P5 Presentation

Terraforming Moon

Humanizing Lunar Living through Human-centric Design

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Lunar Architecture and Infrastructure Graduation Studio 2024/25 | TU Delft Faculty of Architecture

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Settling in the unknown…

Astronaut Harrison Schmitt exploring lunar surface, Apollo 17 (1972), NASA.

Settling in the unknown…

Mount Etna, Sicily, TU Delft Lava Tube Mission (2024)

Settling in the unknown, on Earth

Expansive landscape…no human touch

Mount Etna, Sicily, TU Delft Lava Tube Mission (2024)

Need of something familiar…

human infrastructure as marker

Mount Etna, Sicily, TU Delft Lava Tube Mission (2024)

Lunar environment: physically hostile

Habitat = protection

Source: Architecture for Astronauts, last column added by author

Condition	Earth	Moon	Design Implications
Gravity	1 g	1/6 g	Consider low gravity effects
Atmosphere	1 bar (O2, N2, CO2)	~0 bar (almost vacuum)	Pressurized vessel
Length of day	24 hours	28 Earth days (14 days light / 14 days dark)	Site selection
Temperature	Mean 15°C Range: -89°C – 60°C	Mean -20°C Range: -233°C – 123°C	Thermal enclosure
Radiation	Protection by Earth's atmosphere	Exposure to space radiation, secondary radiation from surface	Radiation enclosure
Water	70.8% surface	In deep permanently shadowed craters & binded in regolith	Limited water
Dust	Generaly not harmful	Pervasive & potentially toxic, electromagnetic cling, lofts above surface	Physical enclosure
Others	-	Micrometeoroids, bright light & glare	Physical enclosure

Astronaut Harrison Schmitt exploring lunar surface, Apollo 17 (1972), NASA.

Lunar environment: mentally hostile

Habitat = protection + **habitability**

Habitability: the suitability and value of a built habitat (lunar habitation) for its inhabitants (researchers) in a specific environment (lunar surface) and over a certain period of time (long-term >1 year)

Adapted from Sandra Hauplik-Meusburger, Architecture for Astronauts

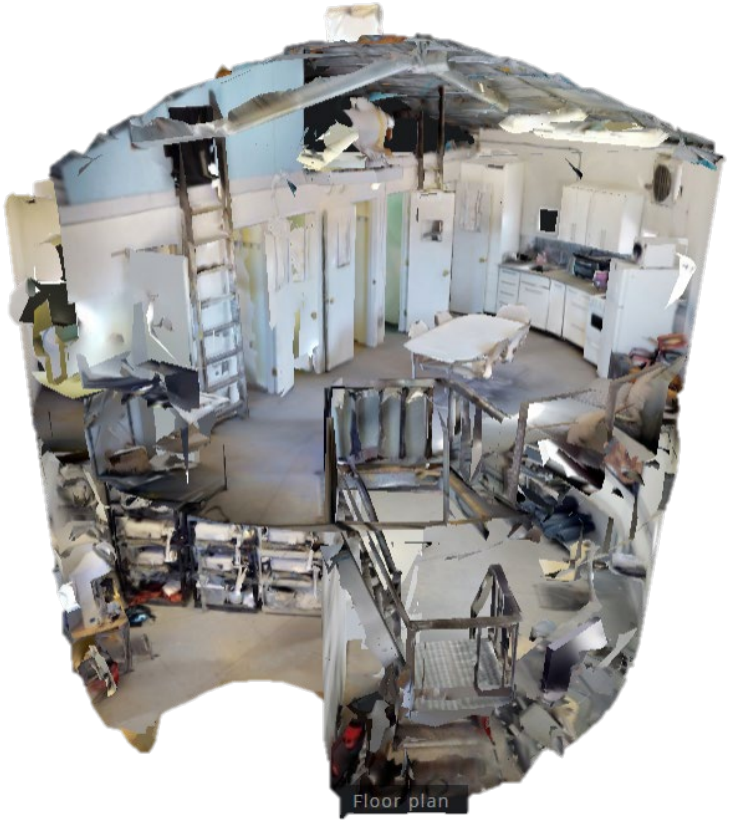
"The **most frightening aspect** (of partaking the analogue testing) was not the lethal cold outside, but the **isolation inside**,"

Beth Healey, comment on her 14-month stay in Concordia Station analogue mission.

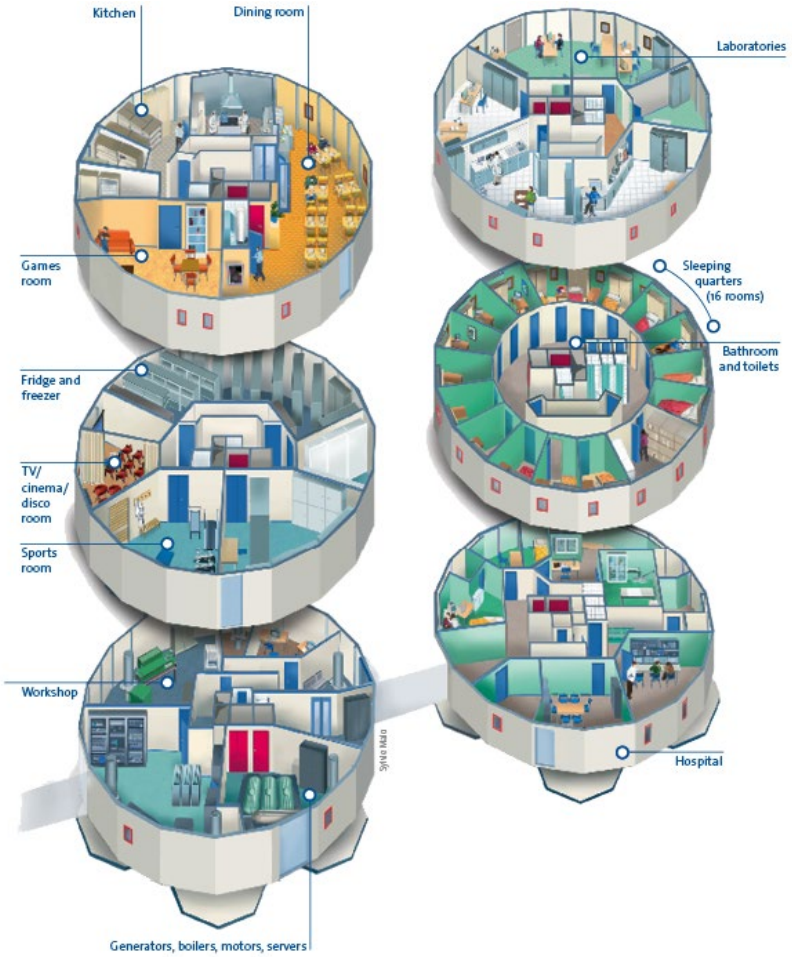
Astronaut Harrison Schmitt exploring lunar surface, Apollo 17 (1972), NASA.

Human de-centered design

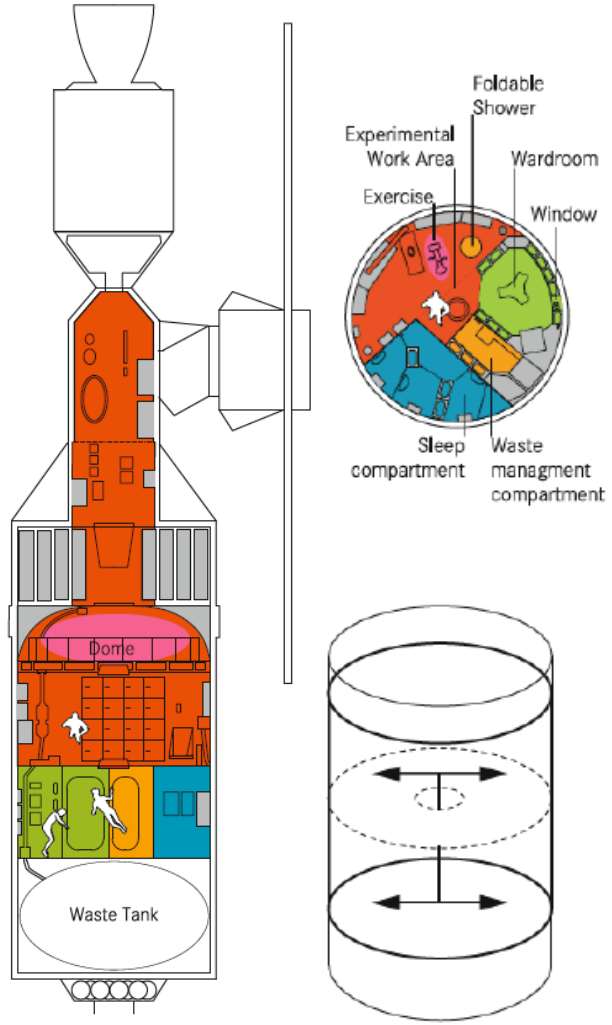
Current schemes developed from functional aspect (not focusing on human behavior)



Mars Desert Research Station, Utah, USA



Concordia Research Station, Antarctica



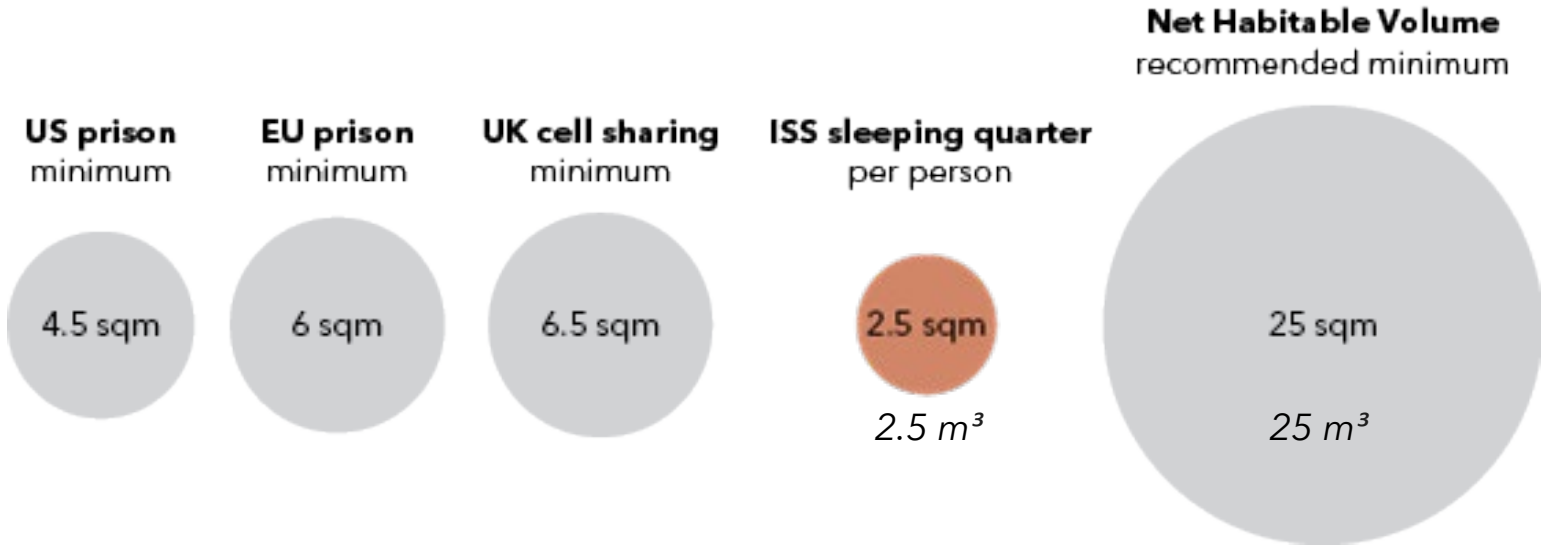
Skylab Space Station

Human de-centered design

Limited private area

"We were stuffed in the capsule [Salyut] like sardines in a can."

Jerry Linenger, 2000



Short-term missions → **Long-term habitation**

Functional design → **Human-centric design**

“surviving” → **“living”**

Human-centric design

in an Isolated, Confined, and Extreme (ICE) habitat

Personalization

"(On sleeping) It's got to be a place that can be modified in the way any **individual desires**."

Gerald Carr, Skylab 4, NASA. 1974

Variety Social Interaction

"…**availability of an open, communal area is very important** for crew morale and productivity during long duration isolation and confinement in space."

Excerpts from NASA Human Integration Design Handbook, on Skylab and Shuttle-Mir experience.

Owen Garriott, Skylab 3

Dedicated dining table, Skylab Station.

Problem Statement

Lack of space architecture precedents that prioritizes human behaviour in the design.

The social and psychological effects of long-term isolated nature of lunar habitation requires more human-centric design approaches.

Research Question

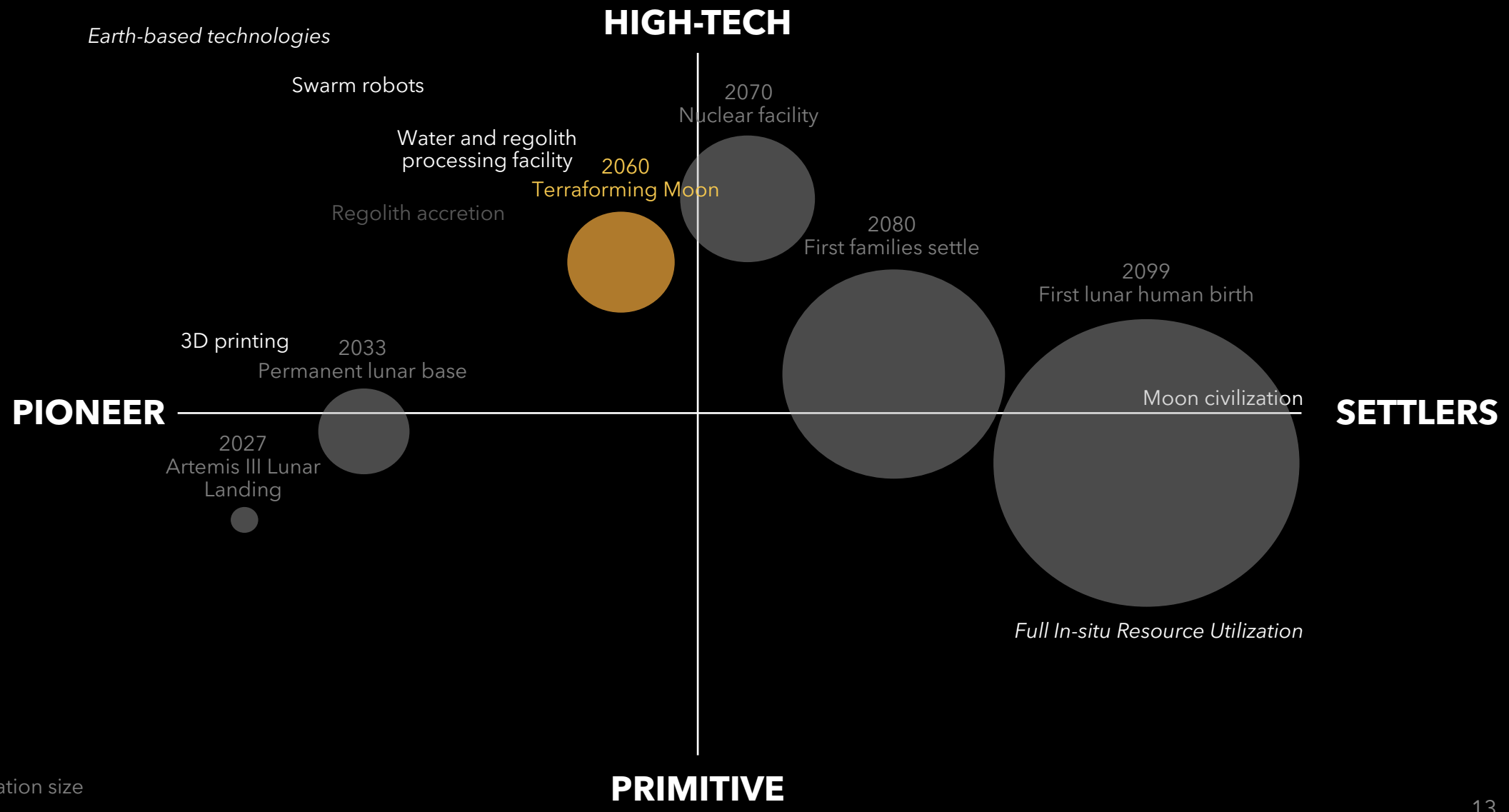
How to incorporate **user-defined spaces** based on **human-centric design principles** in designing long-term lunar habitation that **balances social interaction and private boundaries**, for the psychosocial well-being of the inhabitants?

Design Direction

A lunar habitat with heterogeneous spatial configurations to facilitate graduated access, ranging from communal engagement to secluded privacy.

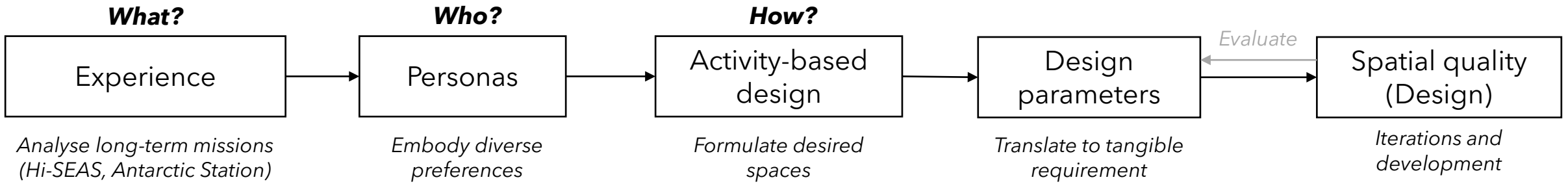
Limitations & Assumptions

Timeline



Human-centric Design

Using human experiences as data and human preferences as design guide



Personal
Preferences
Behaviours

Community
Interactions
Activities

6-crew members
3 men + 3 women
(1 couple)
1 robot

Work

Social

Personal

Openness
Open / Enclosed

Size
Private / Small Groups / All

Access
Direct / Indirect

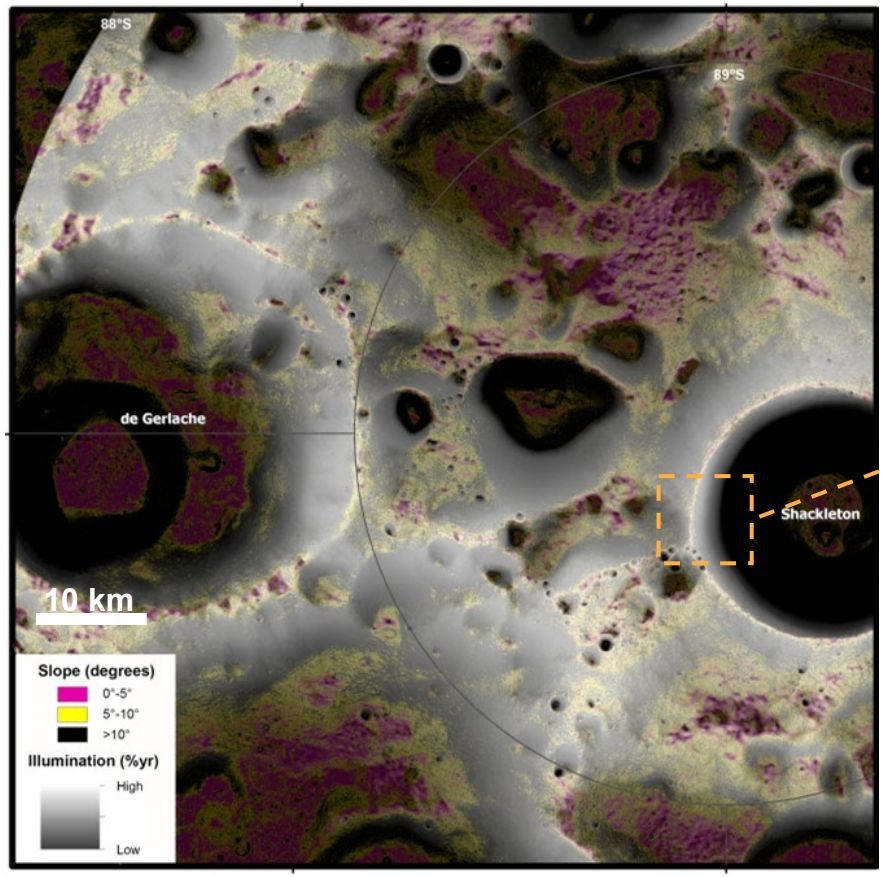
HOW TO REPRESENT HUMAN INTERACTION & PERSONAL PREFERENCES ARCHITECTURALLY?

HOW TO DESIGN FOR IT?

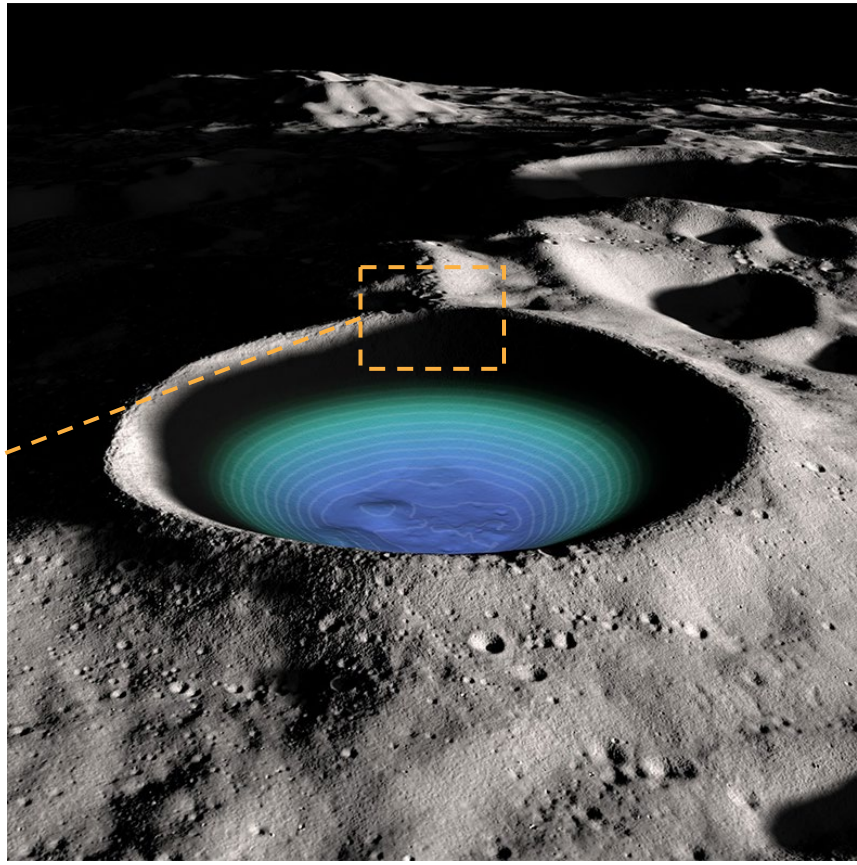
Site: Lunar South Pole, Ridge of Shackleton Crater

1. Candidate for lunar base
2. Proximity to resources:

- **Eternal sunlight area →** energy source and daylight utilization
- **Permanently Shadowed Region →** hosts water-ice, hydrogen, and early Solar System volatiles (for ISRU)



Annual Illumination and Topographic Slope, LPI
*Eternal sunlight areas has >80% illumination/year

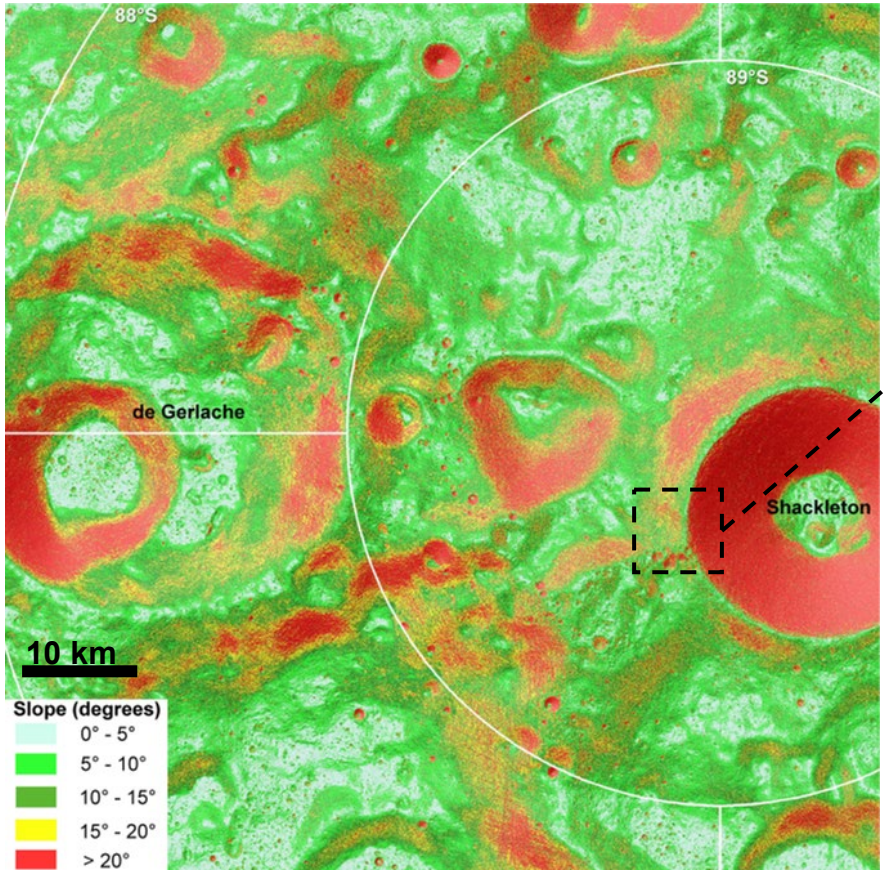


Shackleton Crater, NASA Goddard

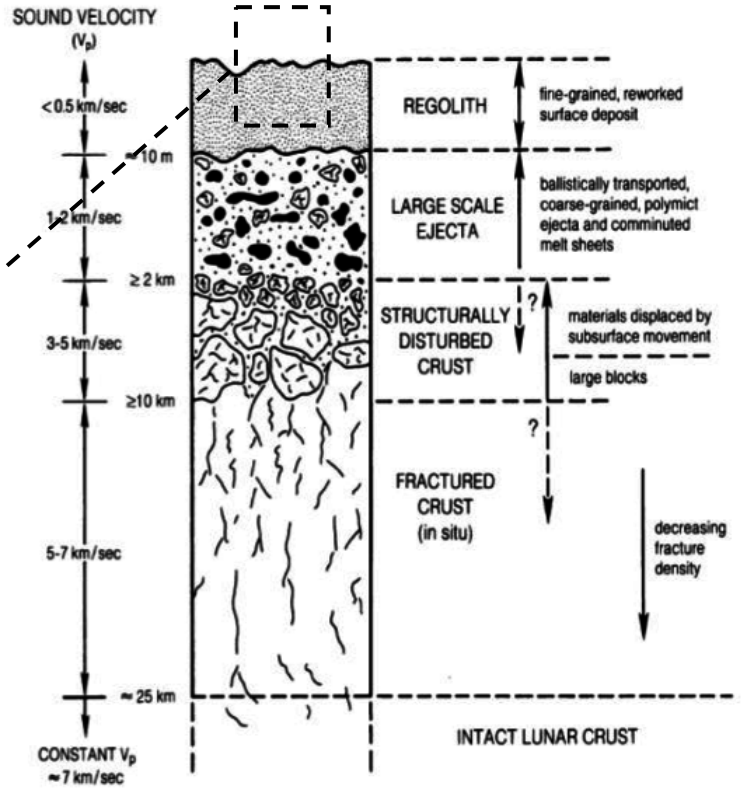
Site Condition

Lunar South Pole, Ridge of Shackleton Crater

- Slope 15° - 20°
- Going underground provides protection from radiation, extreme temperature, and lunar dust
- Loose regolith layer → allows possible excavation & collection of material for in-situ construction (geopolymer binder)



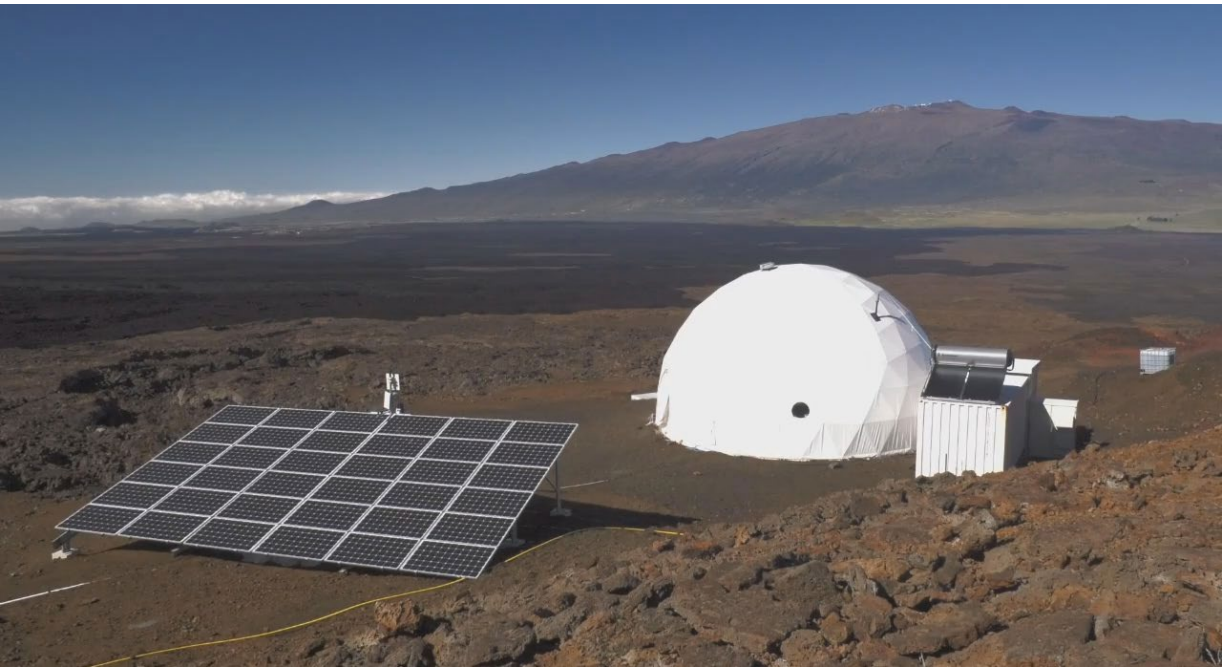
Slope Map of Lunar South Pole
Polarsteregoraphic Projection, Lunar Planetary Institute



Assumed ground composition from Lunar Stratigraphy,
Sakshi Namdeo et. Al.

Analog counterpart on Earth

Learning from long-term habitation within Isolated, Confined, and Extreme (ICE) Habitat



Hi-SEAS, Hawaii, USA
Analog habitat for Mars
Study focus on crew dynamics

McMurdo Station, Antarctica
Research station in extreme environment

Learning from analog

Importance of designated privacy levels

- Social space separated from work areas → allow more **varied social interactions** than purely work habitat

Social space as "third place"

Learning from analog

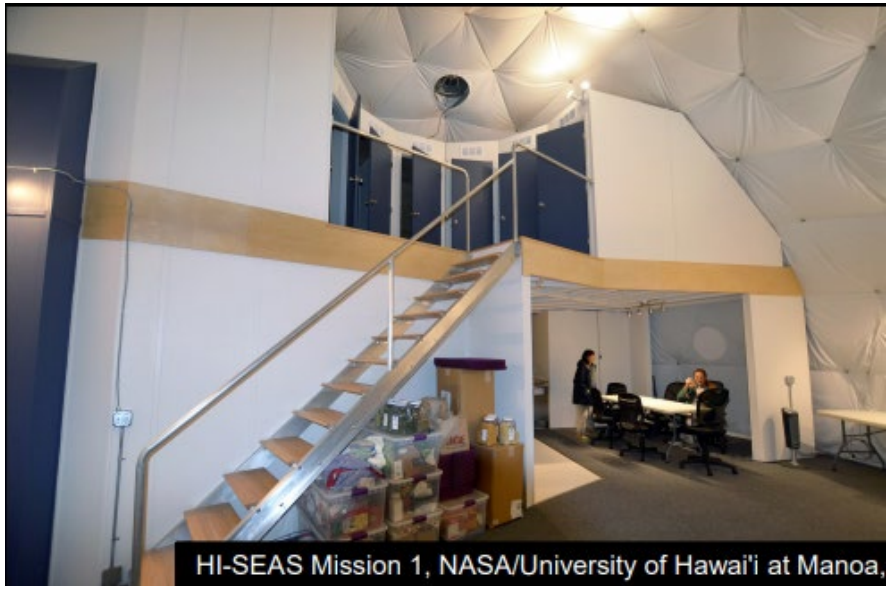
Importance of designated private space

- "The existence of the private quarters is more important than the size."
- "Stairs as physical separation of **rest** and **work** space,with the action of going up as mental cue to rest"
- "Allow personalization as an important creative outlet!"

Angelo Vermuelen on Hi-SEAS Mission, lecture in TU Delft (2024).

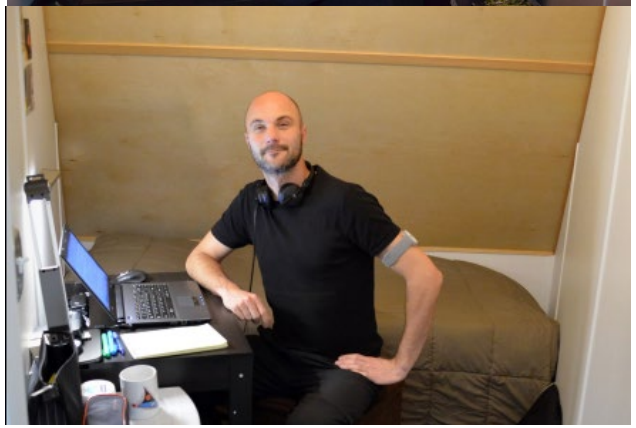
Private quarters

Transition from public to private



Hi-SEAS Mission NASA, Angelo Vermuelen

Personalization of private quarters



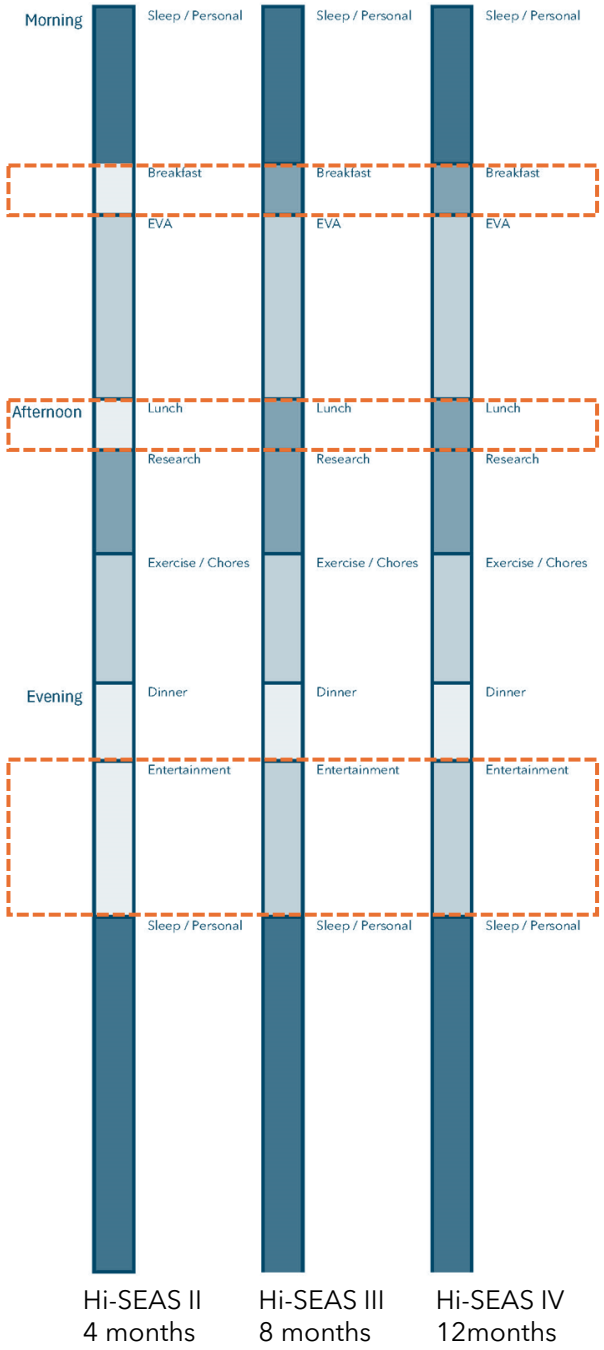
Hi-SEAS Mission NASA, various sources

Learning from analog

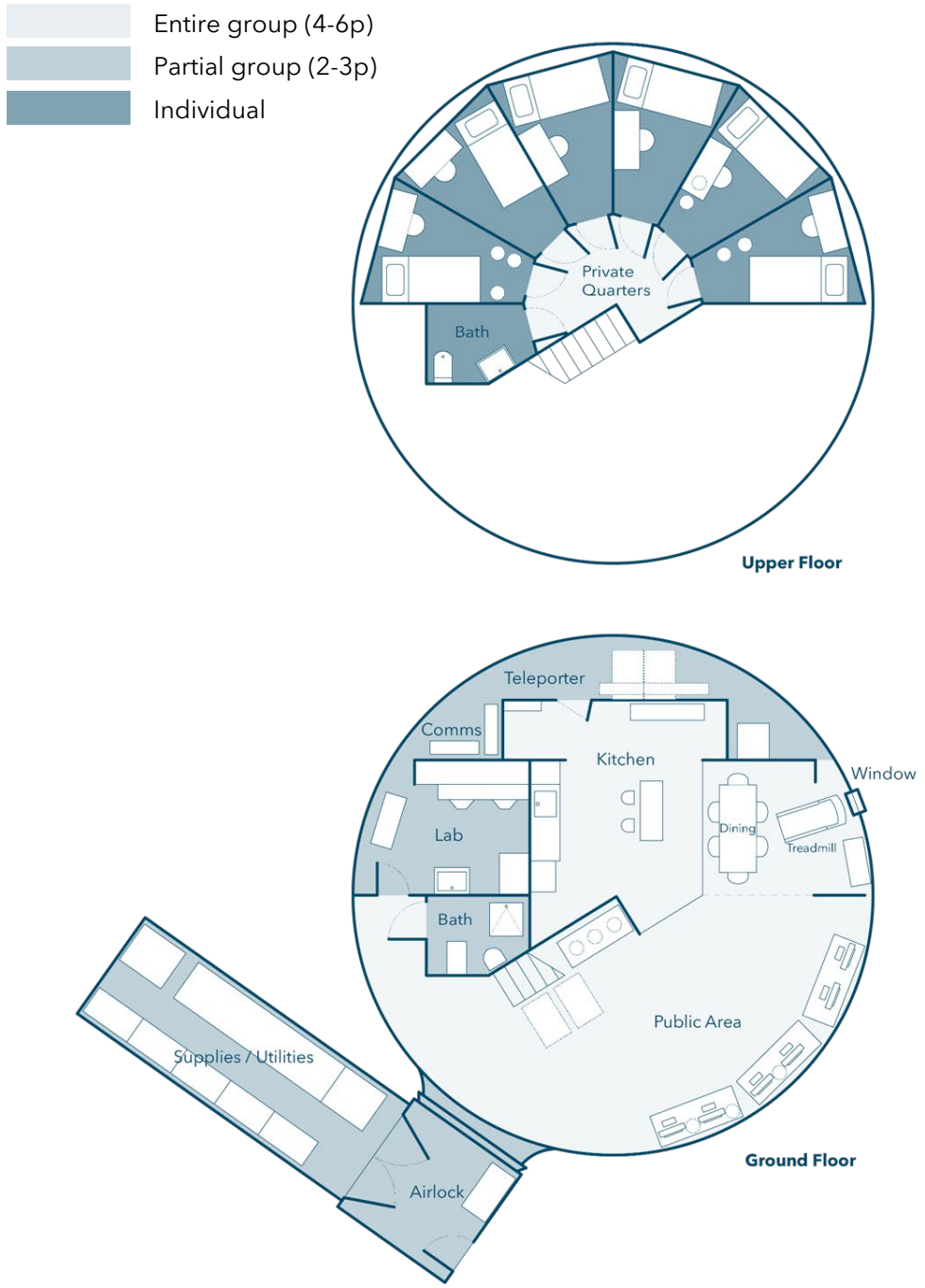
Importance of privacy gradient

Hi-SEAS Missions

- Declining participation in group activities over time
- Formation of social cliques over time leads to frustration on the lack of semi-private space
- *"I abhorred the idea of crew members working in separated sections and made a case for a **flexible open floor plan**."* (Commander Angelo Vermuelen, Hi-SEAS I)
- *"One thing I would consider is **having cubicles** instead of the work bench. There is little privacy, and when you have someone trying to micromanage your own work it's harder to escape. Most of my crew **worked in their rooms** most of the day…."* (Simon Engler, Hi-SEAS I)



Complex social interaction in daily schedule



Dichotomic social interaction in habitat

Learning from analog

Organic social condenser

McMurdo greenhouse initiative in Antarctica, ca. 1990, Phil Sadler

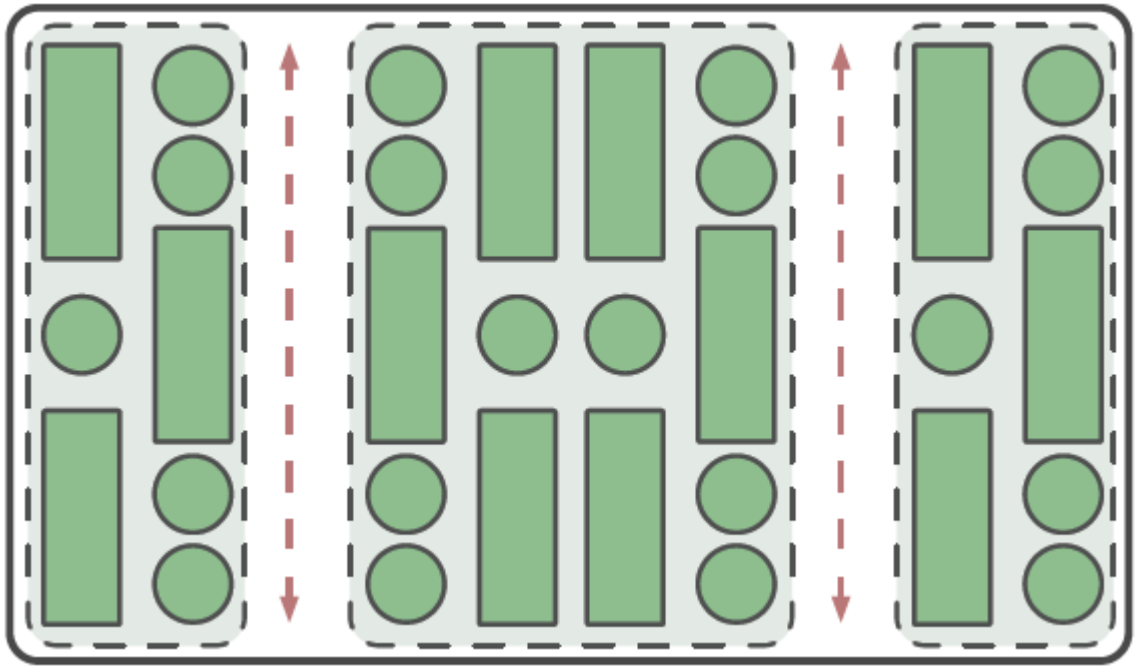
Harvesting plants in Hi-SEAS GreenHab

View to outside cave. Lava Tube Mission (2024)

- Greenhouse as popular therapy space in McMurdo → smell of living plants and feel of warm humid environment
- Cave entrance as popular seating space in Lava Tube Mission → view of greenery

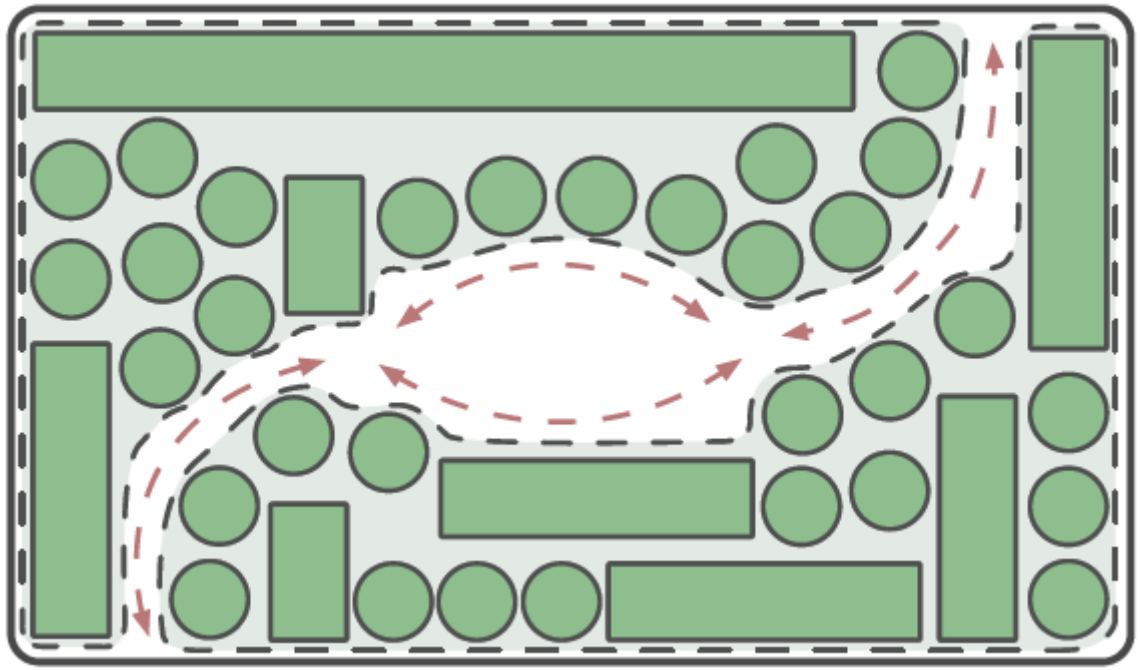
Layout Strategy

Organic layout for long-term health benefits



Rigid greenhouse

- Efficient, prioritizes the **plant research**

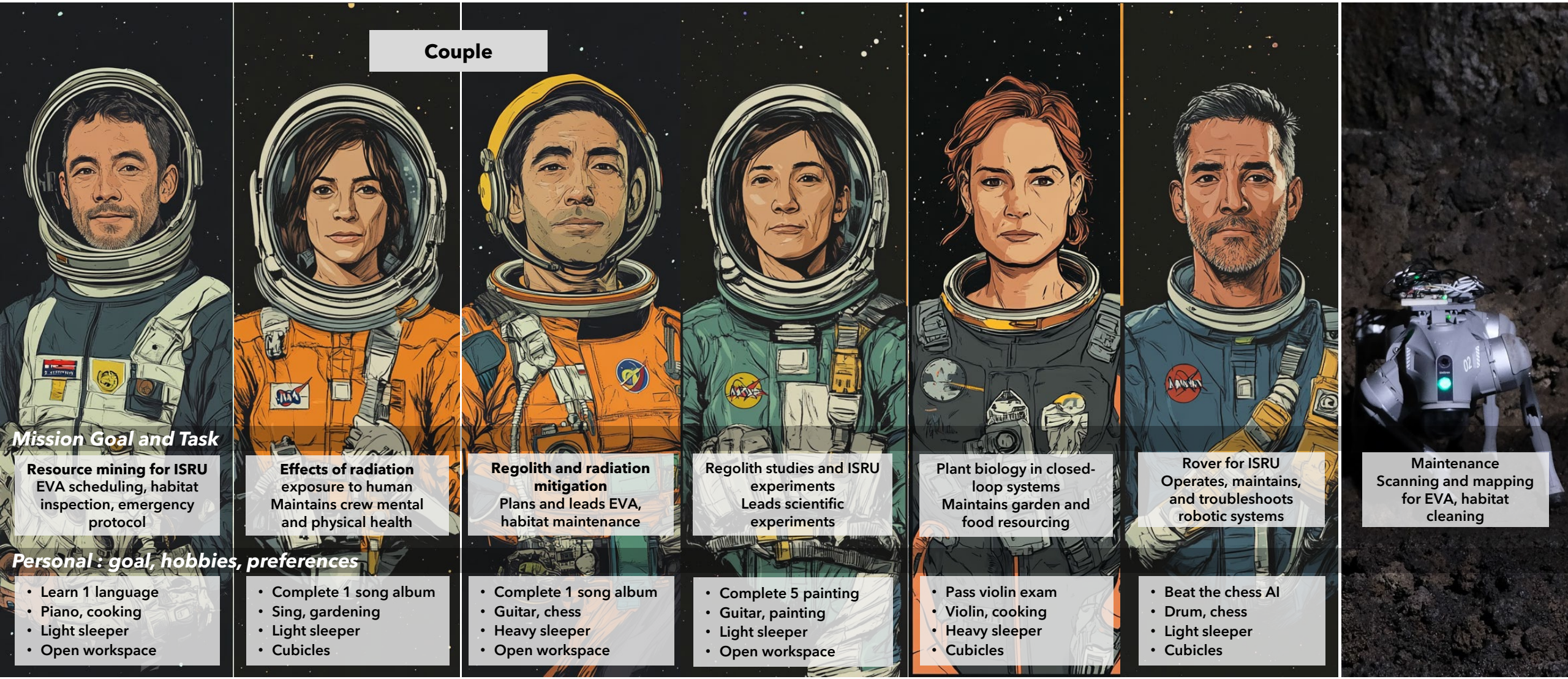


Organic greenhouse

- Habitable qualities, consider the **human experience**

Diagrams from from The Design of Habitats for the Long-Term Health of Inhabitants in the Extreme Environments of Earth and Outer Space (Bassingthwaighte, 2017)

Personas: fictional crew members



Couple

Mission Goal and Task

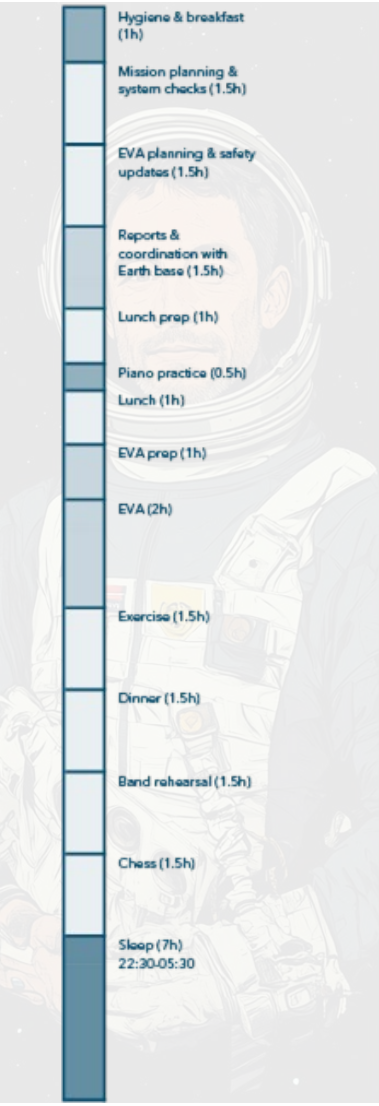
Commander, 37	Medic, 33	EVA Specialist, 35	Geologist, 32	Ecologist, 29	Roboticist, 30	Habitat Robot
Resource mining for ISRU EVA scheduling, habitat inspection, emergency protocol	**Effects of radiation** exposure to human Maintains crew mental and physical health	**Regolith and radiation mitigation** Plans and leads EVA, habitat maintenance	Regolith studies and ISRU experiments Leads scientific experiments	Plant biology in closed-loop systems Maintains garden and food resourcing	Rover for ISRU Operates, maintains, and troubleshoots robotic systems	Maintenance Scanning and mapping for EVA, habitat cleaning

Personal : goal, hobbies, preferences

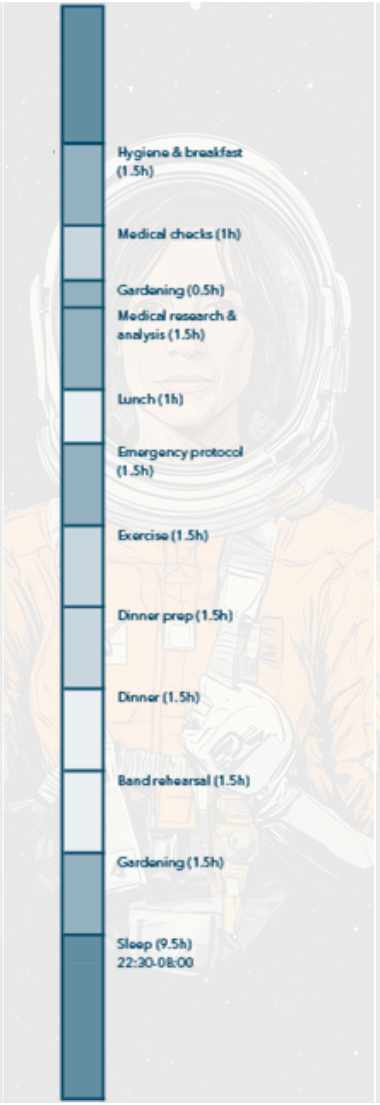
Commander, 37	Medic, 33	EVA Specialist, 35	Geologist, 32	Ecologist, 29	Roboticist, 30
• Learn 1 language • Piano, cooking • Light sleeper • Open workspace	• Complete 1 song album • Sing, gardening • Light sleeper • Cubicles	• Complete 1 song album • Guitar, chess • Heavy sleeper • Open workspace	• Complete 5 painting • Guitar, painting • Light sleeper • Open workspace	• Pass violin exam • Violin, cooking • Heavy sleeper • Cubicles	• Beat the chess AI • Drum, chess • Light sleeper • Cubicles

Personas' activity

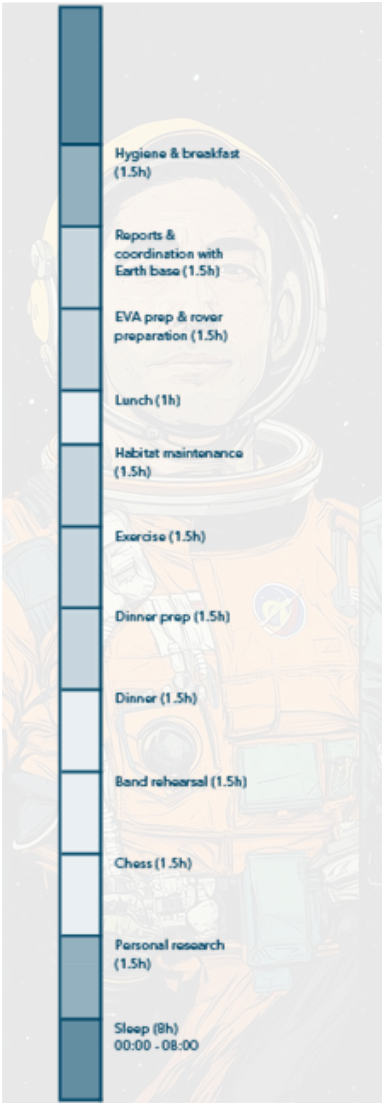
Sleep | Individual | Partial group | Entire group



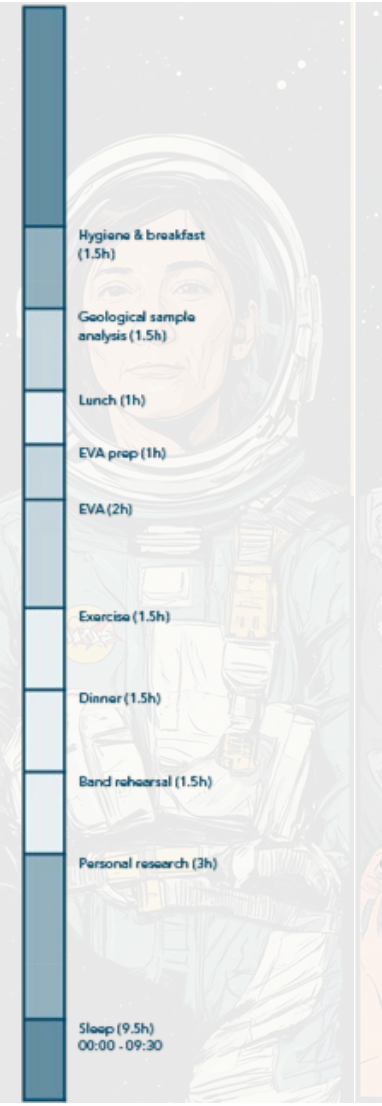
Commander, 37



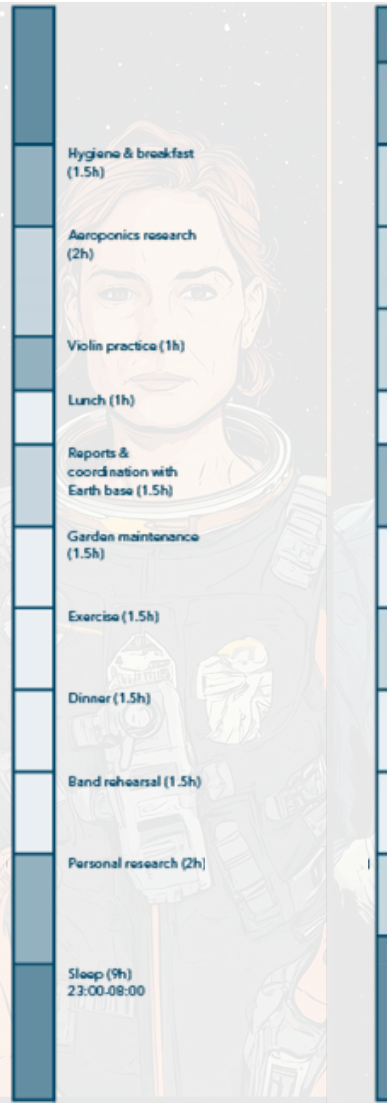
Medic, 33



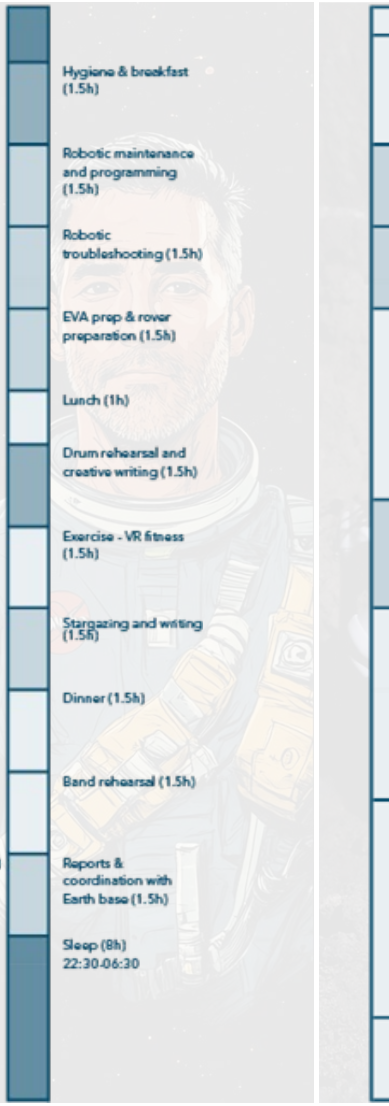
EVA Specialist, 35



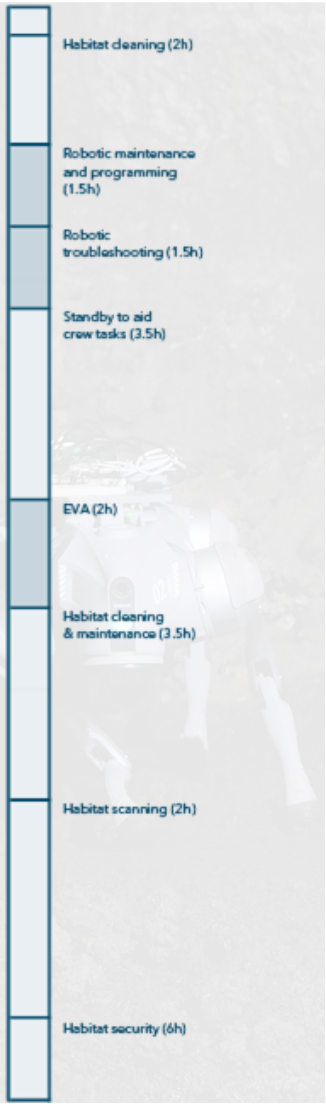
Geologist, 32



Ecologist, 29



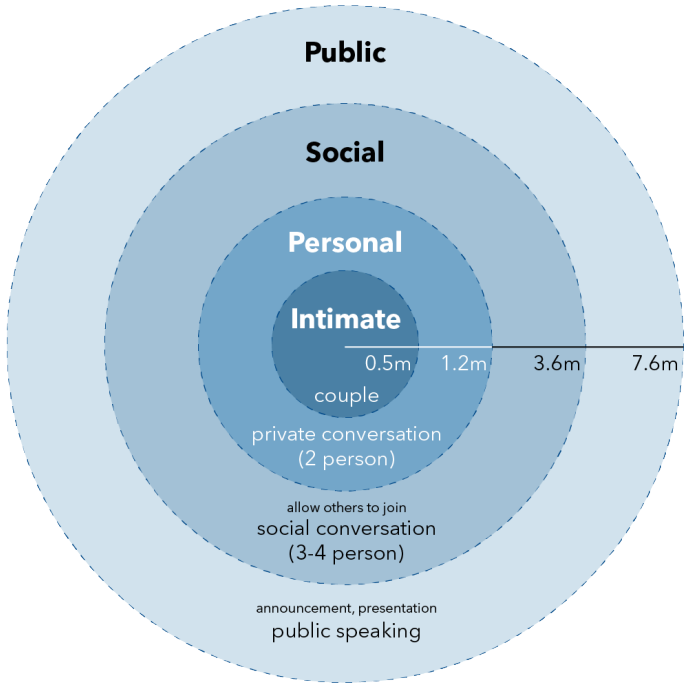
Roboticist, 30

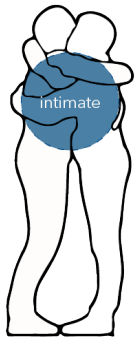


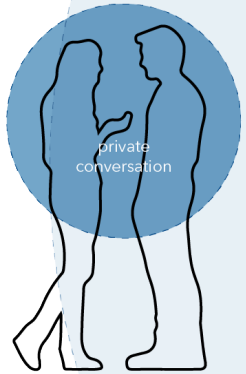
Habitat Robot

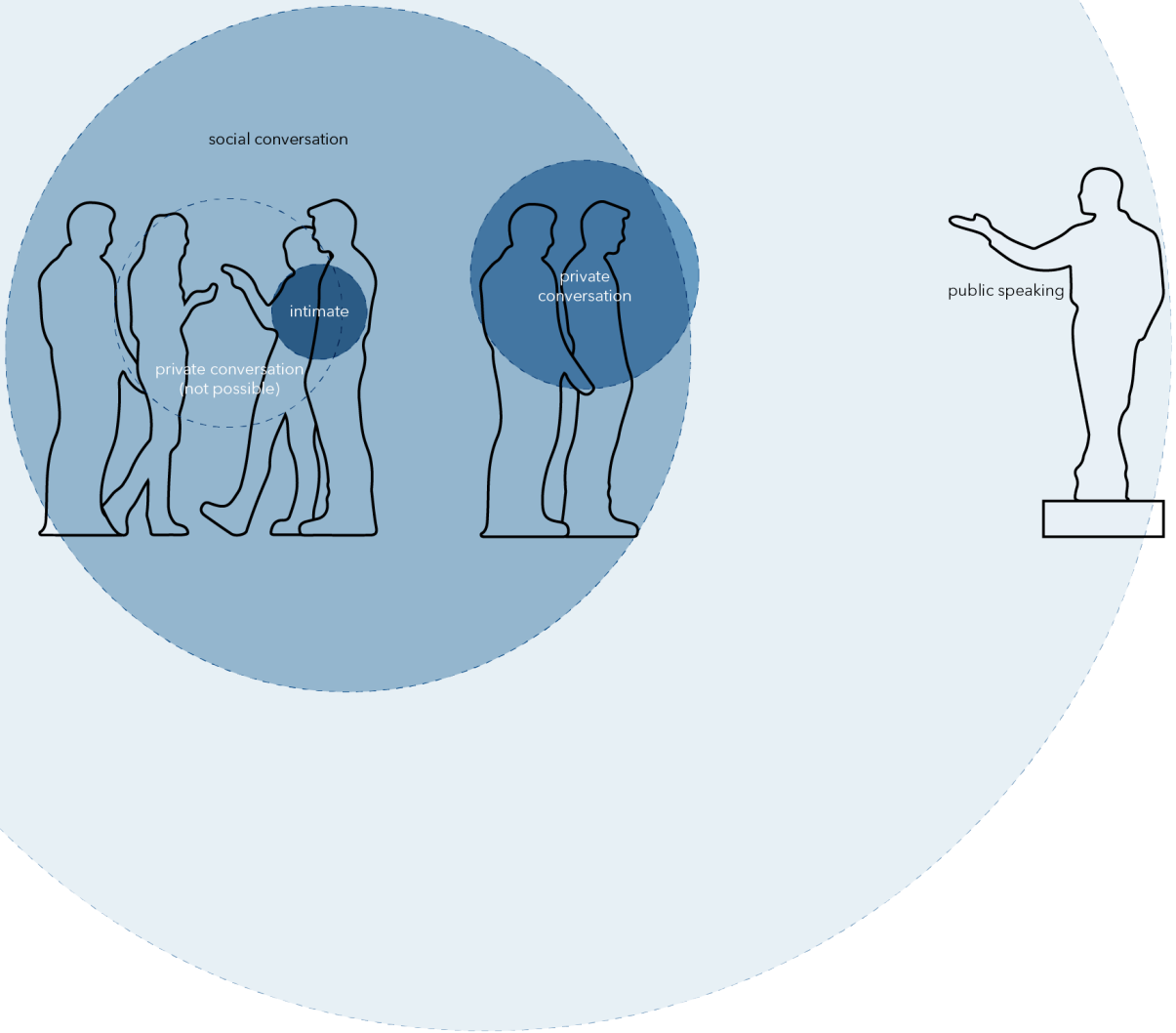
Activity-based catalogue

How do you interact?







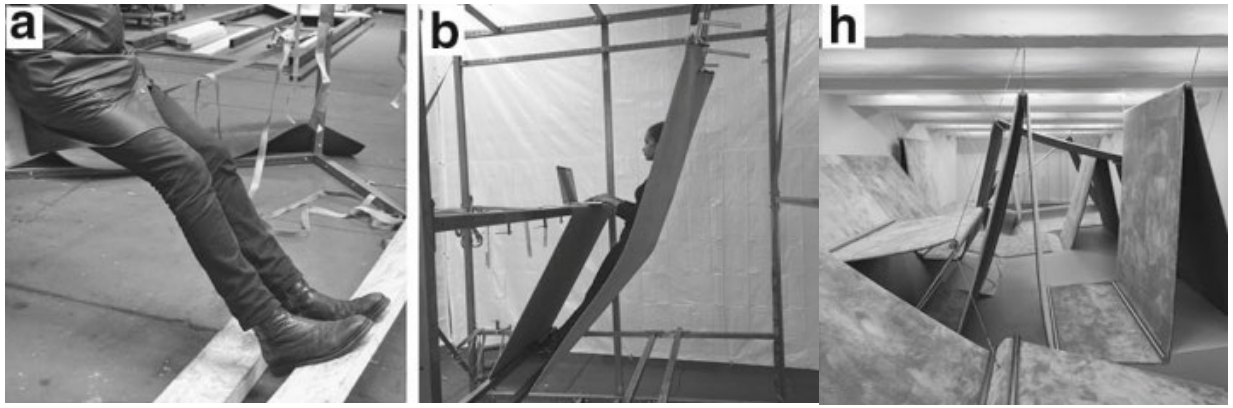


Based on Proxemics by Edward T. Hall

Reference_Situated Interface

User adjusting to the space

to enable and disable certain activity and movement

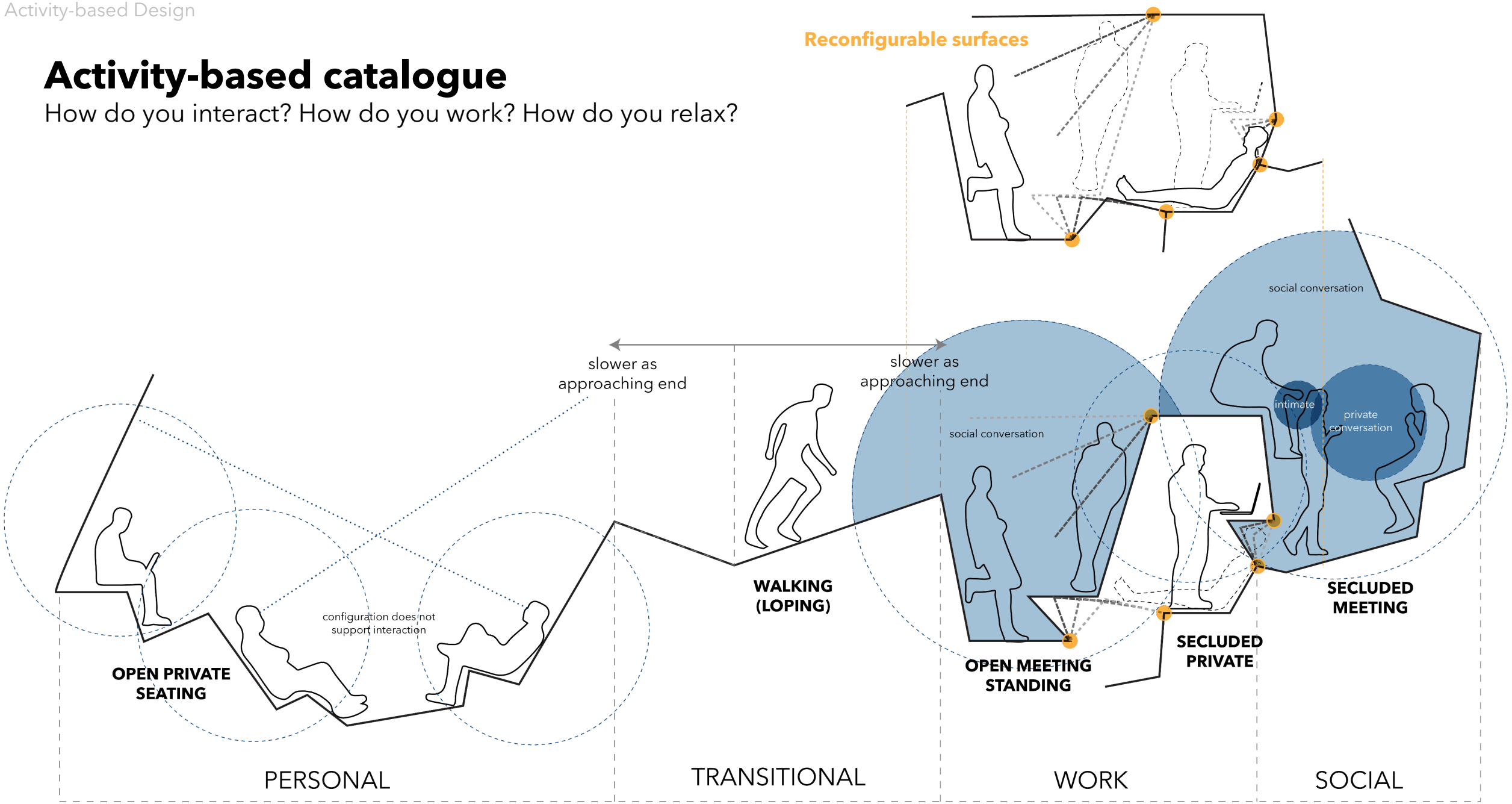


A World Without Chairs
Art installation, van Dijk and Rietveld in Situated Anticipation (2018)

The End of Sitting
RAAAF & Barbara Visser (2014)

Activity-based catalogue

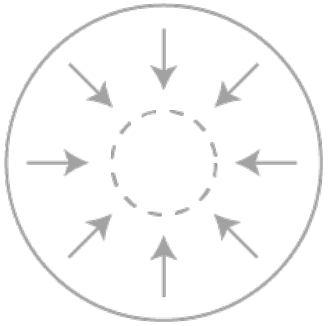
How do you interact? How do you work? How do you relax?



Spatial strategies to vary social interaction

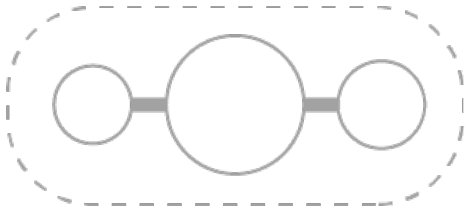
Homogenous space
Early space civilization
(short-term)

Central core

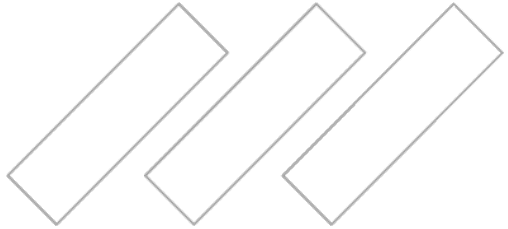


Centralized views

Uniform configuration

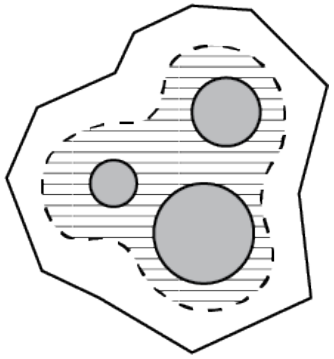


Corridors

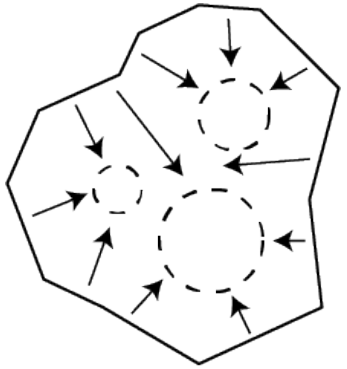


Repetitive structure

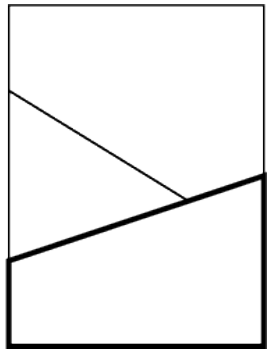
Heterogeneous space
Next generation
(long-term)



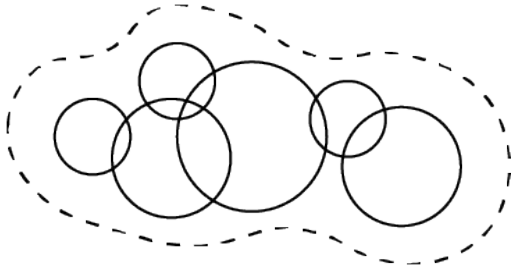
Multiple cores



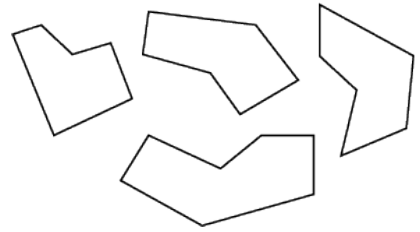
Varying views



Unique configuration



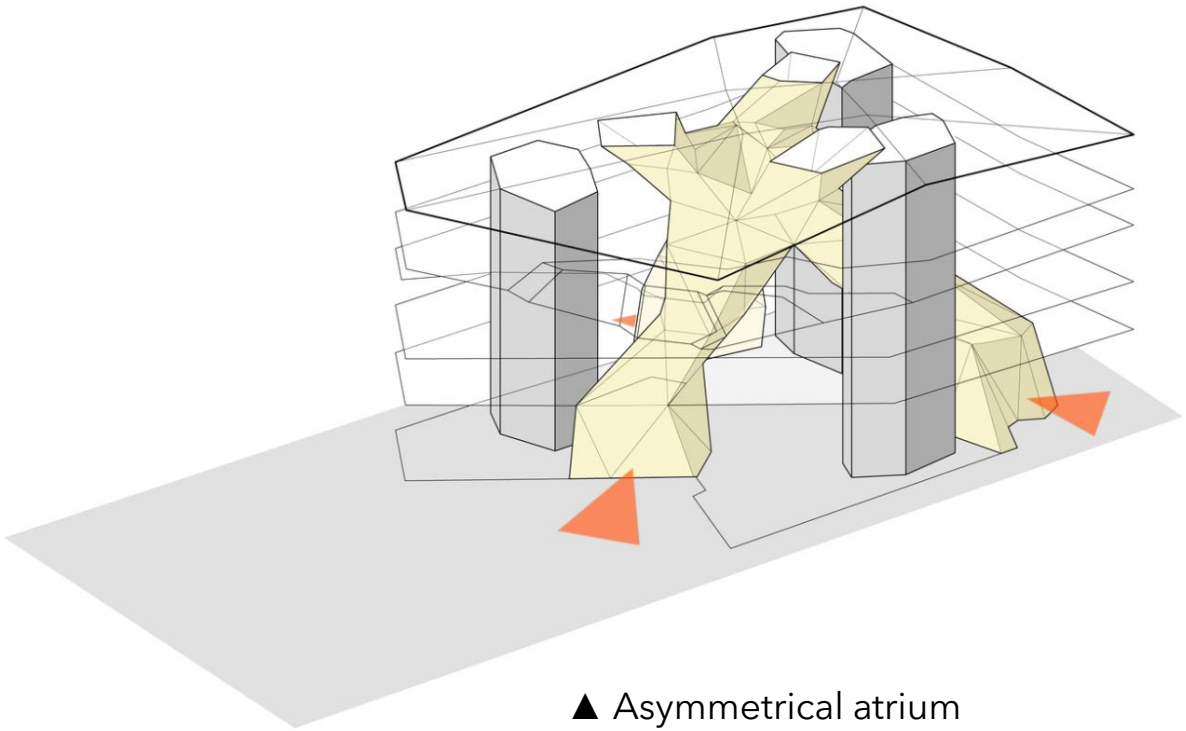
Intersection of spaces



Non-repetitive structure

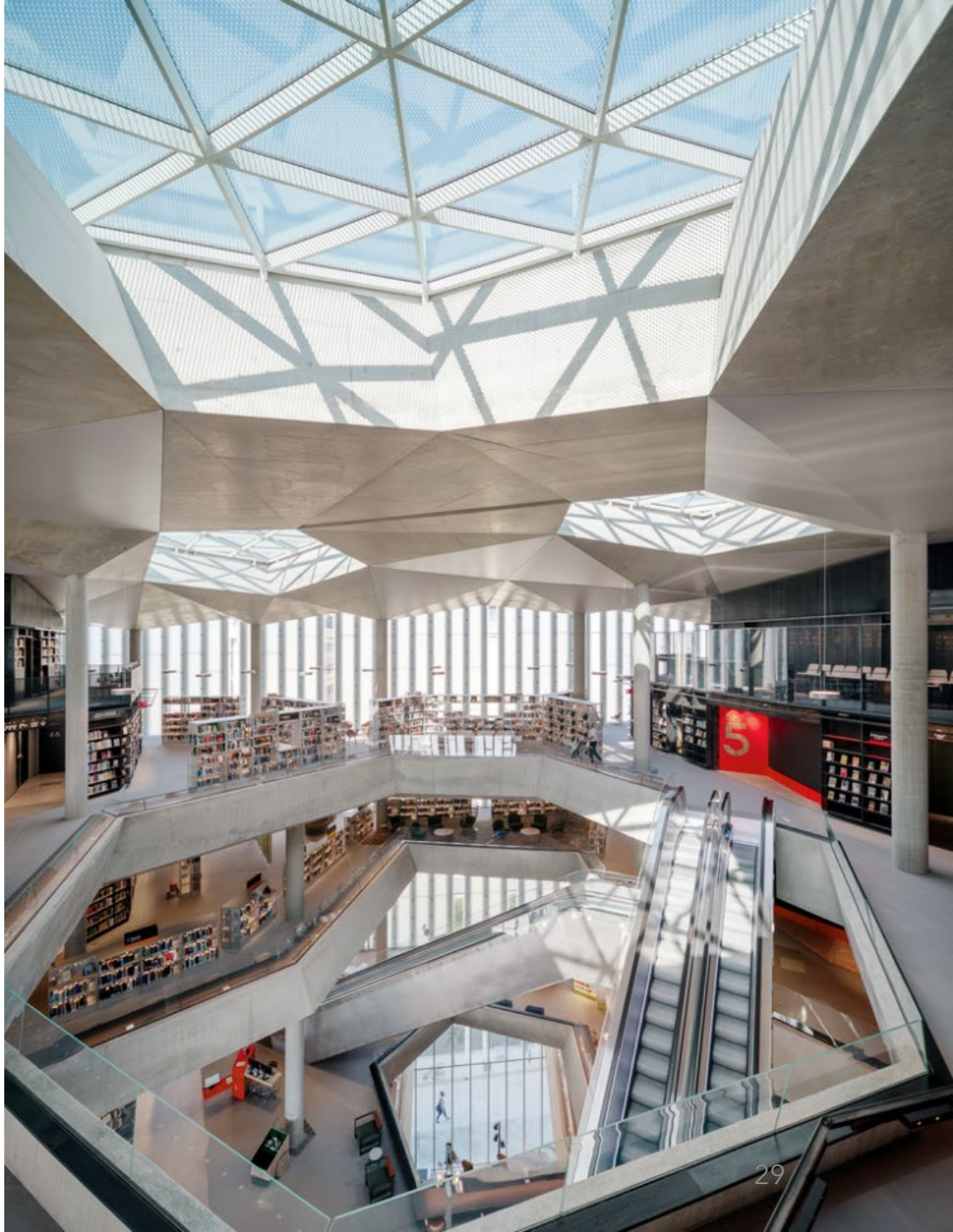
Reference_Intersecting Atriums

"Everyone's living room". Deichman Bjørvika, Oslo.



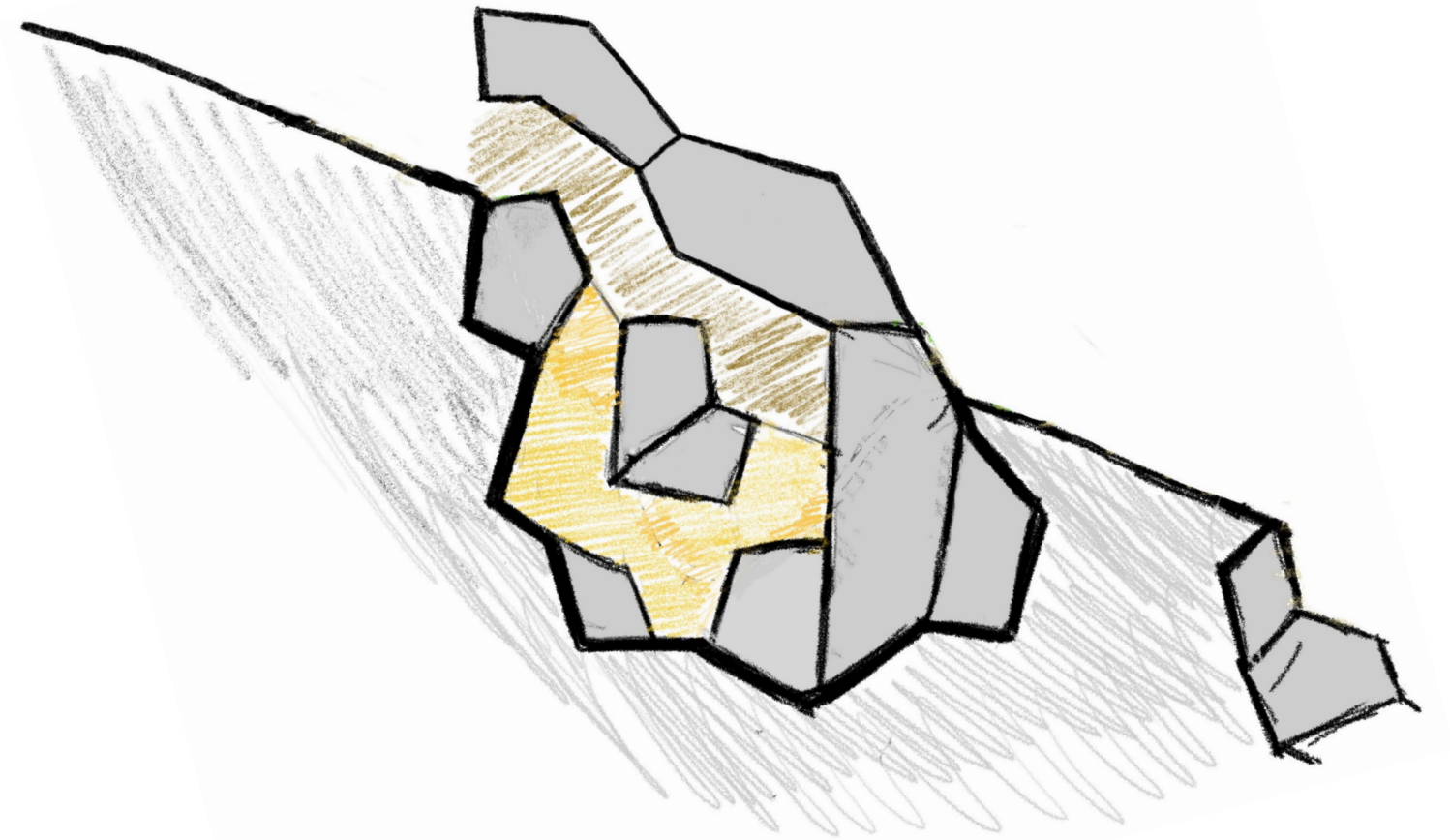
▲ Asymmetrical atrium

Varying pocket spaces & vantage points ▶



Sketch

Layered atriums



Upper atrium

Lower atrium

5m

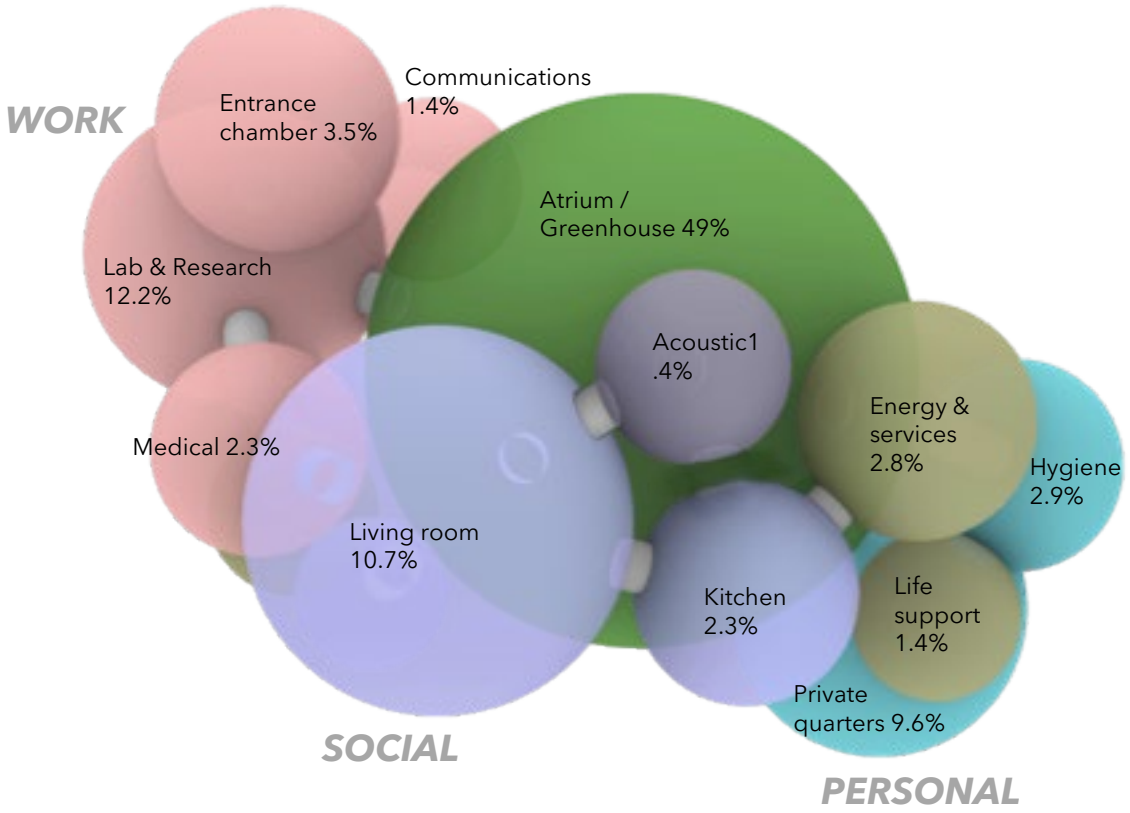

Design

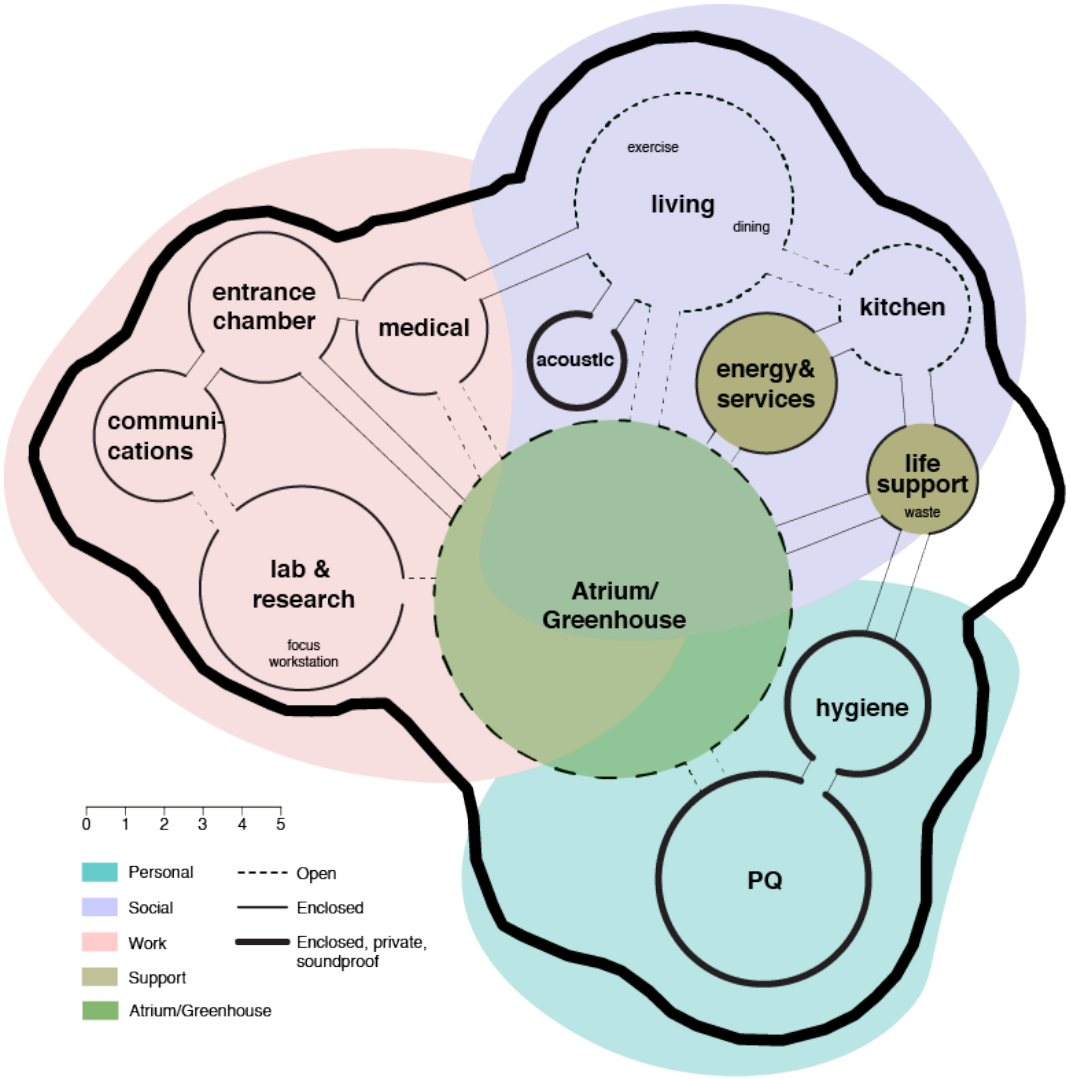
Baseline program requirements

	Rooms	Size					Activity			Privacy			Movement		Protection			
		Vol for 1 (m3)	Factor	Vol for 6 (m3)	% vol	%	Category	Cross-function	Detail	Personnel	Visibility	Audio	Speed	Arrangement	Duration	Garment	View outside	Access outside
PQ	Private Quarter 1 (Single)	15.0	4	60.0	6.99%		Personal	Work	Sleep, work, personal leisure	Individual/Couple	Enclosed	Soundproof	Slow	Flexible	>8 h	Clothed	Optional	No
	Private Quarter 2 (Couple)	22.5	1	22.5	2.62%	12.52%	Personal	Work	Sleep, work, personal leisure	Individual/Couple	Enclosed	Soundproof	Slow	Flexible	>8 h	Clothed	Optional	No
Bath	Bathroom	5.0	5	25.0	2.91%		Personal		Hygiene	Individual/Couple	Enclosed	Soundproof	Slow	Fixed	< 1 h	Naked	Optional	No
Collab	Collab room	2.5	3	7.5	0.87%	0.87%	Social	Work		Small groups (2-3)	Enclosed	Soundproof	Moderate	Semi-flex	1-8 h	Clothed	Optional	No
Kitchen	Kitchen	10.0	2	20.0	2.33%	2.33%	Social	Personal	Food prep, communal	Small groups (2-3)	Open	Neutral	Fast	Semi-flex	1-8 h	Clothed	Optional	No
Living Room	Dining table	5.0	6	30.0	3.49%		Social	Work	Communal, team meeting, game night	Large groups (4-6)	Open	Neutral	Moderate	Flexible	1-8 h	Clothed	Optional	No
	Exercise area (3 equipments)	8.0	3	24.0	2.80%	10.66%	Social	Personal	Combined with adjacent 26.8 m3	Small groups (2-3)	Open	Neutral	Moderate	Flexible	1-8 h	Clothed	Optional	No
	Open area (misc)	5.0	6	30.0	3.49%		Social	Work	Communal, informal meeting, Group exercise min. 11.8 m3	Large groups (4-6)	Open	Neutral	Moderate	Flexible	1-8 h	Clothed	Optional	No
	Observation	2.5	3	7.5	0.87%		Social	Personal	can be integrated in other functions	Small groups (2-3)	Optional	Neutral	Moderate	Fixed	1-8 h	Clothed	Essential	No
Green-house	Greenhouse 1 (food lab)	7.0	6	42.0	4.89%	48.57%	Support	Social	Each person oxygen 20m2 vegetation/year; crops 67m2	Large groups (4-6)	Optional	Neutral	Moderate	Fixed	1-8 h	Clothed	No	No
	Greenhouse 2 (oxygen)	62.5	6	375.0	43.68%		Support	Social	Remaining area to achieve 50% area of the habitat for vegetation	Large groups (4-6)	Open	Echo	Slow	Semi-flex	1-8 h	Clothed	Essential	No
EVA	Airlock (EVA prep)	10.0	3	30.0	3.49%	3.49%	Work			Small groups (2-3)	Enclosed	Neutral	Fast	Fixed	1-8 h	Suited	Essential	Yes
Medical	Medical bay	10.0	2	20.0	2.33%	2.33%	Work		1 bed + minimum storage	Small groups (2-3)	Enclosed	Neutral	Moderate	Flexible	1-8 h	Clothed	Optional	No
Lab & Research	Lab	12.5	6	75.0	8.74%		Work		Geology & biology lab	Large groups (4-6)	Enclosed	Neutral	Moderate	Flexible	1-8 h	Clothed	Optional	No
	Open workstation	5.0	3	15.0	1.75%	12.23%	Work	Social	6 desks open plan	Large groups (4-6)	Optional	Neutral	Moderate	Semi-flex	1-8 h	Clothed	Optional	No
	Focus workstation	5.0	3	15.0	1.75%		Work	Personal	Monitoring, call to Earth, command control	Small groups (2-3)	Enclosed	Neutral	Fast	Flexible	1-8 h	Clothed	Optional	No
Storage	Personal storage	2.0	6	12.0	1.40%	1.40%	Support			Storage	Enclosed	Neutral	Fast	Semi-flex	< 1 h	Clothed	No	No
	Food storage area	2.0	6	12.0	1.40%	1.40%	Support		Service	Storage	Enclosed	Neutral	Fast	Semi-flex	< 1 h	Clothed	No	No
	Lab storage	2.0	6	12.0	1.40%	1.40%	Support			Storage	Enclosed	Neutral	Fast	Semi-flex	< 1 h	Clothed	No	No
Service	Maintenance	8.0	1	8.0	0.93%		Support		System maintenance	Storage	Enclosed	Neutral	Fast	Fixed	1-8 h	Clothed	Optional	No
	ECLSS	8.0	1	8.0	0.93%	2.80%	Support			Storage	Enclosed	Neutral	Fast	Fixed	< 1 h	Clothed	No	No
	Waste management	8.0	1	8.0	0.93%		Support			Storage	Enclosed	Neutral	Fast	Fixed	< 1 h	Clothed	No	No
	Outside						Work			Large groups (4-6)	Open	Neutral	Fast	Flexible	1-8 h	Suited	Essential	Yes
	TOTAL			858.5	100.00%													
	Total green			417.0	48.57%													
	Total non-green			441.5														
	NHV per person	171.00																

Program Distribution

Functional connection and basic proportion

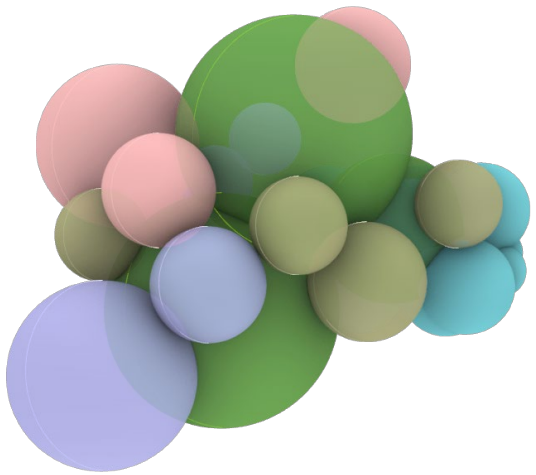




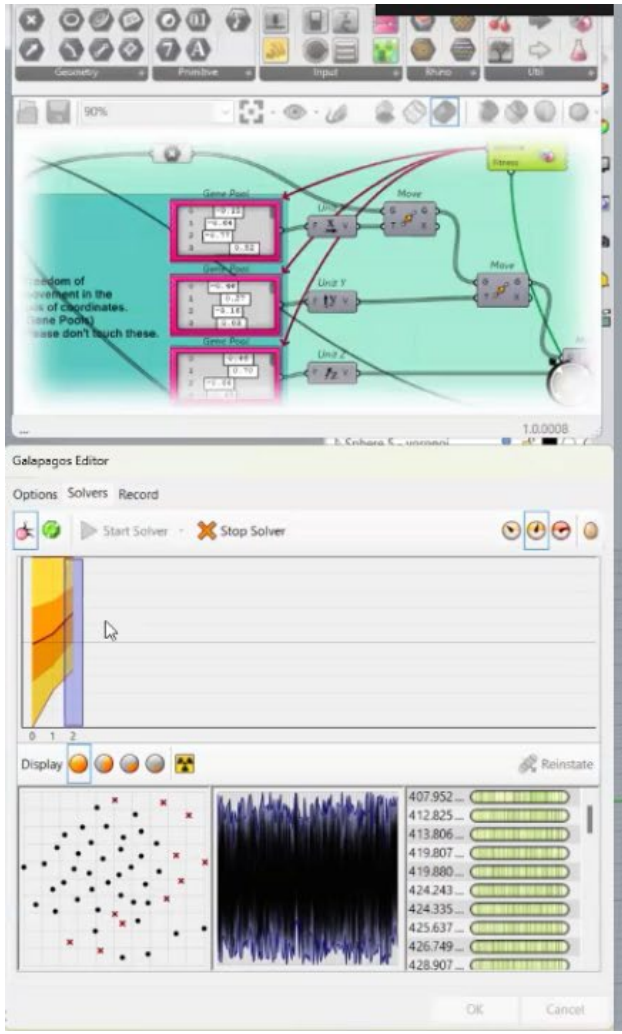
Greenhouse as atrium,
connecting 3 functional clusters

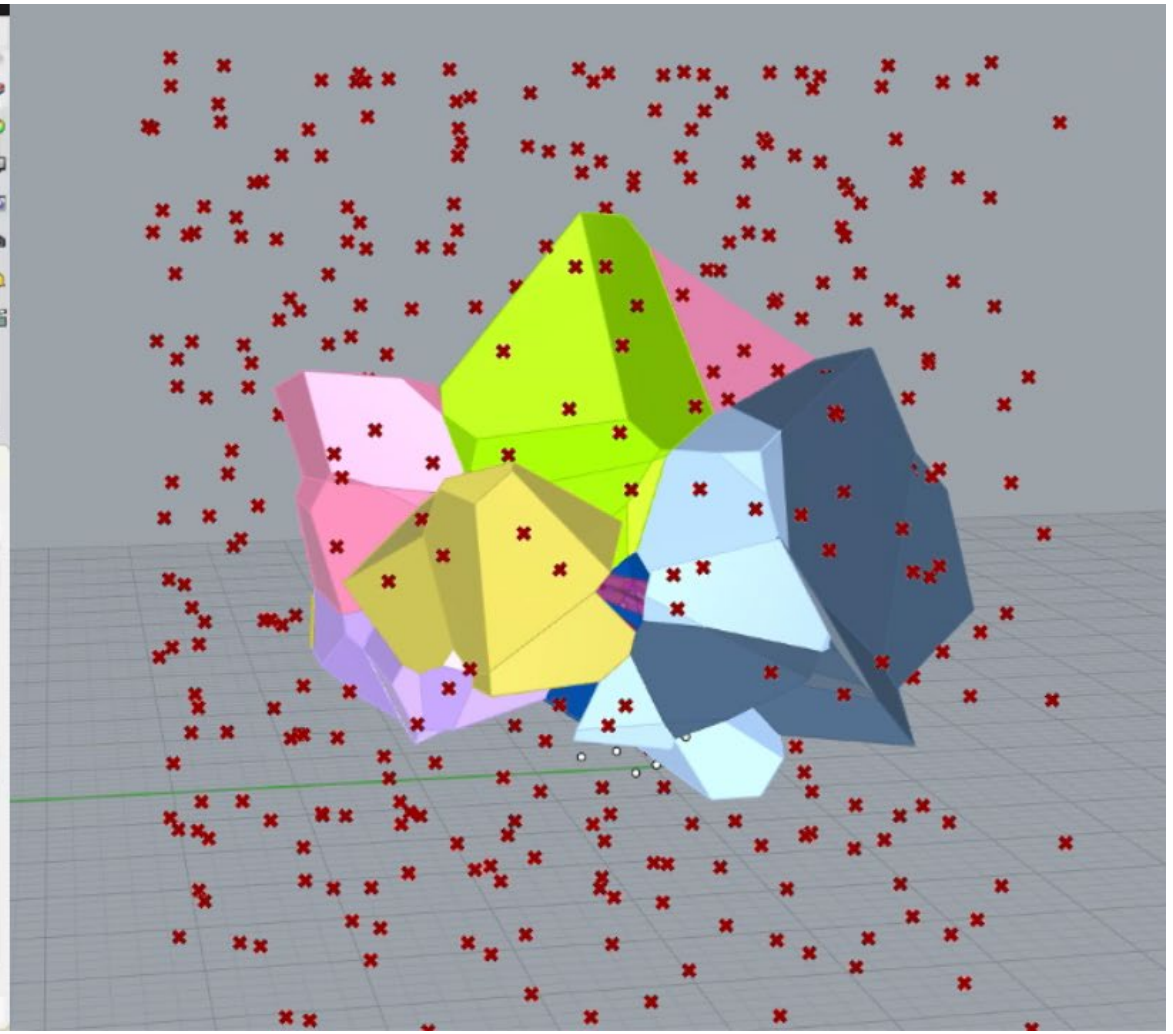
Form Optimisation Process

Translating bubble diagram into Voronoi-based system



Bubble Diagram

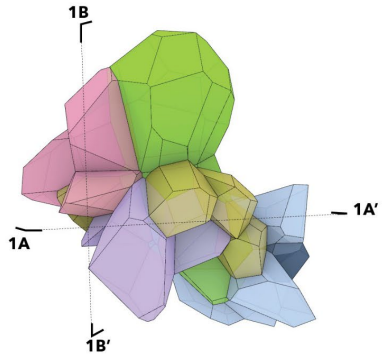


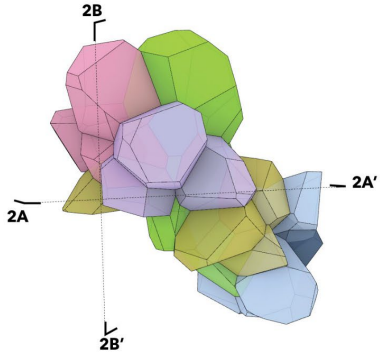


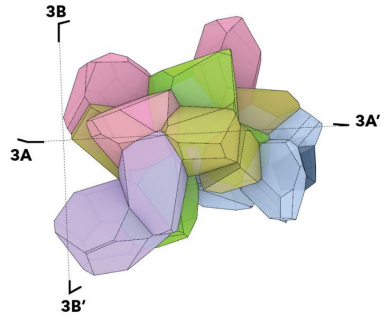
Grasshopper Galapagos to control size and connection

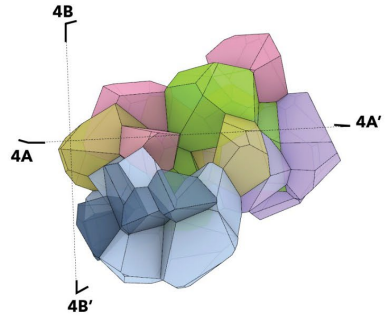
https://youtu.be/oiQ0B0b-MYM

MASSING

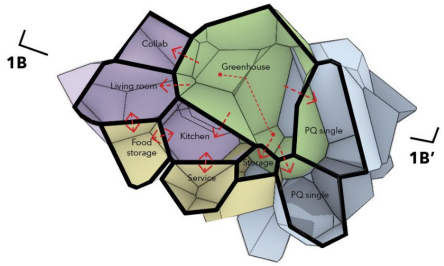


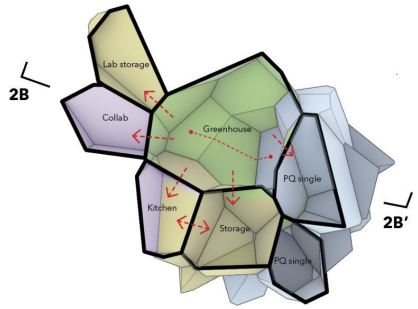


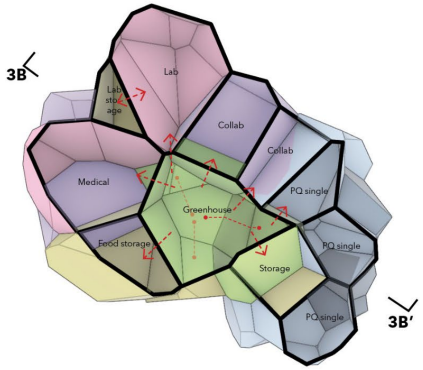


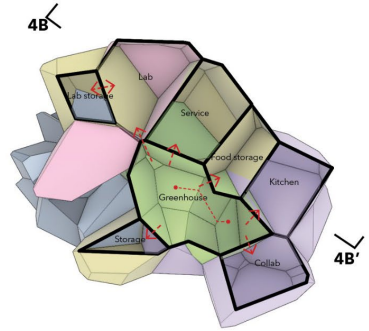


PLAN
A-A'



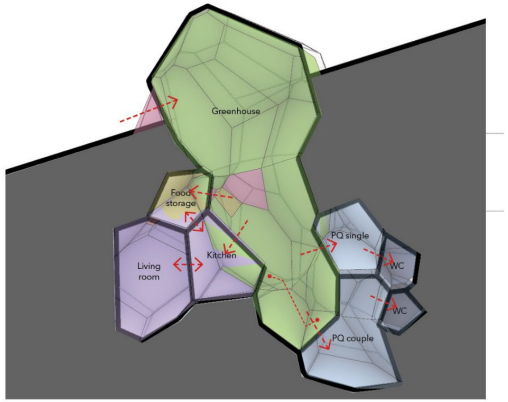




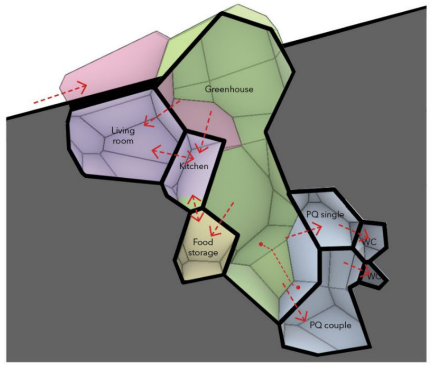


SECTION
B-B'

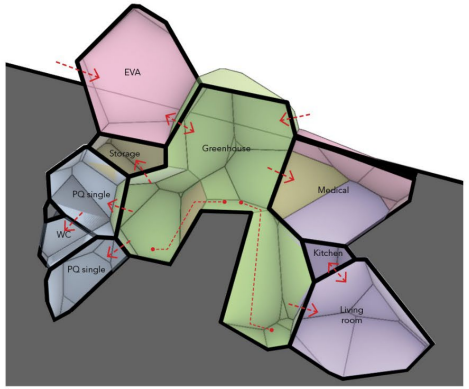
5m



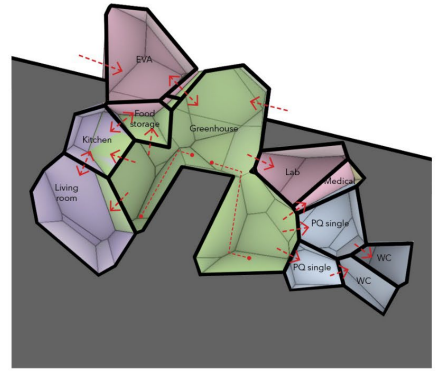
ITERATION 1



ITERATION 2



ITERATION 3



ITERATION 4

Iteration 1 & 2
- Continuous atrium
- Clustered and vertically distributed function

Iteration 3 & 4
- Branching atrium
- Dispersed function, opposing sides to activate circulation

Atrium Study

Establish strategy

1. Connect functional rooms → *Main circulation*
2. Atrium as the in-between → *Spaces of transitions*

Atrium Circulation Study

Inspiration from Lava Tube

Lava Tube Exterior, Grotto Intraleo

Integration of stairs to terrain

Lava Tube Interior, Grotto Catanese

Shift from gentle to steep terrain

Atrium Circulation Study

Strategy to subdivide continuous atrium: Balancing view & access options

Moon Condition

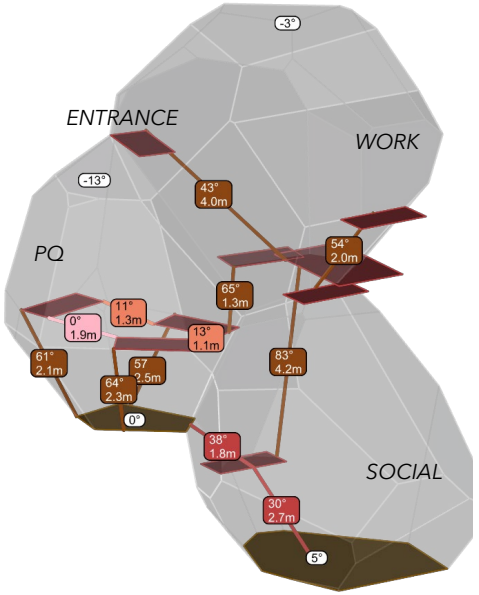
Reference: NASA Guideline

2-5° Walking/loping (normal)

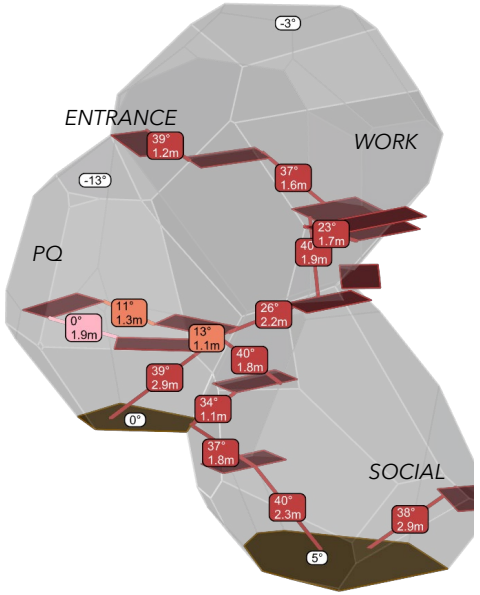
10-20° Ramp

30-40° Steep ramp / stairs

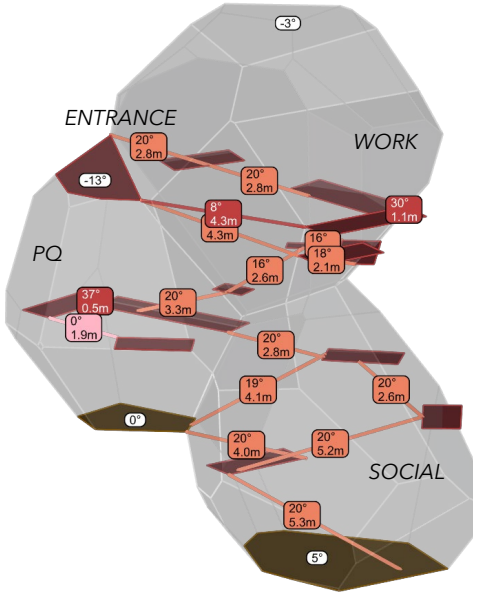
- 0-10° Platform / gentle ramp (walking)
- 10-20° Ramp (reasonable)
- 20-40° Stairs
- >40° Steep stairs / ladder



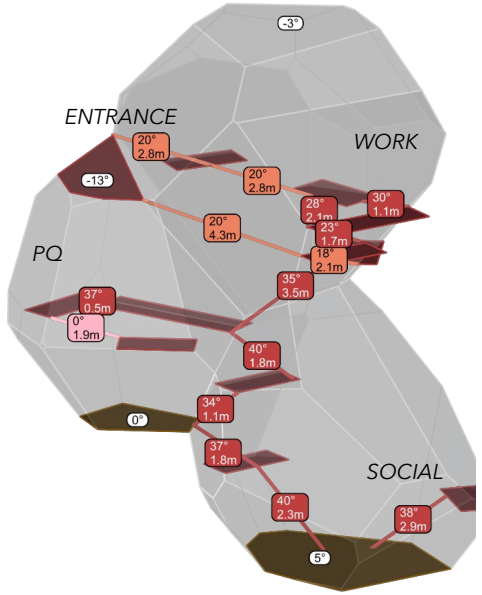
Iteration 1
Shortest distance / steep



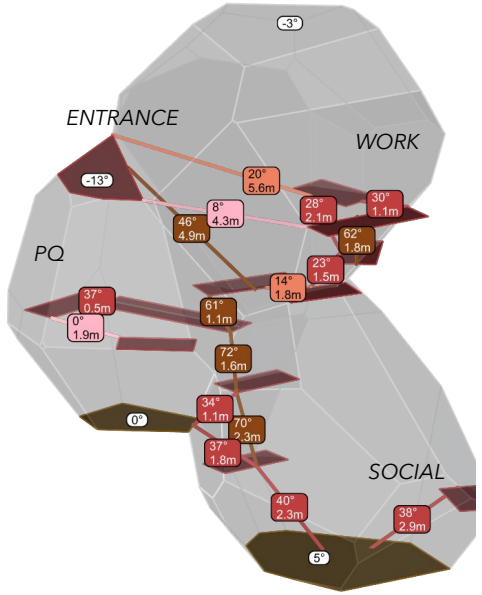
Iteration 2
Stairs



Iteration 3
Ramp



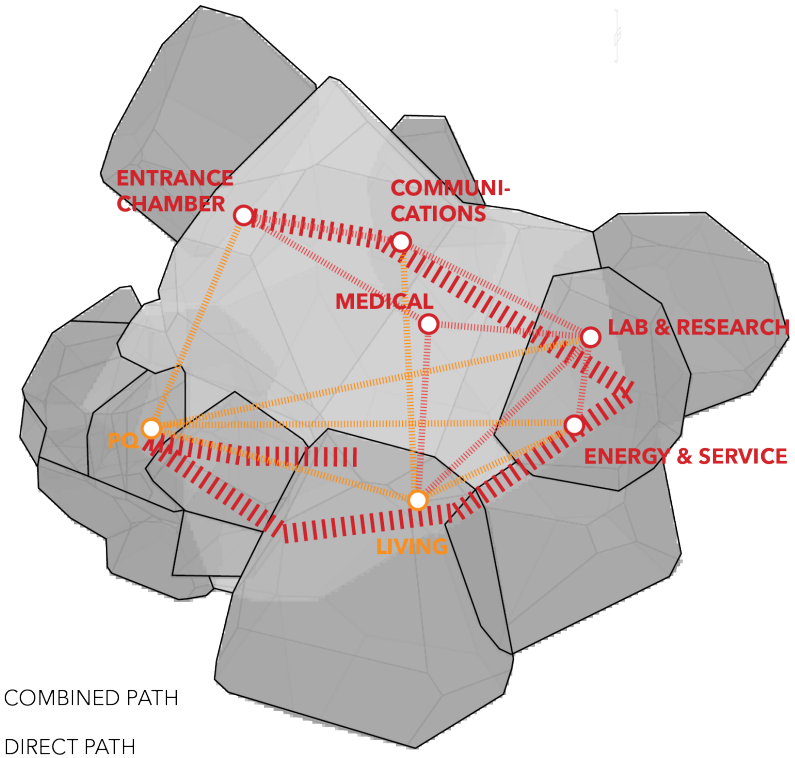
Iteration 4
Ramp (work) + Stairs (living)



Iteration 5
Combination + steep stairs (main axis)

Paths of personas

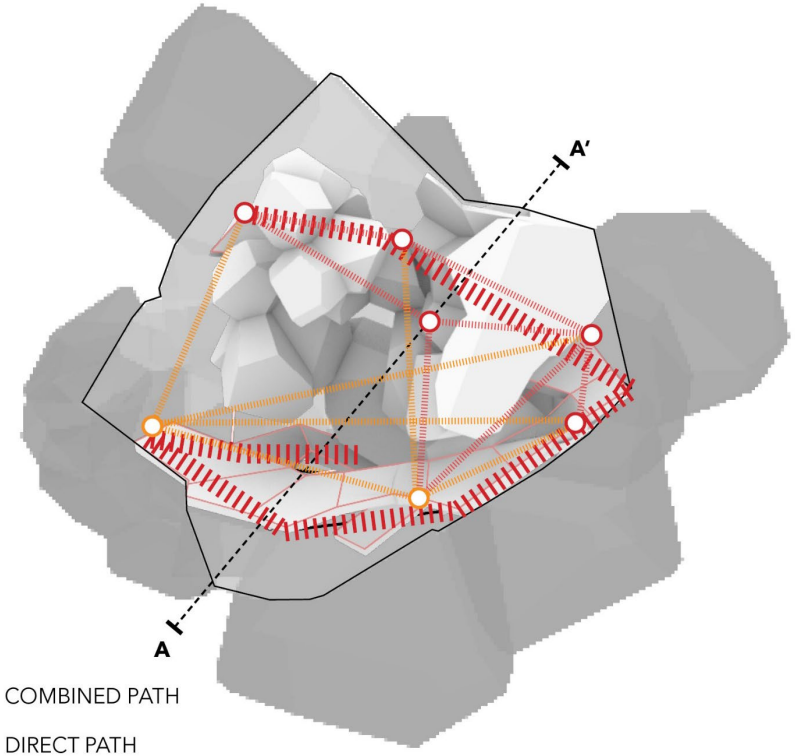
Establishing main circulation



Time	Commander		Medic		EVA Specialist	
06:00	Hygiene & breakfast (1h)	PQ		PQ		PQ
06:30						
07:00	System checks & safety update (1.5h)	Service				
07:30						
08:00						
08:30	EVA & Mission planning (1.5h)	Lab & Research	Hygiene & breakfast (1.5h)		Hygiene & breakfast (1.5h)	
09:00						
09:30						
10:00	Reports & coordination with Earth base (1.5h)	Comms	Medical checks (1h)	Medic	Reports & coordination with Earth base (1.5h)	Comms
10:30						
11:00			Gardening (0.5h)	Atrium		
11:30	Lunch prep (1h)	Kitchen	Medical research & analysis (1.5h)	Lab	EVA prep & rover preparation (1.5h)	Entrance
12:00						
12:30	Piano practice (0.5h)	Acoustic				
13:00	Lunch (1h)	Living	Lunch (1h)	Living	Lunch (1h)	Living
13:30						
14:00	EVA prep (1h)	PQ	Emergency protocol (1.5h)	Lab & Research	Habitat maintenance (1.5h)	Atrium
14:30		Entrance				Service
15:00	EVA (2h)	Entrance				Atrium
15:30			Exercise (1.5h)	Living	Exercise (1.5h)	Living
16:00						
16:30		PQ				
17:00	Exercise (1.5h)	Living	Dinner prep (1.5h)	Kitchen	Dinner prep (1.5h)	Kitchen
17:30						
18:00						
18:30	Dinner (1.5h)	Living	Dinner (1.5h)	Living	Dinner (1.5h)	Living
19:00						
19:30						
20:00	Band rehearsal (1.5h)	Acoustic	Band rehearsal (1.5h)	Acoustic	Band rehearsal (1.5h)	Acoustic
20:30						
21:00						
21:30	Chess and movie (1.5h)	Living	Gardening and movie (1.5h)	Atrium	Chess and movie (1.5h)	Living
22:00						
22:30						
23:00	Sleep (7h) 23:00-06:00	PQ	Sleep (9.5h) 23:00-08:30	PQ	Personal research (1.5h)	PQ
23:30						
00:00						
00:30					Sleep (8h) 00:30 - 08:30	
01:00						
01:30						

Global Openness

Establishing spaces of transitions



COMBINED PATH

DIRECT PATH

INDIRECT PATH

WORK FUNCTION

NON-WORK FUNCTION

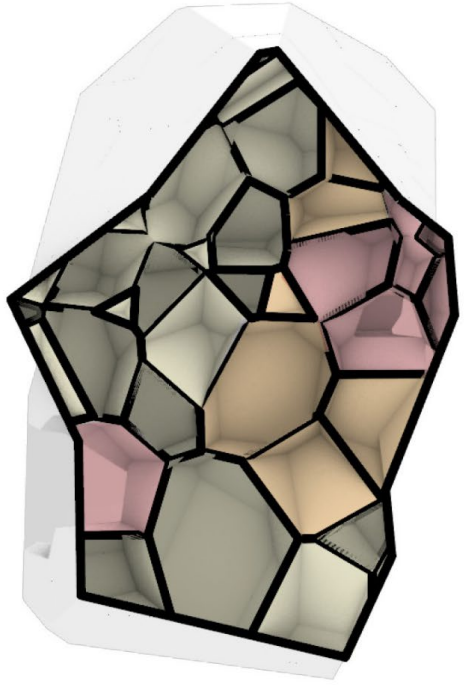
VOID FOR MAIN CIRCULATION

VOLUMES FOR BUSY AREA

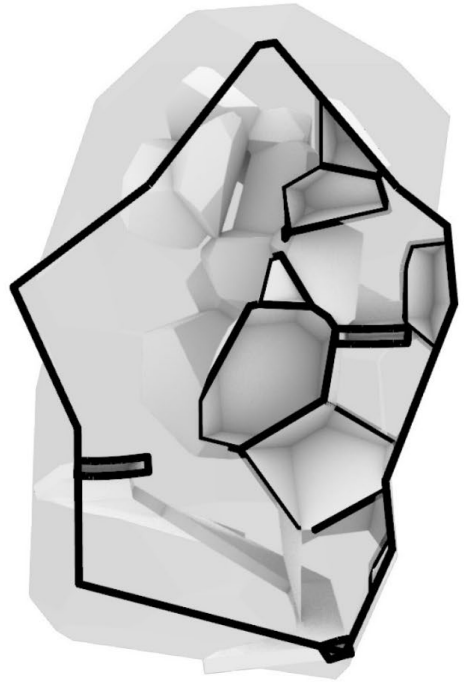
VOID FOR CALM AREA

BUSY

CALM



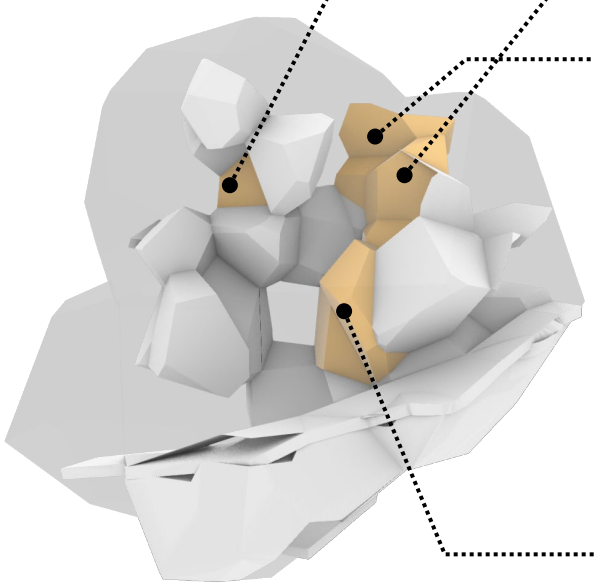
ESTABLISH ZONES



CARVE OUT VOIDS

Local Openness

Enclosure



Room for 1 person

Room for 2 people

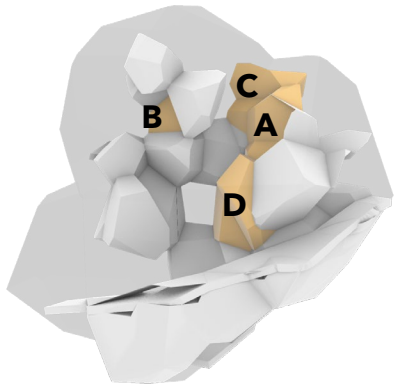
Room for 3 people

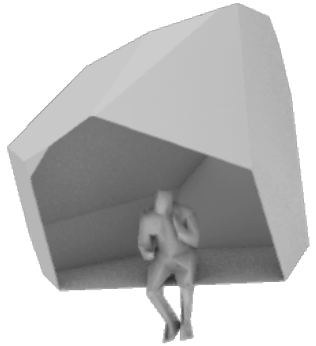
Room for 6 people

Enclosed ***Open***

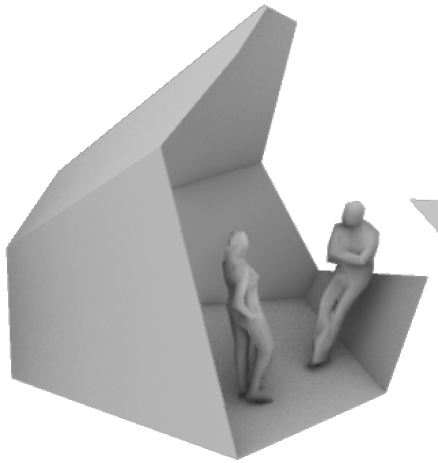
Local Openness

Enclosure

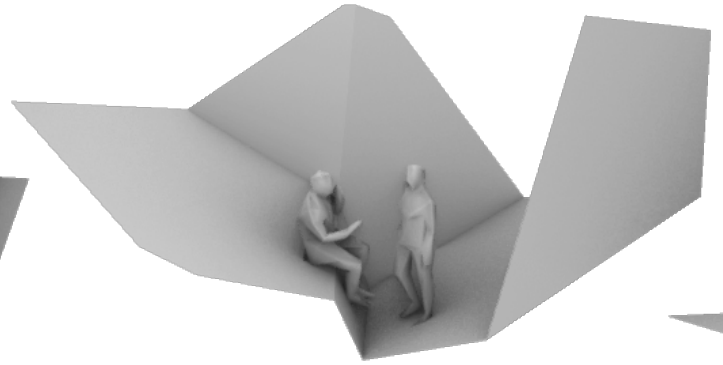




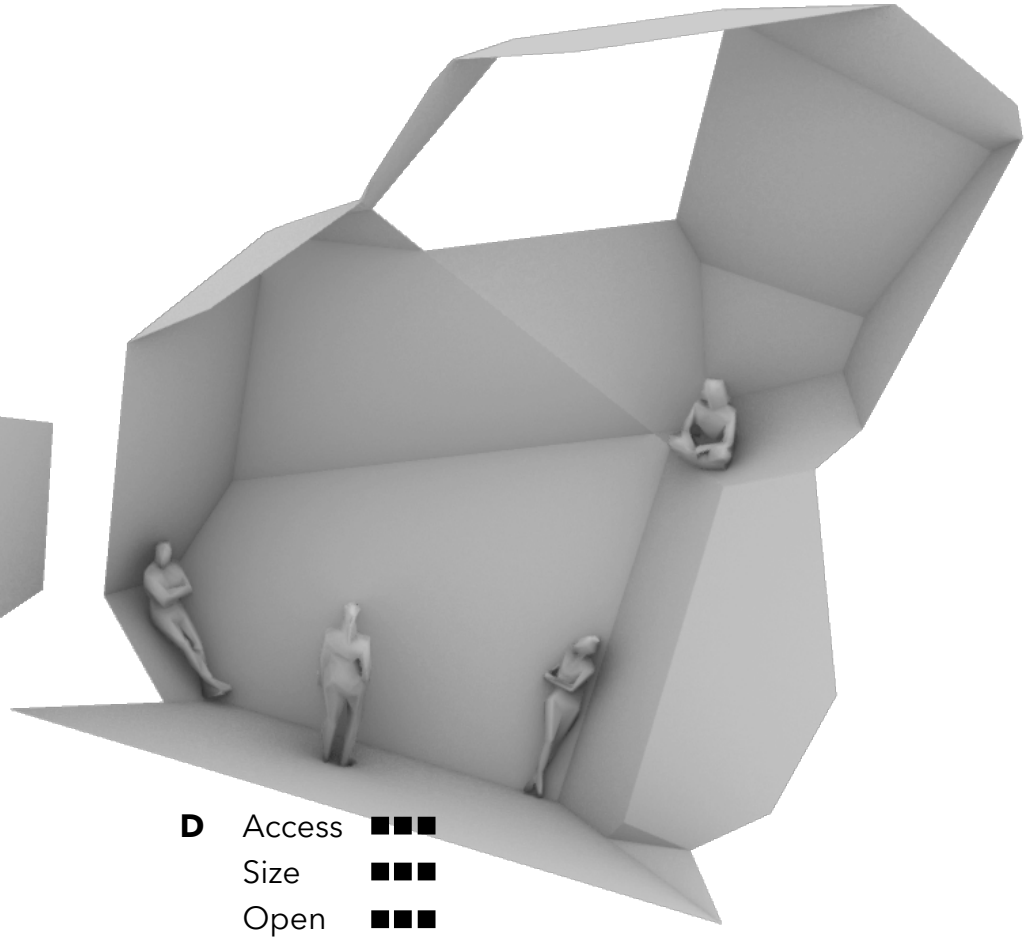
A Access ■■□
Size ■□□
Open ■□□



B Access ■■□
Size ■■□
Open ■□□



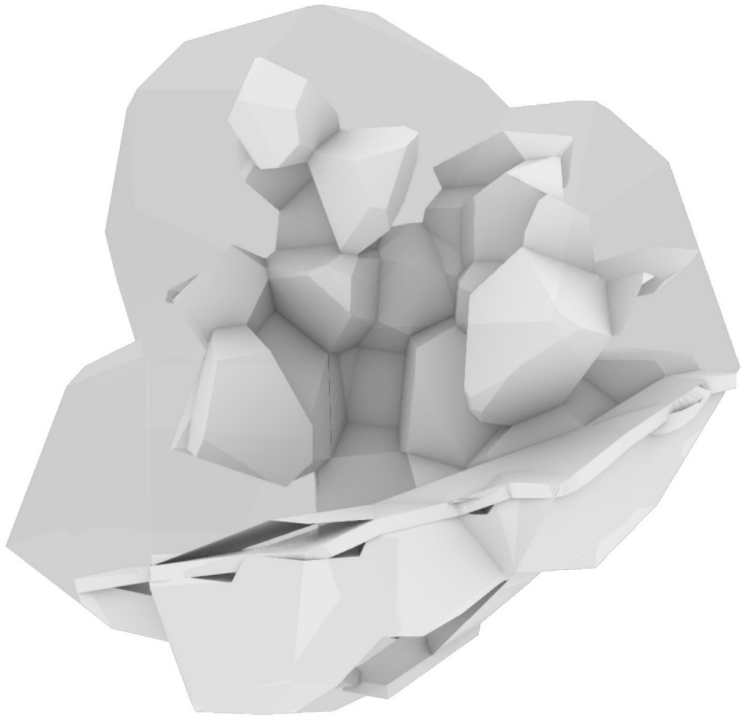
C Access ■□□
Size ■■□
Open ■■□



D Access ■■■
Size ■■■
Open ■■■

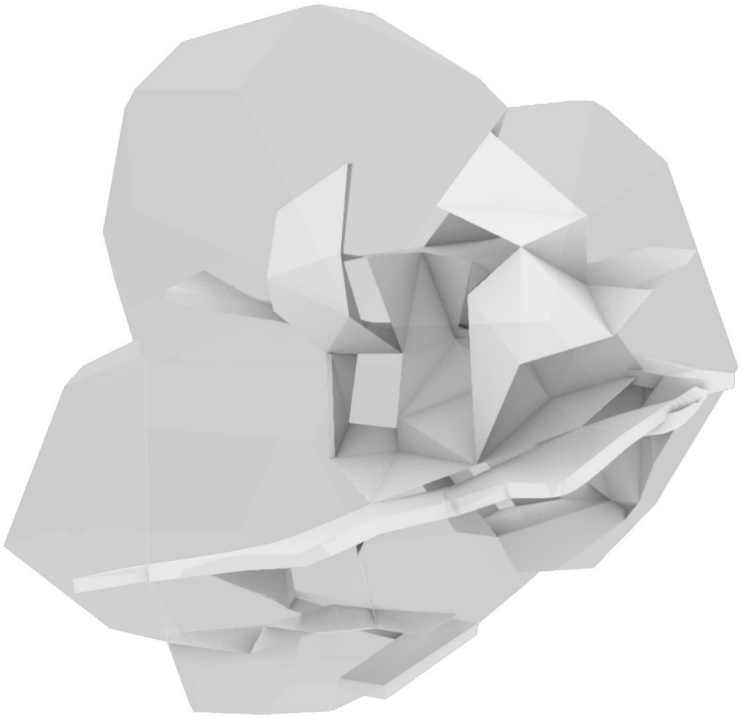
Local Openness

Global application



VOLUME

REMOVE SURFACES



OPEN & ENCLOSED SPACES

Section

4

0 meter

-4

-6.5 (plan)

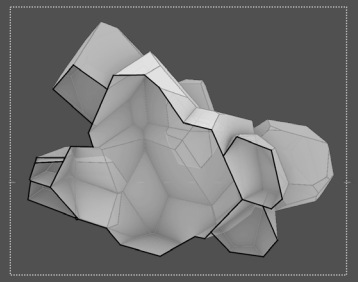
-8

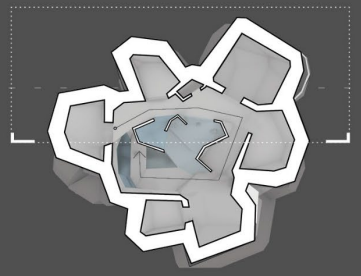
-12

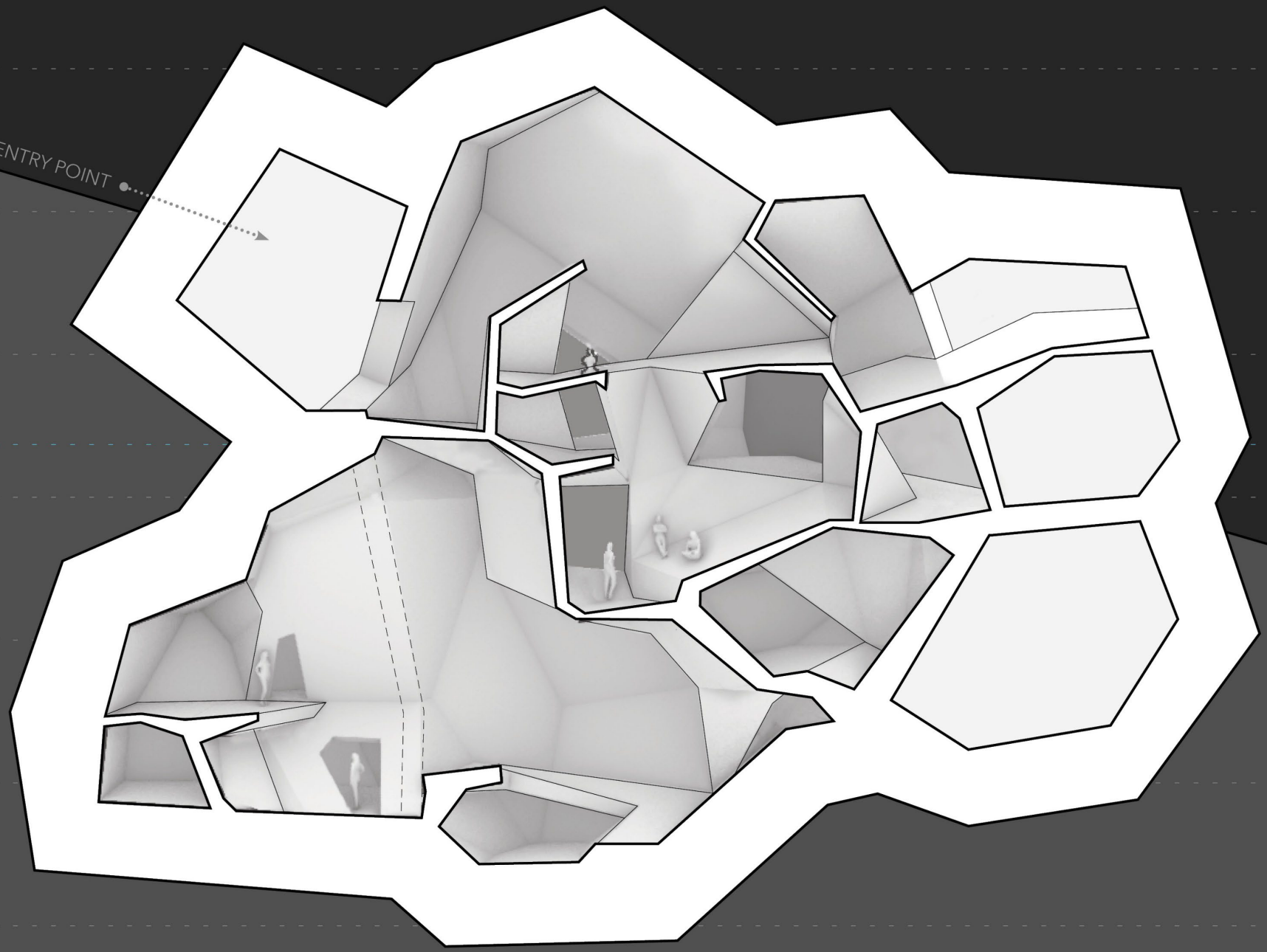
-16

-20

ENTRY POINT







0 1 2 5 meter

Section

Atrium of activities

4

0 meter

-4

-6.5 (plan)

-8

-12

-16

-20

ENTRY POINT

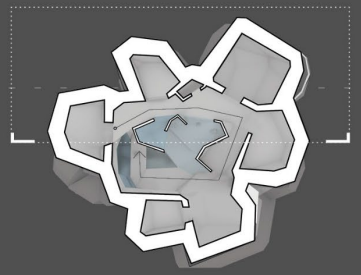
ENTRANCE CHAMBER

INTROVERT
QUARTERS
Open ■□□
Size ■□□
Access ■□□

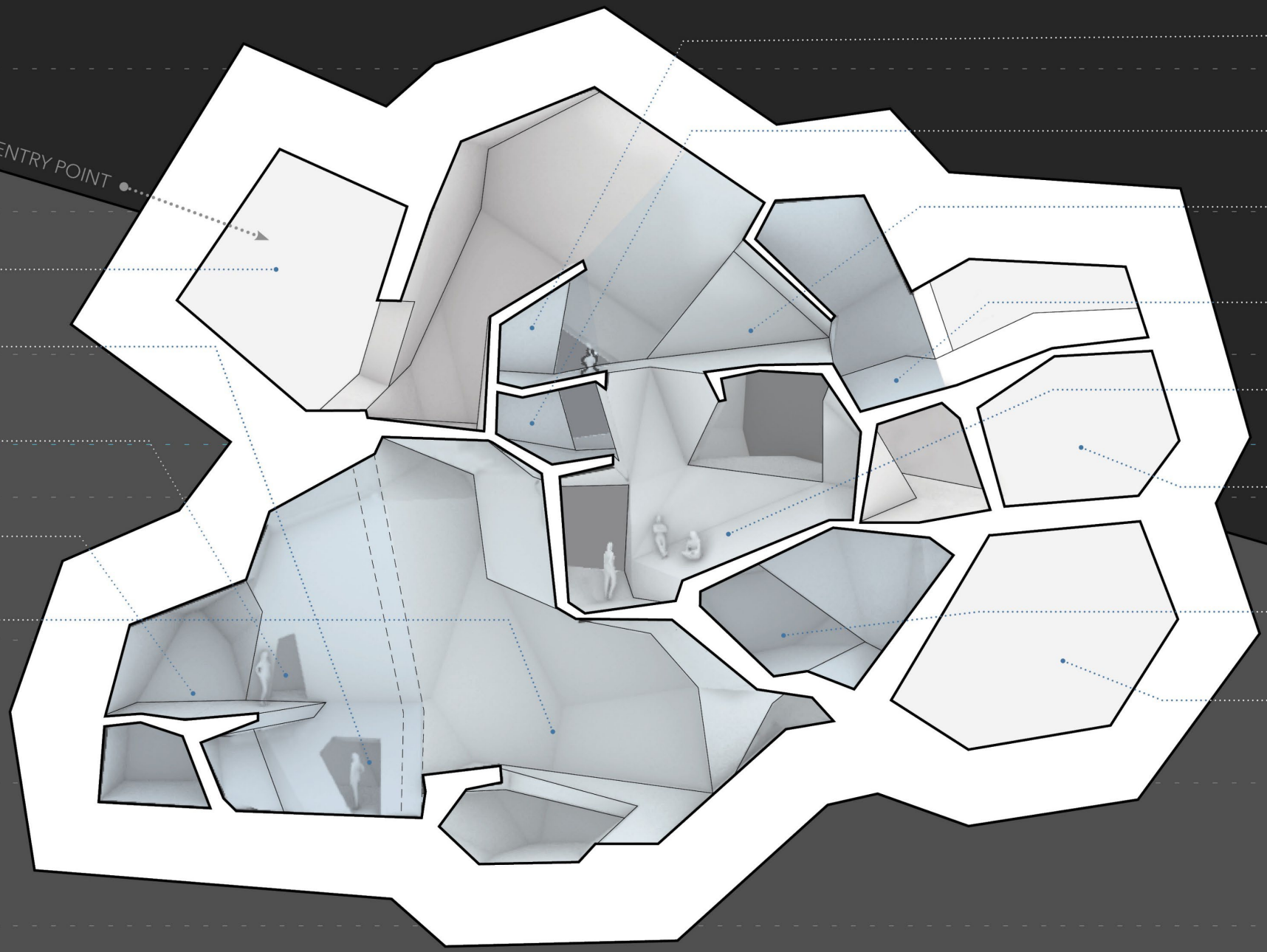
EXTROVERT
QUARTERS
Open ■■□
Size ■□□
Access ■□□

PRIVATE QUARTERS
INNER GARDEN
Open ■□□
Size ■■□
Access ■□□

FOOD GARDEN
Open ■■■
Size ■■■
Access ■■□



0 1 2 5 meter



UPPER
LOOKOUT
Open ■■□
Size ■□□
Access ■□□

LOWER
LOOKOUT
Open ■□□
Size ■□□
Access ■■□

ROOF GARDEN
Open ■■□
Size ■■□
Access ■□□

ROOF GARDEN
EXTENSION
Open ■□□
Size ■■□
Access ■□□

GATHERING
Open ■■■
Size ■■■
Access ■■■

ENERGY & SERVICE

HIDDEN GARDEN
Open ■□□
Size ■■□
Access ■□□

LIFE SUPPORT

Section

Atrium of refuge

4

0 meter

-4

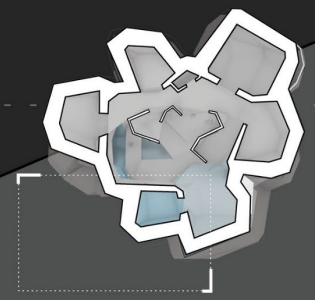
-6.5 (plan)

-8

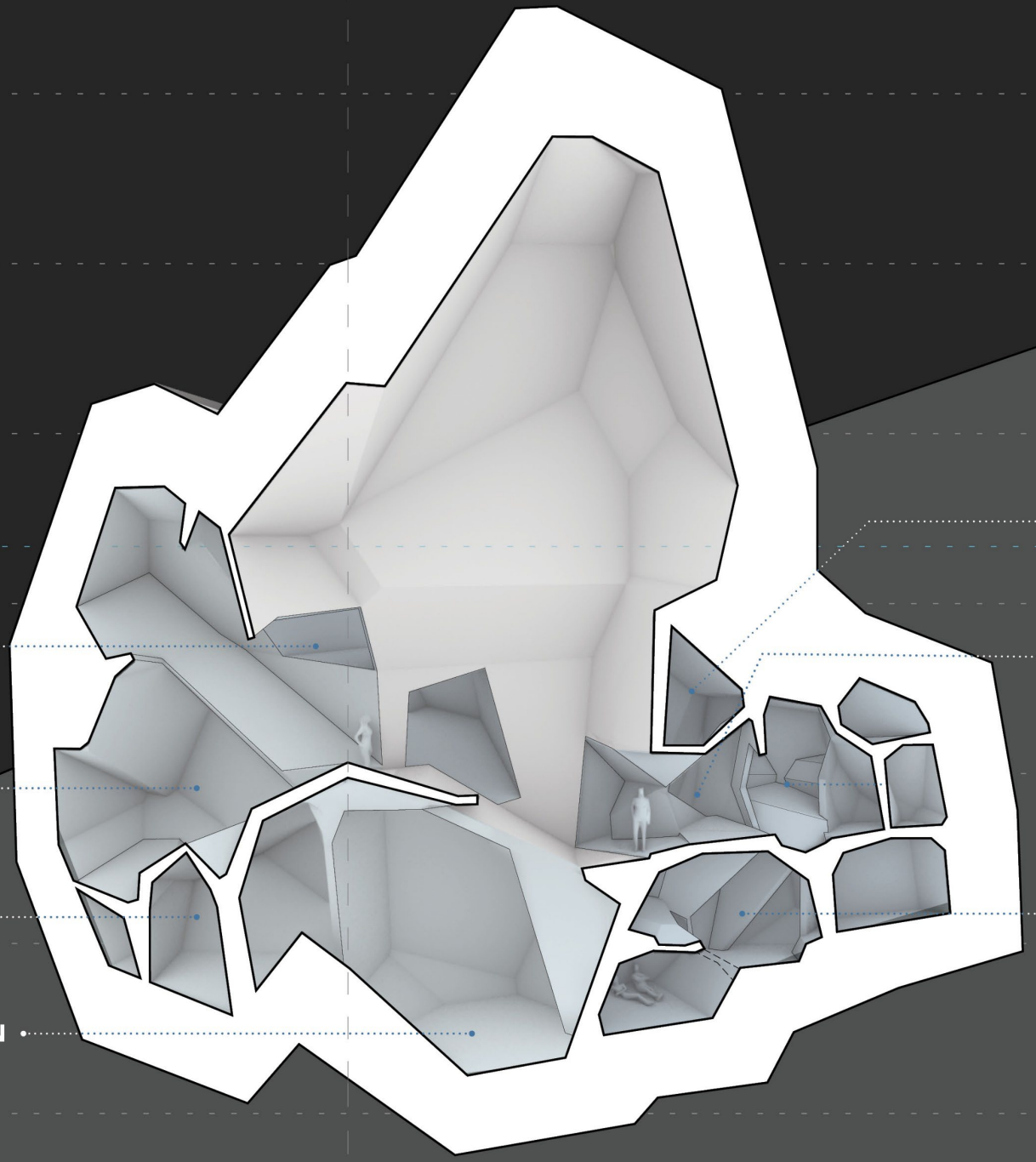
-12

-16

-20



0 1 2 5 meter



ACOUSTIC
Open ■□□
Size ■■□
Access ■□□

LIVING
Open ■■□
Size ■■■
Access ■■■

KITCHEN
Open ■■□
Size ■■□
Access ■■□

FOOD GARDEN
Open ■■■
Size ■■■
Access ■■□

FRONT GARDEN
VESTIBULE
Open ■□□
Size ■□□
Access ■□□

PRIVATE QUARTERS
FRONT GARDEN
Open ■■□
Size ■□□
Access ■■□

EXTROVERT / SINGLE
QUARTERS
Open ■■□
Size ■□□
Access ■□□

INTROVERT / COUPLE
QUARTERS
Open ■□□
Size ■□□
Access ■□□

Plan

WC

COMMUNICATION

LOWER
LOOKOUT

LAB &
RESEARCH

GATHERING

ENERGY &
SERVICE

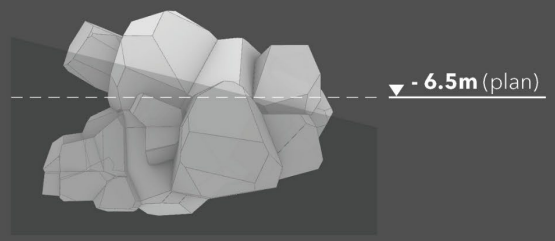
LIVING &
KITCHEN

ENTRANCE
CHAMBER

PRIVATE
QUARTERS

FOOD
GARDEN

ACOUSTIC



0 1 2 5 meter

-6.5 meter

-8

-10

Plan

Meandering pathways

WC

COMMUNICATION

LOWER
LOOKOUT

LAB &
RESEARCH

GATHERING

ENERGY &
SERVICE

to ROOF
GARDEN

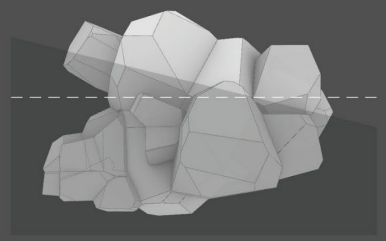
LIVING &
KITCHEN

ENTRANCE
CHAMBER

PRIVATE
QUARTERS

FOOD
GARDEN

ACOUSTIC



- 6.5m (plan)

0 1 2 5 meter

Main circulation

Branch circulation

Work function

Non-work function

-6.5 meter

-8

-10

Plan

Activated atrium

WC

COMMUNICATION

LOWER
LOOKOUT

LAB &
RESEARCH

GATHERING

ENERGY &
SERVICE

to ROOF
GARDEN

LIVING &
KITCHEN

Main circulation

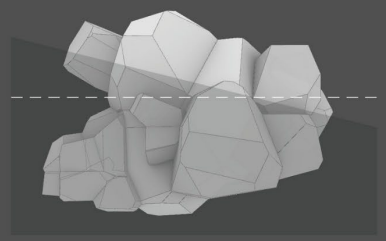
Branch circulation

ENTRANCE
CHAMBER

PRIVATE
QUARTERS

FOOD
GARDEN

ACOUSTIC



- 6.5m (plan)

0 1 2 5 meter

-6.5 meter

-8

-10

Plan

Personalised pathways

WC

COMMUNICATION

LOWER
LOOKOUT

LAB &
RESEARCH

GATHERING

ENERGY &
SERVICE

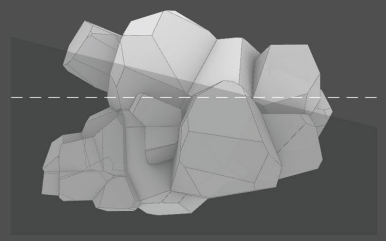
LIVING &
KITCHEN

ENTRANCE
CHAMBER

PRIVATE
QUARTERS

FOOD
GARDEN

ACOUSTIC



- 6.5m (plan)

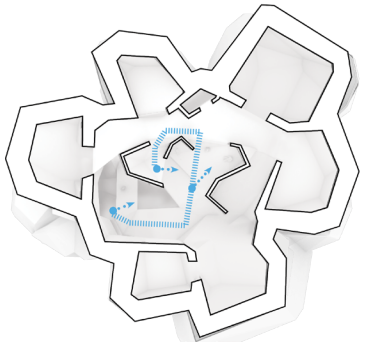
0 1 2 5 meter

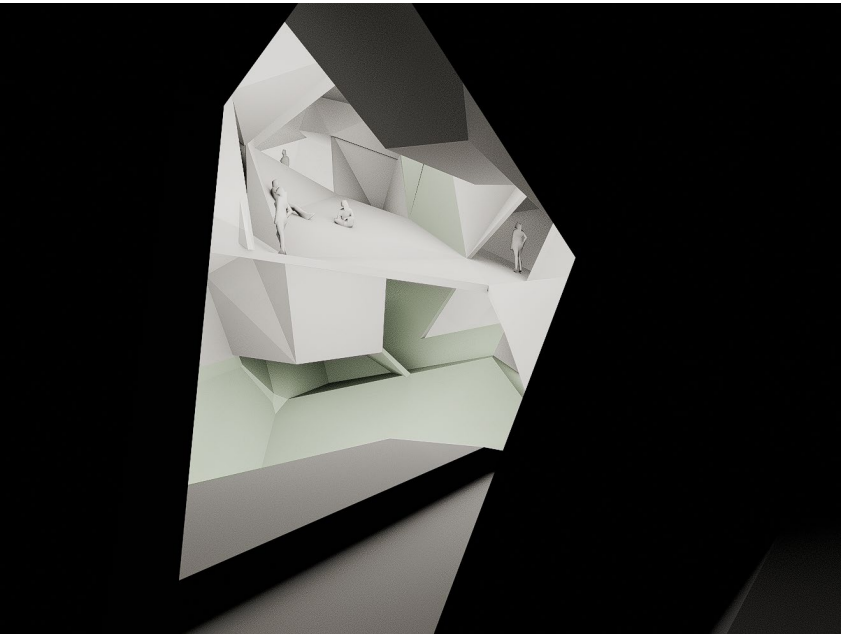
Introvert view
Introvert path
Extrovert view
Extrovert path
Robot path

-6.5 meter
-8
-10

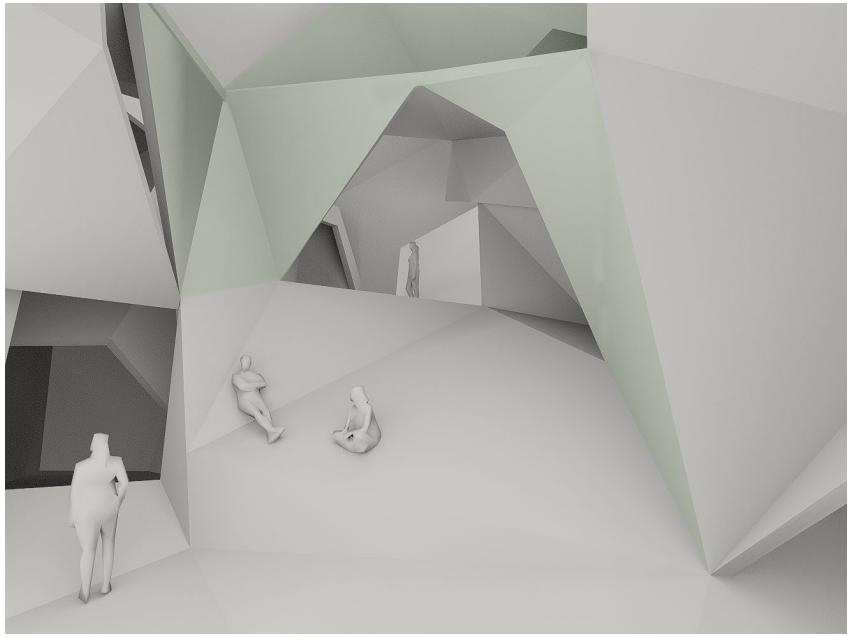
Day in the life: Lunar Restday

The Extroverted Commander

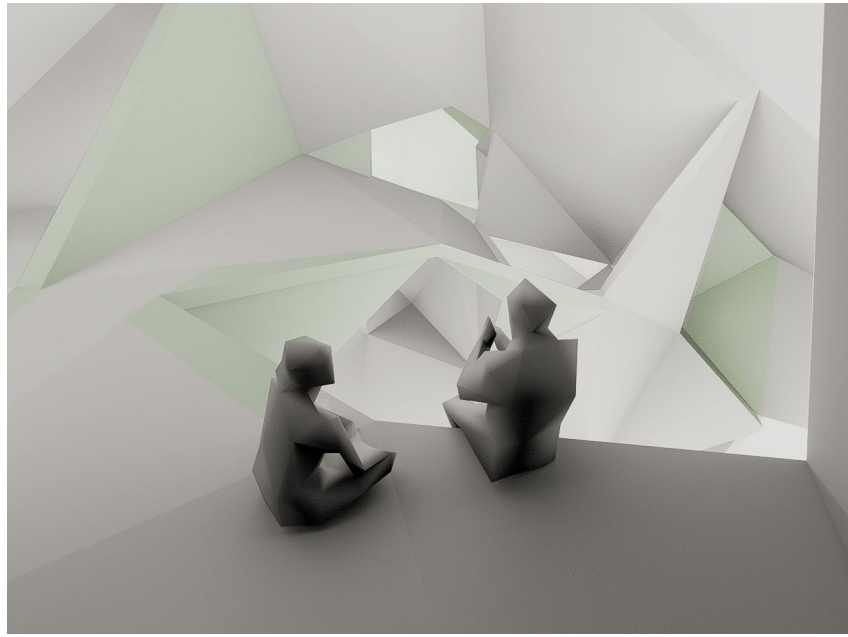




View from room



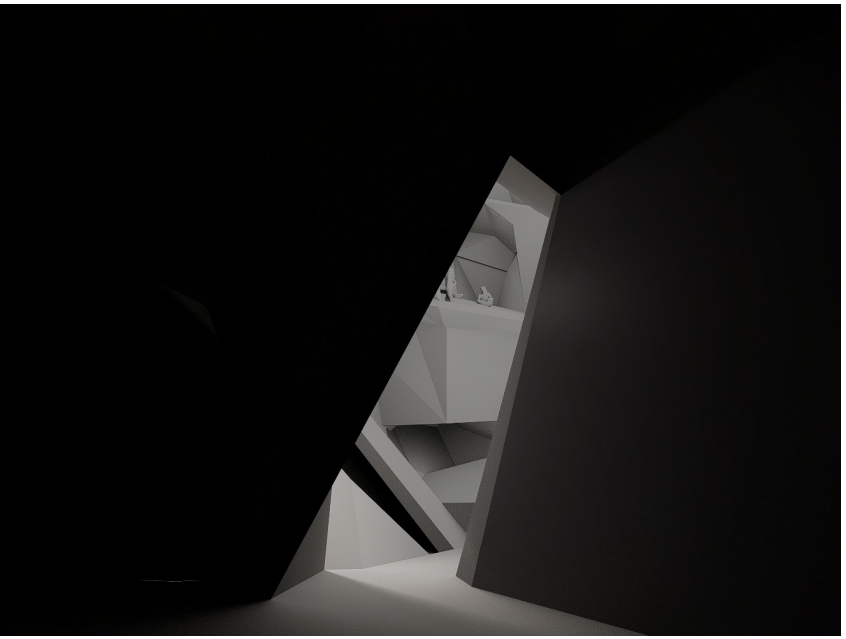
Social Route



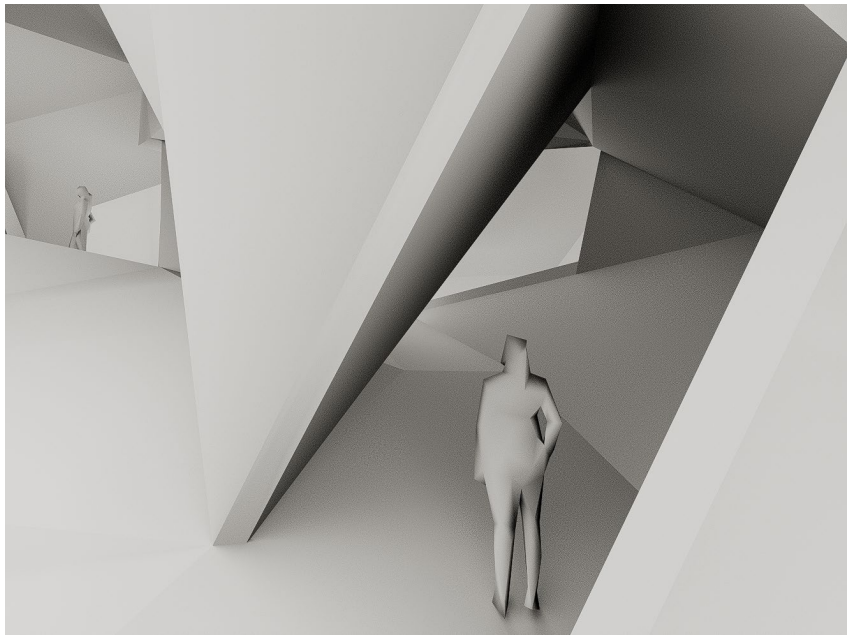
Chat with crew

Day in the life: Lunar Restday

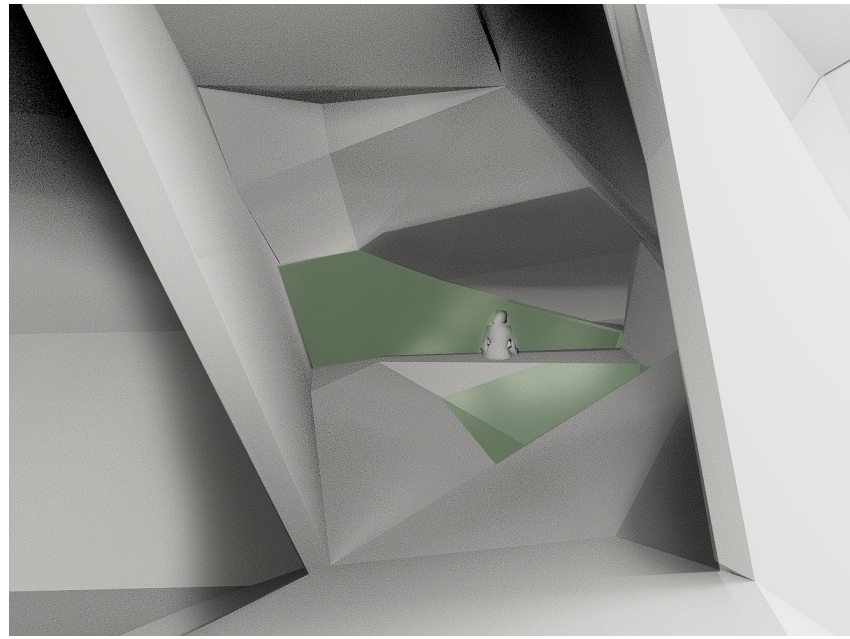
The Introverted Medic



View from room



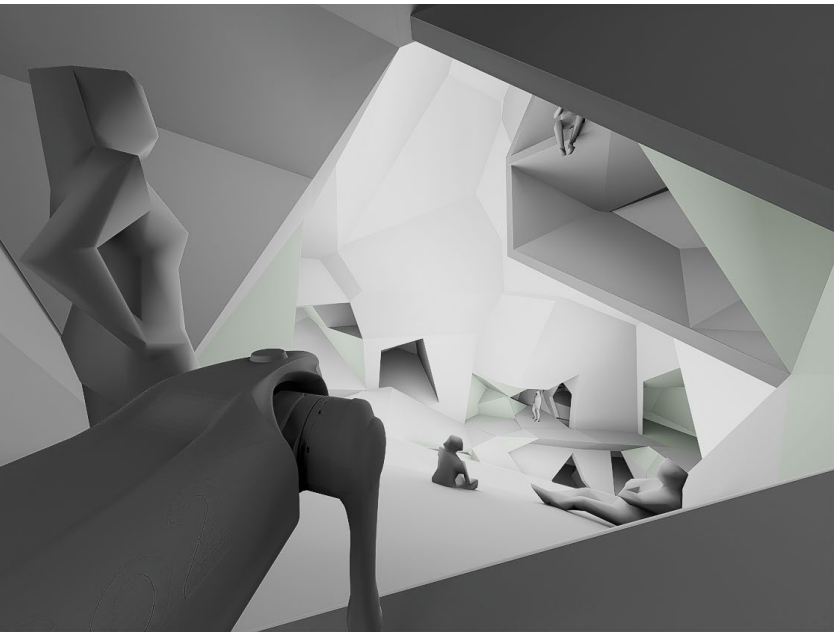
Private Route



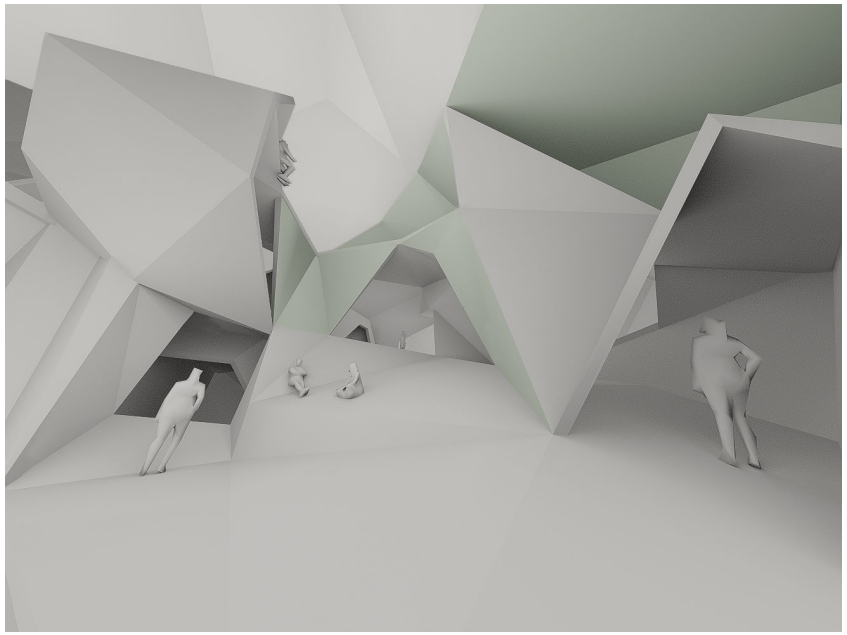
Hidden Garden

Day in the life: Lunar Restday

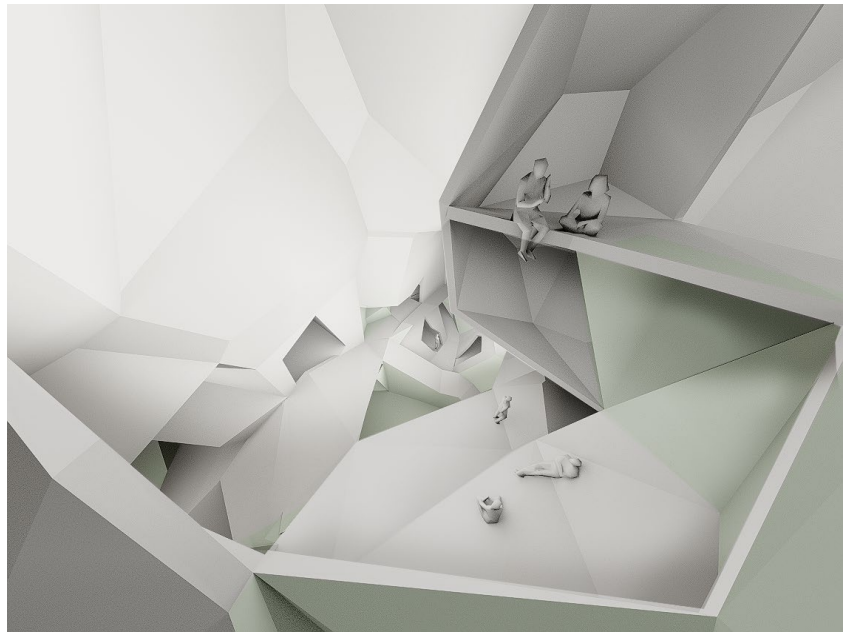
The Active Robot



Robot looking down the atrium



Overview of main routes

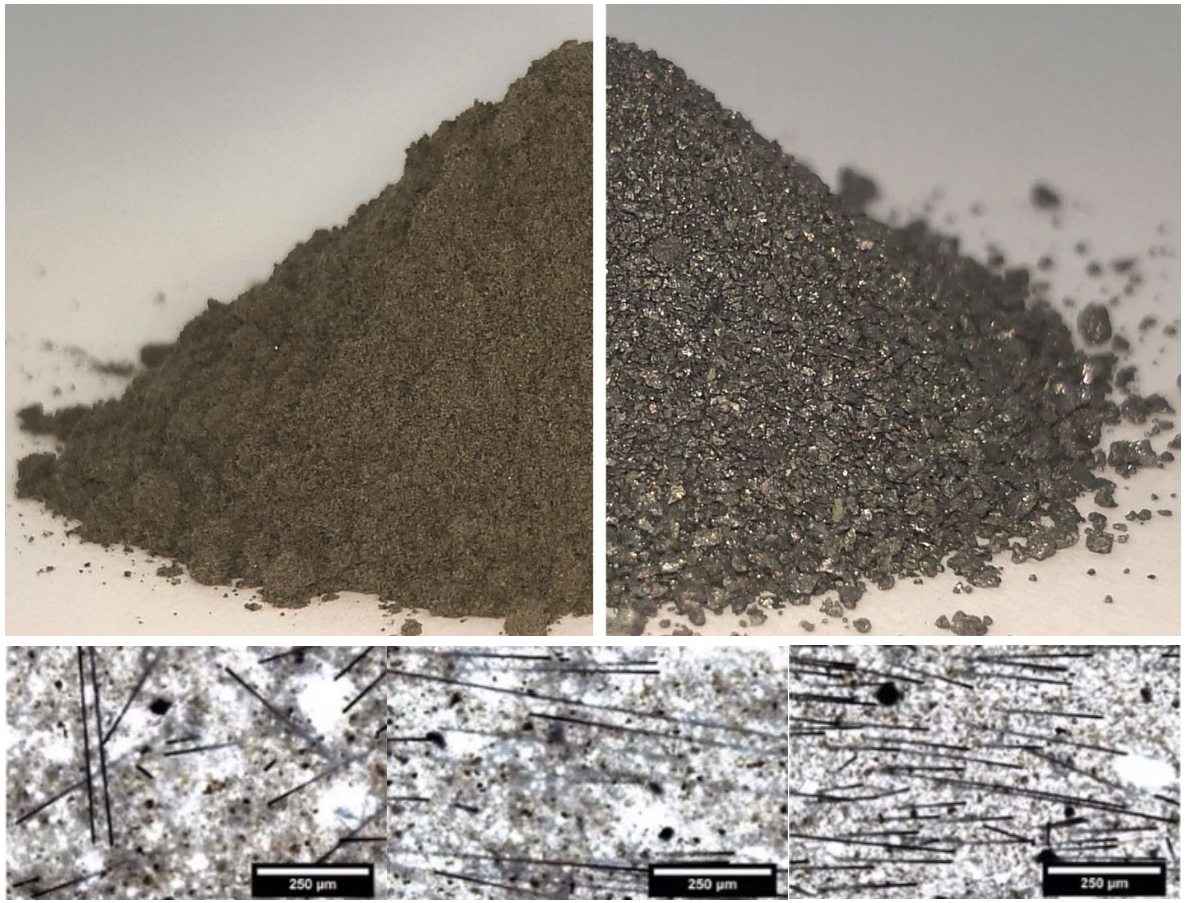


Overview of habitat from above

Construction & Materialization

Building Material

In-situ Resource Utilization



Regolith (top left)

- Radiation protection *(Savage & Schmitz, 2024)*
- Strong compressive strength

Regolith derivated materials (top right)

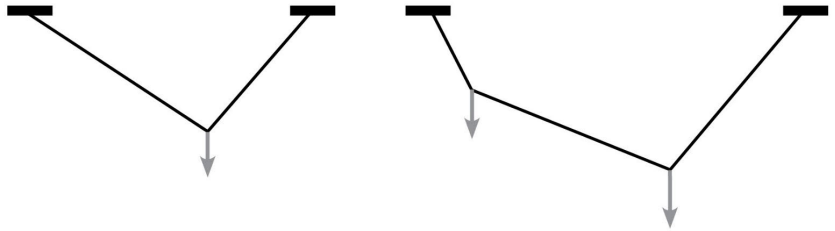
- Oxygen
- Metal
- Silica (for glass)
- Water

Carbon fibre (top right)

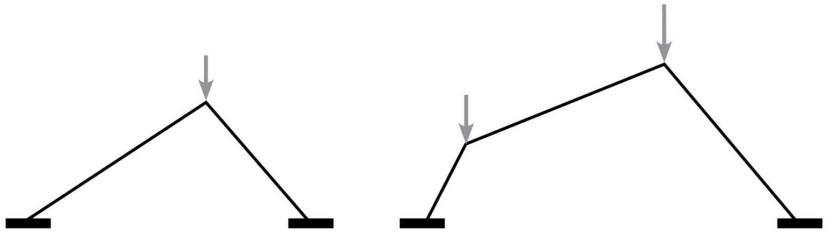
- Substrate of regolith geopolymer, to mitigate tensile forces *(Rutzen et al., 2021)*

Structure

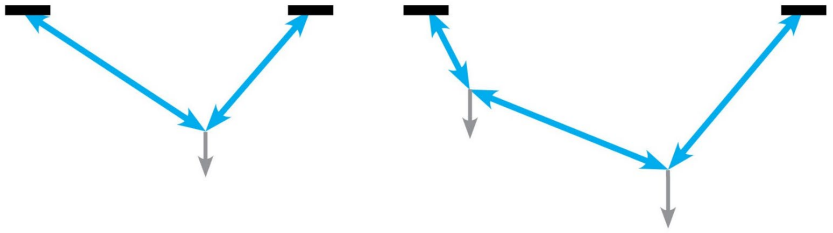
Catenary principle



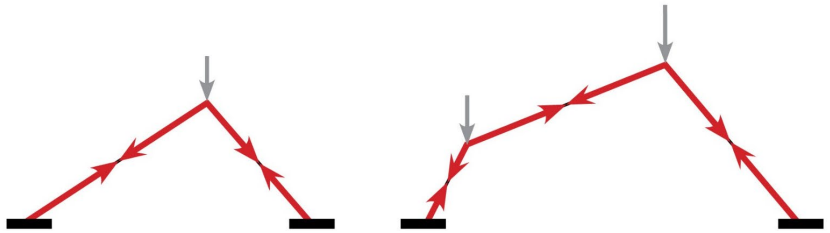
Catenary



Reverse Catenary



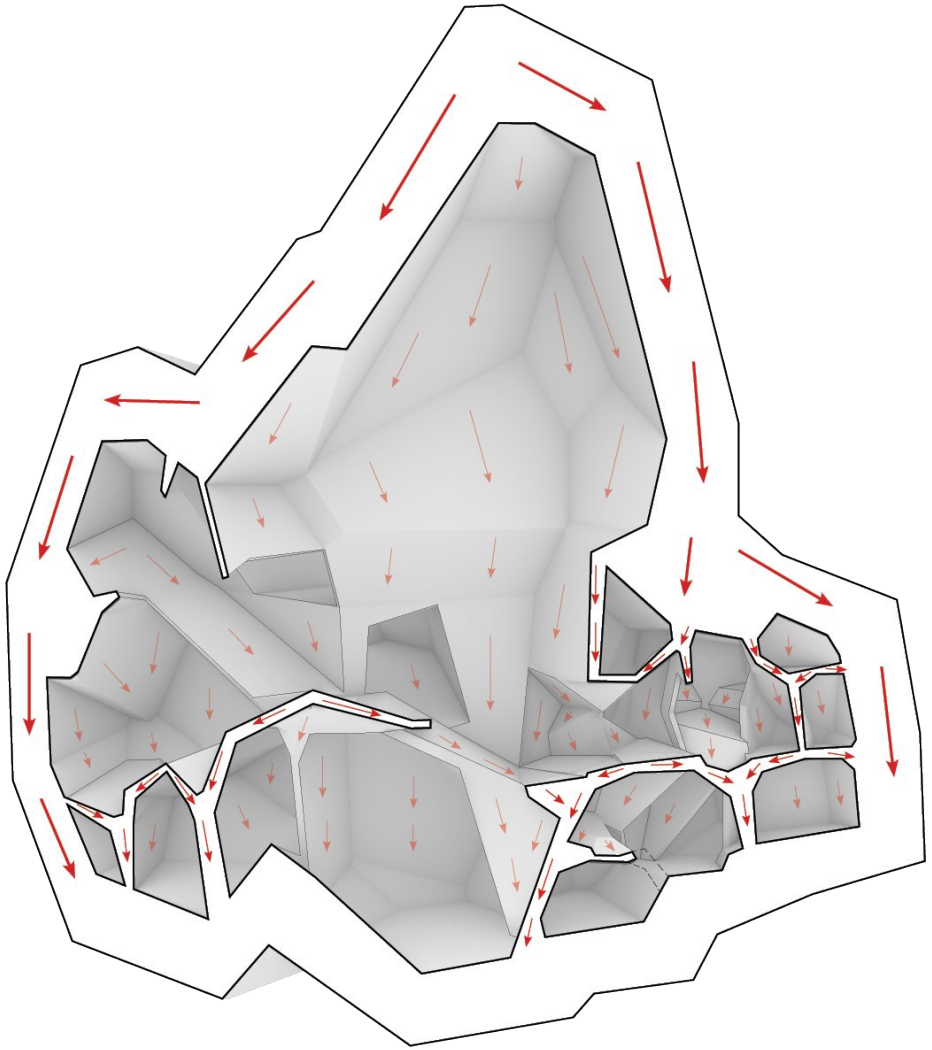
Tension Forces



Compression Forces

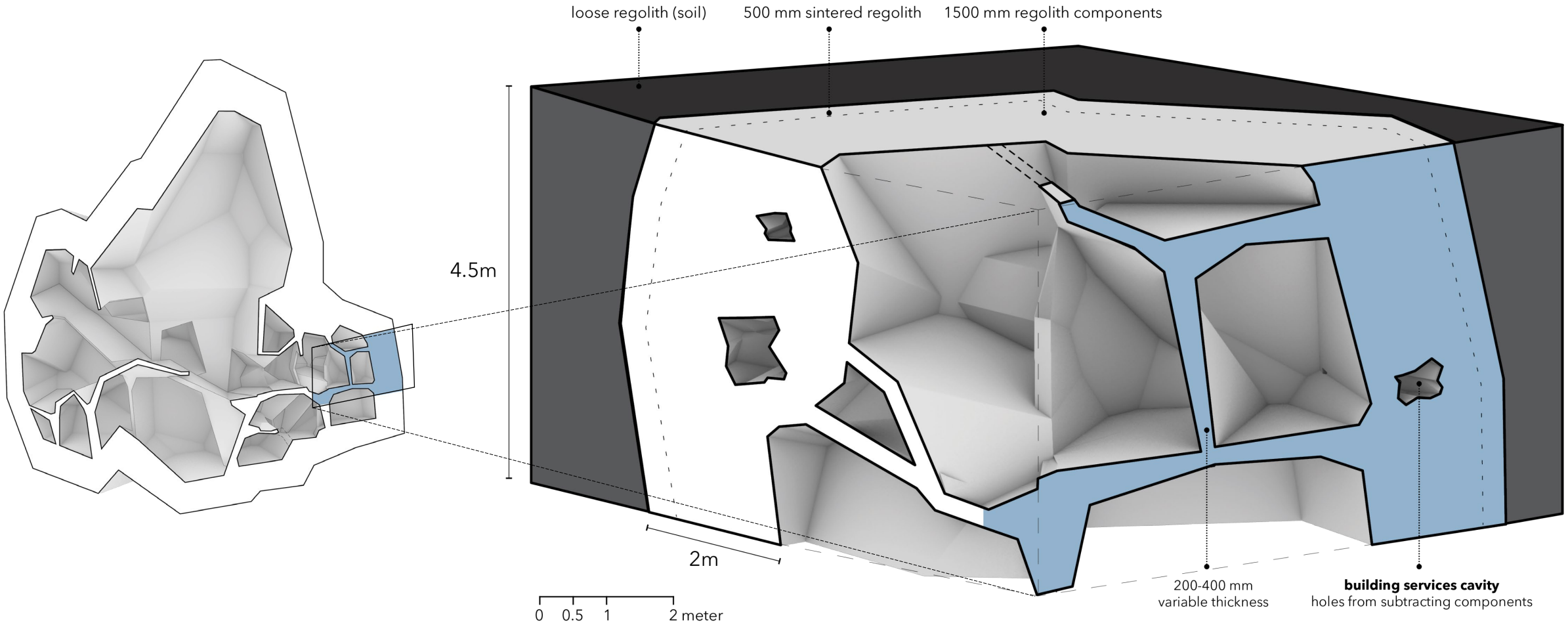
Structure

Distribution of forces



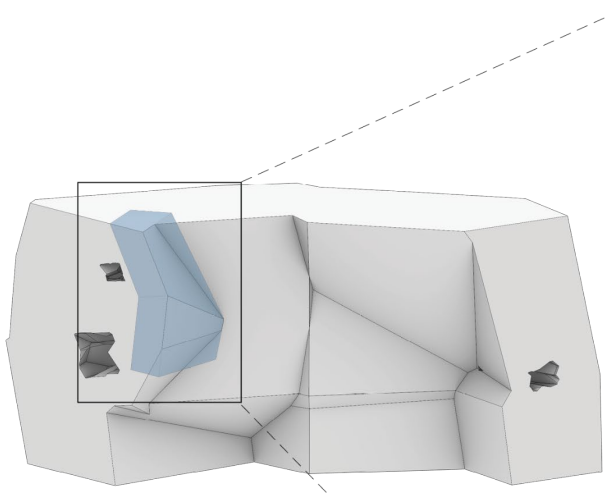
Load transfer direction

Fragment
Private Quarters

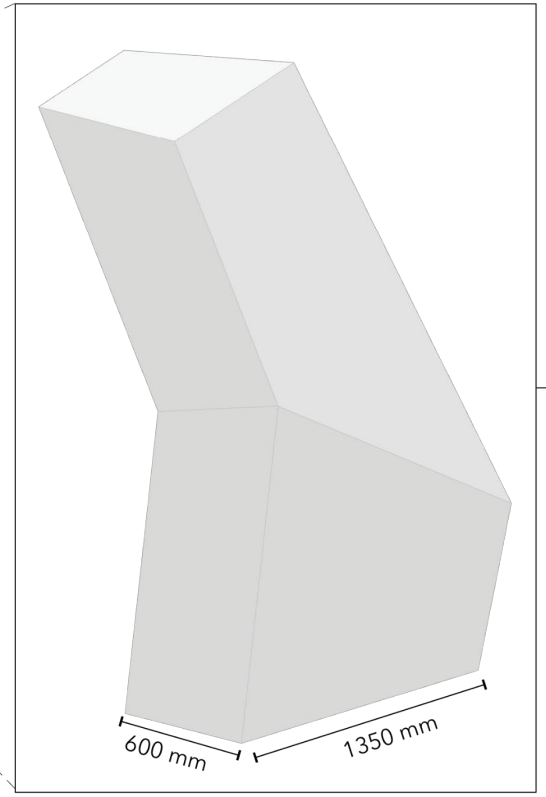


Fragment

Wall

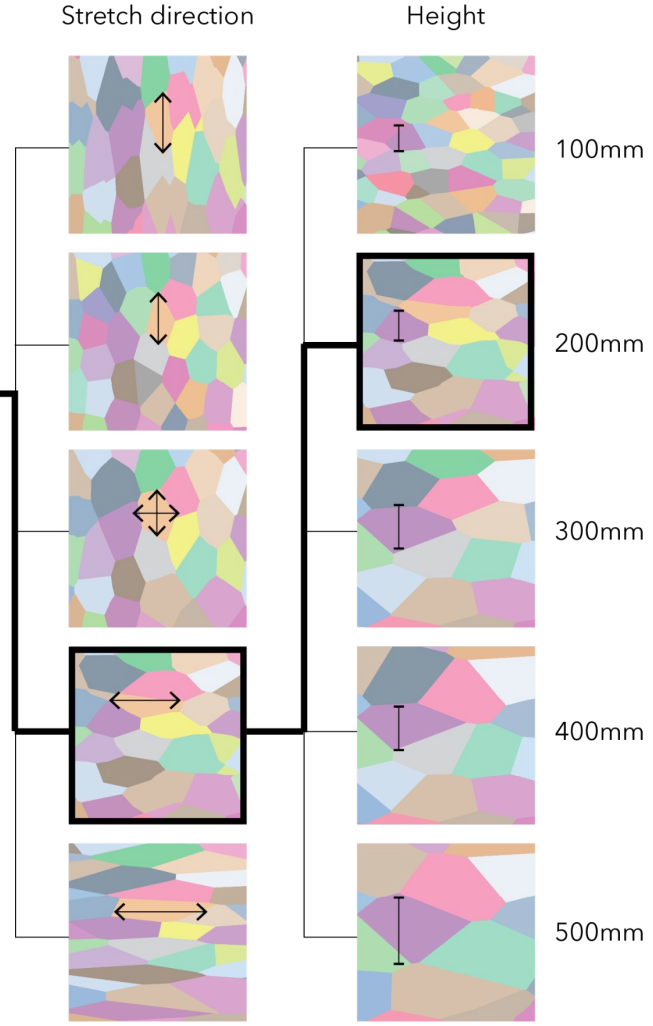


Wall of Private Quarters

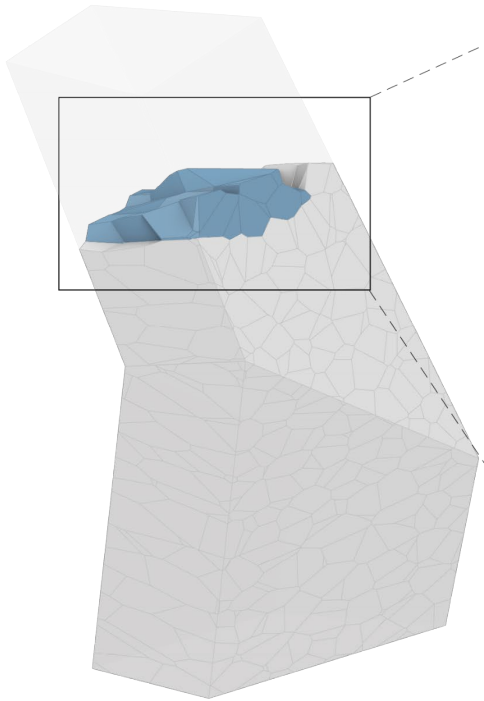


Wall fragment

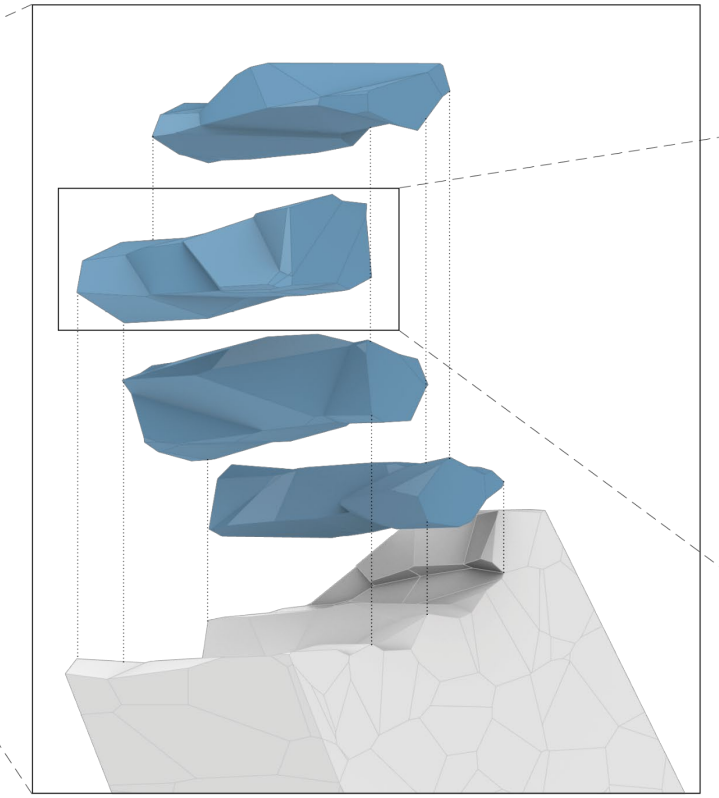
Iterations of wall fragment



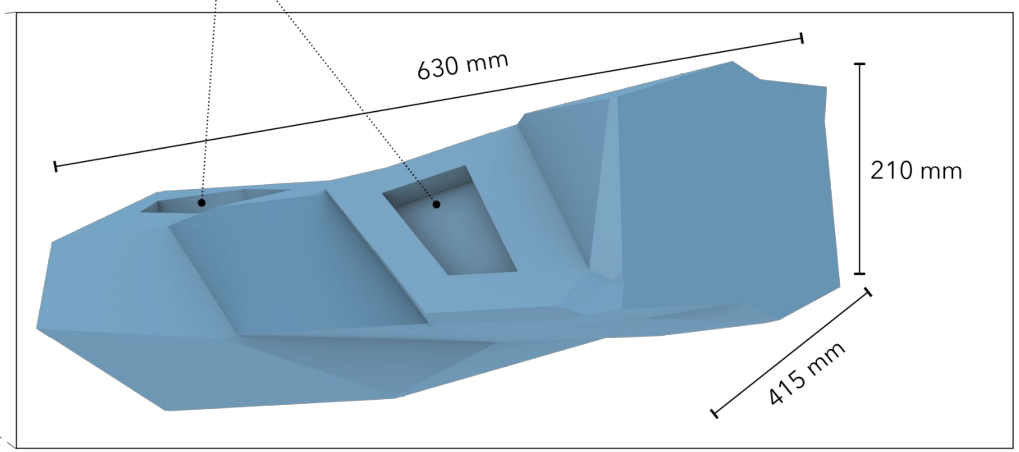
Fragment
Component



Stacked components



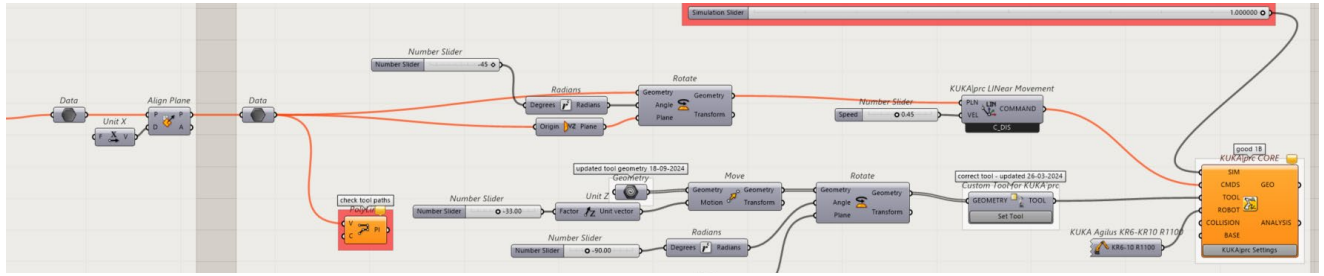
Stacking of components

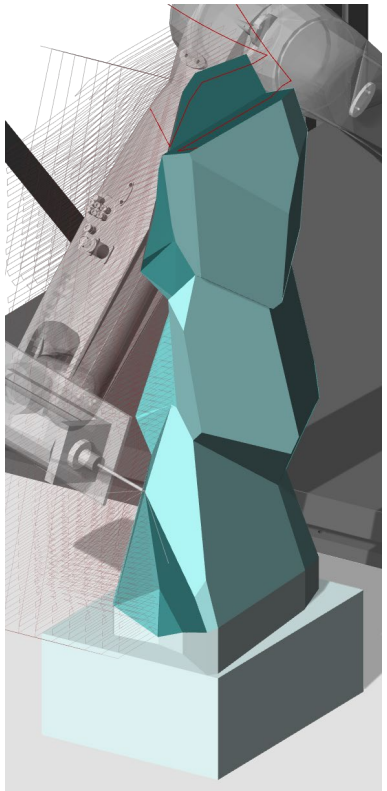


Single component detail

Building Method: Primary

Fabrication of components





Digital Simulation

EPS Milling (Workshop 1)

Concrete 3D Printing (Vertico)

Digital Computation

Robot toolpath

Mock-up

Implementation

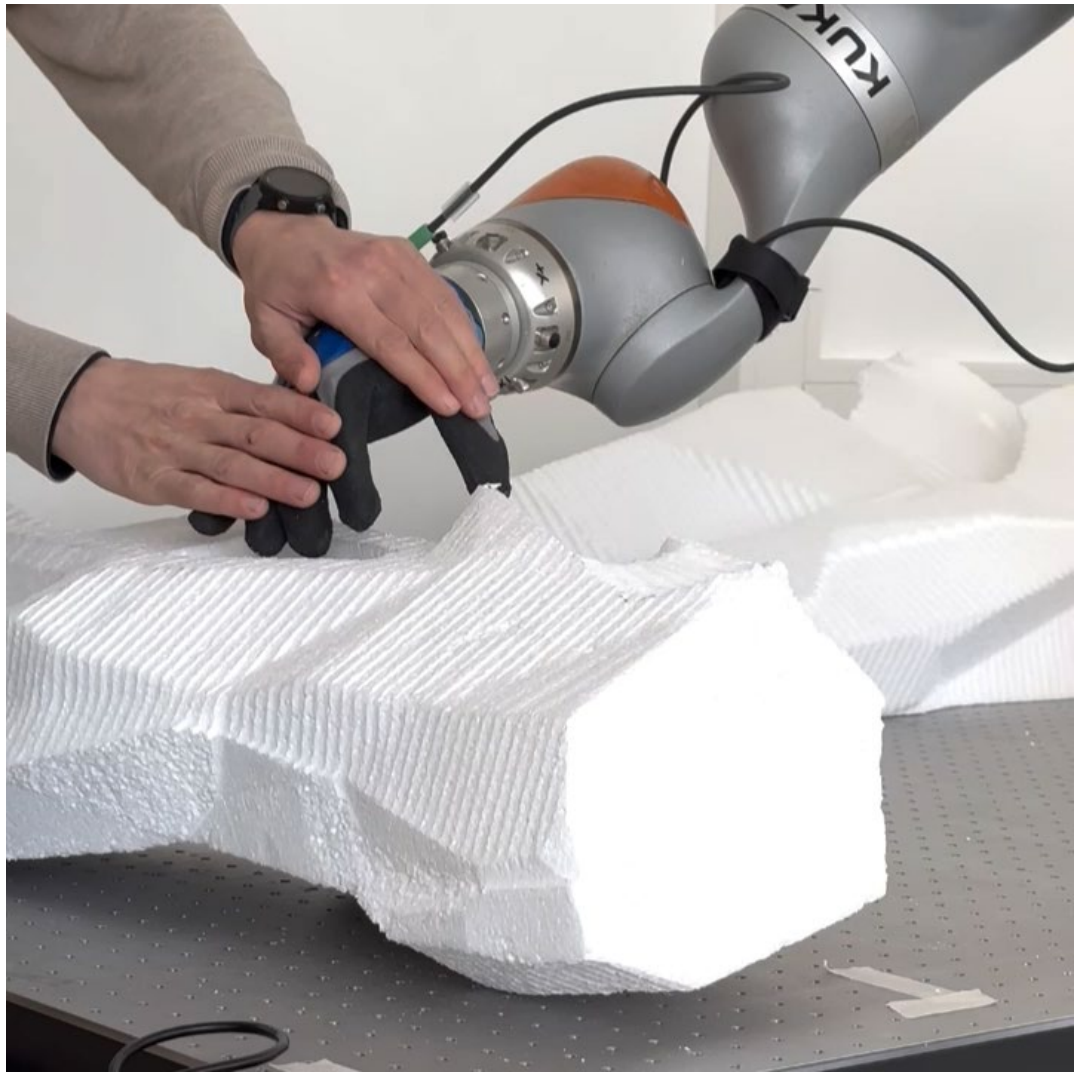
Mock-up using subtractive method

3D-printing using additive method

Robotic Fabrication

Building Method: Primary

Assembly of components



HRI Workshop, 4 April 2025

HUMAN-ROBOT INTERACTION

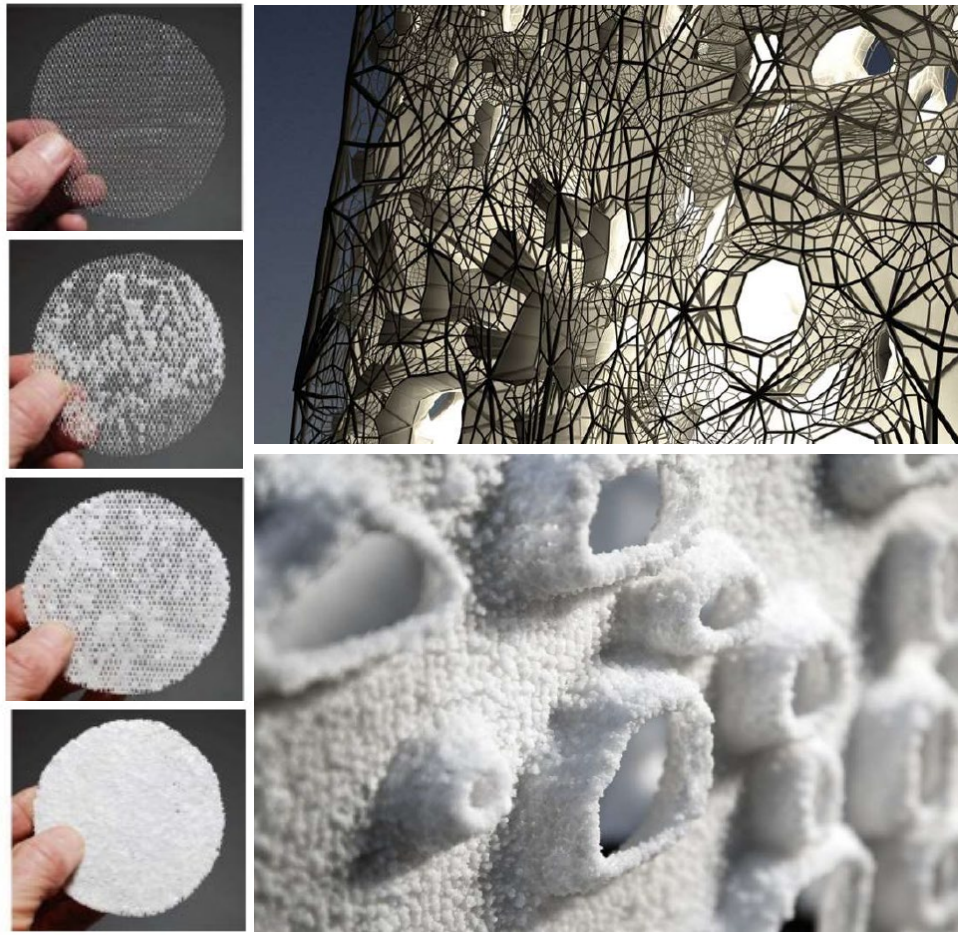
Robot's Strength + Human's Adaptability

Approaching component
Picking component
Transporting component
Placing component

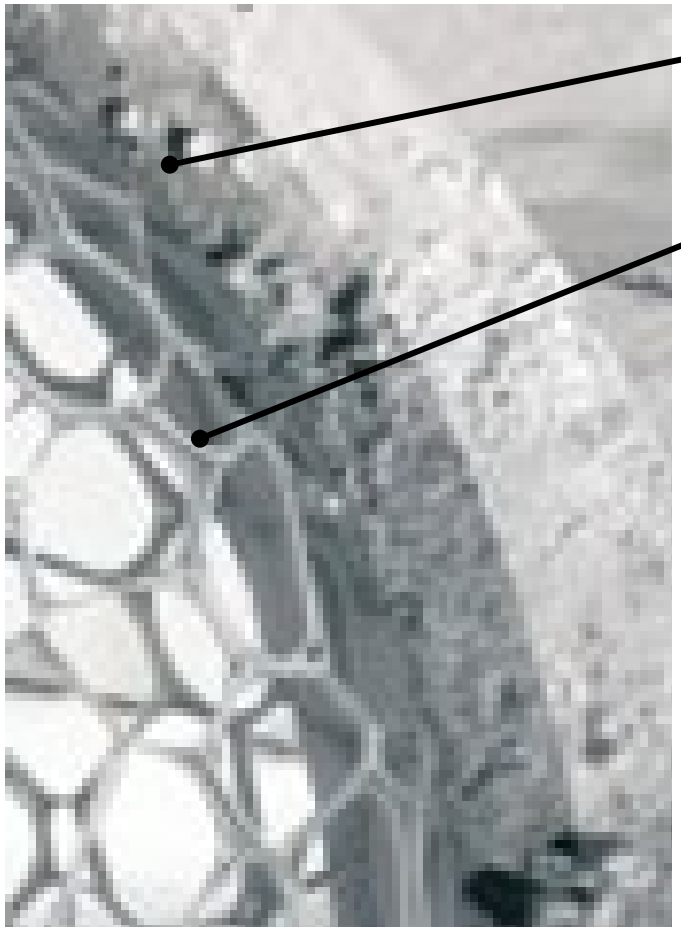
assisted

Building Method: Supplementary

Regolith Accretion



Vertical Salt Deposit Growth System
GEOtube Tower (2009), Faulders Studio, Dubai



Cheibas et. al.,Towards Additive Manufactured Off-Earth Habitats with Functionally Graded Multi-materials, p. 84

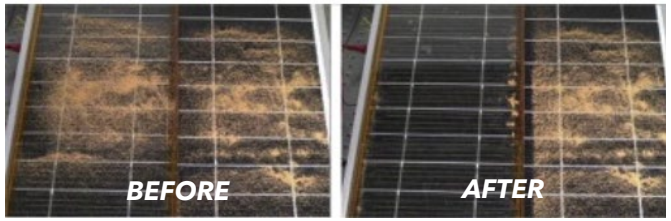
Regolith

- Accretion with electrostatic, sintered with laser heat

Aluminum Metallic Structure

- Medium to conduct electricity
- 3d-printed

Technology reference



Electrostatic cleaning system for sand removal from solar panels (2015), H. Kawamoto & T. Shibata

- Current technology: use electrostatic to **repel** regolith
- Reverse principle: use electrostatic to **attract** regolith

*based on in class discussion with expert

3D Printing + Regolith Accretion

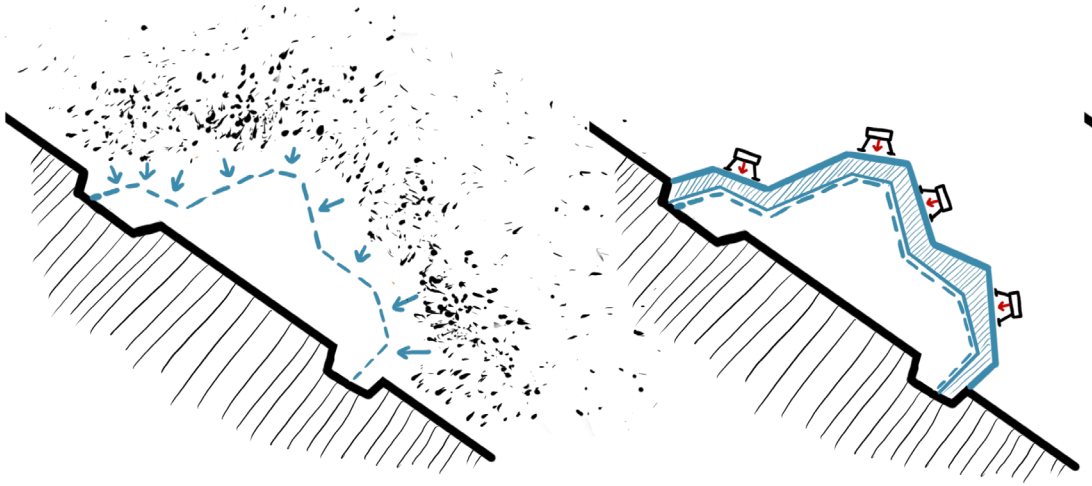
Close-up view of concrete additive 3d-printing, Vertico

Close-up view of salt accretion in scaled prototype, GEOtube Tower

For 1m thickness	3D Printing	Regolith Accretion
Energy	~135 MWh	~72 MWh (+) consume less energy
Time	~1 day (+) faster Construction rate (1-2 meters/day)	~20 days Construction rate (5 cm /day)
Machine complexity	High (3D Printer + assembly robot)	Moderate (low energy continuous electrostatic field + laser_high energy) Minimal machinery required
Scalability	Highly scalable	Limited by charge dissipation
Structural integrity	Geopolymer highly durable	Sintered layered are dense
Conclusion	Better for core building construction	Slower but more autonomous → ideal for no human supervision

3D Printing + Regolith Accretion

Application scheme (developed in discussion with Chris Verhoeven TU Delft)

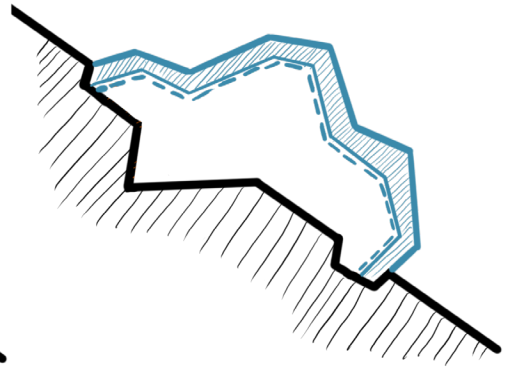


(1) Build envelope

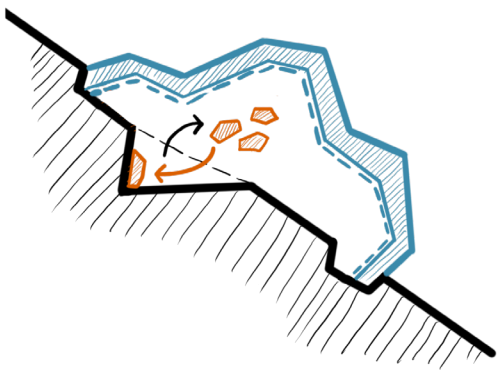
Attract regolith with electrostatically charged metal structure

(2) Laser sintering

with robot

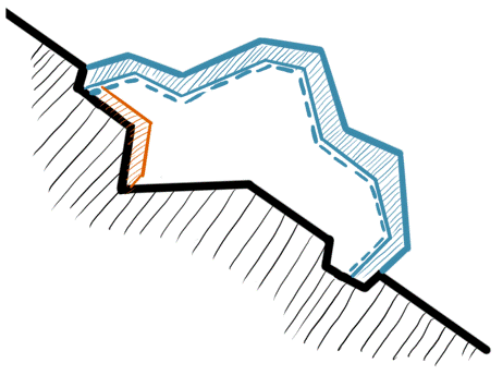


(3) Level-by-level excavation

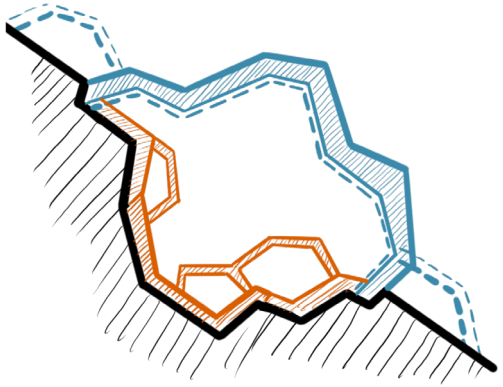


(4) Build 3D-printed walls

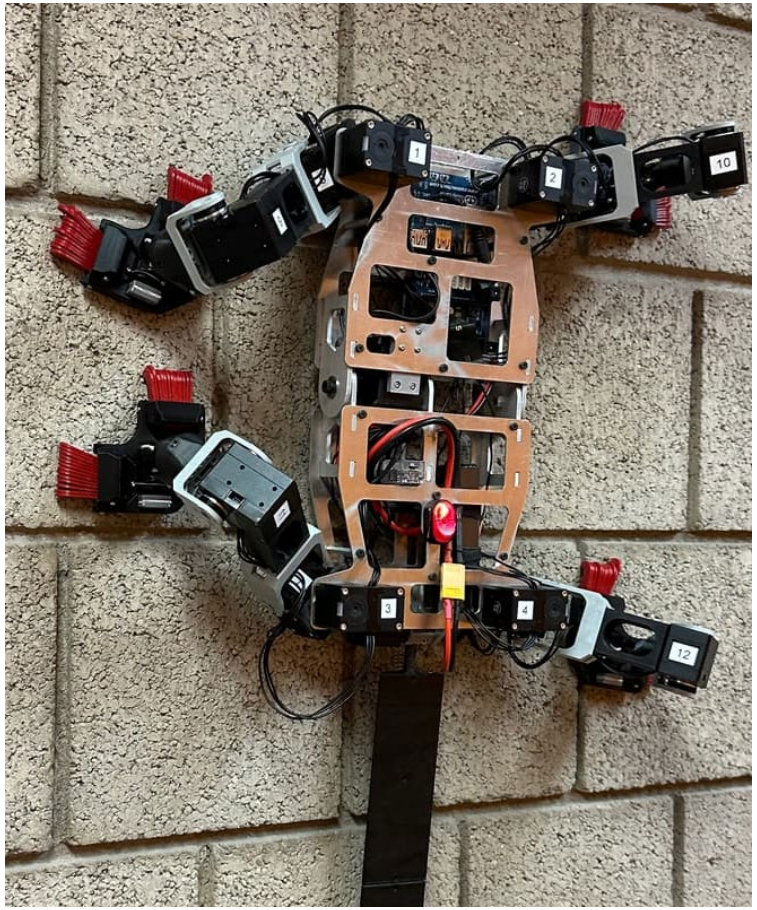
using materials from excavation



(5) Repeat process

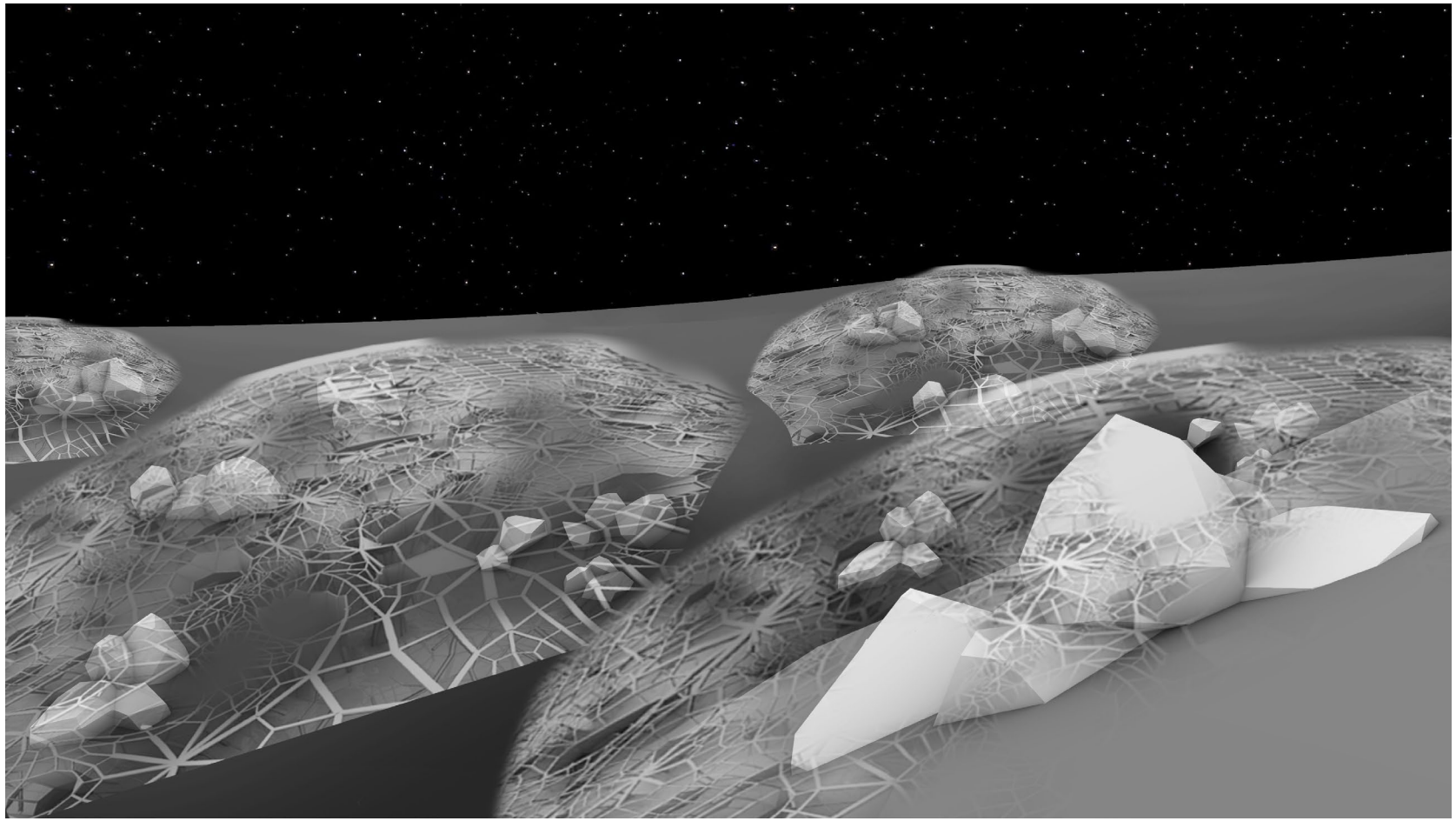


(6) Extend habitat



Climbing robot LORIS

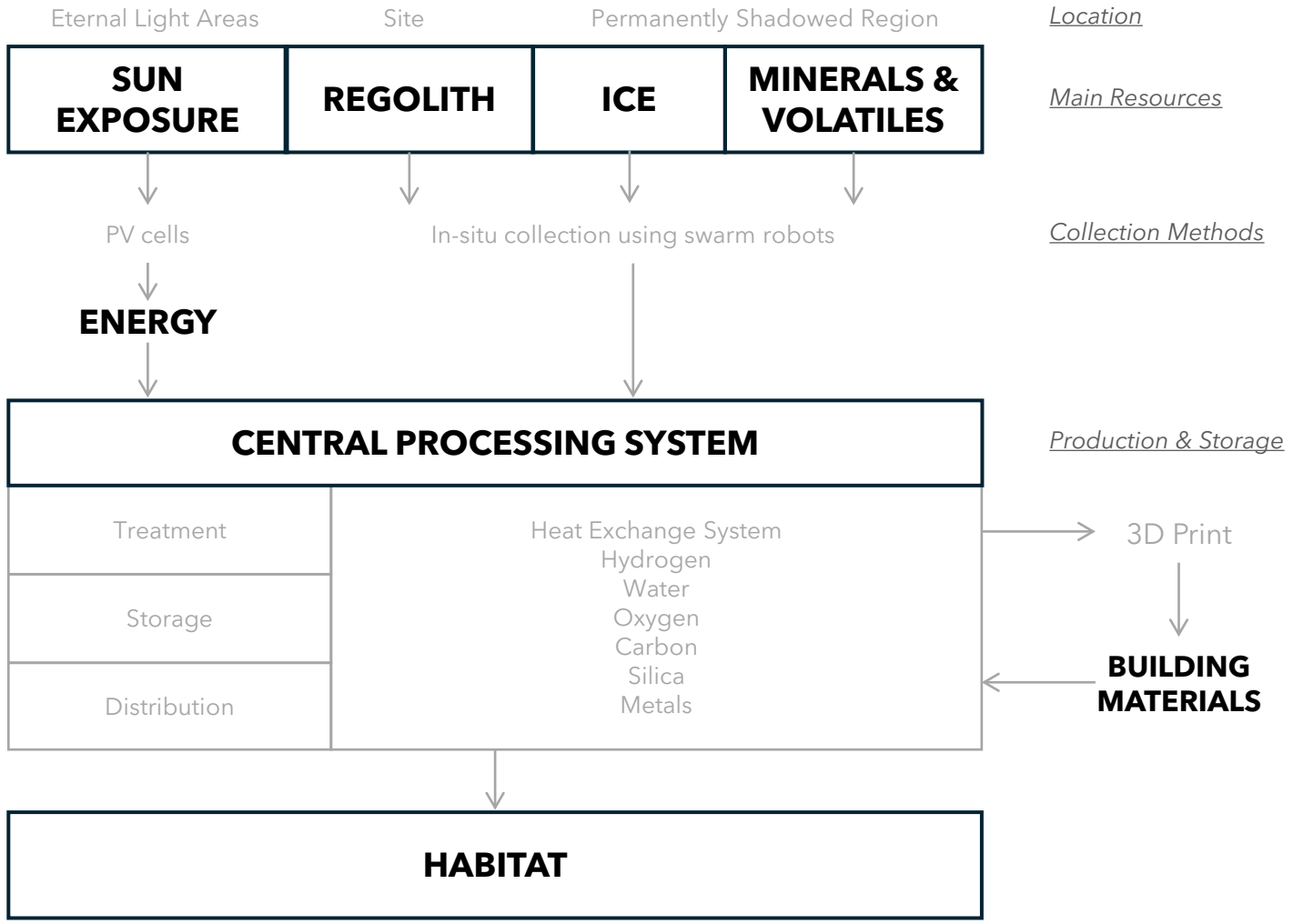
Conceptual Habitat Complex



Energy & Resources Collection

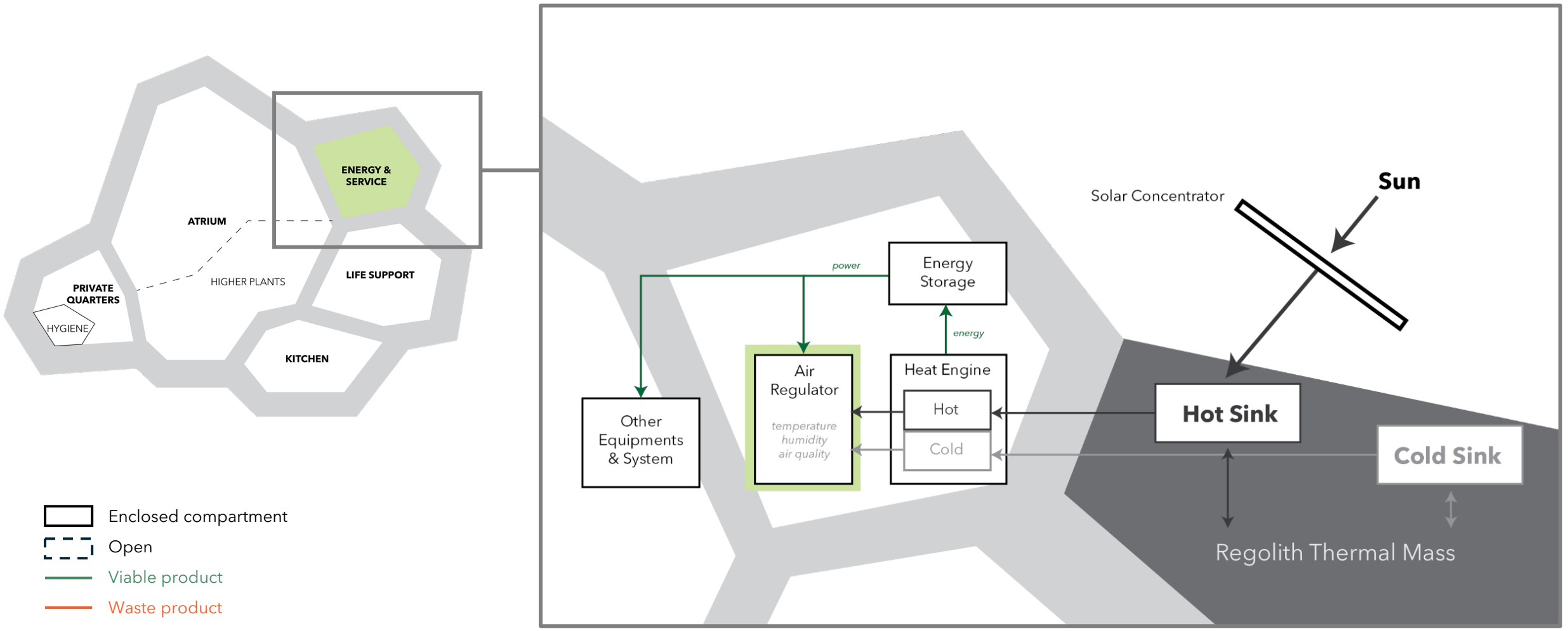
In-situ resource utilization

Shackleton Crater (top), Swarm Robots (bottom)



Space-based Solar Power, ESA; Heat storage and electricity generation in the Moon during the lunar night, Blai Climent et. al., Acta Astronautica; Power and Energy for the Lunar Surface, NASA; Moonshot Symposium, TU Delft, 2024; Adaptive On- and Off- Earth Environments.

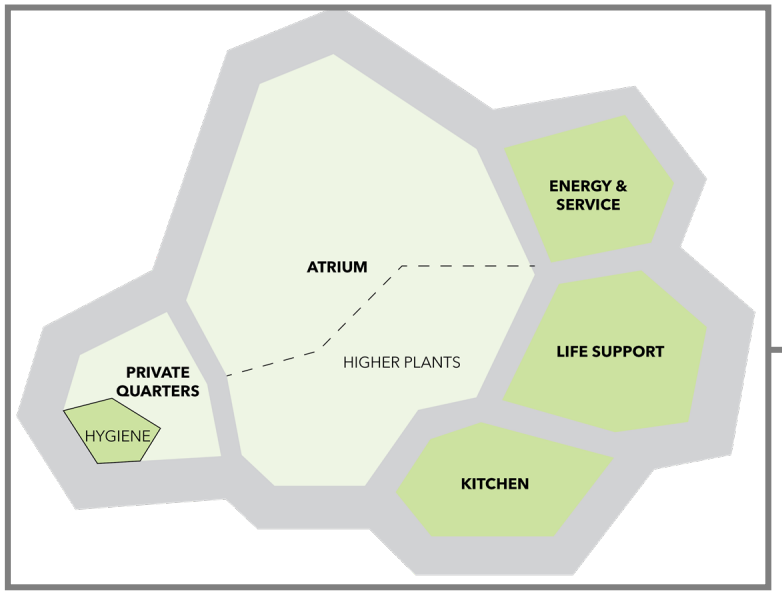
Life Support
Heating/Cooling

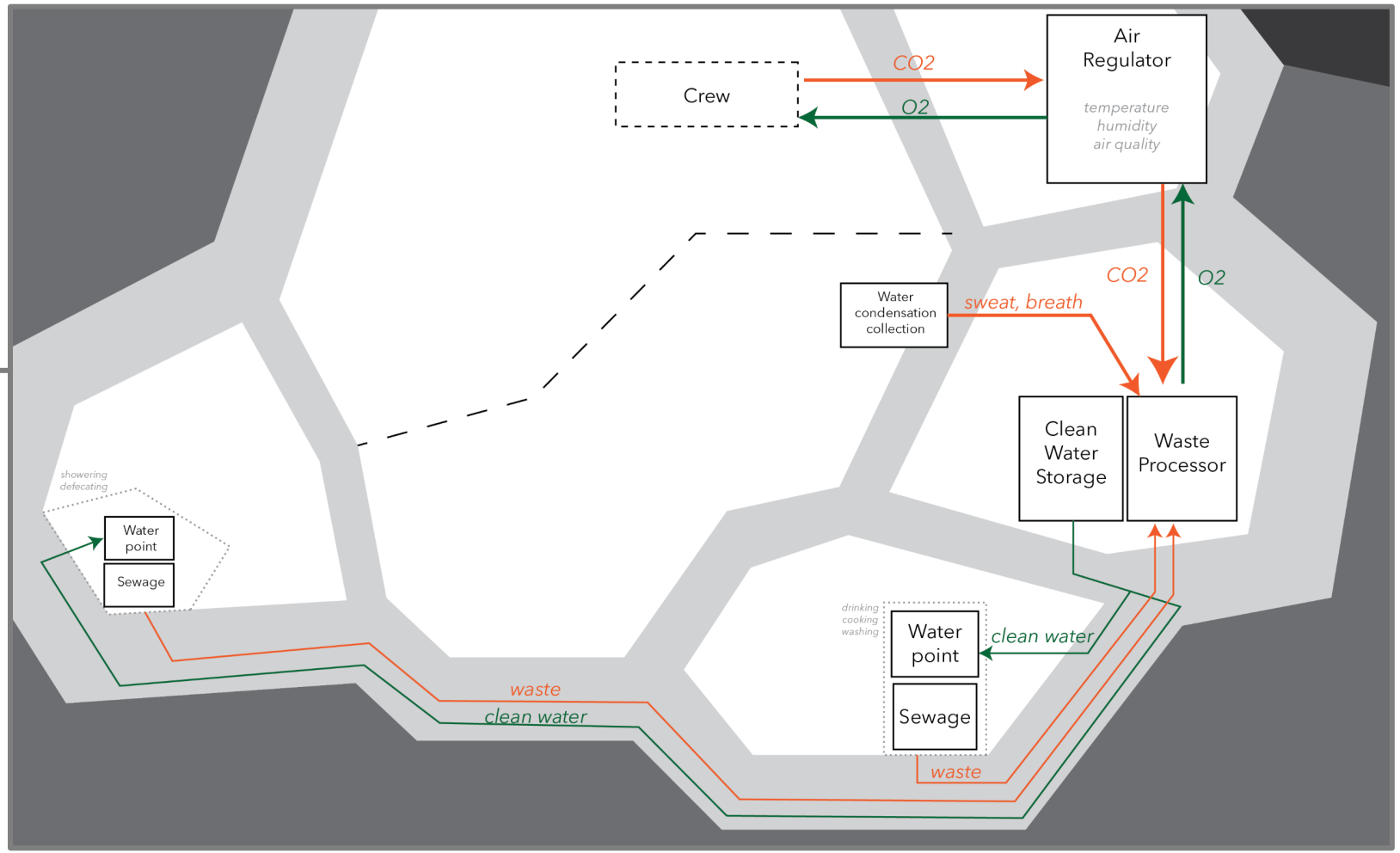


ESA Heat Engine System

Life Support

Habitat Main Mechanical Distribution





Enclosed compartment

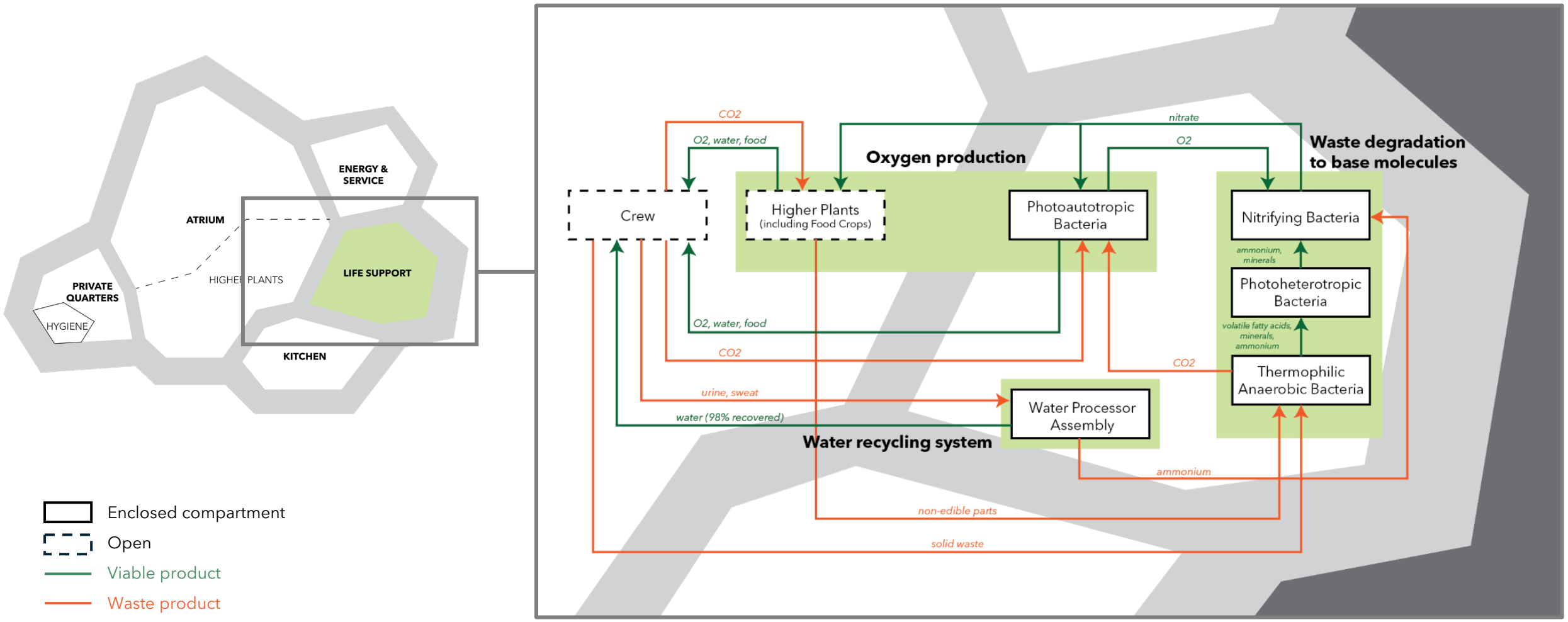
Open

Viable product

Waste product

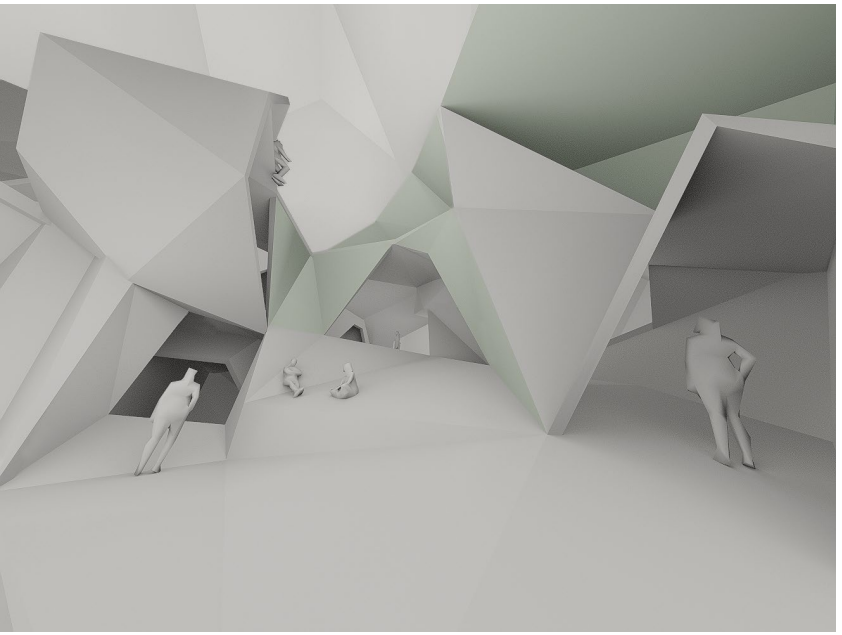
Life Support

Close-the-loop waste recovery system

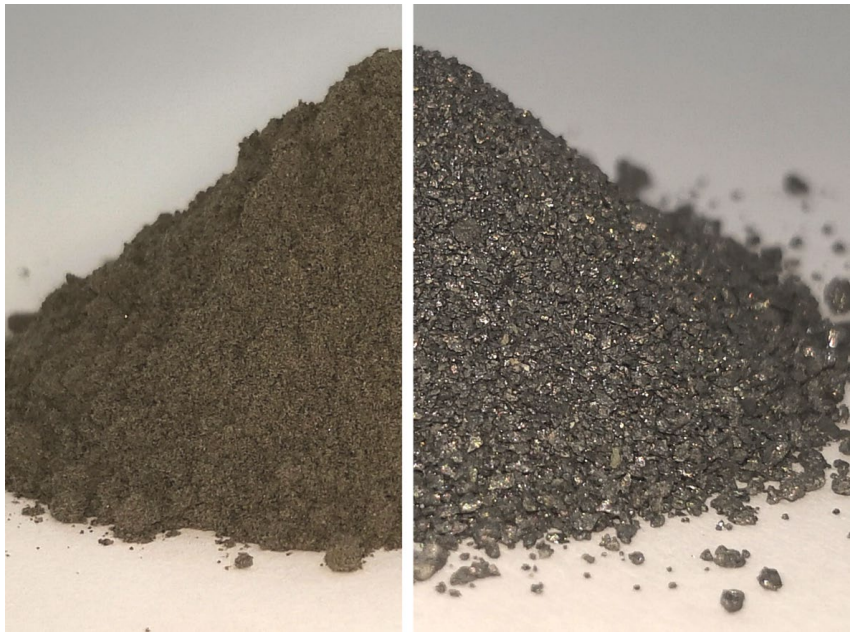


MELiSSA (Micro-Ecological Life Support System Alternative), ESA; Water Processor Assembly (WPA), NASA

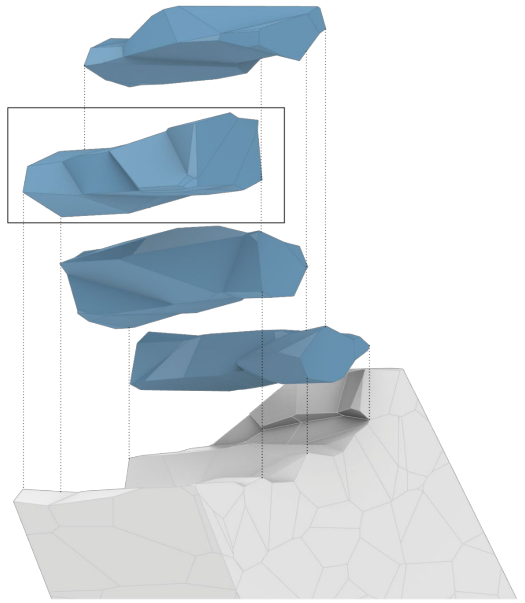
Reflection



Human-centric design



In-situ Resource Utilization



Design to Robotic Production and Assembly

Q&A