In-situ Habitat Design on Mars

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Abstract

In this report we study the isolation in habitats on Mars from society on Earth. We try to understand the construct of this micro-society and identify physical and psychological implications for astronauts. Through this knowledge, previous simulation and analogue research, empirical research, and analysis of this we try to learn how these habitats must be designed in order to facilitate the crew's work and well-being in the Martian environment. Simultaneously we try to understand how in-situ construction with Microbially Induced Calcite Precipitation can create interesting alternatives to designing Mars habitats.

We study why simulated knowledge is indeed scientific knowledge, and why it is of utmost importance to know how to survive and thrive in a completely isolated environment on another planet, before performing the first manned mission. Also, we investigate how and why knowledge about Mars goes through different stages before becoming accepted knowledge, and how this knowledge is important for the future progress of the Earth, its society and development of technologies.

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1. Introduction

1.1 Concept Definition

'Astronauts'

NASA has made a specific list of who's going to attend the first manned mission to Mars. The list includes pilots, physicians, geologists, biologists and engineers (Kennedy et al., 2016). When we use the term astronauts throughout this report, we include the above-mentioned scientists, engineers and pilots.

'Astronomical Units' (AU)

A unit representing the distance between the Sun and the Earth. This distance is used to measure in solar system scale (NASA Science, 2019-a).

'Colonization'

In this report, we use the term "colonization", and we find it important to define the word, so that the reader understands what we mean when we use the term. Throughout history, mankind has colonized through three phases. In phase one, people from wealthy countries crossed the ocean to find new countries to claim (Dettmer, 2018.). In phase two, the same people returned to live in the country which they previously claimed. However, they were not yet an independent colony because of the necessity for the wealthy country to send food and other important resources. In phase three, an independent colony was formed while more people joined the colony, which caused prosperity to rise (Dettmer, 2018).

When we use the term "colonization", we find ourselves in phase one and two. We assume that phase one is more or less complete, while the first robots have already been sent to Mars. In phase two, the first humans, and in this case, astronauts are sent to Mars to explore the planet and examine the materials found on Mars. While we find ourselves in both phases, the astronauts will return to Earth after their mission.

'Delta Velocity' (Delta-V)

The total difference in velocity required to travel from destination A to B in space (Whitley & Martinez, 2015).

'ETFE'

Ethylene-tetrafluoroethylene (ETFE), is a fluoropolymer which is commonly used in wire insulations for flight hardware (Boddapati, 2011). It is a material which compared to other similar materials, such as Polytetrafluoroethylene (PTFE), is much more resistance to radiation (ibid.). ETFE is often used in architecture designs for future space habitats, such as the Mars Ice Habitat.

'Habitat'
Throughout this report, we study how to build a habitat for astronauts going to Mars for research. A habitat is defined as "*the place or environment where a plant or animal naturally or normally lives and grows*" ("Habitat," s.d.). It is a place where a living organism can live and thrive which means it is able to find shelter, protection, food, etc. If we want our Mars habitats to be successful, we need to make sure that the houses we build fulfill the requirements for a successful habitat. It must be a safe environment inside the habitat, to ensure that the astronauts can protect themselves against the hostile environment on Mars. The habitats we're designing will provide the astronauts shelter, food and protection, and furthermore, psychological care.

'Simulation'
When talking about simulations in this report, we refer to smaller- and larger-scale experiments imitating missions or situations in real life, with the purpose of expanding the knowledge base or becoming familiar with specific circumstances.

'Analogue'
When mentioning analogues we refer to environments on earth which are somewhat similar to environments in space or on Mars. An example of such environments could be isolated confined environments or extreme environments like the Arctic poles or in a submarine.

'Hybrid Simulation'
When a simulation occurs in an analogue environment, such as experiments like Mars500 or HI-SEAS, they are called hybrids. In this report they will be referred to as either "hybrid" or "hybrid simulations" depending on the context, but the meaning of the two will be the same.

1.2 Problem Area

Mankind is an explorable creature, who has always been interested in expanding its knowledge by finding new countries, new species and new technologies. Christopher Columbus represented the explorable mankind when he in 1492 crossed the ocean and discovered America. Columbus began the colonization, which quickly expanded to other countries such as England and France. The world was interested in discovering new countries and exploring the animals, plants and food found in them. Some even moved to the newly found countries to start a new and wealthy life there. Soon most of the countries and islands on Earth had been discovered and explored, and mankind began to expand its vision.

The interest of space increased after the mapping of planet Earth had finished, while space was still uncharted territory for mankind. During the Cold War, which was a war between the U.S and the Soviet Union (U.S.S.R), a fight for power had begun, this included the race for space. Both the U.S and the U.S.S.R wanted to be the first nation in space which resulted in a 19-year long fight for space. In 1957 the U.S.S.R launched Sputnik, which was the first manmade satellite in space (Steers, 2013). In 1961, just four years later, the U.S.S.R sent the first man to space. The U.S was for many years losing the race for space. But in 1969 they accomplished something great, when Apollo 11 landed on a foreign celestial body; the Moon. The race ended in 1975 when the U.S and the U.S.S.R began a cooperation. However, the race had resulted in many great discoveries and a significant increase in funding for research and education that led to many advantages, which may not otherwise have been accomplished (ibid.). NASA-technologies made for space travelling such as freeze-dried food and memory foam mattresses got integrated in our everyday life (ibid.).

After the exploration of the Moon our interest turned to Mars. In 1971 one of the first Martian robots, Mariner 9, was sent to Mars to explore the planet. Mariner 9 discovered many significant phenomena on Mars, such as volcanoes and Canyons (Redd, 2017). These findings proved that Mars at some point had liquid water and active plate tectonics which indicates that life could have existed as well. Some scientist suggests that Mars at some point might have looked a lot like Earth and began to compare the two planets. Some even suggest that exploration of Mars could lead to knowledge about our own planet. This suggestion and many others have resulted in a study on how to get to Mars, and furthermore, how to survive a long duration mission on Mars.

Many factors need to be considered when sending humans to Mars. Even though Mars supposedly used to look like Earth, the planet changed completely millennia ago, and today it is a desolate planet with no apparent signs of life (Kent, 2019). Today we know that Mars is the planet in our solar system, that resembles the Earth the most. This is not because of its visual appearance, but because of the processes within and on the planet such as seismic activity and metrology (DTU Space, s.d.). However, what caused Mars to become the cold, desert planet, without any sign of life is one of the major mysteries NASA, ESA and other space organizations want to uncover. Mars is a smaller planet, covered in ice, frozen methane and small dust particles (ibid). Mars is further from the sun than Earth which causes the temperatures on the surface to fluctuate between negative 153 degrees to 24 degrees Celsius (NASA Science, 2019-a). Mars is a hostile environment due to the missing external magnetic field, which normally protects a planet against harmful particles from space, and an almost non existing atmosphere which is more than 100 times thinner than the atmosphere of Earth. The lack of atmosphere and magnetic field causes the planet to be exposed to many dangers such as radiation (NASA, s.d.-a). The radiation on Mars is significantly higher than the radiation experienced on Earth and in some cases the radiation on Mars is deadly (NASA, s.d.-a). Mars is known for its dust storms, which throughout the years have been spotted seven times (Lonnie Shekhtman, 2019).

The hostile environment on Mars isn't the only thing a scientific mission to Mars must consider. Studies from NASA show that a long-term stay in space has a huge impact on the human psyche (Garrett-Bakelman et al., 2019). Scientists therefore must know more about the physical and psychological effects a long-term mission to Mars can have on the human wellbeing while in transit or on the planet. To learn more about these factors and limitations, several scientific experiments and research has been conducted using simulations and analogues resembling the known factors when living in space or in isolated confinement on Mars. Scientific experiments imitate the Martian environment and gain knowledge and experience that can be used on later missions (NASA, s.d-a).

In terms of answering these questions we must be able to send manned missions to Mars, and therefore also be able to construct habitats on Mars where the astronauts are safe from both physical and psychological stressors. Besides different interests in Mars, all proposed manned missions share a necessity for solving how a manned mission to Mars can be planned, and habitats constructed to protect future astronauts from the hostile environment it presents.

New innovations and technologies possibly carry the answer and responsibility to protect astronauts in habitats on Mars. One of such new technologies could be the in-situ constructed material; biostone. Biostone utilizes Microbiologically Induced Calcite Precipitation (MICP) and through this the bacteria *Sporosarcina Pasteurii* (S. Pasteurii), aggregate, water, urea and calcite in creating a synthetic sandstone with concrete-like qualities.

1.3 Problem Statement and Research Questions

The concerns mentioned above regarding living and thriving on Mars has led us to the following problem statement:

"How can the living conditions and well-being of the astronauts be ensured in research habitats on Mars through building with biostone as an in-situ material?"

1.3.1 Research Questions

1. What are the psychological implications of periodic exclusion from society on Earth?
2. How does architecture and technology affect the human psyche in hostile environments such as space?
3. Which considerations must be taken in the design of a habitat on Mars?
4. Which physical limitations occur for survival and building as we know it, in the given environment?
5. Why is pre-arrival in-situ construction necessary, and how could biostone be used for this?
6. How does the relationship between humans and technology appear differently in space than how it is on Earth?
7. How could a design solution with biostone look, and what are the scientific prerequisites of the construction?

1.4 Delimitations

NASA is currently working on a mission with the goal of launching the first manned mission to Mars. Onboard will be engineers, biologists and geologists whose mission will be to search for life, understand the surface of Mars and the evolution of the planet (Kennedy et al., 2016). In doing so, NASA hopes to be able to understand what caused the planet to change so rapidly. Furthermore, NASA is hoping to learn and understand more about our own planet and to get an idea of what the future of Earth could be. NASA wants to make sure that the astronauts they send to Mars can lead a healthy life both physically and psychologically by carefully designing the best possible habitats. The goal of the Mars-mission is for the astronauts to return to the surface of Earth with useful results from the examinations of Mars and with samples to examine further.

NASA and other governmentally funded space companies are not the only actors interested in Mars. Space travel and exploration has until recently been a venture far too costly for any private firms to undertake, but large companies now have the finances to privately fund space travels. Most of the private actors do not show a great interest in Mars as a scientific research destination but more as a means to accomplishing an economic gain. For some of these companies such as *'Virgin Galactic'*, *'Blue Origin'* and *'Bigelow aerospace'*, the main drive seems to be space tourism, such as Martian hotels (Bigelow aerospace, s.d.). For others such as SpaceX, while tourism and private investment are still important actors in funding their mission, going to Mars is a plan B for humanity and possibly all life on Earth. The long-term mission of SpaceX seems to be the permanent colonization of Mars and in an attempt to fulfill this mission, they aim to lower launch costs by reusing 100% of their rockets. Through this approach they hope to lower the total cost of sending objects to space, and Mars (Musk, 2017). Because of the similarities shared by Earth and Mars, these actors find it realistic to imagine a colony, living and thriving on Mars; they suggest that this colonization might take place within the next decades (SpaceX, s.d.). Not all scientists agree on these assumptions because it is unrealistic to imagine that we will know everything we need to know about Mars or have developed the technologies we need to survive on Mars, in just a few decades. It will take a long time before we know exactly how and when we will send the first manned mission to Mars. Furthermore, there is still much information we need to know about Mars, things we can only learn through sending probes on the planet and performing realistic simulations and analogues.

This report focuses on the scientific research approach such as NASA's when developing habitats on Mars. We are examining a one-year mission on Mars with a total mission duration of three years as proposed in the Artemis program (NASA, 2018). This program presumes that one year is enough time to explore and examine the planet and return to Earth with useful results and samples for further experimentation. We want to examine what the effects of this might have on the human body and brain, and recent studies have shown that long term stays in space can have a significant effect on the human body and mind while being exposed to higher radiation and gravitational differences. Recent studies also show that long term stays in space influence the psyche of the astronauts and in a worst-case scenario these astronauts can find it difficult to return to the society from which they came. In this report we hope to design a habitat for the Mars mission, which accommodates these physical and psychological factors.

2. The Case of Mars

2.1 History of Mars

Mankind has a recorded history of tracking the activity of the planet Mars that dates back to the Ancient Egyptians, as far back as 2000 B.C. (NASA Science, 2019-a). The planet Mars has been affiliated with both Roman and Greek mythology, as the god of war in Roman; *Mars* and in Greek; *Ares*. Until the birth of the telescope, Mars could only be viewed as a red dot, seemingly larger than the stars of the sky. This is probably what inspired the Egyptian name '*Har Deche*', meaning 'The red one' (NASA, s.d.-b) or as it is referred to in common speech; 'the red planet'. The first scientific observations recorded of Mars was done by the Danish astronomer Tycho Brahe. He calculated the planet's orbit with relatively high precision, and this before the invention of the telescope (NASA, s.d.-c).

Mars did however not only attract the minds, fascination and imagination of the historic human civilizations or scientists before the telescope. The enlightened writers and scientists of the 19th and 20th century speculated upon the composition of the planet and the meaning of the 'canals' on the surface. It was widely speculated that Mars had plant life, water and even intelligent life living on the surface (Rosenberger & Verbeek, s.d.). One astronomer, who was observing Mars even stated, that the 'Martians' were far greater builders than the people of Earth, as he had observed canals, which he assumed had been built for irrigation, that stretched across the surface of Mars (The New York Times, 1972).

2.2 Mars, NASA and Mankind

Today we know that the red glow of Mars is a result of the highly ferrous (iron) rich regolith that covers the surface of the entire planet (NASA Science, 2019-a). Mars is the second closest planet to Earth with a distance between the planets of approx. 0.5 '*Astronomical Units*' (AU) (ibid.). The planet closer to Earth is Venus with only approx. 0.3 AU (NASA Science, 2019-b), but Venus is not as easy to target from Earth as Mars is. This is because Venus is on an orbit that is smaller than the orbit of Earth, and because the planet Venus has a significantly higher mass than Mars (ibid.). Furthermore, the launch windows to Venus are fewer (Heiney, 2012). These three factors, among others such as atmospheric density and drag, results in the Delta-V required to travel from Earth to Venus being far greater, than the Delta-V required when traveling from Earth to Mars (ibid.). These major differences between Mars and Venus in relation to Earth makes Mars a much-preferred destination for scientific space exploration in general. Key missions to Mars are the *'Mariner'* satellites, the *'Viking'* landers, the *'Mars Global Surveyor'*, the *'Phoenix'* lander, the twin rovers *'Spirit'* and *'Opportunity'* and latest the *'Curiosity'* rover, just to mention a few. NASA's first spacecraft landing on Mars was Viking 1 in 1975, and the latest rover, Curiosity, landed in 2011 (Planetary Society, s.d.). All the above-mentioned missions were NASA missions, and all these missions gave humanity new and groundbreaking knowledge about Mars and even possible glimpses into what *could* be the future of our own planet.

Today Mars has six active satellites in orbit and two active spacecraft traverse the planet (Planetary Society, s.d.). Three of the satellites in orbit and both landers on the surface of Mars are controlled by the American space organization; NASA. Plans for future missions are many, and no later than 2020, another rover will be sent to Mars, the yet to be named *'2021 Rover'*, as it lands in 2021. The rover has many new experiments to perform, one of which being the *'MOXIE'* (NASA, s.d.-d), a direct preparation for sending a manned mission. The MOXIE experiment will test whether it is possible to extract oxygen from the Martian atmosphere in a small-scale experiment (ibid.). This experiment is an example of In-Situ Resource Utilization (ISRU), which will be explained further in section *'4.3 In-situ Building and Biostone'*.

Most of what we know about Mars today comes from images and experiments mediated through these rovers and satellites. This technology provides a constant feed of information for scientists on Earth to decipher, investigate and explore, but it is difficult, and it takes a long time to perform this research. This is due to several factors, but the latency and the effect it has, is one of the key factors. A signal sent from Earth to any technology on Mars takes up to 13 minutes (Ormston, 2012). The technology then has to digest the information, perform the maneuver and transmit the image or result back to Earth with another latency of 13 minutes giving a maximum wait time of 26 minutes for a given result. Then you also have to account for the size of the file transferred, the bigger it is, the longer it takes. Furthermore, the planetary rotation of Mars must be taken into consideration, as the rovers e.g. needs to be on the dayside, pointing towards Earth in order to transmit data (NASA JPL, s.d.-a). The sent data then must be examined by a team of scientists, who then decide what the next step of the technology should be.

2.3 Why Go to Mars?

This technologically mediated exploration of Mars has given humanity a tremendous amount of knowledge. We know for a fact, that Mars once had liquid oceans and a much denser atmosphere (Potter, 2018). Given what we know about Mars today, the planet could have held the keystones for life as we know it. But something happened to the planet, that made it, to our knowledge, uninhabitable for life (see section '*4.1 Limitations for Life and Construction of Habitats on Mars*'). We are unsure, if Mars ever held life, and if life has arisen outside the safe environment of Earth, but given how we know the simplest forms of life can come to exist (Bada & Lazcano, 2012), Mars should at one time have had all the ingredients for life (Potter, 2018). We also know that Mars has a partial magnetic field, and it is speculated whether this once encircled the planet as a whole, much like the magnetic field of Earth (DTU Space, s.d.).

But what could possibly compel any human being to leave its breathable atmosphere and life-giving environment on Earth, place itself in a small space craft, travel almost 60 million kilometers (NASA Science, s.d.), and then live in a slightly bigger enclosed habitat on Mars in an environment, that - if the habitat's technology fails - will destroy every cell in the human body (see section '*4.1. Limitations for Life and Construction of Habitats on Mars*'). Another consideration is the voyage's total duration of minimum 3 years. Several factors could be the deciding one. One reason of popular belief is simply to find the answer to the question; *"Are we alone?"*, hence; is there or has there been life, maybe even intelligent life, on Mars? This is however not the only reason for traveling to Mars, and those brave men and women who will encompass the voyage could, if history will have it, in the future be seen as pioneers much like the Conquistadors of Spain or the Vikings of Scandinavia. But other, and maybe more relevant, questions could lead to knowledge of grave importance for the future of mankind. Questions such as whether there was ever life on Mars, and if so, what happened for the planet to turn dead, when did it happen, what can we learn from it, and will the same thing happen to the Earth? Some of these questions are what NASA and other space agencies aim to answer, but to do so thoroughly and within a short timeframe, human intuition is needed in-situ. Part of the BASALT research initiative published in the Astrobiology Magazine states:

> *"Although robotic exploration and sample return will significantly advance our understanding of martian environmental conditions, as with the investigations reported here in BASALT, the most effective way to generate a coherent synthetic picture of habitability on Mars at all scales may well be to carry out a sustained program of human exploration and large-scale sampling."*
>
> (Cockell et al., 2019)

The BASALT research initiative is a hybrid simulation experiment, that simulates a Mars expedition with astronauts "in-situ", a Mars station on Mars and ground control on Earth, with realistic time delay and mission parameters and goals (Cockell et al., 2019).

The first manned exploration mission to Mars could possibly pave the way for making a permanent colony and maybe even expand or renew our civilization to an otherwise hostile environment; Mars. To ensure the possible future of a colonized Mars, the success of the first missions to Mars is of key importance. The science learned, the archaeological and geologic history uncovered, the experiments performed and the technological spinoffs to civilization on Earth from the technologies developed to facilitate missions to Mars could have life changing implications.

However, the first steps are always time and resource consuming, and a mission to Mars is no exception. It could potentially be the most expensive venture in the history of civilization, but at the same time it could have the greatest feedback to civilization of all time. We have several examples of everyday objects, which are direct derivatives of space exploration (NASA Spinoff, s.d.), one of these being battery powered tools (power tools), or battery power in general. While NASA did not invent this technology, they greatly helped advance the development (Allen, 2008). Before the *'Gemini'* missions, almost every electrical tool on the planet was powered by an electrical grid, and if there was no access to electricity, they were powered by hand. With the necessity of tools for assembling objects in space, and the absence of gravity, power tools and specifically the battery systems for these were created (Allen, 2008). Without this necessity for the specific technology, the industry, and society as we know it, might not have advanced to the point we are today, as the battery technology probably would not have advanced as far as it has.

Today approximately 2000 NASA technologies have contributed with improvements to all aspects of civilization (NASA Spinoff, s.d.). With a mission or several to Mars, new technologies will undoubtedly evolve. Mankind will have to create an entire system that can sustain life in an environment that is completely alien and dangerous. Advances in robotics, rocketry and habitation will be required to perform a mission such as the one to Mars.

NASA Developed the Constellation program for traveling directly to Mars. The infrastructure of this program has been altered and this new program is called the Artemis program. Today the Artemis program has the goal of constructing a base on the Moon and a fuel depot in orbit around the Moon in order to facilitate future missions to Mars (NASA, 2018). In order to complete a return mission to Mars, a lot of rocket fuel is needed, as the mission will have to bring enough fuel to Mars to be able to return to Earth. This along with the modules and technology needed for surviving on Mars require several rocket launches from Earth to Low Earth Orbit (LEO), where the interplanetary spaceship will be assembled and crewed, sent to Moon for refueling, and then put on an intercepting trajectory for Mars (ibid.).

3. Semester Bindings

On Roskilde University (RUC) it is required for students to specify to which extend and specifically how, the report contains the three built-in dimensions of Humanistic Technology (HumTek), the three dimensions are Subjectivity, Technology & Society (STS), Design & Construction (D&K) and Technological Systems & Artefacts (TSA). These three dimensions are the foundation of the HumTek approach. The goal of HumTek is to understand and develop technologies in relation to society and the singular human. This is what the three dimensions should encompass. During the introduction semesters (semesters 1 through 3), the three different dimensions of HumTek are practiced and understood through the semester's projects binding to one of these dimensions. Another dimension is also mandatory, but this other dimension can be chosen at will, and is chosen on the bias of the subject researched or product created. In our project, however, we will include parts of all three dimensions, as all dimensions are required in understanding our case of research.

3.1 The Binding Dimension

In 'Basis project 3' the semester binding is in STS which is based on the humanistic scientific traditions and has a focus on the relation between technology, humans, cultures and societies (RUC, 2019). Our research therefore will focus on the relation between man and technology and how this relationship affects our society. Our approach to the theory of science will mainly be one of Positivism and Rationalism, but because of the majority of our report being based on pre-factual simulations, we have invented our own theoretical model, the *Earth-Space Knowledge Spectrum* presented in section *'5.2 Simulated Knowledge'*, to try and understand how the science of simulation is and can be validated as actual science, and why simulations and analogues are important when focusing on exploration and colonization of space.

Our project is about the colonization of Mars and understanding which barriers and obstacles that exist in the relationship between humans, technology and society. To understand this relationship and how a research habitat on the planet Mars needs to address the problems that can arise in this scenario we will use our own theory based on the theories of the STS dimension. We will try to understand the relation between humans and habitats situated in the hostile environment of Mars, and the effect it can have on humans to know, that this environment is 100% deadly, if the technology supporting their life fails. Both our analysis, discussion and chapter on theory of science will have this as a focus along the understanding of the micro-society created in a research habitat on Mars. We will compare the scientific colonization of Mars to the historic colonization of new lands and continents on Earth to understand how a colonization of Mars could affect society and the possible future of society on Earth. Through this we aim to understand how, and to which extend a technologically based micro-society on Mars can affect the society on Earth and the possible future of society on both planets.

In this paper we will use results and examples of isolation experiments performed by NASA and other organizations, to understand how humans cope and possibly can thrive in total isolation from society and which precautions the design of a habitat for a future mission to Mars has to take in order to ensure the well-being and success of the astronauts on the mission.

3.2 The Other Dimensions

The second dimension of the project is D&K. We will through the DSR theory and its method FEDS try to create a design proposal for a possible habitat on Mars using an in-situ building materials; biostone. The design proposal will be based on the findings of several analyses performed in the paper. An architectural comparative analysis of other design proposals for habitats on Mars, the analysis of the relationship between humans, technology and society, micro-societies and the psychological effects on the human mind and dynamics of the micro-society in an environment that is completely hostile to human life.

The third dimension TSA will be used to understand several internal mechanics of different technologies in the habitat proposal. TSA will be used to understand the utilization and needs of an MICP bacteria when cementing Martian regolith. We will also use TSA to understand the biological needs and process, a habitat needs to be able to support and facilitate in order to ensure quality of life for its crew and possible plant life.

4. Explanatory

4.1 Limitations for Life and Construction of Habitats on Mars

In the exploration of the different planets and moons of our solar system, multiple limiting factors arise, complicating the different aspects of out-of-atmosphere missions and projects. Factors such as radiation and pressure of the surrounding environment can be immediately life threatening to astronauts and researchers and must therefore be considered in the continued exploration of the solar system. The use of MICP on other terrestrial bodies than Earth, require some of the same considerations, because the process utilizes bacteria that are also susceptible to damage from radiation and environmental factors. These were also factors in the construction of the ISS and the Apollo missions, however the larger time frame of Mars missions, means that these factors become of higher risk, if the missions are manned by either humans or bacteria (NASA, s.d.-e).

4.1.1 Cosmic Background Radiation

Cosmic background radiation is the radiation coming from deep space and does not have a source within the solar system. The radiation is attenuated going through Earth's atmosphere, and the radiation amount is therefore highly reduced at surface level (Howe & Sherwood, 2009). This means that when astronauts leave the confines of the Earth's atmosphere, they will be susceptible to an increased amount of radiation. Furthermore, the Earth's magnetic field also protects from radiation. Therefore, the ISS can get by with relatively low radiation protection, even though it is placed outside of the Earth's atmosphere, because it is still within the protective magnetic field (NASA, s.d.-e). Manned spaceflight outside of this barrier, will therefore have to contend with the increased radiation amount, and will have to increase the radiation protection on the vessel to a level where the health risk of radiation damage is lowered enough to ensure the health of the crew.

4.1.2 Solar Radiation

Radiation coming from the Sun will also have to be considered in the planning of Mars missions to reduce the total amount of radiation potential astronauts are exposed to. Solar activity and the corresponding radiation changes might be lower if the Sun is at Solar Maximum. And be higher if the sun is at Solar Minimum. It could therefore be preferable to launch Mars missions during Solar Maximum to reduce radiation exposure. The maximum, minimum cycle last 11-12 years with a peak and bottom activity lasting 12 months (Zell & Fox, 2013). With Mars missions estimated to last three years, (NASA, s.d.-e) it is possible for a majority of the mission to take place during Solar Maximum where radiation would be at its lowest (ibid.). However, considering the length of these cycles, it may be impossible to only conduct missions during solar maximum, if Mars missions are to take place consistently and not only take place during minimum solar activity.

4.1.3 Methods for Handling Radiation

Three basic methods for reducing radiation exposure exist; increasing the distance to the radiation source, reducing the amount of time exposed to radiation, or shielding from the radiation source with a material capable of absorbing radiation (American Nuclear Society, 2014). The former and the latter of these methods focus on reducing the intensity of the radiation, however shielding seems to be the only method that can be used in the design of manned Mars missions. The amount of time exposed to radiation is determined by the length of the mission. The current length of a manned mission to Mars is estimated to last three years, but possible future rocket technology could bring this time down and bring exposure time down with it.

Because of the implausibility of eliminating radiation exposure completely during manned space flights, it is necessary to implement limits for the amount of radiation an astronaut is exposed to during a mission and career. NASA's limits for astronauts in LEO is currently at 50 mSv/year (microSieverts), with no concrete limit for spaceflight further away from Earth. The maximum amount of radiation exposure allowed during an astronaut's career, is between 1000-4000 mSv in total, depending on the astronaut's age and gender (NASA, s.d.-e). This limit is set to minimize the risk of astronauts developing cancer from radiation exposure, with an estimated increased chance of developing cancer by 3%, if this limit is reached (ibid.). With an estimated radiation exposure of 1200 mSv, on a three year Mars trip, the estimated exposure is already above the career limit of some astronauts, this means that for astronauts going on a manned Mars mission, it may be their only mission in their career, if the estimated radiation cannot be brought down.

4.1.4 Atmospheric Factors

The Martian atmosphere is one percent of the atmospheric volume of the Earth (ESA, 2018). With a much lower atmospheric pressure it is unlikely that any biological organisms could survive being situated on the surface of Mars without a habitat containing an artificial environment, with increased pressure and controlled air composition. If humans were to live on Mars unforeseen consequences could occur in relation to human physiology. This will be further elaborated in section *'4.2 A Healthy Environment in Space'*.

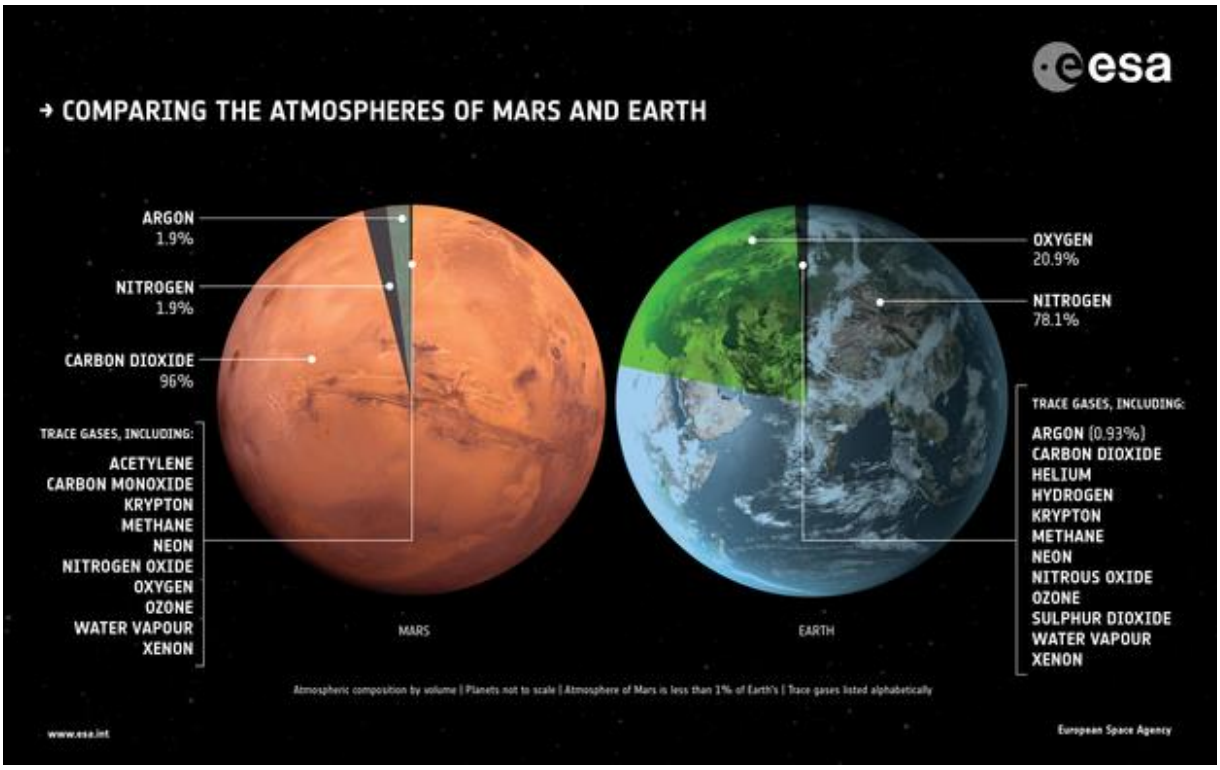


Figure 1: *'Martian atmosphere comparison'* Source: (ESA, 2018)

Data sets from the Trace Gas orbiter satellite show that the Martian atmosphere consists of primarily Carbon Dioxide, with a much lower concentration of Nitrogen and Oxygen than in the atmosphere of the Earth. Due to this, a habitat on Mars would need an inner mechanism artificially transforming the surrounding atmosphere into breathable air for the astronauts.

4.1.5 Extreme Temperature Variation

Extreme temperature variation may prove a limiting factor for both construction and life on Mars. The temperature variation on the surface of Mars ranges from negative 153 degrees Celsius, to a maximum of about 24 degrees Celsius (NASA Science, 2019-a). These extreme temperature variations may be detrimental not only to the health of organic organisms but may induce mechanical and material stress on the technical components and infrastructure of a mission. The design of the mechanical components used in missions to Mars must therefore include inner mechanisms that keep this notion in mind. These can consist of special tolerant materials, internal heat pipes that distributes the heat or passive and active heating and cooling, that keep mechanical parts within their operating temperatures (Howe & Sherwood, 2009).

4.2 A Healthy Environment in Space

Up until recently, the main questions of the scientific debate when it comes to habitats on Mars and other foreign planets, have been merely physical. Questions like: *"How much weight can a spaceship carry to Mars?"*, or *"How and where can humans live without spacesuits?"*, but the closer the Mars mission comes to reality, the more the questions asked have changed. Before humans can live on Mars, there are a lot more than just physical measures to consider. This section will describe how the design of space habitation on Mars has to consider the requirements of the non-physical and physical measures before a Mars mission can succeed.

4.2.1 Space Architecture

Since the early 1980s, *space architecture* has been an architectural field which works on all aspects of designing space equipment. Space architects are involved in all areas of space projects and mission development including robotic rover and probe design, lunar and Mars base design, systems engineering, space mission control support, and extreme Earth environment habitat design and construction (Hall et al., 2013).

In many aspects, space architecture is an extension of Earth architecture since Earth is a part of space just like Mars, the Moon and the rest of the planets. Some of the significant differences would be the extreme environmental conditions such as high radiation, none or low atmospheric pressure, microgravity or low gravity, extreme temperatures and extreme changes in temperature. Although there are significant differences in the environment on other planets which concerns humans a great deal, the goal remains the same; providing shelter that protects and supports good quality of life for the inhabitants, and the central focus of space architecture supporting human activity (Hall et al., 2013; Howe & Sherwood, 2009). In recent times the requirements for human habitats in space has changed and according to former NASA employee and psychologist Albert A. Harrison there are three overall categories of human requirements for living in space; **biological requirements** for safety and good physical health, **psychological requirements** for high performance and good mental health, and **sociocultural requirements** for positive individual and group relationships (Harrison, 2010).

4.2.2 Biological Requirements

Requirements involve achieving the proper and individual requests of temperature, humidity levels, keeping a constant flow of fresh air, good and functional shower and toilet facilities, good sleep quality which requires proofing from sound and light. Furthermore, the planetary base has to be equipped with medical supplies and maybe even doctors and surgeons, and in case of death it would be required to have some facilities for the bodies (Harrison, 2010).

In space the human physiology is affected by microgravity in several ways. It affects the cardiovascular system, musculoskeletal system, immune system, and endocrine system. In environments with reduced gravity like Mars, it is expected that the lack of gravity will affect the human body. It is not yet known to which extent the lack of gravity will have influence on human bodies, countermeasures like exercise and pharmaceuticals are currently assumed. It will be necessary for the inhabitants on Mars to be able exercise daily which requires facilities, capacity and equipment (Howe & Sherwood, 2009).

4.2.3 Psychological Requirements

The requirements needed for a healthy psychological environment are immediately more interesting to the concerns of this examination. Some requirements include sufficient volume to ensure an efficient and comfortable working and living environment for a long period of time, facilities that are easy to maintain and repair and an appropriate amount of light for the workstations. Keywords are; simplicity of design and operation, high reliability, ease of repair and room for improvisation (Harrison, 2010).

The planetary base needs to support leisure time activities, such as being able to listen to music, watching television, looking out at space or the Earth. But the base also needs to facilitate group activities such as eating together, sports and spiritual or religious gatherings (Harrison, 2010; Kanas, 2015). What can be drawn from this, is that personal space and environment plays a massive role for a healthy psychological state of mind. As Tristan

Bassingthwaighte confirms in his doctorate in architecture from 2017, a focus on psychological health and well-being, when designing habitats in space is very important:

> *"Psychological health is defined by the mental and emotional ways in which people react to their environment, both their perceived environment and their actual environment. Stressors on psychological health include but are not limited to weather, confinement, micro-irritants such as the way people chew their food, and perceived levels of risk. Influences on the psychological health of inhabitants are varied, and can be exacerbated by a limited social environment as well. Malaise or apathy, neglect of assigned duties, asocial behavior, and even violence have been among the consequences of psychological degradation of a crew."*
>
> (Bassingthwaighte, 2017, p. 8)

Bassingthwaigthe states that the psychological well-being of the crew members of any space mission is different from person to person, and that the physical frame of the habitat and the indoor habitat environment indeed has an effect on the psychological well-being of the crew members.

4.2.4 Sociocultural Requirements

Living in isolation for longer periods of time can be associated with interpersonal tension. To avoid such implications, designers try to design environments where these tensions are minimized. For example, it is important that designers create workspaces where colleagues can work without interfering (Harrison, 2010).

Privacy is important to all human beings. We all need privacy for resting, recuperation, private conversation, and for astronauts privacy is important when communicating with family and friends on Earth. Although the option for privacy is important, isolating oneself can have grand psychological impacts. The challenge for space architects is to create environments where privacy is possible but where isolation is not (ibid.).

On a mission to Mars, the composition of crew members is important to consider. So far, only astronauts have been sent out of orbit, but on a perhaps terminal mission to Mars, the mission would require other professions such as doctors, biologists, physicists, etc. One could imagine clashes between the professional astronauts and the passengers to rise regarding the use of space equipment (ibid.). Cultural differences are also to be considered. Some might have different understanding of personal hygiene, preference of food and entertainment activities. Most people with different cultures might have different preferences of accommodation adjustment. Cultural differences also concern tradition and religion such as

Christmas and Eid. Space architects have to avoid ethnocentric biases and create spaces where cultural differences are welcome. Space architects also have to keep in mind, that Mars missions in the future might vary in their tasks, personnel and crew size, which is why habitats should be rather adjustable (ibid.).

According to Bassingthwaighte one major obstacle when designing habitats in space is the lack of space:

> *"The most significant difference between the drivers of architecture in daily life and that of ICE environments could be summed up in the idea of space. The space to move freely, to work comfortably and live happily. For an individual living in cities like Paris or Tokyo, there is room to wander, to have a variety of relationships or interactions with others, to visit museums or cafés or to relax or rest in a park. If one yearns for either friendship or solitude, both are easily found; however, during winter at the poles, in outer space, or on other worlds such things are often difficult to find. The ability to indulge in the many facets of life is strictly limited. The social circle of an individual is constrained to those who have come along, and if one wishes to go for a walk, he or she may need to do so using virtual reality or even a rover for the sake of safety. The flexible use of space, creative interior programming, and the careful design of every available habitable space is vital when the only room inhabitants have in which to conduct their lives is highly constrained."*
>
> (Bassingthwaighte, 2017, p. 121)

In order to maintain a healthy state of mind in isolated confined environments, Bassingthwaighte argues, that the issues that can occur because of lack of space needs to be addressed when designing habitats in space. Activities like going for a walk is not possible, and 'escaping' the indoor is not an option. There is limited private space, workspace and social space, but the functionality of these spaces must be optimal to maintain the psychological health of the space inhabitants. In other words, small habitats in space must be perceived larger than the actual volume.

4.2.5 Space Habitats

There are three categories of space habitats: *Class I:* **Pre-integrated modules**, *Class II:* **Prefabricated structures**, and *Class III:* **In-situ derived and constructed units**.

Class I: **Pre-integrated modules** are manufactured and constructed on Earth and fully outfitted and tested prior to launch. Pre-integrated habitats are space-delivered, and mass and volume restricted to launch vehicle volume, and upon arrival they are ready for immediate use (Howe & Sherwood, 2009).

Class II: **Prefabricated structures** are not restricted to launch vehicle volume, even though they are Earth manufactured. These habitats need assembly in space or at the destination prior to use and some or all internal outfitting done in space. This needs to be done by crew members or robots and requires partial subsystem integration (ibid.).

Class III: **In situ derived and constructed units** are not restricted to launch vehicle volume but allow the largest volume of the three types of habitats. They are manufactured on site - *in situ* - with space resources, and therefore constructed and tested in space. They require a lot of robotic or crew time to construct, and also require total integration of subsystems and all internal outfitting is done in space. All critical subsystems are manufactured on Earth and tested prior to launch (ibid.).

Space habitats must be spacious enough to integrate subsystems and fulfill core human needs like water, air, food, temperature control, ventilation, personal hygiene and waste management. This examination will continuously be focusing on in-situ derived, and constructed units as stated in the problem statement.

4.3 In-situ Building and Biostone

As mass and weight are critical issues in space exploration, minimizing the weight of materials to use for building habitats is crucial. This can either be done by producing lightweight and/or inflatable habitats produced on Earth, such as the Bigelow Expandable Activity Module (*BEAM*) (Bigelow Aerospace, s.d.), or by using resources found in-situ. Using in-situ materials for building is one aspect of the practice of ISRU, which is a method for humans to generate their own products in space using locally retrieved materials; be it solar energy for power, carbon dioxide for oxygen, or Martian regolith for construction.

One way of using the in-situ materials for building habitats, is through Automated Additive Construction (*AAC*), which 3D-printing is an example of. Being automated, it doesn't require humans for the gathering of resources or for the actual construction, as it can be done by robots or rovers arriving beforehand. Several examples of how this could be done will be presented and analyzed in section '7. *Analysis*'.

Building with in-situ materials is no new concept on Earth. In prehistoric times, the only building materials used were the ones found in near proximity; from the use of animal bones and skin in some of the earliest discovered huts in today's Ukraine, to sunbaked bricks made from mud in ancient Mesopotamia, and early Chinese houses made from wood and earth

(Moffett, Fazio & Wodehouse, 2003). Throughout history, different means of transportation facilitated trade of raw materials and resources (Mosley, 2010), creating the opportunity to build with materials not naturally found in the given area.

One example of using a plentiful local resource for constructing buildings, is architect Magnus Larsson's Dunes; a proposal for using the bacteria *Sporosarcina Pasteurii* (S. Pasteurii) to solidify loose sand into sandstone in the desert (Larsson, 2010). The process of solidifying loose aggregate into a solid material using bacteria is called Microbially Induced Calcite Precipitation (MICP). In MICP, a urease-producing bacteria stimulates the precipitation of calcium carbonate, which acts like a binding material within the loose aggregate. Besides the aggregate and the bacteria, a source of calcium must be present, and also urea which is subject to hydrolysis where it reacts with water molecules to create ammoniac and carbonate. The calcium ions and carbonate ions create calcium carbonate, and the calcium carbonate precipitates and permeates the aggregate due to a supersaturation, which resultantly binds it together (Henze & Randal, 2018).

By using the method of MICP with the bacteria S. Pasteurii, a "biostone" can be created using sand or regolith as the loose aggregate, although the method and bacteria could work with many other materials such as glass beads, fibers, small stones or soil (Patent Nr. US 8,728,365 B2, 2014). To produce the biostone, one needs cultivated S. Pasteurii, calcium, urea, distilled water, a growth media for the bacteria, oxygen and a setup containing a form for the stone with pipes and pumps for injection of bacteria and growth media. If produced correctly, biostone has the same qualities as naturally occurring sandstone, and it could potentially replace concrete or stone as a building material (ibid.).

Using biostone in desolate environments has the advantage, that the main part of the resources needed for the material - the aggregate - can be found on site. If the wish is to use utilize in-situ materials to the most, and transport the least amount of resources possible, not only sand but also a calcium source is needed. Calcium compounds can be found in minerals such as limestone, and through electrolysis the pure calcium can be isolated. As for urea, it is found in the urine of humans and many animals, as the body secretes the compound when metabolizing protein, and is therefore easily accessible if there are humans or animals nearby. What remains to be transported to the site is then only the bacteria, the growth media, the setup and/or forms, and water, in case there is no access to water on site.

As for construction techniques, the most common use of MICP with S. Pasteurii so far, is creating bricks or solid shapes using confined shapes. Some more conceptual proposals for construction have been made by Thora H. Arnardottir, P.hD candidate in architecture, planning and landscape, who suggest 3D-printing (Arnardottir, 2019) and by Magnus Larsson, suggesting cementing over balloon-like structures or through injection piles (Larsson, 2010).

4.4 Space Simulations and Analogues

As previously mentioned, space habitats and subsystems are tested on Earth before launch to ensure a successful space mission. When space habitats are tested on Earth, they are often tested via simulations, which means that the habitats are tested with inhabitants, in environments that resemble the target environment. This is done to ensure the overall functioning of the technological soft- and hardware, but also to examine how the human psyche and sociocultural differences affect humans in isolated confined spaces.

Space simulations have been used since the beginning of the space-age where researchers have looked beyond laboratories to create useful knowledge about how humans react to space-like conditions such as shuttle and space station simulators, neutral buoyancy chambers, aircrafts that afford brief periods of microgravity through parabolic flight, computer programs that generate virtual space stations, etc. The realism of the simulations depends on the knowledge of interest, the funding and the ingenuity (Harrison, 2010).

NASA has always been using space simulations to prepare astronauts for different situations and conditions. The 'Sonny Carter' training facility is a neutral buoyancy laboratory, where NASA's astronauts practice spacewalks in a massive pool. Water facilitates zero gravity when neutral buoyancy is achieved, and even though there are some differences between zero gravity in water and in space the laboratory is the best way to practice spacewalks (NASA Facts, 2006). Building 9 is another NASA training facility center which helps astronauts getting used to spacecrafts, systems and situations that might occur in space. Building 9 facilitates more than 200 training courses (Space Center Houston, s.d.).

Space analogue environments are environments on Earth that simulate aspects of space environments with a varying degree of fidelity. Over the years researchers have used multiple analogues for space habitats and flights, for example in caves, supertankers, submarines, mines, mountains and national parks. The most viable analogues offer danger and risk, hardship, isolation and confinement. Fidelity, affordability and accessibility learned through analogues are factors that can be leveraged and used in other extreme environments (Harrison, 2010).

One of the assets with space analogues on Earth is the possibility of conducting ethical studies of humans in dangerous environments like on the top of Mount Everest without oxygen, in extremely cold temperatures.

The best way to research simulations and analogues would be a 'hybrid'. This allows the validity of simulations, while adding the dangers and risks of the environments from analogues.

Examples of such hybrid experiments are 'MARS500' and 'HI-SEAS'. Although none of these are performed with actual astronauts the experiments are in the lead when it comes to exploring sociological and psychological effects of isolated confined environment habitats (Bassingthwaighte, 2017).

MARS500 is a 520-day experiment on the surface of Earth conducted by the European Space Agency (*ESA*). The simulation has built-in communication delay and total isolation from civilization. Furthermore, the MARS500 hybrid experiment simulates all parts of the journey to and back from Mars, a landing module transporting them to the surface of Mars and 'walking' on Mars via virtual reality (ESA, s.d.).

HI-SEAS is an experiment operated by the University of Hawaii. The habitat is built in a Mars-like environment on Earth, also completely isolated from civilization and with built-in communication delay. The analogue habitat resembles a very realistic Mars habitat and has been used for multiple experiments lasting 4-12 months. The analogue allows high fidelity geological field since the weathered basaltic materials on this part of Hawaii is very similar to Martian regolith (Bassingthwaighte, 2017; University of Hawai'i, s.d.).

Both research experiments aim to contribute to the understanding of human reactions and psychological health in isolated confined spaces, and how lack of good sleep, space, group dynamics, mood swings etc. possibly can affect a mission to Mars and its success.

4.5 Micro Societies on Earth

Space is not the only place where people are isolated from the rest of the society for a period of time. This form of isolation is also seen in prisons. The prisoners are isolated from the rest of the society for the duration of their atonement, and studies have shown that this isolation has a negative impact on the psyche of the prisoners (Collier, 2014). It is especially seen in the prisoners of the United States of America. The U.S. has some of the world's toughest penalties and the prison guards have a brutal behavior towards the inmates (Friis, 2019). This brutality has been used to scare the inmates to never return to prison after their release. However, studies have shown that this method might not be the most effective one. Therefore the U.S. has begun to look at the methods used in Denmark and the rest of Scandinavia (ibid.).

The Danish prisons use a method where they try to simulate society outside the prison (Westfall, 2017). This simulation is used to prepare the prisoners for life after prison. The simulation has resulted in fewer people returning to prison after their release. Whereas 76% of all prisoners in the U.S return to prison after their release, only 29% of the Danish prisoners do (ibid.). The methods used are very important to look at when designing habitats on Mars. We need to make sure that the astronauts going to Mars, will be able to return and function in their societies, both psychologically but also physically.

The International Space Station (ISS) is currently used to do many types of scientific research. One of these researches is to study what it's like to live and work in space (NASA, s.d.-f). The ISS has acquired a lot of knowledge about what kind of resources and psychological elements humans need to live and work in a space environment (ibid.). However, the ISS is only three hours away from Earth. When preparing for missions further into space, for example on Mars, the astronauts will be anywhere from six to nine months away from home. This has a major impact on the human psyche, which must be considered when building habitats for astronauts on Mars.

In 2015, NASA began 'The NASA twin study'. A study which examined what the effects of a long term stay in space have on the human body and the brain (Garrett-Bakelman et al., 2019). Two identical twin brothers who were both astronauts at NASA, agreed to be part of this experience. One of the twin brothers Scott Kelly was sent to ISS for a year, while he was in space, he gathered data through blood samples, urine samples, etc. In the meantime, back on Earth, his twin brother, did the exact same thing. Kelly returned to Earth in 2016, and the study continued throughout nine months (*NASA's 4-year twin experiment gets us closer to Mars than ever before*, 2019). After four years the results were finally ready to be shared with the rest of the world, and the results showed many interesting findings. His chromosomes were damaged because of the high radiation in space and damaged chromosomes result in damaged DNA, which can cause diseases such as cancer.

Furthermore, the study showed, that his telomeres got longer. Telomeres are DNA found at the end of each of our chromosomes (Your Genome, s.d.). This was a shocking finding whilst the scientists had predicted the opposite. Longer telomere might have occurred because of his healthier lifestyle in space (*NASA's 4-year twin experiment gets us closer to Mars than ever before*, 2019). All astronauts in space have a strict diet and exercise scheme which might result in longer telomeres. The study also showed that some of his genes in his genetic code were activated. This usually happens when people find themselves in stressful situations, such as being in space (ibid.). The most significant discovery was that a few days after Kelly returned to Earth, his body returned to normal, which means that the human body adapts to the environment it finds itself in. This study even proves that a possible long term stay on Mars might be possible.

When travelling to Mars, there are many things to consider. First and most importantly for human survival is to ensure protection from radiation, extreme temperatures and sufficient breathable air. Although the physical requirements for human survival on Mars are the most important requirements, the psychological requirements for Mars habitats, and other long duration space habitats, has in recent times been of increasing interest among space architects. To ensure human well-being in space a major contributor seems to be habitat volume which is more feasible with in-situ derived and constructed units, such as units made of Martian biostone. Before any space habitat or materials for space habitats are even considered as an option, they are tested on Earth.

5. Theory

5.1 Space Analogue and Simulation Reliability

Just like future Mars habitats must be tested on Earth, so must the people we intend to send to Mars. Social scientists have been studying the behavior of humans in extreme environments like isolated confined environments, and environments with dangers and risks, even before the space program began. Of such environments, submarines, Antarctic and Arctic research stations, and high-altitude research stations can be mentioned. It was assumed that since there were similar stressors for the inhabitants in submarines as for astronauts, these earth-bound extreme environments studies could be used as analogues for space travel. With time it was proven that these extreme environments studies in fact were of great use as space analogues and have contributed to a further understanding of social behavior in extreme environments (Wichman, 2013).

Although space analogues and simulations can share some points of similarity to space travelling, there are also dissimilarities. Some analogue environments are good at testing technological hardware but lack relevance to the human operators, their psyche and ability to perform in a team. Other experiments focusing on the human psyche fail to focus on the extreme and dangerous outside environment. Some experiments succeed with fidelity in extreme and dangerous outside environments, but they are hard to compare from environment to environment. Beside the fact that the analogues and simulations fail to resemble all the space factors, space analogues and simulations will never be able to resemble exactly what it is like to be in space, because only space can.

According to Sheryl Bishop a Ph.D. in social psychology and a behavioral researcher in extreme environments, there are still plenty of reasons to study human behavior in analogues and simulations even though they are not the 'real deal'.

> "[…] *studying groups in terrestrial extreme environments as analogues has been sought to provide predictive insight into the many factors that impact group performance, health, and well-being in challenging environments.*"
>
> (Bishop, 2013: p. 25)

Firstly, it has been proven that there is a difference between the data collected from laboratory chambers and other simulations and analogues, and real extreme environment experiments, especially when focusing on the individual and group coping. Therefore, extreme environment analogues and simulations allow the examination of various environmental psychological aspects which are essential for the understanding of human adaptation to the stressors of extreme environments (Bishop, 2013).

Secondly, several analogue experiments have proven that a composition of crew members on a space mission is important to consider regarding the likelihood of a mission's success. Issues such as fatigue, physical danger, interpersonal conflict, automation complexity, risk and confusion, often challenges team effectiveness and therefore it is critical that these issues are understood and examined prior to launch. Analogues have with time developed high-fidelity methods for choosing crew members with the 'best-fit' regarding the individual and the team. Processes involving cognitive, motivational and behavioral processes have contributed substantially to team effectiveness and have identified three types of interventions with the potential to improve team effectiveness; team training and development, team leadership, and dynamic regulation of team member behavior (Bishop, 2013). Team effectiveness and training is confirmed by Eugene Cernan, the last man to walk on the Moon, to be of importance for any space mission: "*You can't specifically train for every moment of the mission, so the key is that you train for knowledge of each other and you train for teamwork.*" (Cernan in: Tabor, 2019).

The use of simulations and analogues is not only an effective method for space travel preparation but is used with great results in many Earth-bound affairs such as in training future surgeons or teaching new medical skills (John Hopkins Medicine, s.d.), or even training pilots. Some aviation simulators are so realistic that pilots can transfer from an airplane simulator to an airplane without any extra flight control training (Wichman, 2013). As mentioned above and in section *'4.5 Micro Societies on Earth'*, it can be very effective and useful to study micro societies and human behavior in extreme environments via simulations, analogues and hybrids of these in order to prepare for a 'new reality' and gain knowledge thereof.

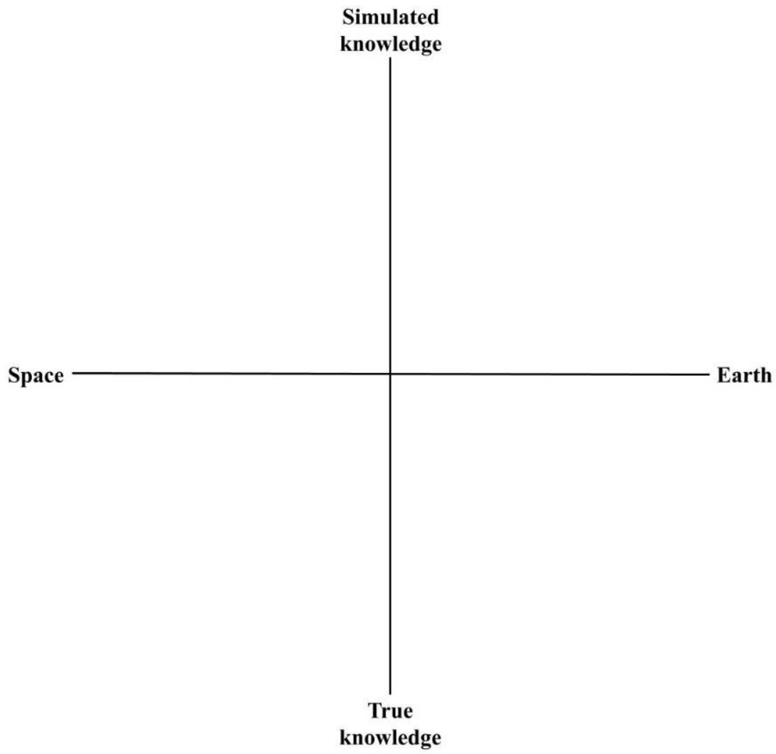
5.2 Simulated Knowledge

According to classical empiricism, knowledge is obtained through observation and sensing, also known as *a posteriori* perception. Positivism, which is based on the same thought, believes that true knowledge must come from systematically gathered empirical data. It makes sense to look at what is sensed and observed, and not what theories may say about the reality "behind" these impressions (Holm, 2011-a).

According to this view, simulations do not make up for actual knowledge about the field, as the knowledge cannot be based on the perceptions of e.g. living on Mars. The data the rovers acquire and send back to Earth is categorized as true or "positive" knowledge, but an experiment on Earth such as the MARS500 cannot say anything true about the circumstances on Mars, unless it is conducted there.

Rationalism opposes this scientific standpoint and claims that true knowledge is acquired through reasoning rather than sensing. Perceptions happen *a priori*, independently from the senses and observations, and in this thread of thought, simulations would be accepted as knowledge. The results from a simulated experiment could still say something about the field it wishes to simulate, as long as the criteria for the observation are clear and coincide with the field the simulation wishes to investigate. Rationalism wishes to uncover the world as detached from the human sensation (Holm, 2011-b).

Based on the theory of simulated knowledge, we have developed our own model for placing different types of knowledge in a spectrum of simulated versus true knowledge in space versus on Earth. This leaves four different fields for four different types of knowledge; true knowledge about the Earth, true knowledge about space, simulated knowledge about the Earth and simulated knowledge about space.

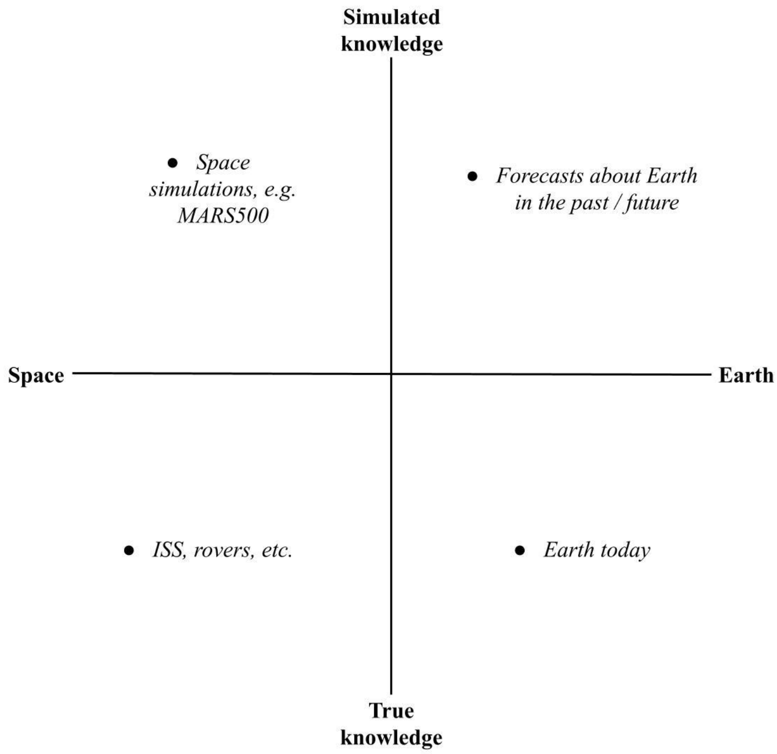


Model 1: *'Earth-Space Knowledge Spectrum'*

Within this spectrum, we can place the different knowledge from this project to demonstrate their situatedness and relation to each other. The knowledge obtained from real-life experiments and praxis on the ISS as well as data from rovers and satellites in orbit or on foreign planets is considered true knowledge about space, as it has been performed or obtained in real life. True knowledge about Earth is everything that is measured or experienced on Earth, which relates to the classical understanding of empirical knowledge.

Simulated knowledge about space could then be something like MARS500 or HI-SEAS experiments, where the knowledge is based on simulations. The simulations could take place on Earth, underwater or maybe on the ISS; the knowledge isn't tested in the actual context, but in environments which are believed to fit the requirements of the simulation, and the results then create a simulation of what the "true knowledge" in the real context would be. Simulated knowledge about the Earth is somewhat similar, but mainly focuses on the future of the Earth, which cannot be measured directly. Instead one can make models about the past and the present and this way simulate the future, which is seen in e.g. climate models from the IPCC (Intergovernmental Panel on Climate Change), prescribing future temperatures, components of greenhouse gases, or the like.

Although these examples suggest that simulated knowledge takes place further into the future, and true knowledge in the past or the present, this is not necessarily true. Simulated knowledge can also simulate something which goes far back in the past, before the right



Model 2: *'Earth-Space Knowledge Spectrum with examples'*

equipment enabled true knowledge to record it. Looking at the example with IPCC models, just as they can be used to project the future, they can simulate the past components of gases based on data from ice caps (The Intergovernmental Panel on Climate Change, 2007).

Another example of simulated knowledge on Earth could be sociologist John Urry's book, *What is the Future?* from 2016, where he creates different forecasts for the technological advances and their effects on human societies in the future, based on current patterns (Urry, 2016). This will be further elaborated in section *'9. The Future of the Earth'*.

The goal of the model is not only to visualize the different types of knowledge, but also to help put into perspective what kinds of knowledge is possible to obtain, and whether simulations can count as credible knowledge in certain situations. When looking at Mars and space, there are many things that cannot be observed or experienced in the true context, so simulations are a way to obtain presumptions about those observations and experiences. However, true knowledge cannot be obtained about a field before the field is truly experienced and observed; in the same way as, true knowledge exists about many things on Earth today.

5.3 Environmental Psychology Theory

> *"One misconception is a concern or theory that the spaceflight environment may be inherently harmful or hazardous, from a psychological standpoint. Sustained life in*

microgravity on board a space vehicle does not appear to cause psychological decrement or psychiatric symptoms unique to that environment.

Any previously reported behavioral health problems have appeared to occur because of common earthbound issues. For instance, placing crews that have potential personality conflicts in a smaller space station environment, with few recreational outlets, and then overwork them or not provide enough meaningful work to do."

(Beven, 2012)

Gary Beven, who has been working for NASA since the 1980s as a psychiatrist, mentions in an interview with Gizmodo in 2012 that any reported psychological issues in space has occurred because of Earth related issues and not space related issues. This is particularly interesting for this report, which wishes to examine the psychological impact of living in isolated confined environments on Mars. This examination will look deeper into the relation between architecture and psychological health, also known as *Environmental psychology*.

Environmental psychology is a field of problem solving endeavor concerning multiple subjects such as anthropology, sociology, animal behavior, urban planning, education, architecture, natural resources and psychology (Proshansky, Ittelson & Rivlin, 1976).

When focusing on social processes in the physical settings it widens from privacy to presence with others. According Proshansky et al. the physical setting "*is no less taken for granted. It is assumed to set the stage for and perhaps define the actors' roles with respect to particular human relationships and activities*" (Proshansky et al., 1976. p. 170). The physical setting has previously been neglected in the social sciences and used to be a mere question of technological development. But the same technological development started the fundamental questions about why behavioral issues and problems still occurred in these man-made environments. This was the beginning of environmental psychology (Proshansky et al., 1976).

Since the theory and concepts of environmental psychology are incredibly broad and can relate to all kinds of environments, the parameters which are related to a given subject must be chosen from the level of relevance (Proshansky et al., 1976). This report will consider some theoretical concepts of environmental psychology with relevance to the field of research.

Learning how to socialize in a specific group and understanding the underlying rules and regulations for behavior in that particular group, all takes place in a specific physical environment. As humans we learn how to behave appropriately in regard to a certain group of people in a certain setting, just like we learn what is expected from us in certain settings.

This cultural heritage that underlie socialization, is why human concepts of territoriality, crowding and isolation differ from other species. Our spatial behavior is by other means influenced by our social influences (Proshansky et al., 1976).

According to Proshansky, "freedom of choice" is a concept that must be taken into account when discussing and understanding the physical environment and the behavior of the individual (Proshansky et al., 1976).

Proshansky proposes three propositions for "freedom of choice":

1. *Man, in almost all instances and situations, is a cognizing and goal-directed organism.*
2. *Man's attempts at need satisfaction always involve him in interactions and exchanges with his physical environment.*
3. *In any situational context, the individual attempts to organize his physical environment so that it maximizes his freedom of choice.*

Proposition 1 and 2 tells us that an individual defines, interprets and searches the physical environment for ways to meet its goals. Often the goal can only be achieved by meeting sub-goals. For example, an individual on Mars who would like to read a book, must firstly find a book to read, but must also find a seat and a place which meets requirements for reading, like somewhere quiet. The same would apply to an individual who would like to interact in a social matter, let us say, play a board game. First, they must find others to play with, secondly a place to play and thirdly, they must find a game to play (Proshansky et al., 1976).

Proposition 3 leads us to "freedom of choice". A physical setting must not only have the capacity to fulfill the main goals and sub-goals. A physical setting must also allow to fulfill goals which are only remotely related to the primary purpose of the setting. An individual's freedom of choice in a given physical environment depends on everything that might happen in the physical space. Changes in light, noise, people, temperature etc. might decrease or increase the freedom of choice. A feeling of maximum freedom of choice minimizes social clashes (Proshansky et al., 1976).

Within freedom of choice, three concepts of spatial behavior are especially important.

Privacy: An individual's permit to feel free to behave in a particular way or to increase its range of options by removing certain classes of social restrictions. Privacy is an individual's freedom of choice to decide when, what and to whom the individual communicates information about himself. Privacy comes with the freedom of choice to communicate differently to different individuals (Proshansky et al., 1976).

Territoriality: All human beings define boundaries of their physical environment, and assume to have the right to determine who can cross those boundaries. Territoriality gives us humans a sense of identity and can be defined as "*achieving and exerting control over a particular segment of space*" (Proshansky et al., 1976. side 178). Territorial behavior is an inner determinant of an individual's desire to achieve its goal. The more options for territorial space, the more freedom of space is given (Proshansky et al., 1976).

Crowding: It must be considered how a space is organized, for what purposes and what activities it must support. Whether or not a physical space can facilitate a certain number of people is not necessarily a question of crowding. Because of cultural differences, crowded places can have positive or negative meaning, and crowding is perceived differently from individual to individual. Crowding must be seen as a psychologically and objectively social phenomenon. Crowding occurs when an individual is prevented from carrying out a specific behavior, which decreases the freedom of choice (Proshansky et al., 1976).

Privacy, territoriality and crowding and the perceived experience of these fundamental human concepts is directly linked to an individual maximum freedom of choice.

6. Methods

6.1 Comparative Analysis

Within the science of humanities, the comparative method is used to analyze and find similarities and differences between two or more systems or objects (Griffiths, 2017). Historically it has been used in fields such as philology, linguistics, anthropology, sociology, history and literature, where it finds both analogies and distinctions between the subjects of the analysis. The findings of the analysis can be used both quantitatively and qualitatively depending on the field and the purpose (ibid).

In order to make the comparison, some parameters or dimensions for analysis must be declared. These are chosen based on theories or technical concepts related to the field of study (Rienecker & Jørgensen, 2018).

In our comparative analysis, we have taken the liberty of not only comparing a selection of design proposals to each other, but also weighing them against the parameters of analysis. To elaborate on this; three parameters have been chosen based on theory from section *'5.3 Environmental Psychology Theory'* and technical concepts about psychology, architecture, construction methods and construction materials from section *'4. Explanatory'*. In the analysis, all the designs are presented and then assessed on the basis of the parameters. The parameters as they prevail in the different designs are then intercompared when relevant, and at times they are pulled into a narrower or a broader context, in order to amplify interesting aspects.

The goal of the comparative analysis is to obtain a thorough understanding of the parameters in context, as represented by the selected designs. The chosen designs are not intrinsically important, but rather important "proof of concepts" for the overall direction of this report as well as the parameters and technical concepts, enabling us to attain insight and expertise.

6.2 FEDS - Framework for Evaluation of Design Science Research

FEDS is a method situated in Design Science Research (DSR), developed by Jan Pries-Heje, John Venable and Richard Baskerville. It provides a framework for the structuration of evaluation for design-oriented research or projects. The basis of DSR is the evaluation of Design science outputs, the use and evaluation of design theory and the evaluation of the designed artifact. Due to this, evaluation is one of the two primary premises for DSR, the others being the construction of the artifact or processes used in a design-oriented project (Venable, Pries-Heje, & Baskerville, 2016). The process of evaluation in a DSR project, is what validates the gathered knowledge. Without a comprehensive evaluation plan, not only for the technical requirements of an artifact, but the design process itself, the design process of said artifact or system can only make assertions about the working order of the artifact in question. In comparison, non-scientific design projects would focus on whether the output of a project is consistent with the goals of the project itself. In DSR the success of a project is not only situated in parameters of the artifact created, but also to what extent the project contributes with new knowledge to the knowledgebase that it builds upon (ibid.).

DSR Evaluation Method Selection Framework	**Formative** **(adaptable summatively)**	**Summative** **(adaptable formatively)**
Naturalistic	• *Action Research* • *Focus Group* • *Field Experiment* • *Collect Client Feedback*	• *Case Study* • *Participant Observation* • *Ethnography* • *Phenomenology* • *Quantitative Survey* • *Collect Performance Measures*
Artificial	• *Criteria-based Evaluation*	• *Mathematical or Logical Proof*

	• *Scenarios*	• *Lab Experiment* • *Simulation* • *Testing*

Figure 2: *'DSR Evaluation Method Selection Framework'*, drawn from: (Pries-Heje, 2016).

Figure 2 shows the difference between formative and summative evaluation and puts forth some of the typical application for doing either artificial and/or naturalistic evaluation methods. The difference between formative and summative evaluation lies in the timeframe of the evaluation. Formative evaluation typically happens in the beginning of the design process and is used for building the required knowledge base and laying out the fundamental criteria of the design.

6.2.1 Why the Use of FEDS?

The use of FEDS instead of simpler iterative design processes is based on the notion that having a framework for the entire design phase of this project will facilitate a more grounded design rationale in the end and facilitate an evaluation of the design process. Using formative evaluation episodes, the group will iteratively set criteria for each episode in order to build the knowledge base needed for designing a theoretical rationale based in human space travel, and the possible colonization of Mars. The purpose of the evaluation episodes will be to set the criteria for the final output of the project. Through FEDS we hope to iteratively guide a way to a feasible design, with well-grounded criteria for its construction. The use of lab experiment, using the MICP process in a Mars regolith analogue, will also provide data, and will work as a summative validation or a "proof of concept" for an otherwise theoretical design (see section *'9.1 Knowledge and Simulations'*).

6.2.2 FEDS Strategy

This project will be using the "Technical Risk & Efficacy Evaluation Strategy" as its main evaluation strategy. This strategy emphasizes artificial formative evaluation, using this iteratively in the early stages of the design process. Later stages of the process could use artificial summative evaluation, in the form of our "proof of concept" lab-experiment and feedback from field expert, to receive feedback regarding the validity of our final design proposal. The characterization of the design process and the corresponding evaluation used in this strategy, will work as an *Ex ante* process, meaning that it will work as a predictive evaluation. Working formative in this way will reduce uncertainty regarding the criteria of the design and will point out areas of improvement that will influence the design of the artefact or system (Venable, Pries-Heje, & Baskerville, 2016).

Table 1 Circumstances for selecting a relevant DSR evaluation strategy

DSR evaluation strategies	*Circumstance selection criteria*
Quick & Simple	If small and simple construction of design, with low social and technical risk and uncertainty
Human Risk & Effectiveness	If the major design risk is social or user oriented *and/or* If it is relatively cheap to evaluate with real users in their real context *and/or* If a critical goal of the evaluation is to rigorously establish that the utility/benefit will continue in real situations and over the long run
Technical Risk & Efficacy	If the major design risk is technically oriented *and/or* If it is prohibitively expensive to evaluate with real users and real systems in the real setting and/or If a critical goal of the evaluation is to rigorously establish that the utility/benefit is due to the artefact, not something else
Purely Technical Artefact	If artefact is purely technical (no social aspects) or artefact use will be well in future and not today

Figure 3: *'Circumstances for selecting a relevant DSR evaluation strategy'*. From: (Venable, Pries-Heje and Baskerville, 2016)

Figure 3 shows the typical circumstances for choosing an evaluation strategy in DSR. The projects evaluation strategy was chosen based on this table. Since the circumstances of the project matched that of "Technical Risk & Efficacy" strategy, this strategy was chosen. Since the project deals with the technical application of MICP on Mars, one could argue that the "Purely Technical Artefact" strategy would fit the project better. But since the project revolves around human habitation systems on Mars, there are still social aspects to consider in the design, even though the process of building these habitation systems may be highly automated. This coincides with the technical risk strategy selection criteria, that it would be prohibitively expensive to do a real-life test about potential mars habitats. However, it is possible to do simulations to test out the potential viability of one's own design, this being the key strategy for space agencies, it was however still out of reach for a project of this scale.

Coming from an earlier project about biostone and use of the MICP to induce a cementation in different types of soil aggregates, the team had a preexisting knowledge base in the use of MICP. It was therefore necessary to expand the team's knowledge base of space, and what hindrances there might be for the viability of the use of biostone in space, and on other planets than earth. Based on early sketches about a possible design, the team then decided which parts of the design may prove problematic and started research in why these parts where less likely to work on Mars than on Earth. This is following the technical risk strategy, using artificial formative evaluation early in the process. Researching other proposed Mars habitats, and the testing of proposed ideas using simulations, was the inspiration to seeing a distinction between true and simulated knowledge (see section *'5.2 Simulated Knowledge'*)

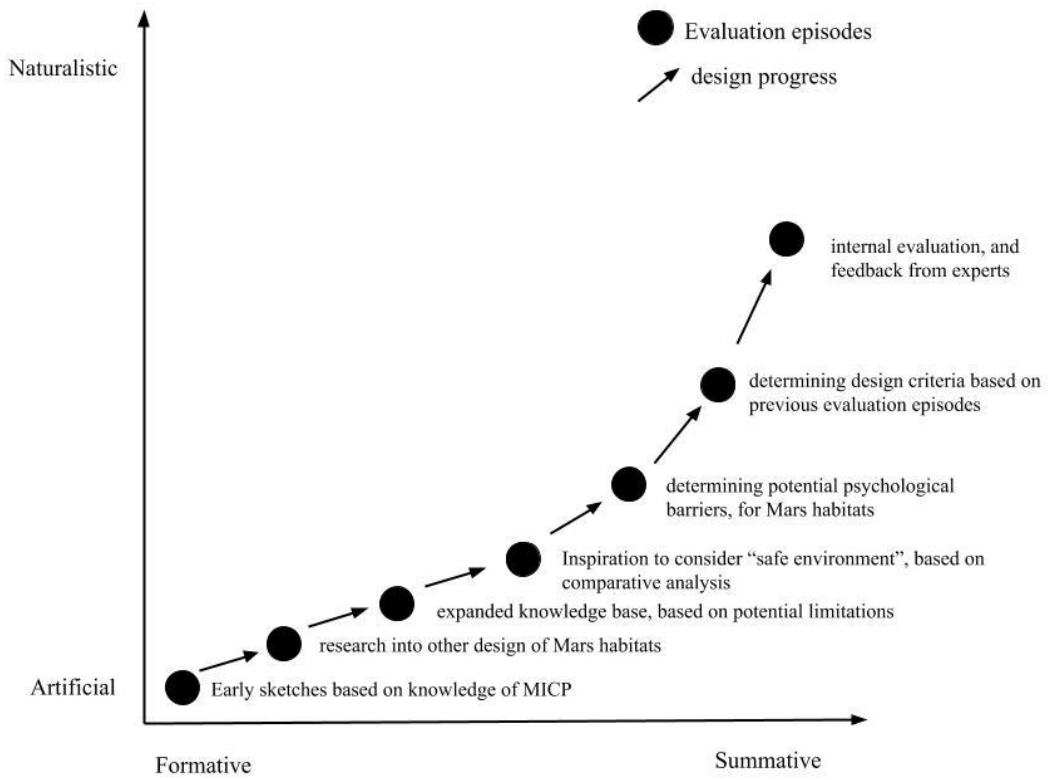


Figure 4: Figure based on (Venable, Pries-Heje and Baskerville, 2016). Figure showing the methodical strategy used in the project.

Using the differentiation between simulated and true knowledge, helped determining which parameters and limitations of the design the MICP could have an impact in, and which technical problems must be solved in advance for the eventual proposed design to be plausible (see section *'8. Design'*). During the comparative analysis of other potential Mars habitats, the criteria created became more focused architectural issues, and the potential psychological issues of human space travel. In this phase the team decides to investigate the differences between space architecture and regular architecture, and with parameters of a potential habitat space architecture could have an influence in. In the later stages of the design development, the team looked at all the previous research material to determine the final design requirements and parameters, before moving into summative evaluation. This evaluation helps to determine which of the previously mentioned parameters, are of most importance in order to create a hierarchy of the design requirements.

7. Analysis

7.1 NASA 3D Printed Habitat Challenge

In 2014 NASA issued the competition "3D Printed Habitat Challenge", with the purpose of advancing construction technologies on extraterrestrial planets as well as on Earth. The design had to be made for four astronauts who could live in the habitat for a year, and the construction had to be autonomous, as there is a lag in the communication time between Earth and Mars (NASA, s.d.-g).

The competition is divided into three phases with three levels each. Phase one was completed in 2015, and here the contestants had to focus on the design aspect and the development of architectural concepts based on the potentials of 3D-printing technologies. Phase two, which was completed in 2017, focused on the material technologies and the structural construction from indigenous and recycled materials. Phase three deals with the actual construction of scaled habitats, and it was completed in 2019 with the final winners being announced (ibid.).

7.1.1 Parameters for Analysis

We have selected four of the participants from the different phases of the challenge and elaborated on their design proposals. The assessment is based on three technical parameters, and also considers space architecture in terms of potential biological, psychological, and socio-cultural barriers that could possibly impede the viability of the habitats.

- **The construction and/or printing system.** What technological artifacts or systems are used to construct or print the habitats?
- **The construction materials**. Which materials are used in the construction of the habitats, and are they brought from Earth or found in-situ? What qualities do these materials possess?
- **The scale and interior design**. How is the space within the habitat utilized, and what kind of activities does the layout facilitate?

Our parameters are based on knowledge acquired in previous sections of the report, and they will form the base of a comparative analysis of the four design solutions.

7.1.2 Mars Ice House

Team 'Space Exploration Architecture and Clouds Architecture Office' (SEACAO) won the first phase with the conceptual design of 'Mars Ice House'. Based on a new scientific belief that there is water and ice on Mars. The SEACAO design seeks to 3D-print with ice in areas of Mars that remain below the freezing point of water. Water effectively absorbs and shields from radiation, and also allows light to enter the structure (Mars Ice House, s.d.-a). In the more technical part of the construction, subsurface ice is turned into water vapor, which then becomes liquid water for the printer to use and freeze into solid ice during the printing process. The water is mixed with fiber and aerogel. The printer takes form as a robot, which during the construction makes steps and edges at the constructions interior side, which it then climbs onto to reach higher levels of the habitat whilst printing. Another robot operates at the exterior of the construction site and gathers ice and water for the printing robot to use. This exterior robot also evens out the foundation of the habitat (Mars Ice House, s.d.-b). As a base for the printing, an inflatable membrane of fluorine-based plastic, ETFE (*Ethylene-tetrafluoroethylene*) with embedded airlocks is used as a "*pressurized boundary between the lander and the Martian exterior*" (Mars Ice House, s.d.-d).

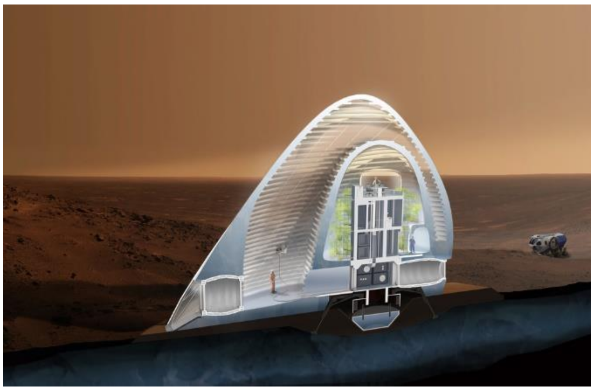



Figure 5 and 6: *'Mars Ice House'* From: (Mars Ice House, s.d.-c).

The interior of the habitat consists of the lander, containing the two robots and the ECLSS (Environmental Control and Life Support Systems), a 'core' containing the lander as well as space for different activities, and the outer shell containing the 'Intermediate Zone', which creates a 'front yard' being neither completely interior nor exterior (Mars Ice House, s.d.-c). The space in the core is used as both a greenhouse, a lab, a hygiene area, a library, medical support and exercise, a food prep zone, and as private space for the crew members. At the top of the core, ETFE inflatable windows with radiation shielding gas creates light and a view spot.

Assessment of Mars Ice House

The concept of the Mars Ice House and its manufacture is thorough and highly autonomous. Having a robotic printer which can climb its own construction ensures that the robot can easily reach different levels and create the necessary shapes of the habitat. By using Martian subsurface ice, the amount of material to be transported is rather small.

The whole design rests on a belief that there is "[...] *an abundance of water in subsurface and exposed ice in the higher and lower latitudes* [...]" (Mars Ice House, s.d.-a). For the construction to remain in a solid state, the location of the habitat has to remain below freezing. The site selection was not only based on this parameter, but also on the access to a shallow ice table (Mars Ice House, s.d.-a.). If the habitat is to be used for astronauts researching the Martian environment, their research would be limited to this specific area or long-distance travels. The concept of the habitat would not be transmissible to areas of Mars with higher temperatures, as the site has to remain below freezing throughout the year (Mars Ice House, s.d.-d), and a different building material would be needed for exploration in the warmer areas of the planet.

The interior design creates different rooms for different activities, but these spaces are all relatively small to the overall size of the habitat. The Intermediate Zone isn't used for any of these activities, and the space - especially towards the top of the structure - whilst wishing to create a '*green courtyards experience*' (Mars Ice House, s.d.-c) also makes up for a lot of unused space.

The technical solution of using water to create the habitat may eventually lead to psychological and sociocultural dilemmas if the scarcity of water is smaller than previously considered. If in the construction of the habitat, surrounding water is drained, it may slow down the expansion of the habitat, if new habitats are constructed far away from the original because of the need for water. This may lead to isolation between different constructions, if it is impractical to travel between habitats. The habitat, being one single structure, may cause psychological difficulties such as crowding, making it difficult for the astronauts to obtain privacy.

7.1.3 Team Zopherus

The winner of the first level in phase three, Team Zopherus, suggests a modular habitat made from indigenous Martian materials in a closed environment. A lander first scans the surface area and selects the optimal spot for the habitat. Rovers are deployed and start gathering materials for construction. The lander then seals to the ground, creating a protected, pressurized environment, in which the construction will take place. The rovers gather ice, calcium oxide and Martian aggregate, which is mixed inside the lander, creating "Martian concrete" for 3D-printing the habitats. This means that the main part of the structures will be found on Mars and doesn't have to be transported. Other necessary items, such as airlocks, windows and furniture, are made on Earth and stored inside of the lander. The 3D-printer has two nozzles; one printing in high-density polyethylene (HDPE) for environmental enclosure and reinforcing, the other printing with the Martian concrete for structural strength and radiation absorption. Once one module is finished, the lander will move to commence printing of the conjoint structure, eventually creating several connected habitats, with the possibility of expansion after need (NASA's Marshall Space Flight Center, 2018).

The immediate design consists of three modules, with each module having one or several activities assigned to it, by which the interior is designed. The communal shell connects the other shells, and serves as location for recreation, social activities, exercise, gardening and meal preparation, and has a walk-out airlock. The crew shell has four bedrooms for the inhabitants and a sanitation room. The third shell contains the laboratory.

Figure 7 and 8: 'Team Zopherus' lander' From: (NASA, 2019)

Assessment of Team Zopherus' Habitat

The cosmic radiation and sporadic storms make human life on Mars difficult and dangerous, and it could potentially endanger the construction of habitats. Team Zopherus' idea of creating a protected environment for 3D-printing eliminates these factors and many more, such as temperature and pressure, thus allowing the printer to build the habitat undisturbed. Using the Martian concrete allows a good use of local materials and a minimization of transported resources. However, the design requires HDPE for printing the reinforcing layer, and together with the windows, airlocks, furniture and the lander and printer itself, it requires quite a lot of space to transport the setup.

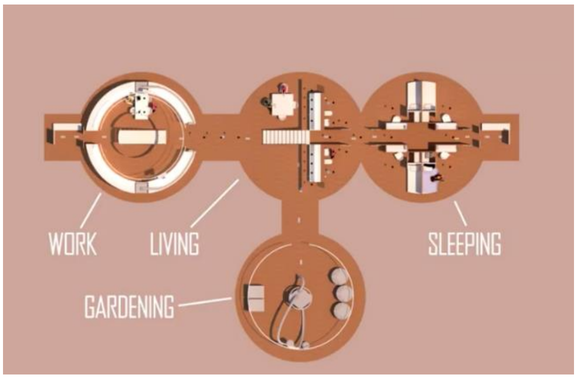
The modular design allows for easy expansion over time, whilst the first humans could arrive after production of just the first three main shells. The modular design allows different modules for different activities, and thus separating work from leisure. However, the size of the habitat is limited by the size of the lander, meaning that each module is relatively small.

The garden in the communal shell serves as a recreational area, and with the plants and the large window it is the closest to having an outside area, although it is once again limited in its size and openness.

The last point of critique would be the same as with the Mars Ice House; using ice as a building material. Having ice as the binding matter between the aggregate and calcium oxide limits the spatial expansion to areas with a constant freezing temperature and could be avoided by using a different binding agent.

7.1.4 Penn State

The habitat by Penn State achieved the 2nd place of the third and final phase. Using a printer attached to a rover, the habitat is made up of different mixtures of concrete, cork and glass. The concrete, or "Marscrete", consists of aggregate from basalt rock, kaolinite which is calcined into metakaolin as a binder, sodium and silicon compounds to activate the metakaolin together with water from Martian ice. By gradually adding and increasing the amount of cork in the concrete mix towards the exterior walls of the habitat, thermal protection and protection from radiation are increased. Adding glass towards the top of the structure allows light to enter (Penn State, 2019). Whilst printing, a retractable dome creates a sealed and controlled environment - much like in Team Zopherus' design - allowing for the printing process to proceed unaffectedly.



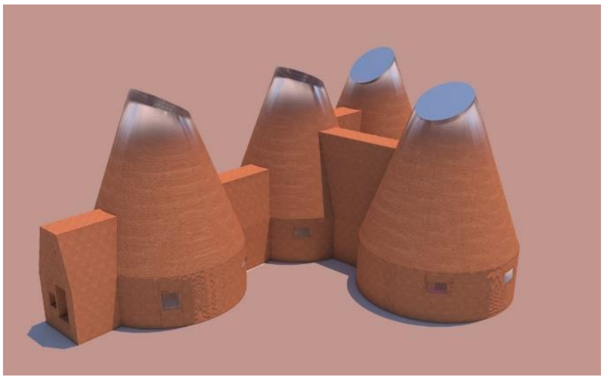


Figure 9 and 10: *'Penn State's habitat'* From (Penn State, 2019)

On the inside the different units for work, living, sleeping and gardening, the furniture is built by smaller printers using geopolymer and recycled plastic. The four units shown to illustrate the concept are for work, living, sleeping and gardening. The work unit consists of a wet lab, a meeting area and individual workspaces. In the living unit we find the kitchen, dining area, bathroom and a leisure area. The bottom floor of the sleeping unit houses the bedrooms, and the top floor a leisure and workout area. In the last unit the life support systems are located together with the hydroponic garden, producing both food and oxygen.

Assessment of Penn State's Design

Much like team Zopherus' design, creating a protected environment for the printing of the habitat eliminates a great part of the external threats of building on Mars. Once again, the main structure is built from locally occurring materials, but mixed with glass and cork, which must be brought from Earth. This poses an issue of space and weight during the transportation. However, the use of glass towards the top gives the structure natural light without the need of large-scale windows, which nevertheless would have had to be brought along.

Besides the cork and glass, all elements for the foundation of the habitat are found in-situ and are processed to bind into a solid material. This leaves no boundaries, except time, for the size of the habitat, which could potentially be built even bigger if needed. The recycled plastics for the interior design are brought from Earth and is therefore a limited resource.

Similar to Team Zopherus' design, the modules with different activities creates a boundary between work and leisure, and the semitransparent ceiling of the habitats gives not only light but an openness to the top floors of the units, much like skylight windows as we know them from Earth.

7.1.5 Hassell Studio

Hassell Studio was on the top 10 list of the third phase of NASA's challenge, and their proposition has a different take on the aspect of 3D printing. Here, an inflated structural tube creates a support structure for a shell, which will protect the actual habitat. Four different autonomous construction robots will work to build around the support structure. First, a "Scout.Bot" finds appropriate Martian regolith through ultrasonic testing and notifies the "Dig.Bot" of the location. The Dig.Bot then retrieves, crushes and deposits the regolith near the support structure. The "Distribution.Bot" then gathers the regolith and applies it in a thin, wide layer around the support structure, after which the "Fuse.Bot" solidifies it using microwave technology, which is a type of Automated Additive Construction (AAC) like 3D-printing also is. Once the shell is completed, the support structure will be deflated, and another lander will arrive with the prefabricated, expandable modular pods which will form the actual habitat under the protective shell (Hassell, 2019).

The modules contain different equipment for different activities in the respective modules, much like in the designs from Team Zopherus and Penn State. The modules consist of; a research laboratory, greenhouse with hydroponic garden, workshop with digital fabrication facilities, sleeping quarters with exercise facilities and living quarters with kitchen.

As for the interior design, once again work and leisure is separated. Hassell Studio's lead of Technology and Innovation, Xavier De Kestelier, mentions how the studio looked at the habitats of the British Antarctic Survey, where the interior design was mainly organized as a workspace rather than a home, until a group of the crew members decided to make it more homely with materials from the site. This has been an inspiration in Hassell Studios work with the interior design, where they work with different materials, such as bamboo, to create alternative finishes (AEC MAGAZINE, 2019). Also, the packaging material from the habitat will be recycled and used to 3D-print furniture.

Assessment of Hassell Studio's Habitat


Figure 11 and 12: *'Hassel Studio's habitat'* From (Hassell, 2019)

The "printing" system of this design is very unlike the other chosen designs. Instead of having an actual 3D printer creating the habitat, the shell is built through different robots placing and fastening the aggregate. There is no binding material, such as ice, mixed with the aggregate, but instead microwave technology is used to mechanically bind it into a solid material. This procedure eliminates the need for a large-scale machine to print the habitat, and using several smaller robots instead. The robots can serve several different purposes by disconnecting and connecting into different shapes and constellations, making them multifunctional and diverse in potential (AEC MAGAZINE, 2019).

Hassell Studio's modular design differs from the other designs, as it creates an 'infinity walk'; a circular connection between the pods. This gives an illusion of having more space to roam around, as one can continue walking around without reaching an end. The design also has more pods than the previous designs, but does not allow for expansion, as the shell limits the size, and more pods would have to be produced on Earth and transported.

There is a lot of thought behind the interior design (AEC MAGAZINE, 2019), but by having the modules consist of the expandable pods alone, one could fear that the habitat feels very much like a temporary shelter rather than a home. The structure is almost like a balloon or a pressurized tent, and it is missing the solid walls and ceiling of a home as we know it.

7.2 Comparative Analysis Based on the Three Parameters

Concerning the first parameter, **the construction and/or printing system**, the first three designs use one main multifunctional robot printing the habitat, with rovers gathering the needed material. The fourth design uses several robots managing simple tasks, which can then be combined for different tasks requiring several functions or larger robots. They are all technological systems, where the different rovers or robots enter in a larger system of actions and functions making the final product.

In Mars Ice House, the printing robot is mobile and can build the structure by simultaneously using the built parts as a framework to climb. Team Zopherus has the printer built into the lander, which simultaneously works as a shield, a storage unit and printer. For Penn State, the printer leaves the lander and stays in one spot, with the arms of the printer creating the movements needed to shape and construct the habitat. With the many robots of Hassell Studio's design, all elements are mobile and constantly move around during construction.

The latter is the only one not making use of actual 3D-printing, but instead a different type of AAC with microwave technology. The first three designs need a printer with hoses and nozzles, creating the risk of e.g. clogging, which would halt the construction. However, it gives more freedom for construction than the microwave technology, which works well for creating a shell as seen in Hassel Studio's design, but which cannot be used to build highly detailed habitats.

A risk seen in all of the above construction methods, and with all automated construction, is that if some of the mechanics in the system malfunction, the whole process is abrupted with slim chances of recovery, as there are no humans to manage the repair. This is a detrimental hazard in the mission, which can be reduced by thoroughly testing the system beforehand, but which cannot be eliminated completely. A way to further reduce the hazard would be to have backups for all tasks; e.g. by having extra systems inside the robots and rovers, or maybe even extra robots or rovers, to manage the needed tasks if a problem should occur.

The construction materials used in the different designs all make use of in-situ buildings to varying degrees. Designs like Mars Ice House make almost exclusive use of materials found on Mars, for constructing the basic structure of the habitat, where designs like the one proposed by Penn State and Team Zopherus have to bring complex materials prepared on Earth, to complete the construction of the habitats. Relying not only on robots and rovers, but also construction materials manufactured only on Earth, may be a hindrance to the potential expansion of a habitat if a new material has to be brought from Earth before expansion can commence. This factor can also be a potential failure point of the mission, if the construction of a habitat fails. However if only in-situ materials are used, the autonomous robots could build a new habitat if the previous habitat failed, provided that materials in the surrounding area are abundant, and the internal power system of the robots has enough capacity to build multiple habitats.

Apart from the ease of construction, the construction materials used in potential Mars habitats may also have an influence in both the biological, psychological, and sociocultural aspects of space architecture, e.g. if the construction material used does not allow for any sunlight, or the possibility of windows it may have an adverse effect on the psychological health of potential astronauts. This means that in the design of potential Mars habitats it is paramount that the choice of construction material not only facilitates a feasible construction method, but also takes into consideration the human aspect of habitat construction, since the construction material used may have a determining factor on the possible interior layout of the habitat.

Regarding the third parameter, **the scale and interior design**, Team Zopherus, Penn State and Hassell Studio design have chosen to build modular habitats to enable a possible future expansion of the habitat. The Mars Ice House is the only design which suggests building upwards in the hope of using as little material as possible. However, by using an upwards designing technique the rooms and the design in general appears as rather crowded, which might have a negative impact on the future astronauts living on Mars. Using the modular designing technique allows for flexibility and a larger sphere of influence for the astronauts. Even though bigger rooms and more space for the astronauts sounds like one of the most important factors to consider when designing habitats, studies have shown that the interior design and the use of the rooms plays just as big a role in the means of designing the best possible living-conditions for the astronauts. A workshop by NASA on factors impacting habitable volume looked at "layout versus volume", and concluded the following:

> *"First, it was determined that most psychological-behavioral health stressors were more dependent upon layout considerations than on overall internal volume. This indicated that the definition of many layout dependent factors (including but not limited to habitable volume) would be required to mitigate potential stressors. For instance, the perception of crowdedness might be mitigated by a shift schedule or privacy partitions as opposed to simply increasing the volume."*

(Simon, Whitmire, & Otto, 2011)

NASA scientists Simon, Whitmire and Otto suggest, that it is important to make sure that the future Martian habitats accommodates the needs of the astronauts such as making sure that they don't feel crowded and always have the opportunity to find privacy. The study also suggests that this can be done by increasing the scale of the rooms inside the habitats. As most of the mentioned designs have chosen to design their habitats with rather small rooms, they have to make sure that the interior design is spacious so that the rooms feel bigger and the astronauts less crowded.

Psychiatrist N. Kanas suggests that the astronauts going to Mars should be seen as a part of the total habitable system. By doing so we must make sure to prioritize the needs of the astronauts.

> *"In general, a space habitat should include some ability to visualize the outside, provisions for privacy, a pleasant color scheme and placement of equipment, buffering of excessive noise and vibration to enhance sleep and peace of mind, and enough flexibility to allow crewmembers to personalize it to their needs. Enough work stations should be available to perform required activities, and space needs to be dedicated for leisure time and recreational pursuits. In manned missions, humans should be seen as an important part of the total system, and their needs should be given top priority."*

(Kanas, 2015)

To summarize, the interior design of the habitats is just as important as the volume of the habitats, while a bad interior design can result in just as many psychological problems as small habitats and small rooms. It is therefore important to weigh these factors equally when designing habitats for Mars.

8. Design

8.1 Systems for Habitational Function

To make livable habitats for future astronauts on Mars, many technologies and factors need to be incorporated in the design of the habitats. These technologies and factors are known as the habitat subsystem (Howe & Sherwood, 2009). Some of the most important technologies, to make the habitats livable, are pressure vessels and the ECLSS. A pressure vessel is used to contain breathable air and provide habitable conditions to ensure the survival of the astronauts. The ECLSS provides clean water and air for the inhabitants (Howe & Sherwood, 2009). This system consists of two main components, a Water Recovery System (WRS), which amongst others, cleans the urine from the astronauts and provides clean water (NASA, 2017). The second component is the Oxygen Generation System (OGS), which provides and produces oxygen for the astronauts and their experiments (ibid.).

All habitats on foreign planets such as Mars need a thermal control system (TCS). TCS is a system which maintains the temperature of the habitat (ESA, s.d.). This system ensures that astronauts as well as delicate technologies and experiments do not suffer from severe temperature changes (ibid.). These extreme temperature fluctuations might have catastrophic impacts on the technologies of the habitat and the health of the astronauts. When on Mars, communication between the astronauts and people from Earth is essential. To provide this, a Data Management System (DMS) is required in the habitats. DMS can provide remote telecommunication between the astronauts living on Mars and people living on Earth. Furthermore, the DMS provides a monitoring system and a computerized system, which secures the collected data from Mars (Howe & Sherwood, 2009).

To simplify our design proposal, we assume that all these technologies are built into the proposed modules. We will not specify the or use of these further, but it should be considered in a later iteration of the design proposal, when knowledge of the different modules size and physical properties are known to us.

Another important factor in the design of the habitat is Crew Accommodations. Crew accommodations include the interior design and the facilities inside the habitat such as private cabins, social interactions, exercise facilities and recreation facilities which are all important, to provide the best possible circumstances for the astronauts (Howe & Sherwood, 2009).

One of NASA's biggest priorities is to protect the astronauts against radiation, by building radiation shelters (Tran, 2019). As previously mentioned in section *'4.1.3 Methods for Dealing with Radiation'*, too much radiation might lead to an increased risk of cancer and other diseases. Radiation is at its highest when the sun is erupting. NASA wants to be able to predict when and where the solar eruptions occur and in doing so, they hope to warn the astronauts early, enabling them to reach shelter before the radiation levels get too high. A shelter in the Mars habitat could be made from natural resources found on Mars itself, such as Mars regolith (ibid.).

8.2 Requirements of a Martian Habitat

The main function of a habitat on Mars is to provide shelter that protects and supports good quality of life for the inhabitants and at the same time ensures the astronauts' work, leisure and general activity. Through our empirical research, theory and analysis, we can surmise the most important factors when designing a habitat for Mars and sort these in three categories. These are as mentioned in *'4.2 A Healthy Environment in Space'*; biological, psychological and sociocultural requirements and will be elaborated in the following sections.

8.2.1 Biological Requirements

We surmise four key physical limitations in relation to the biological requirements in a situated environment on Mars, and account for these via the following precautions:

1) Protection from the Martian atmosphere

Both in relation to temperature and pressure, to ensure the wellbeing of any internal organisms from Earth. The base exterior also must be able to withstand large temperature fluctuations occurring due to the seasons and sols on Mars to avoid material stressing.

2) Radiation protection

As it is neither possible to move the habitat further from the radiation source nor limit the time exposed, unless the mission is aborted. The habitat must be able to shield astronauts from both kinds of radiation (see section *'4.1.1 Cosmic Background Radiation'*).

3) Internal quality

The internals of the habitat must have a good circulation of fresh air, and if possible, facilitate individual adjustment of humidity and temperature. It must also facilitate necessary biological processes such as shielding from sounds and light to ensure good sleep and have toilet and bathing facilities of good quality. The general design must be simplistic and easy to maintain.

4) Reduce Earth dependency

In order to make the mission as cost effective as possible, the weight of the habitat and infrastructure transported from Earth needs to be as low as possible. Also, the design should make use of as much in-situ material as possible, and if at all possible, not require further resources to be transported from Earth.

8.2.2 Psychological and Sociocultural Requirements

To ensure the wellbeing and effectiveness of its inhabitants both individually and socioculturally, several considerations must be taken to ensure:

1) Sufficient internal volume

The key factor in building habitats, seems to be the perceived size of the internal structure, as the astronauts will spend most of their time inside the habitat. The design and layout of the habitat therefore needs to accommodate this.

2) Multifunctional internals

To ensure personal and crew freedom in an otherwise enclosed environment, it is important that the astronauts can use their internal surroundings for many different purposes which also has room for improvisation from the astronauts, giving the crew a lot of flexibility and freedom of choice.

3) Good working conditions

The astronauts will spend most of their mission-time working, and it is therefore important that the working environment ensures noninterfering work, has enough lighting, and freedom of choice.

4) Group dynamics

The habitat must have facilities that accommodates group activities, which at the same time accounts for cultural differences, facilitates celebrations and ensures the possibility of sharing meals in the entire group to ensure good group dynamics.

5) Personal territory, privacy and leisure without isolation

For the astronauts to function well in the confines of a Mars habitat, it is very important, to allow for leisure time and privacy, while making sure it is impossible for anyone to completely isolate themselves from the group. It is important that the astronauts have some form of personal territory, as this will grant the astronauts freedom of choice. This does not necessarily mean crew cabins, but it is one way to accommodate this.

6) Crew accommodations

Taking a walk is impossible, therefore simulating this via the habitat design could have a positive effect on the psychological wellbeing of the astronauts. This could also, if done correctly, contribute to making the habitat feel bigger than it is, and thus also reducing the possible stress factors for astronauts.

8.2.3 Physical Facilities Needed for a Mars Habitat

On this basis we surmise the following physical areas are needed to ensure all aspects of a mission to Mars. While these do not need to be isolated modules, it is important that the habitat is flexible enough to ensure them:

- Radiation shelter.
- Medical facilities.

- Facilities for daily exercise.
- Laboratory and workstations.
- Greenhouse for in-situ food production.
- Mess hall or other area that can support group activities and dining.
- Private environments for leisure time and to ensure privacy.
- Possible way of looking at Earth or outside.
- Adjustable habitats for different screw sizes - Expandable for future missions.

Everything must be designed to give the illusion that the habitat seems larger than it is, and the design should accommodate human improvisation and freedom of choice.

8.2.4 Inspiration from Our Comparative Analysis

Through our comparative analysis, we have learned that several important design decisions are needed in order to ensure a functioning design for a Mars habitat. On the basis of this we surmise, that the habitat design must:

- Ensure a secured construction environment that shields *from* the Martian weather, and which isn't affected *by* the weather.
- Be flexible in scale and size but also to various locations on Mars.
- Rely on little to no material from Earth, to reduce dependency and travel cost.
- Contain some sort of group engaging facility.
- Not make use of ice as a binding material, as this could endanger the structural integrity.
- Create the illusion of a larger space, possibly through an 'infinity walk' design.
- Ensure the feeling of a safe and permanent habitat, and not that of a temporary one.
- Use natural lighting and possibly have an area to support looking out of the habitat.

8.3 Design Proposal

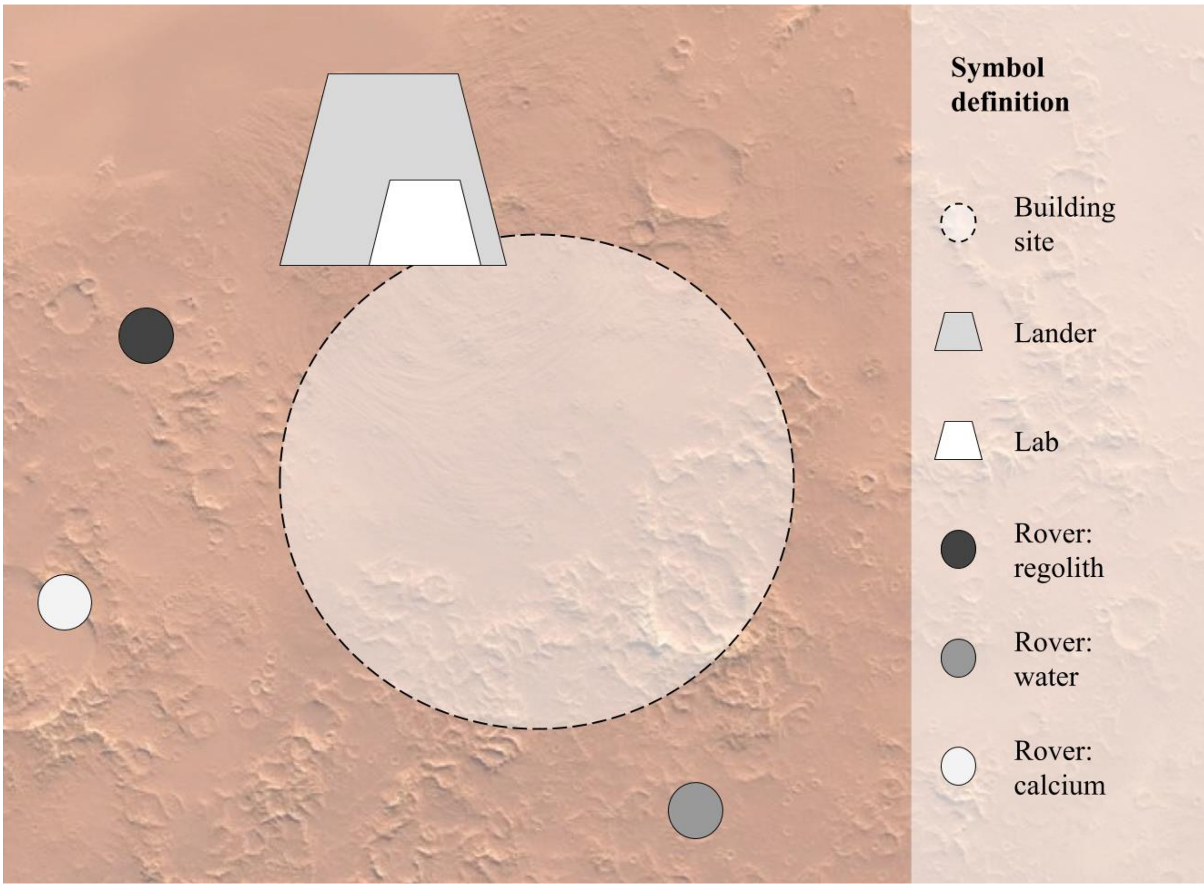
The main inspiration for the project has been to try and incorporate biostone in the design of Mars habitats, due to its apparent qualities when used on Earth. This is however not a simple task, as working with microbiology requires some different scientific technologies than those needed for the other designs presented in the analysis. Whilst some of the materials could already be present on site - aggregate, water and calcium - others such as nourishment will have to be exported from Earth.

8.3.1 Setup and Materials

As mentioned in section *'4.3 In-situ Building and Biostone'*, MICP and biostone require the bacteria, S. Pasteurii, as well as urea and a growth media. Urea can be found in human and animal urine but seeing as the construction of the habitat will take place before human arrival, it will have to be brought along from Earth either in natural or chemical form. During the trip towards Mars, an automated bacterial lab will have to cultivate the bacteria, so there are enough bacterial strains available upon arrival for the construction to be executed. The lab does not have to be large in size, but needs the necessary equipment, and also sufficient amounts of growth media for the bacteria to survive both during the trip and during construction. This also means that the lab - whether locked in the lander or removable from the lander - has to be close to the actual construction site, as there will be a need for a constant supply of bacteria.

Upon arrival, at least three different rovers will be needed to gather materials. One for aggregate, which can either crush large rocks or collect the loose sand. The sand does not need much processing, as it can vary in size and still cement evenly (see *'Appendix 1: Interview with Thora H. Arnardottir'*). A second for water or ice, which can either pump up the liquid water or collect and melt the solid ice, and in both cases distill it - or bring it to another element, which can then distill it. A third for collecting calcium, for example calcium carbonate, and crushing it into powder and getting rid of undesirable compounds.

These rovers will connect into a larger system of either one large robot or several smaller; preferably the latter, which could facilitate many different functions at once, and possibly even construction in several places at once. The calcium and the water will be brought back to the lab to be used for making cementation fluid. The regolith will be brought back to the building site, where it will be used to create biostone.

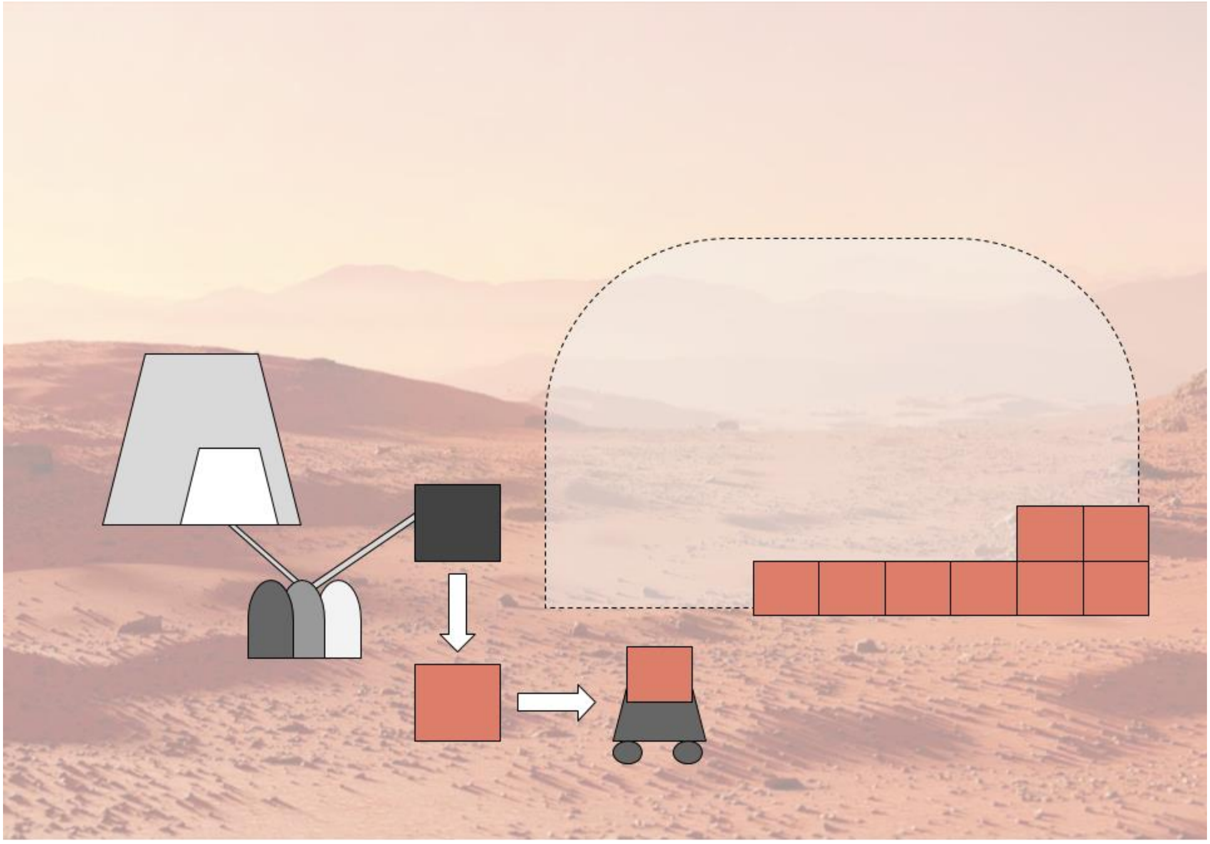


Model 3: *'Plan drawing and components of design proposal'*

8.3.2 Construction with Bricks

Creating the Mars-biostone can be done in several different ways. The simplest way to cement through MICP is by making bricks. This requires either many molds for the bricks, or a lot of patience for the bricks to cement properly. The bricks could be used for creating an igloo-like structure by stacking the bricks (see Model 4). By continuously feeding the bacteria with the cementation fluid after shaping and stacking, the gaps between the bricks would bind, creating one joint structure. As the regolith is brought from the rover to the shape, the MOXIE system (or a similar system) transforms the atmospheric CO_2 into oxygen, which is connected to the brick mold.

This procedure would need an extra structure to support the construction from the inside, which could be an ETFE inflatable membrane or something similar. The membrane also works as an extra isolation and has the needed windows and airlocks, which the bricks will be placed around. Once fully erect, the structure supports itself through the weight distribution of the bricks. Depending on the size of the bricks, the igloo would need a couple of layers to create a barrier thick enough to actually be tenable and protect from the outside conditions. The bricks could also be used to create the interior walls and room separations.

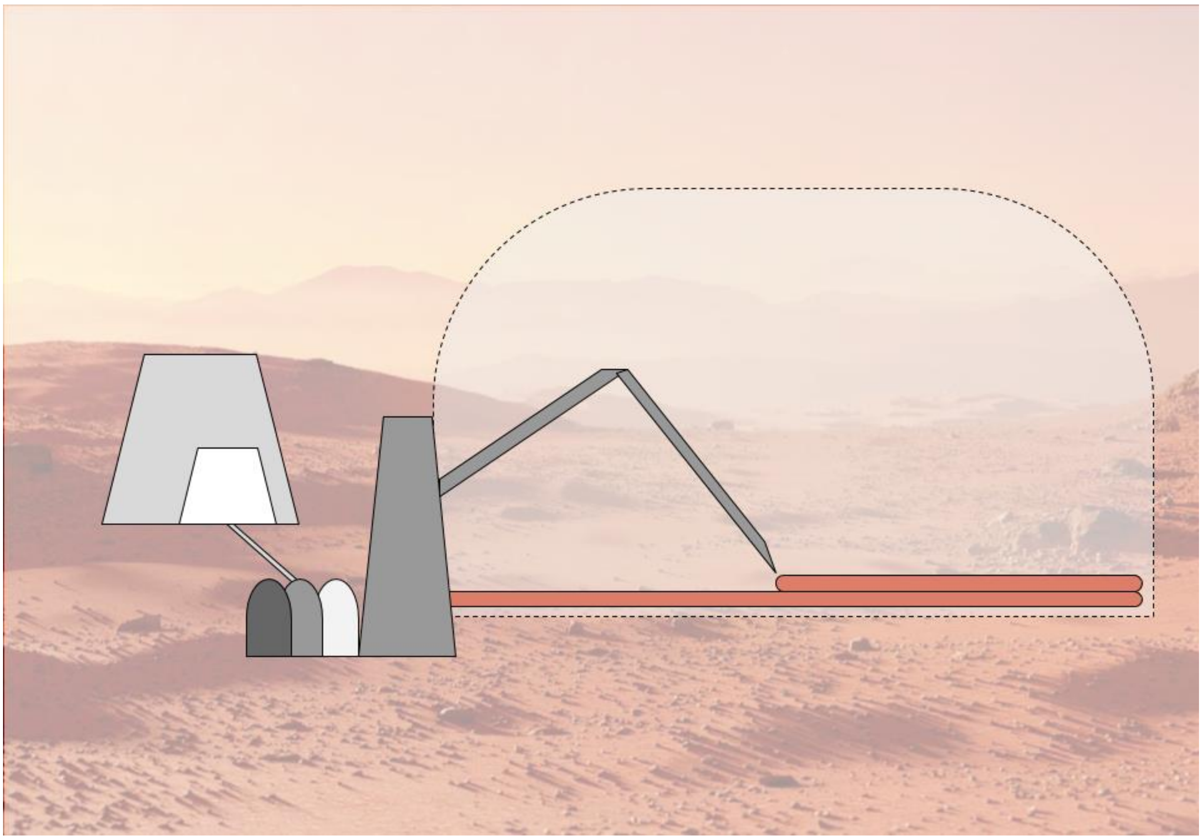


Model 4: *'Illustration of construction using bricks'*

8.3.3 Construction with 3D-printing

Another method for construction would be 3D-printing the biostone. This method would require an outside structure or membrane to create an isolated environment for the printing, which is more sensitive to the outside environment. Otherwise the setup is the same as in model 5. The membrane inflates directly from an opening in the lander, creating easy access to the inside, where the construction will take place. The rovers bring all of the materials back to the lab and the membrane, where a 3D-printer - either placed in one location or a mobile version moving around - will be connected to three reservoirs. One reservoir for the regolith, another for the bacteria in some growth media, and the last for the cementation fluid with the urea and calcium.

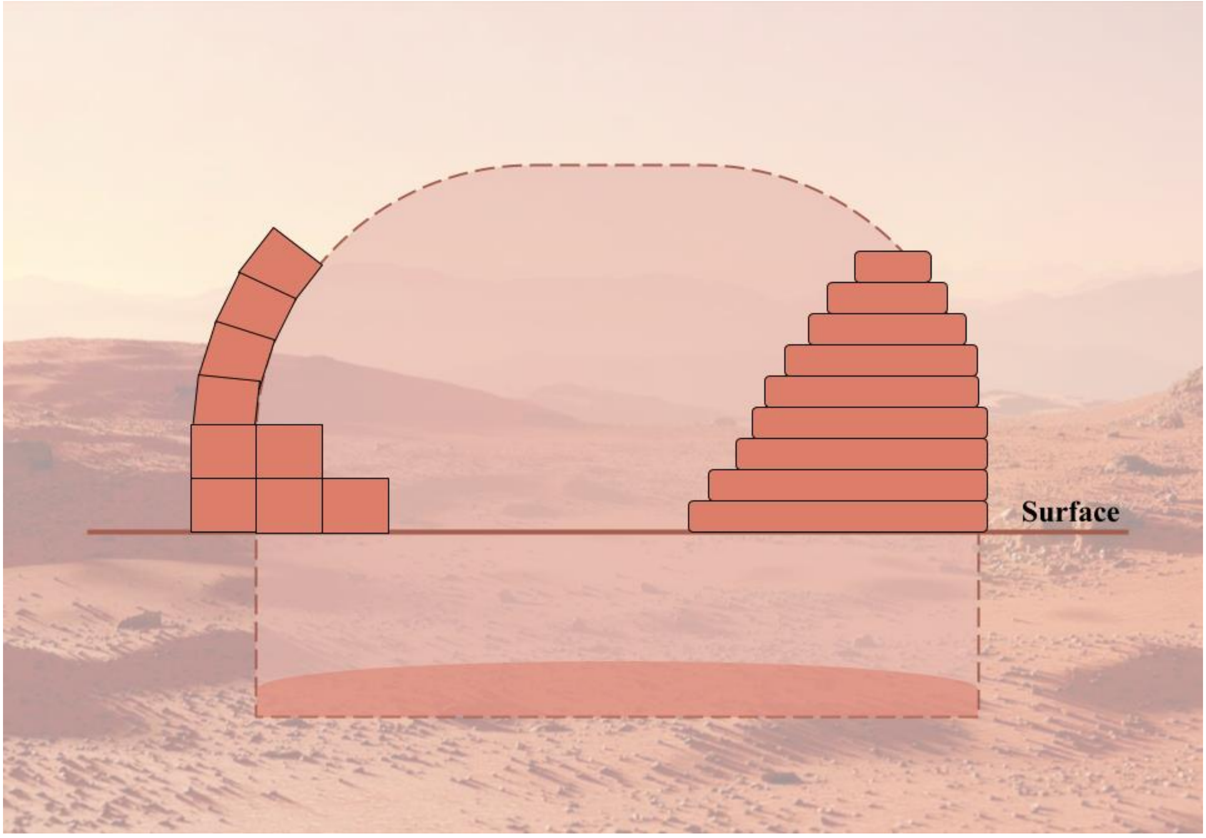
When printing, content from all three reservoirs is transferred to a separate small container, and the mixture is ejected through the nozzle of the printer as a concrete-like material which slowly hardens. This mixture is placed in one row, where after the cementation fluid is repetitively added onto the mixture until the material has cemented sufficiently. Afterwards more layers are added on top, one row at a time, until the construction is finished. This allows for printing the interior and exterior walls simultaneously. Like with the previous method, the rows will cement onto each other, creating one solid structure.



Model 5: *'Illustration of 3D-printed construction'*

8.3.4 General Design Ideas

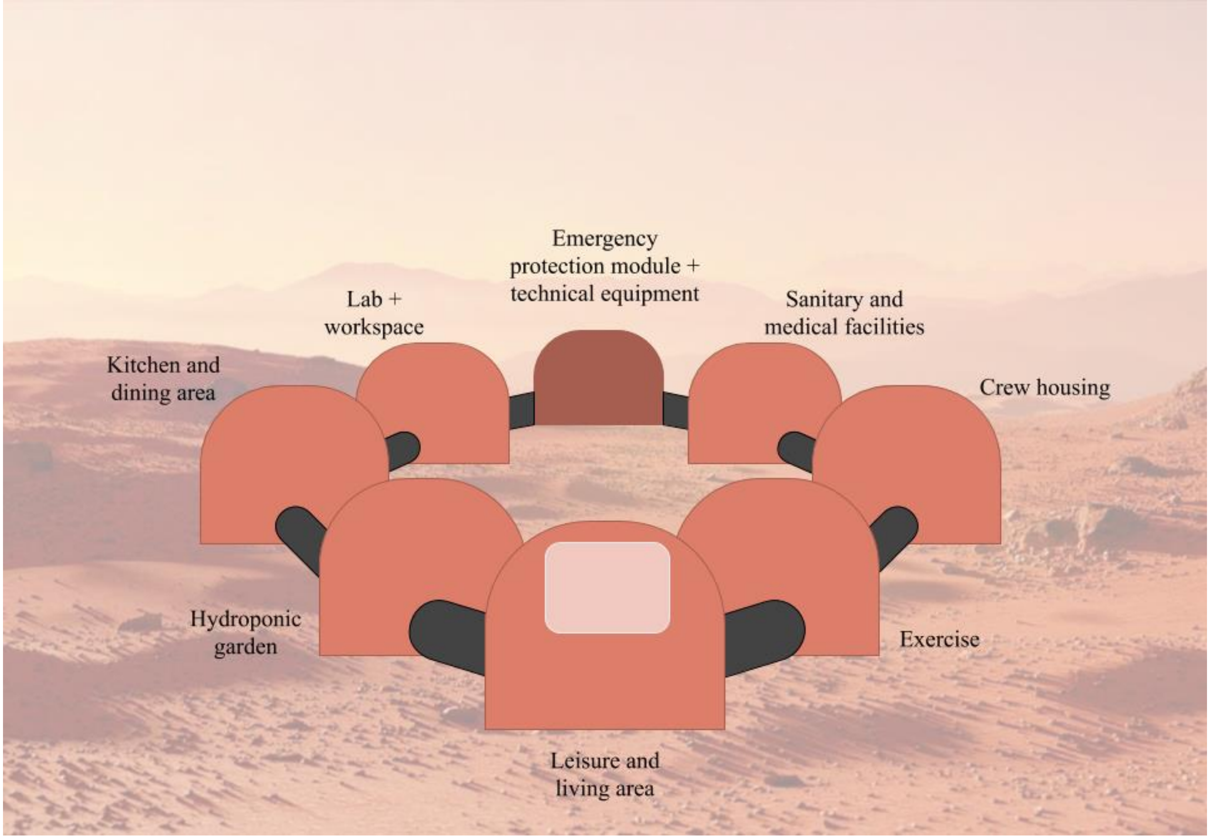
Since the cementation process is rather time-consuming, some time could be spared if instead of building the full height of the structure, some digging rovers were to dig a hole on the building site, corresponding with the size of the inflatable membrane. This would not only stabilize the construction further, but would save time and resources, as the actual constructed structure would be reduced significantly by using the walls of the hole as part of the structure.



Model 6: *'Illustration of underground construction'*

Using both methods, the size can vary depending on needs and the criteria for internal layout and volume. It can also be made modular, if several inflatable membranes are brought together with connecting links for passages between the modules. The most time efficient construction method for this, would be 3D-printing, as each layer of biostone for all modules could be printed in one go, together with interior walls. If needed, the passages could even be covered with a layer of biostone for extra protection. In case of extreme conditions, one module could be covered in extra layers to create a super protected and safe environment for the crew, in case of high radiation exposure, whilst still being functional as a normal room in the habitat.

In the picture below, we have illustrated an example with an "infinity walk" module, where the modules are connected in a circle, inspired by the design from Hassell Studio. Each module has its own function as e.g. crew housing, lab, workroom, kitchen, garden, etc., creating a clear distinction between work and leisure and allowing for different activities, both private and social, for the crew to maintain a healthy state of mind during the stay.



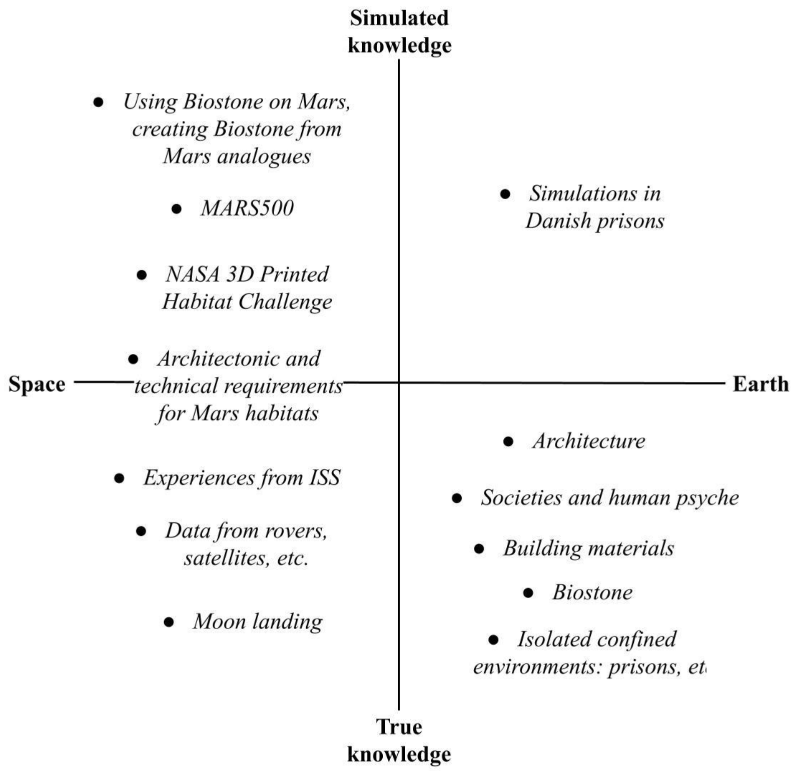
Model 7: *'Illustration of modular design proposal'*

In the "Emergency protection module" we also find all of the life support systems and other technical equipment, and the module is connected to the airlock allowing exit of the building. This module is directly connected to the lab and workspace, as well as the sanitary and medical facilities. The leisure and living area has a large window for view and recreation. Having the interior and exterior walls consisting of biostone, the look and feel will be a reminder of brick or concrete homes from Earth, and the connectedness of the modules will give a similar feeling to that of going from room to room in a large house. This way, the crew will not feel crowded or enclosed by the size, as the design allows for free movement and plenty of options for staying in different environments within the habitat. In the future, Mars missions might require more crew members or laboratory facilities, which modules made of biostone facilitates rather well since it is possible to produce more modules and binding the new module to the old construction. This facilitates a great level of future adaptability.

9. Discussion

9.1 Knowledge and Simulations

If one was to put the different types of knowledge from this project specifically into the Earth-Space Knowledge Spectrum, it would look something like this:



Model 8: *'Earth-Space Knowledge Spectrum with examples from the report'*

The architectonic requirements from the analysis and from Space Architecture, are partially based on simulated knowledge and partially on true knowledge. The true knowledge about Mars has proven technical specifications about temperature, radiation, and many other factors, which have been measured; although not yet by humans. By having humans living on the ISS, more true knowledge about living in space has been proven; although not yet on Mars. The latter is difficult to place definitely in the spectrum, as it tells true knowledge about life in space - and Mars is of course located in space - but it has some qualities of simulated knowledge, as it is unsure whether living on Mars will correspond to that of living on the ISS, as there are obvious differences, such as the distance from Earth. However, there are also obvious similarities, such as the dependency on technology as a constant shield from the fatality of what is outside.

This issue is the same as with many other aspects of preparing for missions on Mars. Although simulations can prepare for some aspects of the mission, there are many unknown factors which could potentially be detrimental to the construction of habitats; both regarding construction with biostone and other proposals for construction. If the aggregate contains salts or radioactive components, this could make survival for the bacteria impossible. Robots sent to the planet for assembly could get buried by storms and sand and stop the construction process completely. The astronauts could suffer psychological stress from the isolation, which could make them sick or unable to perform the required tasks. All of these are elements that can be simulated, but never be truly known, and will only be visible when the time comes.

A lot of what we know about biostone and MICP is true knowledge, as it is based on real life experiments. We are currently in the process of experimenting with cementation of Martian regolith analogues in cooperation with Arnardottir. In this attempt to create a 'Mars-biostone', we are producing simulated knowledge. We know that it is possible to form a solid material through the process, and if the experiment with Mars analog proves successful, we simulate what the process would create in situ on Mars, as it is not possible to create true knowledge about this yet. The Mars analog of course doesn't come from Mars but is an imitation of the composition of the actual regolith. Even if actual regolith was brought back from Mars to Earth and was used in the experiment, it would still be simulated knowledge - although 'truer' on the spectrum than by using the analog - seeing as the experiment isn't performed in situ. The 'truest' simulation would be in an imitated extreme environment with extreme temperatures, radiation and possible radioactive components in the regolith or in the surrounding air, with the surrounding environment consisting of CO_2, and conducted automatically by robots. This would give the most realistic simulation of the situation we wish to explore.

The function of simulations is to constitute knowledge that cannot be measured in context because of the circumstances; for example, NASA has to make simulations to prepare the astronauts for life on Mars before they go there, so that they have previous experience or expertise to help them manage certain tasks or situations. Depending on what kind of task or situation is being simulated, and how extensive it is, the simulation can supply some proficiency, but may not prepare the astronauts for the actual context of being on Mars, as some things can't be simulated in enough detail. Although experiments and simulations try to prepare the astronauts for the isolation of being on a foreign planet, the psychological effects of actually being a year's travel away from home are difficult to imitate.

Looking at the BASALT simulation preparing for both travels to Mars and the Artemis program to the Moon, it especially helped with preparing the crew in the field and the crew on Earth to communicate effectively in spite of the delay (Tabor, 2019). With the cooperation and empathy between the groups being fundamental for the BASALT simulation (ibid.), the crews would have to consist of the same people in the simulated mission as on the actual mission, for the experience to be fully applicable.

To repeat the quote from Cernan, "*the key is that you train for knowledge of each other and you train for teamwork*" (Cernan, in: Tabor, 2019). Although much can be learned about the general teamwork between the different crews, which could be easily transferred to general "groups" of people rather than specific persons, there is a lot of thought behind the actual persons training together beforehand. This is mostly important for the astronauts, who will be living together in confined spaces for several years.

9.2 Theory of Science

In order to investigate our problem statement, we have chosen to focus on the field between simulated and true knowledge, with a rationalistic approach. This approach has made it possible to research a field which is yet to be observed and experienced by humans, as simulations make up for the main part of the knowledge available.

No matter how close to true life a simulation comes, it will never be true knowledge, but nonetheless a thorough simulation is the best option for creating some sort of knowledge about a field such as Mars, where the technical risks are too high to test in context without preparation and practice. The rationalistic approach would give arguments for the reasoning, that a detailed analog and simulation can create valid knowledge about the actual case. There will always be risks when conducting new missions, and preparation through simulations can help reduce some of these risks. As seen in the previous section, a simulation such as the BASALT prepared the participants on e.g. teamwork, and other simulations can prepare technical abilities, which will become applicable on the actual mission. Of course, these simulations cannot be guaranteed to be true to the actual situation in the future, which is a clear disadvantage. However, true knowledge and data can be used to construct the most realistic circumstances for conducting the simulation.

Without looking into simulations and the fidelity of these, investigating the problem in this project would be impossible. All designs of habitats for Mars are partially based on true knowledge but are in reality simulated knowledge. The theories about human psychology and well-being in a future Mars habitat are also simulated knowledge, which may be based on true knowledge from e.g. the ISS, but in the context of Mars they can never constitute true knowledge. The design that we present later in the report, and the conclusions from our study, will be simulated knowledge as well. Our standpoint in theory of science has made it clear just what kind of knowledge we wish and expect to produce, and how this should be grasped.

9.3 The Future of the Earth?

In John Urry's *What is the future?* from 2016, many different scenarios for the future are predicted and analyzed, based on different "triggering" technological aspects from the present day, such as climate change, automobiles and manufacturing. Urry argues that the future should neither be seen as fully determined by technology, nor as completely open (Urry, 2016).

The future is distinguished into three different kinds; the probable future, the possible future and the preferable future. This means that a given thought or forecast about the future can either represent something which is the most likely, something which is within the limits of what is realistic, and something which is the overall most desired outcome. About the preferable future, Urry says:

> *"It is often presumed that, because a particular future is preferable to the present, then it will be realized, since the members of that society will see it has to be brought about. But there is no guarantee that what is best is what actually develops, even if there is widespread agreement in a given society that it is the most desirable of possible futures."*
>
> (Urry, 2016: p. 16)

An example of this could be the goal of having human habitation on Mars for a longer or shorter period of time. This future is something which is agreed upon by scientists in NASA and probably other parts of society as well. This is in some ways presumed to be better than the present state, since it allows for further exploration than just Earth-bound, and since it will allow for technological breakthroughs, which can even help life on Earth. However, just because this future is desired, doesn't mean it will actually happen.

In some ways, this could also be considered a possible future, since technological development and successful experiments and simulations indicate that habitation of Mars is possible within the near future. As similar experiments and smaller missions could be successfully implemented over time, the plan might even become a probable future. Much of this, of course, relies on technology. When it comes to technology, Urry comments on technological extrapolations, where the future is derived from elements of the present or the recent past (Urry, 2016). He comments:

"Much future-making here normally involves the assumption of 'business as usual'; and the main issue is the new 'technology' that might develop and what it might do to the future. Such forecasting involves seeing some feature of the present as the key mechanism in how people's lives will predictably unfold in the future."

(Urry, 2016: p. 71)

According to this quote, technology is deterministic of how the image of the future looks. However, Urry arguments that the technology might play a completely different role in the future, than what it plays in the present, and in response the future might also look completely different.

Seeing as the future image of habitats and astronauts on Mars rely heavily on existing - and not yet existing - technologies, these determine whether the scenario is plausible or not. Technologies such as Moxie make the scenario more and more realistic, as we in present day imagine the technologies to not only be made for this future, but for the future to rely on their existence. However, it is uncertain whether or not the technologies will even be used for that purpose in the future. Maybe they will be used for solving problems on Earth, maybe they will be used for different planets, and maybe again they won't even prove successful or useful at all.

9.4 Incentive for Innovation

In line with the above speculation about the future of technologies, comes another speculation about the incentive behind the creation of the technologies. Moxie is created specifically for NASA's Mars program, in order to create a breathable environment from the CO2-filled atmosphere, and many other technologies are being fine-tuned or altered in order to create new types of homes and habitats. According to NASA, the 3D Printed Habitat Challenge was not only a challenge to create homes on foreign planets, but to the same extent a challenge to inspire new ways of thinking homes on Earth. They describe it as a competition, which:

"[...] seeks to advance additive construction technology needed to create sustainable housing solutions for Earth, the Moon, Mars and beyond. On Earth, these capabilities could be used to construct housing wherever affordable housing is needed and access to conventional building materials and skills are limited."

(NASA, s.d.-g)

It is, however, interesting that the American space agency are the ones to summon teams of architects and engineers to research this. The main focus of the teams is of course to present an idea for a habitat suited for Mars, and the fact that the technologies could be otherwise utilized on Earth is almost a "bi-product" of the challenge.

In a shift of interest, affordable housing could easily be in the front seat of the technological development, with space travel and habitation of foreign planets being the secondary focus. This would of course not be in the interest of NASA to the same extent and would require different institutions to take action. If NASA are in control of the challenge and have the cogency to attract the needed actors, they will quite naturally make the challenge in their own favor and interest.

9.5 Why Space?

As we have already discussed throughout this report there are multiple positive contributions to life and society on Earth which space exploring have brought to life. NASA is one of many companies which invest a lot of money in Space research, to learn more about the Universe which we are a part of, but also to gain knowledge of Earth itself. Even though NASA studies and research has introduced us to new knowledge and technologies, one might wonder whether the money could have been used more effectively elsewhere. The Mars mission is a mission with two purposes, firstly to learn and explore a new planet, and secondly to research the planet to learn more about Earth. But is the exploration of a foreign planet truly the best possible way to estimate what the future on Earth might look like.

Our planet has changed a lot throughout the years, and everything we know about these changes have been from research made on Earth itself. This is one of many examples to why investment in Earth might seem like a better alternative, when learning about the future of the Earth. The question is whether or not a company, whose focus is to research and learn more about Earth would make better use of the money invested in space research, while the study on Earth already have shown great results. Nonetheless, is it impossible to know whether it's the study of Space or the study of Earth that teaches us the most, as both studies have many different advantages. Changing the way, we nowadays invest in space research could also change the society of which we are part of and possible future technologies.

In hindsight we must acknowledge that we most likely would never have had memory foam mattresses, freeze-dried foods, and other spinoff technologies which have made today's life a lot easier, modern and even safer. Other spinoff technologies are technologies such as LED-lights, phone cameras, land mine removal, foil blankets, CAT scans, baby formula, water purification systems, etc. (NASA JPL, s.d.-b). Space exploration technologies such as satellites have also contributed to a major improvement of discovering and predicting weather phenomena, which e.g. is helpful when in need of evacuation people from natural disasters and in agriculture to determine when to plant seeds and harvest crops. Satellites also helps in terms of discovering geographical and climate changes on Earth. NASA and other governmental space companies might have used a lot of capital, but the gain that society gets in return when it comes to knowledge and technologies are invaluable. It would be unlikely to think that future space technologies will no longer yield any spinoff technologies which can lead to an even safer and more sustainable future on Earth.

10. Conclusion

In the attempt of answering the problem statement: "How can the living conditions and well-being of the astronauts be ensured in research habitats on Mars through building with biostone as an in-situ material?" we can conclude that there are many factors to consider when designing habitats for foreign planets such as Mars.

Mars is similar to Earth in terms of weather and geology, and scientists believe that Mars once used to be like Earth with running water, a thicker atmosphere and maybe even living organisms. Today scientists know that Mars have high radiation exposure, an atmosphere 100 times thinner than Earth's atmosphere which contains 96% Carbon Dioxide. Mars is in general a hostile planet for humans but nonetheless is Mars the planet in our solar system which humans might have a chance to survive on.

NASA is currently planning a manned Mars-mission, with the purpose of gathering new knowledge about Mars and if lucky, we might discover new knowledge which is useful in regard to Earth. In order to send humans to Mars, it is necessary to design and build habitats where astronauts can live and thrive. To ensure an environment on Mars where astronauts can survive, technologies such as pressure vessels, radiation shelters, oxygen and water tanks must be integrated into the habitats. To ensure the well-being of the astronauts one must consider many other things that are mere physical. Beside the hostile environment on Mars there are many psychological factors to consider as well.

We have throughout this report come to the realization that requirements of biological, sociocultural and psychological matters, play a major role when designing space habitats. A 'freedom of choice', a feeling of being able to find privacy, territoriality and avoid crowding is a major concern in order to ensure individual well-being and group dynamics; volume, or perception of volume, inside the habitat seems to be one of the greatest factors to ensure freedom of choice. We have also found that a greater freedom of choice includes interior design, such as flexibility, adaptability, quality of light, temperature control, etc.

Through investigating theory of simulated knowledge, we have set up a theoretical model of simulated versus true knowledge, investigating where the knowledge which lies behind our study is placed, and where the knowledge produced through this study is placed. Simulations and analogues from NASA and other institutions constitute simulated knowledge, and so does much other information used to create an image of what we need to know before manning Mars. However, this does not mean that it isn't important knowledge. Seeing as it is impossible to test an advanced mission in detail before departure, hybrid simulations are the closest we can come to obtaining useful and vital information and experience.

Due to the criteria mentioned throughout this report, we have decided that the best way to design our own habitats, is by using the "infinity walk" modular design with the use of biostone. By doing so we hope to maintain a healthy physiology and state of mind of the astronauts during their stay. Due to the separation of the facilities inside the modules we hope to establish a feeling of "freedom of choice" while this results in larger rooms and the opportunity of privacy. We hope that the use of biostone will accommodate most of the psychological matters while biostone makes it possible to build larger habitats and therefore larger rooms as well. The use of biostone also gives the opportunity of using the in-situ building technique, which is very helpful because of the reduced transportation of material from Earth to Mars.

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