usability of such a system. The frequent change of the interior also makes planning the schedule much more necessary than a static environment. Once different things cannot be accessed at the same time, it has to be well known which tasks depend on each other and which can be carried out individually. The basic arrangement of different modules needs to take all those things into account. Still, things used very often or used for multiple tasks may even stay permanently, while things only in use rarely can be stored most of the time.

Furthermore, all kind of racks have to be well planned in order to make them compressible/storable. Additional implementation of folding or sliding mechanisms might be necessary or further increase of the usable space.

Individual reconfiguration

The possibility for the crew to change the interior configuration of their habitat also adds one important aspect. From the ISS, as well as from analogue missions, it is known that a closed environment, with the same visual appearance as long as people live there, can decrease the performance of the crew. With (almost) no possibility to look outside or any other chance for a different visual experience, the so called visual monotony can become a considerable problem as mission duration increases. (Bishop et al., 2016) During our average day on Earth, we experience so many changes in our environment, from colours, materials or light to different levels of temperature or even wind. Once isolated inside a single volume, the human brain tends to be under-stimulated. Even if a habitat provides the best interior environment, it still provides the same environment 24 hours a day, 7 days a week.

A habitat that allows for different spatial configurations could serve as a countermeasure to this effect. Additionally, different racks could have different colours or even materials to create changing visual experiences for the crew and maybe even give the possibility for individual adaptation. That effect is also achievable in case two.

Nevertheless, the ever changing environment will also need some permanent points. First of all, some equipment, especially for emergencies, needs to be accessed at all times. Second, personal experience, as well as input from the EAC team, clearly shows the necessity of something permanent. These fixed points of each crew member could be the later added personal compartments in the habitation module. Nevertheless, also in the working module, it might be exasperating and inefficient if things need to be stored or cleaned up after use due to rearrangement. Therefore, also movable elements should be designed in a way that equipment or tools can stay in their place even when not in use.

Another critique of the concept is the fact that it will be hard for spontaneous change between activities. While in a static environment, where everything is accessible at all time it is easy to change to different tasks or areas of the room, the moveable rack system creates dependencies between racks or spaces that can make some areas inaccessible. Also, for quick access to certain elements, for example to remove one tool, the whole rack would have to be moved, which may cause rearrangement of the whole interior space.

Apart from these unintentional dependencies, some of them could also be used to force certain activities. For example, it is of vital importance for the social life of a crew to have activities such as lunch or dinner together (chapter 2.2). The fact that the dinner table might only be accessible when all workstations are closed, does not allow for another choice but to have the meal together. Apparently, this kind of dependency has to be investigated with caution as it can also create a big conflict potential as social interaction should always be considered as an option, not as a duty. Therefore, it is necessary to be aware of the interaction of racks once a configuration is used for a simulation.

Summary

In general, the movable concept adds an extra amount of complexity. The more often things should be changed, the more efficient the habitat can be equipped, but also the more planning in advance is needed. For example, when arranging racks, it even has to be considered where tools for one experiment are stored, otherwise they might be ‘blocked’ by other racks when needed. Nevertheless, the possibility to change the interior space adds opportunities for the crew as well as more equipment within the same space if well planned.

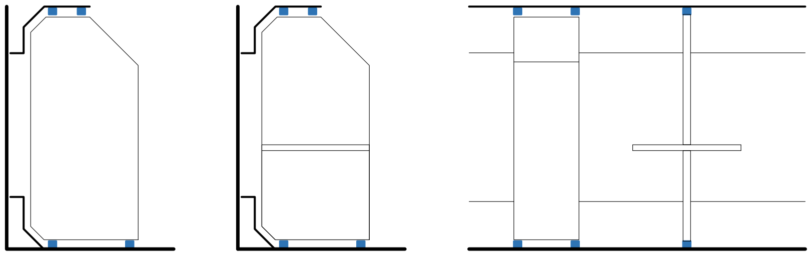
4.2.4 Design aspects

Rails

As already mentioned in chapter 4.1.2, rails are needed for the movement of the racks and are located on the floor and the walls. Despite the initial concept of having rails on the floor and the ceiling, the rails on the walls have been chosen for the reasons explained in the following trade-off:

Bottom and top rails:

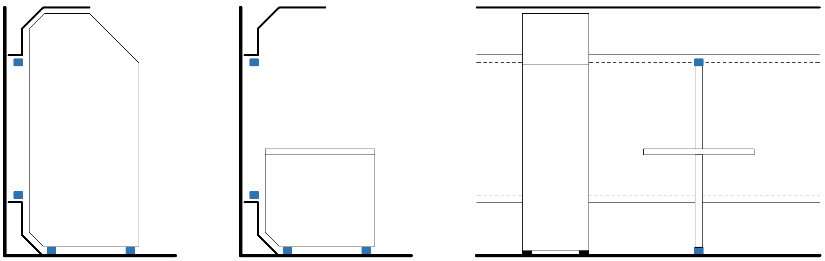
- \+ **No reduction of interior width**
- – **Reduction of interior height**
- – **Single frame racks (table, workstation) require full height**



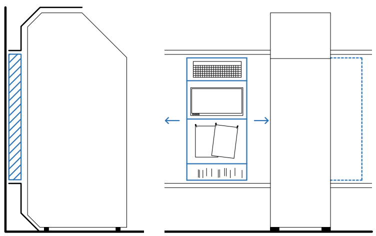
4.44 Rails on floor and ceiling

Bottom and wall rails:

- \+ **Flexibility in rack height**
- \+ **No reduction of interior height**
- \+ **Use of window reveal**
- \+ **Wall mount of racks possible**
- – **Reduction of interior width**



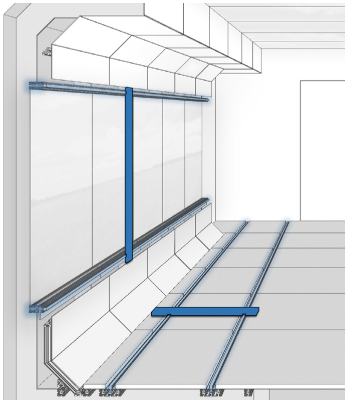
4.45 Rails on floor and wall



4.46 Secondary layer for slides

The rails can either be directly equipped with racks, or also with pre-mounted profiles where the racks can be slide on to (image 4.47). But also other elements can be mounted, such as frames similar to the previous described RAF approach, or one of the more individual solutions which will be explained in the prototype. Racks can also be mounted just on the floor, or just on the wall (as long as structural requirements are allowing).

The area between the wall rails allows the integration of a second layer as shown in image 4.46. Additional to the movable racks, this layer allows a secondary rail system for tools, documents, or lamps. These can be moved along the longitudinal axis of the module independent from the racks, allowing the user to transfer them without the need of rearrangement and carrying. For example, an often used set of tools could be integrated into the secondary rails and is therefore available within the immediate surroundings of all racks on that side of the habitat.

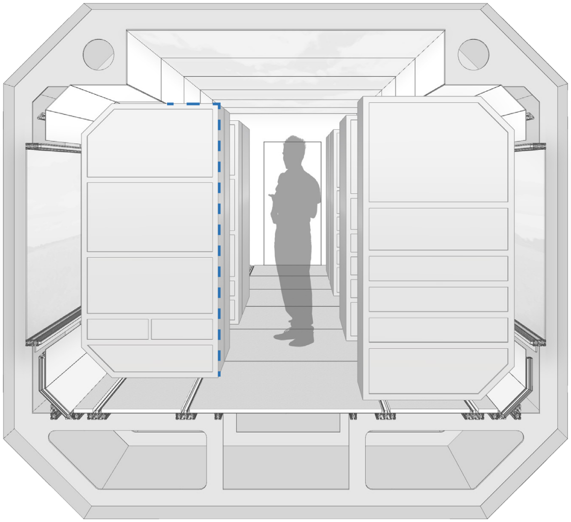


4.47 Pre-mounted profiles on rails

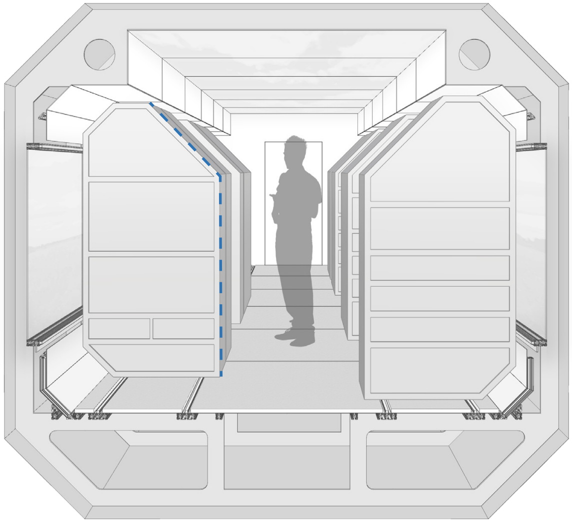
Rack form and dimensions

Once the habitat gets equipped with racks, they very much define the interior space. Considering a maximum payload, the goal is to still create a comfortable interior volume for the user. Therefore, the maximum available volume, referring to the defined dimensions in chapter 4.1.1, is reduced by cutting of the edge of the racks in the height of human eye (considering different size). Even though it reduces the rack capacity, this measure increases the perceived available space drastically as illustrated in images 4.48 and 4.49.

The so created angular shape of the racks is adapted to the functional shape of the habitat, creating a more harmonic appearance. Further, the reduction of the outpointing edges of the racks reduces the impact of shadow from the ceiling light.



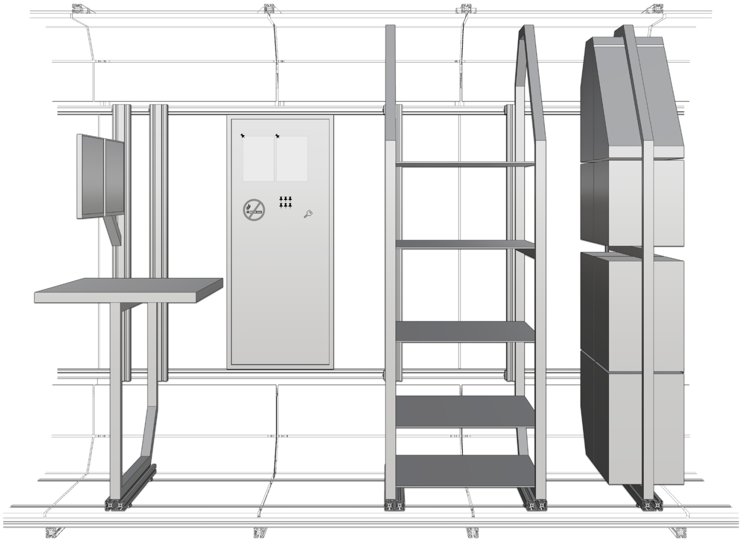
4.48 Variation in rack design



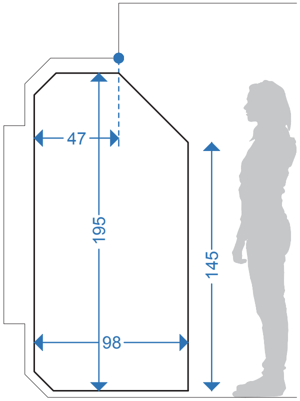
4.49 Variations in rack design- cut-off edges

The shape of the interior, as well as the now performed action already define most of the rack dimensions, leaving only the depth to be defined. As the rail system of FLEXrack anyway allows individual depths, they can be chosen by the functional requirements. The only thing that needs to be considered is the relation of rack depth to required area of movement.

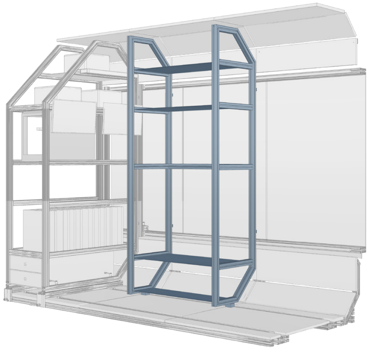
Within the maximum dimensions given for the racks, the design allows freedom of rack design. As shown in image 4.50 a variety of solutions is possible. Nevertheless, the overall impression of the interior should not be forgotten. Too many different shapes could create an over-stimulating or even confusing visual appearance.



4.50 Variations of rack design



4.51 Rack dimensions



4.52 Rack orientated to corridor

A reduction in width is also possible, together with an increase of the depth, creating a rack that is oriented to the corridor. This could be suitable especially for standing tasks, due to the limited interior height in the area close to the walls or for permanent access.

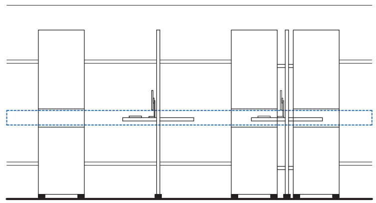
Stacking, sliding, folding

Different configurations within the habitat are not just achievable through the rearrangement of the moving racks. For certain tasks it is necessary to extent the basic dimensions of the racks. That requires the integration of additional mechanisms to increase the available space. To allow the racks being horizontally stacked, some things need to be extendable and removable. Especially horizontal surfaces, such as a table, require quite a lot of space while in use and could be easily transformed for more efficient storage.

As an example, in chapter 4.2.1 the table has already been mentioned. Through a folding mechanism, the available surface area with a maximum width of about 100 cm can be temporarily extended. While the table is not in use, it fits in between the adjacent racks. That possibility requires specific planning of the table and the surrounding racks.

Basic evaluations and input from potential users have shown that it is highly desirable for especially workstation tables to not require complete clearing after use, which would be necessary if the surface is tilted. Therefore, a solution was developed that allows any tool or equipment to stay on the table even though it is not in use or stored, respectively.

Throughout the FLEXrack system, a horizontal layer is defined for the integration of horizontal surfaces, i.e. tables and workstations. Experiment or storage racks will be left empty in that area, in order to allow the integration of the surfaces, giving enough space that equipment can stay on them. Even though this reduces the capacity of the rack, the more efficient storage allows the implementation of additional racks that more than compensate for that loss. (Image 4.53)



4.53 Horizontal layer for stacking

Tables and workstations therefore need to be designed in a way they only use a thin vertical layer in between the other racks. Additionally, they still have to provide adaptability in height due to ergonomics. The special design of the required construction will be explained on exemplary racks in the prototype, as individual solutions have to be found for different racks.

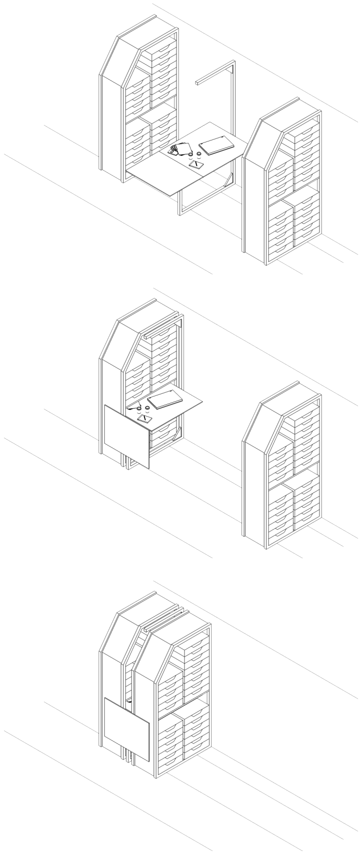
Lighting

The tasks carried out on specific racks also require specific lighting. In general, more precise work requires a higher level of illumination. Further requirements can be necessary due to decent colour reproduction, safety requirements, or wavelengths.

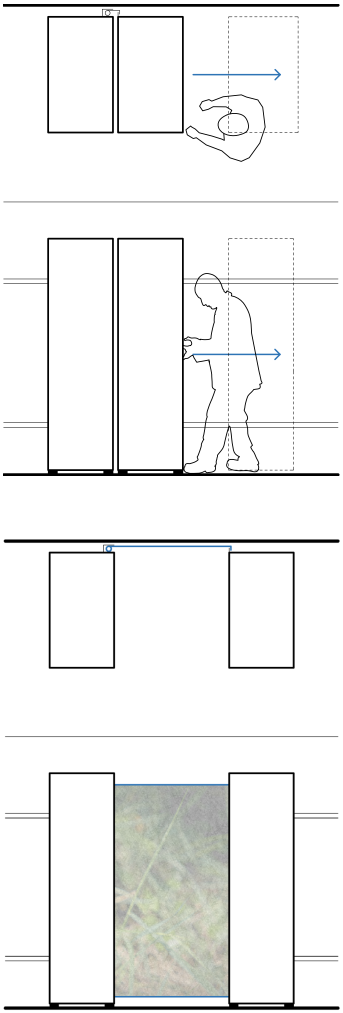
Especially workstations might need additional illumination for repair work or experiments. FLEXrack allows different possibilities for integration of those. Apart from the already existing lights integrated in the ceiling or upper edges of the habitat, also the rails on the wall allows for mounting lamps. In particular if the rails are equipped with pre-mounted profiles. Apart from that, racks can be equipped with lamps to illuminate certain experiments or surfaces.

Materials and colours

For the racks, generally the same requirements apply as for the overall interior (4.1.4). Their visual appearance can be designed according to their purpose, keeping in mind a consistent overall interior. Extensive use of different materials and/or bright colours is not recommended. The material for the basic construction of the racks should be consistent. Specific experiments might nevertheless need to be covered or sealed,



4.54 Sequence of storing a table



4.55 Roller blind concept

also drawers or other storage will create closed surfaces. The covering of all racks was considered during the design process, as a countermeasure to an over stimulating interior, but was considered as counterproductive for the perceived available volume of the habitat, especially for the corridor area. For clear identification of functions, a consistent colour code could be applied to the racks. For example, storage racks will have the same colour, while workstations have another colour.

Additional functional and design elements can be implemented, especially interesting is the use of acoustic textiles, as they can act as a decorative element, introducing colours and textures, and further improve the acoustic properties of the interior space. Those textiles can also be used for covering racks or visually separate areas within the habitat. Even though it might sound banal, the implementation of a curtain or a roller blind may even improve the feeling of having a window. Connecting the racks with some kind of roller blind, would create a changing visual appearance according to which functions are currently in use. (Image 4.55)

Those things can be easily integrated either within the racks, or individually through the previous created window reveal layer. Studies can be done on the physiological impact, in terms of acoustics, as well as the psychological impact on the crew.

4.2.5 Technical aspects

Infrastructure

Within the movable system, the sufficient supply of infrastructure is of vital importance to the usability. Electricity and data need to be provided throughout the whole module. Additionally, experiments may need water or even gas, which also have to be supplied within the racks.

For electricity, in the current design, the pre-mounted profiles on the rails are supplemented with plugs. The layer for infrastructure created at the edges of the module allows for cable management through the implementation of hose carriers. Similar solutions can also be used for more advanced supplies. (Image 4.56)

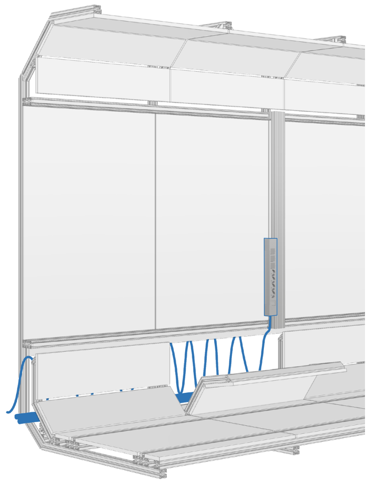
The pre-mounted profiles, especially on the wall, can be used to mount, for example, plugs for electricity and data independently from the racks. Racks and equipment can than simply be plugged without additional cable management.

Construction

For the construction of the rails as well as the racks, the goal is not just to create a functioning rack system, but also to create a clear visual appearance of the inner surfaces. For that reason, and to avoid obstacles, the railing system on the floor should be integrated within the surface with as little gaps as possible.

Furthermore, the movement of the racks should be automated, which requires additional room for drives. The racks have to be movable individually but also simultaneously and in particular synchronous within one rack to avoid rotational forces. That requires the implementation of an overall control system.

For construction of the racks, the movement, possibly creating rotational forces and tensions within the used material and joints, needs to be considered.



4.56 Cable management in edges

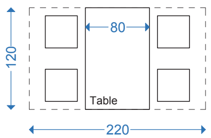
4.2.6 Arrangement of racks

Based on the given requirements, as well as the developed interior design, a possible configuration of the FLEXrack within the main compartment will be presented and explained.

The scenario shall include the maximum amount of racks while considering the relevant standards and dimensions and still providing the necessary space for each task.

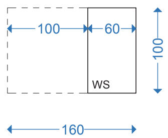
The following setup is chosen for the configuration (max. dimensions):

1x Table for the whole crew of 4



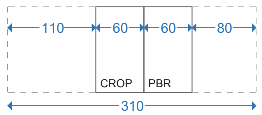
- Bigger table located at end wall
- Permanent access

1x Multi-purpose workstation



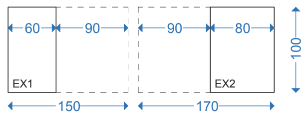
- Storable through horizontal stacking

CROP and PBR

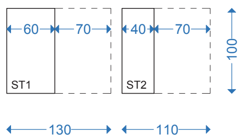


- Connected racks

2x Experiment racks

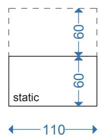


2x Storage racks

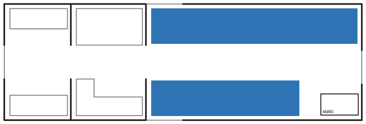


- Access from both sides possible

1x Static rack



- Orientated to corridor
- Limiting FLEXrack reconfiguration (image 4.57)



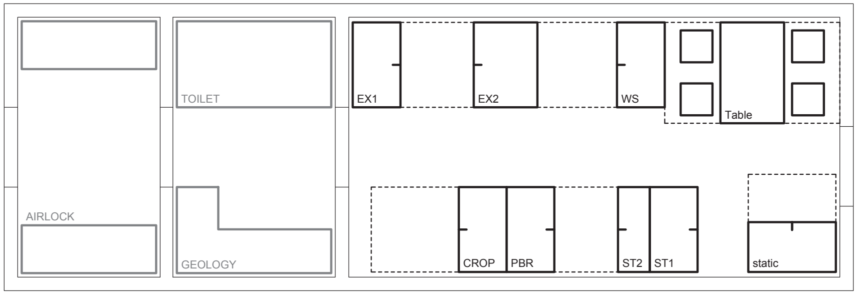
4.57 FLEXrack location

Those racks are based on an assumption by the author with input from the greater EAC team. Different upcoming requirements or activities will result in other racks and arrangements. Nevertheless the following scenarios can serve as an example, and visualise the overall idea and potential of FLEXrack.

Static rack arrangement

- \+ **Less effort in construction**
- – **Flexibility (no rearrangement)**
- – **Efficiency (Maximum space for each rack always necessary)**

Minimum corridor width 87.5cm (ArbStättV, 2004)



4.58 Static racks

Arrangement considering STATIC racks, so no FLEXrack system. For the dimensions of the designated areas the maximum values apply, as no rearrangement allows to increase the space temporarily.

FLEXrack - basic

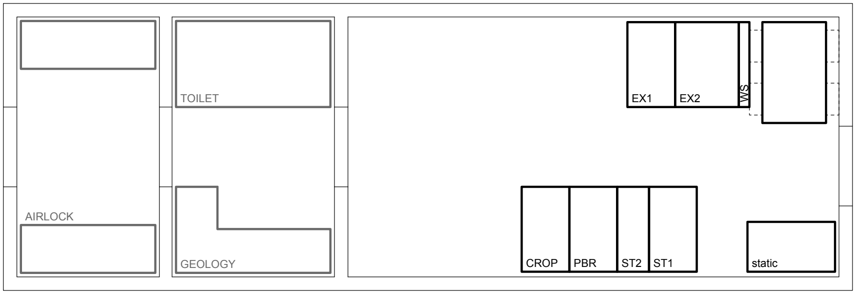
- \+ **Flexibility**
- \+ **Efficiency**
- – **Increased effort in construction**
- – **Not everything accessible**

Racks in use

4.59 Static racks

Introducing the FLEXrack, the same racks are at first arranged in the ‘worst case scenario’, meaning the 4 racks with the most space needed are opened up at the same time. Some things can still be stored while not in use. This creates more available space.

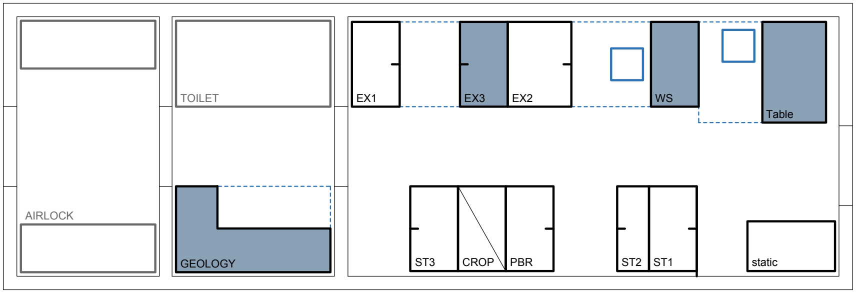
The ability to move and stack the racks allows a bigger space to open up, as shown in image 4.60.



4.60 FLEXrack- stacked

- **+ Opens up Space when needed**
- **– Specific design of racks (for stacking)**

FLEXrack - extended



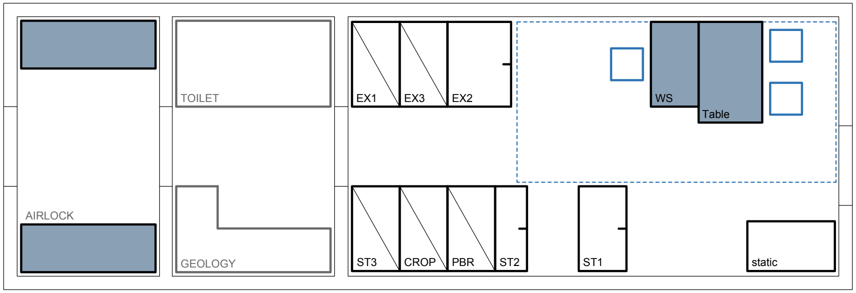
4.61 FLEXrack- extended arrangement

- **+ Additional racks**
- **– Less things accessible at the same time**

Assuming that neither the worst case of configuration nor the maximum available area at each rack will happen all of the time, especially not simultaneously, this image shows a 'daily life' scenario, for example during a simulation. In that case, the integration of additional racks would even be possible, especially in the first phase of the project. (ST3, EX3)

Use-case: EVA simulation

- Workstations and airlock in use
- + Supportive layout

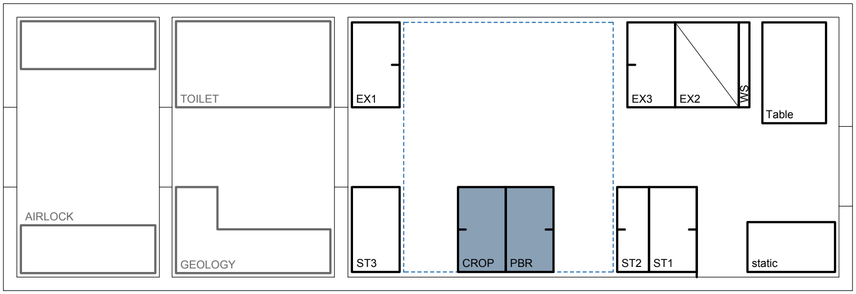


4.62 FLEXrack- EVA simulation

Special arrangements can be done for the simulation of an EVA, when two crew members are preparing in the airlock and get later supported by the rest of the crew and maybe additional people such as instructors and trainers.

Use-case: Demonstration and training

- Only two racks in use
- + Efficient training
- + Space for more people



4.63 FLEXrack- demonstration and training

For astronaut training, the reconfiguration allows space to open up for training on certain experiments. For explanations or instructions, more space might be needed for equipment. Procedures or operation of experiments can be trained and observed by instructors.

FLEXhab phase 3 - additional modules

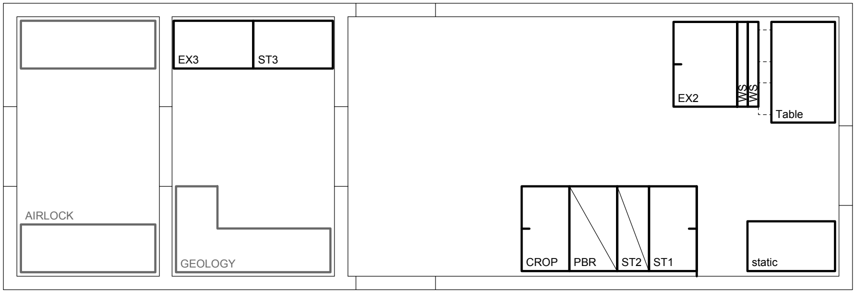
4.64 FLEXrack- phase 3

- **Rearrangement of racks (additional requirements due to increased simulation duration)**
- **Access to other modules available**

\+ **Space in front of doors can still be used in case no access is required**

Once the working module is supplemented by a habitation module, not just access needs to be provided, which may result in less racks in the main compartment, but also the toilet in the engineering compartment is no longer needed due to the bathroom in the new module. Therefore, the basic configuration of FLEXrack is changing. Assuming that the habitation module also hosts a table for the crew, the one currently in FLEXrack can be turned into solely a workstation, requiring less space. The extension of simulation duration also requires more individual work places for the crew, due to free time and paper work as well as communication.

Nevertheless, FLEXrack still allows space to open up for special activities, which is especially relevant for long duration simulations. Basically the same possibilities are applicable as before.



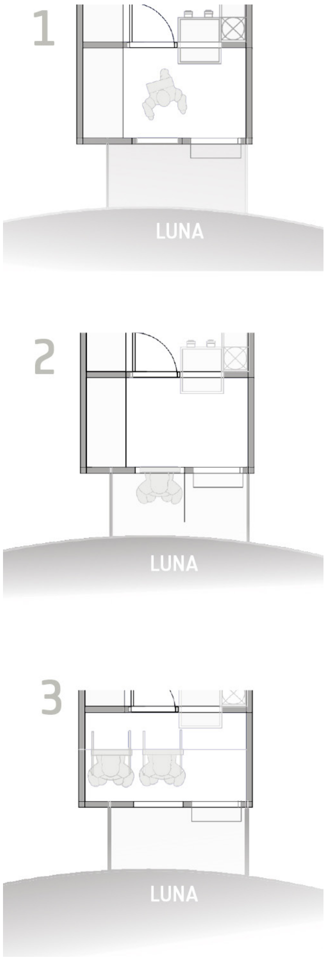
4.65 FLEXrack- phase 3 stacked

- **Stacking still allows to open up the space**

\+ **Additional comfort for longer simulations**

The presented configuration allows a huge variety of combinations; through relocation and more detailed planning of the racks, even more efficient configuration can be achieved.

4.3 Static payloads



4.66 Airlock configuration
Credit: Orla Punch

Apart from FLEXrack, other payloads are also integrated into FLEXhab. This can be payloads that need to be static due to special experiment requirements or, as mentioned earlier, the necessity of a permanent position in case of emergencies.

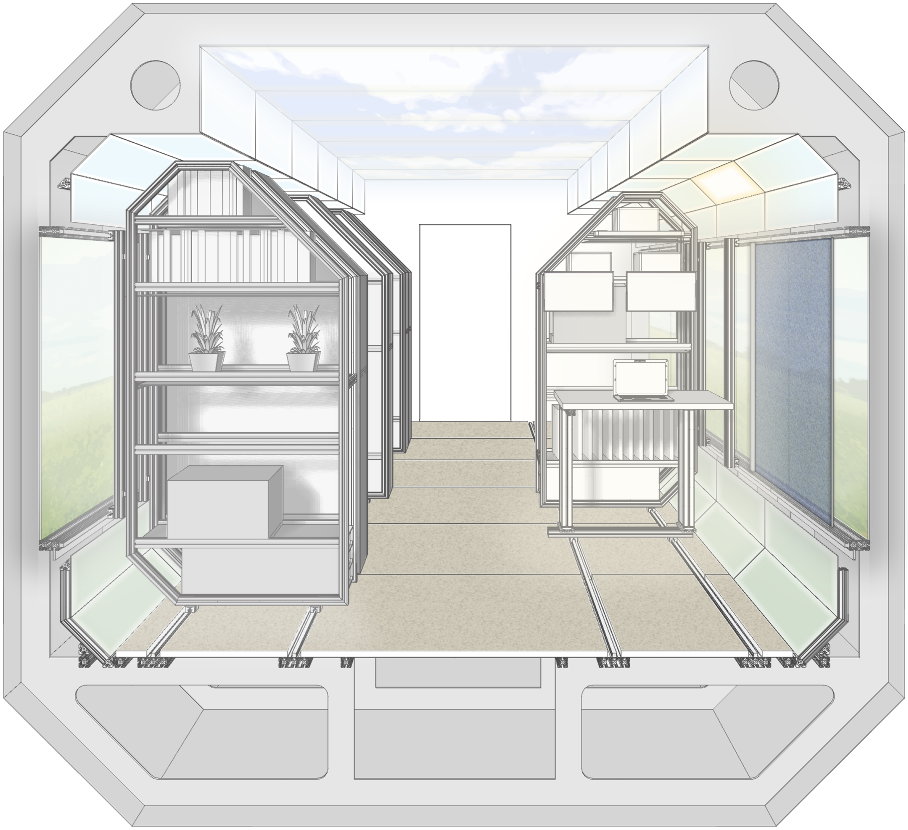
Nevertheless, the same design requirements and decisions previously defined also apply to these payloads. In particular, the dimension and form should be kept the same as FLEXrack to create a harmonic overall interior.

The engineering compartment, separated from the main compartment needs to accommodate a geology workstation for sample analysis. That workstation is not defined by now and can therefore only be assumed on the previous concept as well as similar workstations. Similar to the glove-box on the ISS (chapter 2.2), connected to the airlock. Also equipment and samples need to be stored in the immediate surroundings.

Apart from that, the engineering compartment will also host a toilette. Hence, visual separation is absolutely necessary, as well as for acoustics and odour.

The airlock requires space for the crew to put their suites on, do the pre-breathing, and exit or enter the module. Its dimensions have already been defined during the previous studies. It needs to be sealed from the rest of the habitat once the crew enters or exits. As it is only used for that single purpose, it should be as small as possible considering the needed space for the crew members. Additionally, the space should allow assistance either from other crew members as well as astronaut trainers for putting on and off the EVA suits.

In the previously developed concept by Orla Punch (Spaceship EAC, 2016), the possibility of different configurations of the airlock was considered, which is shown in image 4.66 and should be kept. Scenario one would be a conventional airlock, two and three show the possibility to integrate the suitport concept. (Cohen, 1995)

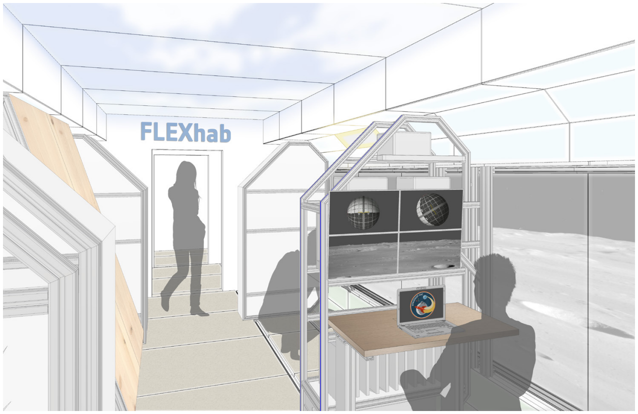


4.67 Overall design of the interior including FLEXrack

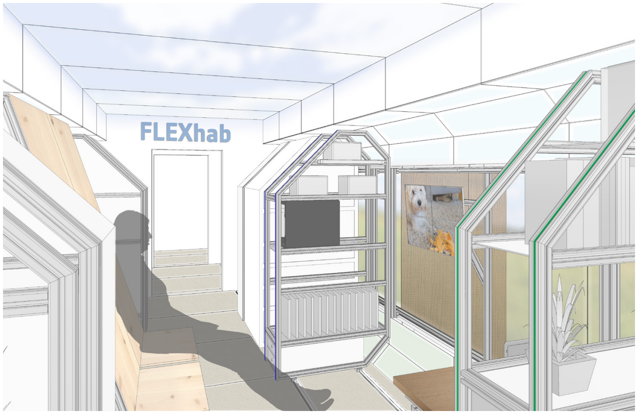
FLEXHAB INTERIOR IS CAPABLE OF:

1. SIMULATION OF THE LUNAR ENVIRONMENT

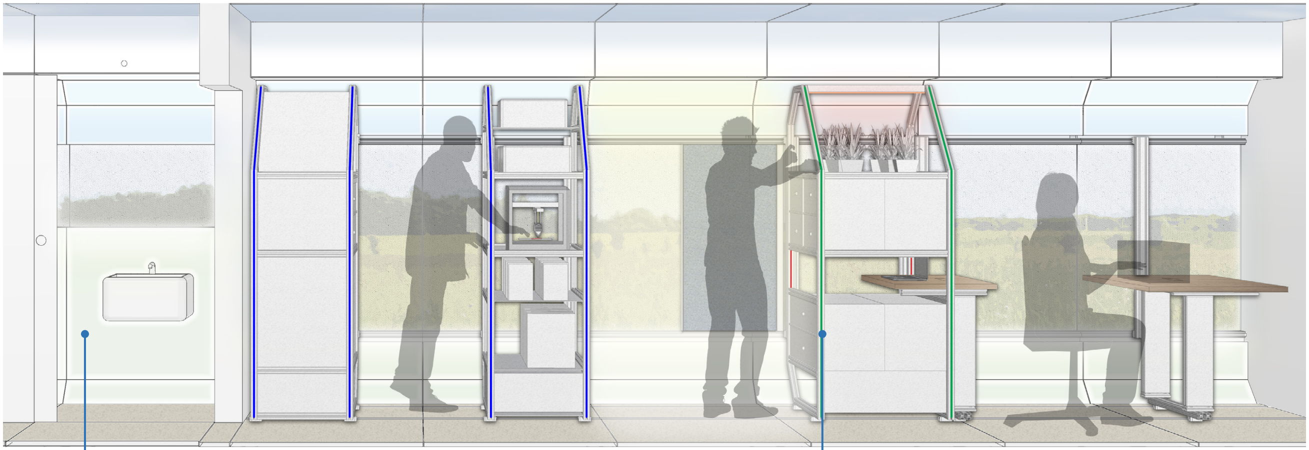
2. SIMULATION OF A NATURAL ENVIRONMENT WITHIN AN ISOLATED SPACE



4.68 Simulation of the lunar environment



4.69 Additional comfort in later stages



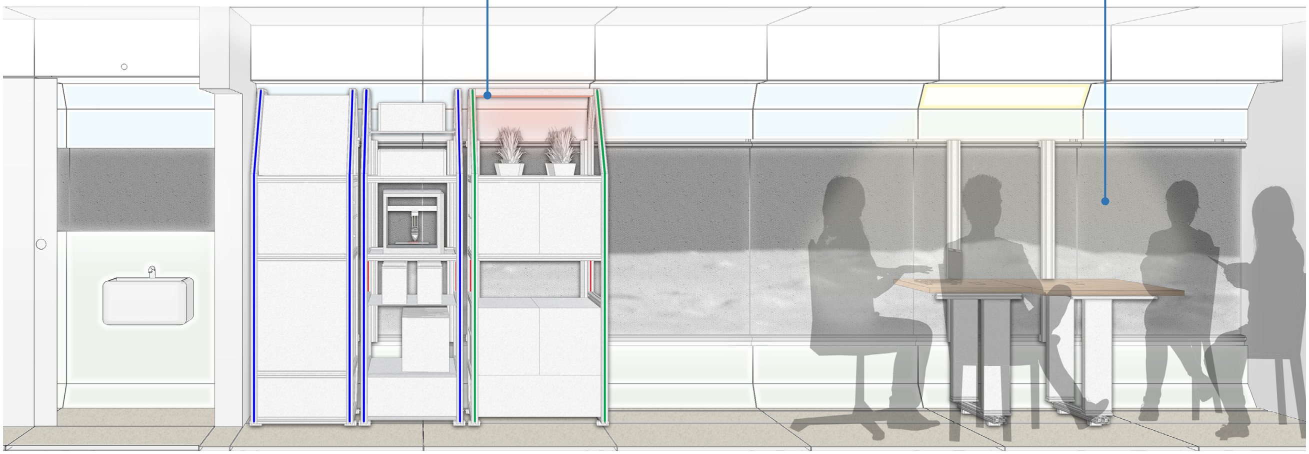
4.70 Interior arrangement: work and experiments

APPLICATION OF DESIGN MEASURES TO OTHER COMPARTMENTS

SPECIFIC LAMPS FOR EXPERIMENT RACKS

COLOUR CODE APPLIED TO RACKS ACCORDING TO FUNCTIONS

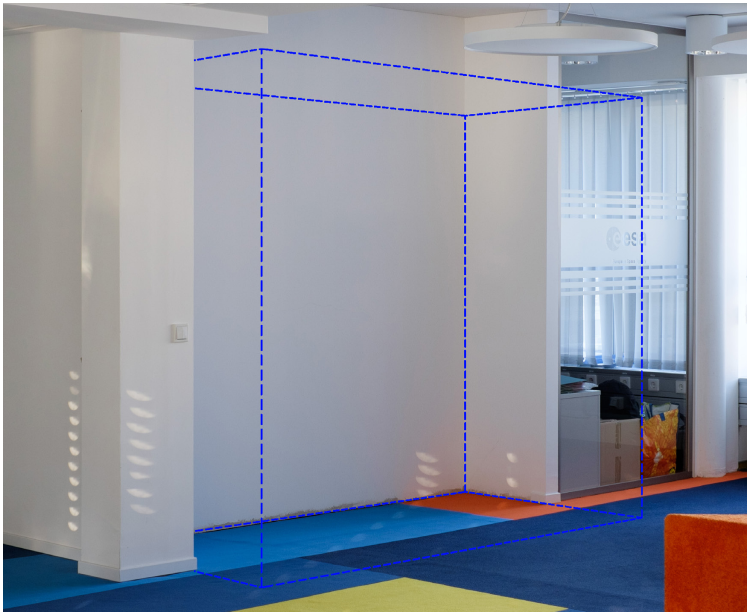
SIMULATION OF LUNAR ENVIRONMENT THROUGH MATCHING BACKGROUND



4.71 Interior arrangement: communication

5. Prototype construction

The previously described interior design, as well as the FLEXrack concept, shall be proven in a prototype located in a foreseen space within the Agora office space at EAC. (Image 5.1) Considered to be a small part of FLEXhab it will allow to evaluate and adjust the general design approach and further serve as a real size model to visualize the FLEXrack concept, which can also be evaluated on small scale.



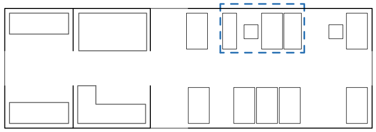
5.1 Location of the prototype

5.1 Purpose of the prototype

The spatial requirements for activities previously related to literature can be tested and evaluated. Apart from that the prototype serves as an important tool to get input and feedback from project related experts for further improvement of the final design.

The design of the prototype is therefore chosen to be a small part of FLEXhab (image 5.2). For that reason, a structure is built to create the same interior dimensions as FLEXhab. As the available space only allows for demonstration of one half of the habitat, it is not possible to create the same spatial felling as a whole. The construction therefore only displays the area previously described as accommodation area of the module.

Considering a similar construction approach for the real habitat, the prototype also allows for identification of improvements in detailed design and cost driving factors.



5.2 Part of FLEXhab as prototype

5.2 Constraints of the prototype

For the construction of the prototype priority was given to ease of assembly and also exchangeability. It is fully constructed out of COTS products.

Priority was also given to easy replacement of all elements as well as keeping connections, fixations and joints not just simple but also within one overall system. A modular system, produced by company called Item, allows for easy adaptations and changes as well as extensions due to the vast amount of possible solutions the system offers. (Item, 2017)

For the above described reasons, some differences exist between the prototype and the FLEXhab design:

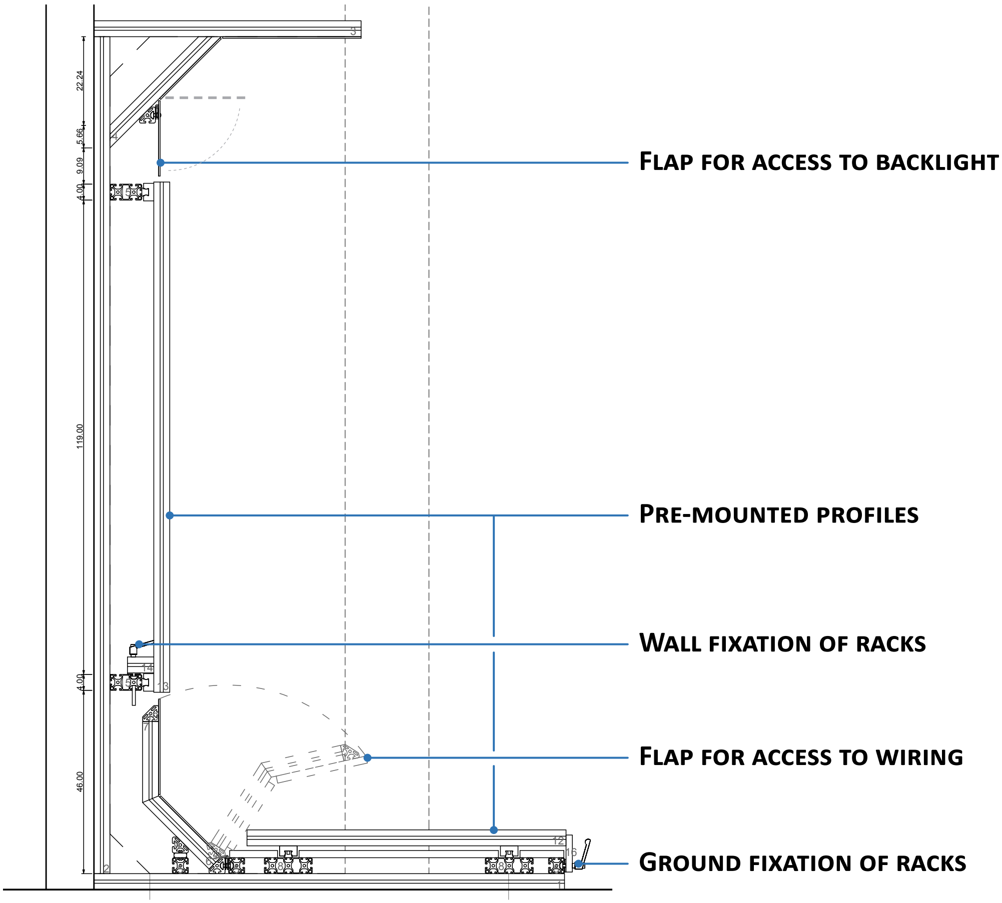
The prototype is constructed in a conventional open office space. This means, the space is not a closed volume with limited dimensions.

Its location is a niche with dimensions of approximately 2.6 m in width and 2.7 m in height. Even though, the prototype itself has the same spatial dimensions as FLEXhab, it is perceived differently due its surroundings.

The railing system is a key element of the FLEXrack concept and therefore requires special attention for two main reasons: firstly, because its usability is essential for the whole concept and secondly its presence will likely affect the interior space of the module. Easy movement needs to be provided, otherwise the advantage of quick effortless rearrangement is gone. A manually operated rail system was chosen in the prototype for simplicity and ease of assembly, whilst the rail system used in the actual FLEXhab will be automated. That results in the need of manual fixation and release before and after movement of the racks.

5.3 Construction

The construction of the prototype was entirely designed and constructed with a modular system of aluminium profiles by the company called ITEM (Item, 2017). The design described in chapter 4 was transformed into detail plans and procurement lists and afterwards assembled by the author with the help of colleagues of the Spaceship EAC team.



5.3 Construction plans for the prototype

5.4 Setup elements

The prototype will be equipped with three racks, which serve as technology demonstration, but are also adjusted to the needs of the office space.

For that reason, the setup is focusing on a basic workstation, thus providing space for at least one person working, for example with a laptop sitting and standing. Additional screens allow the workstation to become a control station for rovers. Two additional racks, serve as shelves but can also be seen as racks for experiments. The design and construction of the racks will be explained now.

Workstation

With the goal to create a movable, comfortable, and adjustable desk for different occasions, the requirements for construction are quite challenging. Especially when effortless rearrangement should be possible.

Due to the horizontal stacking approach, the width of the table is limited to 89 cm and the depth is chosen to be 60 cm. The adjustable legs are mounted onto one of the base profiles. For stabilizing the table and to avoid rotational forces on bearing carriages, additional fixation is provided by the wall-mounted profile. Adjustment in height is still provided. Furthermore, special attention needs to be given to the placement of cables as they have to move with the table. Horizontal movement of cables is realised within the bottom edge of the wall by fixation to slides that use the groove of the aluminium profile. For equipment used on the table that needs to be plugged, additional cable profiles are added to provide fixation. Through additional length of the cables, which can be hidden within the construction, also vertical movement is provided.

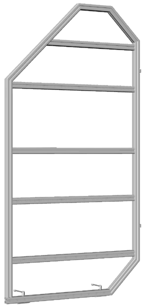
Illumination of the workstation is integrated into the rack next to it. The same applies to additional screens. This is done in order to leave the surface of the table free and to create an obstacle free meeting table.

Racks for experiments and storage

The racks designed for the prototype follow a construction approach similar to the RAF concept (p.50; Howe / Polit-Casillas, 2014). That means they are based on frames, which supplemented with boards in between, create a basic shelf. This allows for the creation of racks with different depth. Apart from that, pre-mounted frames could be used for assembling basic racks inside the habitat, thus reducing the required dimensions for openings and translation paths.

For the prototype each pair of bearing carriages is connected with a profile for two reasons. Firstly, the connection of two carriages reduces the rotational forces impacting on the individual carriage. Apart from that, connecting the racks directly to the bearing carriage would require improvement of the available connection. As the goal is to achieve easy exchangeability, the profiles serve as an interface where the racks can be slide onto much easier and are fixed with two handles. Furthermore the profiles on the wall are also equipped with power sockets, which can be upgraded with network sockets.

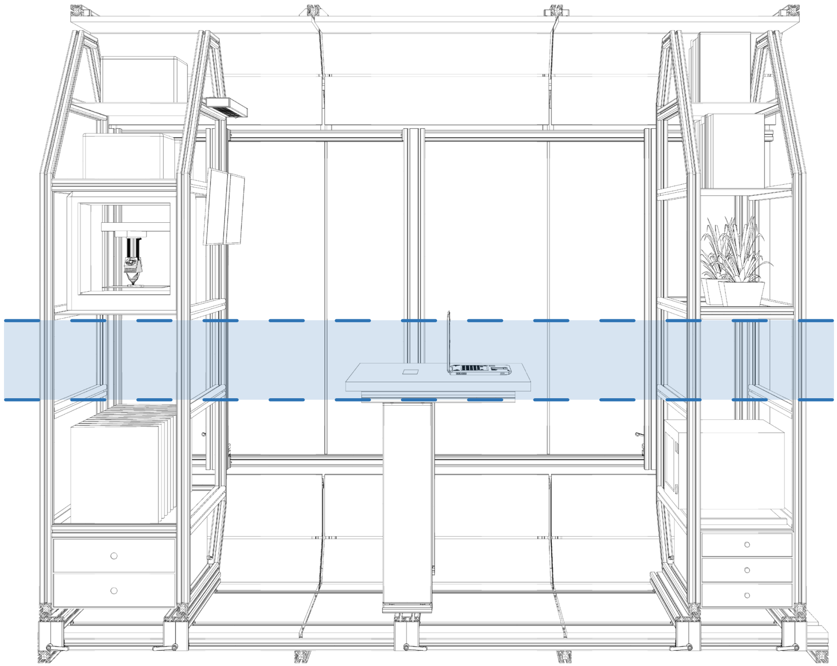
The horizontal layer allowing for horizontal stacking of the racks, as explained in chapter 4.2, is equipped with red indicators, signalling that equipment must not be placed there. A horizontal profile further marks the lower limit.



5.4 Single frame

5.5 Pre-mounted profiles connecting pairs of rails

5.6 Frame attached to profiles



5.7 Prototype setup with horizontal layer for stacking

5.5 Scenarios

Apart from testing and demonstrating the overall design of FLEXhab and FLEXrack, the prototype was specifically built to test the following scenarios:

Scenario: work

1. Robotic workstation

Referring to a project currently under development at Spaceship EAC, FLEXhab will need a workstation to control a rover inside LUNA (chapter 3.1). As no specific requirements are available yet, input from the Spaceship EAC team resulted in a configuration consisting of several screens in addition to a conventional computer workstation.

Controlling the rover happens while the workstation is attached to another rack, which increases the amount of screens to have the capabilities of controls and visual feedback. Furthermore, users should be able to work at the workstation in a seated position as well as standing upright.

2. Maintenance

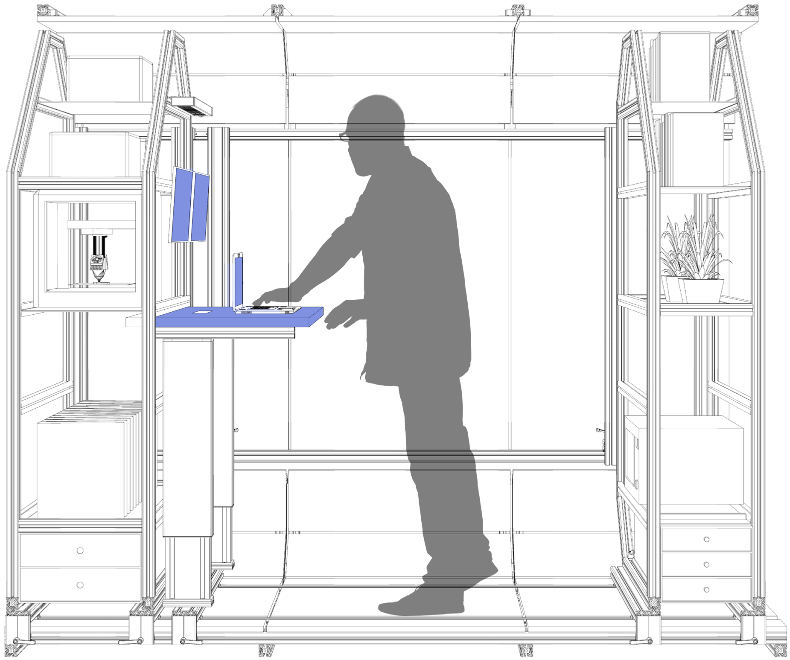
For repair work or experiment preparation additional illumination might be needed. The experiment rack next to the workstation is equipped with additional lighting that provides the necessary illumination.

3. Office

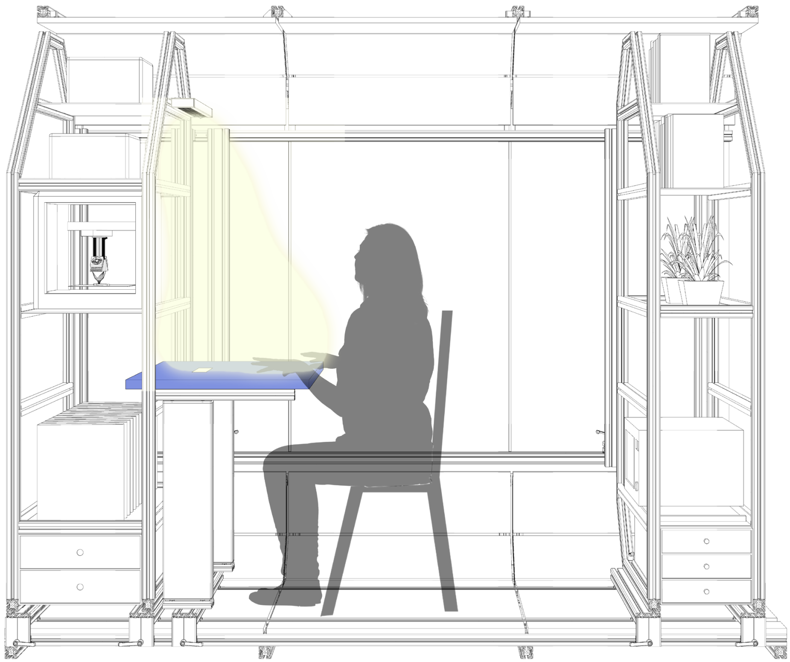
For regular office work, which includes writing reports, reading or skyping, you may not need the additional screens or lamps. Therefore attachment to the other rack is not necessary. Even though, the space in the prototype is limited, enough space can be provided to allow for temporary access to the experiment rack.

Testing:

- **Use of workstation in different positions by different users**
- **Implementation of different display layouts**
- **Different tasks on the table**
- **Different lighting configurations with the implemented lamps.**



5.8 Prototype - workstation, standing



5.9 Prototype - workstation, additional light

Scenario: meetings

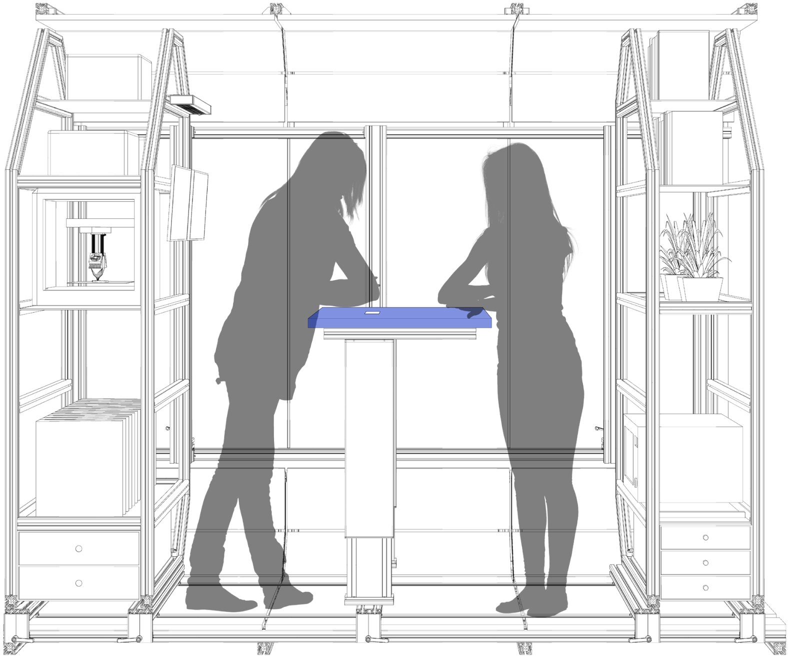
The desk can also be used as a standing table for short meetings of two or three colleagues, which increases the efficient use of space. For that scenario it is essential that there are no screens etc. blocking the sight of the users, which is why those are located on another rack. Another option would be flexible monitor stands that allow the screens to be moved towards the wall. The same applies to lamps.

Scenario: scientific experiments

The whole FLEXrack concept is based on the assumption that not all elements are used at the same time. Unused elements can be stored to open up space for other tasks. That is why the configuration of the prototype allows for all racks to be moved to one side of the structure, thus opening up space to operate machines or conduct larger experiments. Therefore, the prototype will allow for testing of minimal spatial requirements for different tasks.

Testing:

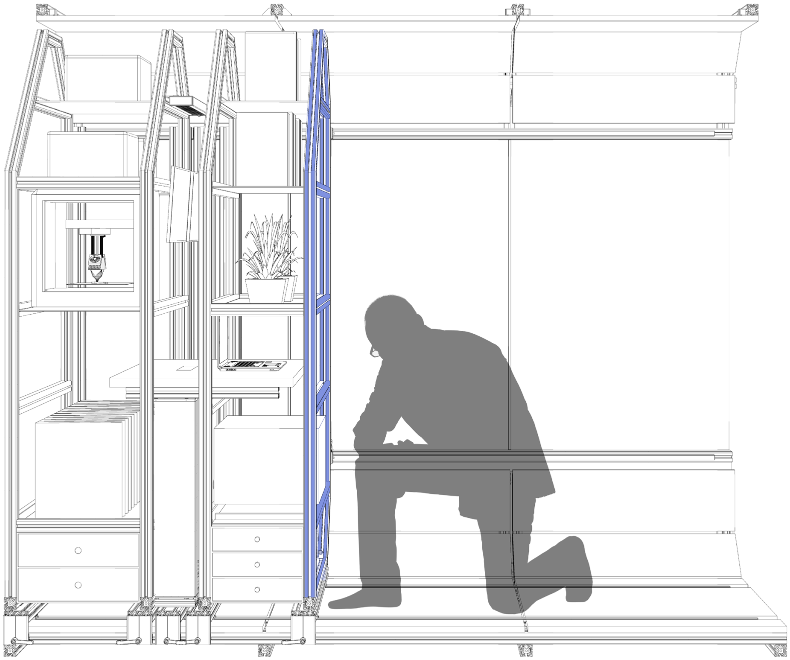
- **Change of configuration**
- **Use table for meetings**



5.10 Prototype - meeting

Testing:

- **Use and exchange of equipment**
- **Evaluation of minimum and maximum needed space by different users**



5.11 Prototype - experiment

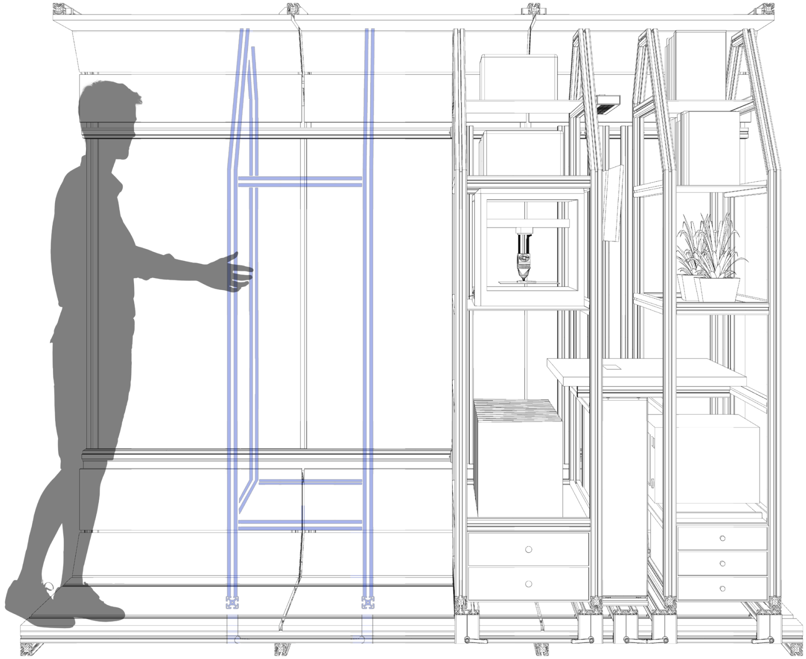
Scenario: maintenance

Wires and infrastructural systems like the ECLS have to be accessible in FLEXhab. That is where the movable racks are an advantage compared to fixed furniture or ISPR racks. Wall and floor panels can be easily removed by simply moving racks aside. The size of the boards, which determines the available space between the racks, is therefore adapted to that. Adjustments of board dimensions and orientation might be necessary afterwards. Nevertheless the visual appearance in changes on that must not be forgotten.

For maintenance two different scenarios can be considered. The first one is the training necessary to maintain the habitat during a mission. The other one is the actual maintenance and rearranging of things inside the module between different mission scenarios.

Testing:

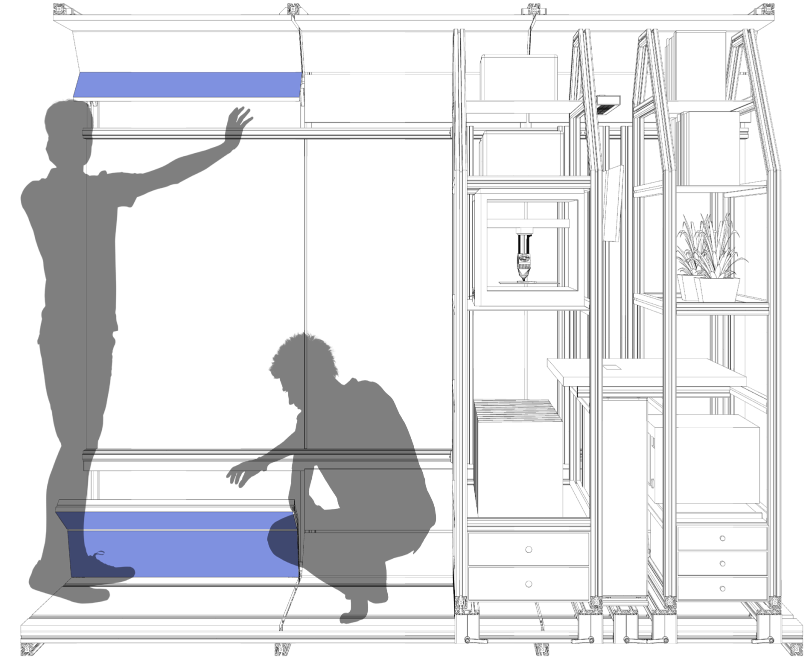
- **Movement of racks**
- **Implementation of new experiments/devices**
- **Exchange of racks**



5.12 Prototype - rearrangement

Testing:

- **Implementation of cables**
- **Maintenance of backlight**



5.13 Prototype - maintenance

5.6 Evaluation

Both, design and usability, are evaluated by testing the previously described scenarios as well as through individual use. This was done by the author and additional test subjects. Through feedback and personal experiences, the following résumé can be drawn for the prototype.

Overview

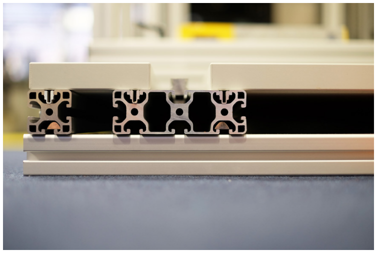
The movement of the racks works fine and several test subjects achieved different configurations without intention by the author. Especially the manual movement and therefore the physical interaction with the elements and environment seems to be attractive to many people. Nevertheless, the integration of a more advanced system for movement of the racks is indisputable. The simultaneous movement of all fixations of one rack, for example through a synchronous rack drive is more appropriate. Furthermore, it will allow automatic movement, while keeping the possibility of manual movement.

During the assembly of the hull, as well as the racks, the possibility to move certain elements has already proven to be useful. For instance, the desk was the first rack assembled, and could already be used for assembly support of the others. The movability of the racks was particularly helpful for integration and exchange of boards and elements on the hull. Ease exchangeability of panels as a maintenance task as well as access to elements of the hull can therefore be seen as a big advantage of FLEXrack.

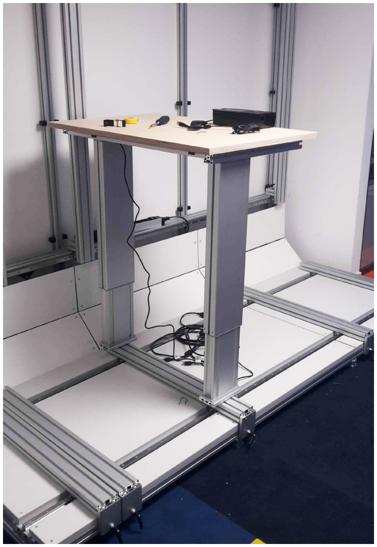
The approach of pre-mounted profiles on the rails appeared to be helpful, especially when assembling the racks in place. Pre-assembled frames can already be fixed in position, which allows for easy mounting of the boards in between. A similar mounting of the racks should be considered for easy and quick assembling as well as exchange in FLEXhab.

Due to gaps created by the rails and panels, the rolls of an office chair get stuck easily, which makes their use uncomfortable. A similar problem is caused by the angular panels on the bottom. In particular when using the table directly next to the wall, the rolls of the chair interfere with those panels, and might even damage them.

The following pages display the most important aspects of the evaluation process.



5.14 Gaps due to rails



5.15 Pre-mounted profiles and workstation

Movability

- Hard but gentle movement of racks
- Railing system needs improvement (automation)
- Physical interaction with built environment
- No things dropping off, even without cover

5.16 Prototype, basic setup

Construction and maintenance

- Flaps require handles and fixation
- Difficult access to power supply in filled racks
- Sharp edges of panels
- Adaption of board height harder than expected
- Chairs interfering with gaps on the floor

5.17 Prototype scenario maintenance

Space

- Required space for most tasks less than the given maximum
- Installing/removing equipment requires most space (4.2.1)
  Dependent on the amount of people
- Tasks at the bottom require more space than others
- Duration of activity increases space required
- Little space more acceptable for short durations

5.18 Prototype scenario: workstation + experiment rack

Workstation

- Far less space required for standing tasks
- Height adjustment needs attention due to possible interfering with other racks.
- Cable management for height adjustment improvable
- Most space required for getting up and sitting down

5.19 Prototype scenario workstation - sitting

Lighting

- Fixation of backlit panels visible
- Lamps inside racks might be required
- Ambient light by office lamps shows importance of homogeneous light inside FLEXhab.

5.20 Prototype lighting

5.21 Different positions of the workstation

5.22 Stacking the racks for opening up the space on each side

5.23 Activities on the floor requiring the most space

5.24 Rearrangement and individual adaption allow for additional activities

5.25 Scenario - Maintenance: removing and mounting of wall panel, movable racks allow to open up space for the task.

5.26 Scenario - Office: use of FLEXrack for working, less interfering with gaps on the floor with different chair.

6. Lessons learned

Based on the previous evaluation as well as the overall design development, requirements for the final design of FLEXhab and a lunar base analogue in general will be defined. Even though the hull of the habitat was considered as a given parameter in the previous design approach, it has not reached its final design yet. Therefore, recommendations will also be given for improving or at least maintaining the developed interior qualities through the final design process in case of changes.

Simulation of the lunar environment

The question of how the lunar environment affects the design of the lunar base has been covered in chapter 2.1. The analysis has shown, that on Earth mostly the effects on the interior are relevant, resulting in an isolated confined environment. As a similar situation would occur for example on Mars, those design actions are easily transformable to a Mars analogue.

The environmental aspects result in isolation, confinement and the absence of natural light.

The overall layout of the habitat is influenced by environmental conditions not achievable in an analogue. Therefore, those parameters are defined either by terrestrial restrictions (building site, climate) or they are based on a specific concept of a lunar base.

Most relevant for the interior are isolation, confinement, and the absence of natural (Earth-like) light and the limited view to the outside.

Simulation of activities

As activities can be simulated more easily than the environment, an analogue has to be flexible enough to accommodate a variety of tasks Those are not defined exactly and can only be assumed for a lunar base, as well as the analogue. Training capabilities even need to extend that flexibility.

A proper definition of activities for the analogue allows for evaluation of similar requirements and therefore elements of multiple use.

For a lot of activities, horizontal surfaces are need, such as a computer workstation or a table. Those occupy a huge are in the habitat that can potentially be stored in case not needed.

Spatial requirements for specific tasks turned out to vary a lot regarding the duration of the activity as well as individual preferences. The latter was particularly observed during the prototype evaluation. It was mentioned, while using the workstation, the shelf immediately in the back can be useful, for example when using equipment. Having protection in the back can also be a positive aspect compared to the open office space, especially when sitting with the back to the door. Despite having the possibility (and legal requirement) of one metre between table and rack, the chosen distance was sometimes less.

Individual preferences and duration of the activity have great influence on the spatial requirements.

In particular for the use and training on experiments, it might be possible to develop strategies and procedures with efficient use of space. That means that tasks can be done with less required space due to the right technique.

Reconfiguration allows for the achievement of almost all regulations. Nevertheless, for increased efficiency they should not be applied unreflected.

Relevant standards

The possibility of individual configuration through FLEXrack, allows for meeting the legal requirements in terms of health and comfort. Nevertheless, the goal is to evaluate the actual required space to increase efficiency within the habitat. Therefore, the legal requirements might not be met anymore. The application of these without reflection is not recommended.

As an example, the area of movement for a workstation is given: The spatial requirements of one by one metre as given in 4.2, essentially meets the minimum dimensions. Additionally, it is required to have at least 1.5 m² available for movement. If that cannot be provided at the workstation itself, the area has to be available in the immediate surroundings. (Verordnung über Arbeitsstätten, 2004, ASR A1.2) Again, FLEXrack allows even more space through reconfiguration.

Requirements in case of fire protection and escape routes shall of course be applied to meet the safety restrictions. Requirements for lighting will be met anyway due to more advanced solutions required for the simulations.

Envelope

Dimensions of FLEXhab are similar to the current ISS module Columbus, but exceeding in length and constructed in a more rectangular way due to less cost intensive construction (Chapter 3.2). Launch systems are not the defining parameters for the analogue. Nevertheless, in case of referring to a real lunar base concept, the launch system defines the maximum dimensions. In that case, more recent systems, for example the Falcon Heavy by SpaceX, would allow different, bigger module size. (SpaceX, 2017)

The modular layout allows the addition of further modules in later phases, which is essential for the extension capabilities.

Additionally, FLEXhab should be transportable through European road transport in one piece. That fact adds constraints to the dimensions of the habitat. Increasing the analogue in size, will make transport significantly more time consuming and therefore expensive due to the requirement of special permissions.

With the current width of 3.5 m several limits are already being exceeded. Regular road transport, without any additional permission, does only allow a width of 2.55 m. The development of the previous concept has already shown that those dimensions are not feasible for the habitat. The next relevant limit is given at 3 m where transport companies usually have permanent permission for road transport. With a width of 3 m, the current layout would still not be feasible. Once exceeding the width of 3 m permissions for the exact individual case are needed, depending on the length of the trip and the final destination (national or international). Those permissions can be obtained easily, but as mentioned before, the timely and budgetary aspects need to be considered. (EU Directive, 2015)

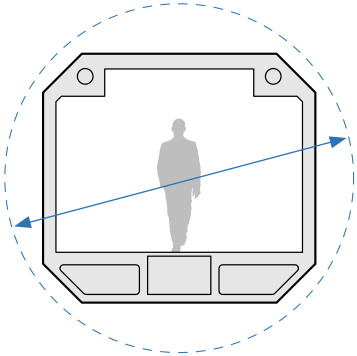
The length of the module is not considered as the limit in length will not be reached anyway.

Interior dimensions

The interior space requires certain dimensions in order to perform the required tasks. The previous developed concept suggests an interior layout, consisting of three compartments with a translation path in the middle of the module, along the longitudinal axis (chapter 3.2; Punch, 2016). On both sides experiments and workstation are located within FLEXrack. During the design study in 4.1 that layout was also considered as the most suitable one within the current dimensions.

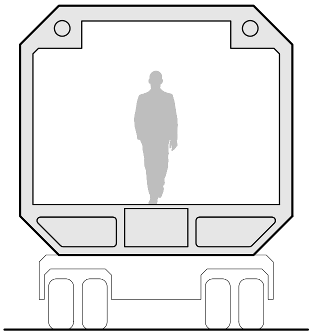
The spatial studies as well as the prototype have shown that the so

LOCATED IN EARTH, A LUNAR BASE ANALOGUE MIGHT STILL BE LIMITED BY LAUNCH SYSTEMS.



6.1 Limitation of dimensions

TRANSPORTATION CAN BE A DRIVING FACTOR FOR THE MAXIMUM DIMENSIONS.



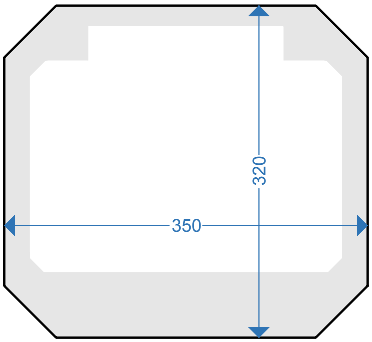
6.2 Limitation of dimensions

achieved 1 m in width for racks provides enough space for most of the activities, whereas it should not become smaller according to the evaluation process. Together with the corridor dimension of 1 m, the current interior width of 3.26 m is therefore defined as the minimum (not including interior wall panels or construction for sliding etc.). By applying more advanced solutions or using different materials, space savings can be achieved. As this is a cost driving factor (higher planning effort, individual design), another solution could be the extension of the outer hull in order to create a realistic interior. A reduction of the corridor area can be considered, and mostly depends on the equipemt and rack dimensions used in FLEXhab.

Priority in terms of dimensions can given on a maximum exterior, or a minimum interior.

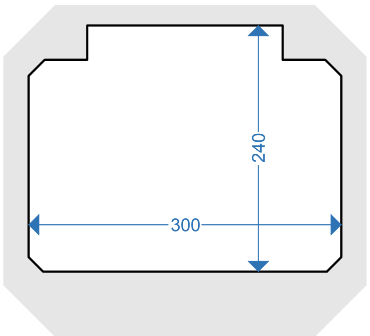
In general, for the relation between the interior and exterior dimensions two different scenarios are relevant:

1. If priority is given to realistic interior dimensions, the outer hull could exceed the feasible dimensions, as they are not relevant for the simulation. The construction could be built in a less expensive way in order to save costs. The transportation costs might be higher if certain limits will be exceeded, which would need more detailed evaluation in form of a cost-benefit analysis.
2. Priority can also be given to the exterior dimensions, for example to not exceed limits for transportation. Also other circumstances can cause a limited available space such as site selection or the precise simulation of a specific lunar base concept. In that case, within the limited volumes for space habitats, the construction of the module with all its subsystems and insulation etc. needs to be as thin as possible to reach the biggest available interior volume.



6.3 Given outer dimensions

In FLEXhab the current rack width of 98 cm (as in the prototype) can be seen as a lower limit. Experiments might also fit in smaller racks, but especially workstations should not be reduced in their current dimensions. That means that in case the thickness of the hull (currently roughly 10 cm) should increase during the final design process or if further evaluations lead to more space required for certain experiments, it has to be decided on one of the cases described before. If the current interior layout should be kept, the dimensions cannot be reduced.



6.4 Given inner dimensions

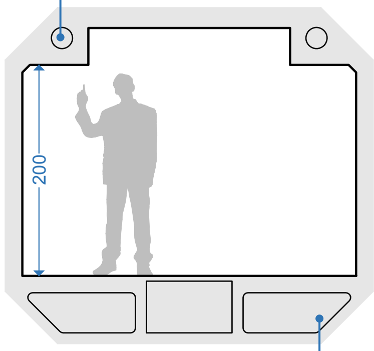
Interior height

When considering a lunar base, due to reduced gravity, the usual room height on Earth might not be appropriate. As the analogue cannot simulate that, terrestrial dimensions still apply.

In FLEXhab, due to the structure and the integration of a false floor for the different sub-systems of the habitat, a room height of 2.4 m is achieved in the centre of the module. In a 60 cm area on the sides of the habitat only 2.0 m are achieved, which had a big influence on the design as it is a prominent characteristic of the interior. It is to say, that decisions made under that aspect cannot just be transferred to other interior volumes.

The final design of the envelope will show the needed dimensions for construction and installations of the module. That can significantly change the inner dimensions as well as the interior space in its shape. The current room height of about 2.4 m is already lower than the limit of German legal guidelines for working spaces (Technische Regeln für Arbeitsstätten, ASR A1.2). Even if those regulations are not taken as requirements, a room height of 2.5 m is recommended. Especially, if the ceiling is equipped with lighting, additional head space is needed. The areas with lower ceiling height towards the sides turned out to be not as challenging and oppressing as assumed. Nevertheless, especially for tall people, 2 m might already be too small, which could be unacceptable. Therefore, it is especially recommended to increase the height in this area. For the maximum height, again the regulations for road transport apply. Depending on the chosen truck, the height can be seen as less critical as the width, nevertheless regulations for special permission apply as stated in EU Directive (2015).

CURRENT INTERIOR HEIGHT OF FLEXHAB IS NOT SUITABLE FOR TALL PEOPLE OVER LONGER PERIODS.



6.5 Limitation of interior height

During evaluation of the prototype, which is located in an office space with a room height of 2.7 m, it has been observed that the reduced height is perceived as a cosier, accommodating area. A distinction between zones of different functions is desirable for long duration missions, as different levels of privacy are becoming more important as the mission duration increases. A spatial differentiation can be done through different heights in ceiling or floor levels. Especially in more public areas where more people are accommodated at the same time, more volume should be available per person. This is particularly relevant for the future habitation module. In the now considered working module, the difference in height enhances the distinction of translation and accommodation area.

DIFFERENTIATION IN HEIGHT CREATES DIFFERENT QUALITIES AND LEVELS OF PRIVACY WITHIN THE HABITAT.

In case that spatial distinction gets lost during the final design process of FLEXhab, it is not recommended to artificially create a similar shape. Other solutions for differentiation of areas could achieve a similar effect, for instance through the use of materials or lighting. Apart from that, a less characteristic interior shape would allow to extend the flexibility into the third dimension. Different heights could be achieved temporarily and allow for comparison of their effect.

Interior layout

Some functions of a habitat need to be separated from others. This may refer to technical necessities, such as the pressurisation capabilities of an airlock, for entering and exiting the habitat, or according to specific requirements that are not compatible with other functions. Another example would be noisy activities like the continuous operation of a 3D printer, which will be disturbing for the crew in the long run. It is necessary to know the different functions as good as possible to create the most suitable interior layout.

Similar to terrestrial buildings a differentiation can be made between different levels of privacy. Those different zones significantly improve the social interaction of the crew as well as the personal well-being of crew members. According to Romain Charles (2017, personal conversation), during the Mars 500 simulation, the kitchen acted as a semi-private space which was used for studying. The spatial layout allowed for interaction with people passing by, while being a bit more separated from the common area. The initial function of the room was therefore changed as it allowed multiple uses.

Spatial arrangement should allow for different levels of privacy

Those spatial differentiations can either support or impede certain functions within a specific area.

For the distribution of functions in FLEXhab, a layout of three different compartments has already been defined in the previous studies. This was done mainly due to technical requirements, but also allows an appropriate arrangement of different activities according to their requirements.

Main compartment

The main compartment will host a variety of functions and will serve as the main area for experiments and workstation. Its design as described in chapter 4.1 is dominated by the FLEXrack which is covered in chapter 6.3.

In general it is to say, that the design approach applied to FLEXrack would also be applicable on static racks, as long as they follow the same layout.

As a general concern the layout itself could be seen. The width of a workstation is only one metre, only one person working per rack is implied. Some activities or simulations may require interaction of the crew while using a rack or a workstation. Wider racks would allow for more people working next to each other. In a static arrangement, that could be problematic. Through rearrangement of the racks, different configuration can either allow for interaction or separate different functions as shown in image 6.6.

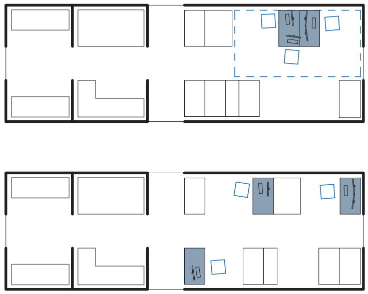
Airlock and EVA

The size of the airlock mostly depends on the amount of crew members that conduct an EVA. It needs to be considered, that anthropometry for suited crew members applies. The previous concept, as discussed in chapter 4.3, allows for several configurations of airlocks.

In times where no EVAs are performed, the airlock could be used for other activities. In general, multiple use for certain areas should always be considered. Thinking of a lunar base, for example located near the equator, during the lunar night EVA´s might be not possible, which would result in an unused airlock for two weeks.

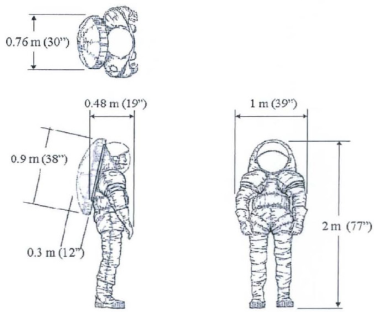
Engineering compartment

The engineering compartment accommodates the geology workstation which needs to be connected to the airlock for analysing samples brought in from the outside, and a toilet. For later stages of the project, when an additional habitation module exists, it might be possible to remove the toilet, as the habitation module will include a sanitary unit.



6.6 Spatial configuration supporting or impeding interaction

INVESTIGATION OF POSSIBILITIES FOR MULTIPLE USE CAN INCREASE THE AVAILABLE SPACE.



6.7 Basic anthropometry of a suited crew member (Griffin, 2003)

Besides the interior design of FLEXhab, this thesis specifically evaluates the concept and integration of FLEXrack into FLEXhab. Designing the FLEXrack, building a prototype, and evaluating it, leads to a conclusion respectively requirements and conditions under which the use of FLEXrack is beneficial for FLEXhab. These will be presented in the following.

Rearrangement

The evaluation of different scenarios within FLEXhab has shown, that a changeable interior is generally beneficial. Not just different simulations can be done, adaptations for the use of external partners or different trainings would be possible in the lunar base environment as well.

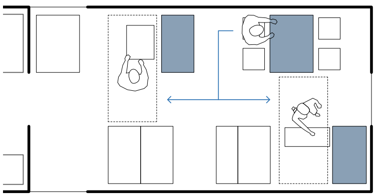
Depending on the frequency of reconfigurations, this is basically also achievable with conventional furniture or static modular racks. The more often the interior needs to change, the more flexible in terms of reconfiguration a system has to be. The use-cases described in chapter 4.2.3 show that the strength of the movable racks lies in the possibility of daily changes to account for the different needs of simulations and trainings (Case 2). Nevertheless, the concept only provides an advantage if the majority of required racks is already inside the module and only needs to be reconfigured by sliding.

Configuration of racks

THE BASIC CONFIGURATION OF RACKS NEEDS TO CONSIST OF ALMOST EVERYTHING NEEDED.

This implies that FLEXhab is equipped with a basic configuration of racks, which mostly stay in place and only need to be replaced in special cases. Single racks might need to be exchanged from time to time, but the more exchanges are needed, the less beneficial the system becomes.

For the arrangement of the different racks, a huge variety of configurations is possible. One of the most important things to know is, which and how many racks need to be accessible at the same time, in order to define the maxim amount. Special attention has to be given if racks need to extend into the corridor due to escape routes.



6.8 Blocking escape routes needs to be considered

An example configuration is given in chapter 4.2.6. Different focus of the simulations may require different basic configuration. For example if the focus in the first phase of the project is on EVA simulation, most of the time only part of the crew needs to work inside the main compartment, resulting in different requirements than in a 2 week simulation in phase 3.

Apart from that, dependencies in between racks, for example tools for a specific experiment need to be considered. Additionally, some permanent accessible racks might be needed for that purpose, or for experiments sensible to movement.

The evaluation of functions has shown that many expected tasks have similar requirements, resulting in racks that can be used for multiple application. Therefore, no exchanges would be required most of the time, which supports the concept. However, those tasks are based on assumptions for now. Consequently, the exact definition of what needs to be inside of FLEXhab for the mentioned basic configuration is particularly important.

Usability

A big advantage of FLEXrack is the adaptability to different spatial requirements for some racks, as well as their frequency of use. Some experiments only need maintenance rarely and therefore can be stored for the majority of time. The same applies for maintenance tasks where temporary access to covered subsystems must be provided.

FLEXhab should not just allow simulations, but also training on equipment, experiments, or workstations. The capability of reconfiguration, for example to extend the space around a workstation for several people attending a demonstration, presents another potential of FLEXrack.

Apart from those functional aspects, the movability of racks allows for different spatial configurations. From a design perspective, this presents an interesting circumstance that is worth further investigation. A reconfigurable environment could increase comfort and therefore performance of the crew by reducing visual monotony. Once FLEXrack is integrated in FLEXhab, it should therefore not just be designed for basic reconfiguration between simulations or different occasional trainings. Even though additional planning is necessary, the chance to investigate the actual potential of spatial rearrangement should not be missed. Through the integration of more advanced sliding and folding mechanisms the efficient use of space can even be increased. The visual, acoustic, and haptic elements as described in chapter 4.1 can even add additional comfort. FLEXhab and FLEXrack can serve as an analogue and test-bed for habitability and design.

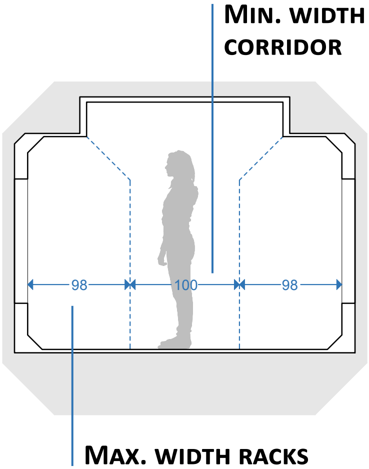
Organisational aspects

These advantages and potentials of the concept are only ensured under the explained conditions and therefore very much rely on the operational structure of the habitat. For example, if changes to the interior only occur weekly or even less often, the additional effort necessary, as well as increased costs, may not be justified. It has to be evaluated, how often different configurations are needed for training, simulation, or demonstrations.

Reduction in space over short periods allows for efficient use of space without reduction of comfort.

6.9 Spatial requirements compared in prototype

The organisational structure is essential to support the use of FLEXhab.



6.10 Limitation of rack size

Layout

In the scenario described in chapter 4.2.6, one rack and the table provide a more static environment on one end of the compartment. The table can still be moved, but is always accessible. Especially in the beginning, when the users might not be used to the reconfigurable interior, static things may be helpful.

During the first phase, the doors to the other modules will not be used. The space could therefore be used for additional racks. Extending the FLEXrack also to those areas should therefore be considered. Also once the additional modules are attached, it is likely that not for all simulations access is needed to the other modules.

Dimensions

The dimensions of the racks in this thesis are defined by the available volume of the habitat. After applying space for circulation, supplemented by visual elements for crew comfort, the 'leftover' space presents the defined maximum dimensions as shown in image 6.10.

Within a certain range, the current design of FLEXrack allows for flexibility in rack design. However, the decision against wider racks, requiring a different layout, was made already during the definition of the layout. (Chapter 4.1)

The functional analysis has shown that most of the assumed tasks fit into the maximum available space. Nevertheless, exceptions such as a bigger table require special solutions. While in the scenario in chapter 4.2.6 that exception was handled through relocation, another approach would be the implementation of folding mechanisms, for example. It is recommended that another interior layout or even size of the habitat is chosen, if more exceptions are necessary.

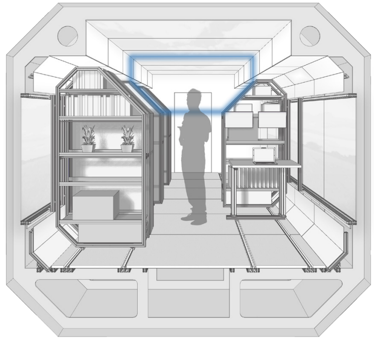
It should be highlighted that the size of the supply opening limits the rack size, its design, assembly, and therefore its transportability. However, the current design of the racks allows different widths. A more flexible solution, allowing bigger racks without the necessity of an opening with enormous dimensions, would be the approach of partially assembling the racks inside the module, which was also used in the prototype (see chapter 5.4), but might not be possible for externals.

Rack design

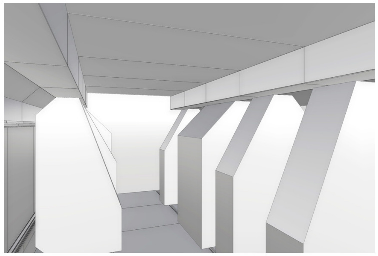
Similar to the dimensions, also the form of the racks is a result of the interior layout and the applied design measures. As these actions refer to the interior shape and dimensions of the habitat, adaptations might be necessary in case of changes. The approach of opening up the space on eye level to increase the perceived space of the interior nevertheless can serve as a countermeasure to the confined environments also in different shaped habitats.

The changing environment, especially when done frequently, may require the application of a colour code (or similar) to have a clear distinction between the different racks and allow to identify the current arrangement. This can also be supported through the use of different materials as explained in chapter 4.2.4.

The design of the rails allows some freedom in rack design. Nevertheless, it also bears the danger of an inconsistent maybe even confusing visual appearance. Therefore, within all the racks inside a compartment not too many parameters should be changed. As an example, to create different shapes of racks with the angular design in this thesis, racks with different angles in accordance with the use could be installed. Even though every rack is different, they follow the same standards and a consistent overall appearance is ensured. Racks with less width could for example be adapted to the edge of the ceiling. (Image 6.12)



6.11 More volume at eye level



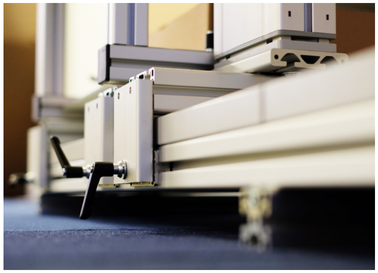
6.12 Angular racks approach

Technical aspects

The movability of the racks obviously adds technical complexity to the habitat. This results in higher amount of planning and costs. Apart from that, moving elements have been mentioned as potentially at risk of failure on the ISS by EAC experts. At least they require a higher amount of maintenance.

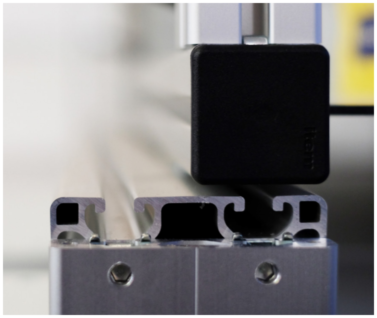
Therefore, the design and construction of the movable parts of FLEXrack requires special attention. The rail system used for the prototype never intended to be used for FLEXhab as it only allows for manual movement, requires greasing, and is not ideal for higher loads. For the integration into FLEXhab a more advanced and automated solution needs to be implemented such as a rack drive.

For automation, different scenarios would be possible. Racks could individually be moved by the crew one by one. For different mission scenarios or when more racks have to be moved at the same time, the implementation of predefined scenarios is recommended. With one click, the whole compartment could be transformed to achieve a configuration for a specific simulation. That also requires safety precautions, possibly in form of sensors between the racks. While moving, space has to be provided for the crew.

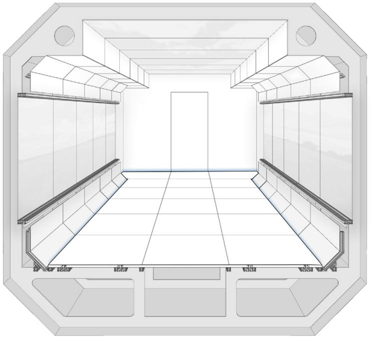


6.13 Manual fixation in prototype

The construction and evaluation of the prototype has shown the advantage of the pre-mounted profiles as support for the racks to be assembled



6.14 Pre-mounted profiles



6.15 Reducing gaps on the floor

and attached. However, with more advanced rack drives, the same effect might be achievable without profiles that not just increase construction height but also create an obstacle on the floor when not in use. Profiles on the walls that are used for the integration of screens or smaller racks can still be added later if needed.

The gaps induced by the rails, made the use of chairs quite tricky. Apart from that, dirt and dust easily get stuck there and bigger things may even block the slides. Therefore, those gaps should be reduced (or at least the distance in between increased) and if possible even avoided in the final design. One solution could be to move the rails from the floor to the ceiling. Inverting the system would allow for a seamless floor, free of any obstacles.

In that case, the additional payloads have to be considered for the structure of the habitat, as well as the requirements for the rails.

6.4 Lighting

Evaluation of the designed lighting is limited, as the prototype does not provide the same conditions as FLEXhab. Ambient lighting is provided by the existing office lamps. Additional lighting was planned to be integrated through the backlit panels on the wall. Unfortunately, that could not be tested as planned at the time the thesis was written due to technical issues. The purpose of that lighting was to visualise the concept as well as to give the possibility to experiment with different solutions.

Nevertheless, due to the importance of lighting in a closed confined environment, requirements will be given according to literature and personal experience.

The legal requirements, as stated in chapter 3.3 give an orientation of the required illumination of workspaces according to different tasks. In particular, the absence of daylight requires countermeasures in form of appropriate artificial light as well as simulated windows as explained in chapter 4.1.3.

Ambient lighting

Ambient lighting serves as a replacement of sunlight. It therefore needs to create the necessary illumination for basic tasks.

According to the legal restrictions (Verordnung über Arbeitsstätten, 2004, ASR A3.4) illumination of 500 lx is at least necessary for tasks such as writing or reading. This is to be highlighted as an **absolute minimum** value and is dependent on several factors such as light colour, location of light source, direction of the light, and personal preferences. Additionally, racks, furniture or any kind of equipment can create shadows. Those cannot only reduce the visibility of tools, equipment or obstacles, but also add strong visual elements disturbing the perception of the crew.

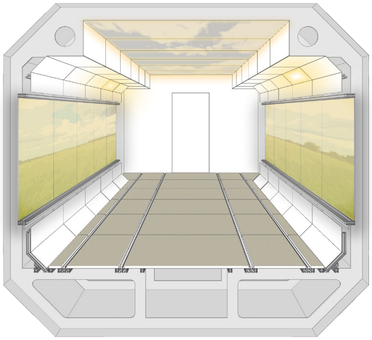
Therefore, the ambient lighting should provide a **uniform light distribution** to avoid dark, shadowed areas. This could be achieved through homogenous area light sources and/or the implementation of several light sources from different directions. Especially the changeable environment requires a homogenous distribution of light sources.

Besides the provision of appropriate illumination, light can also be used as a design element in order to create a more comfortable interior space. The focused implementation of indirect light sources as well as illumination of certain surfaces can increase the perceived interior volume as illustrated in chapter 4.1.3.

By highlighting different areas users can also be guided through the habitat visually. With the introduction of different light colours, also different functions can be implied through lighting. Relaxation areas are often equipped with lamps close to colour temperatures of a classic light bulb. Areas for precise work often require colour temperatures close to daylight.

“Light impacts on our circadian rhythms more powerfully than any drug.”
(Czeisler, Nature, 2013)

Differentiation of light colours, which means the use of different wavelengths, cannot only support certain tasks, but also different overall light situations within the whole module. By using an overall lighting system that allows for individual configuration of intensity, wavelength and duration, the simulation of a natural light rhythm can be achieved. Recent studies on biological effective light for influence on the circadian rhythm, have shown that the main aspects for creating a positive effect are illumination, colour, direction, dynamics, and planarity. (Pross et al., 2015) Especially important is the possibility of manual control due to individual preferences.



6.16 Simulation of natural light

Apart from the psychological effects created from different light environments, the absence of sunlight also causes physiological effects. Without the usual UVB radiation the human body is not capable of producing Vitamin D. As a countermeasure, the implementation of special UVB lamps should be considered and evaluated for long term mission scenarios. Furthermore, different wavelengths can for example synthesise or suppress melatonin, causing to feel more awake or sleepy, respectively. (Kolodziejczyk/Orzechowski, 2016)

In FLEXhab ambient light is achieved through an illuminated ceiling. Additional light from walls creates a window-like lighting. The latter should only be used when not covered by racks or equipment. Therefore, it should be connected to the arrangement of the racks to avoid unnecessary reflections or shadows, as well as to save energy.

6.17 Background lighting in prototype

In general it is recommended that all those light sources can be controlled individually and partially. Meaning that a part of the wall light can be turned on in one place of the module in a specific brightness and colour, while it is turned off in other areas or used differently somewhere else, same applies for the ceiling. This will increase the complexity, but will allow the crew to configure according to their needs.

Studies on the effect of light in such a confined isolated environment are very important for future space missions. In particular, the integration of biodynamical light to maintain or influence the circadian rhythm should be investigated in further studies. Together with the implementation of simulated windows, the interior quality can be improved drastically.

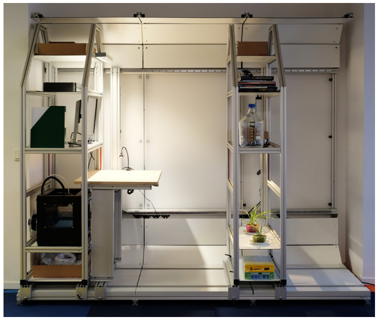
Task lighting

For the performance of scientific experiments, detailed repair work or assessment of samples, additional requirements apply. Increased illumination of 1000 lux and more are commonly used for fine works, additional colour rendering qualities may be necessary for sample analysis or similar applications. (Verordnung über Arbeitsstätten, 2004, ASR A3.4) As such tasks take place only from time to time and only on specific workstations, racks, or areas of the module, they can be achieved through specific additional lamps.

The different racks and workstations can be complemented with light that is specifically designed for the purpose of the workstation.

As mentioned in chapter 4.1.3 additional lamps could also be integrated in the upper corner of the accommodation zone. With them being able to switch on/off individually, certain sectors of the module can be additionally illuminated. Those lamps could also act as an indicator to enhance the visibility of the current configuration of FLEXrack, enlightening the areas that are accessible.

In the prototype, for better illumination a lamp was mounted to one of the racks. Apart from that, it works independently from the ambient light. So no matter of the current light simulation, it provides the necessary illumination for certain tasks. Adaptability of the brightness allows further adaptation for the user. Through attachment of the workstation, that as well can benefit from that light.



6.18 Task lighting in prototype

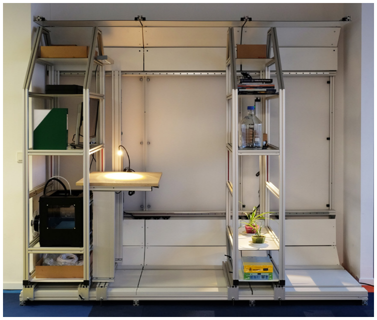
SPECIAL TASKS REQUIRE SPECIAL LIGHTING, INDEPENDENT FROM THE AMBIENT LIGHT.

Individual lighting

As already mentioned above, different tasks require different lighting. Creating a specific environment through light and materials, as well as spatial design, as described in chapter 6.2 can imply a certain activity for an area. Personal experience as well as input from the EAC team has shown, that preferences in lighting conditions, like for instance colour temperature, vary significantly. As probably not all lamps can be provided with adjustable colour temperature, the possibility should be given to easily implement smaller lamps to meet personal preferences of the crew.

Another approach could be the integration of movable lights. Lamps providing a specific illumination (brightness, colour rendering, wavelength, etc.) could then be used where they are needed. This makes an infrastructure necessary that allows for movement or easy relocation.

In FLEXhab, that concept could be achieved with the secondary sliding system introduced in chapter 4.2.4.

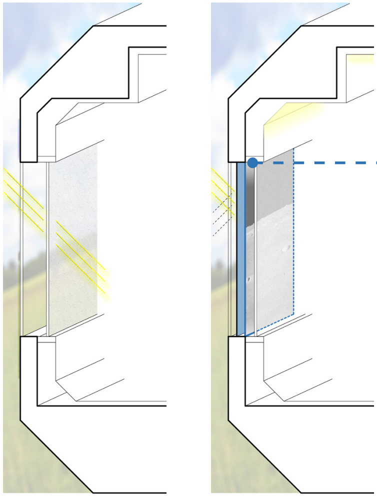


6.19 Individual lighting in prototype

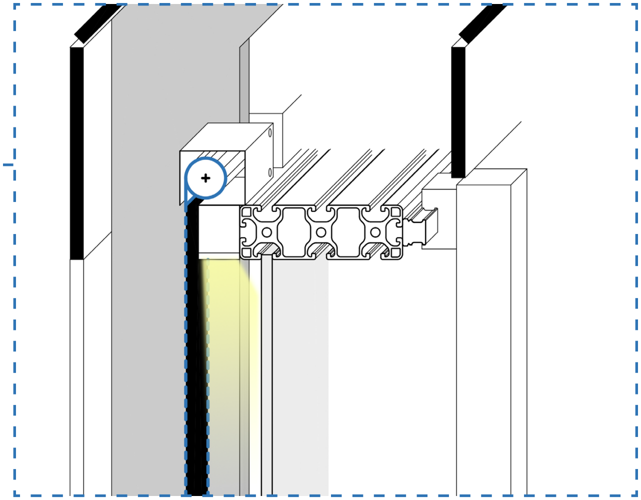
Natural light

The integration of natural light was excluded of the design due to a realistic simulation of a lunar base. Nevertheless, the habitat also serves for astronaut training. For all kind of work outside a simulation, natural light would be preferred.

Considerable would be windows located behind the simulated windows. Opened remotely, they could provide natural light through the translucent layer integrated on the wall. Switching from natural to artificial light could even allow to study the different effects on the crew during a simulation. An idea of how to create such a solution is given in the images below. The integration of windows into the hull should therefore be considered.



6.20 Comparison: natural light / lunar simulation



6.21 Solution allowing for natural light while keeping the option of simulating Moon conditions

6.5 Materials and colours

The use of materials and colours is of similar importance than the use of light. The application of different materials while different simulations to study their influence would be desirable. Especially for the integration of functional materials, providing acoustic insulation as well as a visual improvement. Individual changes in colours could be achieved by implementation of coloured lights, for example through the backlit elements on the wall. Nevertheless, the importance of haptic properties of different materials must not be forgotten. The prototype is equipped with white panels to allow for easy application of other colours through paint or adhesive foil, as well as to have a comparison to the sterile environment similar to the one currently used on the ISS. In contrast to that, a wooden table was implemented to visualise and intensify the effect of different material properties.

6.22 Wooden table in prototype

Wood may not be the ideal material for example, to operate with fluids. Nevertheless, its smell and haptic properties allow for perception of the room with all our senses.

Different materials allow for perception of the room not just visually, but also with our hands and even our nose.

Even though the use of different materials is suggested, not too many different types of materials should be used. This would on the one hand impede relevant results from studies and on the other hand might overstimulate the users.

The extensive integration of handles, grips, controls etc. can also be over-stimulating. Those safety relevant should of course be highlighted, while others, less important or seldom in use should be rather unobtrusive.

The integration of subsystems and the ECLS has a similar influence, as removable panels create seams. At least handles and openings should be designed in a way that they do not create too much of an obstacle or gap. This also applies to any other panels inside the habitat as the visual influence of those elements should be kept at a minimum.

Within the confined, possibly crowded environment, a flat plane surface here and their might increase the comfort of the crew. As Frank Lloyd Wright already recalled after the design of the Charnley house *“[...] I first sensed the definitively decorative value of the plain surface [...]”* (Treiber, 2008: 12). The end walls of the main compartment are therefore foreseen to be free of any obstacles.

“[...] I first sensed the definitively decorative value of the plain surface [...]”
(Frank Lloyd Wright, cited after Treiber, 2008: 12)

Through materials and especially colours, the distinction between movable and static elements within the main compartment is supportive, in particular if also static racks or other non-movable elements are integrated.

6.23 Railing on the wall

6.24 Seams between panels

The evaluation of the prototype has shown that the use of COTS products, in particular the chosen modular system, allows for easy construction as well as adaptation. That is important not just for a prototype but also for a habitat requiring changes and adaptation due to changing requirements throughout its life span.

Nevertheless, more individual solution might result in less construction height and therefore more interior space available with the same dimensions on the outside. The relation of these two dimensions and their impact on the design are described in 6.2.

As mentioned in chapter 6.3, the railing system needs to be improved. It must provide sufficient automatic movement, while still gentle enough for equipment and experiments.

The wall panels require more advanced fixations where access is needed and the visual appearance can be improved in terms of seams. Thickness of the panels needs to be increased compared to the prototype.

The overall design of the racks, including their dimensions proved to be fine in the prototype. Different materials for the surfaces might be needed to be prepared for heavier loads on the boards.

Improvement needs to be done on the construction of the workstation. Even though the movement in both directions worked well, more durable solutions need to be put into place through individual solutions or improved details on the different connections, especially the moving ones.

Depending on the final location of the rails and the fixation of the racks, those need to withstand not just vertical loads but also horizontal ones through movement but even more important: people might lean against them. This has to be considered in the construction of the racks and railing system.

6.7 Conclusion

The evaluation of the lunar environment and lunar base activities have shown that the most relevant aspects for lunar base analogue design are isolation and confinement. Living in an isolated artificial environment requires countermeasures to create not just a comfortable environment, but is also critical for mission success. Similar effects would also appear for example on Mars, therefore those are applicable for analogues in general.

Apart from the spatial requirements given by the activities, the design measures presented in this thesis are focusing on three main elements:

Lighting – To allow for natural Earth-like conditions (4.1.3)

Colour and Materials – to avoid visual monotony as well as to increase comfort contrary to current sterile space habitats.

FLEXrack – to increase flexibility and efficient use of the limited space and allow for adaptions, as well for sensory stimulation.

The prototype allowed for evaluation and improvement of the spatial and technical requirements. Together with the developed scenarios for FLEXrack, specifically a conclusion for the integration of FLEXrack is presented in the following:

FLEXrack

Based on the suggested design as well as the defined requirements, the use of FLEXrack can add significant potential to the FLEXhab analogue. Nevertheless, conditions and design other than the ones described, might reduce those advantages.

The biggest concerns are on the one hand operational aspects, meaning that FLEXhab will be used in a different way than what FLEXrack is built for. On the other hand, usability must be ensured. The introduction of FLEXrack must not limit the user in any case compared to a non FLEXrack solution, which is mostly depending on technical aspects.

The required flexibility of the interior is not just seen as a necessity for the unknown tasks or different training techniques that will be carried out in the habitat. The integration of a movable rack system adds potential value: the analogue can be used for simulations with different spatial configurations. The different cases, as described in chapter 4.2.6, can even be tested and evaluated to investigate the concept's benefit for future space habitats.

As the goal is also to develop new training methods, FLEXhab allows not just for training specific tasks, but more creates an overall simulation of a lunar base environment.

Additionally, studying the effects of different design measures will not only increase habitability of future space habitats, but will also lead to spin-off for terrestrial applications. The fact that colours, materials, and light have a big influence on human beings, is a well known fact everyone can experience on their own. Nevertheless, those positive effects are hardly measurable. In a closed environment, those are likely even more intense, which will result in more significant results.

One major issue encountered during the design process was the combination of flexibility and efficiency. Those two interfere with each other for the following reason:

The most flexible interior is probably an empty room as it can be equipped with whatever is needed at the moment. Furthermore, rearrangement is easy.

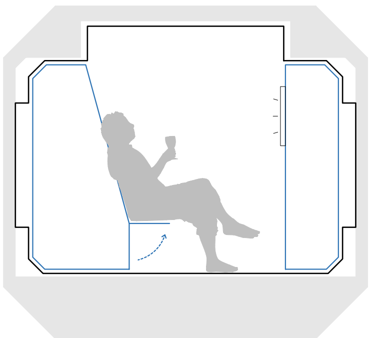
The most efficient space is planned into every detail, adapted to specific needs.

Combining both of those approaches, creates the danger of one reducing the other. With the design of the FLEXrack system a solution is presented, which combines the strengths of both, by easy reconfiguration that allows for multiple use of space.

One of the biggest disadvantages of the concept is the fact that some racks are not accessible permanently. Precise planning needs to be done in order to avoid situations, where things in need cannot be accessed. Spontaneous changes between activities might be prevented by the current configuration of racks. Looking for an experiment that is stored will not happen casually, which was mentioned as a concern by members of the EAC team. Furthermore, warnings and signs in case of failure need to be located on a place that is always visible.

The limitation of access is defined by the amount of racks in the habitat. Therefore, different scenarios can also be tested to improve the concept and adapt to people's needs.

Besides those disadvantages, the crew of simulations gets the possibility to create different interior arrangements according to their preferences. Additionally, the space gained through the concept serves the crew. Especially for long duration simulations, the additional space can be used to add comfort, which would be impossible in a conventional layout. FLEXrack can therefore also be seen as a tool for future astronauts to create and design their own physical environment. A lot of potential lies in the design of the racks, by the implementation of sliding and folding mechanisms as well as through combination of different rack forms.



6.25 Combination of racks

6.7 Conclusion

Supplementary to all the movable parts, within the whole habitat also some stationary parts are required. Even though, FLEXrack shall only be implemented in the main compartment, meaning the other two serve as a steady environment, it will still be beneficial to have some stationary parts in there as well. Similar to the arrangement in chapter 4.2.6, the table for multiple use can serve as a more permanent point.

A final prove of concept can only be achieved by several real simulations. However, FLEXrack is designed to not just allow moving racks, but also enables easy replacement of racks like a static rack system.

Even without frequent rearrangement, a positive effect is achieved. As of now, astronauts living in unpleasant spatial conditions have no chance of improving their situation. An adjustable environment would increase crew comfort significantly. The private compartments in the Mars 500 mission, for instance, did not provide sufficient acoustic separation (2017, personal conversation). Even though it was not the case often, the medical compartment could be used for more privacy or better acoustic insulation due to its location. Simply having the possibility to change an unpleasant situation adds additional comfort for each individual, even though it is not used.

Overall, FLEXhab, including FLEXrack, **allows**

- easy and quick reconfiguration within short time
- increased amount of racks compared to static solution
- flexibility in rack design
- evaluation of reconfigurable space for future space habitats
- testing the effects of design and especially the changing environment on crew's performance
- functional and visual reconfiguration

but **requires**

- precise planning in advance
- defined spatial requirements of racks
- higher technical effort
- more expensive construction than static racks
- a suitable operational structure.

7. References

7.1 Bibliography

Adams, Constance (1999): Habitability as a tier one criterion in advanced space vehicle design: Part one-habitability. doi:10.4271/1999-01-2137.

Benaroya, Haym (2010): Lunar Settlements. In: Advances in Engineering, CRC Press

Bishop, Sheryl / Häuplik-Meusburger, Sandra / Guined, Jamie / Peldszus, Regina (2016): Bionomic Design Countermeasures for Enhancing Cognitive and Psychological Functioning and Crew Performance in Isolated and Confined Habitats. 46th International Conference on Environmental Systems, ICES-2016-375, Vienna, Austria.

Broughton, Hugh (2016): Polar Research Facilities: Living in isolation. 46th International Conference on Environmental Systems, ICES-2016-158 , Vienna, Austria**.**

Clément, Gilles (2017): International roadmap for artificial gravity research. Review article, NPJ, online:
https://www.nature.com/articles/s41526-017-0034-8.pdf (cited 13.03.2018)

Cohen, Mark (1995): The suitport's progress. Life Science and space medicine conference, AIAA-95-1062, Houston, USA.

Cristoforetti, Samanta (2016): European researchers invited to board 'Spaceship EAC'. 02.09.2016, online:
http://www.esa.int/About_Us/EAC/European_researchers_invited_to_board_Spaceship_EAC (cited 16.01.2018)

Czeisler, Charles A. (2013): Perspective: Casting light on sleep deficiency. In: Nature 497, S13 (23 May 2013)

Durao, Maria Joao (2002): Color Consideration for the Design of Space Habitats. The American Institute of Aeronautics and Astronautics Inc.

Eckart, Peter (1999): The lunar base handbook- An introduction to lunar base design, development, and operations. U.S.A. : The McGraw-Hill companies, Inc.

ESA [EDR2] (2001): The European Drawer Rack for the ISS and its Scientific Capabilities. ESA Bulletin 108, 11.2001, online:
http://www.esa.int/esapub/bulletin/bullet108/chapter13_bul108.pdf (cited 20.03.2018)

ESA [NBF] (2006): Preparing for Space- EVA Training at the European Astronaut Center. ESA Bulletin 128, 11.2006, online:
http://www.esa.int/esapub/bulletin/bulletin128/bul128e_bolender.pdf (cited 21.03.11018)

ESA [ISS], 2013: Pushing the boundaries of science and technology. Online:
http://www.esa.int/Our_Activities/Human_Spaceflight/International_Space_Station/Pushing_the_boundaries_of_science_and_technology (cited 05.03.2018)

ESA [Zero-G] (2015): Airbus A310 Zero-G. ESA research – human spaceflight and exploration. European Space Agency, online:
http://www.esa.int/Our_Activities/Human_Spaceflight/Research/Airbus_A310_Zero-G (cited 06.03.2018)

ESA [EDR1] (no date): European Drawer Rack. Revision 1.1, EUC-ESA-FSH-011, online:
http://www.capcomespace.net/dossiers/ISS/europe/columbus/Nouveau%20dossier/fs016_11_edr.pdf (cited: 20.03.2018)

EU Directive (2015): For certain road vehicles circulating within the Community the maximum authorised dimensions in national and international traffic and the maximum authorised weights in international traffic 2015/719, online:
https://ec.europa.eu/transport/modes/road/weights-and-dimensions_en) (cited 11.03.2018)

Griffin, Brand Norman (2003): Lunar habitat airlock/suitlock. NASA Technical Reports Server (NTRS), online:
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080018968.pdf (cited 25.03.2018)

Häuplik-Meusburger, Sandra /Peldszus, Regina / Holzgethan, Verena (2010): Greenhouse design integration benefits for extended spaceflight. 60th International Astronatuical Congress (IAC), Daejeon, South Korea.

Häuplik-Meusburger, Sandra (2011): Architecture for Astronauts – An Activity-based Approach. Wien/Heidelberg: Springer-Praxis Books.

Häuplik-Meusburger, Sandra / Bannova, Olga (2016): Space Architecture Education for Engineers and Architects. Switzerland, Springer.

Häuplik-Meusburger, Sandra / Binsted, Kim / Bassingthwaighte, Tristan / Petrov, Georgi (2017): Habitability Studies and Full Scale Simulation Research: Preliminary themes following HISEAS mission IV. Conference Paper: 47th International Conference on Environmental Systems, ICES-2017-138, Charleston, South Carolina.

Howe, Scott / Polit-Casillas, Raul (2014): Random Access Frames (RAF): Alternative to Rack and Standoff for Deep Space Habitat Outfitting. Conference Paper: 44th International Conference on Environmental Systems, ICES-2014-038, Tucson, Arizona

International Space Exploration Coordination Group (ISECG) (2018): Global Exploration Roadmap 2018, online:
https://www.globalspaceexploration.org/wordpress/wp-content/isecg/GER_2018_small_mobile.pdf, (Zugriff: 09.03.2018)

Item (2017): Der item MB Systembaukasten. Online:
https://www.item24.de/produktwelt/mb-systembaukasten.html (cited 10.03.2018)

Jones, Tom (2010): Lost In Space. Microgravity's mysterious side effect: Stuff disappears. Air & Space Magazine, September 01, 2010, online:
http://www.airspacemag.com/space-exploration/Lost-In-Space.html?c=y&page=1 (cited 10.03.2018)

Kolodziejczyk, Agata Maria / Orzechowski, Leszek (2016): Time Architecture. Acta Futura 10 (2016) / 37-44, doi: 10.5281/zenodo.202172

Meuser, Philipp (2014): Galina Balaschowa – Architektin des sowjetischen Raumfahrtprogramms. Berlin: Dom Publishers

NASA [MSIS] (1995): Man-System Integration Standards, Revision B, online:
https://msis.jsc.nasa.gov/ (cited:19.03.2018)

NASA [ISS] (1998): International Space Station Familiarization. Houston Texas, USA: Lyndon B. Johnson Space Center, 1998. TD9702A, online: https://er.jsc.nasa.gov/seh/td9702.pdf (cited 10.03.2018)

NASA [Materials] (1998): Space Station Requirements for Materials and Processes. Revision F, SSP 30233, online:
http://everyspec.com/NASA/NASA-JSC/NASA-SSP-PUBS/SSP_30233F_3099/ (cited 23.03.2018)

NASA [ISS] (2000): ISS User's Guide. Release 2.0, online:
http://www.spaceref.com/iss/ops/ISS.User.Guide.R2.pdf (cited 20.03.2018)

NASA [NEEMO] (2004): Habitability Assessment: Habitat Utilization Analysis from Human Factors Perspective (NEEMO-HABITABILITY), online:
https://lsda.jsc.nasa.gov/scripts/experiment/exper.aspx?exp_index=1099 (cited 06.03.2018).

NASA [HIDH] (2014): Human Integration Design Handbook (HIDH), Revision 1, Washington DC: NASA JSC

NASA [Analogues] (2017): About Analog Missions. Timothy Gushanas, NASA, online: https://www.nasa.gov/analogs/what-are-analog-missions (cited 21.03.2018)

Neufert, Peter / Neufert, Cornelius / Neff, Ludwig / Franken, Corinna (2002): Bauentwurfslehre. Edition 37, Braunschweig/Wiesbaden: Vieweg

Pross, Achim / Stefani, Oliver / Bossenmaier, Sebastian / Bues, Matthias (2015): LightWork - Benutzerakzeptanz und Energieeffizienz von LED-Beleuchtung am Wissensarbeitsplatz. Bauer Wilhelm, Fraunhofer IAO.

Schlacht, Irene Lia (2012): SPACE HABITABILITY- Integrating Human Factors into the Design Process to Enhance Habitability in Long Duration Missions. Dissertation at 'Fakultät V- Verkehrs- und Maschinensysteme der Technischen Universität Berlin'

Schrunk, David / Sharpe, Burton / Cooper, Bonnie / Thangavelu, Madhu (2008): The Moon – Resources, Future Development, and Settlement. Second Edition, Berlin / Heidelberg / New York: Praxis / Springer

SpaceX (2015): Payload User's Guide- Falcon 9 Launch Vehicle. Revision 2, online: http://www.spacex.com/sites/spacex/files/falcon_9_users_guide_rev_2.0.pdf (cited 21.03.2018)

SpaceX (2017): Falcon 9. online: http://www.spacex.com/falcon9 (cited 11.03.2018)

Treiber, Daniel (2008): Frank Lloyd Wright. Edition 2, Basel: Birkenhäuser-Verlag

Verordnung über Arbeitsstätten (2004): Arbeitsstättenverordnung – ArbStättV. in: BGBl. I S.2179

Vogler, Andreas / Jørgensen, Jesper (2004): Windows to the world- Doors to Space - a reflection on the psychology and anthropology of space architecture. Space: Science, Technology and the Arts (7th Workshop on Space and the Arts), ESA ESTEC, Noordwijk, The Netherlands.

Wörner, Jan (2016): Interview: Moon Village: Humans and Robots together on the Moon. 01.03.2016, online: http://www.esa.int/About_Us/DG_s_news_and_views/Moon_Village_humans_and_robots_together_on_the_Moon (Zugriff: 09.03.2018)

Summary of the conversation with Romain Charles, flight engineer of the Mars 500 simulation. (02.10.2017, EAC, Cologne)

Limited space:

Romain experienced the habitat as big enough, it could have even been smaller. The kitchen was mentioned as not ideal, because the person sitting in the corner could not leave without others getting up as well, which did not cause any troubles but was mentioned as improvable. Apart from that, people are prepared to adapt to the available space. As there is no possibility to change anything, you get used to it. Additionally, the shorter missions done before the 520 days already allowed for some improvements.

One crew member wanted to walk, therefore he opened all the doors to maximise the walking distance without interruption or the need to turn around. For that case a circular layout was mentioned as possibly beneficial. The dimensions of the corridor did not allow for two people crossing each other. The private compartments, which mostly where opened, were used to let someone pass. Unloading the marsian lander at about half of the simulation duration was difficult due to the limited dimensions. Tall people could not walk up straight because of the curved walls. Also the room height was mentioned as improvable by increasing.

Activities:

Favourite activities were things like reading, watching series, etc. Essentially, things that do not need a lot of space. In general, nobody comes up with an idea that is not possible within the limited space. Romain’s favourite places were the private compartment and the living room. He sometimes used the kitchen for learning Russian as people passing by could help. The medical compartment could be used for private retreat.

Lighting:

The habitat was equipped with basic neon lamps which broke quite fast resulting in a darker environment within the habitat. Light was turned off at night, independent from the current activities of the crew members to create a day and night situation.

Materials:

Even though, the extensive use of wood was mentioned as not appropriate for all tasks, Romain still considered it as positively influencing. Materials related to certain tasks was seen as an option for improvement.

Noise:

The walls did not provide sufficient acoustic insulation. In case of disturbance, the medical compartment could serve as a more isolated space in case somebody wanted to sleep during the day or listen to loud music. Noisy equipment was an issue once, when the pump in the greenhouse had a malfunction. Romain woke up and turned it off which might have even saved the pump.

Individualisation:

As furniture was fixed, no essential changes have been made on the interior. One of the crew members used the wood from one of his drawers that did not work properly to add some extra space to his desk. A fixation for laptops was built for the treadmill to allow for watching films during exercise. Similar to the general limitation of space, people do not come up with ideas they know are not possible. The possibility of adaptions was mentioned as a way to improve comfort, for example to increase the size of the bed for taller people. Individualisation was mostly done in forms of pictures, flags and posters on the walls.

Privacy:

The private compartment was described as a cocoon. Even though, more space is always nice, it could have actually been even smaller. Throughout the mission, the walls got more and more covered with pictures. Romain spent most of the time in his private compartment, especially sleeping got more towards the end of the mission.

What was missing?

Mostly a natural environment; the sun, rain, wind etc. Apart from that, food and the possibility to cook properly.

Advices for analogue design:

As nobody can ever think of every detail, things should be adaptable between simulations to allow for evaluation and improvement.

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

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