POLITECNICO DI TORINO
Repository ISTITUZIONALE

# ‘Back to the Cave’- designing symbiotically operating habitation modules in Martian caves to facilitate the research for the human exploration of space

*Original*
‘Back to the Cave’- designing symbiotically operating habitation modules in Martian caves to facilitate the research for the human exploration of space / Borovina, M., Sumini, V., Rossi, M.. - (2024), pp. 558-566. (52nd IAF Student Conference at the 75th International Astronautical Congress, IAC 2024 Milan (ITA) 14-18 October 2024) [10.52202/078379-0049].

*Availability:*
This version is available at: 11583/3006403 since: 2026-01-09T17:26:02Z

*Publisher:*
International Astronautical Federation, IAF

*Published*
DOI:10.52202/078379-0049

*Terms of use:*

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

*Publisher copyright*

(Article begins on next page)

24 June 2026

75th International Astronautical Congress (IAC), Milan, Italy, 14-18 October 2024.
Copyright ©2024 by the International Astronautical Federation (IAF). All rights reserved.

IAC-24- E2,IP,4,x88744

# ‘Back to the Cave’- designing symbiotically operating habitation modules in Martian caves to facilitate the research for the human exploration of space

**Magda Borovina** [a], **Valentina Myriam Anna Sumini** [b], **Marta Rossi** [c]

[a] *School of Architecture, Urban Planning and Construction Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 22, Milano 20133,* magda.borovina@mail.polimi.it
[b] *Department of Architecture, Construction Engineering and Built Environment, Politecnico di Milano, Piazza Leonardo da Vinci 22, Milano 20133,* valentina.sumini@polimi.it
[c] *School of Architecture, Urban Planning and Construction Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 22, Milano 20133,* marta2.rossi@mail.polimi.it

## Abstract

In recent decades, the research in the field of exploration of human habitation in space, particularly on Mars, has intensified due to its proximity, favourable gravitational conditions, and potential water sources. Designing a sustainable habitat on Mars poses challenges, notably protection from the Martian atmosphere and addressing psychological issues associated with living in a different environment. ‘Back to the Cave’ habitat is a dual module symbiotic structure system which aims to be expanded on a modular basis within a man-made cave system in the eastern Noctis Labyrinthus. The aim of the project is establishing a human base on Mars and researching the plausibility of human colonisation of the planet with the habitat specifically focusing on providing facilities for research of food growth, search, and validation of water sources. The initial habitat base will consist of two modules containing the greenhouse and the living/research spaces, conceptually inspired by the division of cells. The modules will operate on a symbiotic relationship exchanging the $CO_2$ and $O_2$ between the living/research and greenhouse modules. The infrastructure of the modules can be expanded on a modular basis creating a system of interdependent habitats. The modules are organised to provide the habitants with workspaces, communal living spaces, private living areas and a greenhouse in order to improve the psychological needs of the habitants. The eastern part of Noctis Labyrinthus has been chosen as a suitable location due to proximity to a relict glacier in order to conduct water research. Another benefit of this location is the valleys (cavus) that spread across the area which would provide a suitable landing site. The cave also provides protection from micrometeoroids and solar radiation. The modules will be thermally insulated from the inside and some internal furnishings will be grown out of mycelium. These methods aim to reduce the amount of transported materials. The project is divided into two missions, aiming to finally bring a selected group of six humans on Mars and eventually preparing the ground for a future colonisation of the planet. The modular structure system and the cave inhabitation system aim to offer sustainable design principles for incremental expansion of human colonisation of Mars.

**Keywords:** symbiotic structures, modular expansion, habitability research, sensible material transport, cave, colonisation of Mars

**Acronyms/Abbreviations**

Galactic Cosmic Rays (GCRs)
Solar Energetic Particles (SEPs)
National Aeronautics and Space Administration (NASA)

## 1. Introduction

For decades humans have been imagining diverse ways to create a base on Mars and expand our influence beyond Planet Earth [1,2,3,4, 5, 6, 7, 8, 9, 10].

‘Back to the Cave’ habitat is a dual- module symbiotic structure system which aims to be expanded on a modular basis within a man-made cave system in the eastern Noctis Labyrinthus. The aim of the project is establishing a human base on Mars and researching the plausibility of human colonisation of Mars with the habitat specifically focusing on providing facilities for research of food growth, search, and validation of water sources.

This project aims to suggest an initial base for human colonisation of Mars and a masterplan for its expansion into a self- sufficient system of ‘cave neighbourhoods.’

The initial base will be used as a test base for further inhabitation for at least 5-10 years after the date of arrival. In case of practical success, it is aimed to last until resources are depleted.

The initial mission will include six people, limiting the design to include their needs specifically. The crew will perform inhabitation and terrain research, meaning that, the modules will include research as well as living facilities.

The proposed structure aims to be modular and lightweight to reduce transport weight, cost and increase reproducibility in case of expansion.

### *1.1 Site- Noctis Labyrinthus*

The Noctis Landing site is located on Mars at 6° 29' 38.3" S, 92° 27' 12.3" W, in a vast 200 km-wide regional depression (see Figure 1, exact coordinates subject to change considering atmospheric conditions upon arrival). The soil in this area is full of minerals (clay, sulphates, hydrated silicas). The area is characterised by recurring fog which can be used as a source of $H_2O$.

Noctis Labyrinthus is a network of deep valleys located at the western edge of Valles Marineris on Mars, with depths of several kilometres and up to 30-kilometer widths. It was shaped by tectonic forces over time and is characterised by its labyrinth-like look [11].

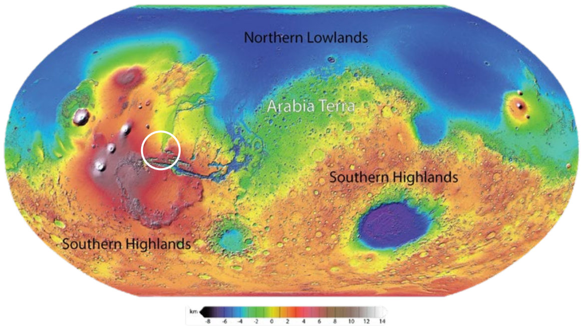


Fig. 1. Location of Site (Source: NASA/JPL/MOLA Science Team)

Evidence of various morphological changes also makes this area suitable for research into history and habitability of Mars.

Similarities between Earth and Mars suggest an easier adaptation for the crew. The gravitational force is around 0.38 G. The temperature varies between -150°C and +30°C. Ultraviolet radiation presents at wavelengths greater than 190 nm. The ionising radiation dose is approximately -90, primarily consisting of Galactic Cosmic Rays (GCRs), Solar Energetic Particles (SEPs), and neutrons. The atmospheric pressure ranges between 0.6 and 1.2 hPa, with the dominant gases being carbon dioxide ($CO_2$), nitrogen ($N_2$), and argon (Ar). Movement of the groundwater from the uplifted Syria Planum into the direction of Noctis Labyrinthus creates a natural system of drainage due to morphological characteristics. Additionally, there have been water bearing minerals found in the depressions in the region. These canyons also create a natural wind obstruction which channel the wind away making it safer during sandstorms and increase protection against solar and cosmic radiation [12, 13].

This makes it a very suitable place to consider for human habitation and colonisation research.

## 2. Project timeline

The mission to inhabit Mars will be divided into two phases, a robotic and a human one, in order to minimise labour, material and transportation cost and to allow for mitigation of any issues before the arrival of humans.

The project for human colonisation of Mars starts with the first robotic mission and is followed by the settlement of humans. Then, begins a period of assessing the initial habitats and all the possibilities for further human colonisation of Mars. It is expected that the initial habitat will be the only habitat for 5 to 10 years due to safety and economical concerns.

The initial mission considers a crew of six people to whom this timeline has been adjusted for the first period. Once the initial habitats are self-sufficient the option of creating more habitats and bringing more humans will be evaluated. The project is expected to last at least a hundred years to evaluate various aspects of human colonisation of Mars. Eventually, it is aimed to create a sustainable relationship between Mars and Earth.

### *2.1 First mission- Robotic*

The aim of the robotic mission is to prepare the site for human inhabitation. This mission will transport materials and robots for the first phase of the settlement. The robotic mission will land in Noctis Labyrinthus. Using an audio and video connection to Earth the location for the first digging site will be confirmed. Following that, excavators will proceed to dig into the Martian soil creating an artificial cave for the first habitants. It is approximated that the preparation of this mission, transport of robots and materials, as well as the process of drilling the cave will last at least 3-4 years.

It would seem easier to use an existing Martian cave, however, due to uncertainty of the terrain, it is deemed safer to initially dig a flat-bottomed man-made cave and to further explore the option of using existing caves for expansion of the habitat after human settlement and initial tests [14, 15].

After the cave has been dug, robots with 3D printing capability will erect the rigid metal structure of the habitats. The rigid structure also includes all structural support for internal elements (floors, stairs) [16].

Following the construction of the module 'skeleton,' an inflatable Kevlar structure will be added to the rigid structure completing the modules. Due to atmospheric conditions, the module structure will be a dome, and the shell structure will protect the modules, allowing for development of separate conditions suitable for humans within the modules [17, 18, 19].

Further inspections by the robotic helpers will be conducted to ensure that the structure is withstanding Martian conditions and that it is safe for human inhabitation.

There will be an expected buffer period of several months before a human mission is considered to be deployed in order to collect feedback on the plausibility of human inhabitation.

It is expected that the cave will also serve as a protector against solar and cosmic radiation, sandstorms, meteors, and any other possible physical atmospheric threats. A sealable door will be added to the cave opening to prevent any issue for the structures.

In addition to setting up the habitat structure, the robots will set up the energy source Kilopower, in hopes to start providing the finished modules with oxygen. The oxygen levels will be evaluated rigorously prior to the arrival of humans.

### *2.2 Second mission- Human*

During the robotic mission everything will be structurally set up for the humans to move in. The buffer period will determine the habitability of the modules following the sealing of the cave against atmospheric conditions.

It is expected that the vehicle with which the humans will arrive would be their initial habitat for the first month, until all the living and research equipment is moved in and set up. This vehicle is also expected to store food for up to 2 years from the initial 'move in date'.

The modules will be prepared to move in any furniture and final fixings as well as the astronaut's personal belongings. The Kilopower [20,21] will initially provide energy to power breathable air system in the modules until the symbiotic relationship between living spaces and the greenhouse can be established. The Kilopower will also provide electricity for running water, light, and heating systems.

Once this relationship is established the mission to colonise Mars is in full motion.

## 3. Design Process

The design for the Martian habitats relies on several key considerations: modularity and expandability, regulation of atmospheric conditions, energy supply, structural integrity using lightweight and easily transportable materials, use of in-situ resources to minimise transportation costs, establishing food sources and self-sufficient systems and prioritising the wellbeing of the inhabitants.

### *3.1 Environmental Considerations*

The cave and the selected materials will ensure that the big temperature ranges are mitigated, and the interior temperature regulation systems can operate without interference, creating a comfortable thermal environment within the habitats.

Reduced gravity effects will be mitigated with an addition of a curated exercise area in which the inhabitants will be able to train their bodies to adapt to the unfamiliar environment.

Solar and cosmic radiation, sandstorms, meteor showers will be mitigated by placing the habitats inside the caves. Caves and their entrances have been proposed as habitable environments and regions that could have preserved evidence of life, mostly due to their natural shielding from the damaging ionizing and non-ionizing radiation present on the surface [22, 23, 24].

Due to atmospheric pressure the structures will have to be carefully engineered.

Location near possible water resources allows for a solid base for expansion making the modularity of the habitats a priority. Since the habitats are lightweight and use natural in situ resources for many functions, supply for 'Earth materials' can be sustainable, provided that systems supporting basic life functions are self-sustaining.

The canyons allow for placement of Kilopowers outside of the caves with some protection from atmospheric conditions.

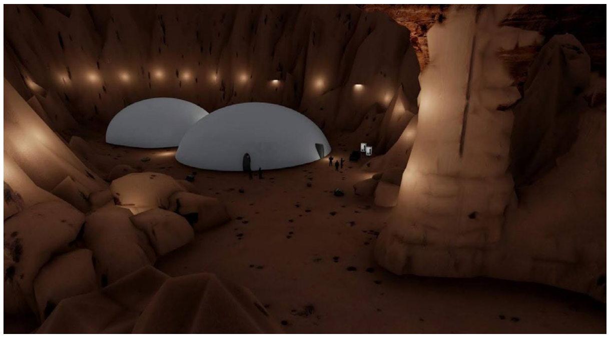


Fig. 2. Inside of the Cave (Source: Anton Ahlstedt)

### *3.2 Human Centric Design*

The physical effects of the environment are somewhat mitigated by safety precautions; however, a bigger threat is posed for the mental well-being of the crew. The fundamental issues are being away from Earth and being in a small space with limited amount of people to interact with and no possibility of going outside [25, 26, 27, 28, 29, 30].

The modules will have a communication system to ensure connection to Earth for safety and wellbeing reasons. The connection is expected to be inevitably delayed due to distance so management of this will be trained in emergency preparations.

The living spaces will feature individual sleeping chambers in order to allow for some privacy.

The greenhouse can be used as a garden to create an illusion of connection to nature in a foreign environment.

### *3.3 Concept Design*

Due to form finding results obtained by Kangaroo the shape of the habitats resembles two bubbles connected to each other. Consequently, inspired by the intrigue of human colonisation of Mars and its implications on human life on Earth, the concept is inspired by the basis for what we consider the creation of life- cell division (see Figure 3). The seemingly simple act of cell division becomes the underlying concept for the development and expansion of the habitats. Firstly, the robotic mission establishes a base for sustaining life and creates the infrastructure. Secondly, the human mission sets in motion the work of an organism consisting of a residential/ working module and greenhouse module. These two modules support the expansion of the habitat, connected by sealed corridors creating a speleological ecosystem of human Martian habitats (see Figure 4).

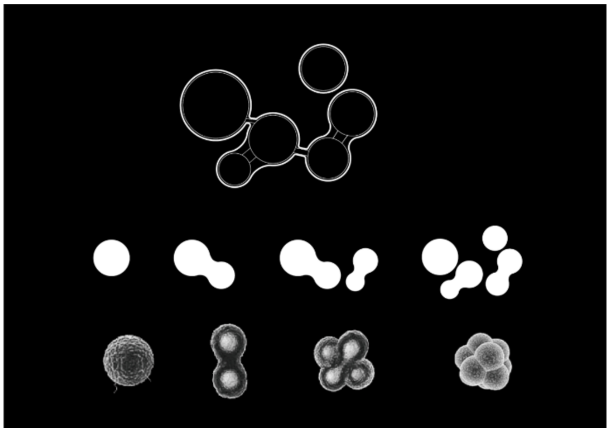


Fig. 3. Cell Division based Concept (Source: Weng Junyan)

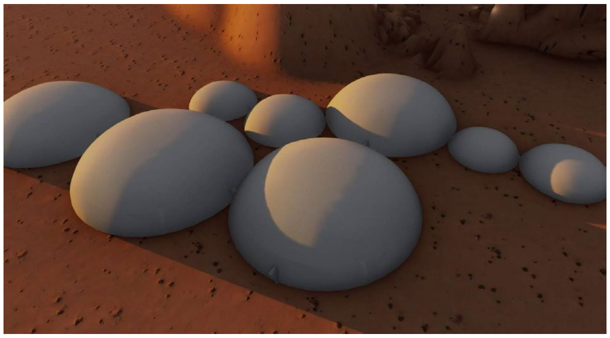


Fig. 4. Location of Site (Source: Weng Junyan)

*3.4 Function Distribution and Interior Layout*

The habitat is divides into two modules which are interconnected functionally (see Figures 5-8).

The first module is the greenhouse (see Figure 9); it consists of two floors filled with vertical food growing spaces and accessible by stairs. This module has two exits and one connecting corridor to the other module. It is also envisioned as a green space where the crew can have a walk when they are not working.

The other module is the living/ working spaces. It consists of three floors. The ground floor contains the kitchen, shower, toilet, lounge space, gym, and a food growth research space. The first floor contains the laboratory for any habitability research. The second floor contains private dormitories for the crew (see Figure 10). This module has three exits to the cave.

Any element of the internal furnishings possible will be grown out of mycelium as to reduce transport costs due to the module's structural trade-offs found through Karamba 3D.

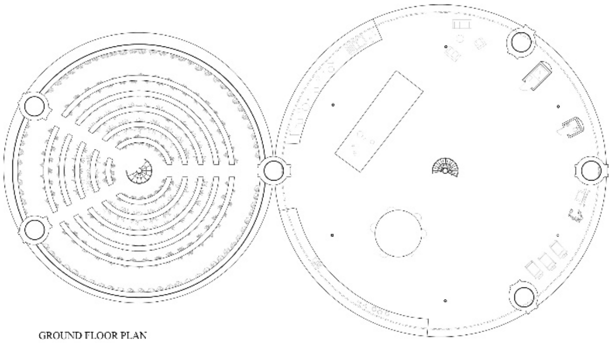


Fig. 5. Interior Layout Ground Floor (Source: Magda Borovina)

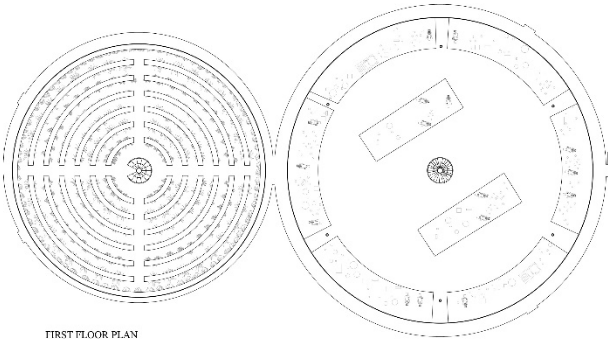


Fig. 6. Interior Layout First Floor (Source: Magda Borovina)

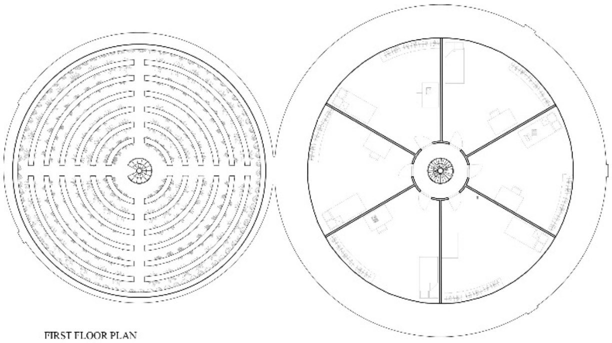


Fig. 7. Interior Layout Second Floor (Source: Magda Borovina)

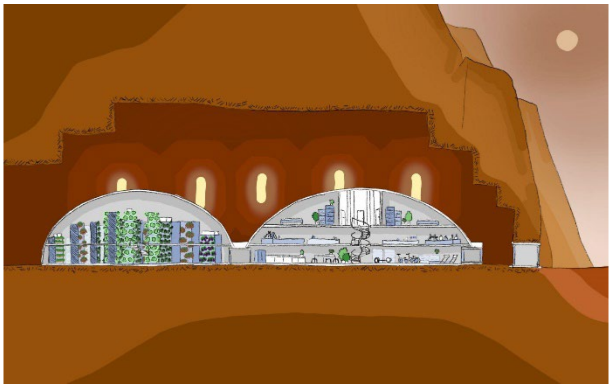


Fig. 8. Illustrated Section (Source: Daniel Nowak)

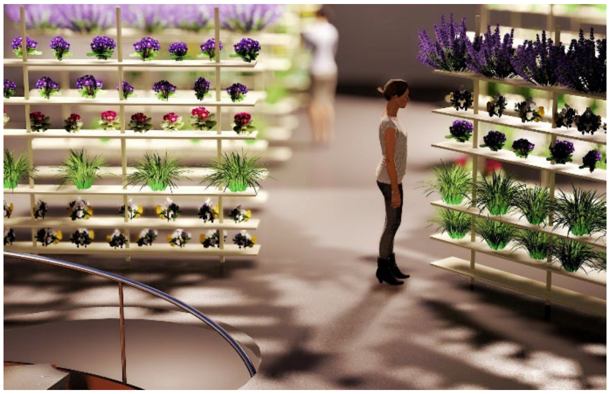


Fig. 9. View Inside the Greenhouse (Source: Anton Ahlstedt)

Fig. 10. Inside the Private Areas (Source: Anton Ahlstedt)

*3.5 Structural considerations*

The atmospheric pressure is one of the first considered conditions because it dictates the shape of the structure. The shape is domed due to its strength, stability, efficient use of lightweight materials, ease of assembly, energy, and functional efficiency.

Other structural considerations include structural integrity of the habitats; however, these parameters are simplified due to the use of the caves for many atmospheric considerations. Inside of the cave it is important that the habitats are big enough to support the crew, structurally stable, and easy to build. The structural stability of the habitats will be able to be examined in greater detail during the buffer period between the robotic and human missions. The live load considered are equipment and personal belongings brought during the second mission.

The living spaces will consist of two floors inside a circular domed module, divided into communal and personal living spaces to ensure privacy.

The greenhouse will also consist of two floors containing vertical gardens for food growth. The modules are identical in shape but different in dimensions.

Each module is connected by a sealed corridor which can also be used to connect new modules during the expansion period of the project.

This connection is important for linking the greenhouse and the living modules, since during the 'settling in' period a symbiotic connection between the oxygen produced by the plants and the carbon dioxide produced by humans will be established and will become the base parameter to sustainable life on Mars. An example of this technology can be found in the works developed by NASA [31, 32]. Although this example uses algae, it is assumed that the technology can be adapted to a bigger system. Other energy needs will be supplied by the Kilopower system.

Software used to determine the form of the modules were Rhino, Grasshopper, Kangaroo, Octopus and Weaverbird [33, 34, 35, 36].

The material used for the inflatable shell is Kevlar. supported by a rigid metal structure. The rigid elements will be 3D printed by robots during the first mission. Following that, the inflatable shell will be added and deployed, followed by interior finishes. An insulation layer is also added to further mitigate the temperature differences. Specified materials would require further examination of the habitat structure.

Another addition are the doors of the cave which will protect the habitats from atmospheric conditions and allow exit to the landing site and energy supply.

During the expansion phase, there is the possibility of interconnecting caves and chains of modules working interdependently to sustain themselves, however this would need to be confirmed on site.

*3.6 Resource Utilisation*

The resources brought from Earth are the robots, metal for 3D printers, Kevlar inflatables, interior finishes, and furniture. The Kilopower nuclear energy supply will also be brought from Earth although throughout the project it will be aimed to switch to renewable energy sources such as solar or wind power, turning the Kilopower into a backup energy source.

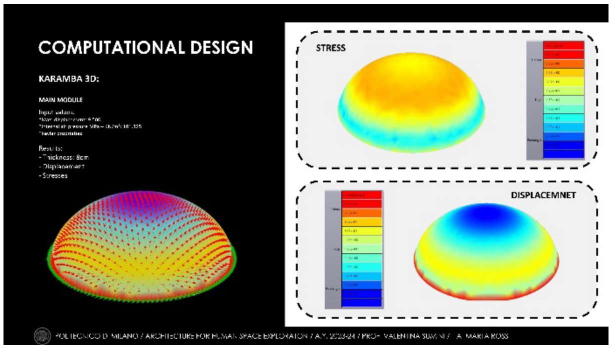
The resources found on Mars are regolith in which the caves will be dug and water from the Syria Planum which will be used for research and hopefully plant growth. The caves allow for use of lightweight materials in the habitats with simple construction methods in order to minimise transportation and material costs as well as increase potential for expansion. Access to water on Mars reduces need for water circulation systems within the modules and therefore reduces energy consumption. The habitats will make use of the morphological advancements of the site and with time establish water collecting tanks which will be used to grow food and supply drinkable water.

Self-sufficient systems of the habitats include the Kilopower which produces up to 1 kilowatt of electricity, but its design can be scaled up to a capacity of about 10 kW [21]. This system will provide power to breathing, electricity, heat, ventilation, irrigation, and transportation systems, although the end goal is to transfer as many of these functions to use renewable energy found on site.

The greenhouse spaces are also used as walkable green spaces by the inhabitants in order to simulate a connection to nature in a foreign environment, to hopefully improve their wellbeing. Additionally, it forms part of the symbiotic structure utilising the oxygen produced by the plants and the carbon dioxide produced by the humans. The plants are also used for food, sustaining human research on Mars.

## 4. Design Development

Through the auxiliary software the habitat form was developed. Firstly, the geometry is modelled using Rhino and Grasshopper aided with Octopus (Multi-objective Optimization tool), Kangaroo (form- finding tool) and Weaverbird (mesh optimization tool) to determine the optimal version of the habitat structure. Parameters used as guides were shape, volume, floor numbers, area, material inputs, atmospheric conditions, displacements, forces, stress, and mesh properties. Form optimization research focused on the main living module adjusting the diameter of its shell, concluding that the inhabitable volume and the total floor will be maximised and area the surface area of the shell will be minimised. The trade-off for this an increase in the material needed to be transported. Structural specifications were also aided by Karamba 3D (see Figure 11).



COMPUTATIONAL DESIGN

KARAMBA 3D:

MAIN MODULE

Input values:

Results:
- Thickness: 8cm
- Displacement
- Stresses

Fig. 11. Karamba 3D Computational Design (Source: Anton Ahlstedt and Natalia Mardegam Morais)

### *4.1 Multi-objective Optimisation*

In order to combine all the desired functions of the habitats observed during the design process, for transportation and cost considerations it is beneficial that the functions of the habitats and their use of space overlap to reduce material related costs. To efficiently distribute the functions a Multi-objective Optimisation diagram is created [38].

The variables considered for this process are size of habitat, layout of interior spaces, materials used in each phase of the project and site location. The parameters considered for this process are radiation, atmospheric pressure, meteor showers, sand and dust storms, microgravity. The shell geometry of the habitat is calculated by considering variables and parameters using a multi-objective optimisation software called Octopus. These are then adapted to human centric design principles regarding wellbeing of the crew. The constraints of the habitat modules are the six-person crew, site located in a robot excavated cave, availability of local materials and an unknown site prior to mission start. Through utilisation of aforementioned software, a form for the habitats was found- circular domed structure. It was chosen due to its ease of construction and lightweight properties. The objectives of the mission are maximising protection against atmospheric conditions, maximising in situ resource utilization, creating self-sufficient energy and food providing systems, maximising human centric design methods to improve crew wellbeing, enabling a secure connection with Earth, minimising transportation costs and transported material mass. The Pareto Filter applied includes minimising material needed for atmospheric protection by using the robotically excavated cave, therefore maximising utilization of in situ resources and minimising the transportation costs and material mass. Interaction between habitat modules ensures establishment of self-sufficient energy and food resources and maximizing design for human wellbeing. The solution set indicates a two-mission resolution with focus on sustainability and mental wellbeing.

### *4.2 Expansion Masterplan*

Figures 12 and 13 visualise a version of the expanded base consisting of a landing site, Kilopower 'field', waste field and separate cave entrances marking distinct phases of the project. If logistically allowed, the caves could have passageways connecting all the phases together into an internal circulation system. With time, some natural caves could also be used.

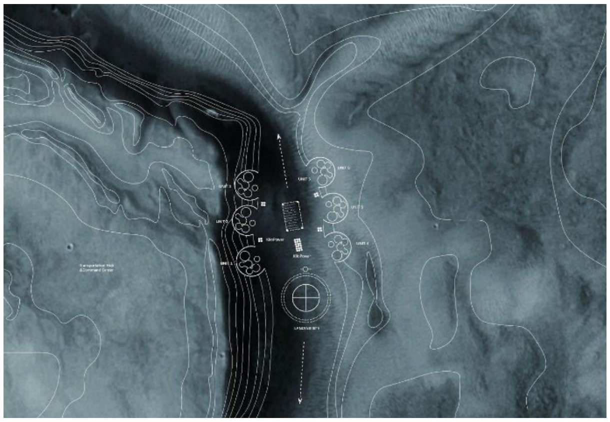


Fig. 12. Site Masterplan (Source: Weng Junyan)

Fig. 13. Human Base (Source: Weng Junyan)

## 5. Conclusion

This project aimed to illustrate possible human settlement on Mars and an establishment of bases for further human colonisation of Mars.

The cave solution proposes a habitat design which minimises transport cost and material mass, significantly maximising in situ resource utilisation and efforts to optimise self-sufficient systems for sustaining life. The design reflects greatly on crew wellbeing to ensure smooth project execution and possible expansion.

This solution aims to inspire future Martian habitat designs. The project's feasibility, however, will need to be reevaluated to determine definite steps and costs.

## Acknowledgements

Many thanks to Anton Ahlstedt, Weng Junyan, Natalia Mardegam Morais, Daniel Nowak and Mario Panayotov for initial development of the 'Back to the Cave' project.

Special thanks to Professor Valentina Sumini and Marta Rossi for their guidance and patience during the development of the project during the 'Architecture for Human Space Exploration' course, held in A.Y. 2023/2024 at Politecnico di Milano, as well as support during the writing of the manuscript.

## References

[1] Department of Architecture, College of Engineering & Architecture, Prairie View A&M University, Mars Habitat, Texas, USA, 1900-1

[2] Fosters & Partners, Mars Habitat, 2015, https://www.fosterandpartners.com/projects/mars-habitat (Accessed: 19.01.2024)

[3] Zaha Hadid Architects, mars colonization, 2013, https://zaarchitects.com/en/other/103-mars-colonization.html (Accessed: 19.01.2024)

[4] Space Factory, Marsha, 2019, https://spacefactory.ai/marsha (Accessed: 19.01.2024)

[5] Bjarke Ingels Architects, Mars Science City, 2017, https://big.dk/projects/mars-science-city-6213 (Accessed: 19.01.2024)

[6] SEArch+ & CloudAO & NASA Langley Research Centre, Mars Ice Home, 2016, https://www.spacexarch.com/mars-ice-home (Accessed: 19.01.2024)

[7] SEArch+ & CloudAO, Mars Ice Home, 2015, https://www.marsicehouse.com/habitat (Accessed: 19.01.2024)

[8] SEArch+ & Apis Cor, Mars X-House V1, 2018, https://www.spacexarch.com/marsxhousev1 (Accessed: 19.01.2024)

[9] SEArch+ & Apis Cor, Mars X-House V2, 2019, https://www.spacexarch.com/mars-xhouse-v2 (Accessed: 19.01.2024)

[10] Politecnico di Milano & MIT Senseable City Lab: MIT Webinar Series Fall 2023; Melodie Yashar, Mars House V1&2, 06.10.2023.

[11] Thollot, P., N. Mangold, V. Ansan, S. Le Mouélic, R. E. Milliken, J. L. Bishop, C. M. Weitz, L. H. Roach, J. F. Mustard, and S. L. Murchie (2012), Most Mars minerals in a nutshell: Various alteration phases formed in a single environment in Noctis Labyrinthus, *J.*

*Geophys. Res.*, 117, E00J06, doi:10.1029/2011JE004028.

[12] Forget, F.; Millour, E.; Lebonnois, S.; Montabone, L.; Dassas, K.; Lewis, S.R.; Read, P.L.; López-Valverde, M.A.; González-Galindo, F.; Montmessin, F.; Lefèvre, F.; Desjean, M-C. and Huot, J-P. (2006). The new Mars climate database. In: Second workshop on Mars atmosphere modelling and observations, 27 Feb - 3 Mar 2006, Granada, Spain.

[13] Politecnico di Milano & MIT Senseable City Lab: MIT Webinar Series Fall 2023; Valentina Sumini, Environmental Conditions on Mars, 06.10.2023.

[14] ACCESS Mars1, A. Al Husseini, J. Apeldoorn, et al., The Role of Caves and Other Subsurface in the Future Exploration of Mars, IAC-09-A5.1.4, International Astronautical Congress, Daejeon, South Korea, October 2009

[15] Anderson P. S., Exploring Mars Caves, Leaving Breadcrumbs, 10th March 2023, https://earthsky.org/space/exploring-mars-caves-robots-hansel-and-gretel/ (Accessed: 19.01.2024)

[16] Politecnico di Milano & MIT Senseable City Lab: MIT Webinar Series Fall 2023; Allessandro Zomparelli, Computational Design Advanced Concepts, 13.10.2023.

[17] Politecnico di Milano & MIT Senseable City Lab: MIT Webinar Series Fall 2023; Valentina Sumini, Form Finding and Structural Optimization, 06.10.2023.

[18] S. Häuplik-Meusburger and O. Bannova, Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth.: Springer International Publishing, Cham, 2016. DOI: 10.1007/978-3-319-19279-6.

[19] Politecnico di Milano & MIT Senseable City Lab: MIT Webinar Series Fall 2023; Roberto Naboni, Digital Form Finding, 27.10.2023.

[20] Mohon L. (NASA), Kilopower, 12th December 2017, https://www.nasa.gov/directorates/stmd/tech-demo-missions-program/kilopower-hmqzw/ (Accessed: 19.01.2024)

[21] NASA, Demonstration Proves Nuclear Fission System Can Provide Space Exploration Power, 2nd May 2018, https://www.nasa.gov/news-release/demonstration-proves-nuclear-fission-system-can-provide-space-exploration-power/ (Accessed: 19.01.2024)

[22] D. Viúdez-Moreiras, The ultraviolet radiation environment and shielding in pit craters and cave skylights on Mars, Icarus, Volume 370, 2021, 114658, ISSN 0019-1035, https://doi.org/10.1016/j.icarus.2021.114658. (https://www.sciencedirect.com/science/article/pii/S0019103521003171)

[23] Politecnico di Milano & MIT Senseable City Lab: MIT Webinar Series Fall 2023; Marco Sumini, Radiation Shielding Strategy: Nuclear Topics in Space, 03.11.2023.

[24] Politecnico di Milano & MIT Senseable City Lab: MIT Webinar Series Fall 2023; Lorenzo Isolan, Radiation Protection Strategy: Radiation Protection Exercises, 03.11.2023.

[25] Gushin V, Ryumin O, Karpova O, Rozanov I, Shved D, Yusupova A. Prospects for Psychological Support in Interplanetary Expeditions. Front Physiol. 2021 Nov 3;12:750414. DOI: 10.3389/fphys.2021.750414. PMID: 34803734; PMCID: PMC8597023.

[26] Connors M., Harrison A., Akins F.R., NASA, prepared at Ames Research Center, NASA SP-483, Living Aloft Human requirements for Extended Spaceflight, 1 January 1985, https://ntrs.nasa.gov/citations/19850024459 (Accessed: 19.01.2024)

[27] NASA, Human Integration Design Handbook, 3rd revision, National Aeronautics and Space Administration, Washington, DC, 2022

[28] Sandra Häuplik-Meusburger, Sheryl Bishop, Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space, Springer Nature, Switzerland, 2021

[29] The Millenium Charter. "Fundamental Principles of Space Architecture." AIAA DETC Aerospace Architecture Subcommittee Space Architecture Workshop. 2002

[30] NASA STD-3001: NASA Spaceflight Human System Standard; Volume Human Factors, Habitability, and Environmental Health: 8 April

2022 https://www.nasa.gov/hhp/standards (Accessed: 19.01.2024)

[31] Granath B. (NASA), Lunar, Martian Greenhouses Designed to Mimic Those on Earth, 24th April 2017, https://www.nasa.gov/science-research/lunar-martian-greenhouses-designed-to-mimic-those-on-earth/ (Accessed: 19.01.2024)

[32] Politecnico di Milano & MIT Senseable City Lab: MIT Webinar Series Fall 2023; Conrad Zeidler, Greenhouses in Space, 17.11.2023.

[33] Politecnico di Milano & MIT Senseable City Lab: MIT Webinar Series Fall 2023; Guillermo Trotti, Space Architecture & Computational Design, 29.09.2023.

[34] Grasshopper, Algorithmic Modelling for Rhino, https://www.grasshopper3d.com/ (Accessed: 19.01.2024)

[35] Vier R., Octopus Plugin https://www.grasshopper3d.com/group/octopus?overrid eMobileRedirect=1 (Accessed: 19.01.2024)

[36] Kangaroo3D, http://kangaroo3d.com/ (Accessed: 19.01.2024)Weaverbird, https://www.grasshopper3d.com/group/weaverbird

[37] Politecnico di Milano & MIT Senseable City Lab: MIT Webinar Series Fall 2023; Valentina Sumini, Multi- objective Optimization, 13.10.2023.