Martian Vorovoid

MSc 2 2025
Group C3
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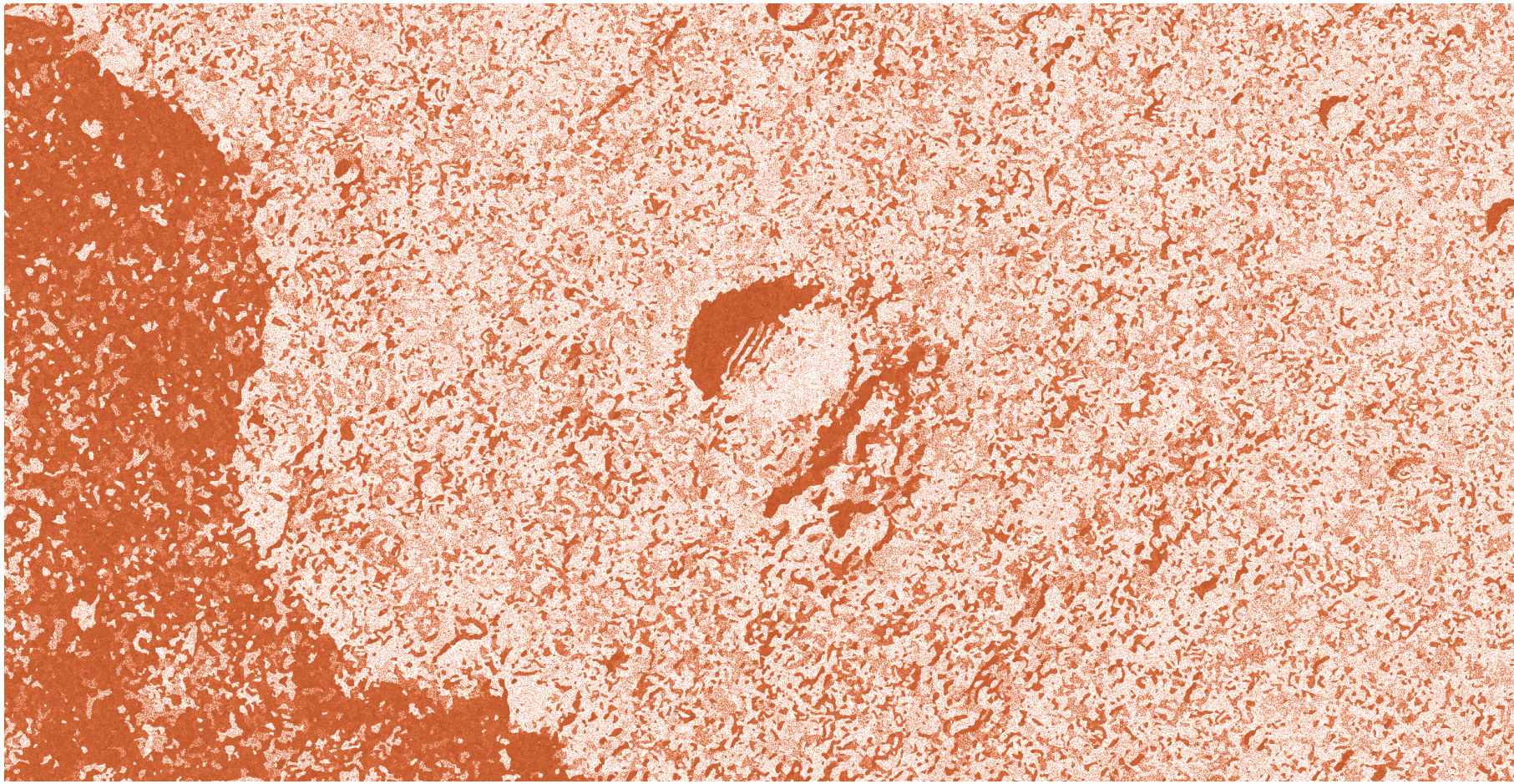
Conditions on Mars

Tabel of Contents

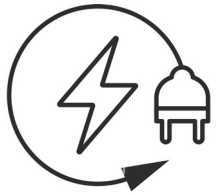


Site on Mars

Considerations & Opportunities

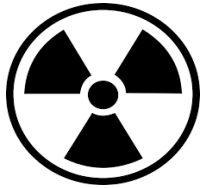
Geological Features

- Lava tubes offer a structurally stable environment, minimizing radiation exposure and thermal fluctuations.
- The presence of basalt-rich regolith can be leveraged for In-Situ Resource Utilization (ISRU) in construction.



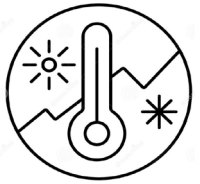
Energy Potential

- The combination of wind and solar power can be optimized to sustain the habitat.
- Subsurface placement within lava tubes can reduce energy needs for thermal regulation.



Protection from Radiation

- Martian surface is exposed to cosmic and solar radiation, but lava tubes provide natural shielding, reducing exposure risks for inhabitants.



Temperature Stability

- The underground environment within lava tubes helps mitigate extreme temperature fluctuations, which range from -125°C at night to 20°C in the daytime.

Site on Mars

Analysis

STRENGTHS

- Lava tubes offer a structurally stable environment, minimizing radiation exposure and thermal fluctuations.
- The presence of basalt-rich regolith can be leveraged for In-Situ Resource Utilization (ISRU) in construction.

WEAKNESSES

- Accessibility challenges related to lava tube entry and exit points.
- Limited direct solar energy due to terrain obstructions.

OPPORTUNITIES

- Development of hybrid energy solutions combining wind, solar, and nuclear options.
- Advancements in robotic excavation and 3D printing could enhance habitat scalability.

THREATS

- Unpredictable Martian dust storms could affect energy generation.
- Structural uncertainties of lava tubes requiring in-depth geotechnical analysis.

Site on Mars

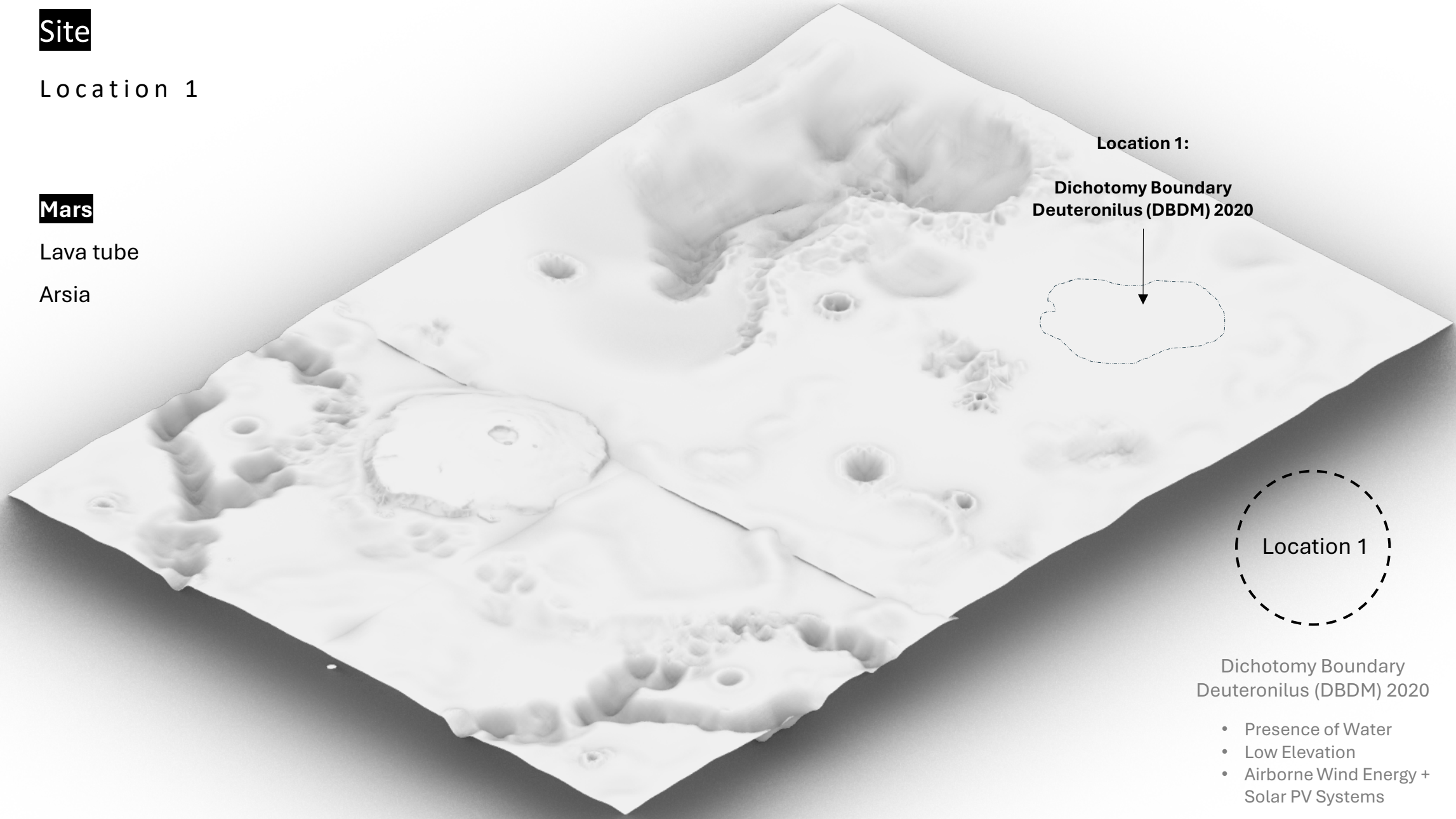
Site

Location 1

Mars

Lava tube

Arsia



Dichotomy Boundary
Deuteronilus (DBDM) 2020

- Presence of Water
- Low Elevation
- Airborne Wind Energy + Solar PV Systems

Reference: Development of an Autarkic Design-to-Robotic-Production and - Operation System for Building Off-Earth Habitats, Rhizome, TU Delft, ESA - D8_Location.pdf - Google Drive

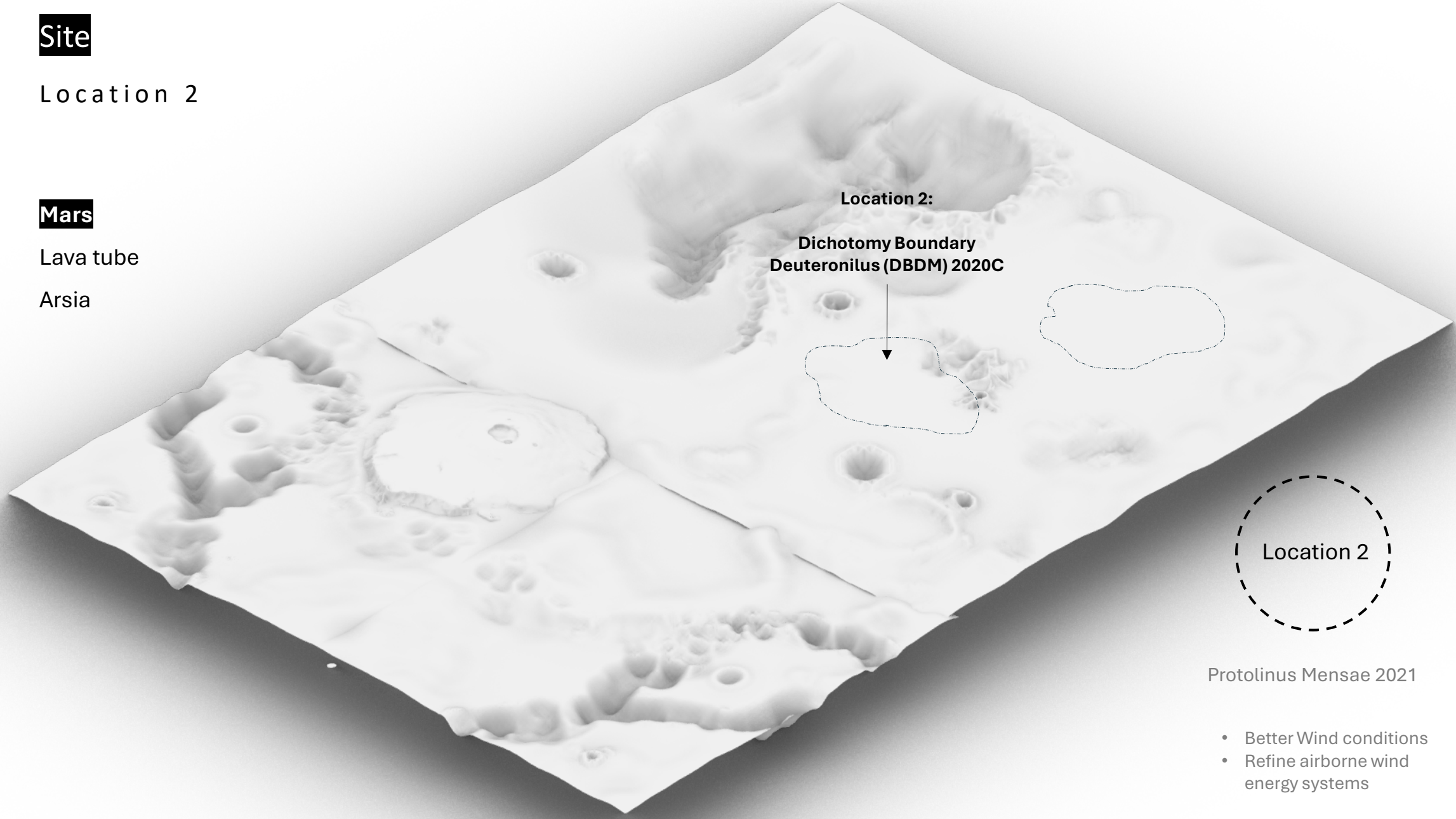
Site

Location 2

Mars

Lava tube

Arsia



Protolinus Mensae 2021

- Better Wind conditions
- Refine airborne wind energy systems

Reference: Development of an Autarkic Design-to-Robotic-Production and - Operation System for Building Off-Earth Habitats, Rhizome, TU Delft, ESA - D8_Location.pdf - Google Drive

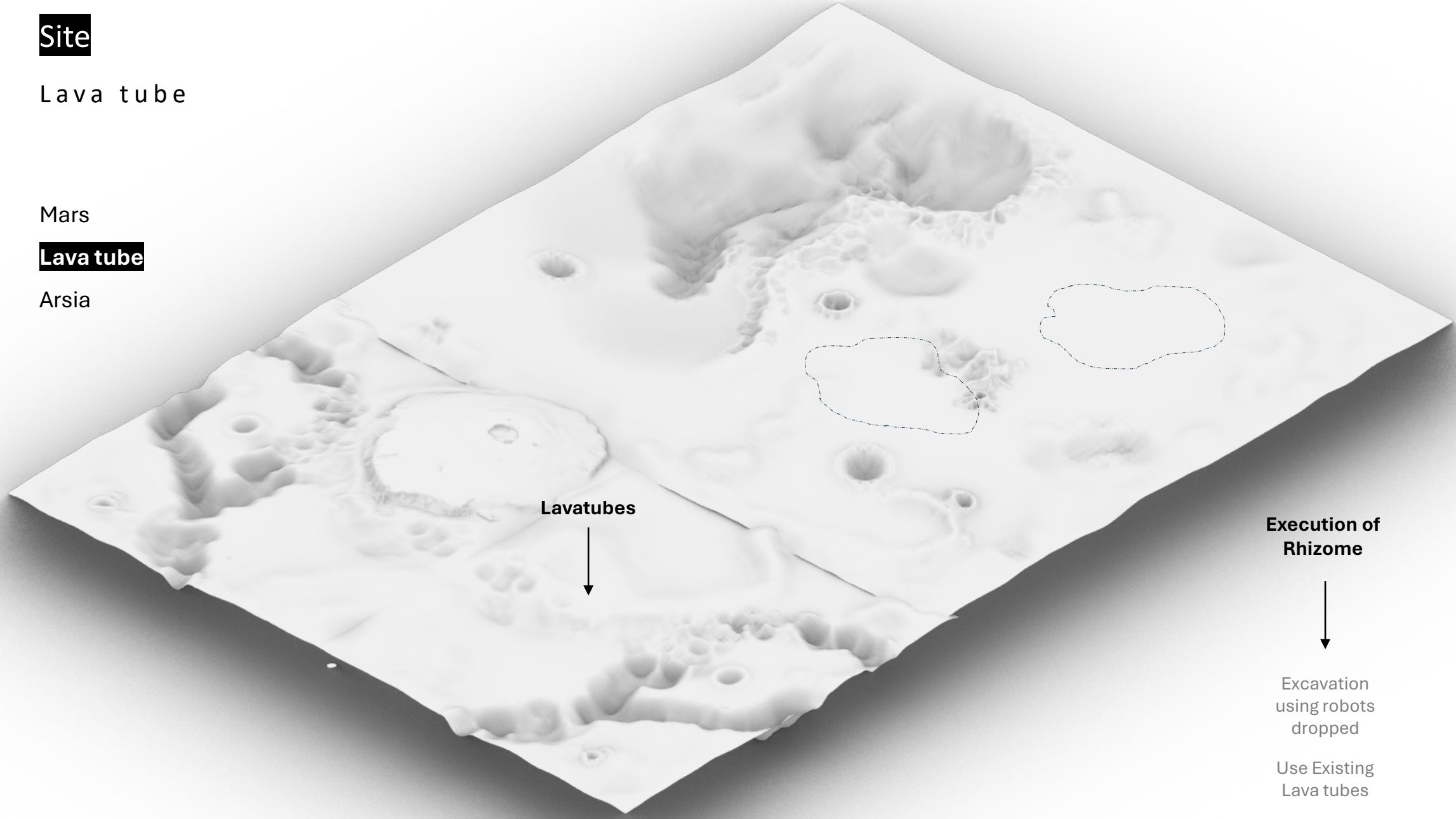
Site

Lava tube

Mars

Lava tube

Arsia



Execution of Rhizome

Excavation using robots dropped

Use Existing Lava tubes

Reference: Development of an Autarkic Design-to-Robotic-Production and - Operation System for Building Off-Earth Habitats, Rhizome, TU Delft, ESA - D8_Location.pdf - Google Drive

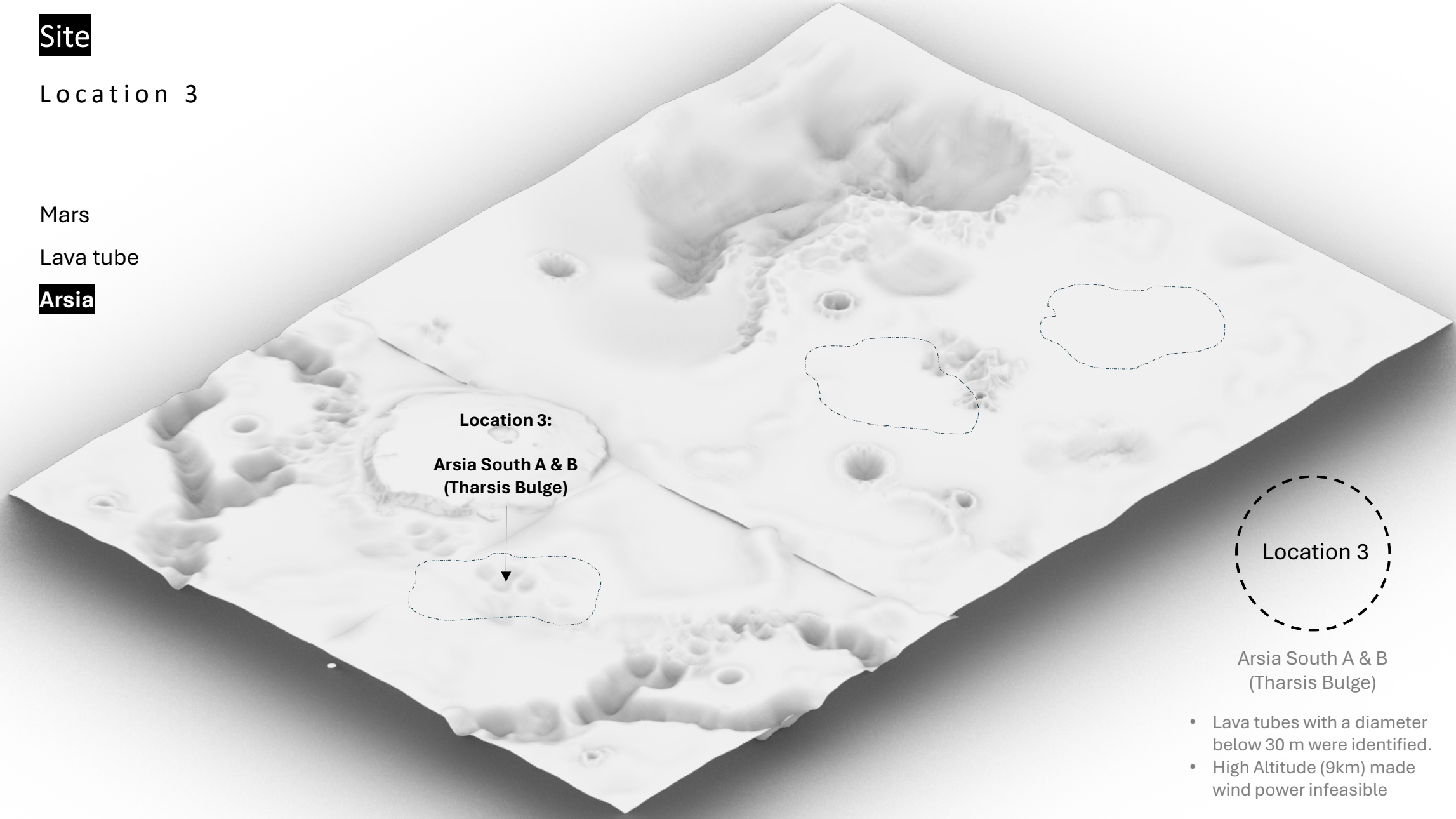
Site

Location 3

Mars

Lava tube

Arsia



Location 3

Arsia South A & B
(Tharsis Bulge)

- Lava tubes with a diameter below 30 m were identified.
- High Altitude (9km) made wind power infeasible

Reference: Development of an Autarkic Design-to-Robotic-Production and - Operation System for Building Off-Earth Habitats, Rhizome, TU Delft, ESA - D8_Location.pdf - Google Drive

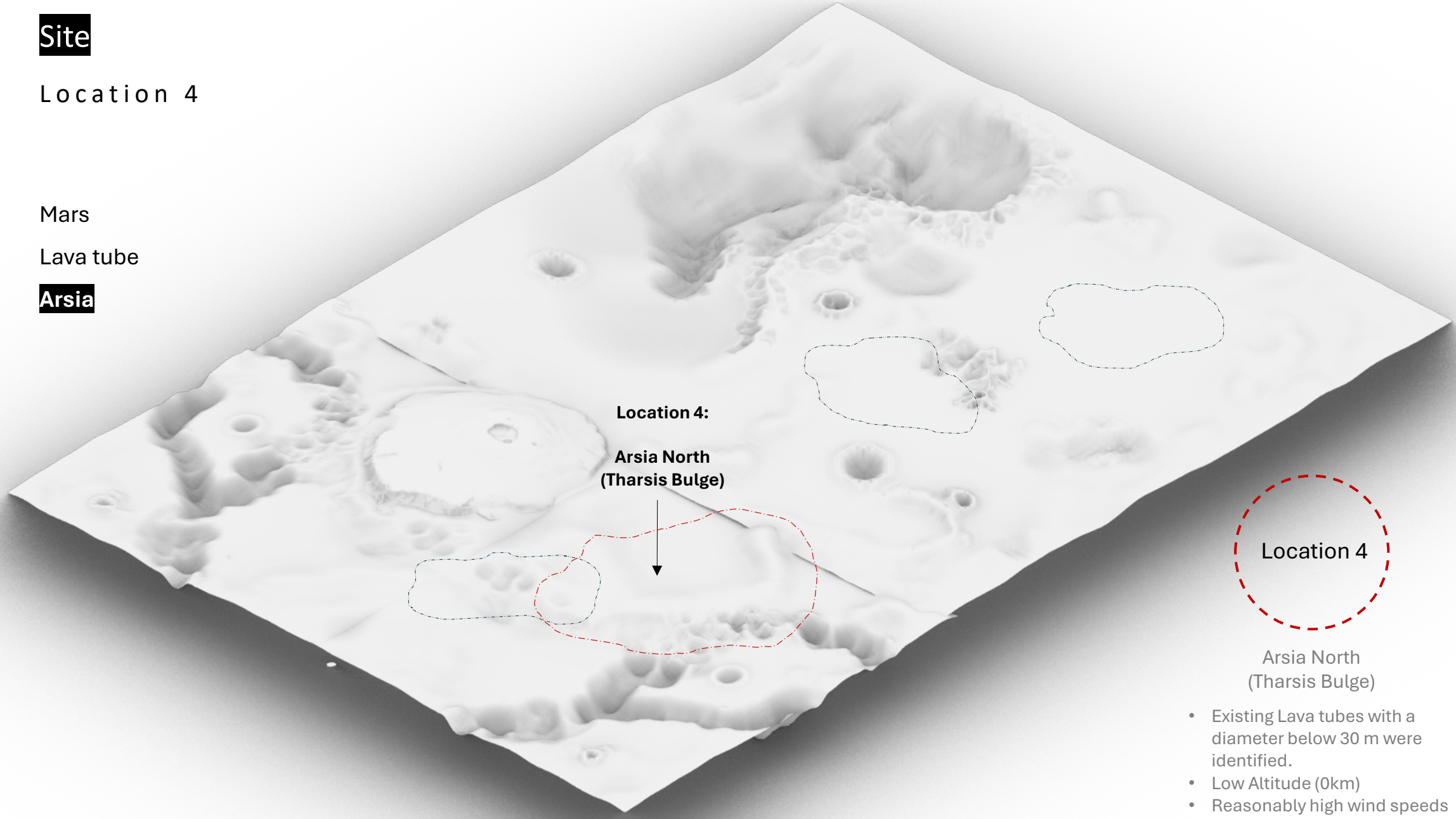
Site

Location 4

Mars

Lava tube

Arsia



Location 4

Arsia North
(Tharsis Bulge)

- Existing Lava tubes with a diameter below 30 m were identified.
- Low Altitude (0km)
- Reasonably high wind speeds

Reference: Development of an Autarkic Design-to-Robotic-Production and - Operation System for Building Off-Earth Habitats, Rhizome, TU Delft, ESA - D8_Location.pdf - Google Drive

Site selection

The final habitat location was identified as Arsia North, a region of the Tharsis bulge. This selection was based on several key factors:

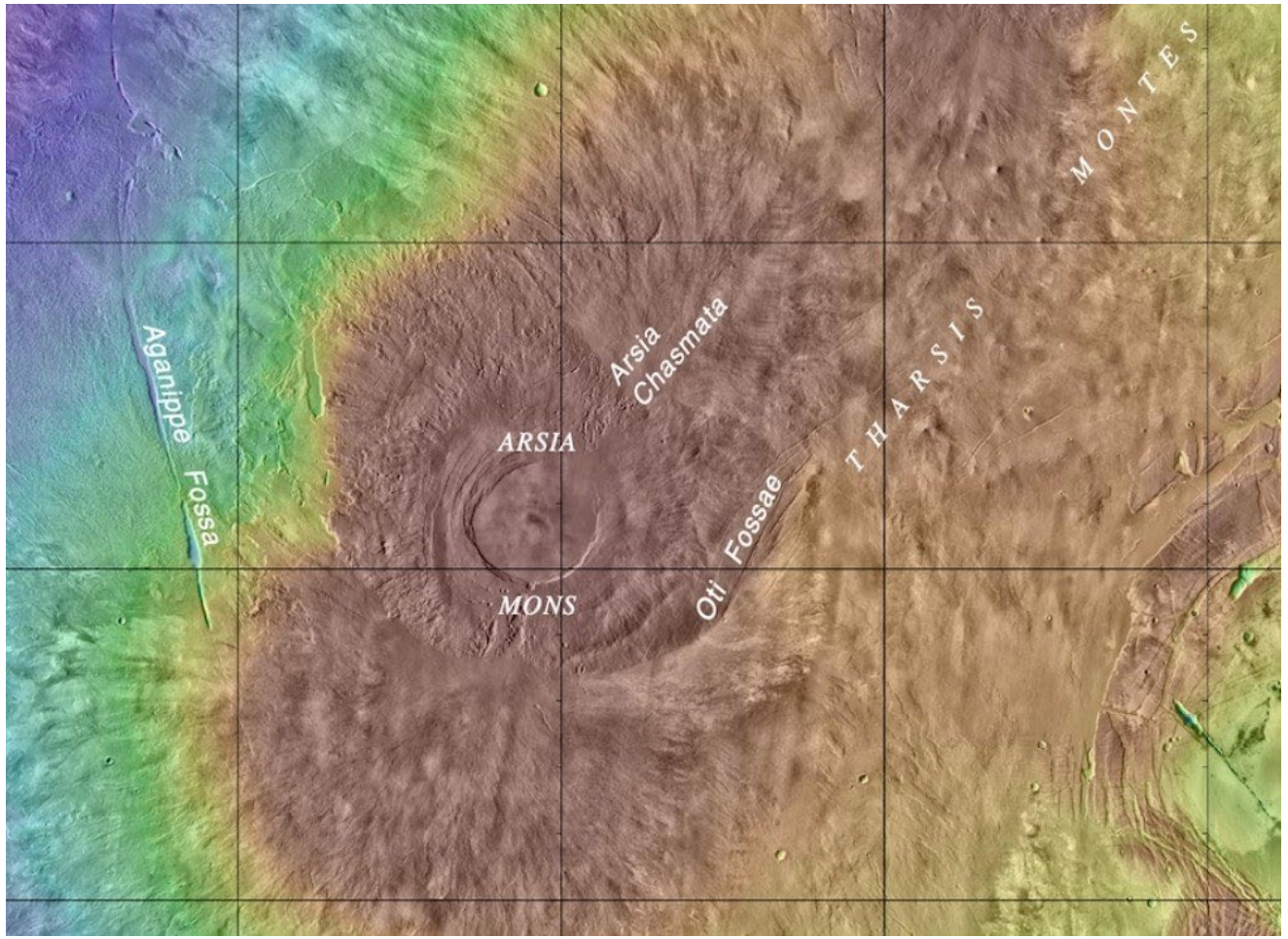
+ Presence of Lava Tubes

+ Low Altitude (around 0 km)

+ Favorable Wind Conditions

+ Stable Geological Conditions

+ Lava tubes minimize radiation exposure and thermal fluctuations



Reference Image: The Arsia Mons expedition | VolcanoCafe

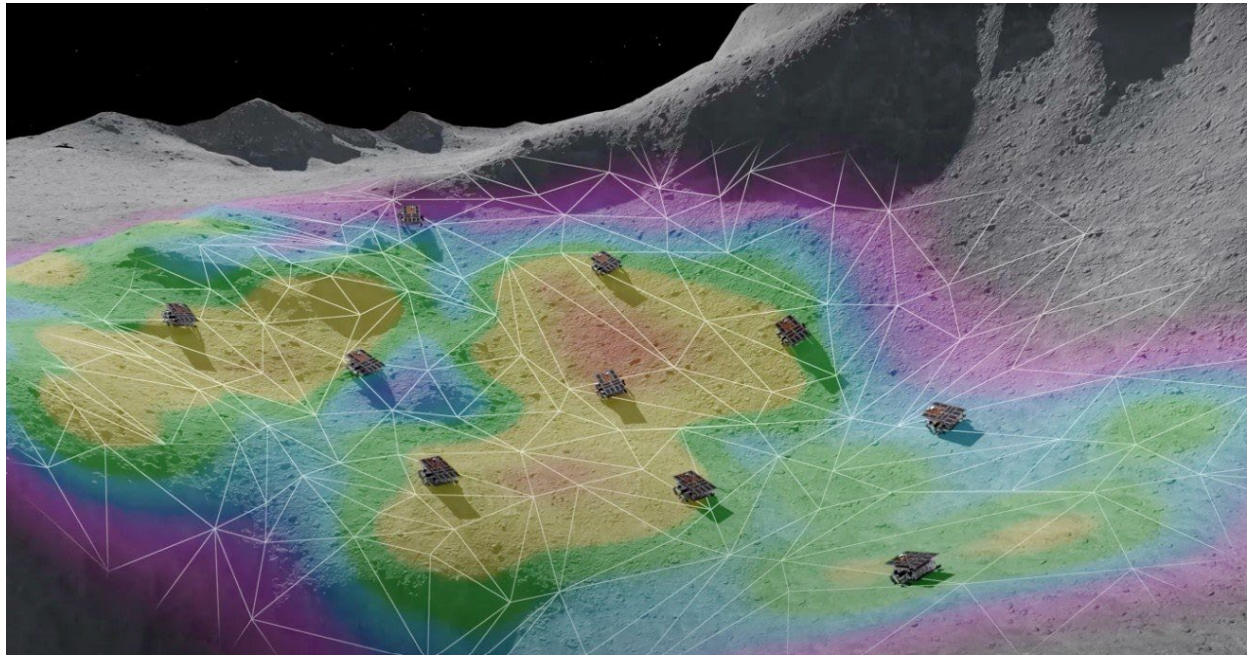
Reference: Development of an Autarkic Design-to-Robotic-Production and - Operation System for Building Off-Earth Habitats, Rhizome, TU Delft, ESA - D8_Location.pdf - Google Drive

Case Studies

Previous projects analysis

Moonshot

Rhizome (1) & (2)



Mooonshot & Moonshot+: Lunar Architecture and Infrastructure

Develop **critical infrastructure** for **lunar colonization**, supporting the long-term sustainability of human presence on the Moon.

Challenges:

- **Environmental Extremes**: Designing habitats that can withstand **extreme temperature fluctuations**, **radiation**, and **micrometeorite impacts**.
- **Material Constraints**: Using **local materials** (lunar regolith) while addressing issues like **strength, durability**, and **ease of 3D printing** for construction.
- **Autonomy and Scalability**: Ensuring **robots** can operate independently and build structures on a large scale without constant human oversight.

Learnings:

- **Autonomous Construction Technologies**: Proving the viability of **robot-based construction** and its potential to reduce reliance on human labor in dangerous environments.
- **Material Innovation**: Overcoming the challenges of working with lunar materials (e.g., regolith) for practical construction.

Reference: Moonshot - cpa

Previous projects analysis

Moonshot

Rhizome (1) & (2)

Rhizome 1 & 2: Autonomous Subsurface Habitat Construction

Develop a **3D-printed Martian habitat** in lava tubes using **In-Situ Resource Utilization (ISRU)** and autonomous robotic construction.

Challenges:

- **Scalability:** Can the method work at real-life construction scales?
- **Autonomous construction:** Coordinating swarm robots for mining, 3D printing, and assembly.
- **Material properties:** Ensuring cementless regolith concrete is durable in Mars' extreme conditions.

Learnings:

- **R/HRI-supported robotic workflows** are crucial for off-Earth construction.
- **Lava tubes offer natural protection**, but adaptability in habitat design is essential.
- **Energy self-sufficiency & closed-loop life support** are key to long-term survival.

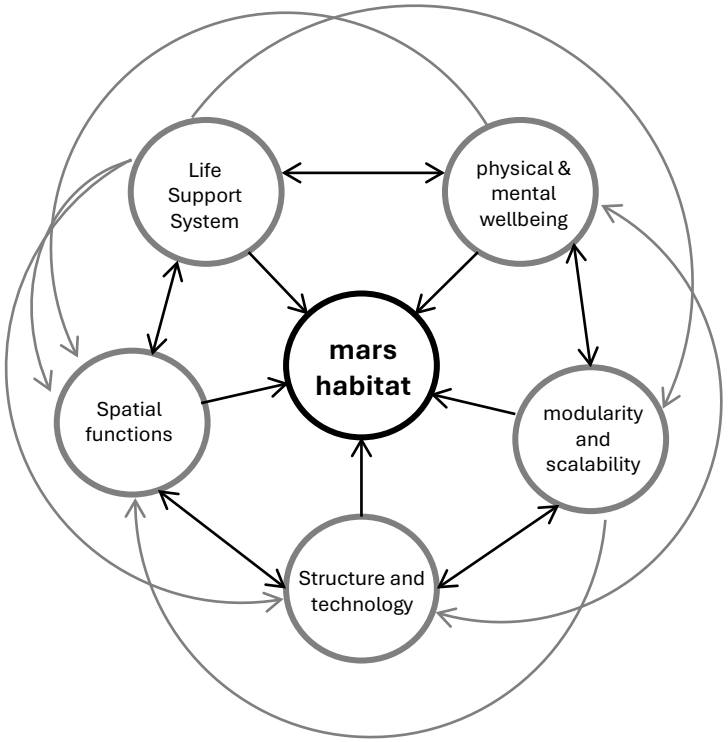
Reference: Rhizome 2.0: Scaling-up of Rhizome 1.0 – Robotic Building (RB)

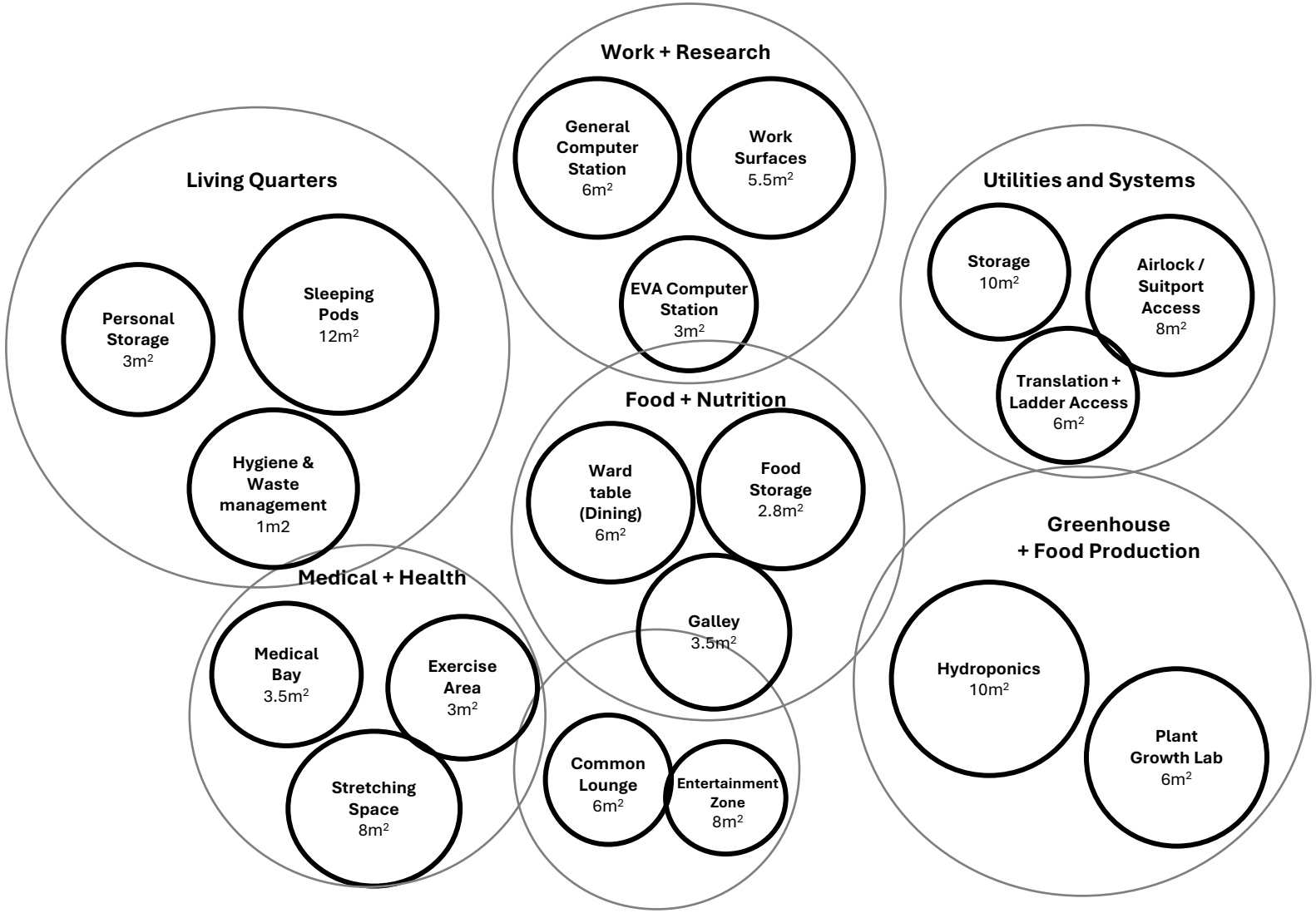
Concept

Design Concepts

Stage 1 – spatial relations

Stage 2 – form and function





Design Concepts

Stage 1 – spatial relations

Stage 2 – form and function

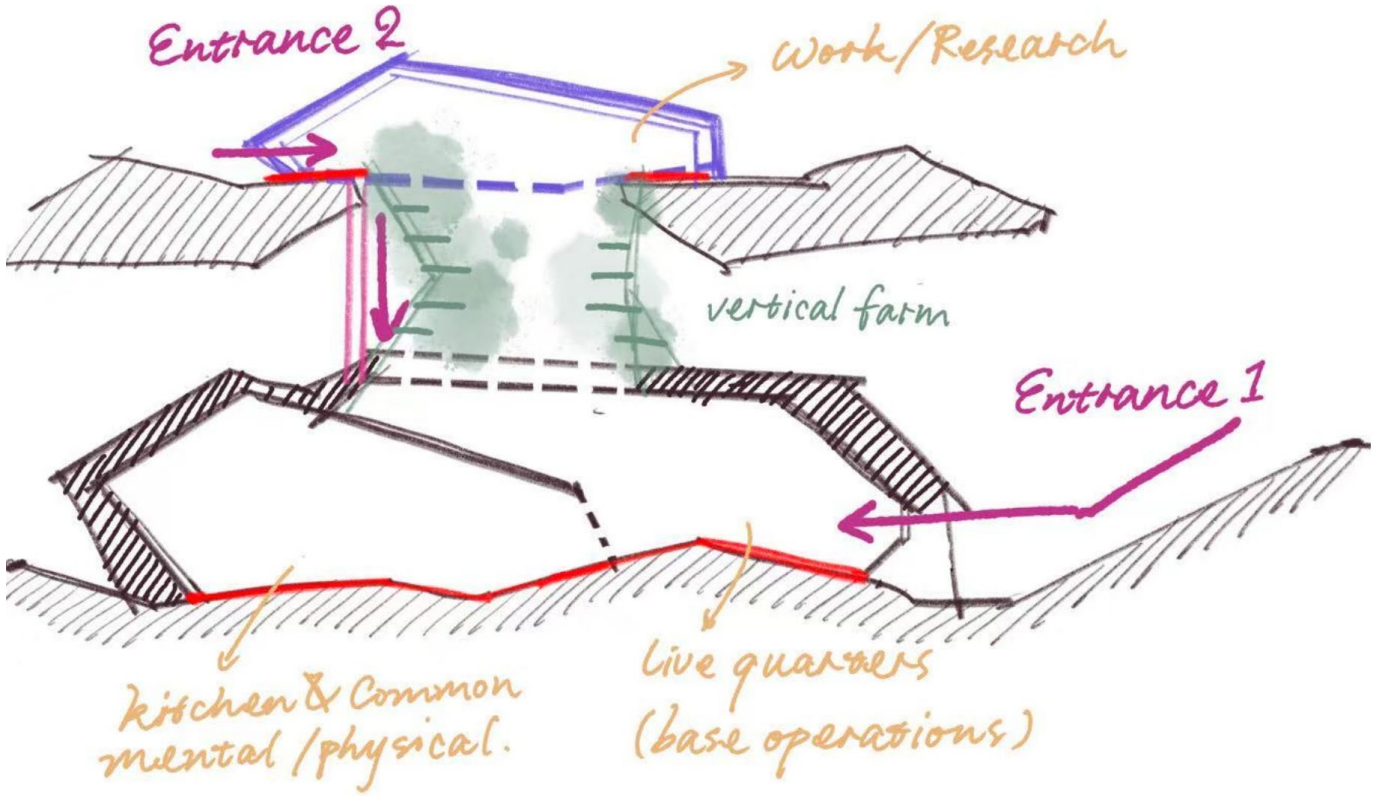
Variants 01

Pros:

- Equipped with Surface laboratory, mechanical equipment warehouse and surface entrance;
- Providing dual-layer protection for underground living spaces;
- Guaranteeing double entrances, one from the planet surface and one through the lava tube.

Cons:

- Difficult to shape
- Difficult to combine the horizontal mobility with the vertical one
- High material consumption caused by the previous aspects



Design Concepts

Stage 1 – spatial relations

Stage 2 – form and function

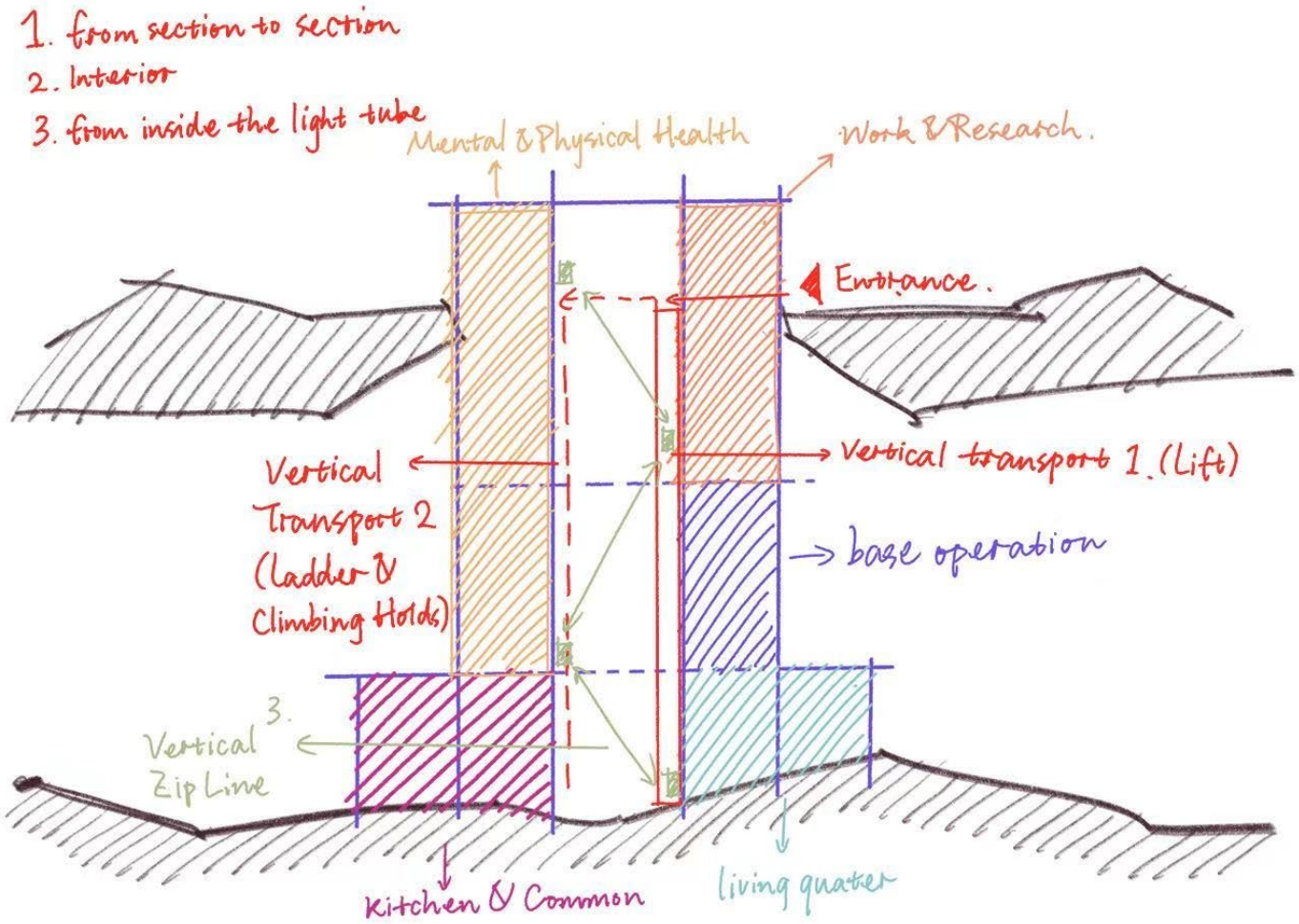
Variant 02

Pros:

- Equipped with Surface laboratory, mechanical equipment warehouse and surface entrance;
- Providing dual-layer protection for underground living spaces;
- Guaranteeing double entrances, one from the planet surface and one through the lava tube;
- Continuous and centralized vertical distribution;
- Enabling the penetration of natural light and its diffusion to the lower levels through the central void

Cons:

- LSS must follow vertical distribution



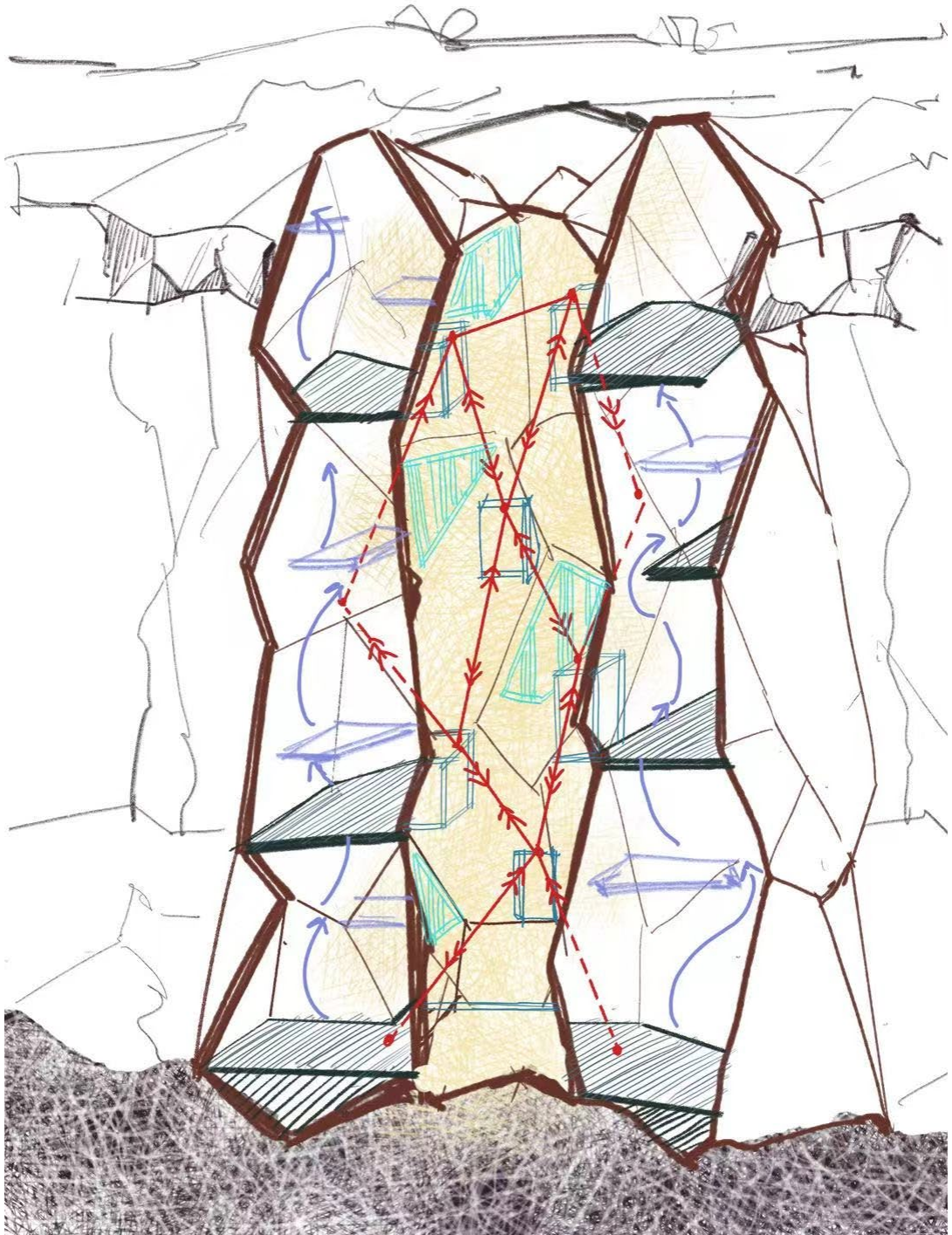
Design development

Design Development

Concept Recap

Conceptual Sketch

Voronoi Structure Development

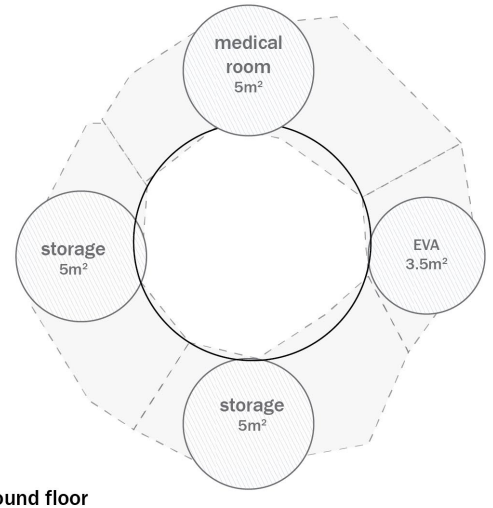


Design Development

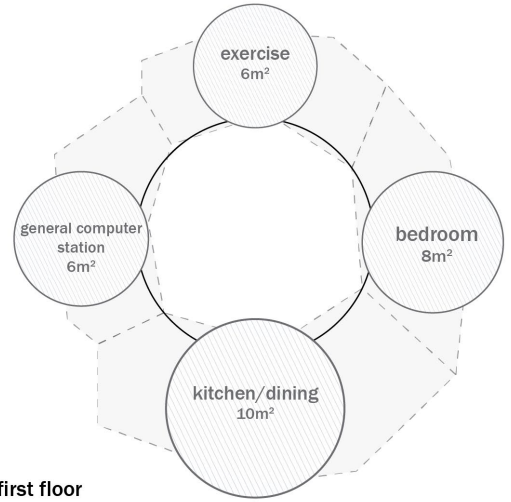
Concept Recap

Conceptual Sketch

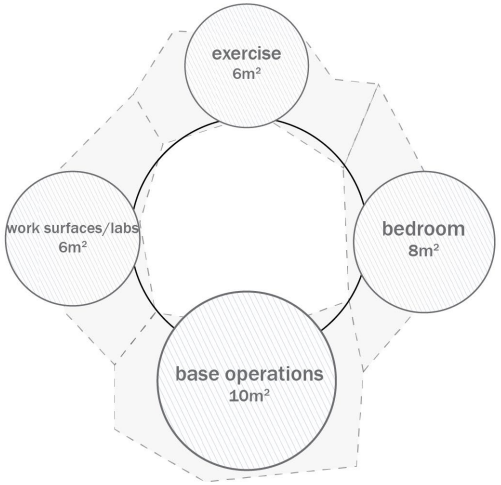
Voronoi Structure Development



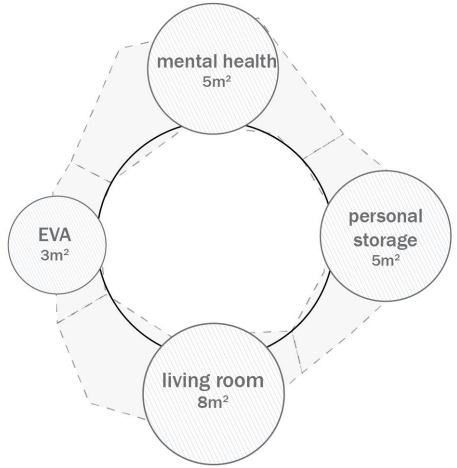
ground floor



first floor



second floor



third floor

Floor plan concept

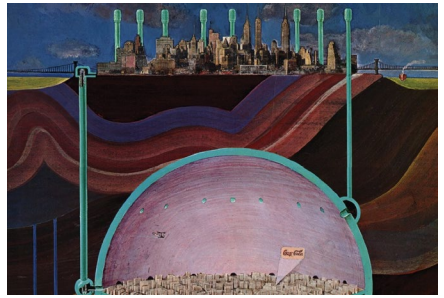
Design Development

Concept Recap

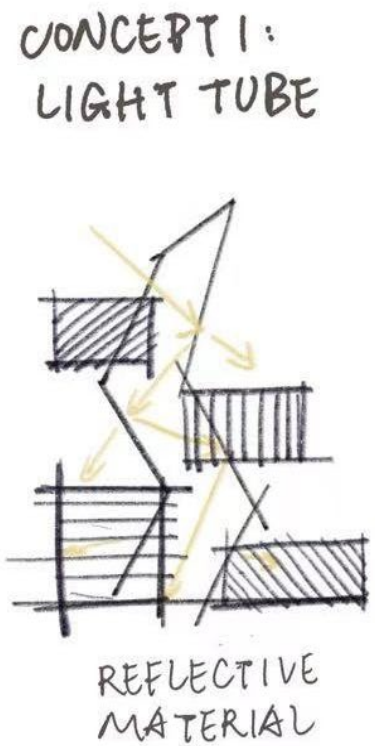
Conceptual Sketch

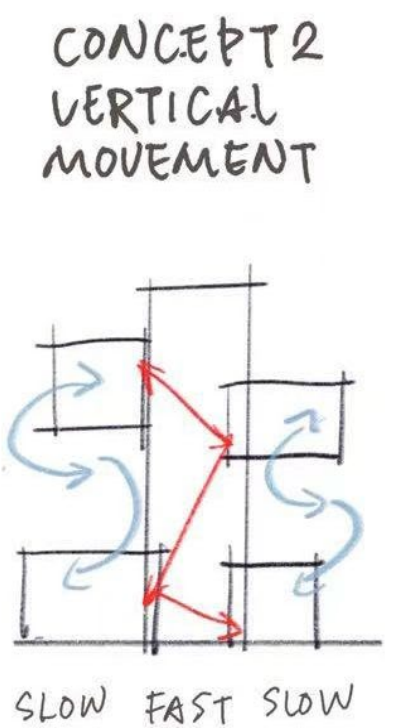
Voronoi Structure Development

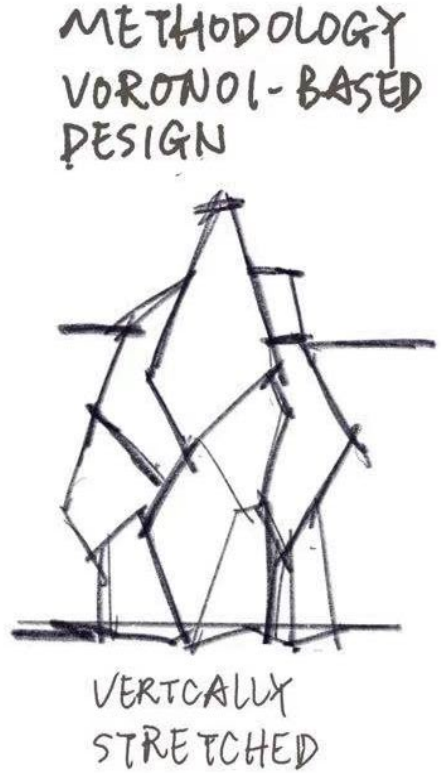
Underground oasis for Martian habitat



Oscar Newman’s fantasy, nuclear metropolis deep underground in New York







Design Development

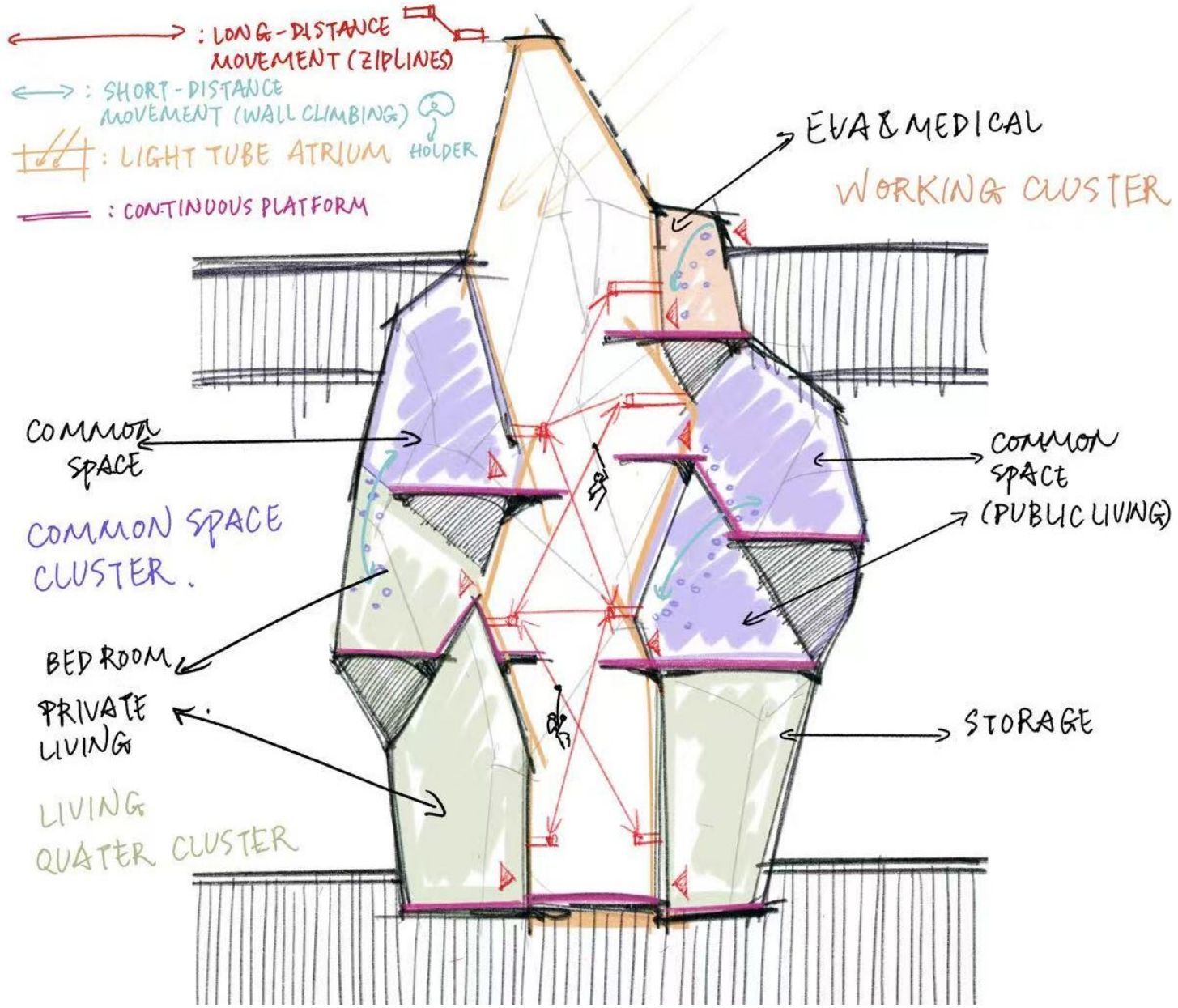
Concept Recap

Conceptual Section

Voronoi Structure Development

Use 3 methods for vertical transportation inside the building:

- The ramps ensure robotic and human regular vertical movement between all the levels.
- Ziplines provide an angled mode of movement, primarily used for traveling between different functional clusters.
- Wall climb holders provide an internal mobility solution within each functional area, facilitating short-distance vertical movement.

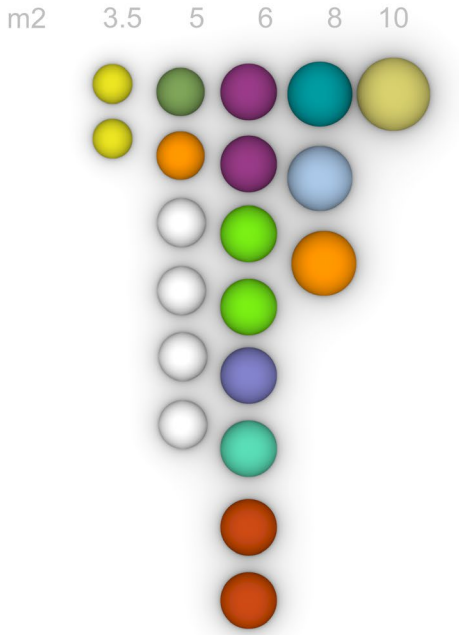


Design Development

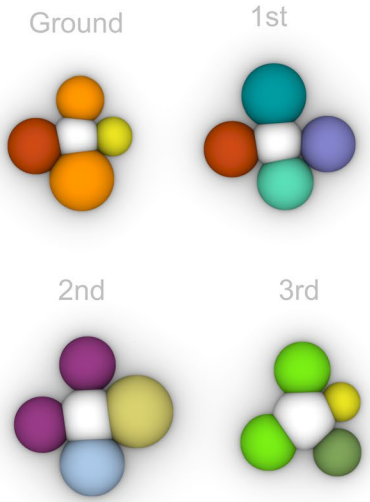
Concept Recap

Conceptual Section

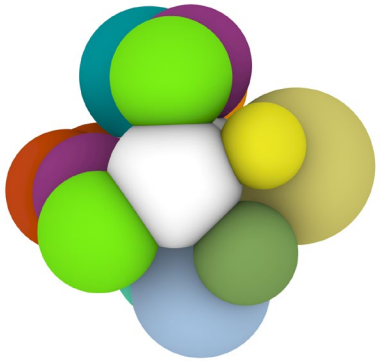
Voronoi Structure Development



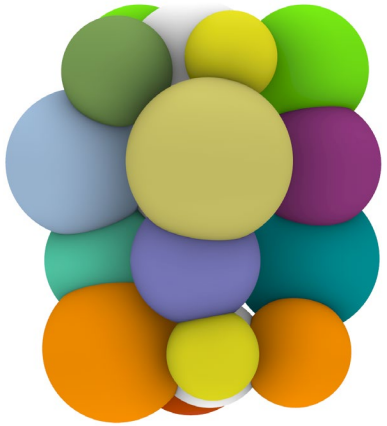
Room types and area



Bubble plans



Plans stacked top view



Plans stacked elevation view

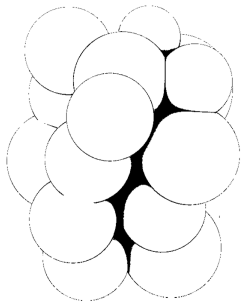
Key!

Design Development

Concept Recap

Conceptual Section

Voronoi Structure Development



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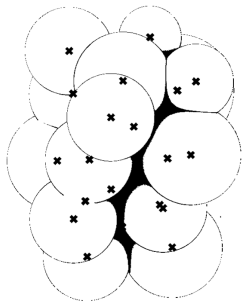
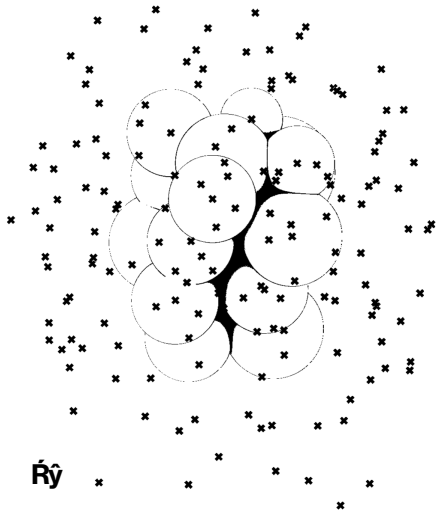


oey



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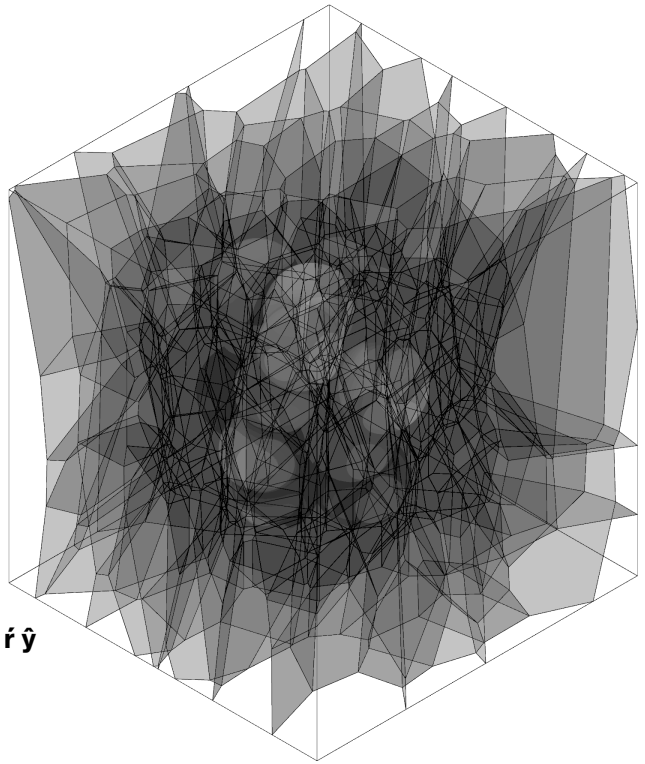

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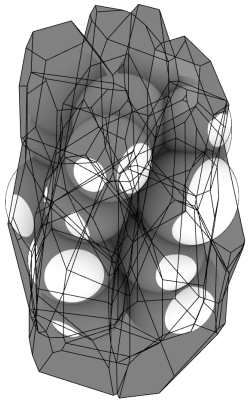

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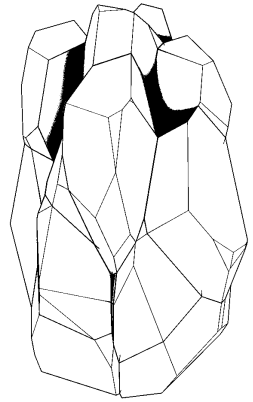

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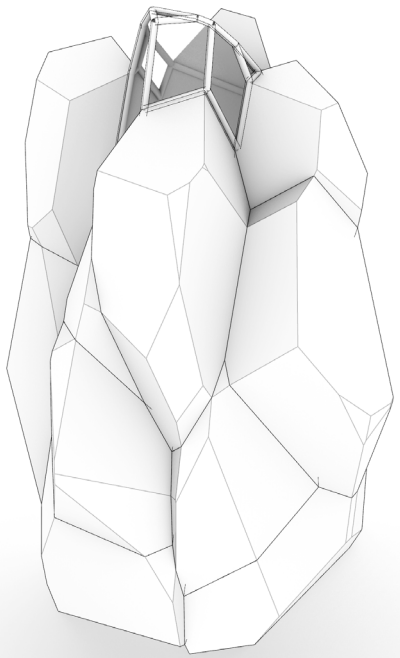
Design Development

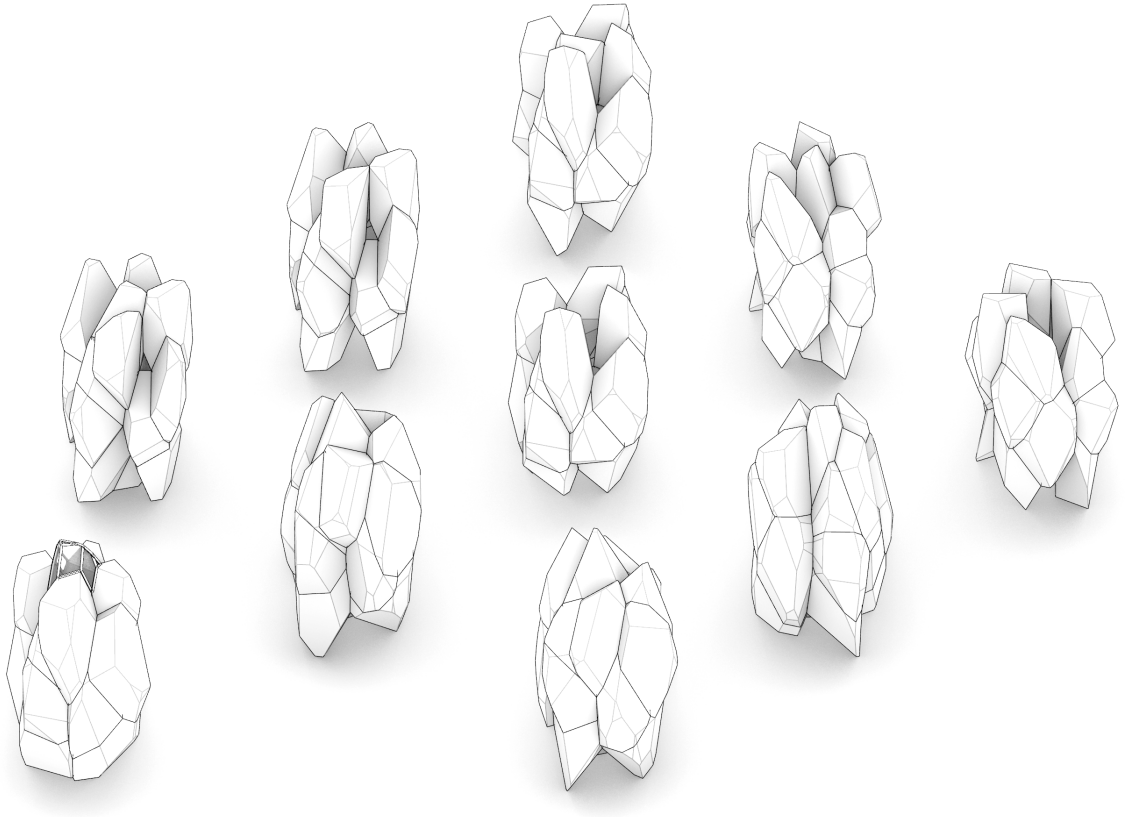
Concept Recap

Conceptual Section

Voronoi Structure Development



selected variant

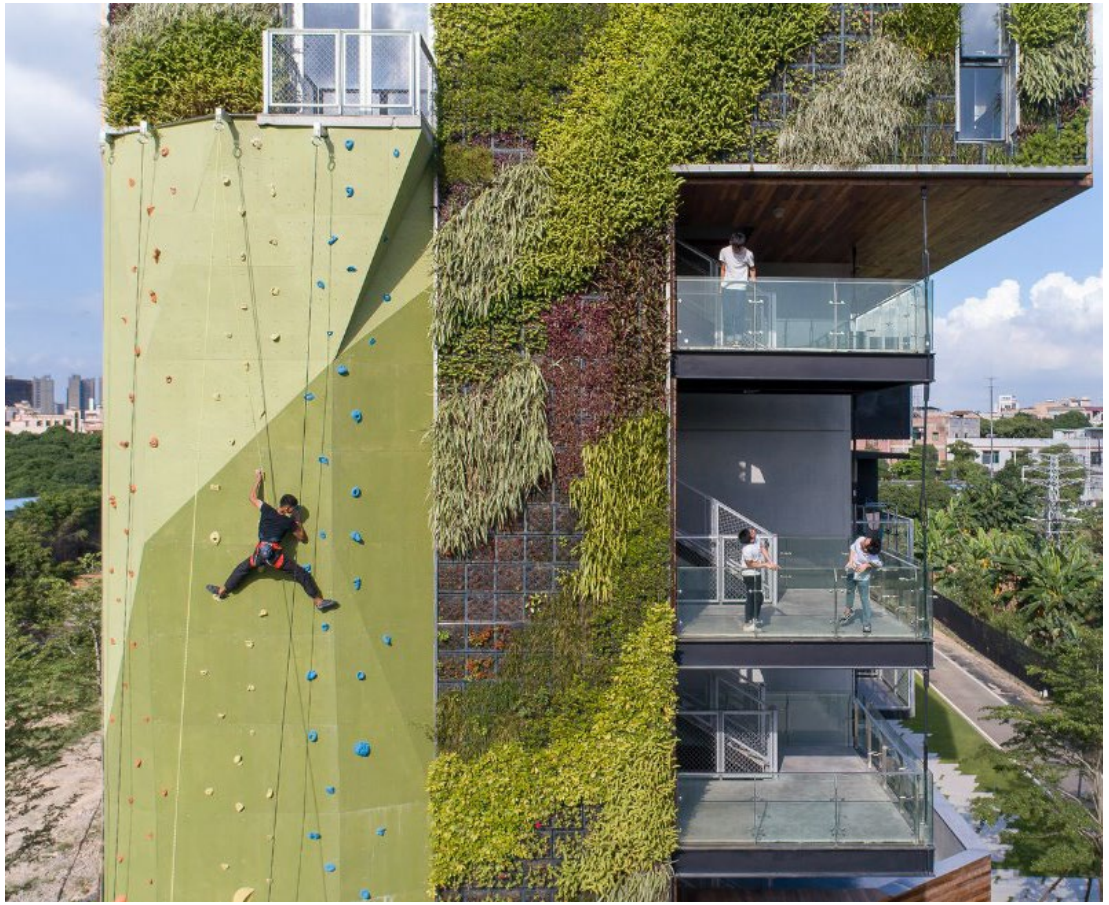


Final Design

Central Void

References

Concept



New Collectivism / O-office Architects

Climb House

Void

References

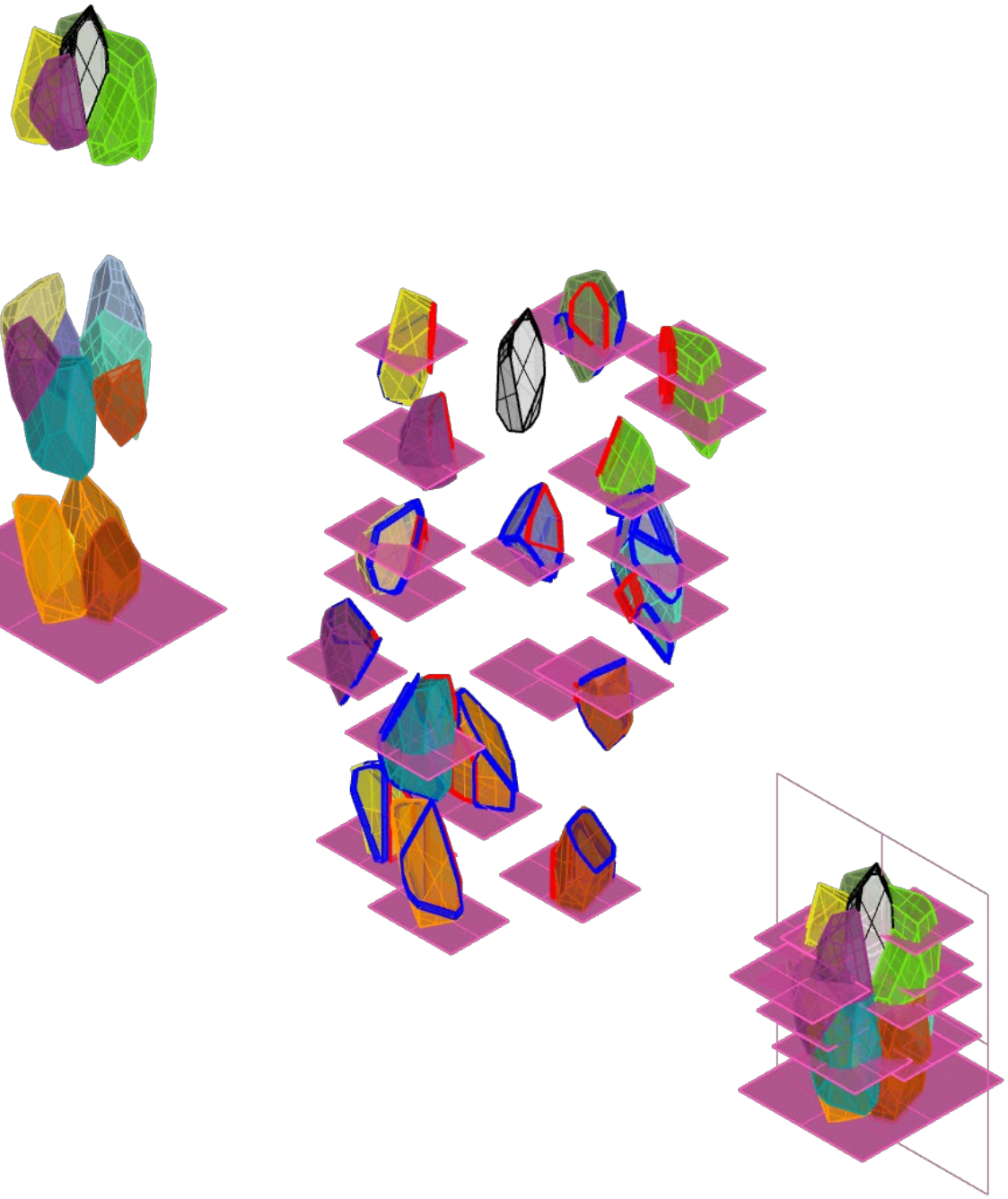
Concept

Central void:

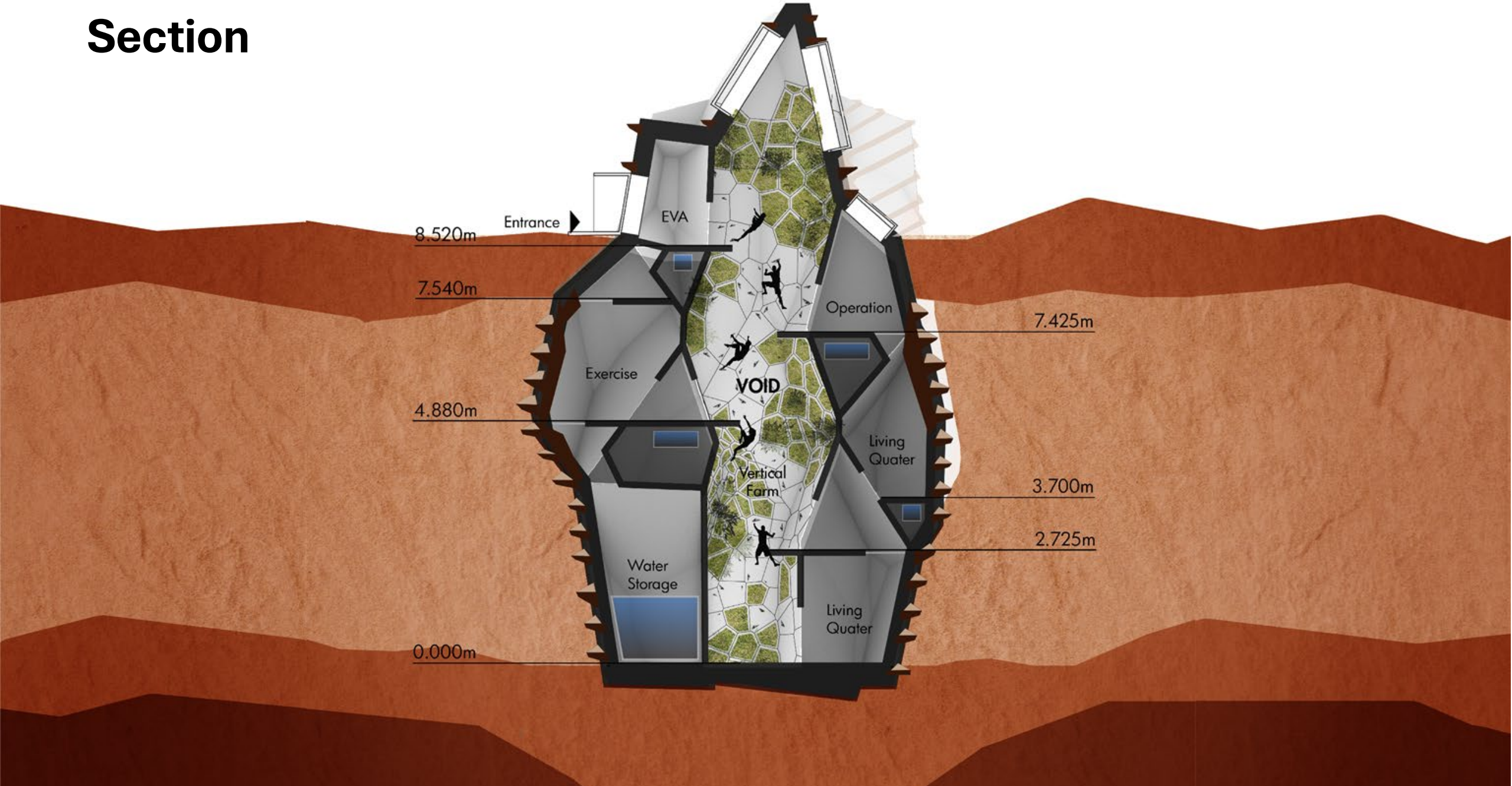
- Diffusing natural light
- Working as a circulation core
- Giving different mobility solutions
- Functioning as a vertical garden

Defining Horizontal Planes

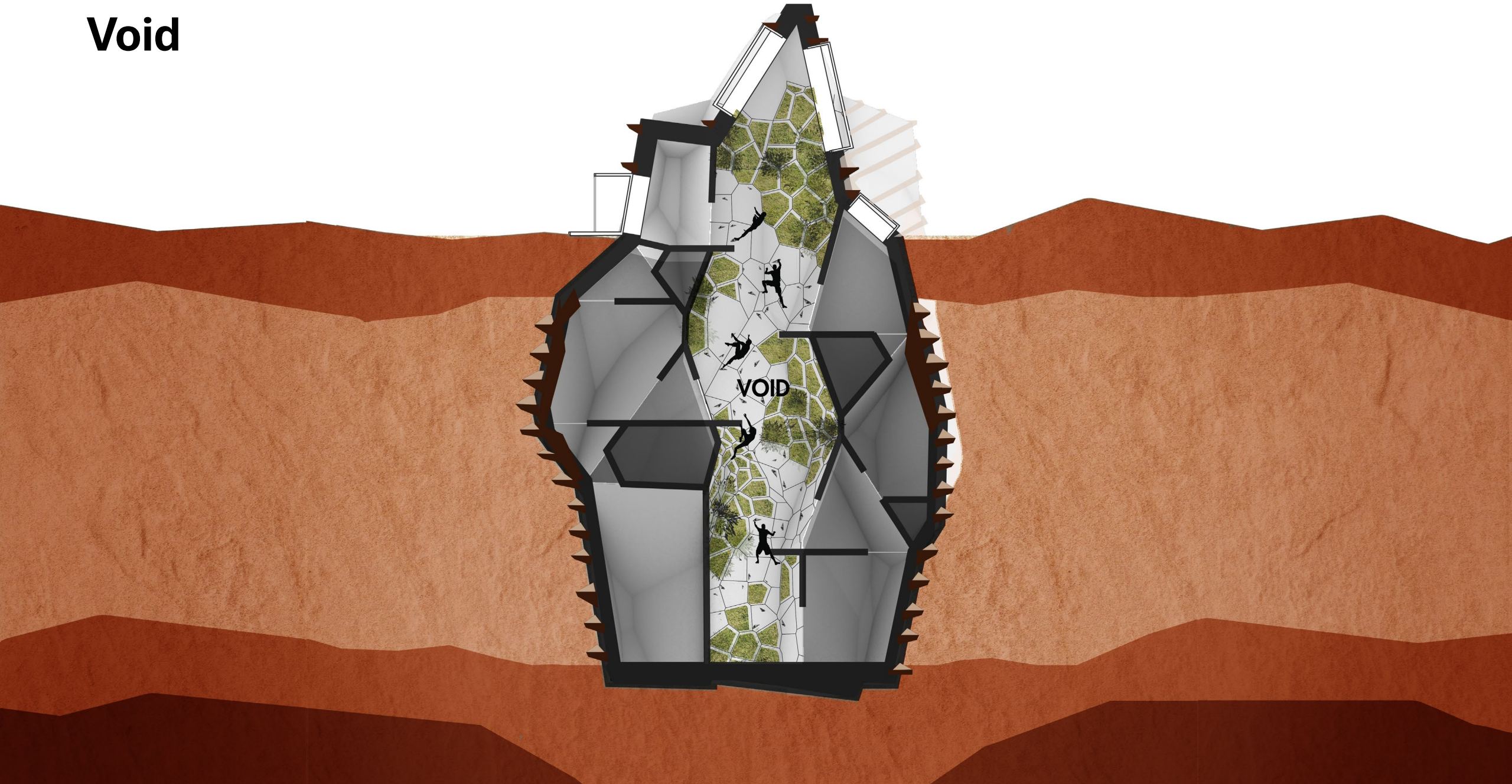
- Different horizontal plane within each volume
- Considered the height of space
- Connection with the openings
- Connection between the volumes
- Space for mechanical room in each cluster



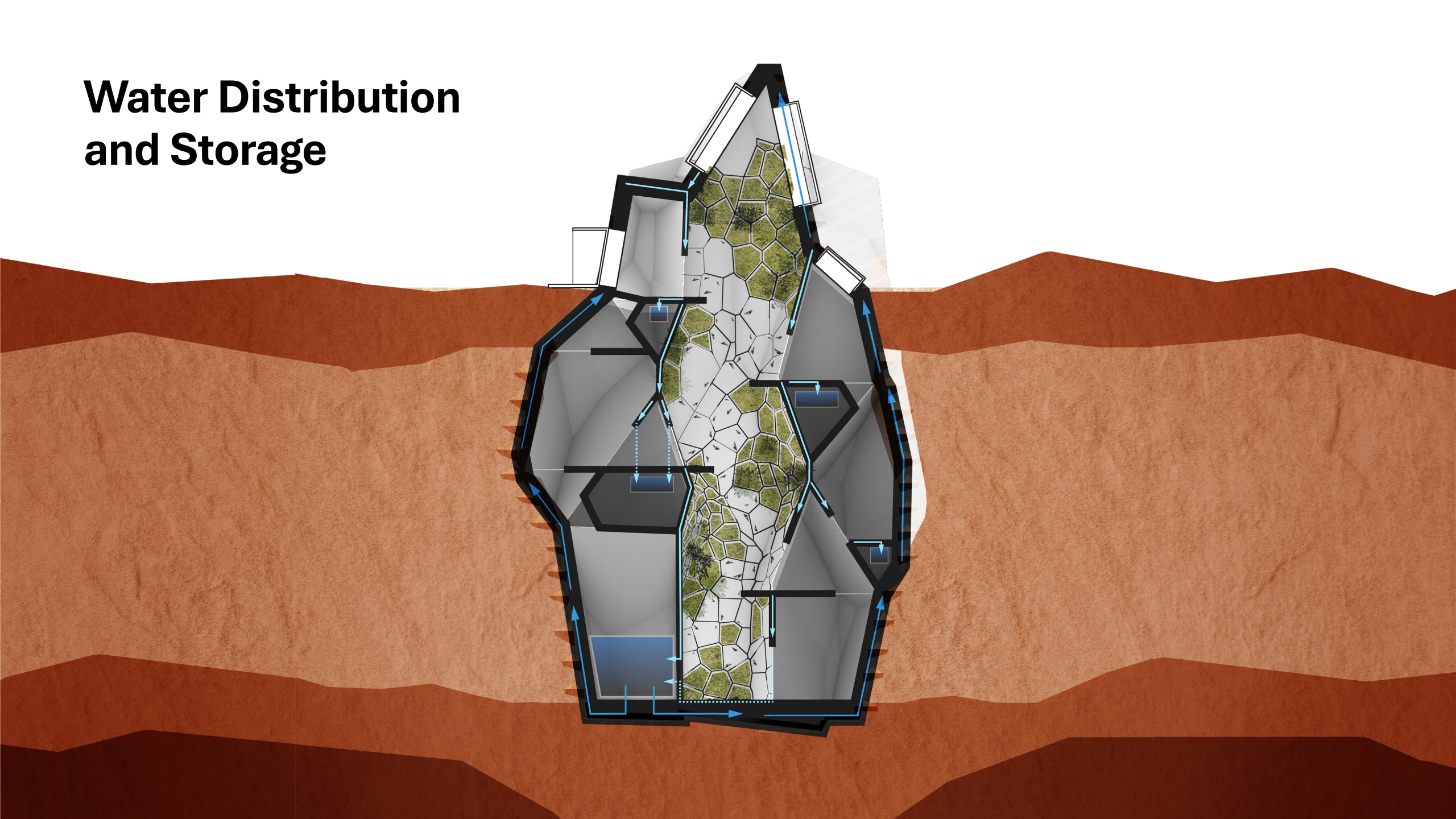
Section


Entrance
EVA
8.520m
7.540m
Operation
7.425m
Exercise
VOID
4.880m
Living
Quater
Vertical
Farm
3.700m
2.725m
Water
Storage
Living
Quater
0.000m

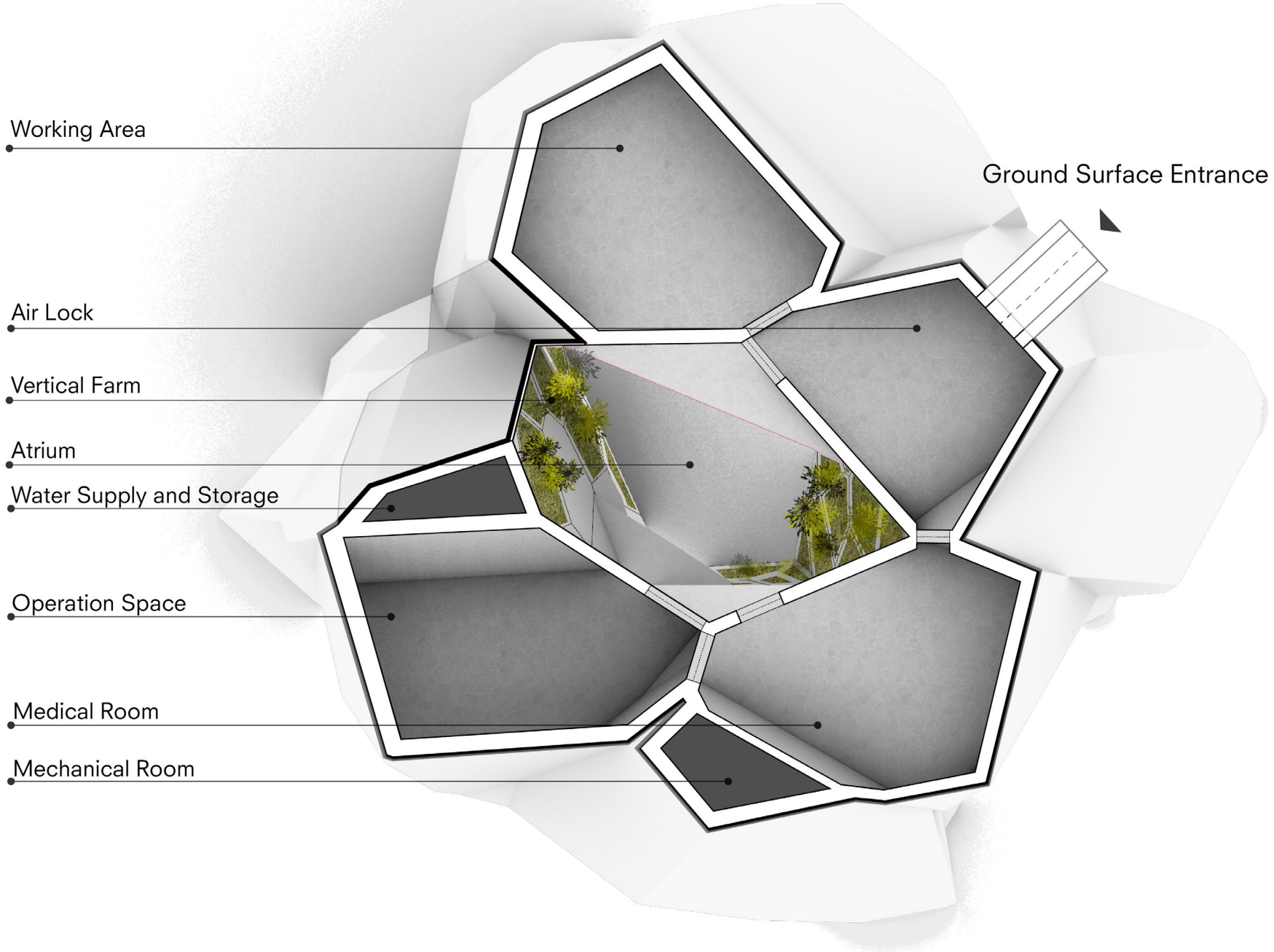
Void



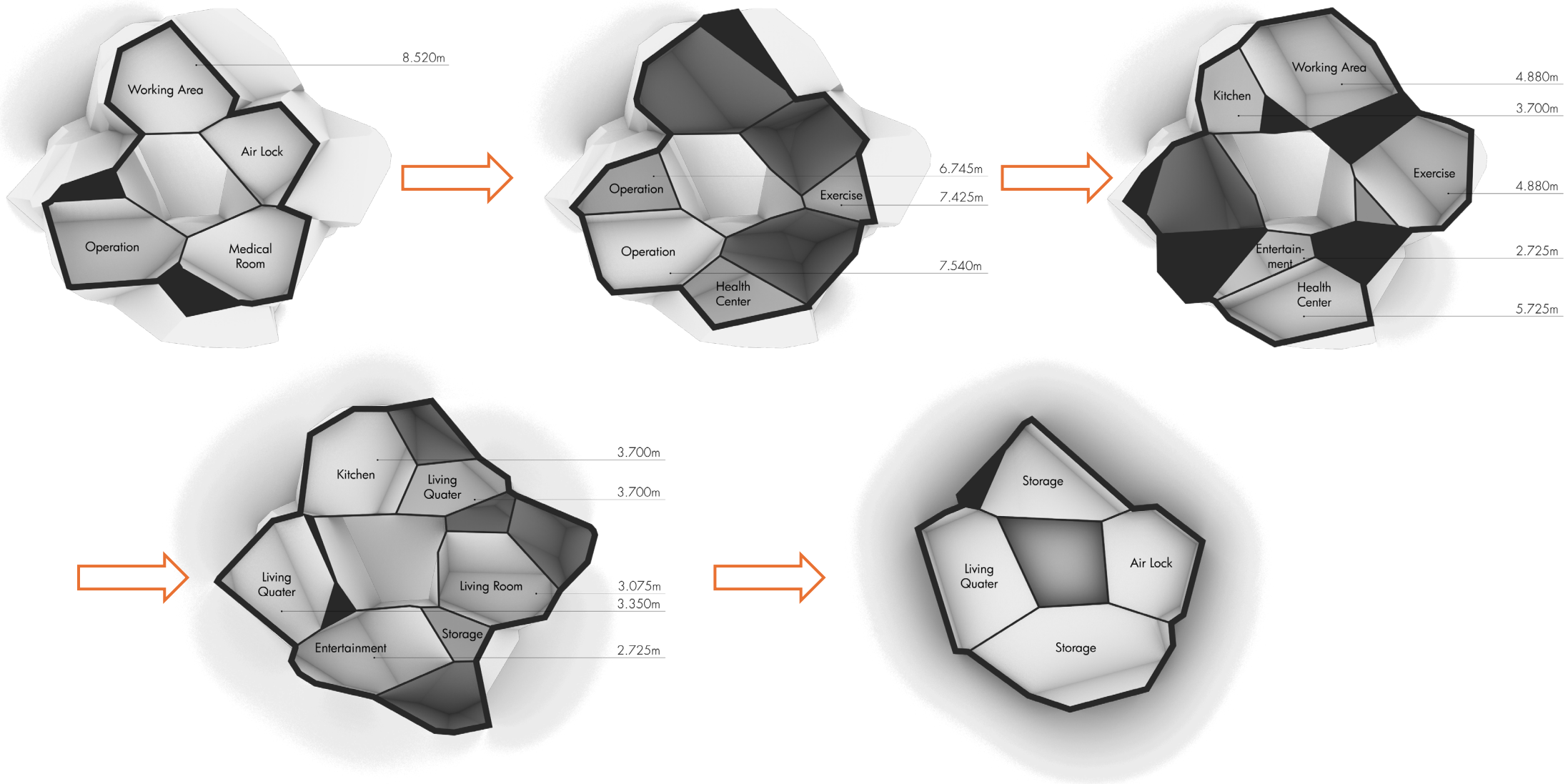
Water Distribution and Storage



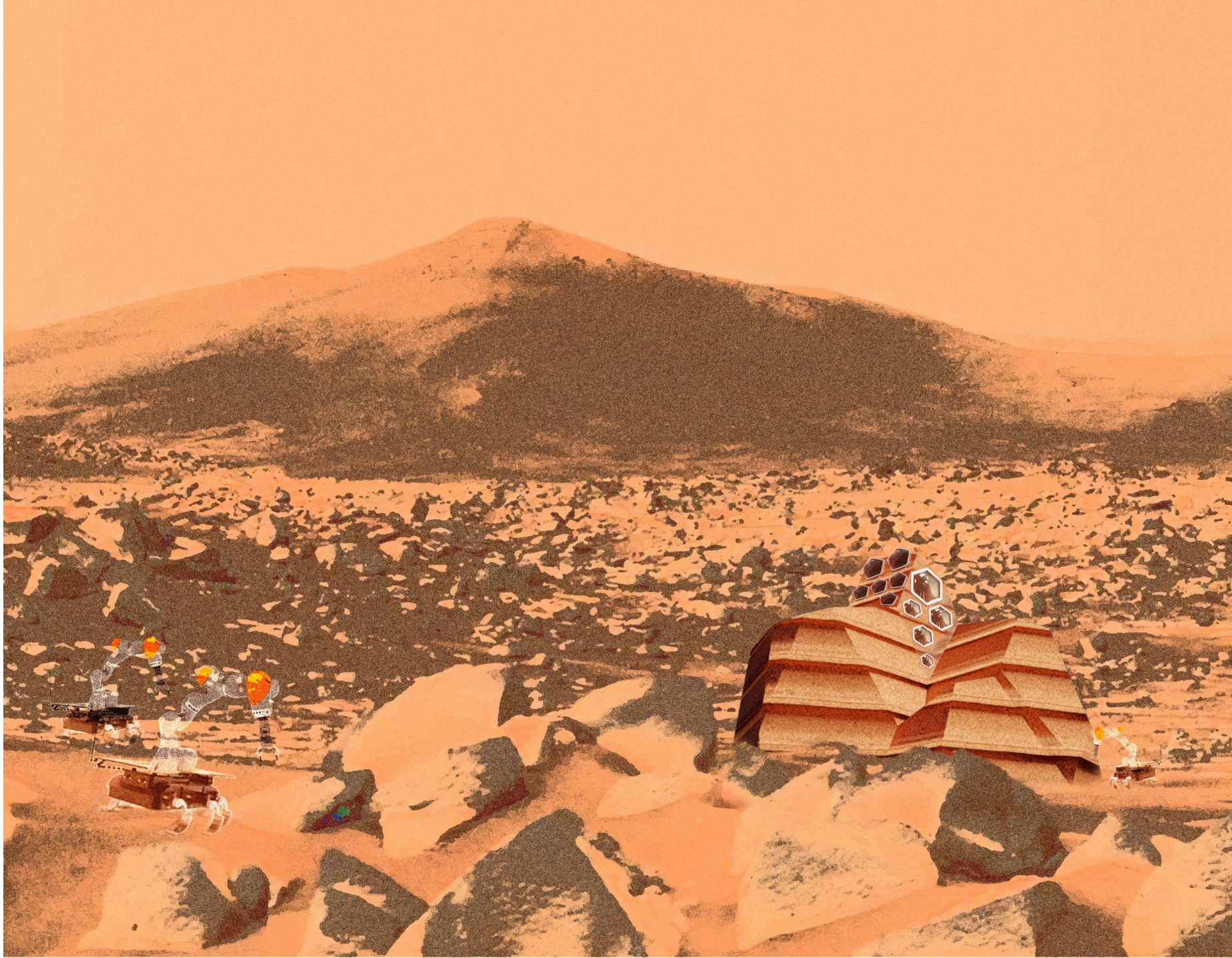
Entry level plan



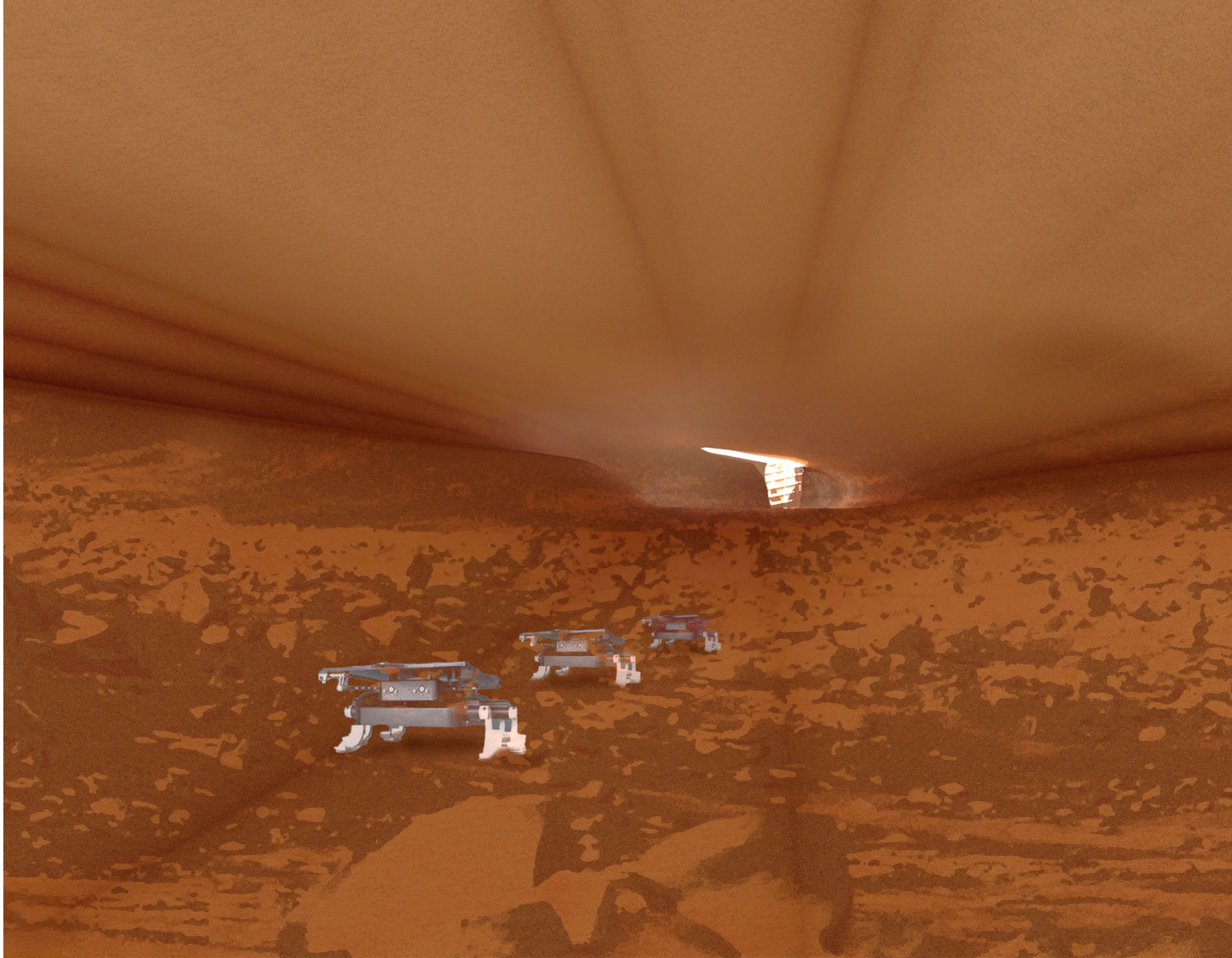
Floor Plans

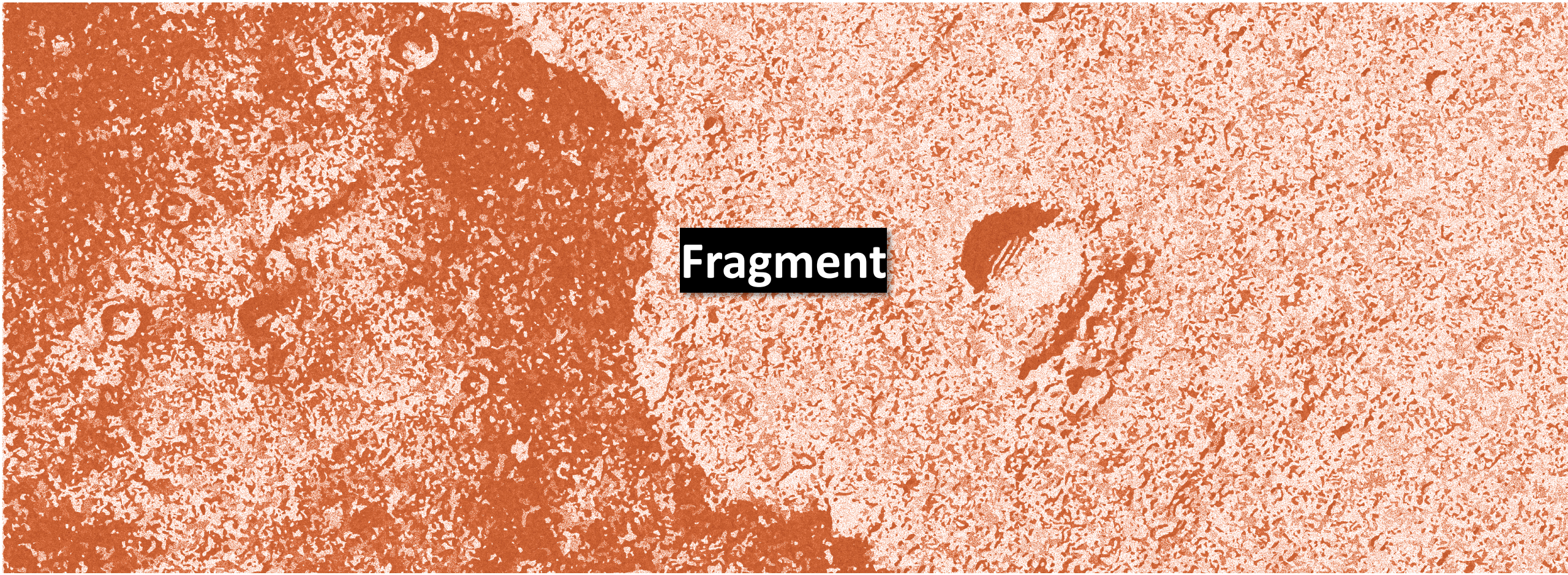

8.520m
Working Area
Air Lock
Operation
Medical Room
6.745m
7.425m
7.540m
Operation
Exercise
Operation
Health Center
Working Area
4.880m
3.700m
Kitchen
Exercise
4.880m
2.725m
Entertain-ment
Health Center
5.725m
3.700m
3.700m
Kitchen
Living Quater
Living Quater
Living Room
3.075m
3.350m
Storage
Entertainment
2.725m
Storage
Living Quater
Air Lock
Storage

Visualisation



Visualisation

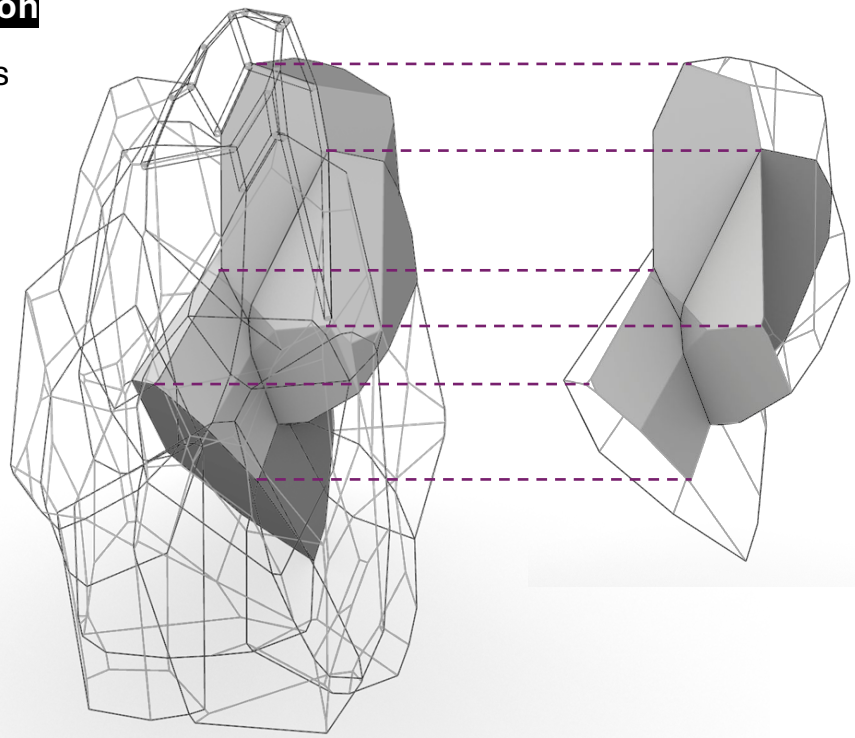



Fragment

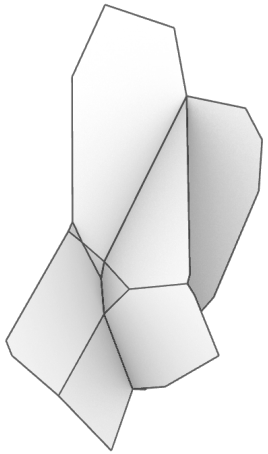
Fragment Selection

Fragment Selection

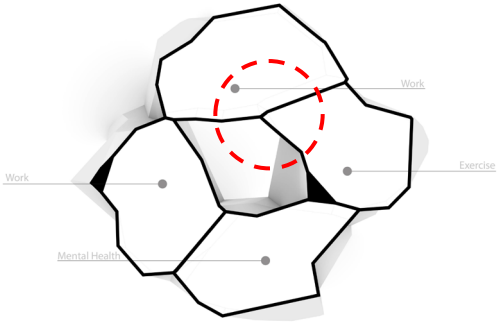
Structural Analysis



Selecting the fragment from the habitat



Selecting surfaces

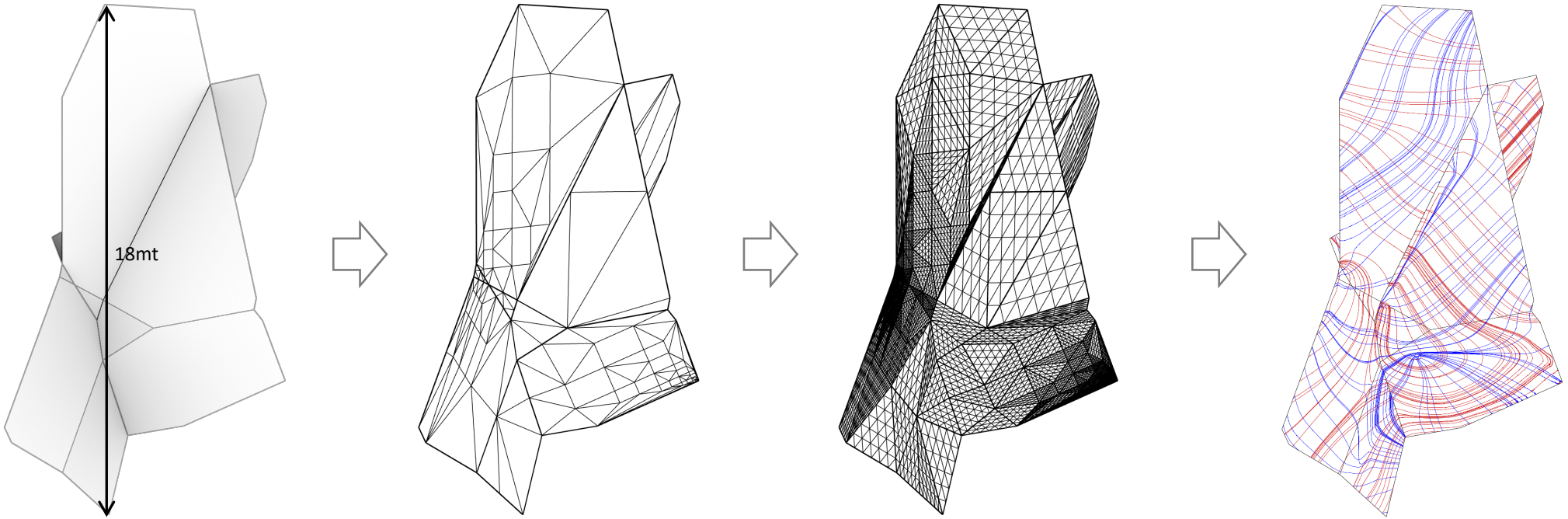


Floor plan reference

Fragment Selection

Fragment Selection

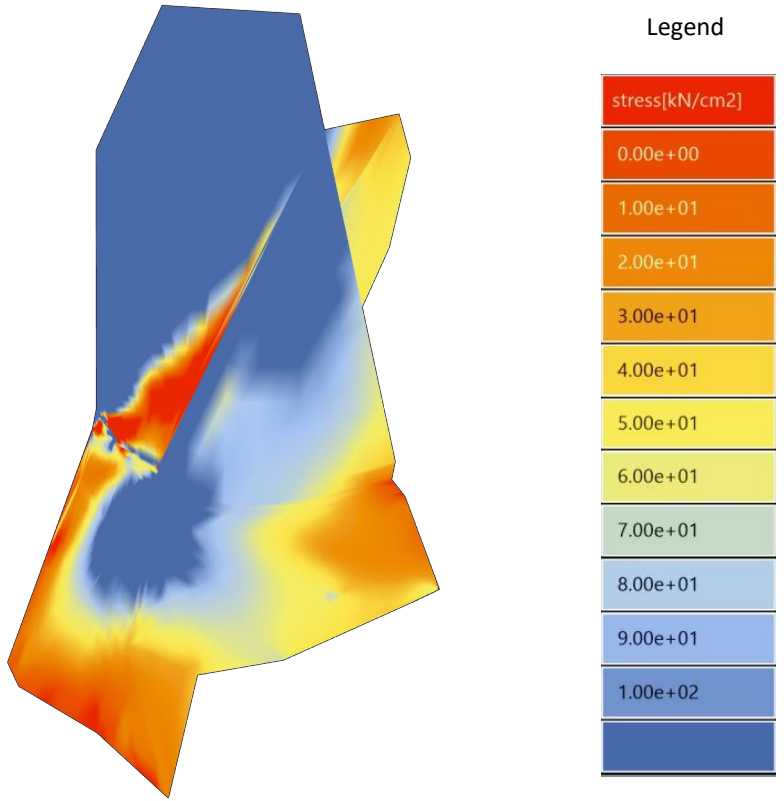
Structural Analysis



Fragment Selection

Fragment Selection

Structural Analysis

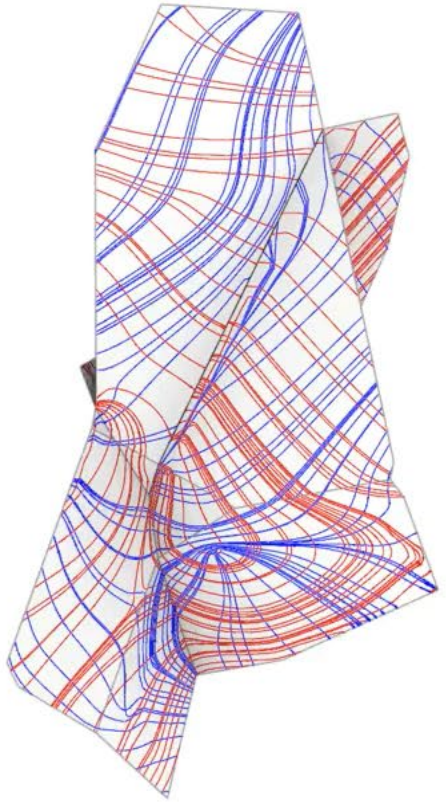


Stress loads values

Fragment Selection

Fragment Selection

Structural Analysis

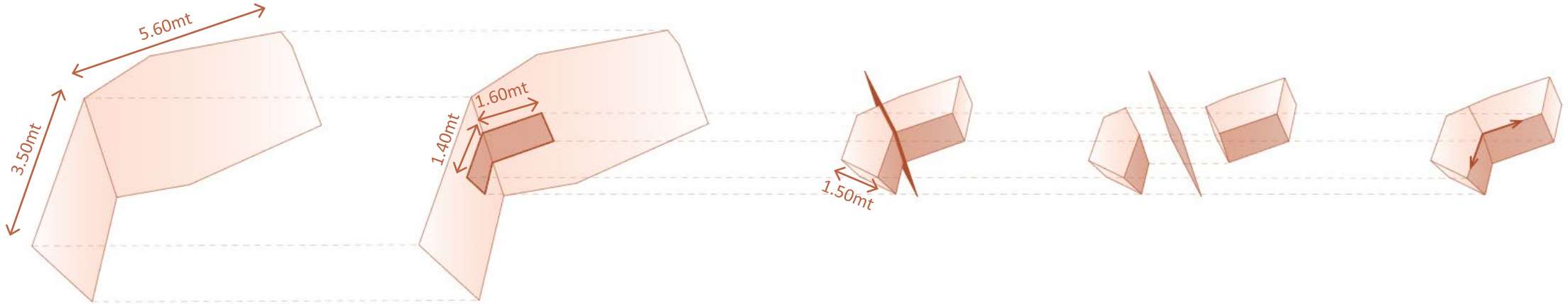


Stress and tension lines from all sides of the fragment

Kinked Voronoi Cells Generation

Kinked Voronoi Cells

LSS piping and cables



Selecting two polysurfaces from the fragment

Choosing one small part of the fragment

Defining the double surface

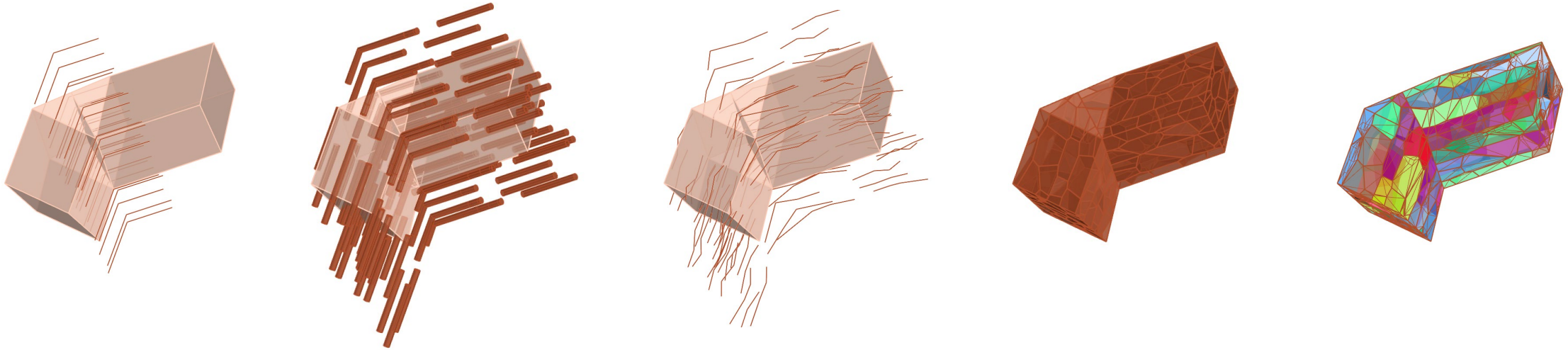
Dividing the fragment in two brep segments

Creating the two directions

Kinked Voronoi Cells Generation

Kinked Voronoi Cells

LSS piping and cables



Generating upper and lower lines from geometries

Generating upper lower and mid mesh pipes

Giving polylines random configuration

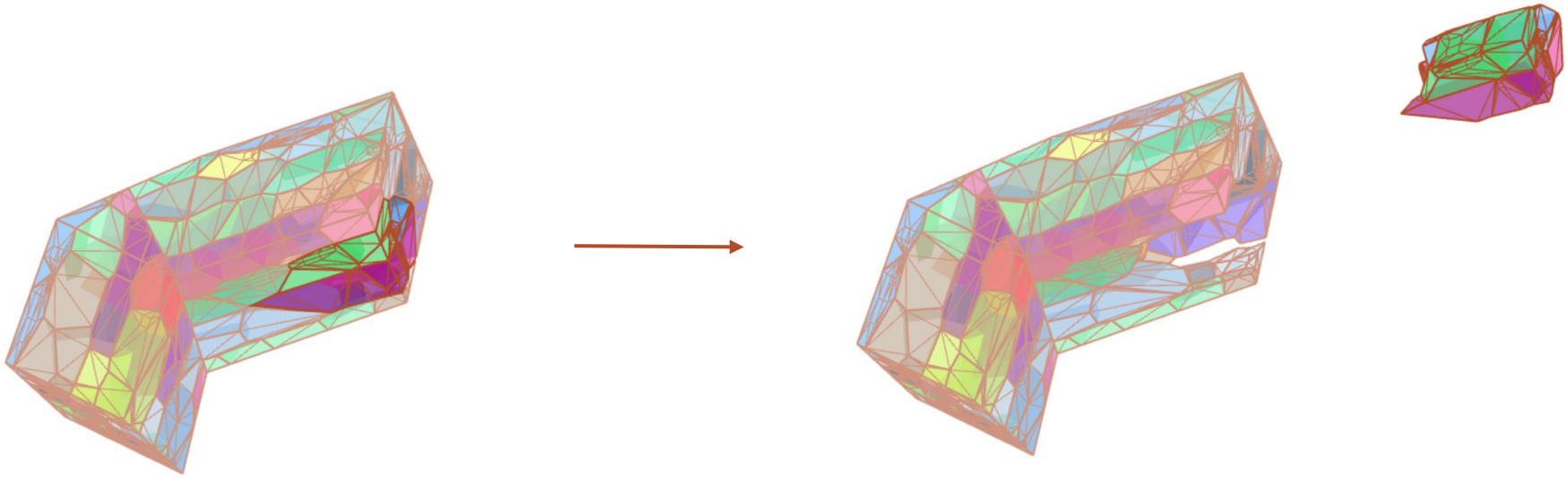
Generating voronoi cells inside the fragment geometry

Baking the cells generated

Kinked Voronoi Cells Generation

Kinked Voronoi Cells

LSS piping and cables

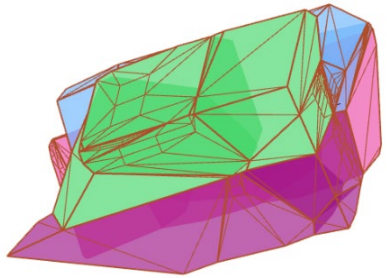


Selecting a small group of meshes for the integrate voronoi-based LSS piping and cables LAST

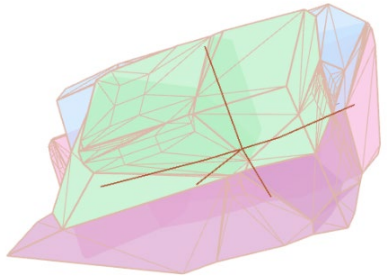
Kinked Voronoi Cells Generation

Kinked Voronoi Cells

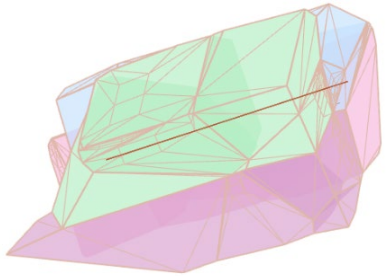
LSS piping and cables



Setting the four geometries in the script



Setting the attractor curves that will determine the paths of the integrated channels

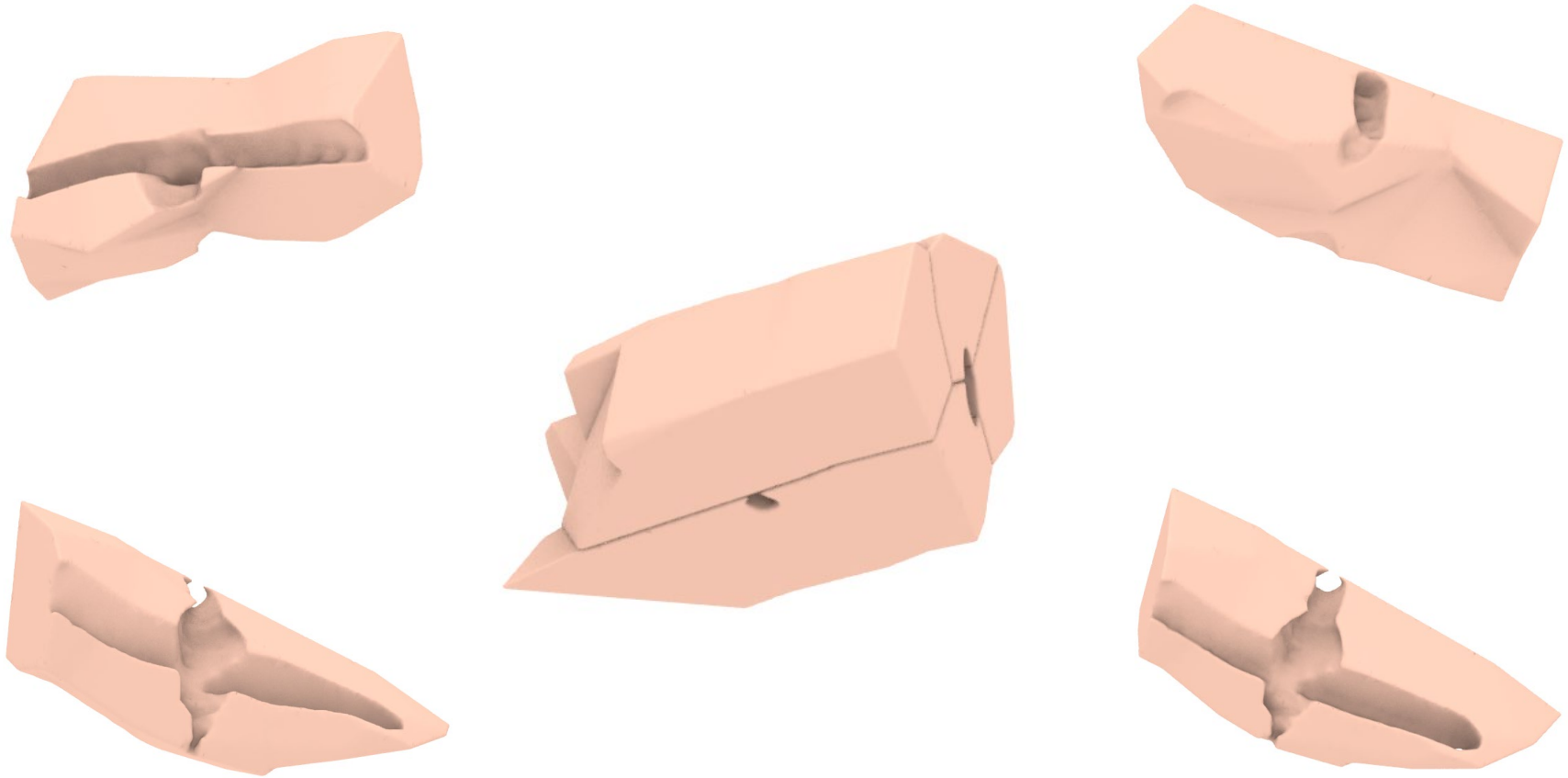


Setting the voronoi stretching direction

Kinked Voronoi Cells Generation

Kinked Voronoi Cells

LSS piping and cables

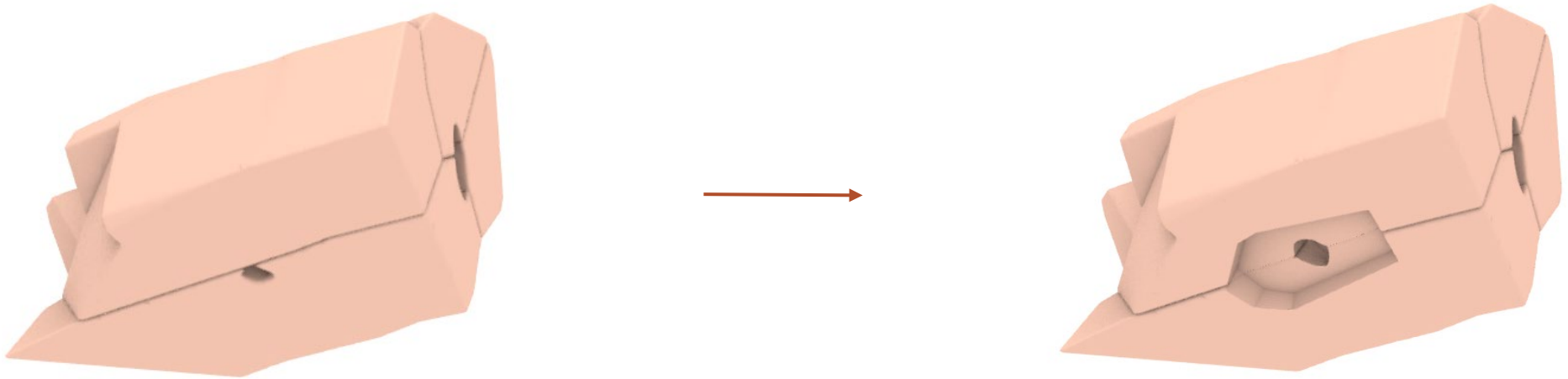


Generated components with integrated pipes

Kinked Voronoi Cells Generation

Kinked Voronoi Cells

LSS piping and cables

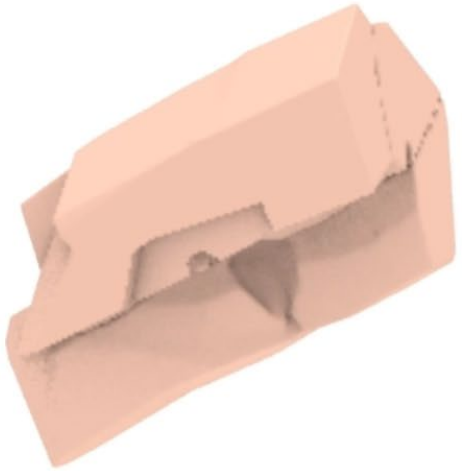


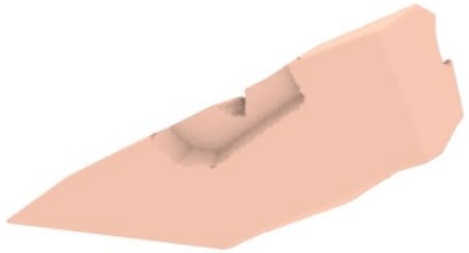
Final components with pot for hydroponic plants generated with boolean difference

Kinked Voronoi Cells Generation

Kinked Voronoi Cells

LSS piping and cables



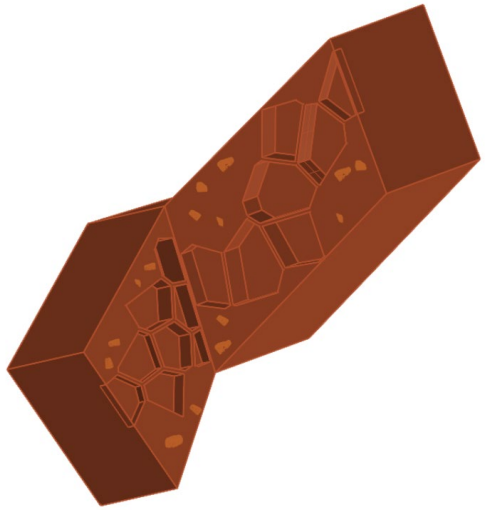


Components selected for the milling process

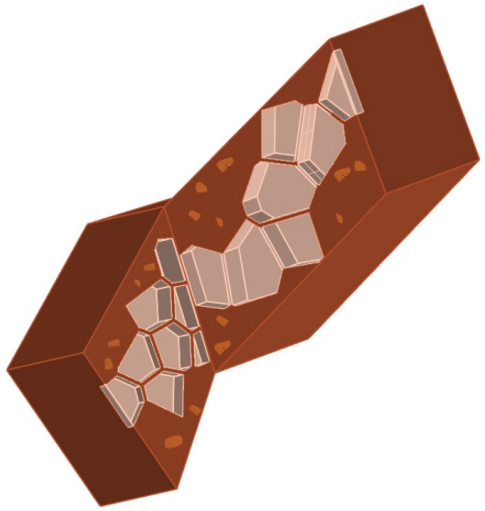
Fragment Design

Schemes

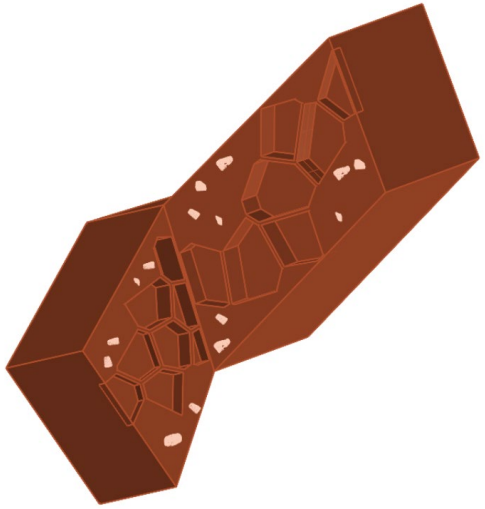
Render



Fragment conceived either as a climbing wall or a vertical garden



Pots for hydroponic plants generated with boolean difference



Climbing holds generated with boolean union

Fragment Design

Schemes

Render

Milling Process

Milling process

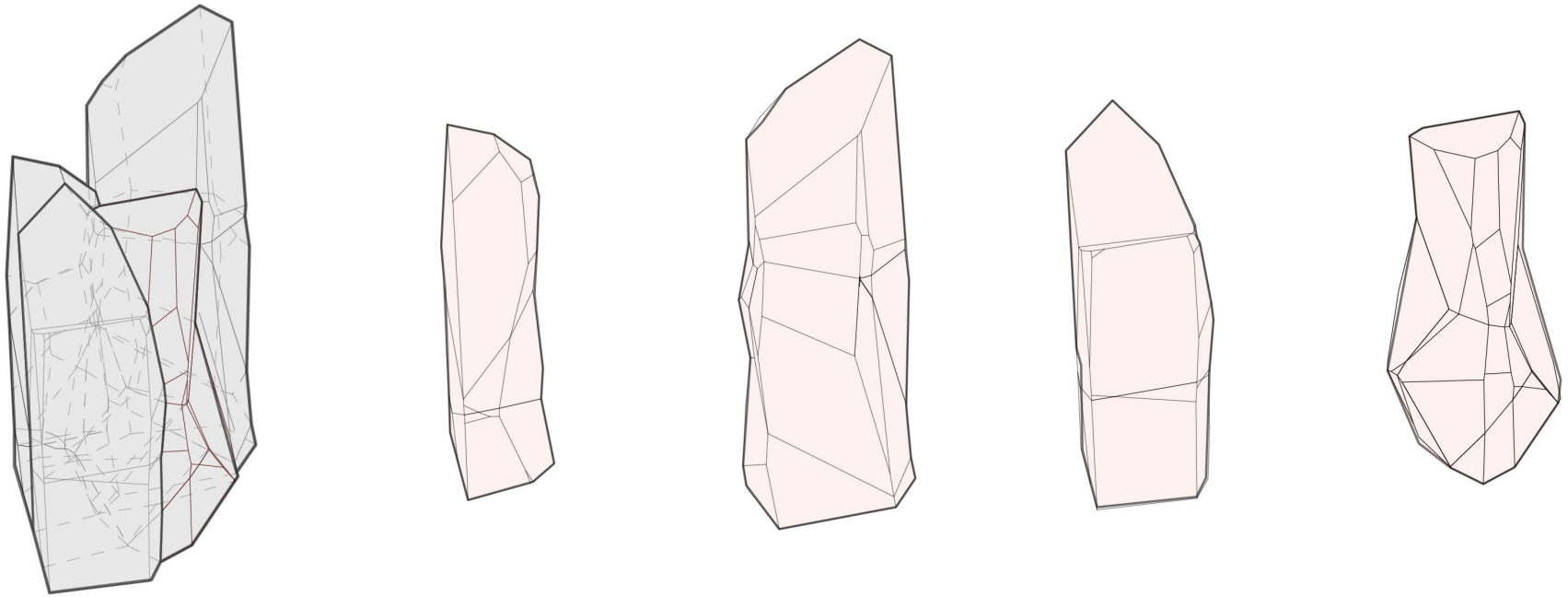
Component subset

Milling steps

Dimentions

Toolpath planes

Milling simulation



Component subset | Component No. 1 | Component No. 2 | Component No. 3 | Component No. 4

Milling process

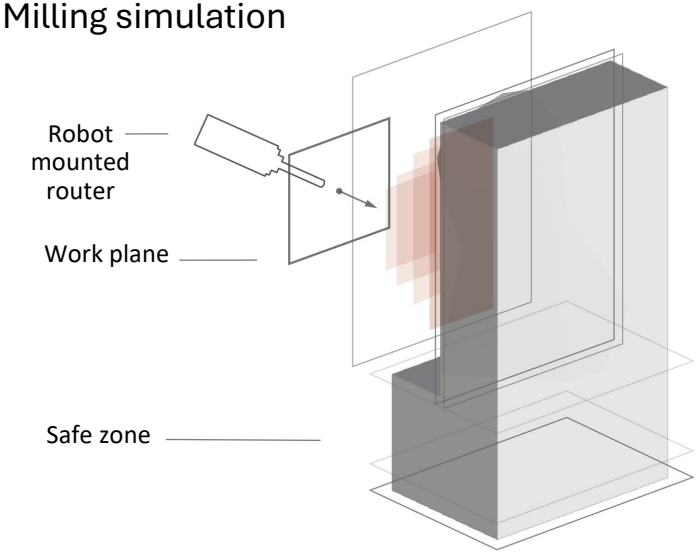
Component subset

Milling steps

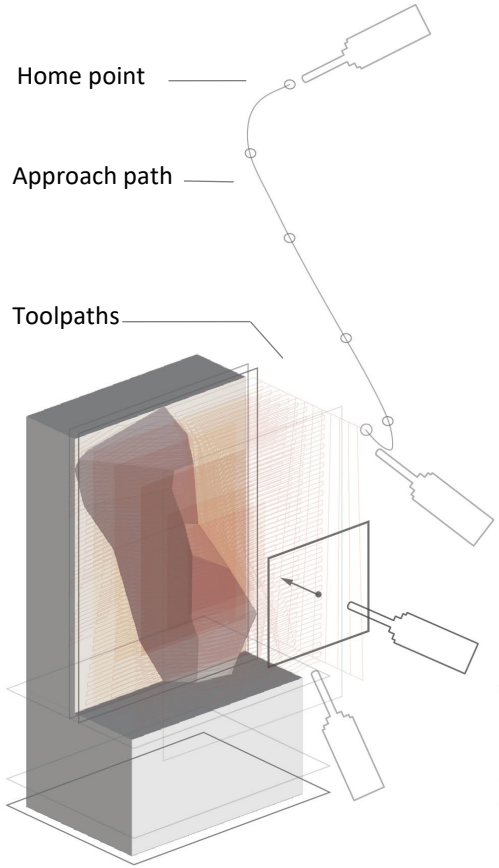
Dimentions

Toolpath planes

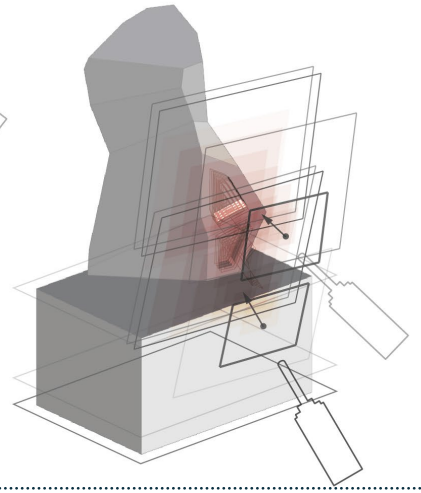
Milling simulation



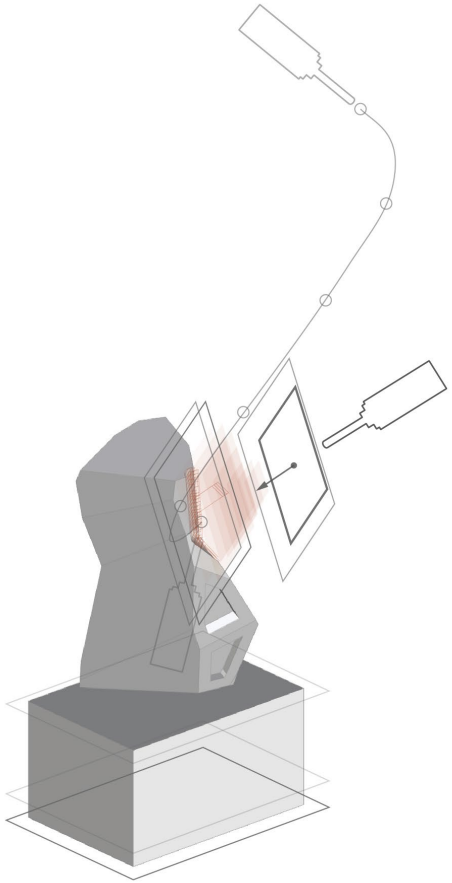
Milling side one
(Component No.3)



Milling side 2
(Component No.3)



Milling the holds for the hands



Milling the LSS piping channels

Milling process

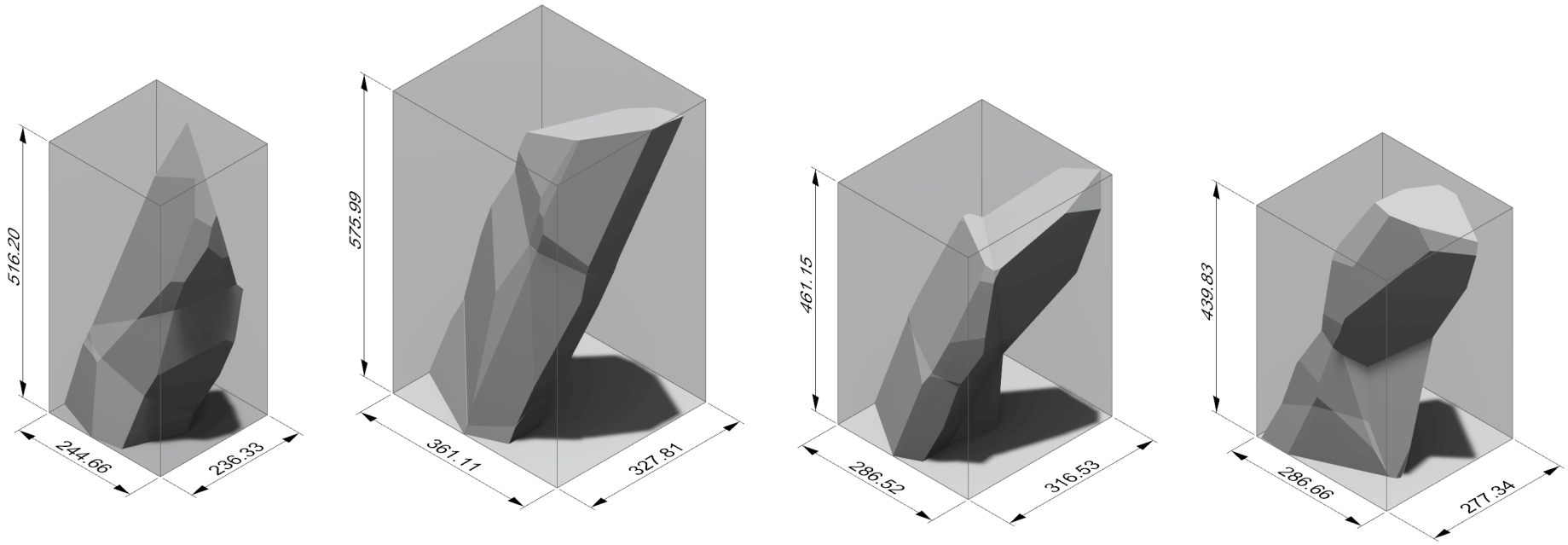
Component subset

Milling steps

Dimentions

Toolpath planes

Milling simulation



Dimentions of bounding boxes for each of the components | in mm

Component No. 1

Component No. 2

Component No. 3

Component No. 4

Milling process

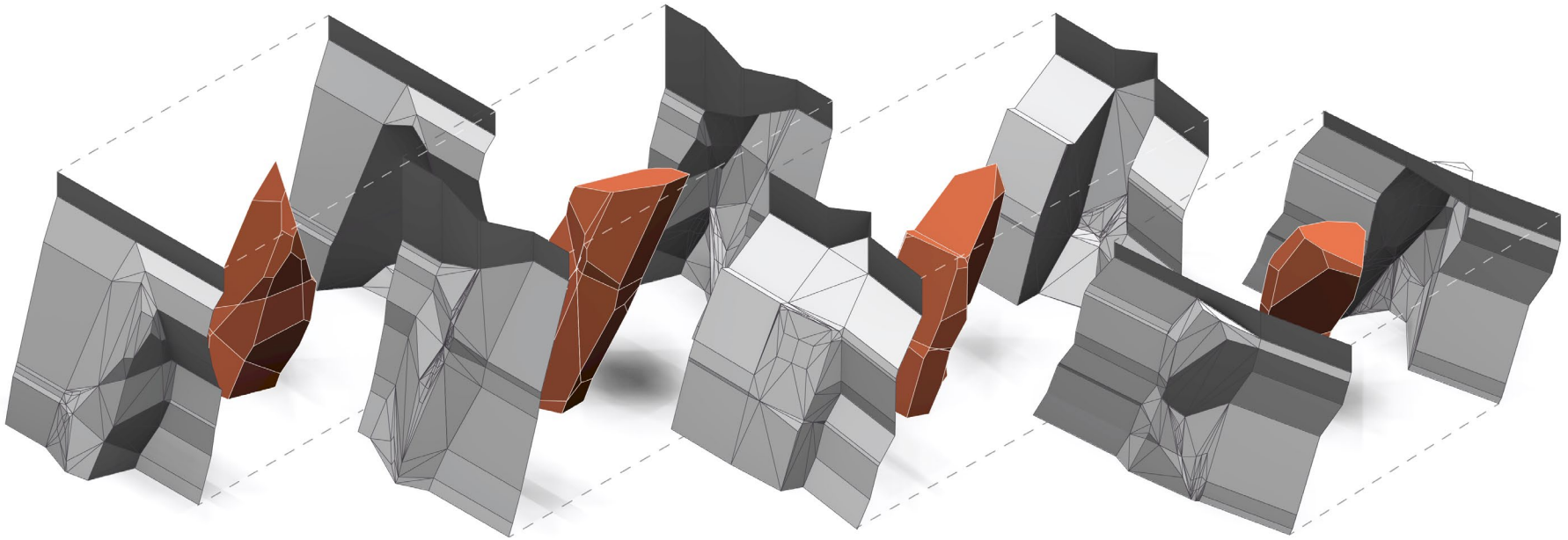
Component subset

Milling steps

Dimentions

Toolpath planes

Milling simulation



The planes for toolpath generation each component is split into 2 sides

Milling process

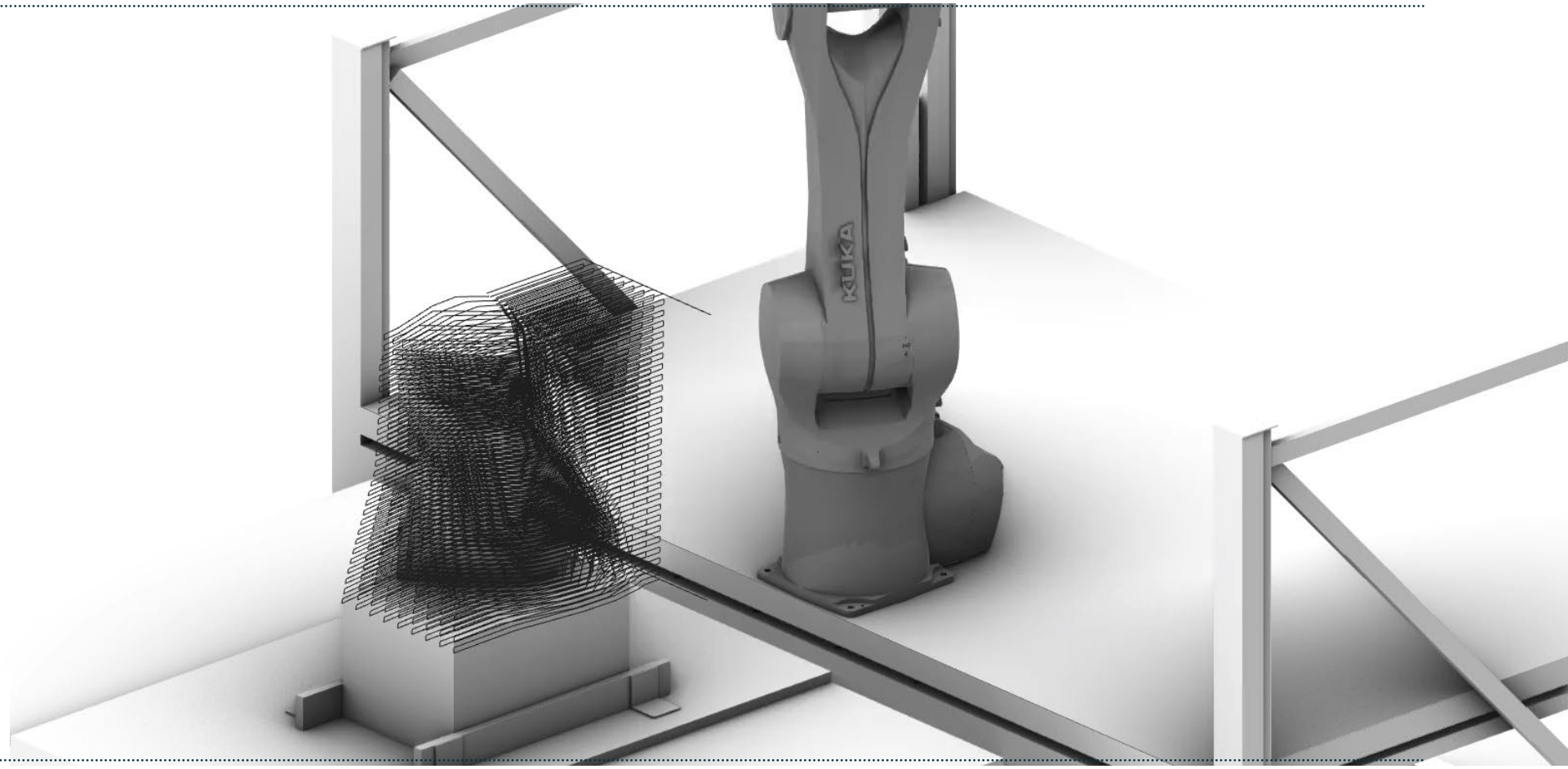
Component subset

Milling steps

Dimentions

Toolpath planes

Milling simulation



Simulation of miling for side 2 | Component No. 3

Milling process

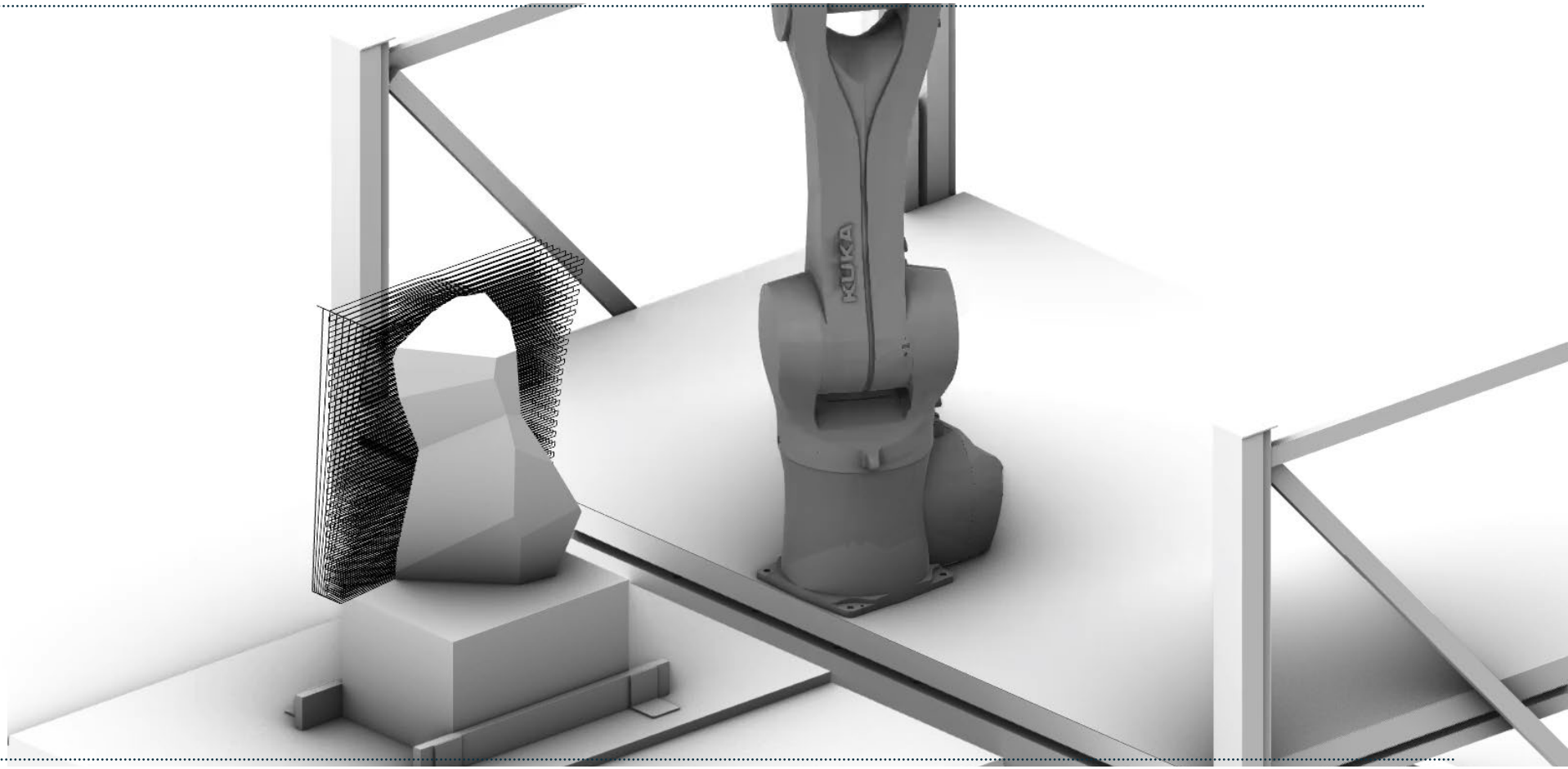
Component subset

Milling steps

Dimentions

Toolpath planes

Milling simulation



Simulation of miling for side 1 | Component No. 3

Milling process

Component subset

Milling steps

Dimentions

Toolpath planes

Milling simulation

Picture taken in the lab during the milling simulation

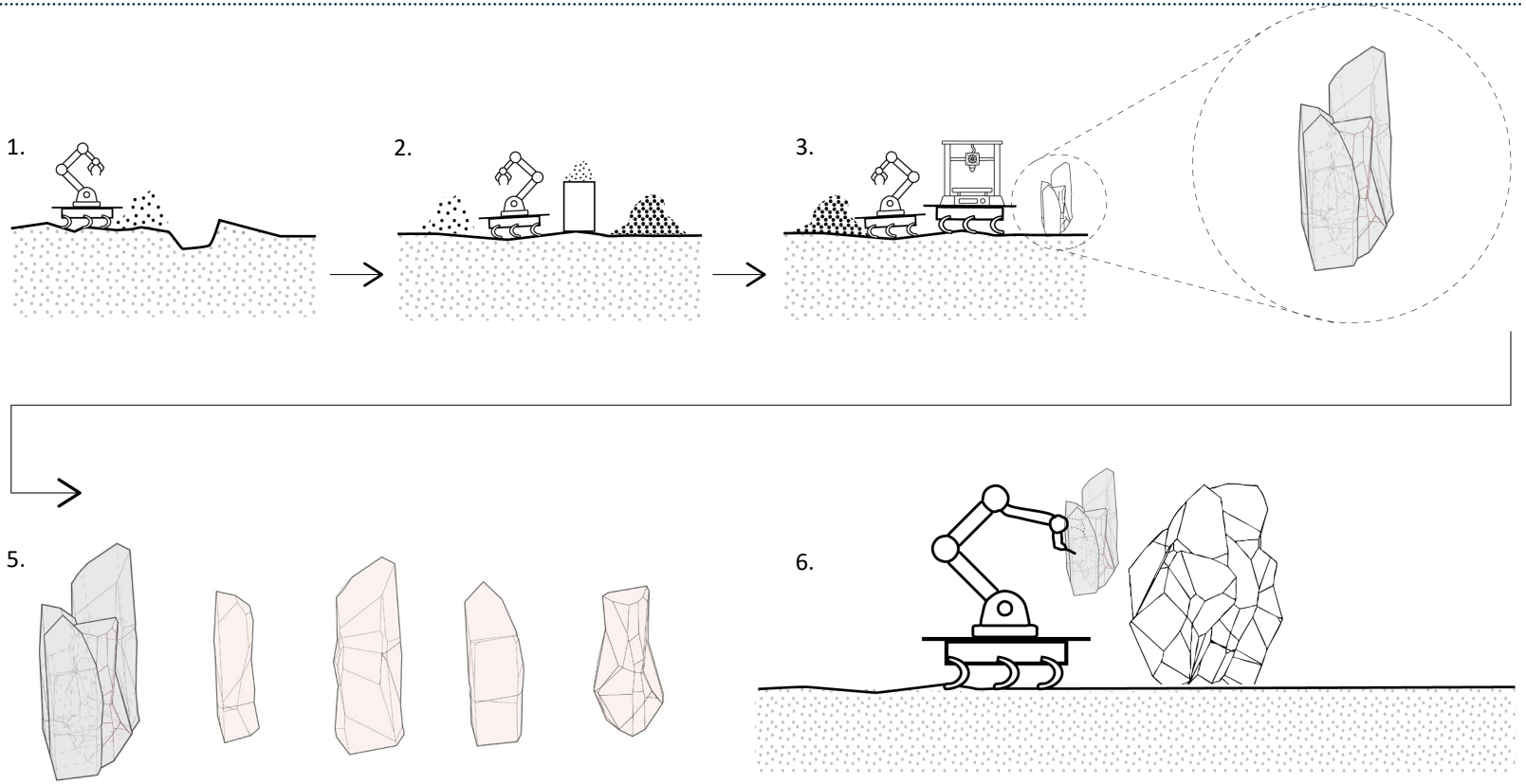
HRI & Assembly Plan

HRI & Assembly Process

Assembly Fragment Selection

Assembly Concept

HRI



1. Regolith is extracted

2. Regolith processed to create 3D printing material

3. Material is 3d printed into fragments for assembly

4. Family of components ready for assembly

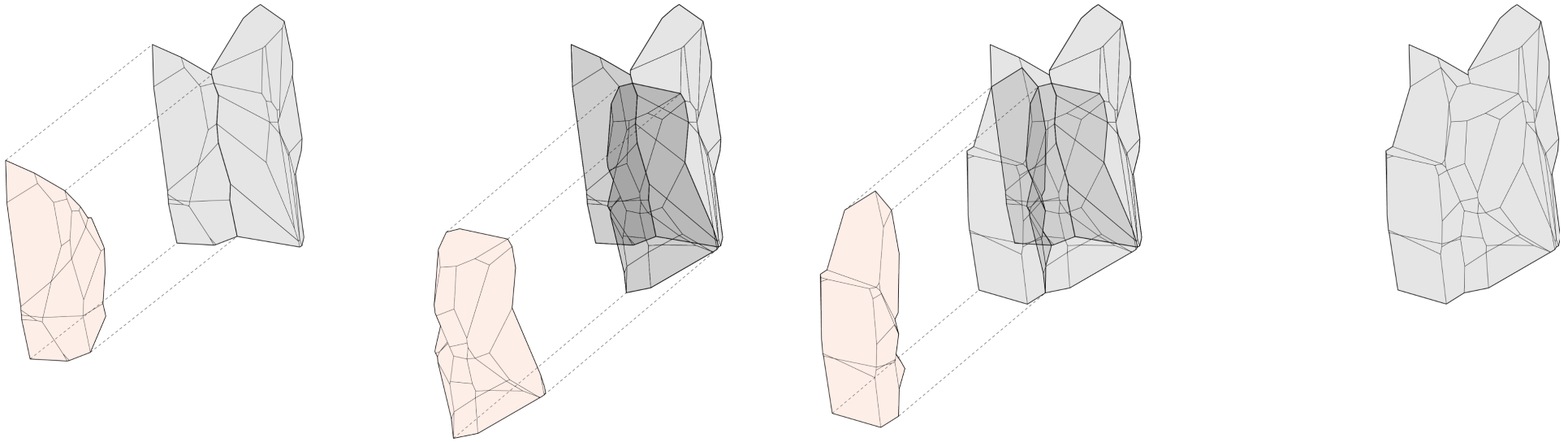
5. Lunar Zebro rover with robotic arm assembles components

HRI & Assembly Process

Assembly Fragment Selection

Assembly Concept

HRI



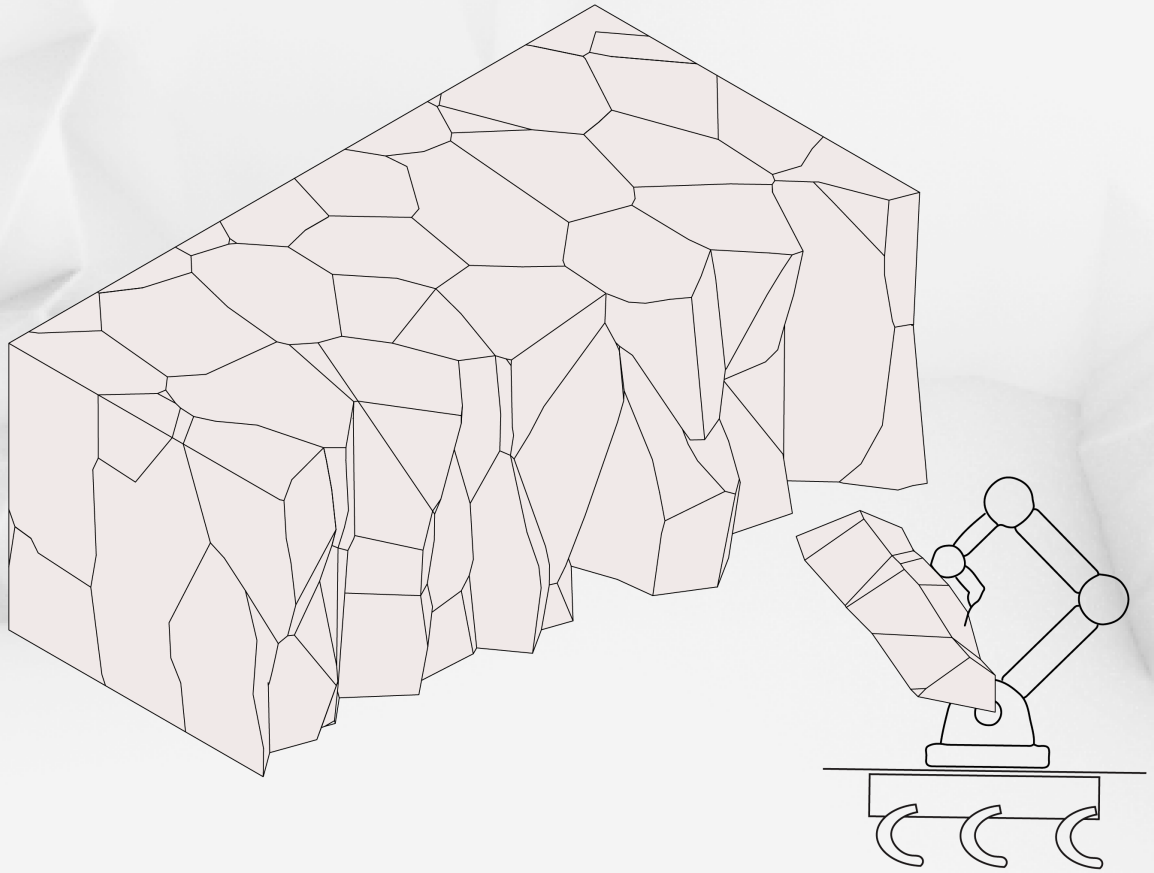
Assembly process consisting in interlocking vertically

HRI & Assembly Process

Assembly Fragment Selection

Assembly Concept

HRI



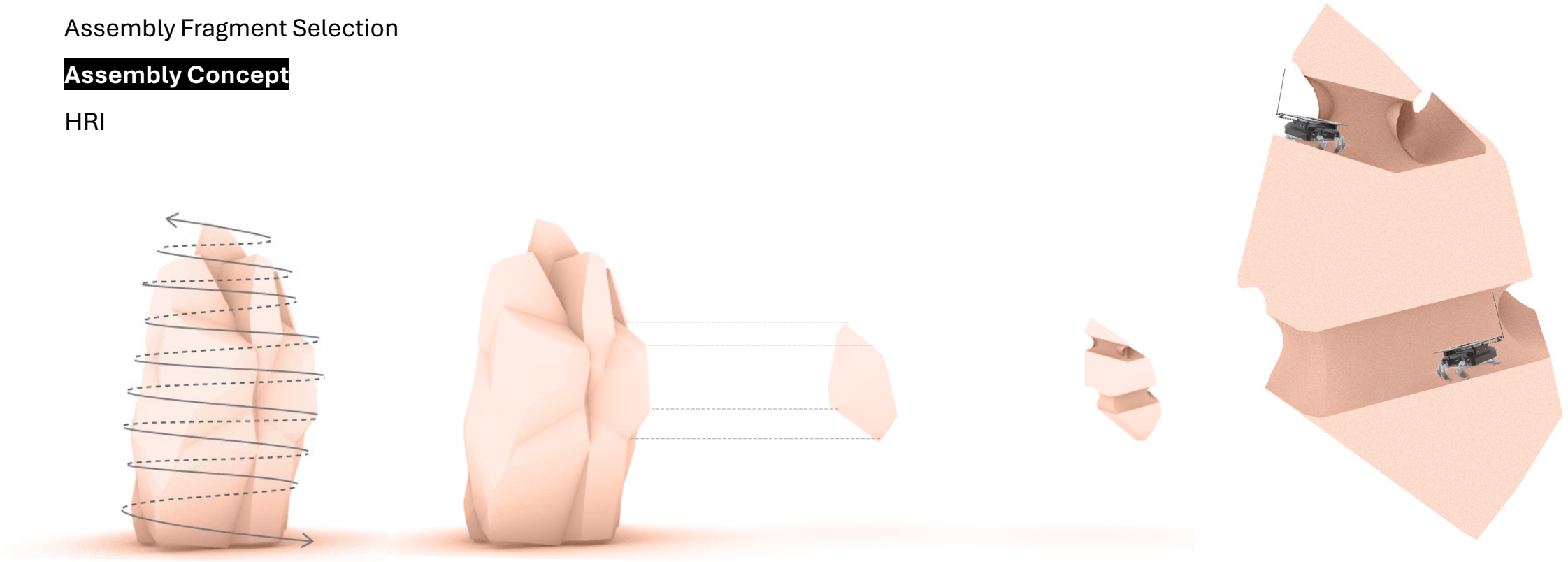
Wall robotic assembly simulation

HRI & Assembly Process

Assembly Fragment Selection

Assembly Concept

HRI



External map built into exterior walls to allow for construction and maintenance with Lunar Zebro rovers

Fragment example

Lunar Zebro Robots are able to move up and down the structure

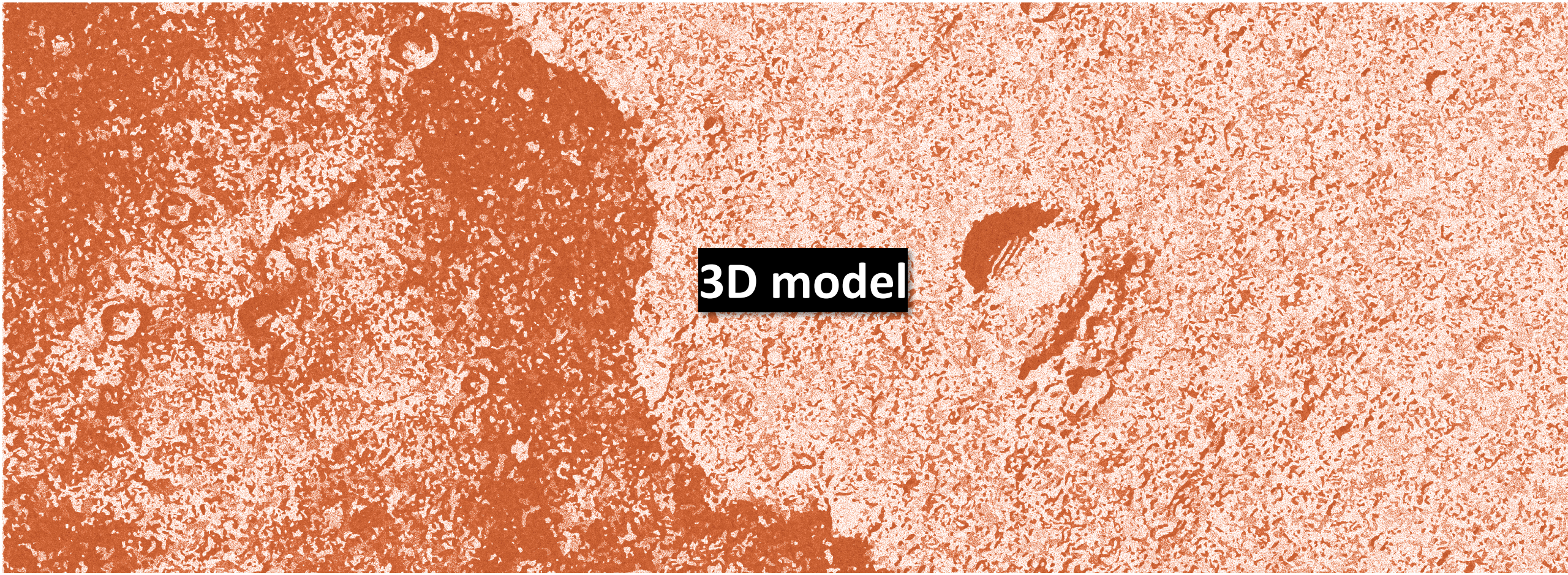
HRI & Assembly Process

Assembly Fragment Selection

Assembly Concept

HRI

Human Robotic Interaction (Self-made, 2025)

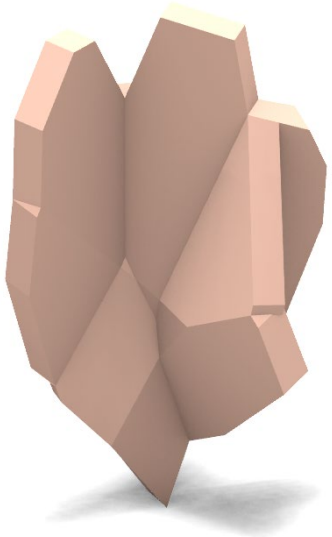

3D model

3D Model

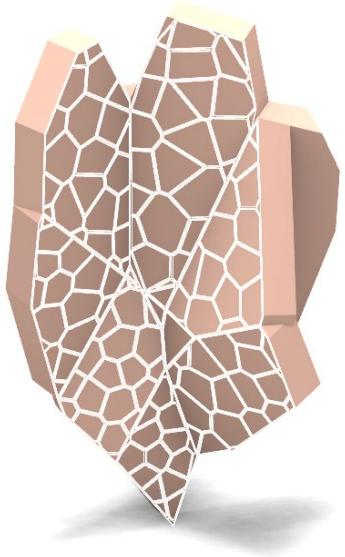
Digital Model

Printed model

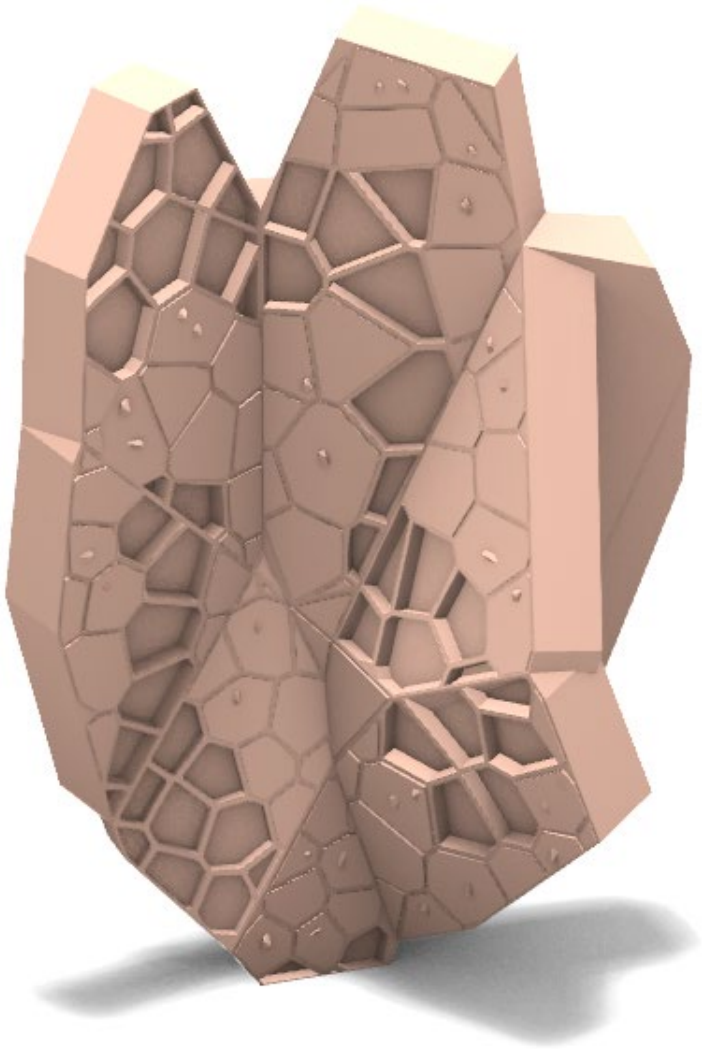
Step No. 1
Selecting the surfaces



Step No. 2
Extruding the surfaces
creating volumes



Step No. 3
Generating the Voronoi pattern
to define the walls



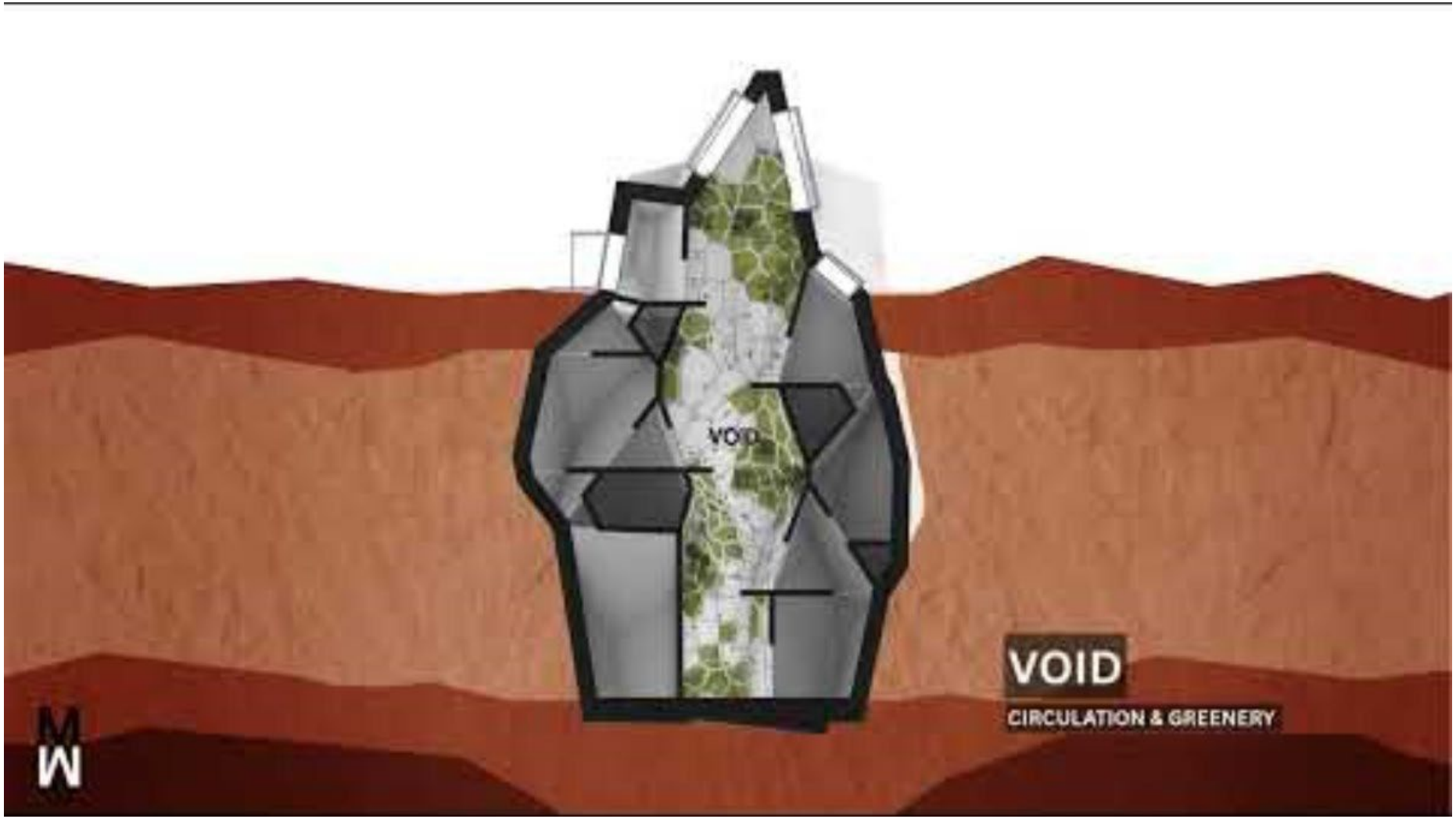
Final Digital Model

3D Model

Digital Model

Printed Model

Video



https://youtu.be/Hlxlo0ZeRl8