P4 Presentation

Terraforming Moon

Humanizing Lunar Living through Human-centric Design

LA&I Graduation Studio 2024/25

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Settling in the unknown…

What makes a place suitable for human habitation?

What are the demands for long-term settlement?

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

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

Settling in the physically hostile lunar environment

Habitat provides enclosure for protection

Source: Architecture for Astronauts, last column added by author

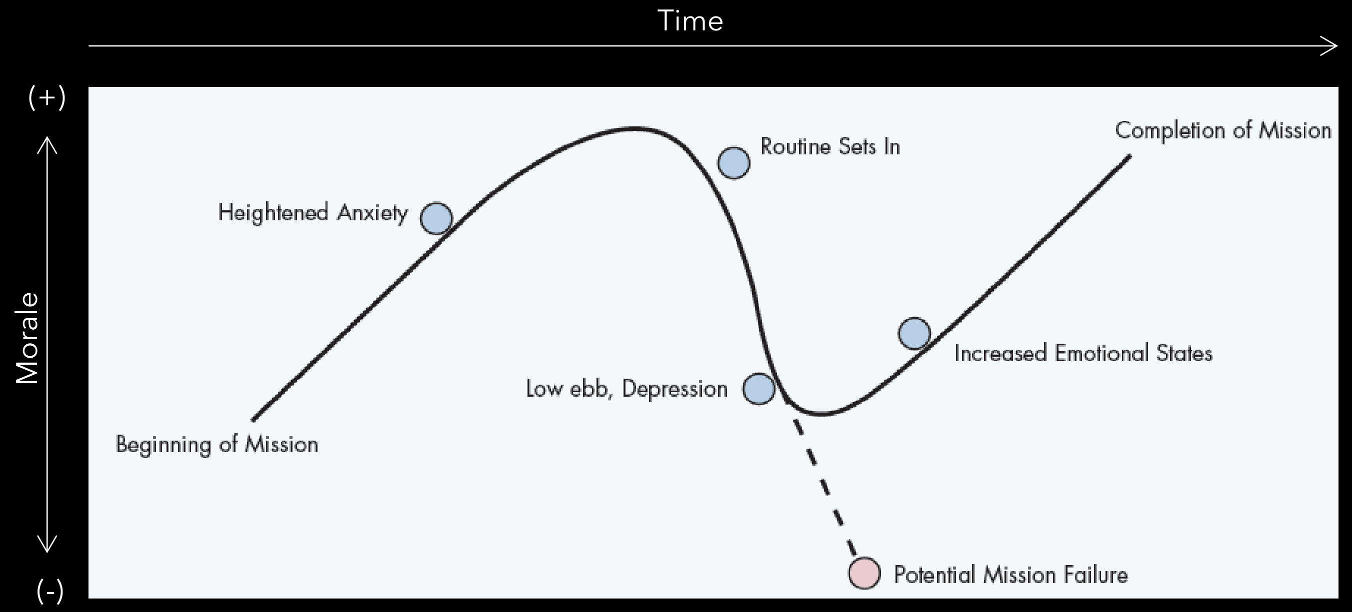
Condition	Earth	Moon	Design Implications
Gravity	1 g	1/6 g	Consider low gravity effects
Atmosphere	1 bar (O2, N2, CO2)	~0 bar (almost vacuum)	Pressurized vessel
Length of day	24 hours	28 Earth days (14 days light / 14 days dark)	Site selection
Temperature	Mean 15°C Range: -89°C – 60°C	Mean -20°C Range: -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.

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

Settling in the mentally hostile ICE environment

*Isolated, Confined, and Extreme (ICE) Environment



Stages of emotional condition during long-term mission.

"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.

What are the demands for long-term settlement?

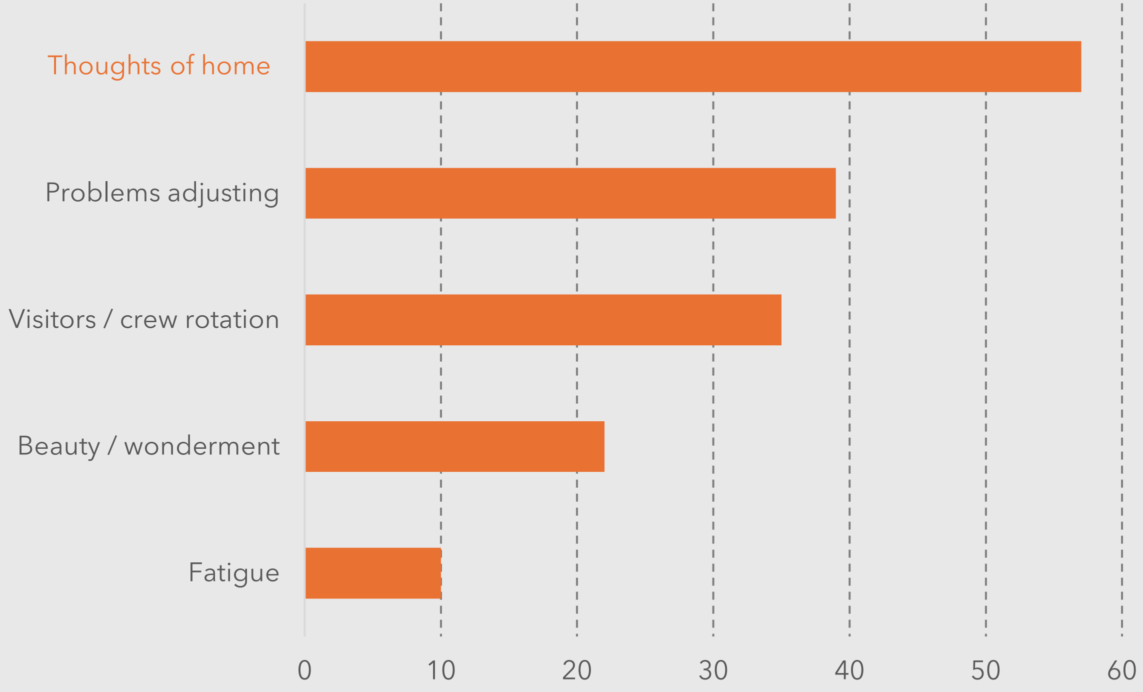
Excerpts from space missions

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

- Thoughts of home as highest journal entry



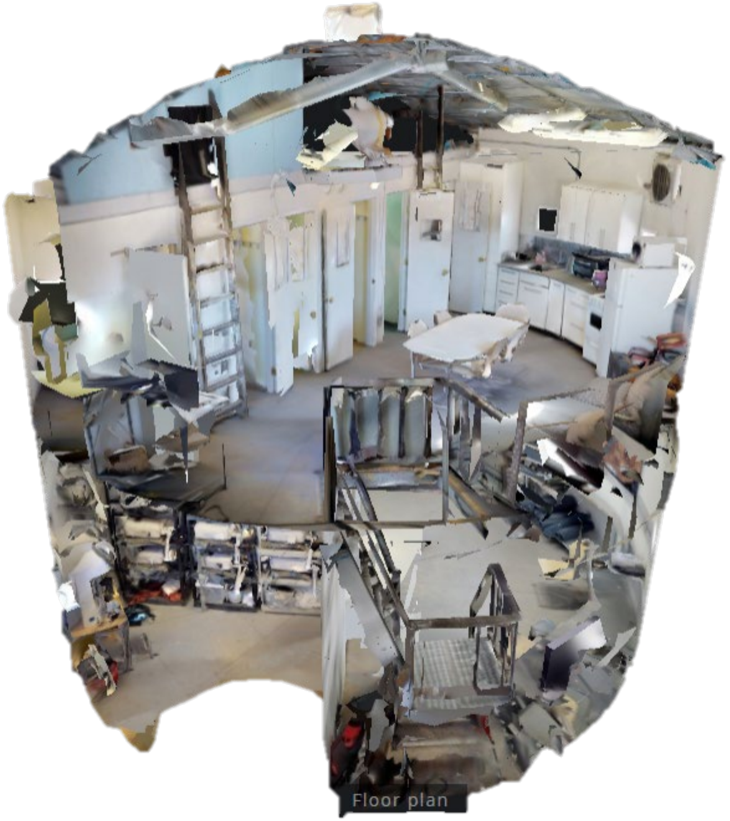
Distribution of journal entries by astronauts aboard the ISS,
Olga Bannova in Space Architecture: Human Habitats Beyond Planet Earth.

"…we wash using no-rinse soap and shampoo and a towel (…) it works really well. That being said I am looking forward to a long hot shower when I get home!"

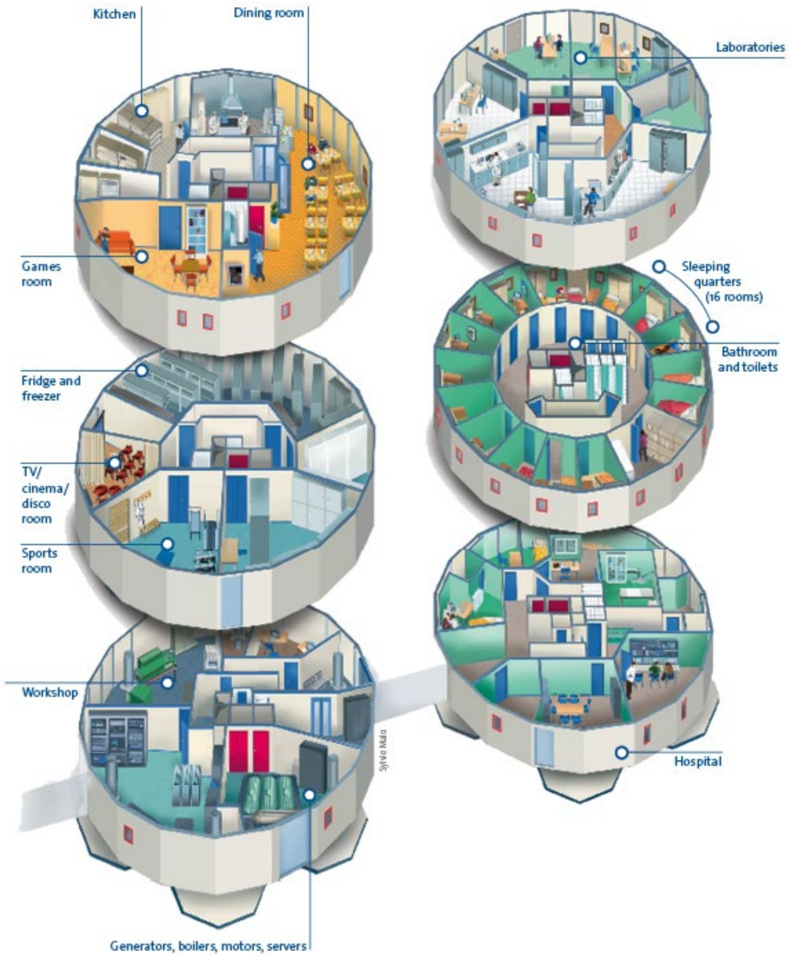
Ed Lu, ISS, Expedition 7 (185 days), NASA, 2003

Human de-centered design

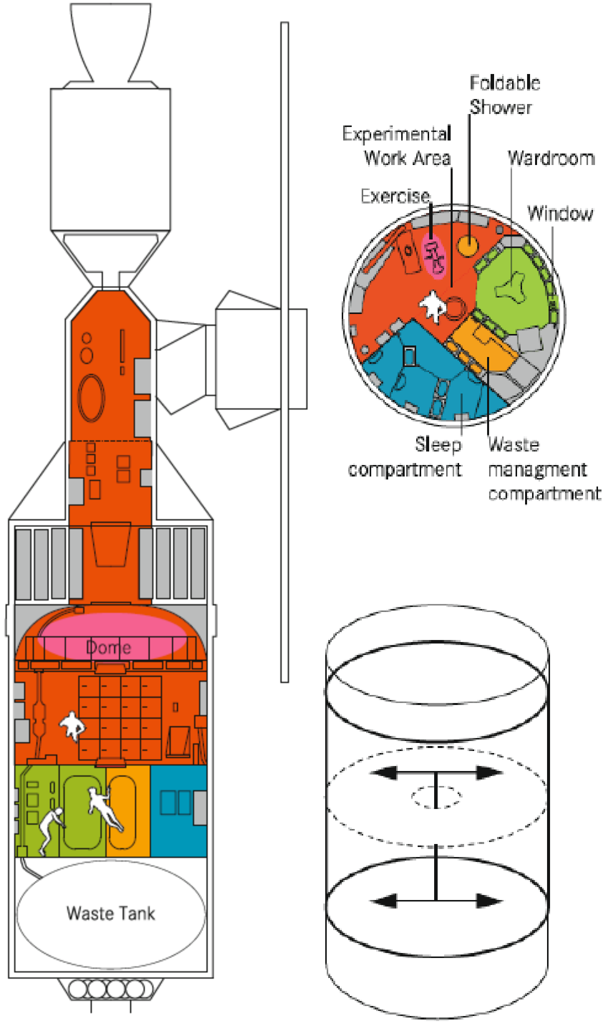
Schemes developed from functional aspect (not focusing on human behavior)



Mars Desert Research Station, Utah, USA



Concordia Research Station, Antarctica



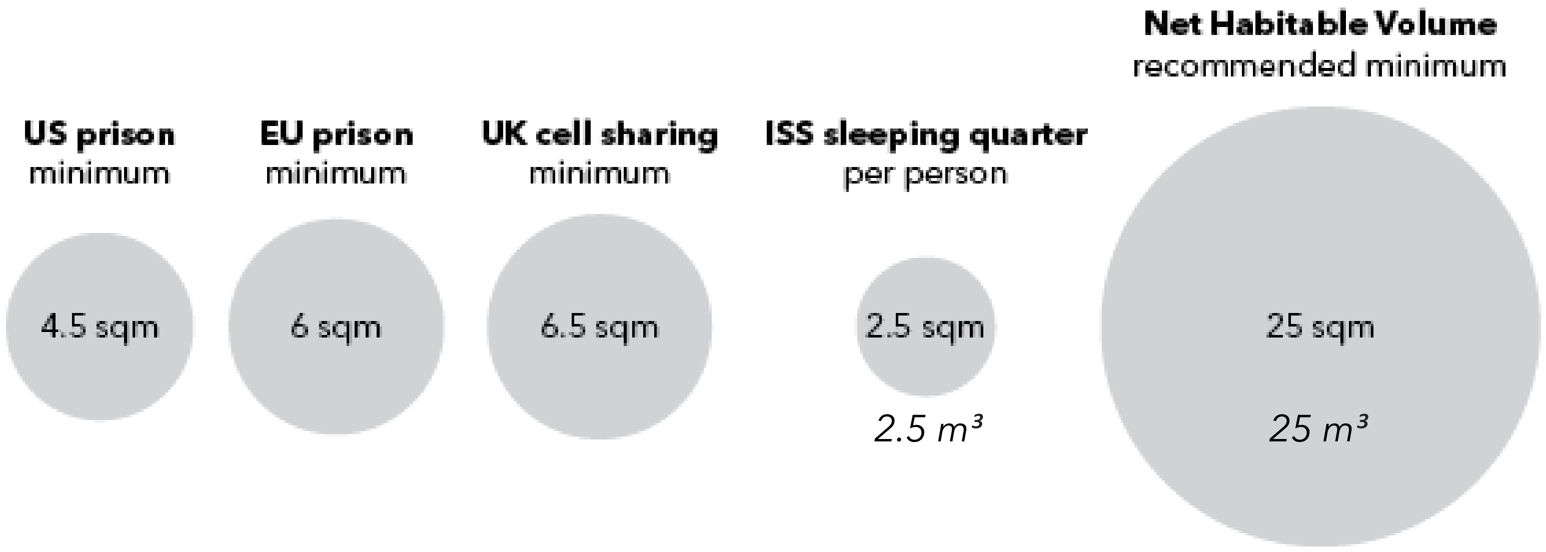
Skylab Space Station

Human de-centered design

Limited private area allocation

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

Jerry Linenger, 2000



Human-centric design

Success in design for human behavior in ICE environment

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

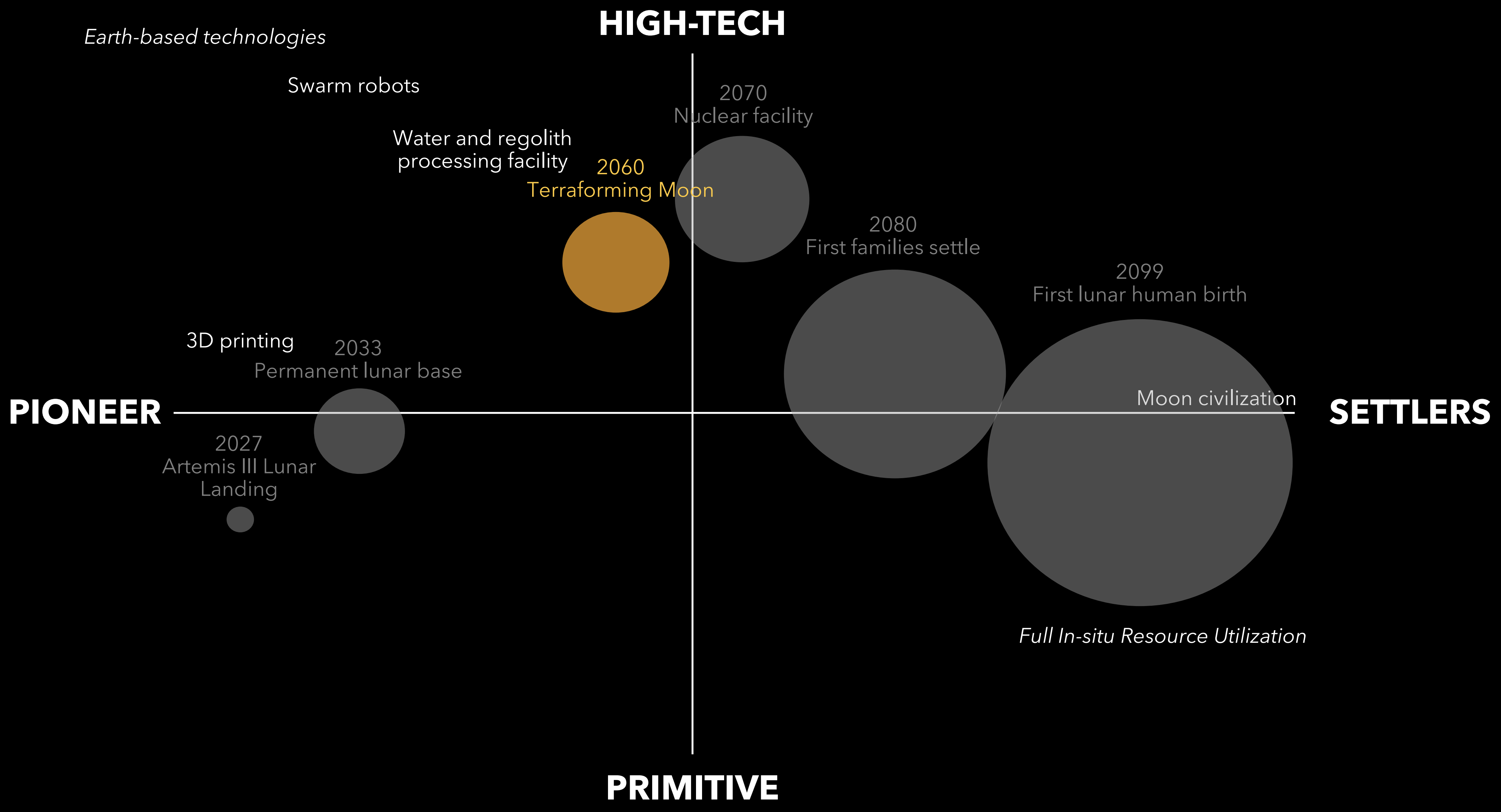
How to incorporate **user-defined spaces** based on **human-centric design principles** in designing long-term lunar habitation that **balances social interaction and private boundaries**, for the psychosocial well-being of the inhabitants?

Design Direction

How to design a long-term lunar habitat with **heterogeneous spaces** that balances between **social interaction and private boundaries**, within the isolated nature of space habitats?

Limitations & Assumptions

Timeline



Human-centric Design

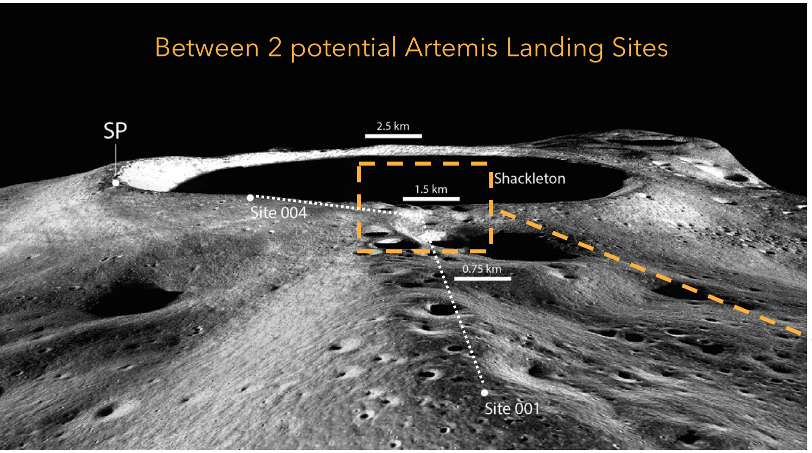
Using human experiences as data and human preferences as design guide

Experience *Humanization + Habitability*	→ Personas	→ Activity-based design	→ Design parameters	→ Spatial quality
	Who will live?	***How will they live?***		
Personal Preferences Behaviours **Community** Traditions Interactions	**6-crew members** 3 men + 3 women (1 couple) 2 robots → Design for diverse preferences	**Personal** **Social** **Work**	**Openness** Open / Enclosed **Size** Private / Small Groups / All **Access** Direct / Indirect	**HOW TO REPRESENT HUMAN INTERACTION & PERSONAL PREFERENCES ARCHITECTURALLY?** **HOW TO DESIGN FOR IT?**
Analog Mission (Hi-SEAS, Antarctica Stations) *Space Mission (ISS, Skylab)*	*Speculate individual requirements*	*Inform functional requirements*	*Translate to tangible requirement*	*Answering the requirement*

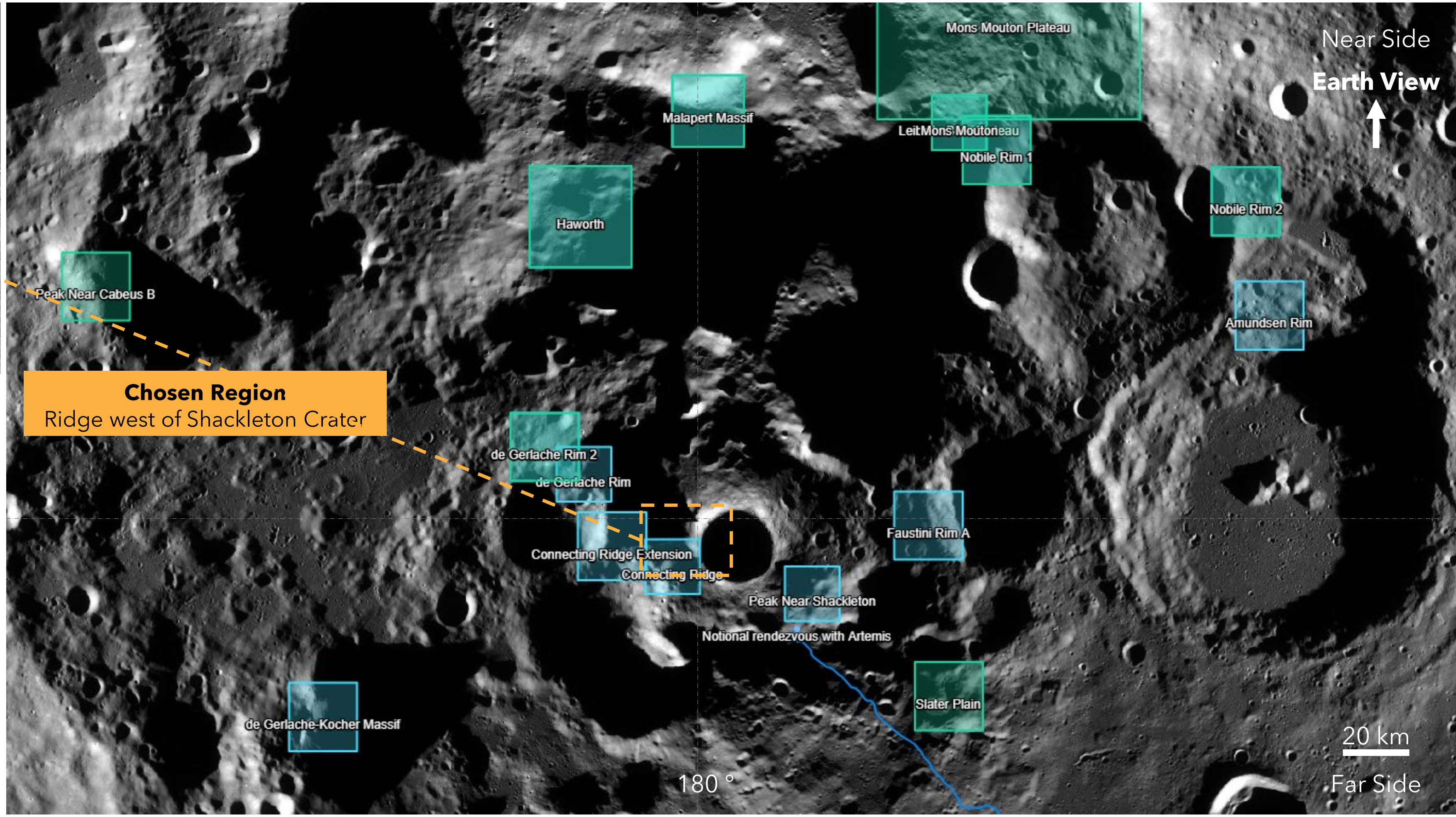
Site Selection

Lunar South Pole: Potential high human activity and abundant resource

Between 2 potential Artemis Landing Sites



Artemis Landing Sites along Shackleton Crater ridge



Artemis III potential landing regions 2022 (approx. 15x15 km)

Artemis III potential landing regions 2024

LROC WAC Mosaic Lunar South Pole Polar Stereographic, 300 mpx

High human activity potential

- Lunar base candidate → center of lunar civilization
- Earth is visible

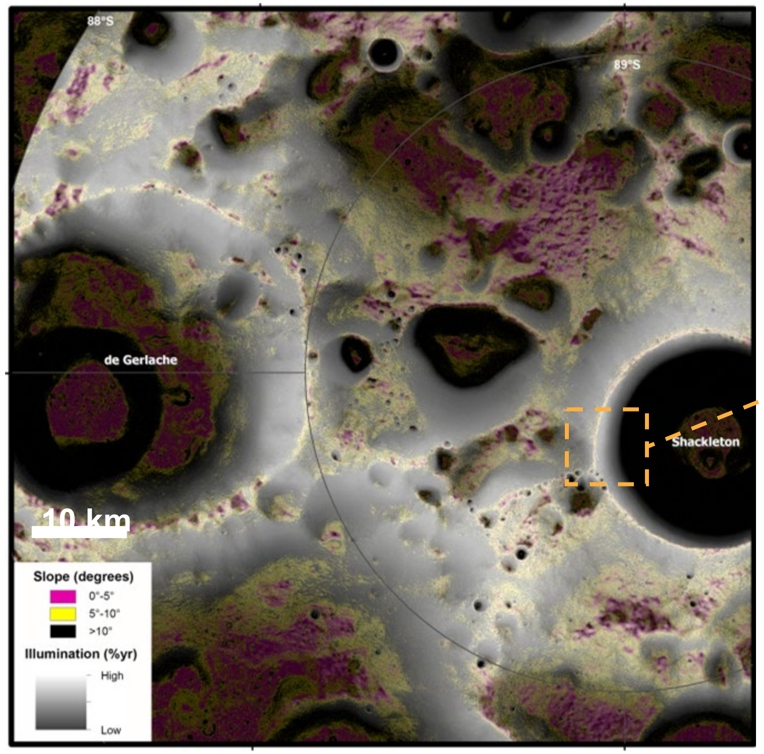
Abundant resource

- Proximity to eternal sunlit areas & permanently shadowed areas

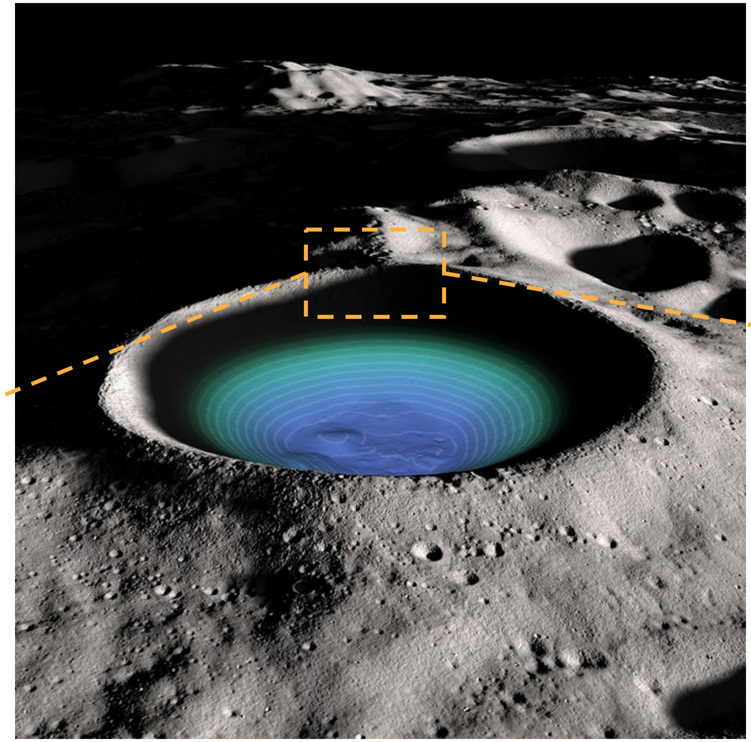
Site Selection

Sun and Earth visibility, resource availability

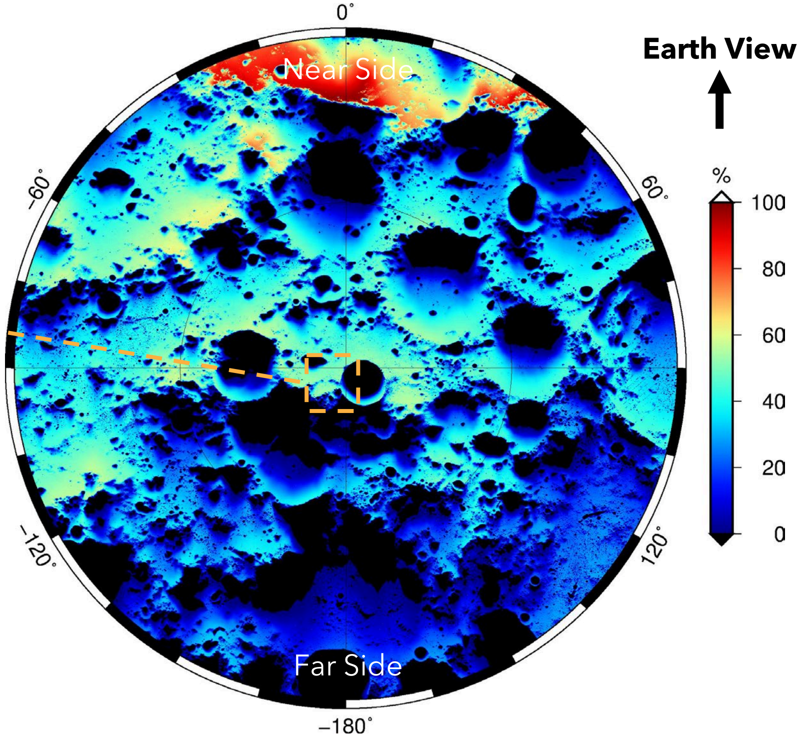
- **Eternal sunlight areas** (illuminated >80% of the time) as energy source and daylight utilization
- **Permanently Shadowed Regions** provide water-ice (possible water collection system and ISRU) and fossil records of hydrogen and other early Solar System volatiles (planetary research)
- **Earth view** to alleviate potential homesickness



Annual Illumination and Topographic Slope, LPI



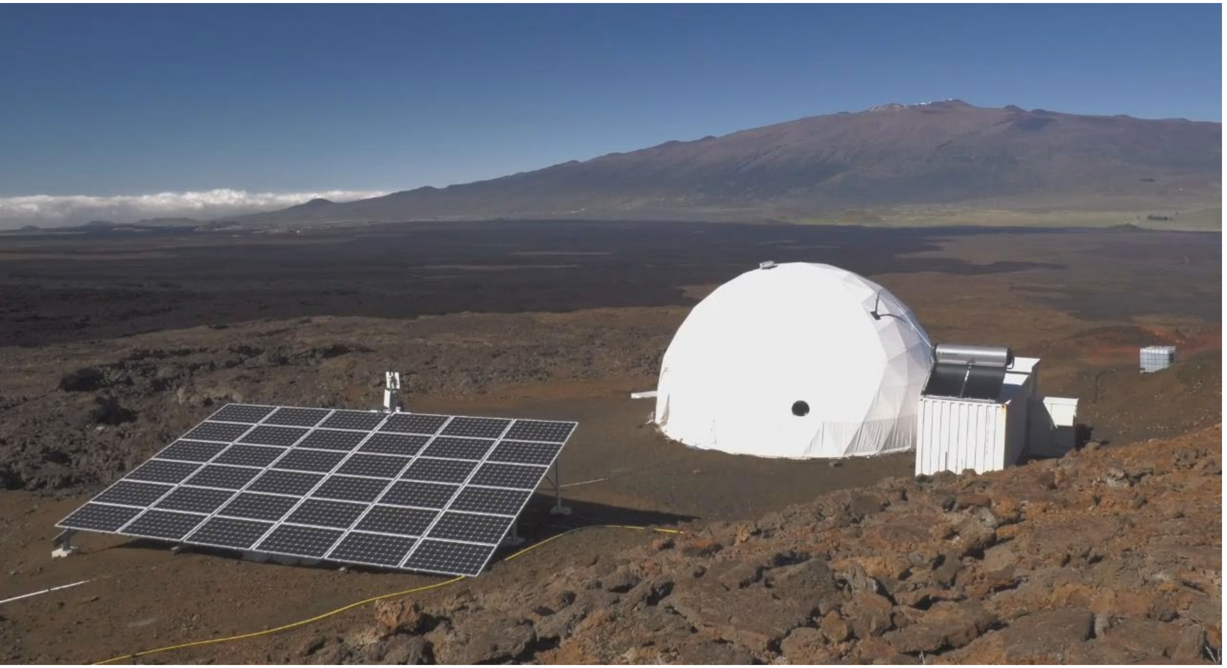
Shackleton Crater, NASA Goddard



Average Earth Visiblity in 85 °S - 90 °S, NASA Goddard

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"

Bunkbeds in shared room, McMurdo Station

Wine Bar-Coffee House, McMurdo Station

Hallway of a scientist group, McMurdo Station

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 → the action of going up as mental cue to rest

- Design should support variation → personalization as a creative outlet!

Angelo Vermuelen on Hi-SEAS Mission

Transition from public to private

Hi-SEAS Mission NASA, Angelo Vermuelen

Personalization of private quarters

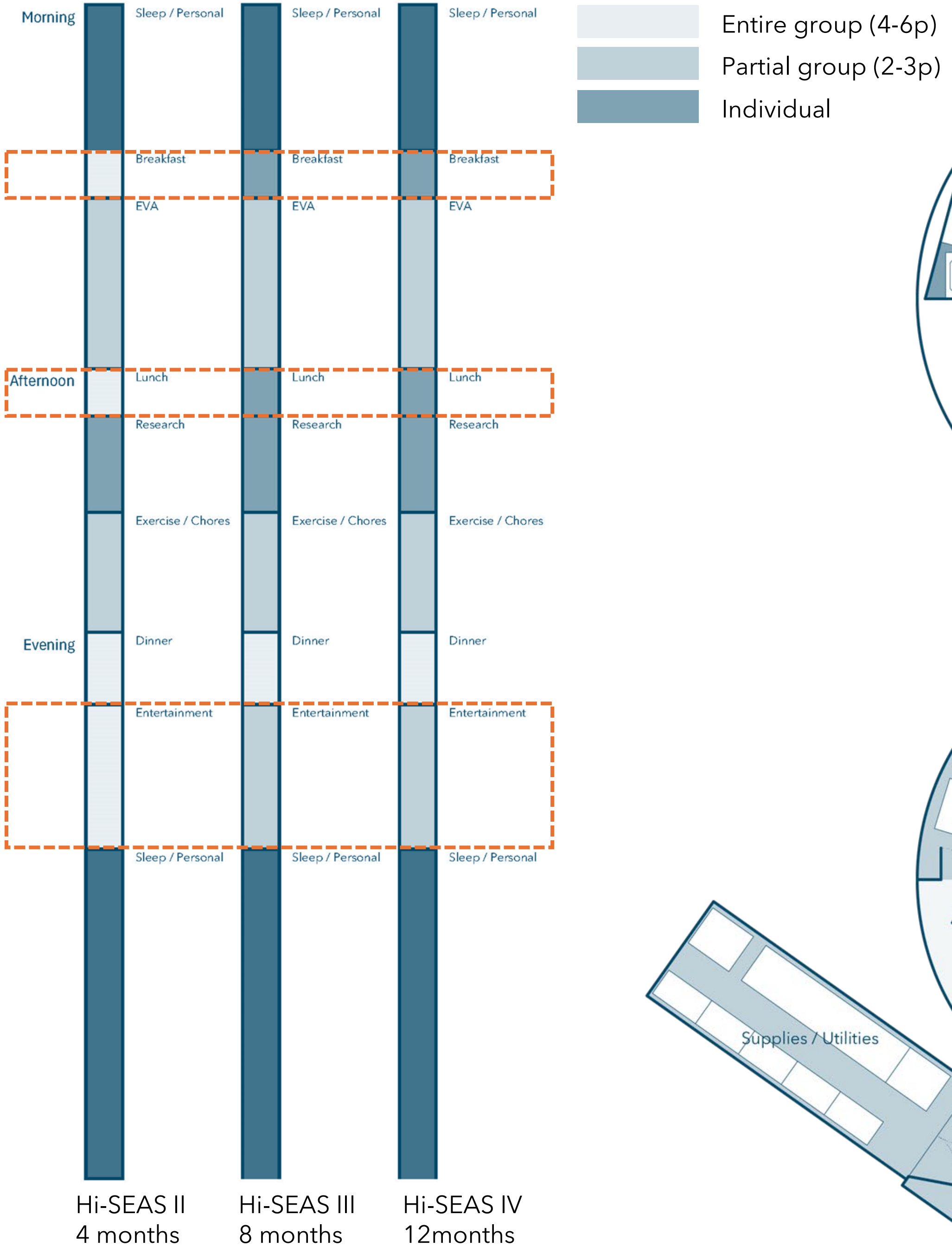
Hi-SEAS Mission NASA, various sources

Learning from analog

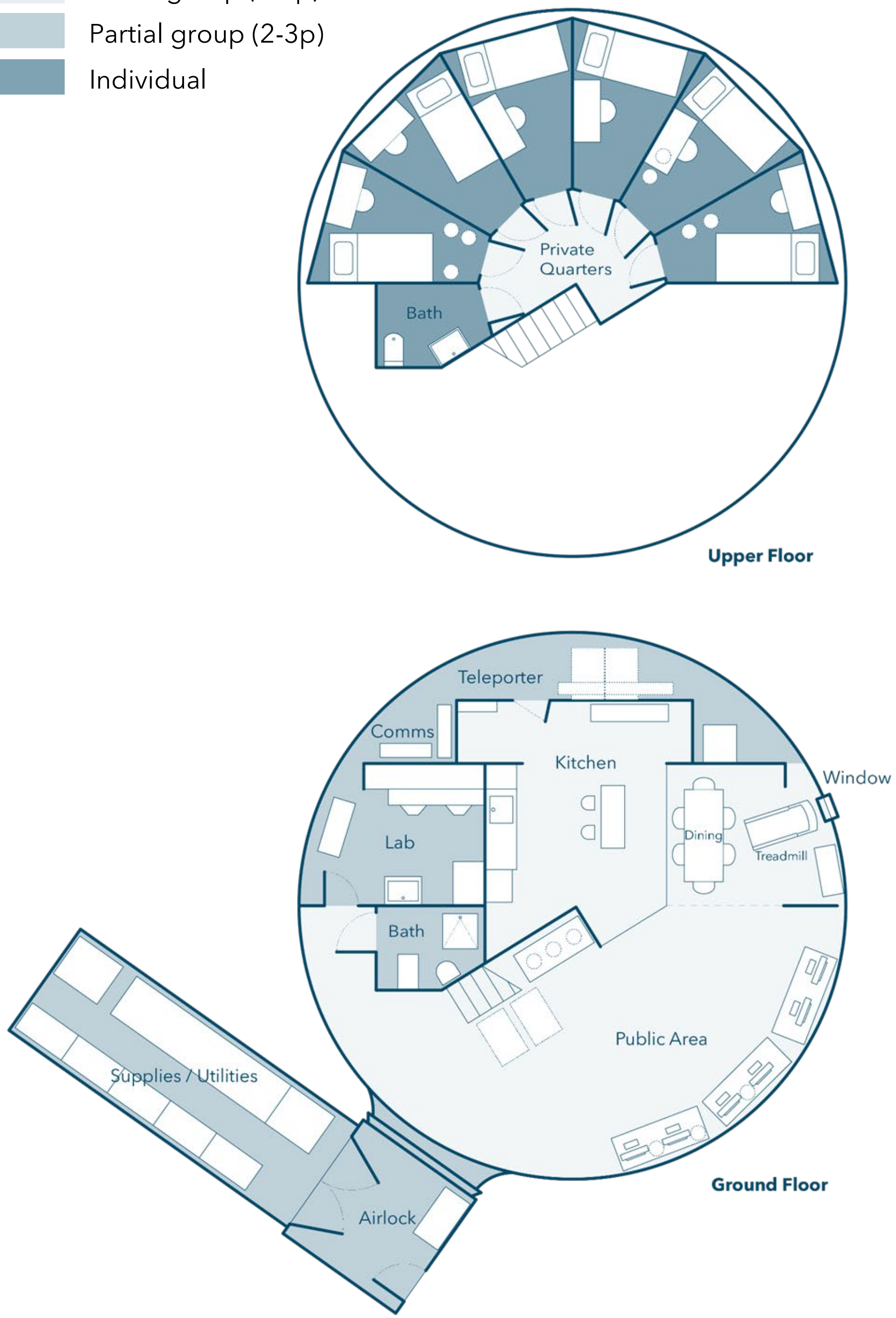
Importance of privacy gradient

Hi-SEAS Missions

- Declining participation in group activities over time
- Formation of social cliques over time
- Frustration: 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)



Schedule based on social interaction



Learning from analog

Greenery as social condenser

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

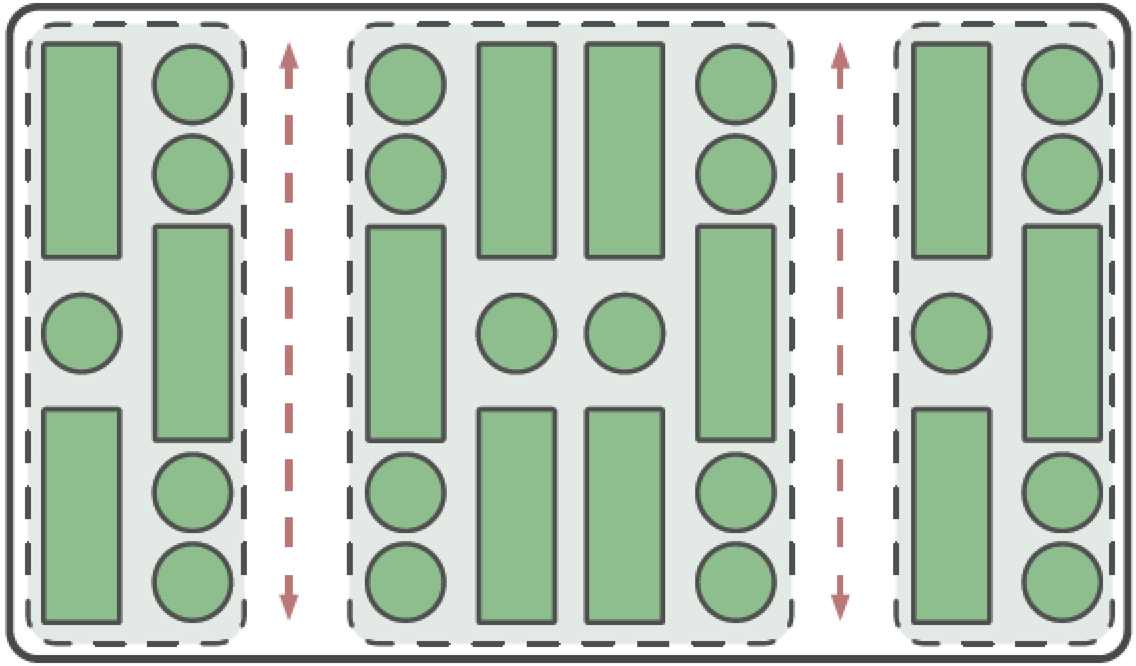
Harvesting plants in Hi-SEAS GreenHab

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

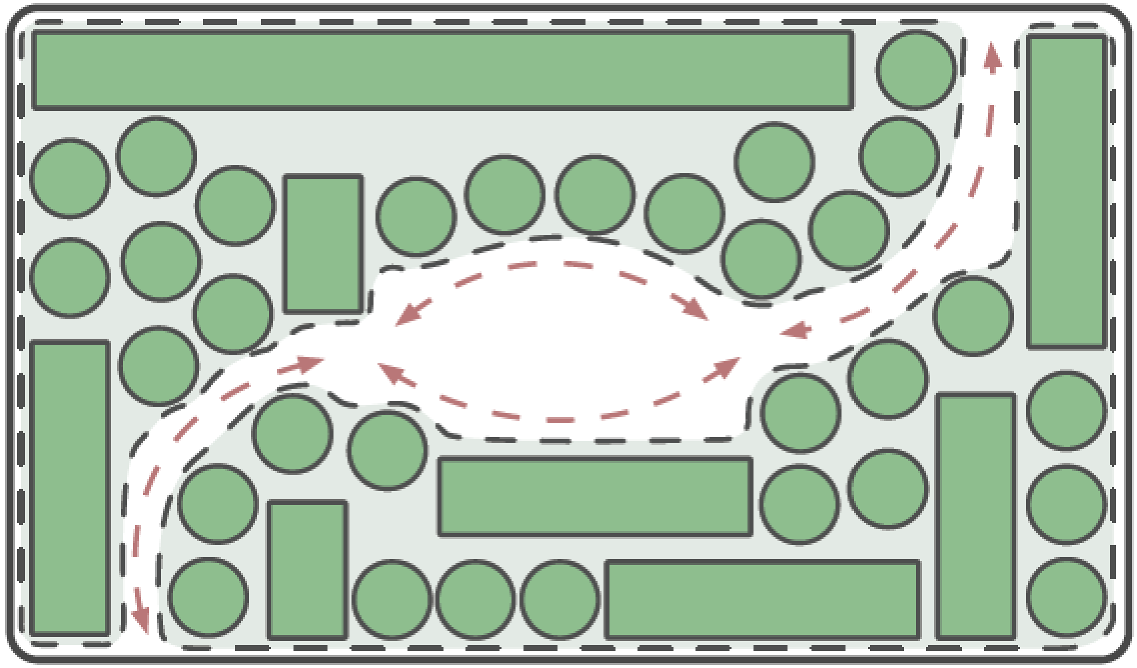
Greenery Layout Strategy

Organic layout for long-term health benefits



Rigid greenhouse

- Efficient, prioritizes the **plant research**

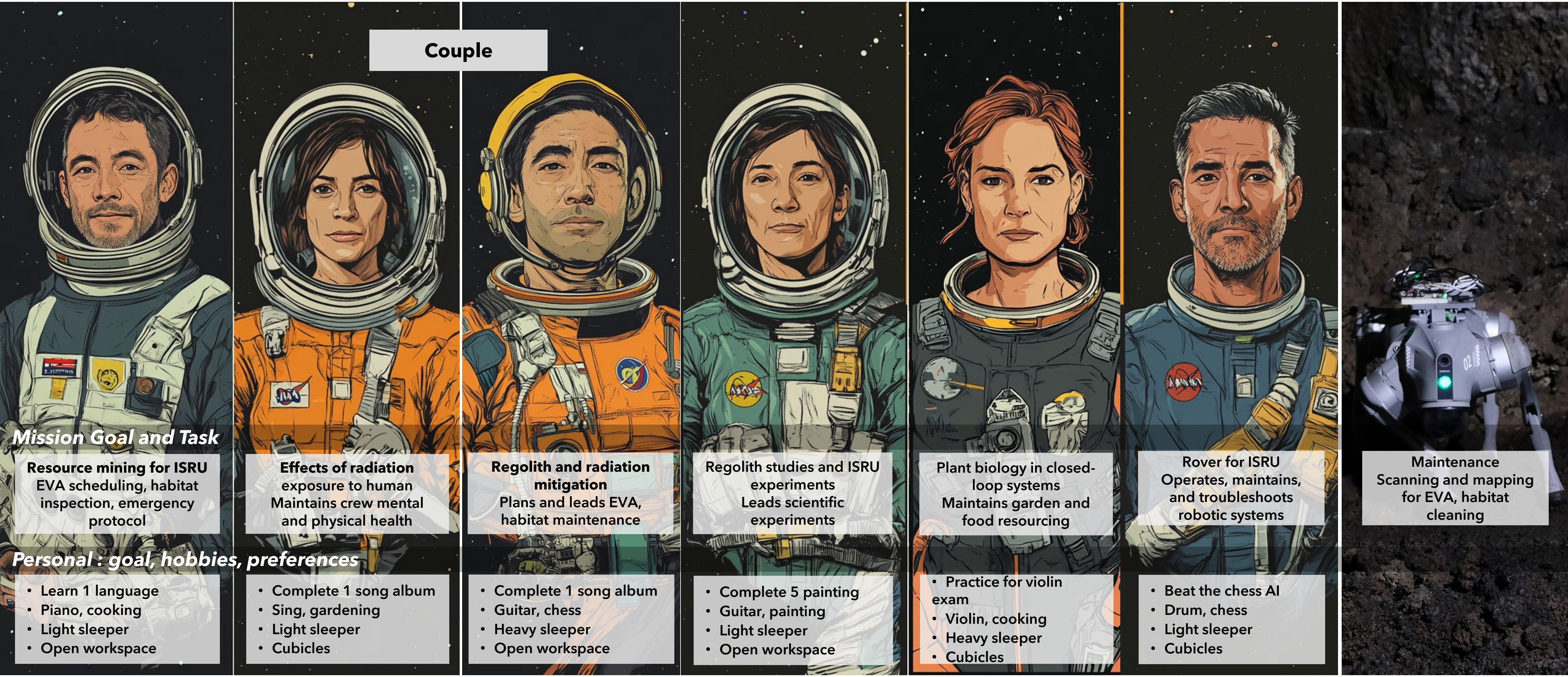


Organic greenhouse

- 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



Commander, 37

Mission Goal and Task: **Resource mining for ISRU** EVA scheduling, habitat inspection, emergency protocol

- Learn 1 language
- Piano, cooking
- Light sleeper
- Open workspace

Medic, 33

Mission Goal and Task: **Effects of radiation** exposure to human Maintains crew mental and physical health

- Complete 1 song album
- Sing, gardening
- Light sleeper
- Cubicles

EVA Specialist, 35

Mission Goal and Task: **Regolith and radiation mitigation** Plans and leads EVA, habitat maintenance

- Complete 1 song album
- Guitar, chess
- Heavy sleeper
- Open workspace

Geologist, 32

Mission Goal and Task: Regolith studies and ISRU experiments Leads scientific experiments

- Complete 5 painting
- Guitar, painting
- Light sleeper
- Open workspace

Ecologist, 29

Mission Goal and Task: Plant biology in closed-loop systems Maintains garden and food resourcing

- Practice for violin exam
- Violin, cooking
- Heavy sleeper
- Cubicles

Roboticist, 30

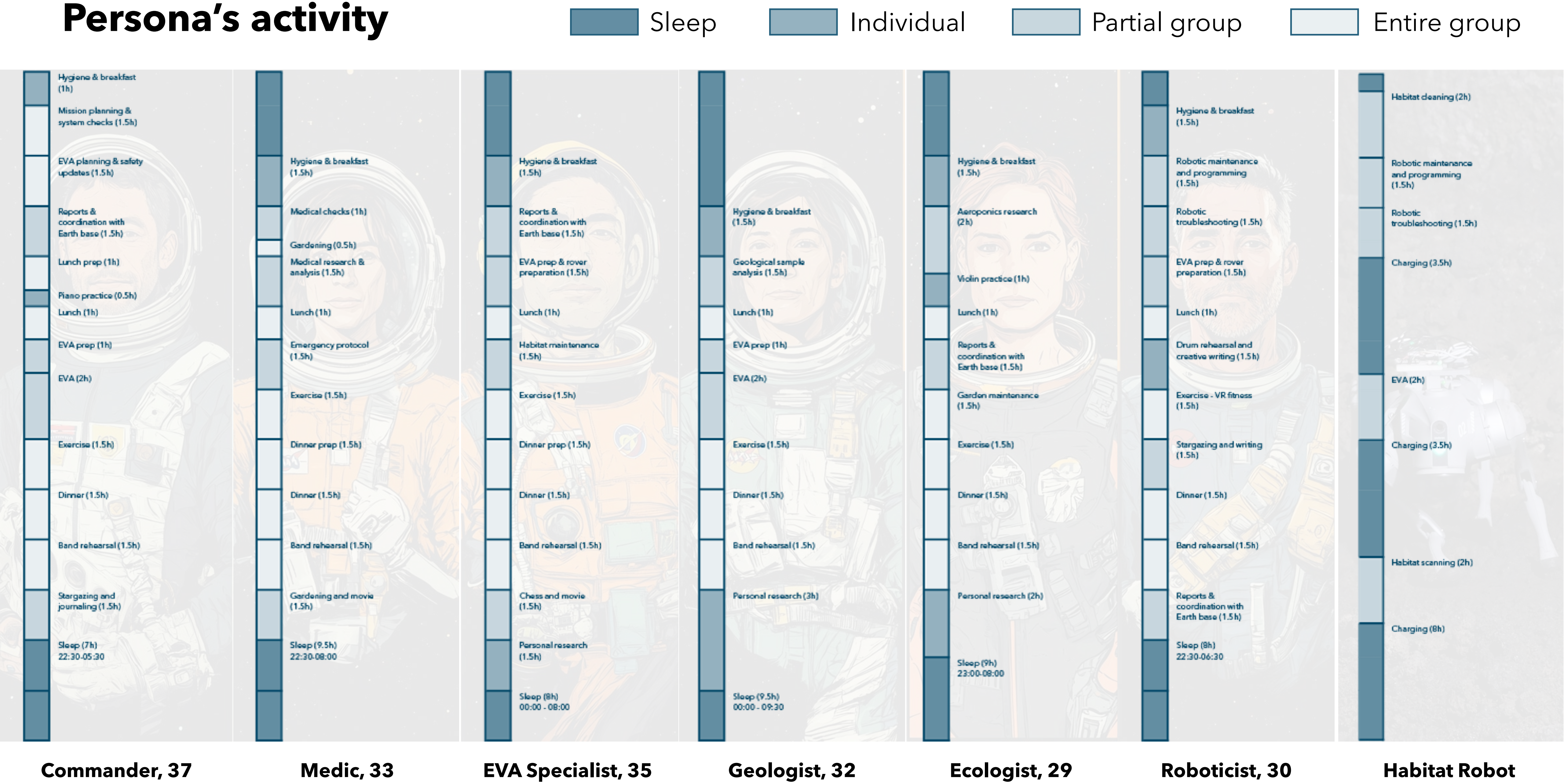
Mission Goal and Task: Rover for ISRU Operates, maintains, and troubleshoots robotic systems

- Beat the chess AI
- Drum, chess
- Light sleeper
- Cubicles

Habitat Robot

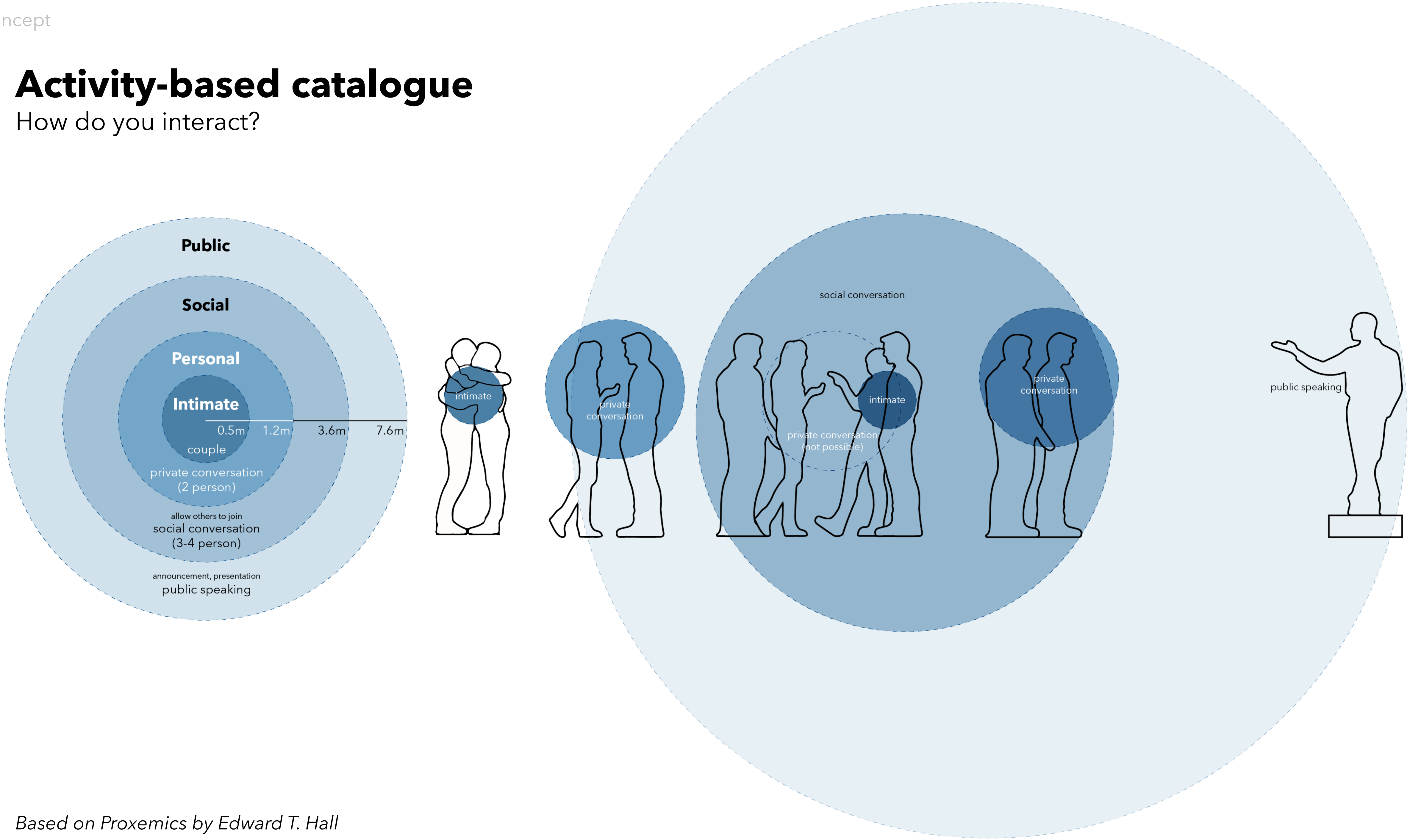
Mission Goal and Task: Maintenance Scanning and mapping for EVA, habitat cleaning

Persona’s activity



Activity-based catalogue

How do you interact?

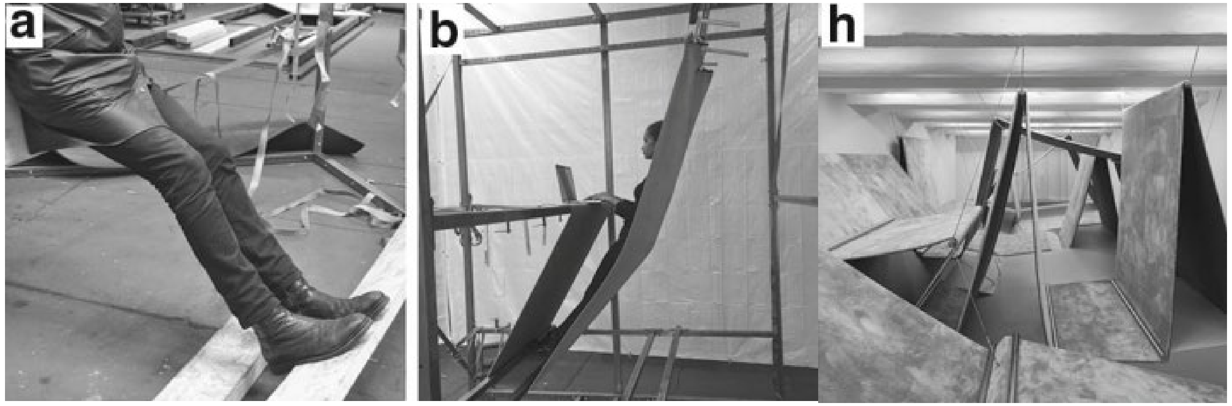


Based on Proxemics by Edward T. Hall

Reference_Situated Interface

Permanent: the user adjusting to the space

to enable and disable certain activity and movement

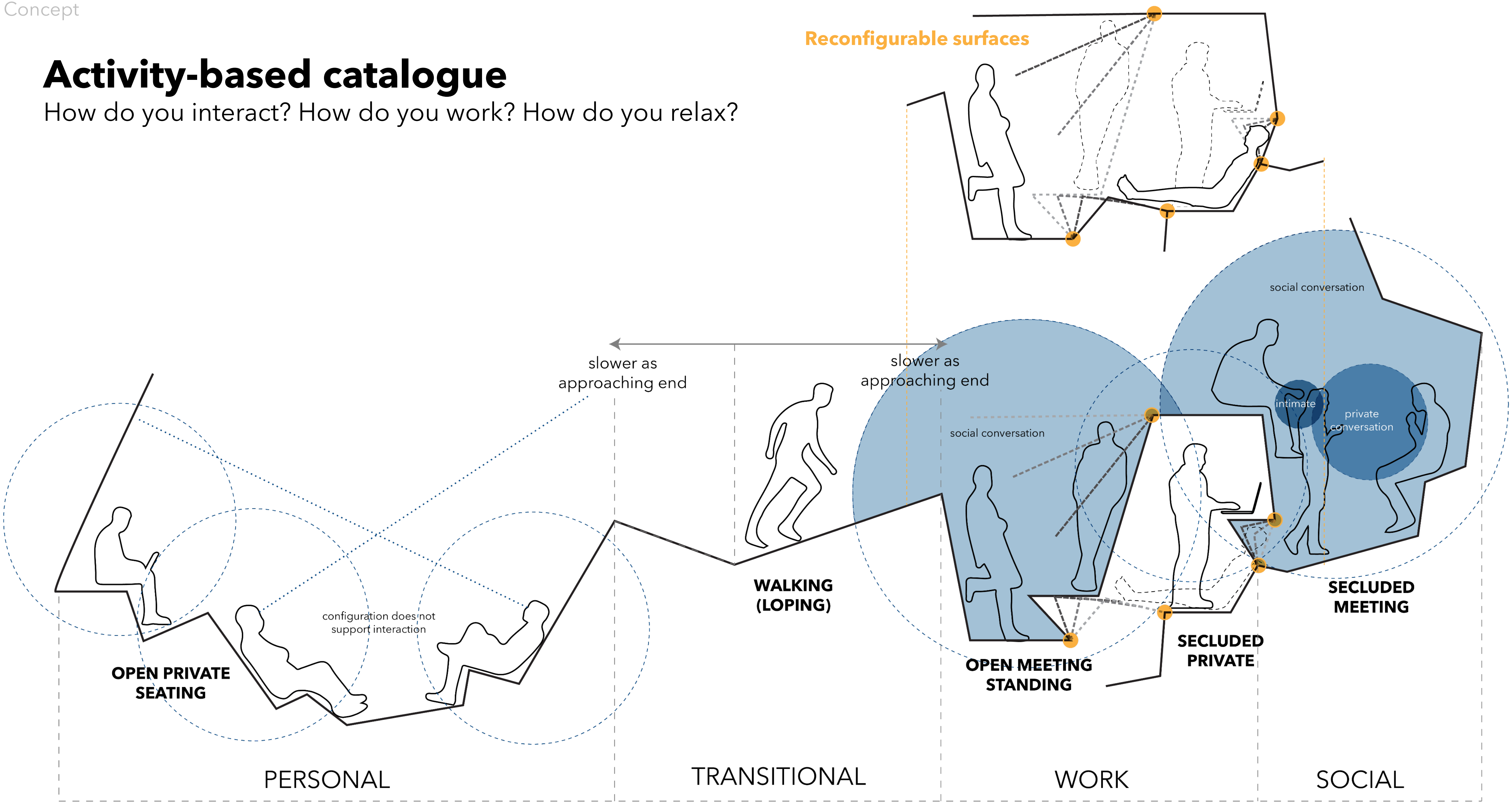


A World Without Chairs
Art installation, van Dijk and Rietveld in Situated Anticipation (2018)

The End of Sitting
RAAAF & Barbara Visser (2014)

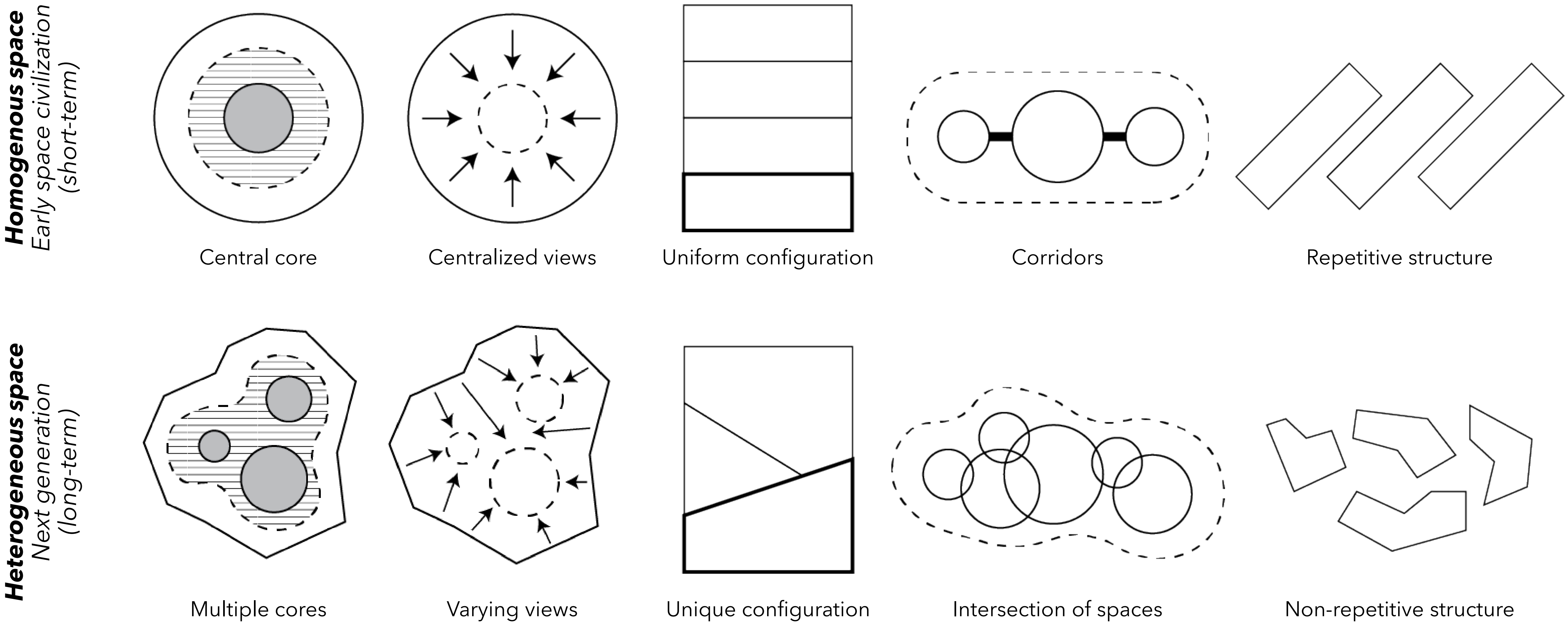
Activity-based catalogue

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



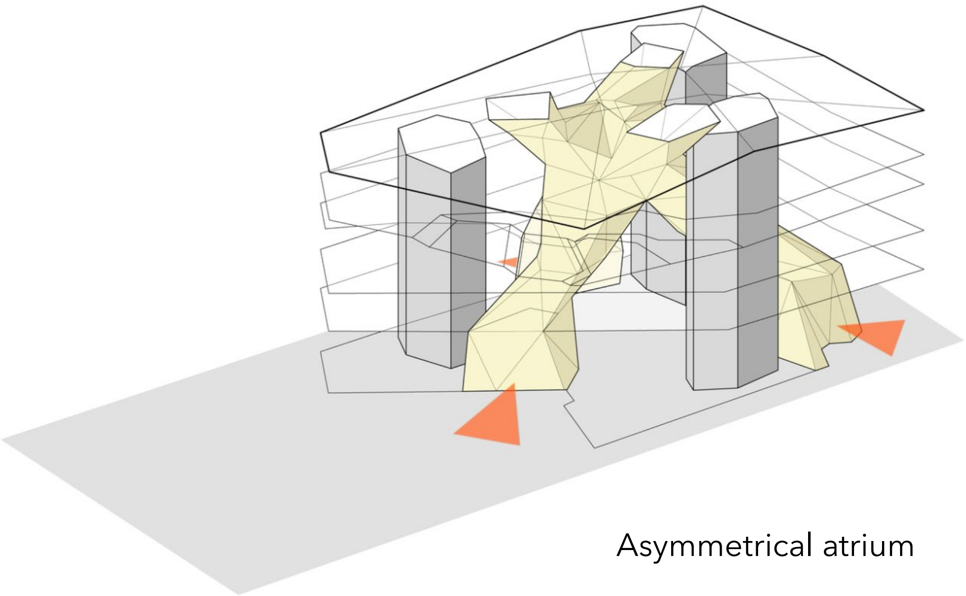
Heterogenous Space

Spatial strategies to vary social interaction



Reference_Intersecting Atriums

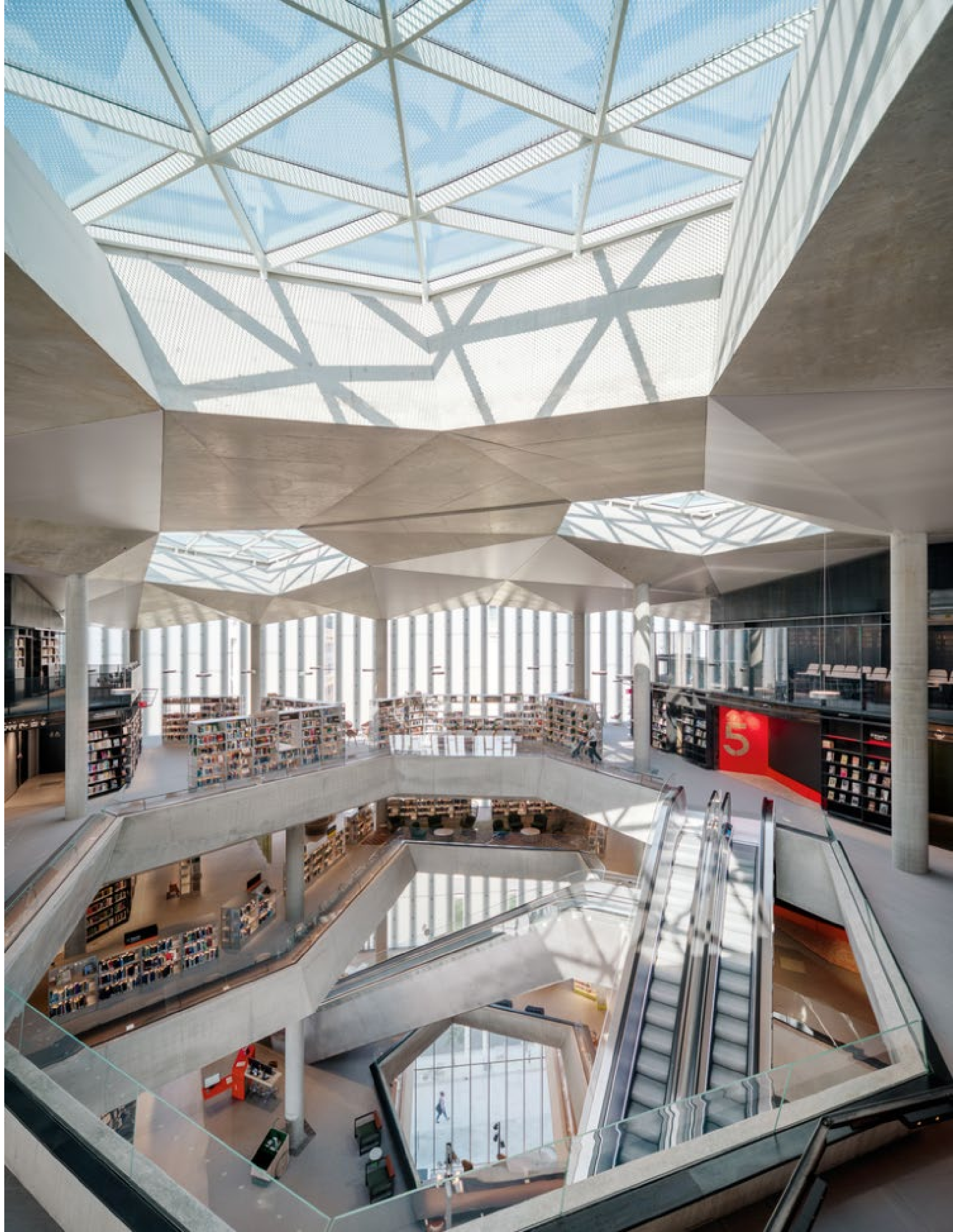
"Everyone's living room". Deichman Bjørvika, Oslo.



Asymmetrical atrium

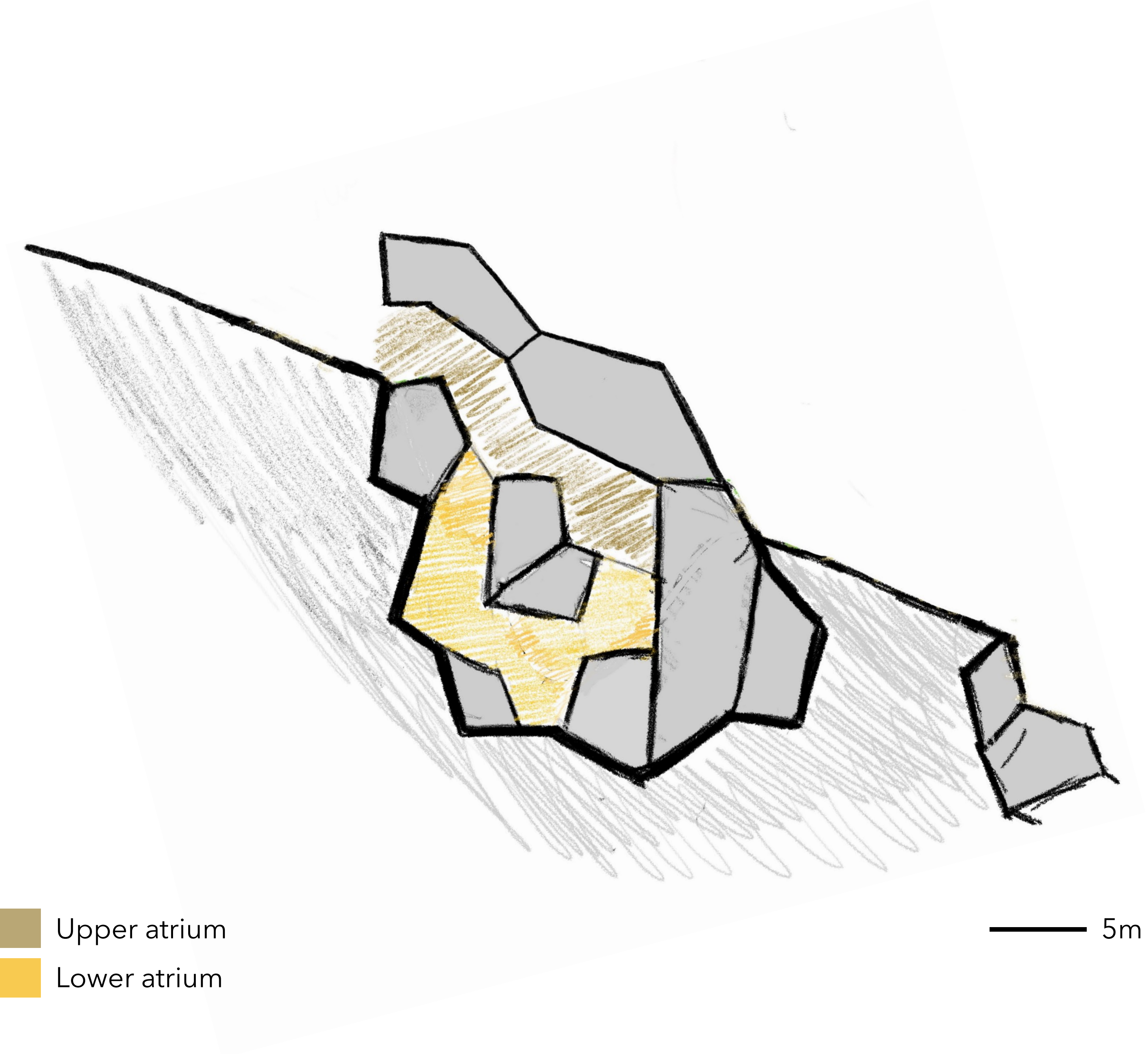
Pocket spaces

Varying vantage points



Sketch

Layered atriums



Upper atrium

Lower atrium

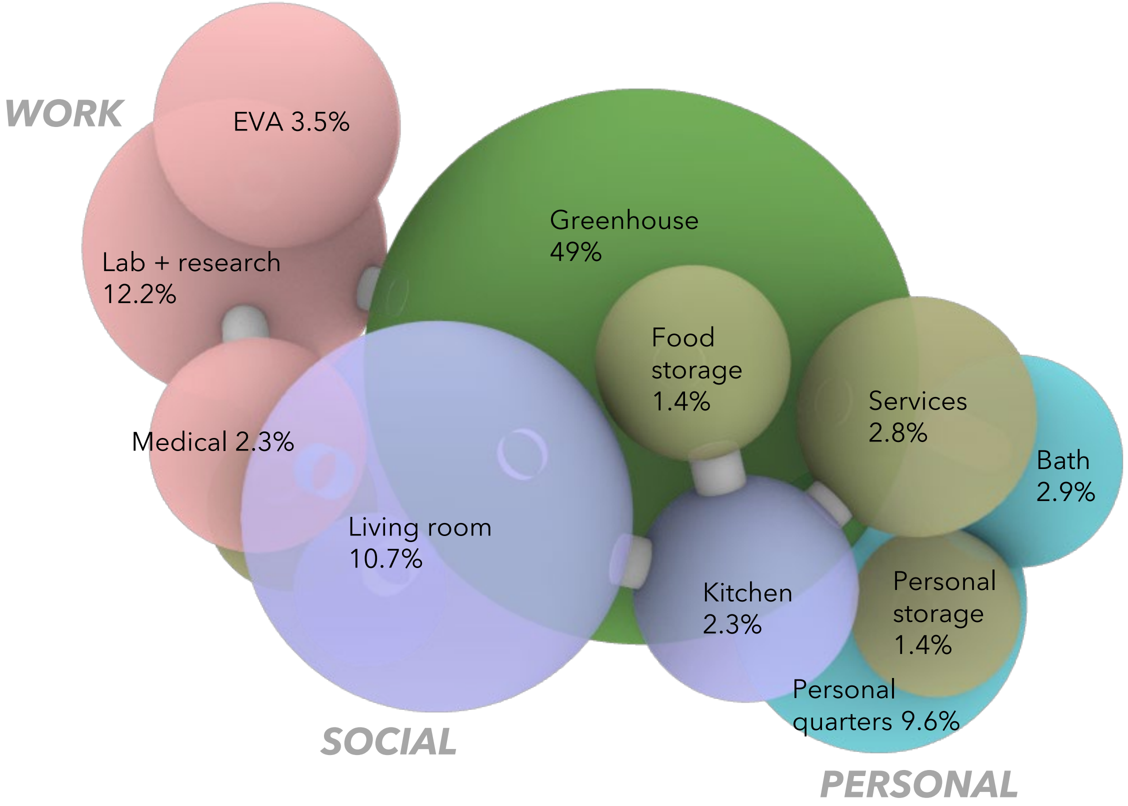
5m

Baseline program requirements

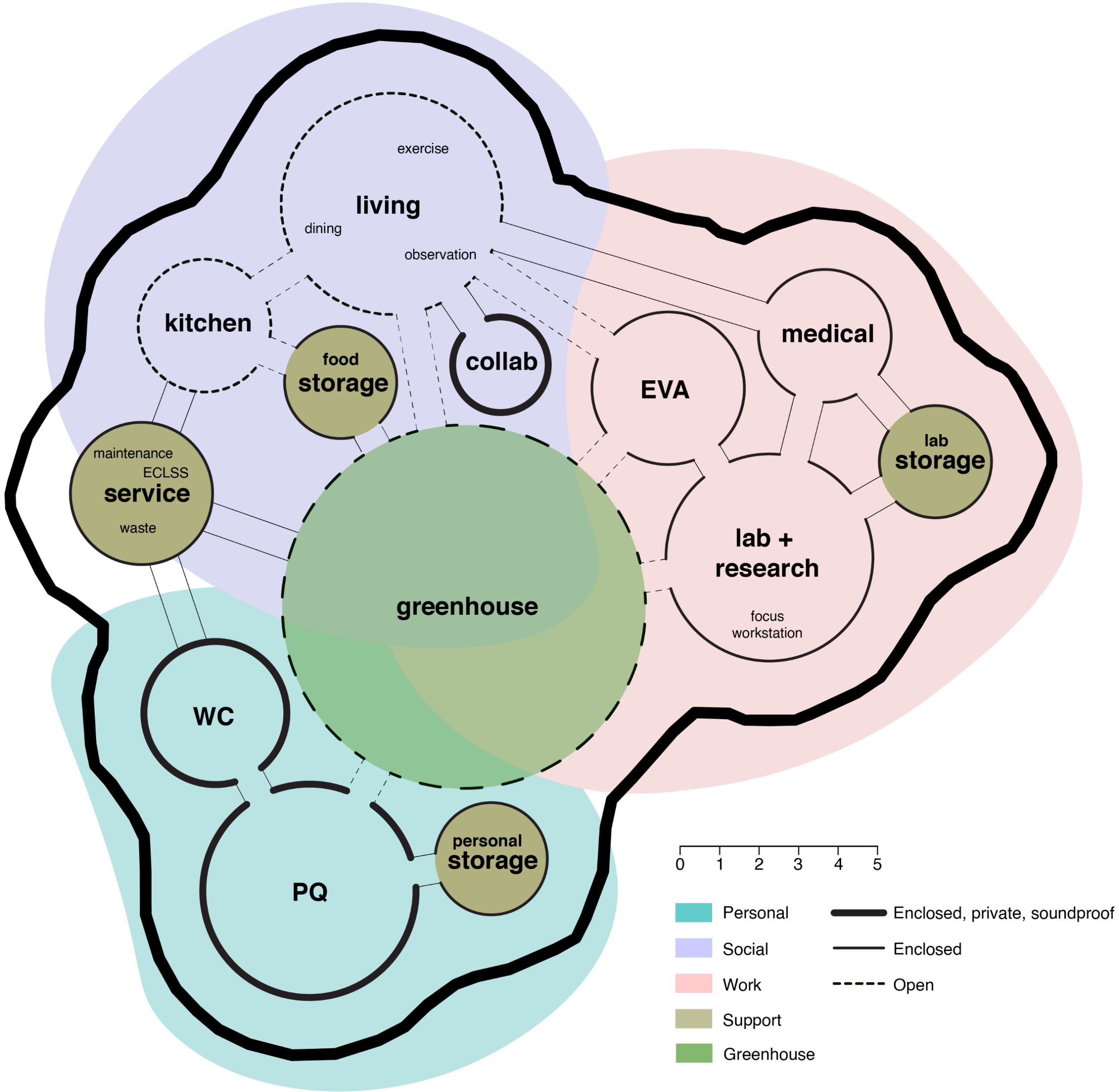
	Rooms	Size					Activity			Privacy			Movement		Protection			
		Vol for 1 (m3)	Factor	Vol for 6 (m3)	% vol	%	Category	Cross-function	Detail	Personnel	Visibility	Audio	Speed	Arrangement	Duration	Garment	View outside	Access outside
PQ	Private Quarter 1 (Single)	15.0	4	60.0	6.99%	12.52%	Personal	Work	Sleep, 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%		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%	10.66%	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%		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%	12.23%	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%		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%	2.80%	Support		System maintenance	Storage	Enclosed	Neutral	Fast	Fixed	1-8 h	Clothed	Optional	No
	ECLSS	8.0	1	8.0	0.93%		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

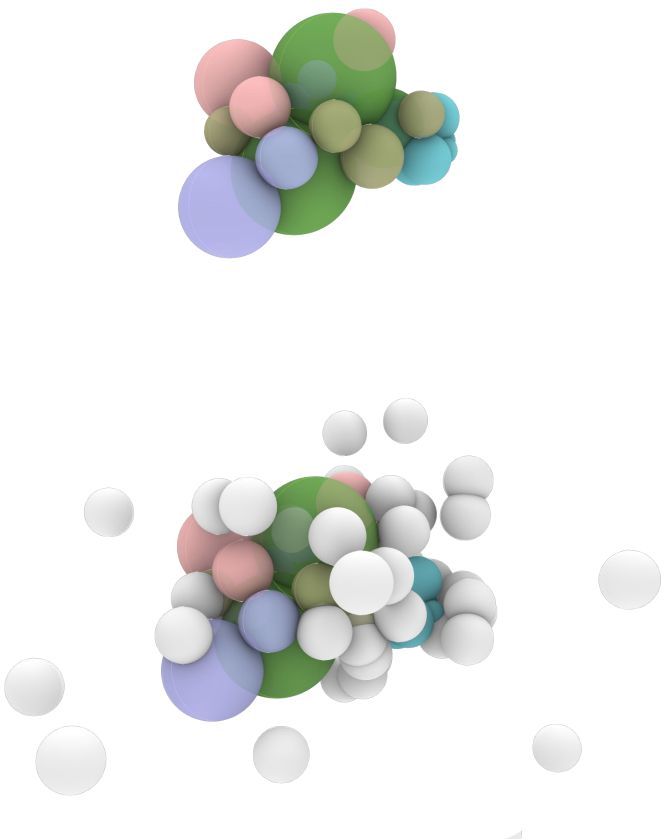


Greenhouse as atrium,
connecting 3 functional cores

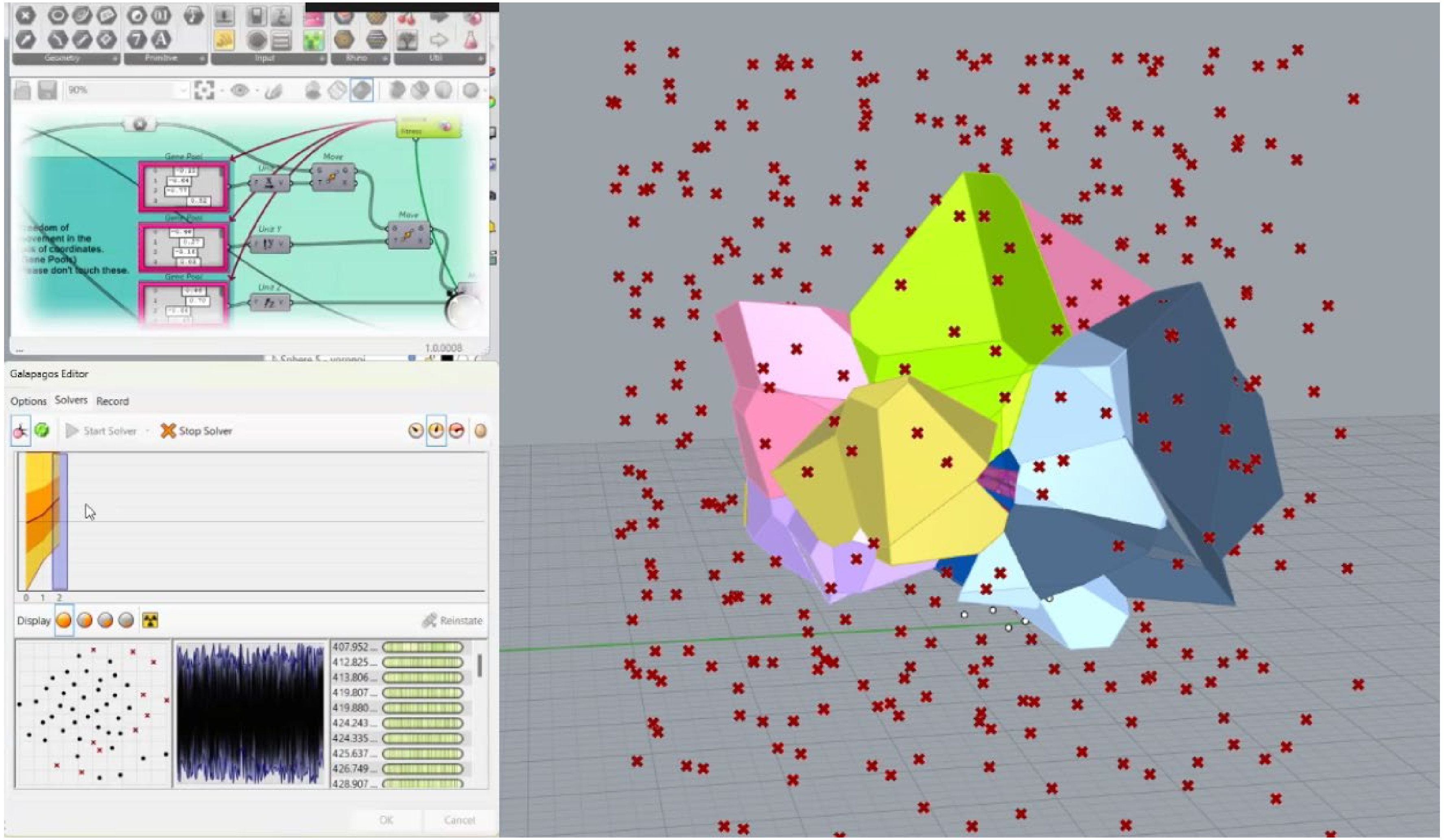


Form Optimisation Process

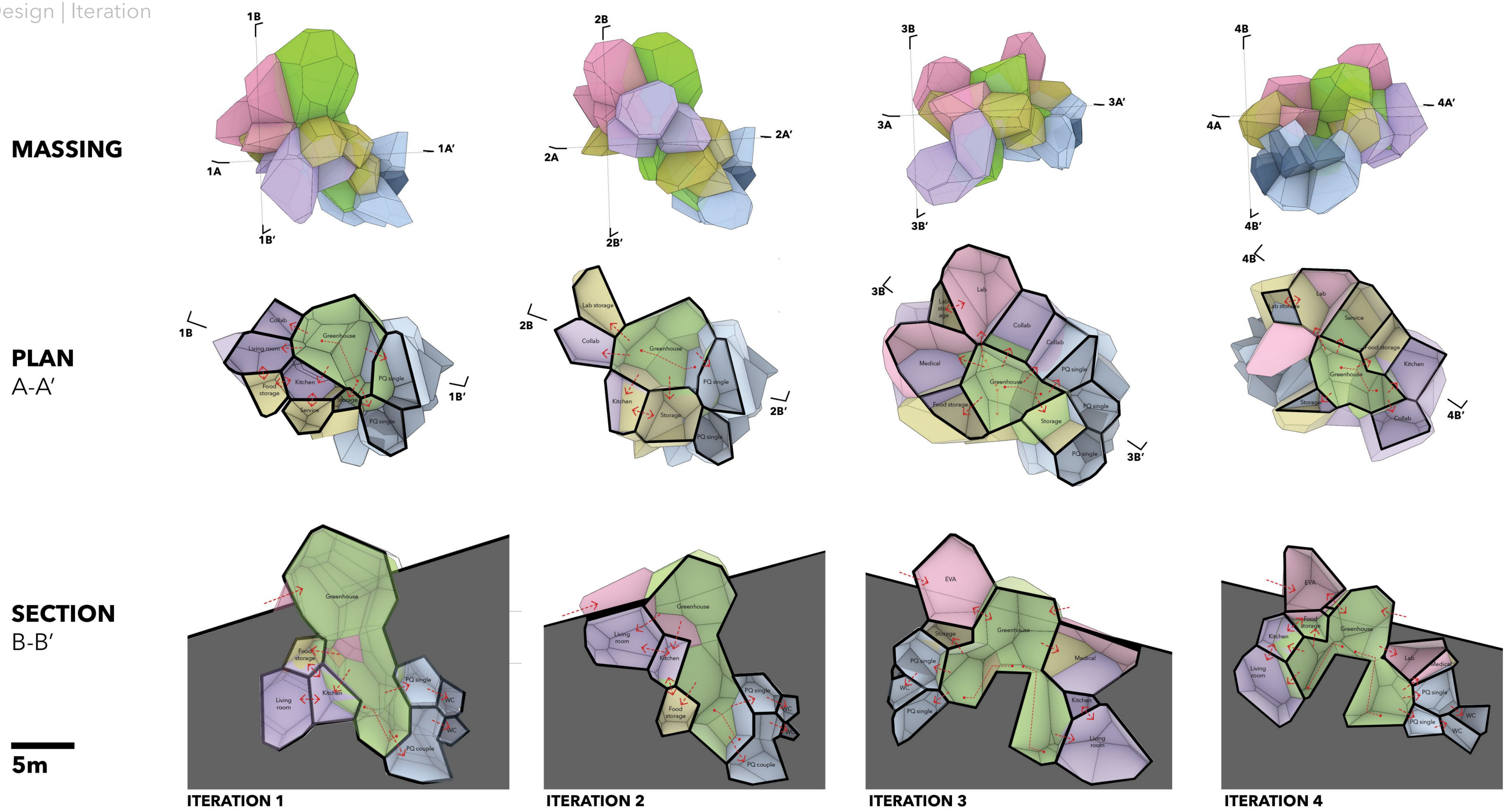
Sphere to Voronoi volume optimization using Galapagos



Script to optimize Voronoi control points



https://youtu.be/oiQ0B0b-MYM



Iteration 1 & 2

- Continuous atrium
- Clustered and vertically distributed function

Iteration 3 & 4

- Branching atrium
- Dispersed function, opposing sides to activate circulation

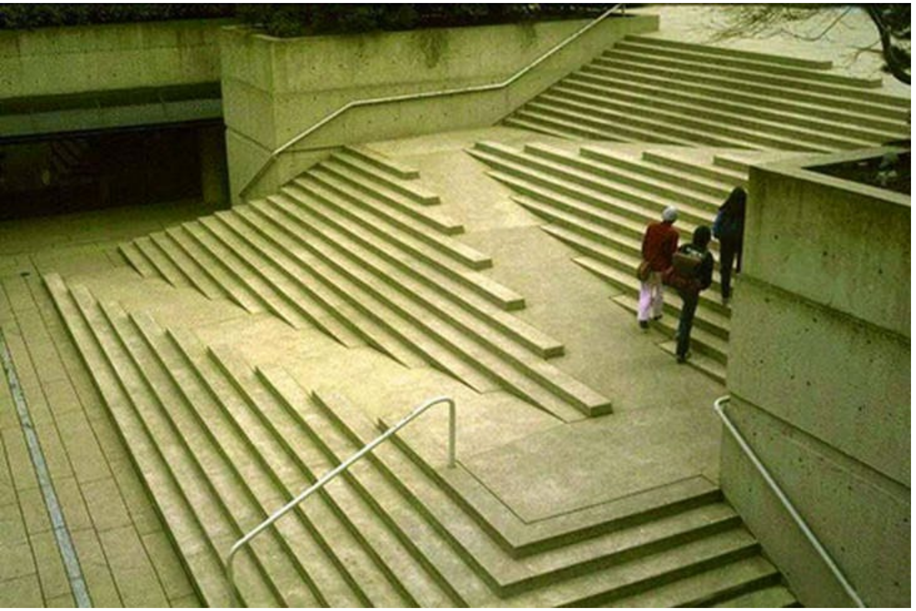
Atrium Study

Establish strategy

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

Atrium Circulation Study

Reference_Ramp/stairs



Ramp/stairs combination

Ramp/stairs reference

Ewha Women's University, Korea

Atrium Circulation Study

Reference_Steep stairs

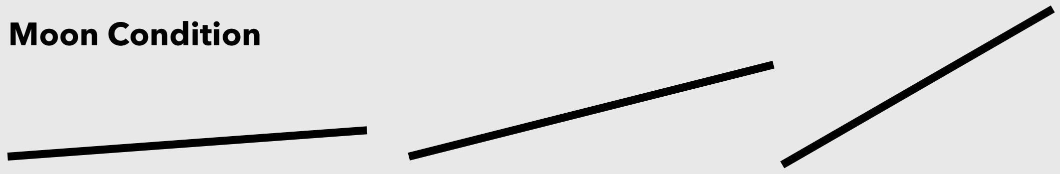
MARS Ice House

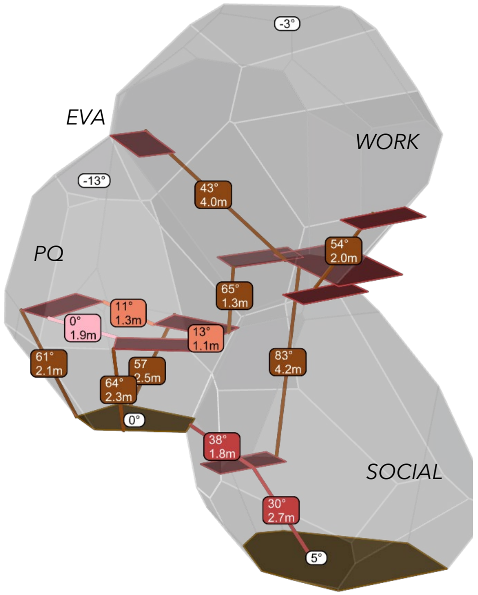
Atrium Circulation Study

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

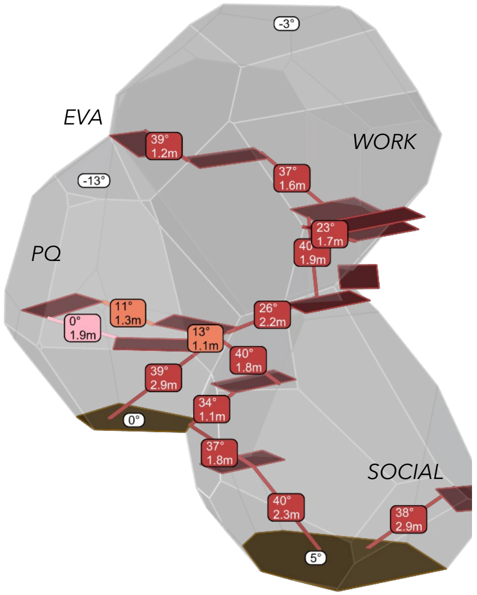
- Ramp is ideal for comfort, but need strategic placement
- Iteration 4 potential: variety in experience (access, view framing, atrium size subdivision)

Moon Condition

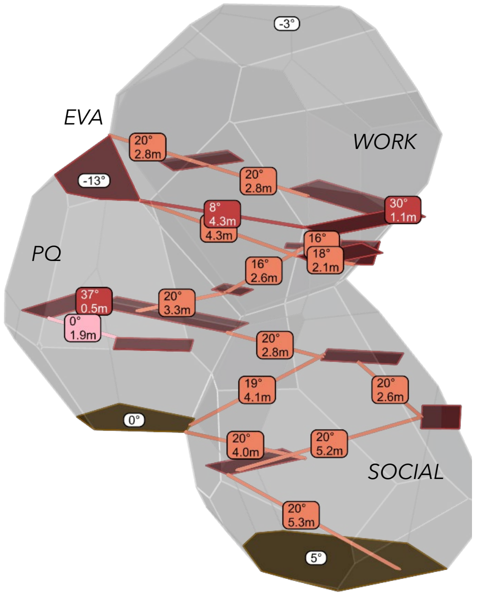




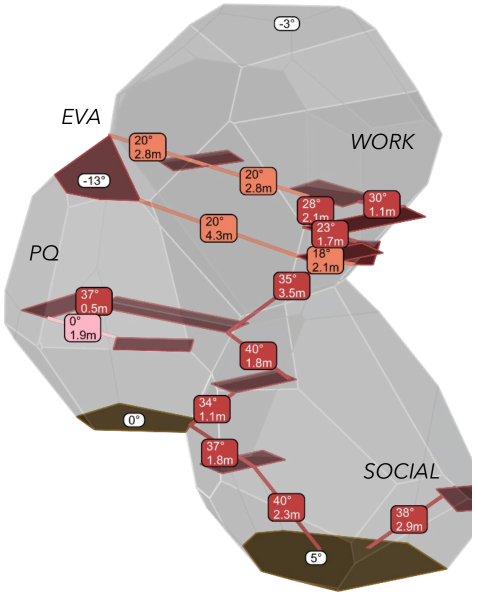
Iteration 1
Shortest distance / steep



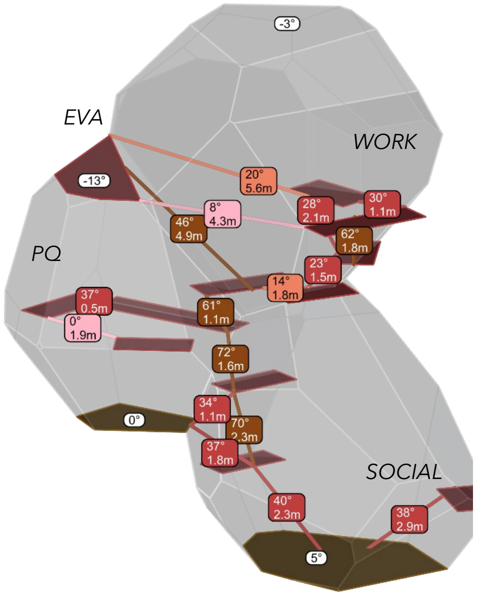
Iteration 2
Stairs



Iteration 3
Ramp



Iteration 4
Ramp (work) + Stairs (living)

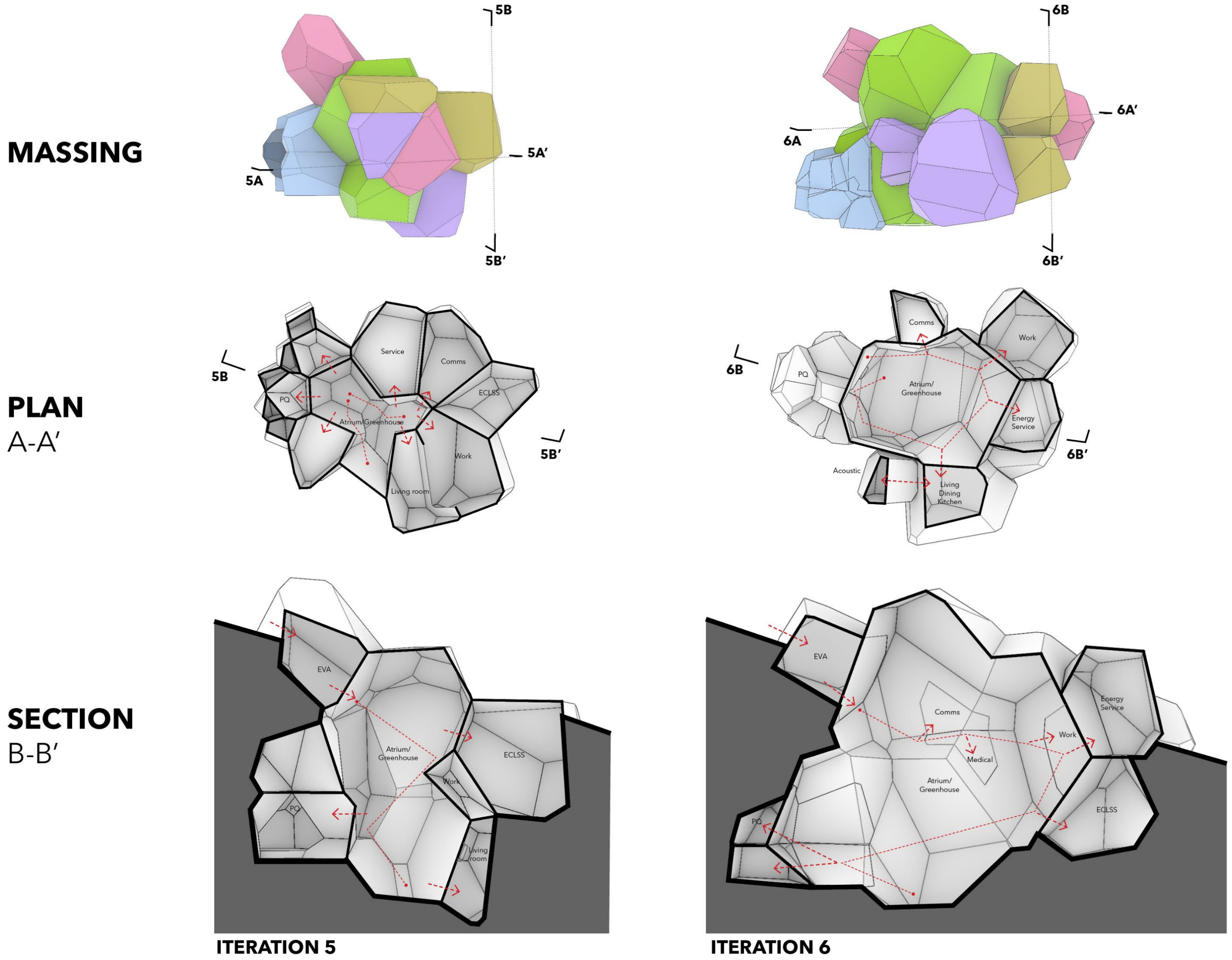


Iteration 5
Combination + steep stairs (main axis)

Atrium Circulation Study

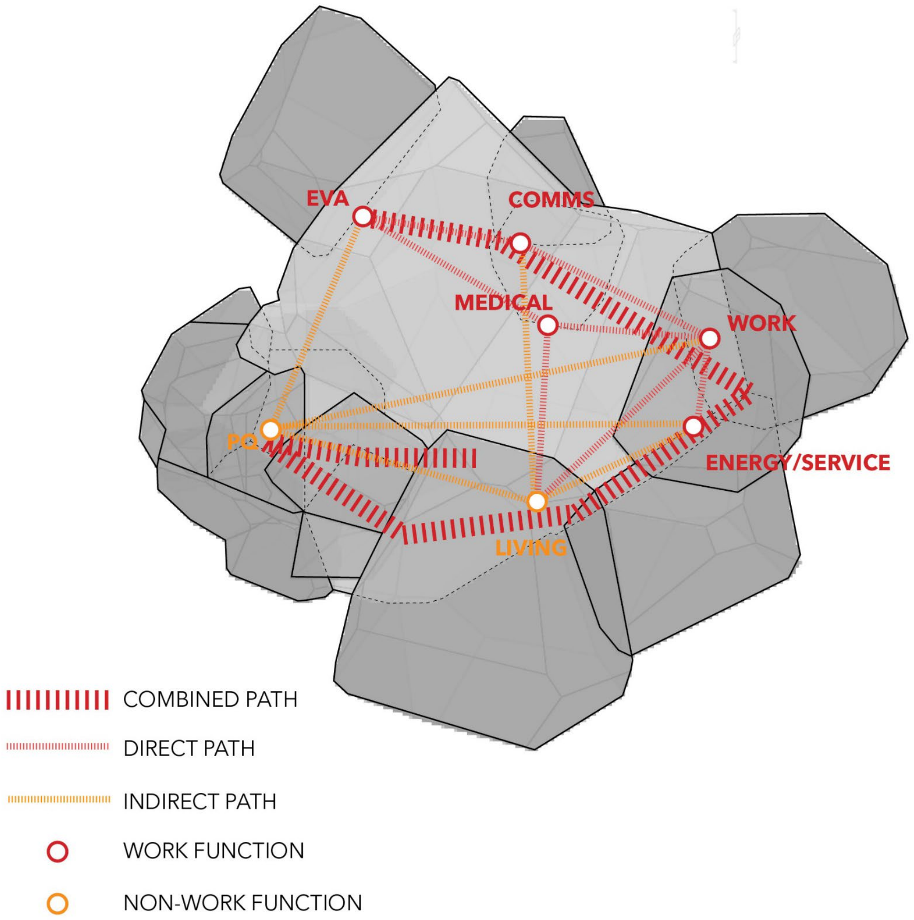
Application to iteration

- Study inform form development → atrium needs to be wider to optimize for ramps
- Continuous atrium, with <u>circulation</u> as strategy <u>to break down atrium</u>



Paths of users

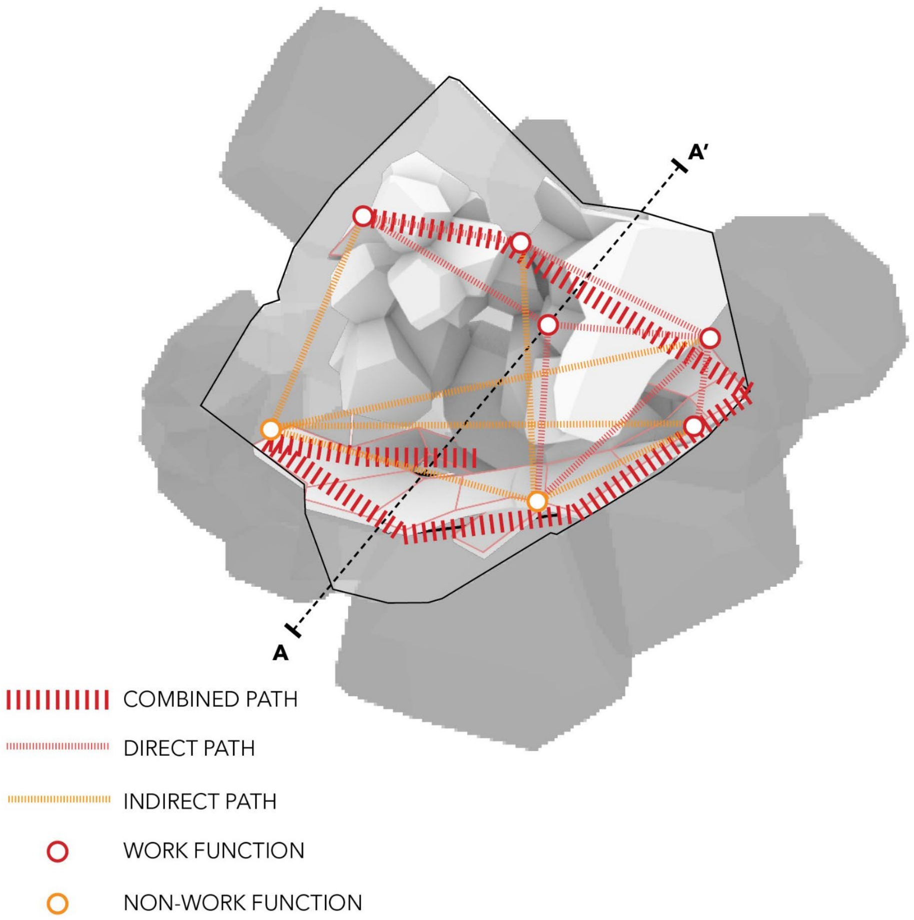
Establishing main circulation

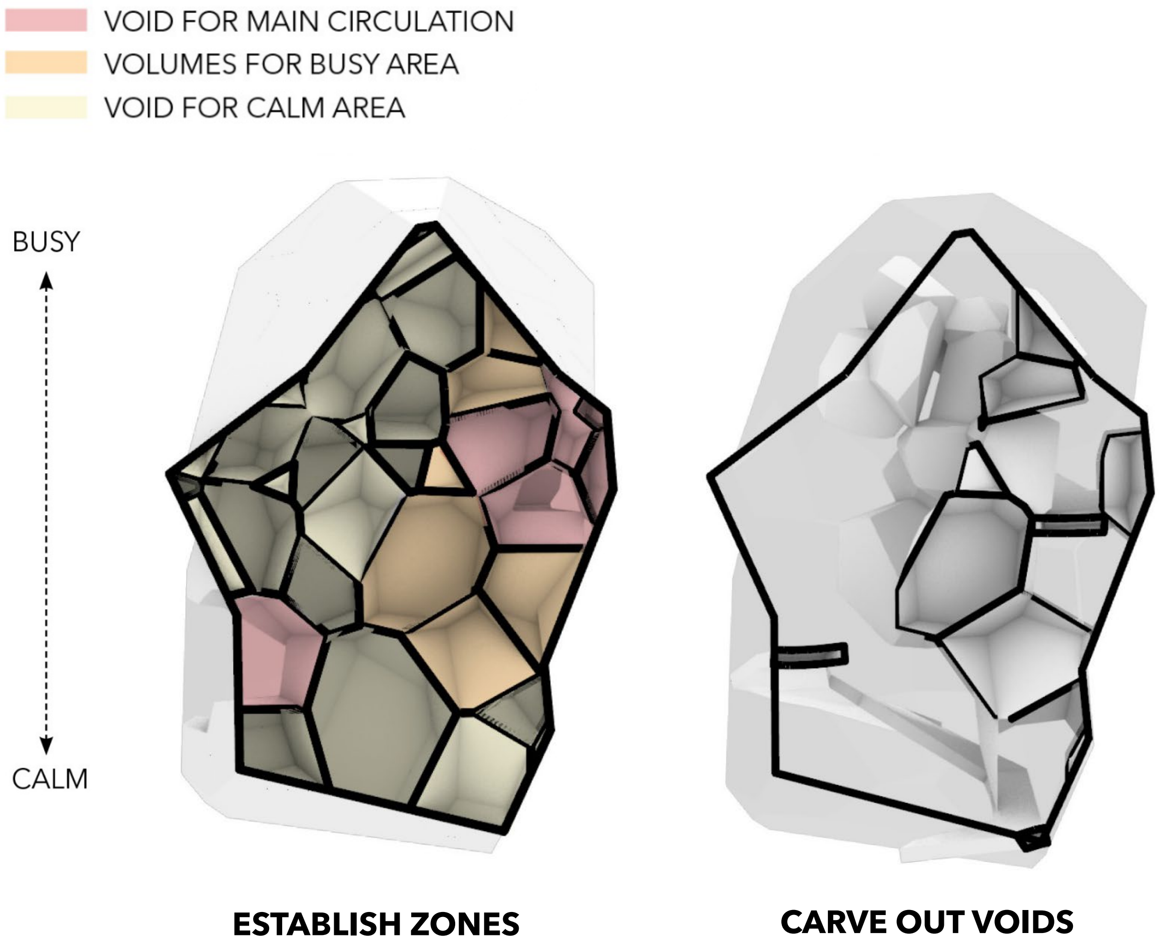


Time	Commander		Medic		EVA Specialist	
06:00	Hygiene & breakfast (1h)	PQ		PQ		PQ
06:30						
07:00	System checks & safety update (1.5h)	Service				
07:30						
08:00						
08:30	EVA & Mission planning (1.5h)	Workstation	Hygiene & breakfast (1.5h)		Hygiene & breakfast (1.5h)	
09:00						
09:30						
10:00	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)	EVA
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)	Workstation	Habitat maintenance (1.5h)	Atrium
14:30		EVA				Service
15:00	EVA (2h)	EVA				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	Stargazing and journaling (1.5h)	Observatory	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						

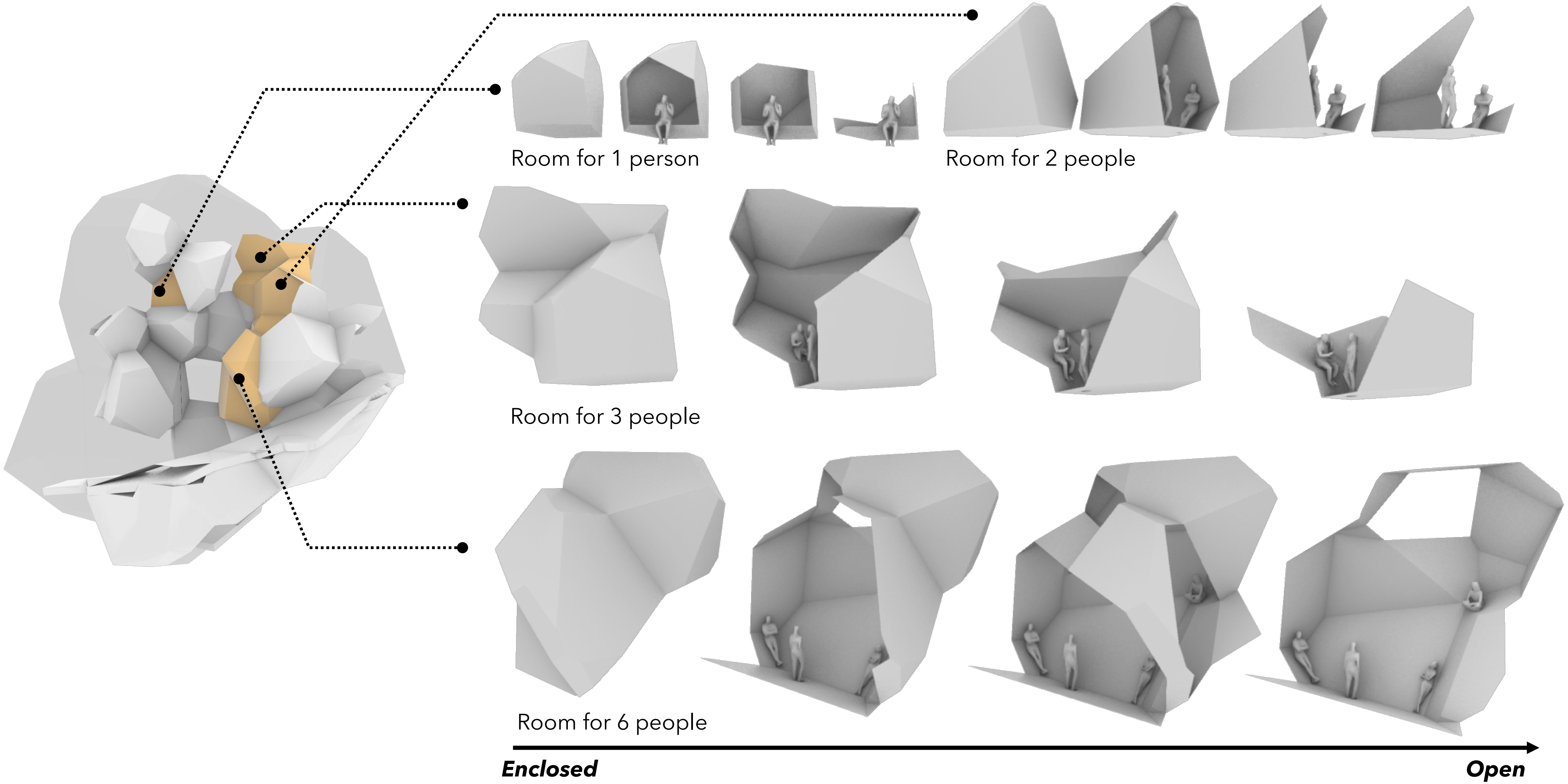
Global Openness

Negative space for circulation and void



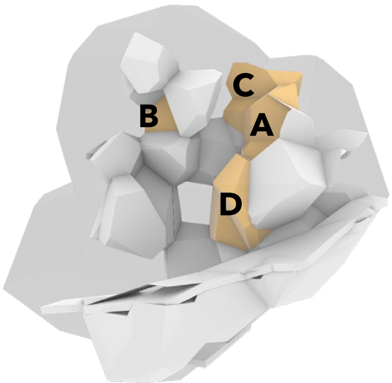


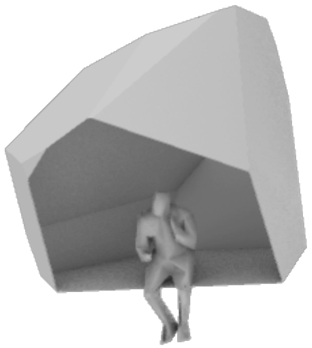
Local Openness
Enclosure

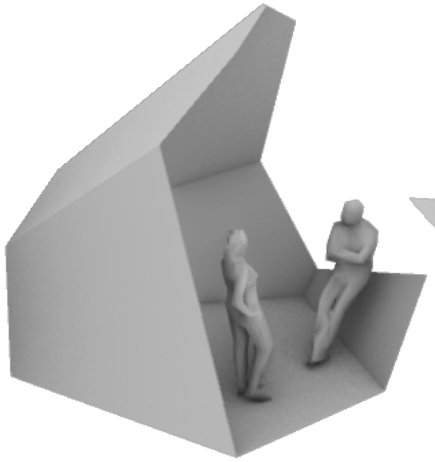


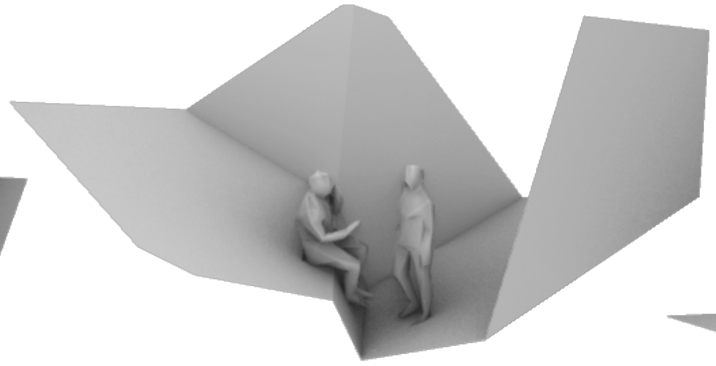
Local Openness

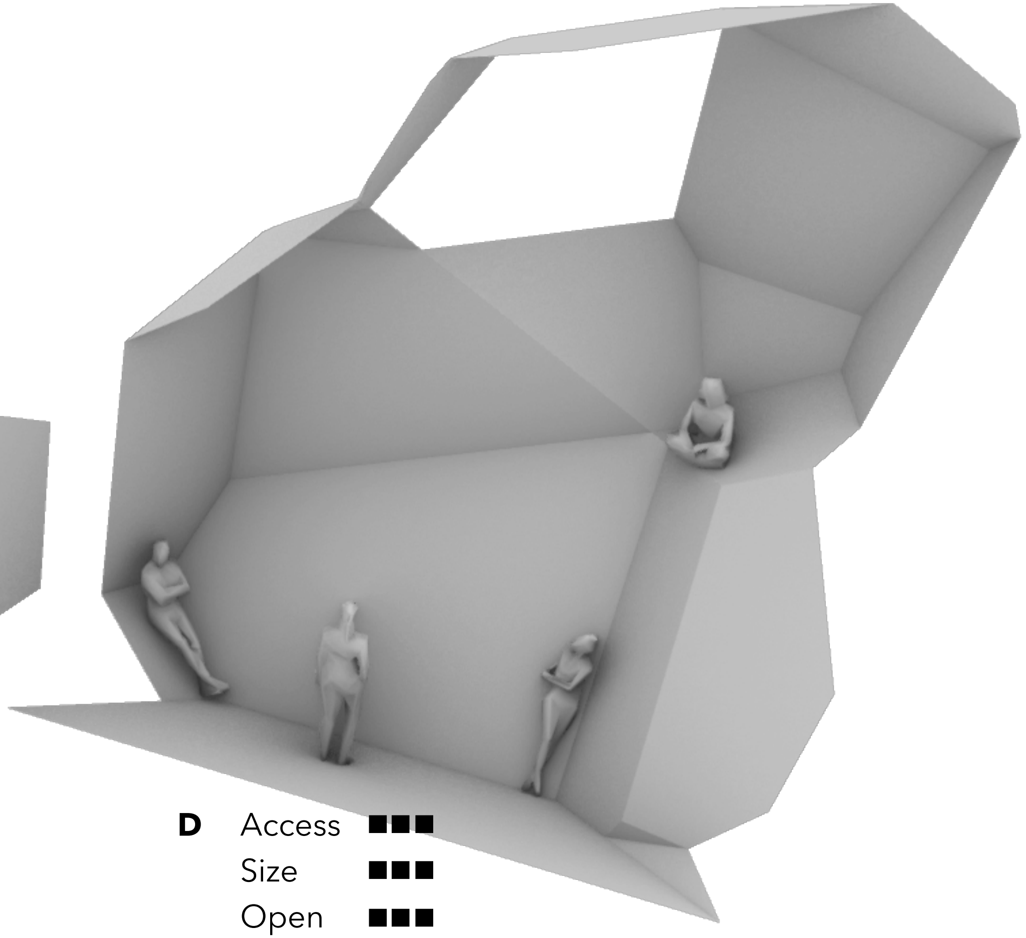
Enclosure







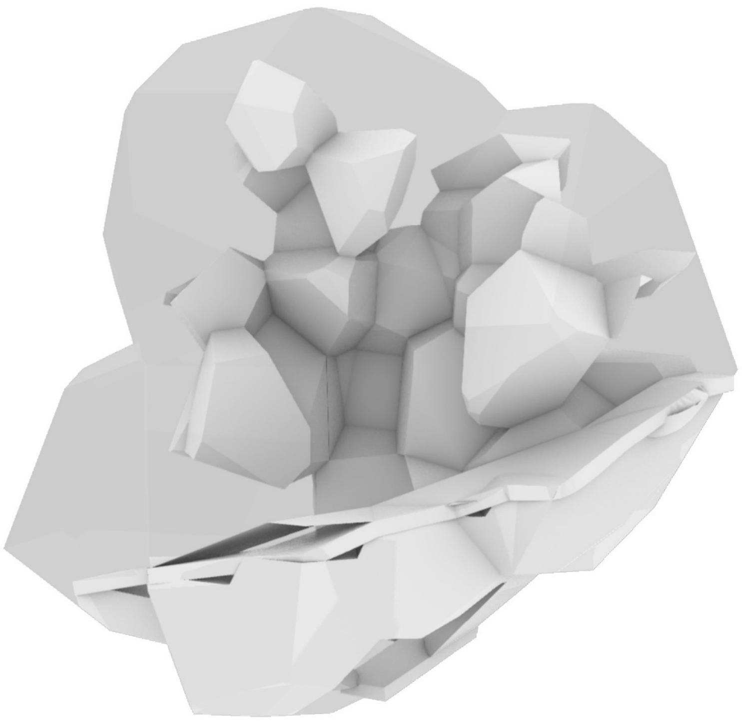




		A	B	C	D
	Access	■■□	■■□	■□□	■■■
	Size	■□□	■■□	■■□	■■■
	Open	■□□	■□□	■■□	■■■

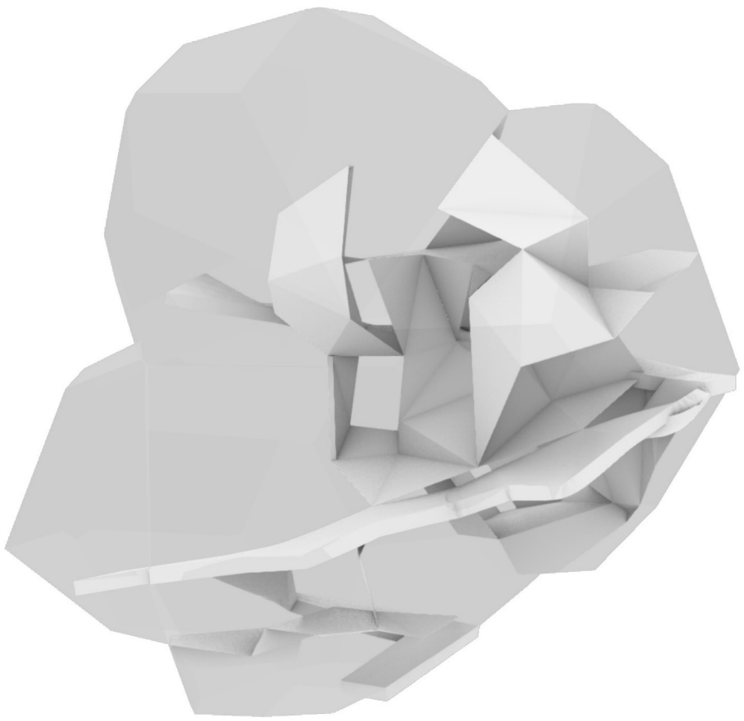
Local Openness

Global application



VOLUME

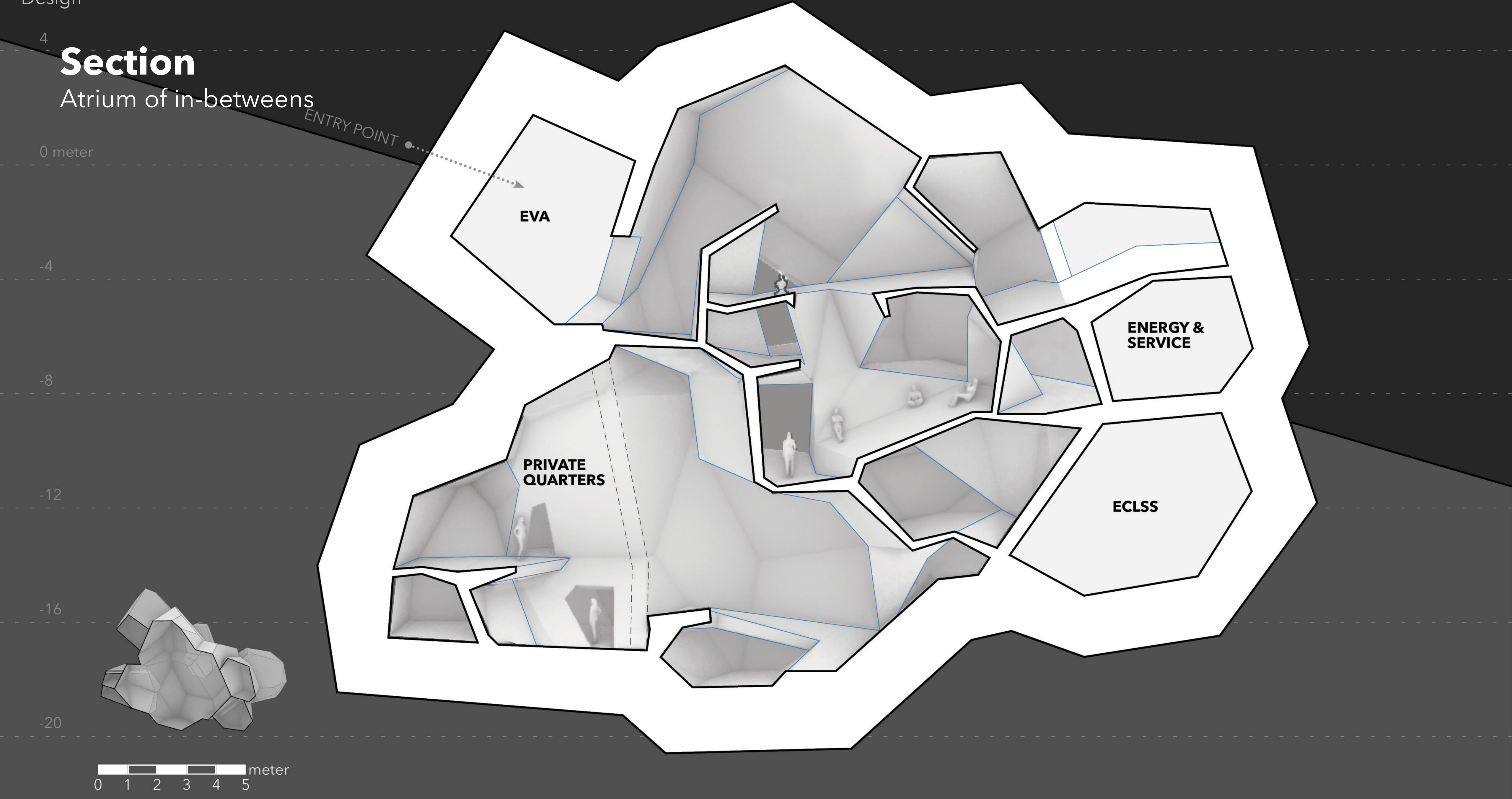
REMOVE SURFACES



OPEN & ENCLOSED SPACES

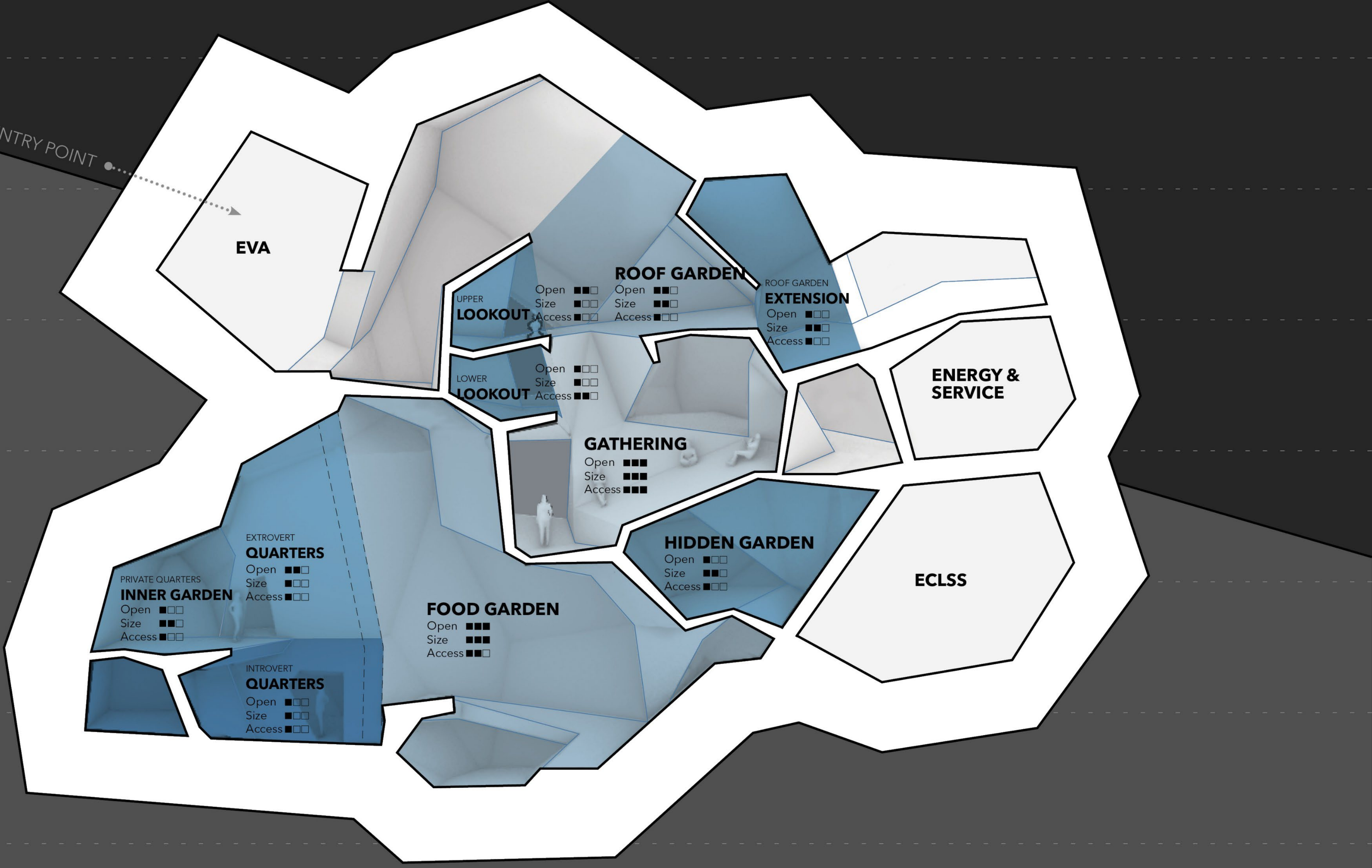
Section

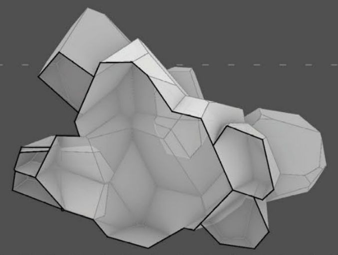
Atrium of in-betweens



Section

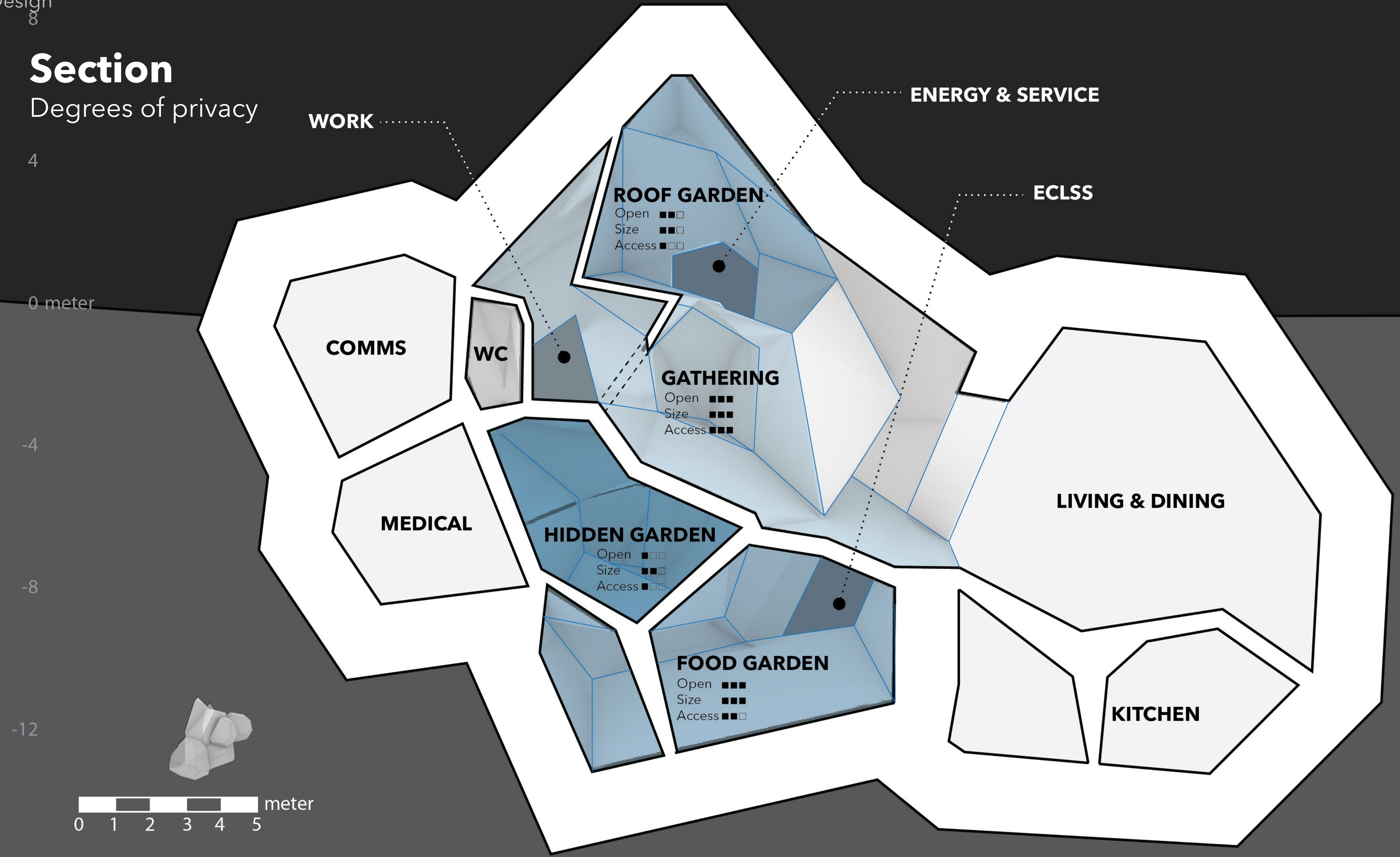
Degrees of privacy





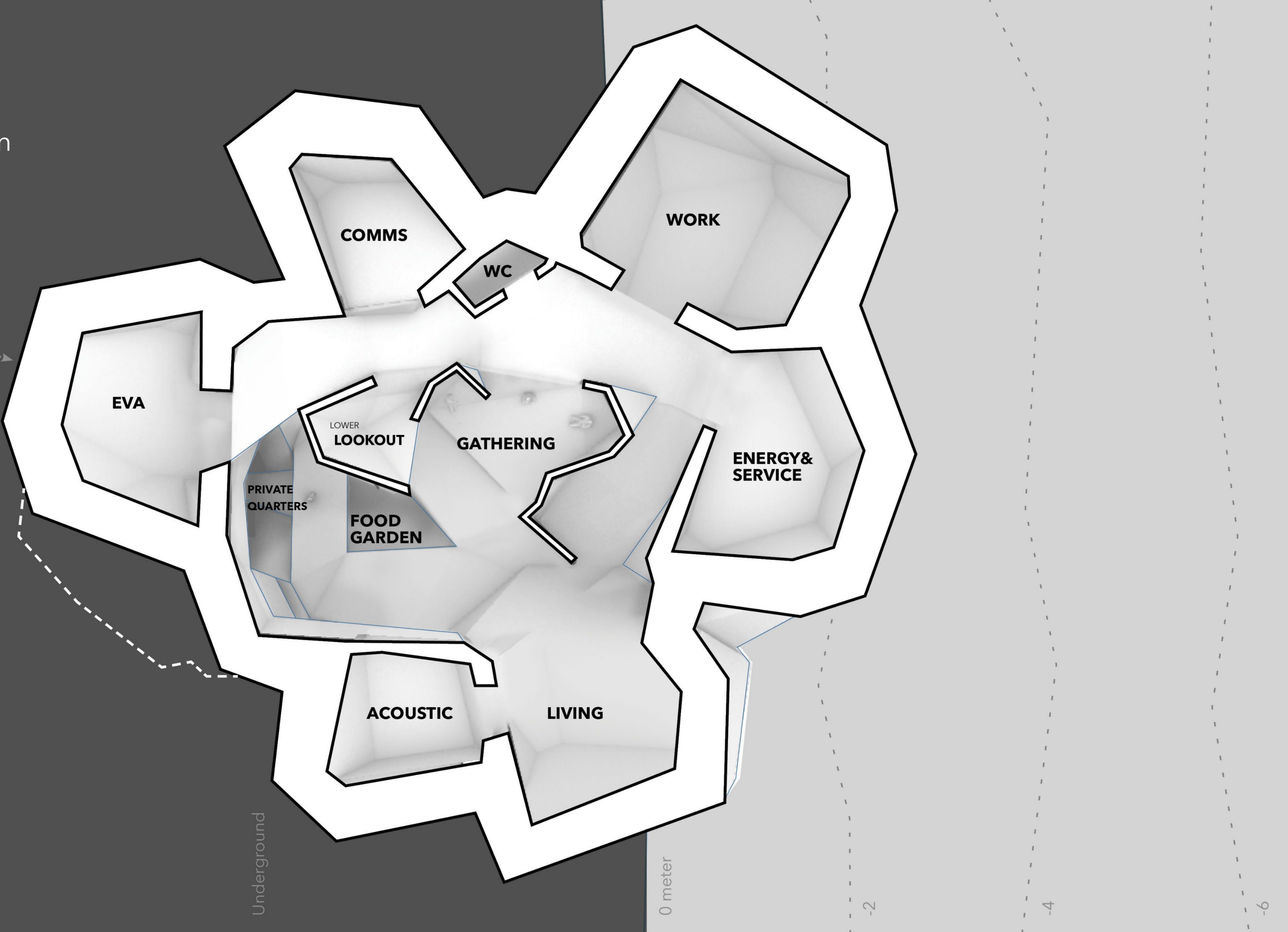
Section

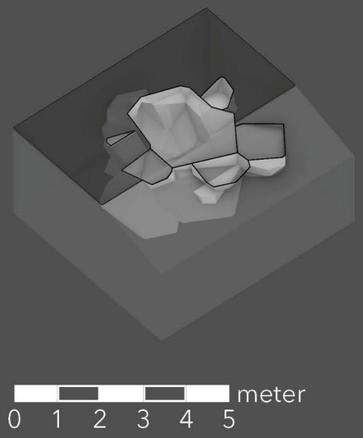
Degrees of privacy



Building Plan

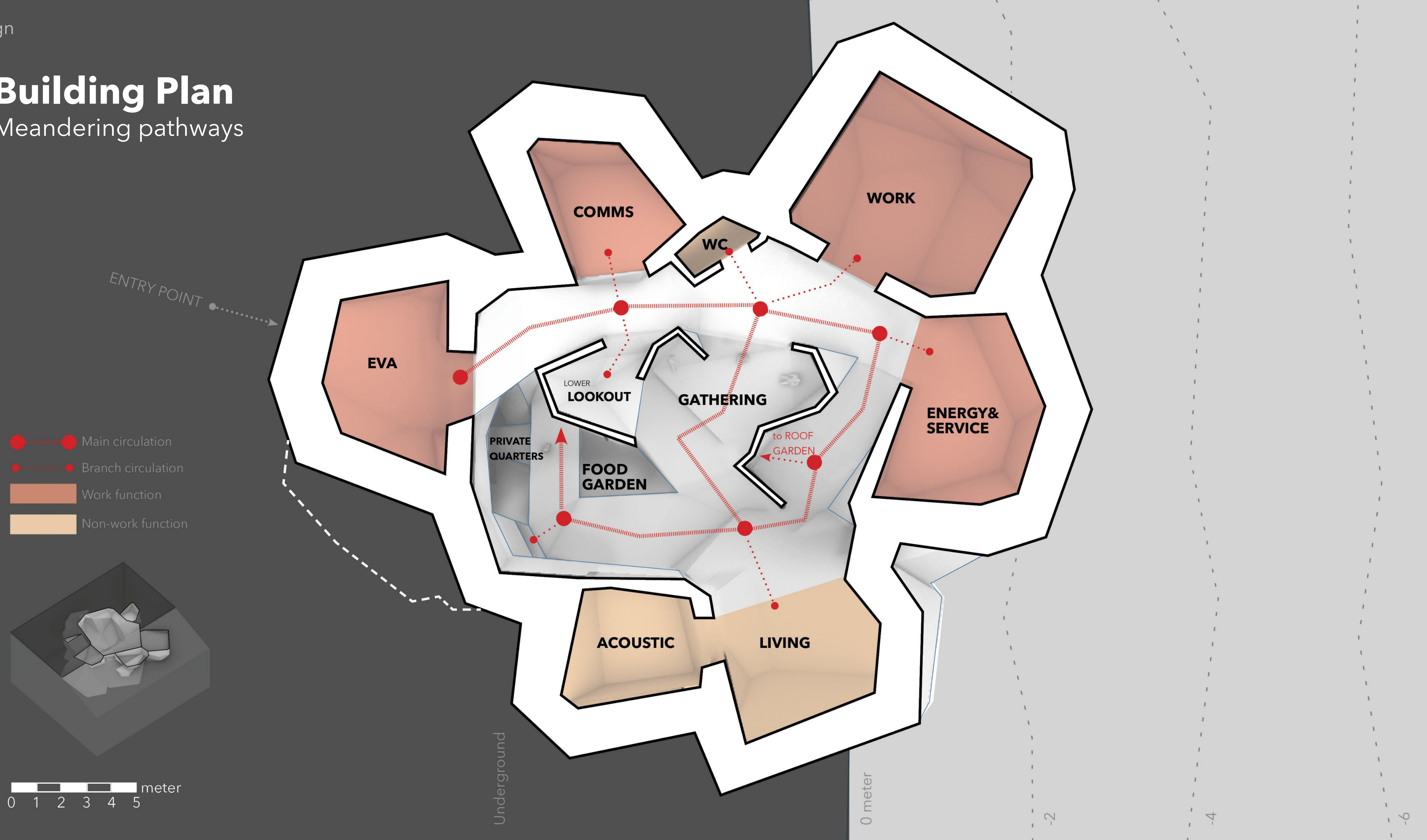
Atrium as the in-between





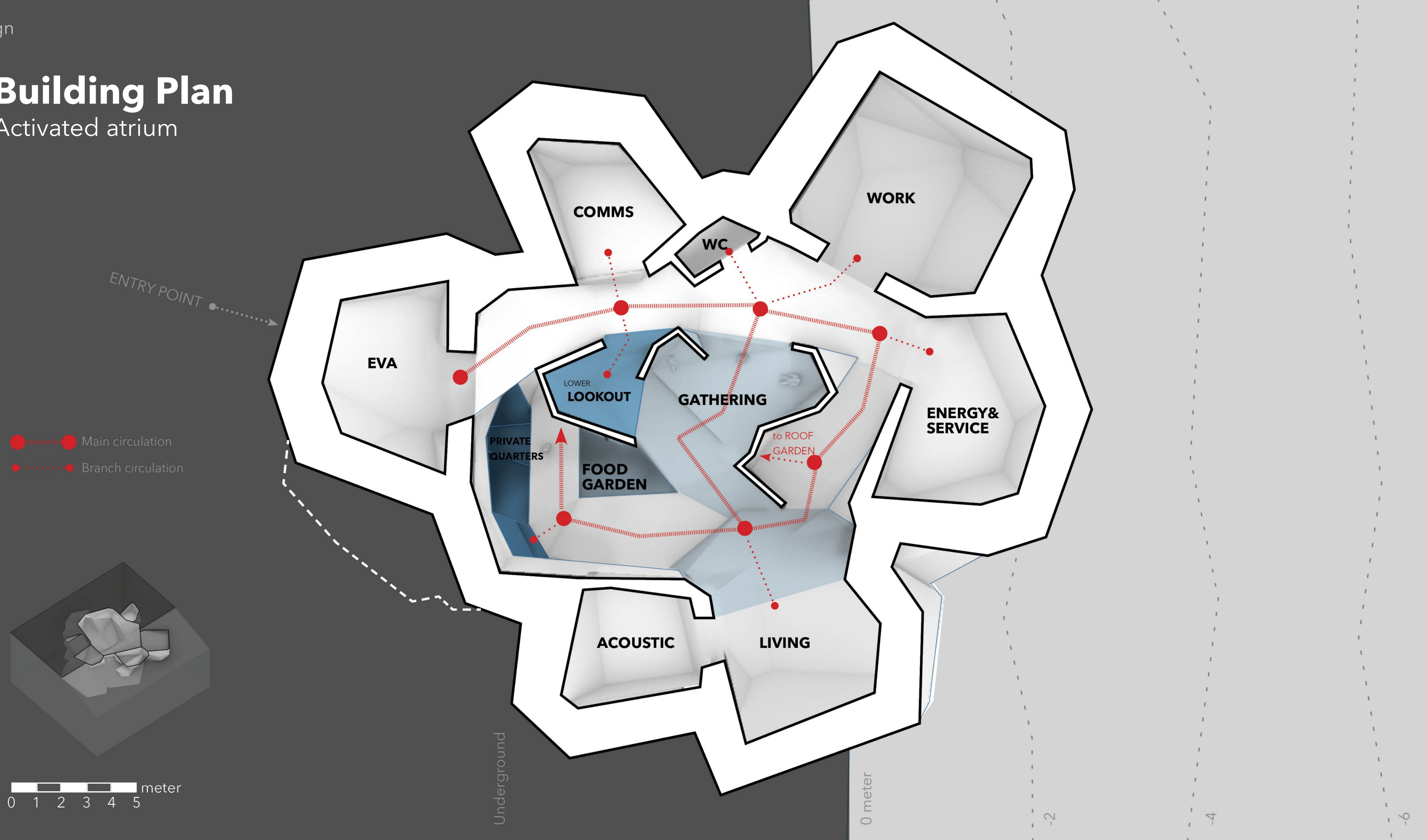
Building Plan

Meandering pathways



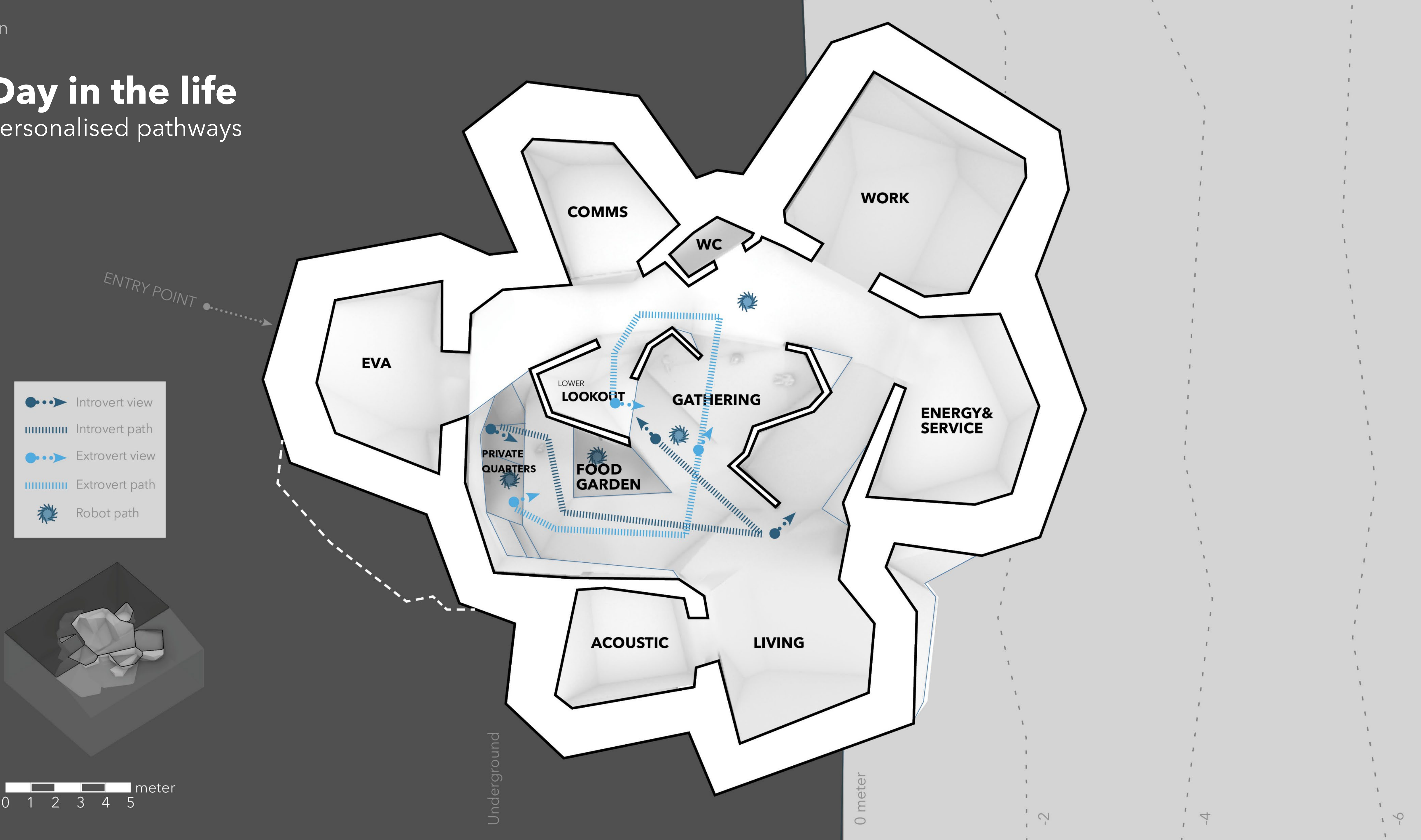
Building Plan

Activated atrium



Day in the life

Personalised pathways

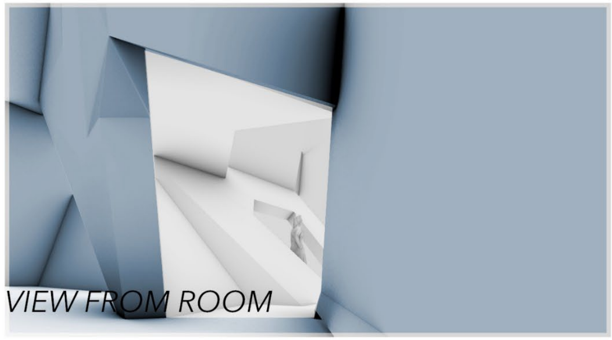


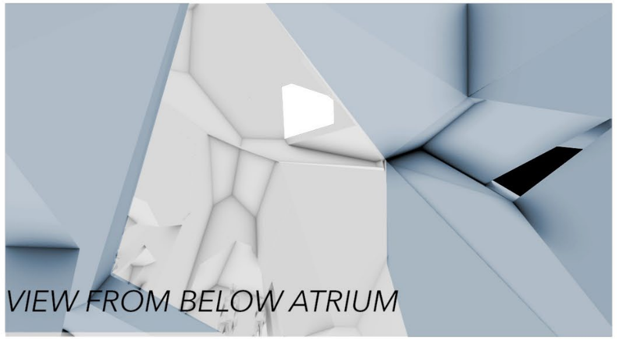
Day in the life: Lunar Restday

Framing views

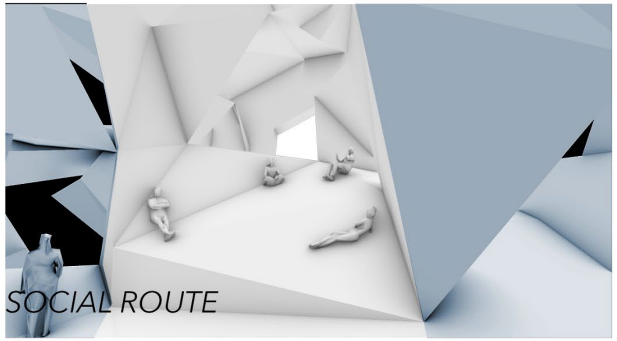
INTROVERT **EXTROVERT** **ROBOT**

ORIGIN

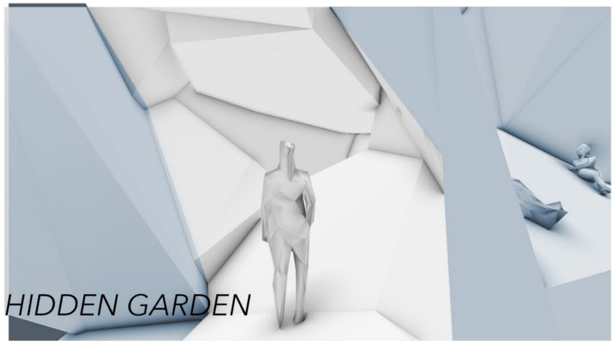


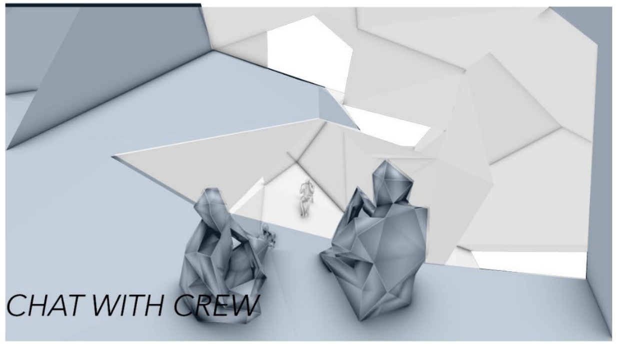


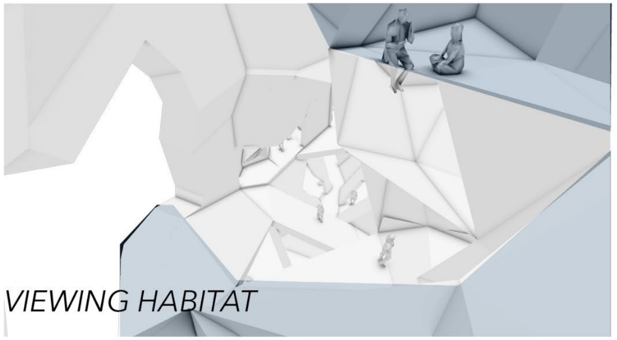
PATH



DESTINATION

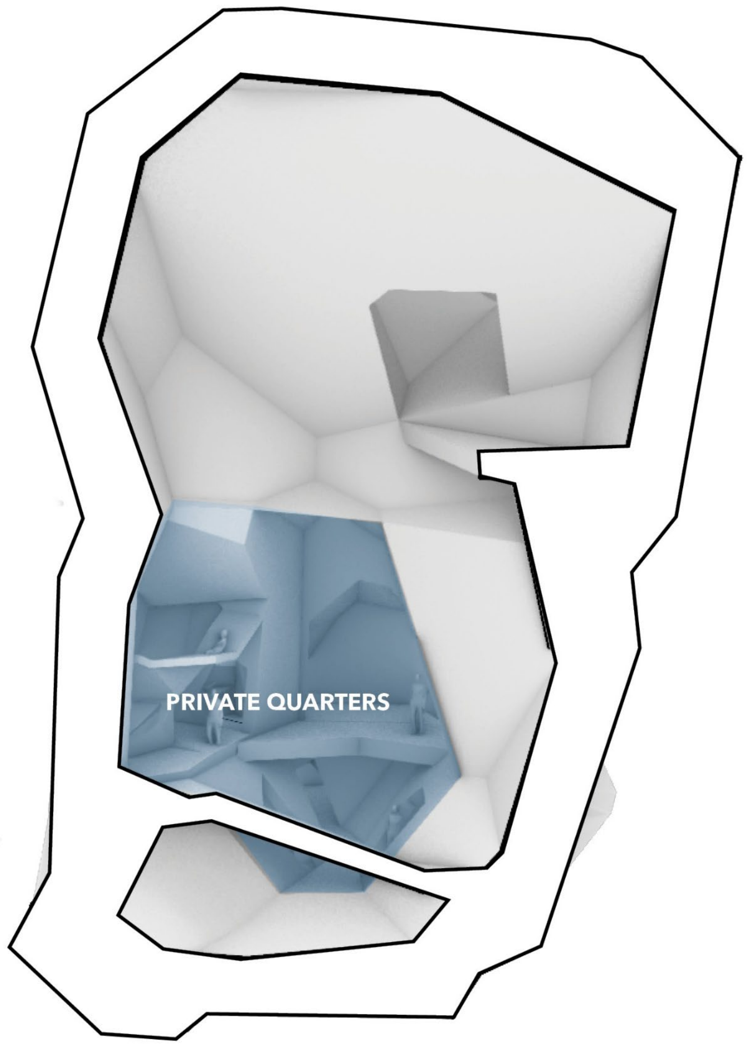


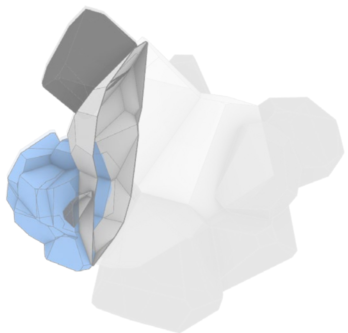


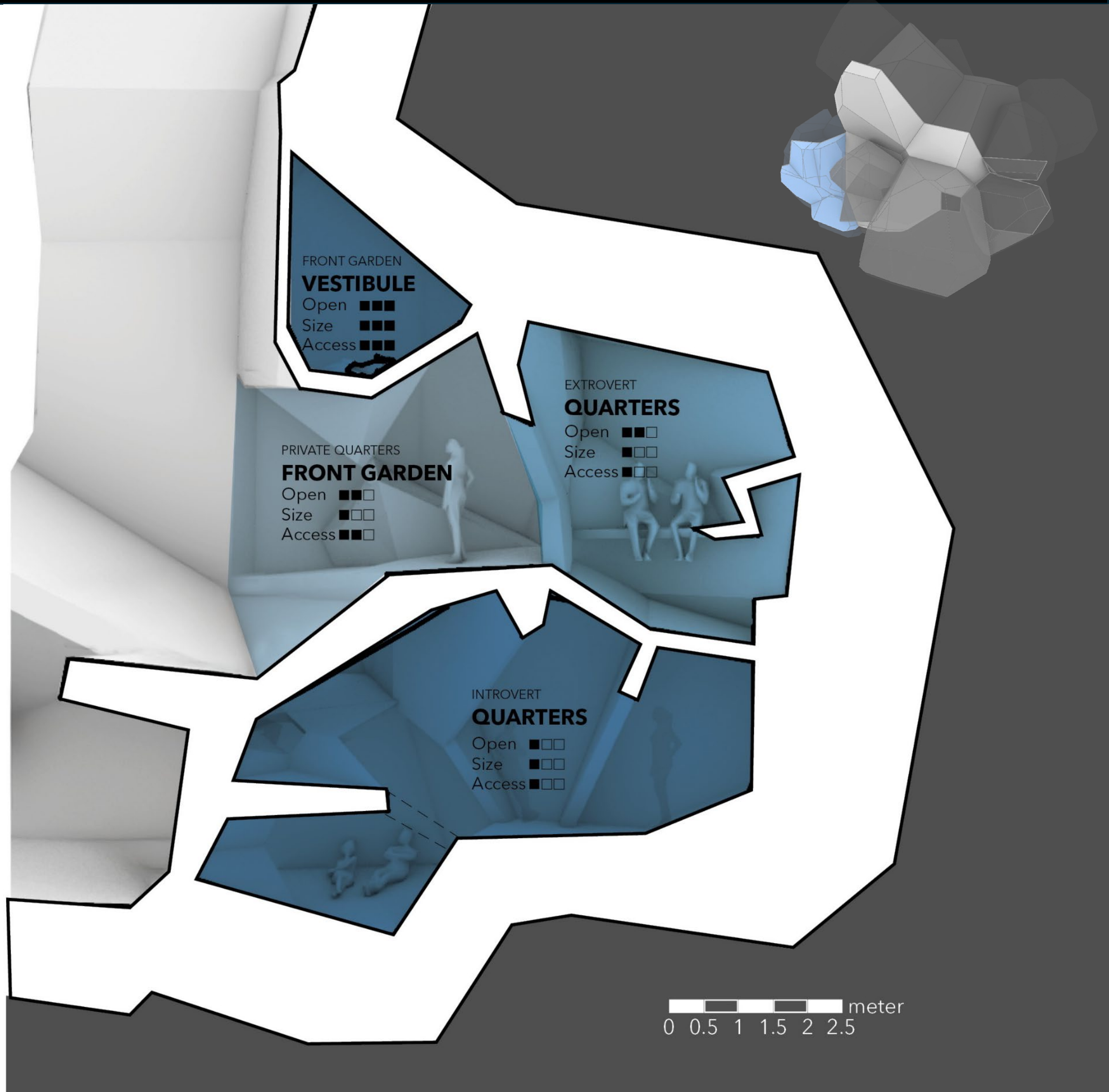


Private Quarters

Personalized spaces

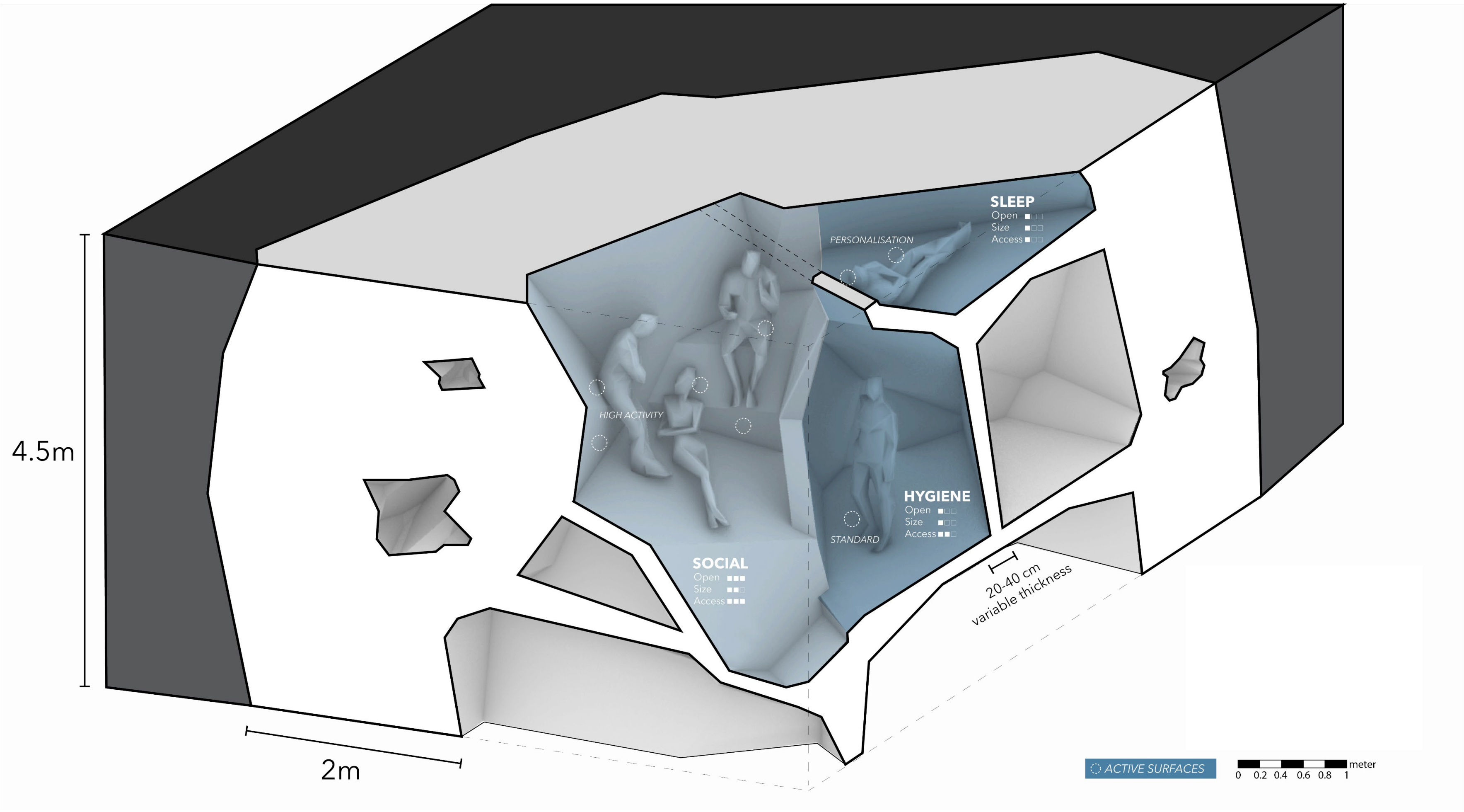


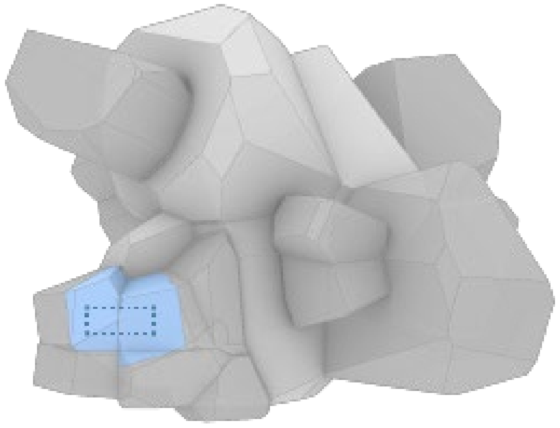




Fragment

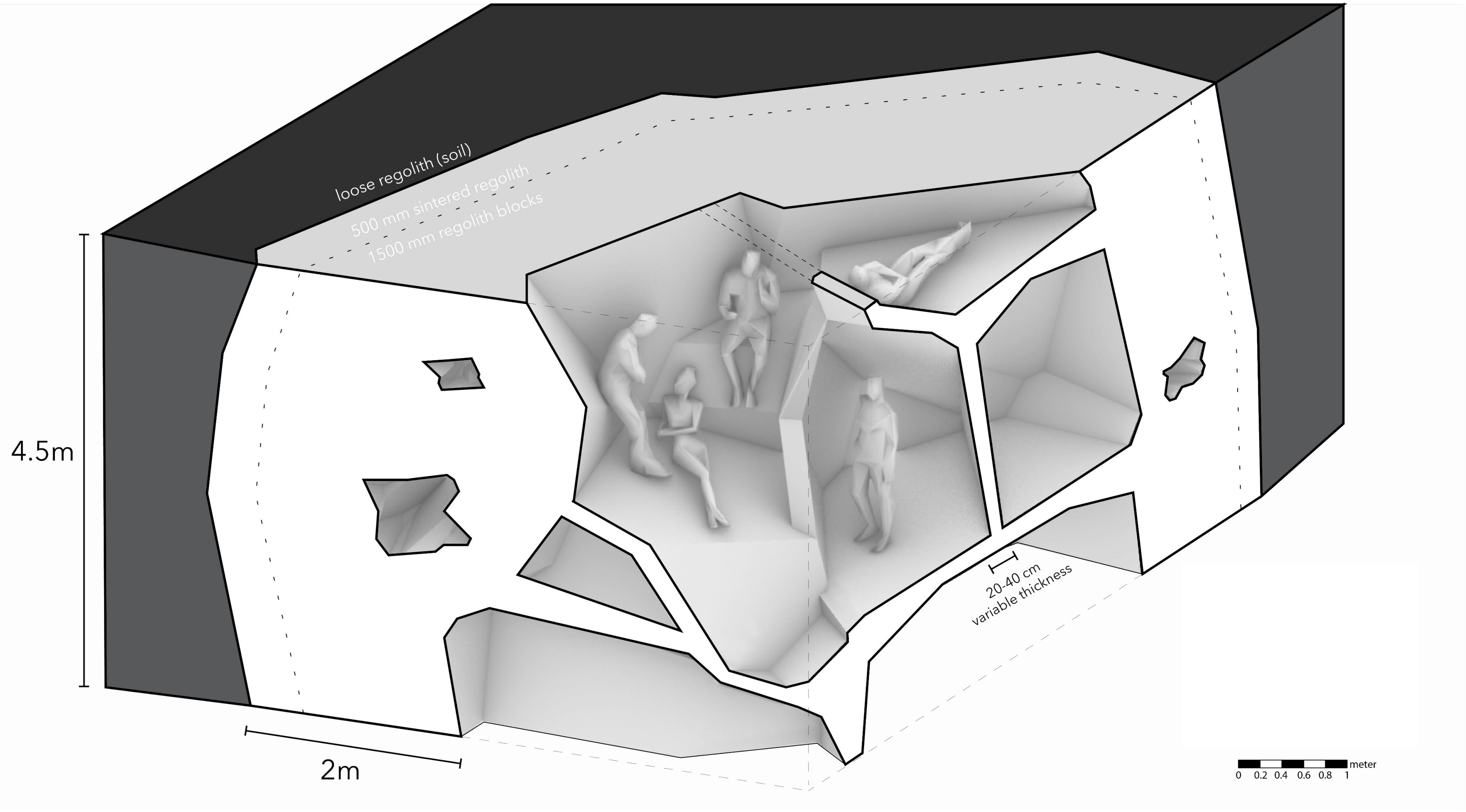
Private Quarters for the Single Extroverted Commander

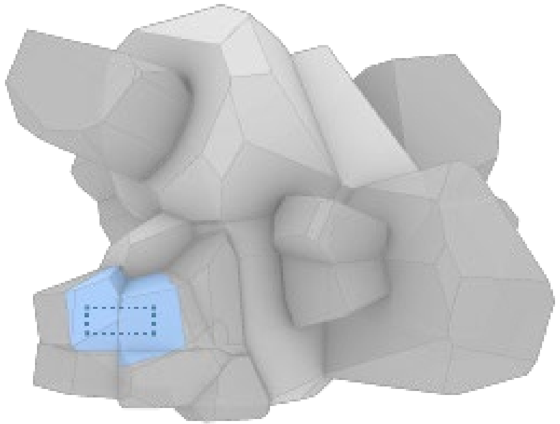




Fragment

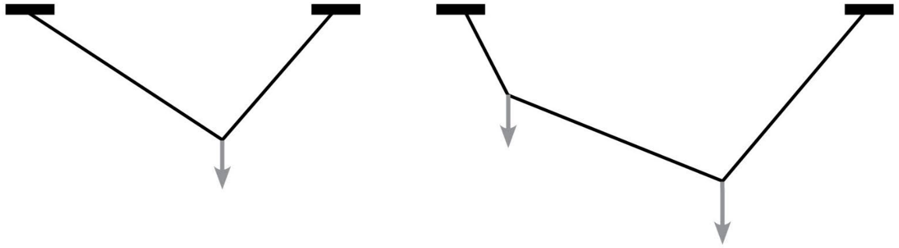
Private Quarters for the Single Extroverted Commander



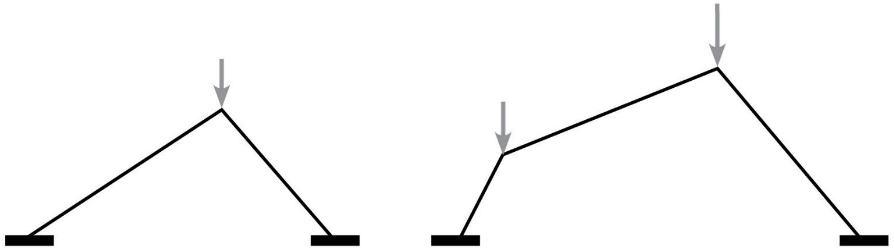


Structure

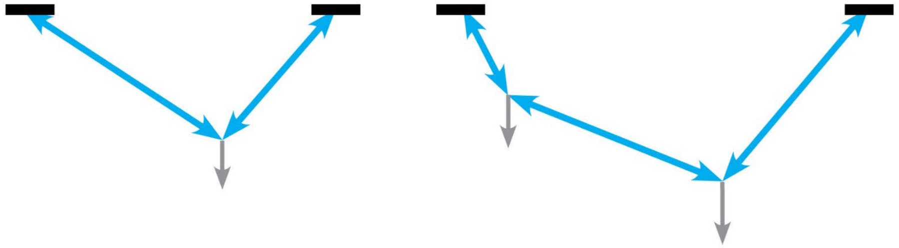
Catenary principle



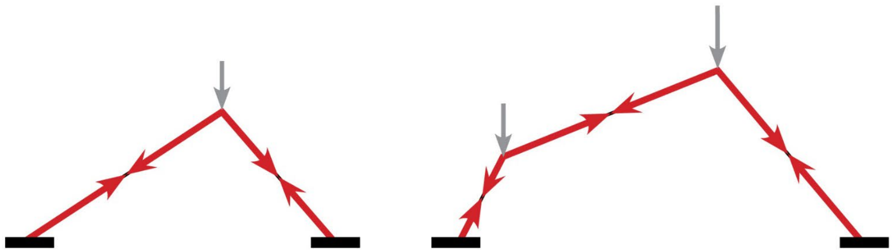
Catenary



Reverse Catenary



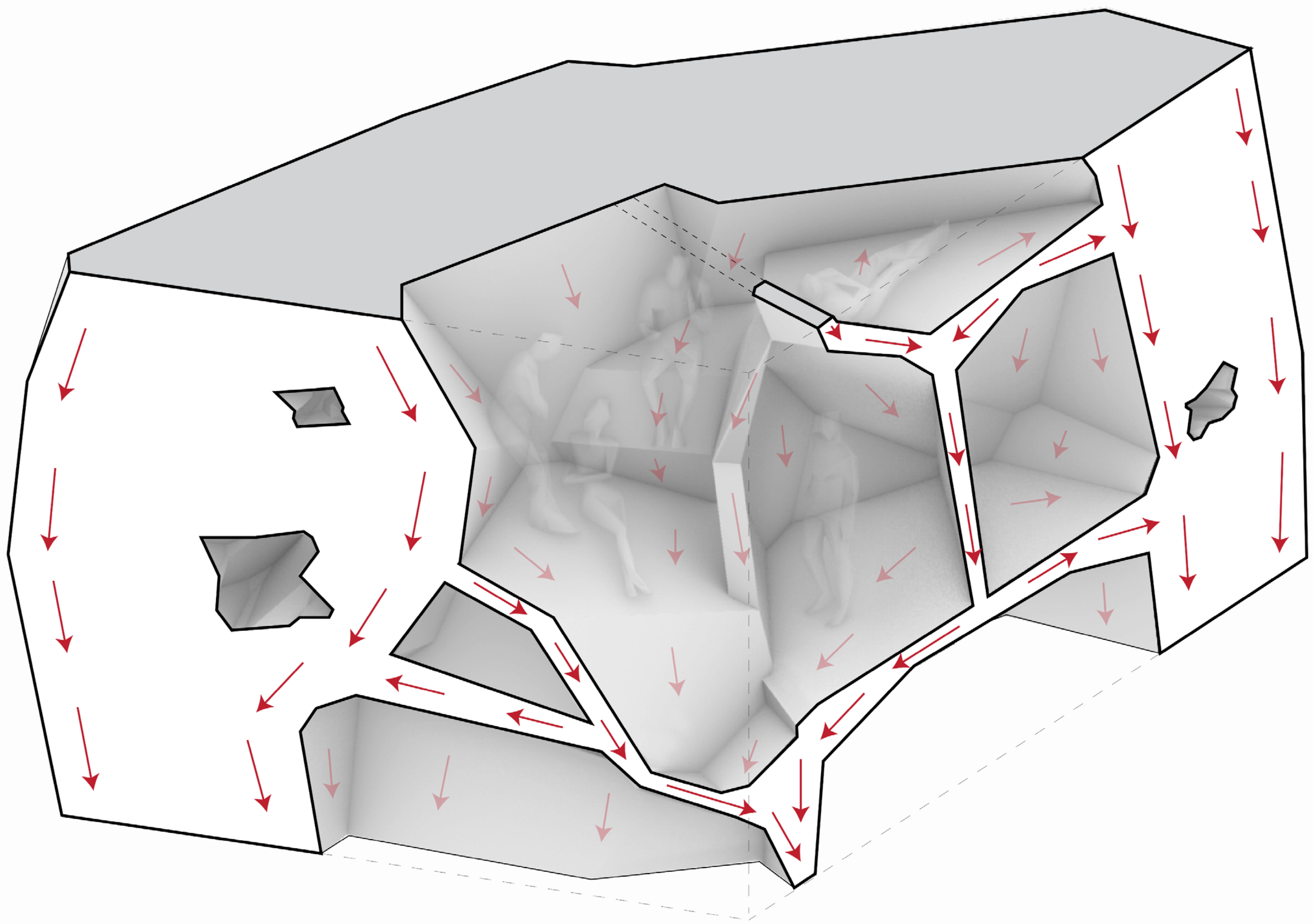
Tension Forces



Compression Forces

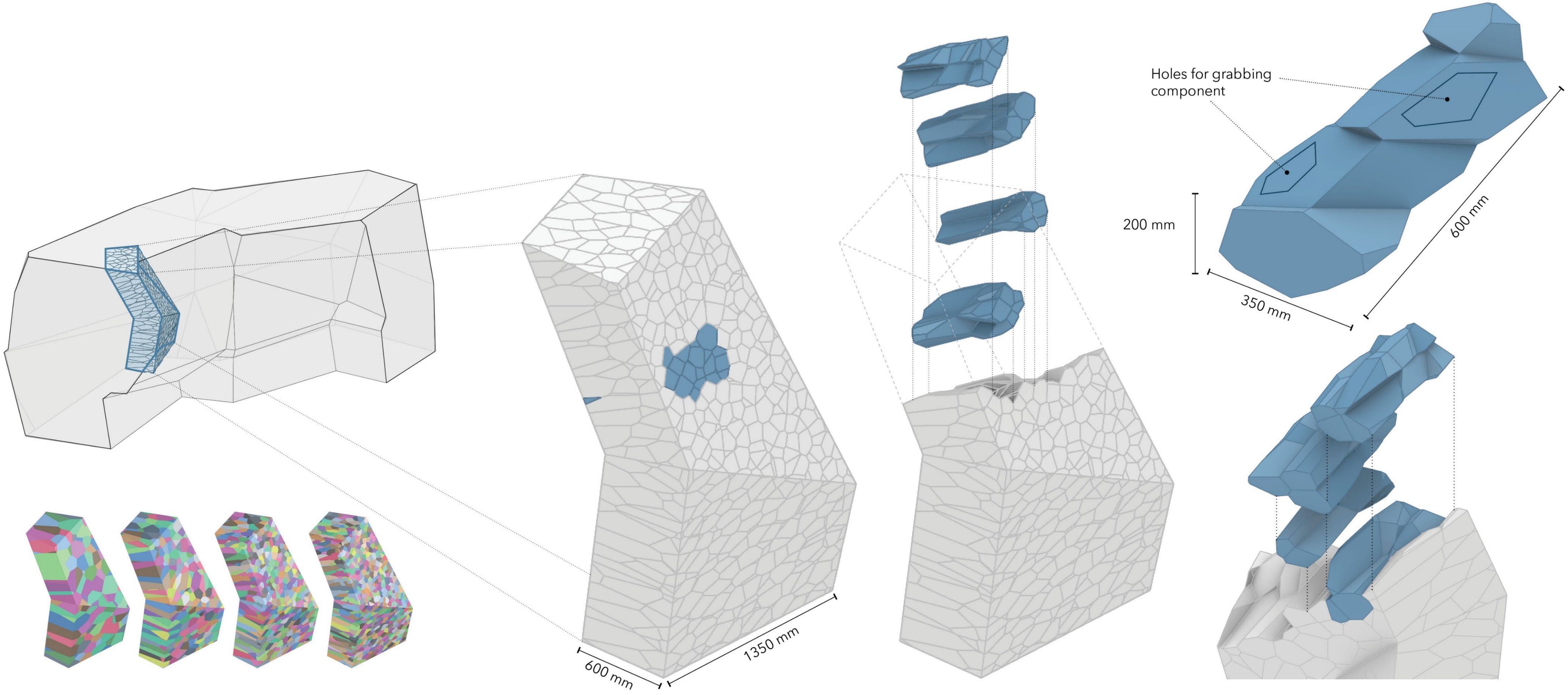
Structure

Forces in fragment



Building Method: Primary

3D-printing building blocks_*Traditional*



Iterations of wall fragment

Wall fragment

Build-up components

Interlocking components

Building Method: Primary

3D-printing building blocks_*Traditional*

Voronoi-based system as core

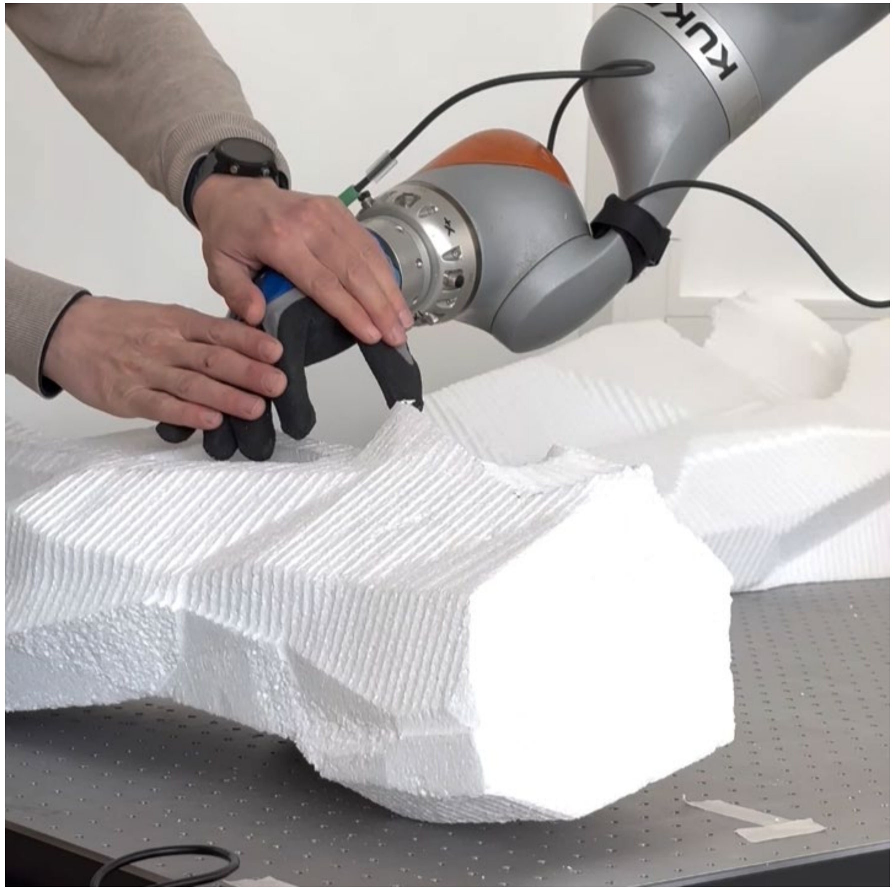
- Efficient: no framework needed since it's self-supporting structure
- Interlocking construction method

Suitable for heterogenous space

- Scalable from components to building scale
- Additive method suitable for mass customization

Assembly

- Human-robot interaction



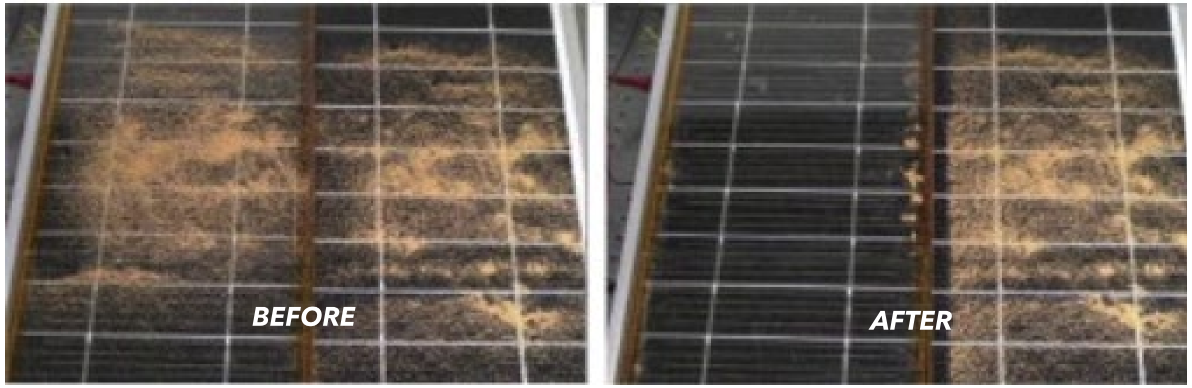
HRI Workshop, 4 April 2025

Material: Regolith

Strong compressive strength

- **Abundant → In-situ resource utilization**
- **Electrostatic properties**
- **Rich in derived materials**
- **Radiation protection**
- **Geopolymer material for additive printing**

Electrostatically charged



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

Derived materials

Regolith → **Metal alloy**

Oxygen extraction

Water (for ISRU)

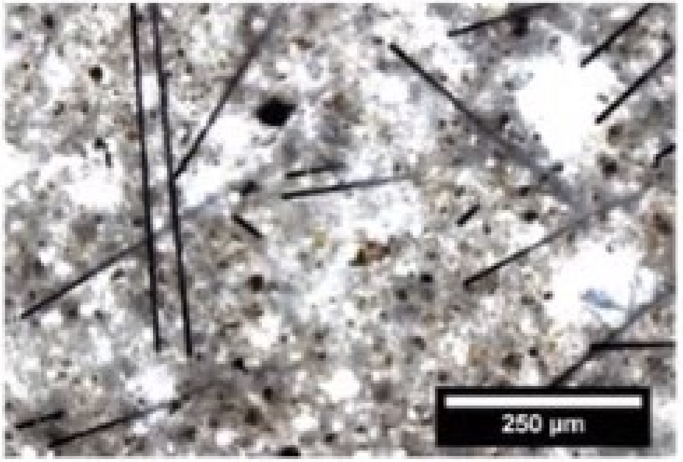
Silica (for glass)

Material: Carbon Fibre

Strong tensile strength

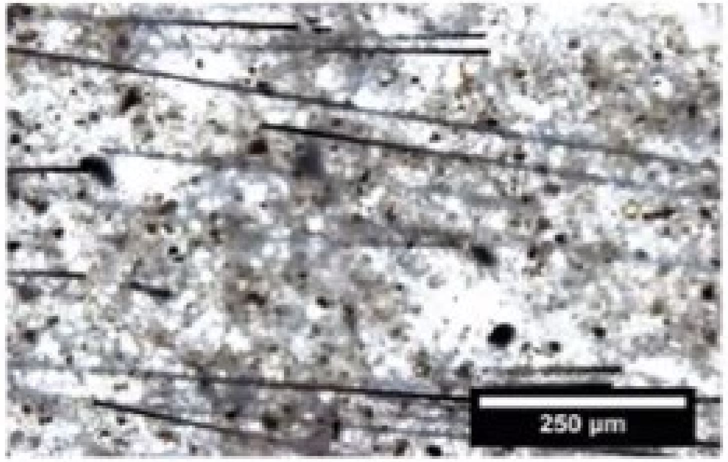
- **Supporting material**
- **Lightweight**
- **Added as substrate to reinforce regolith building components**
- **Can be pre-laid or added to regolith geopolymer filament**
- **Carbon available in Permanently Shadowed Regions (near the site)**

Carbon Fibre Reinforced Polymers suitable for secondary structures, ESA.

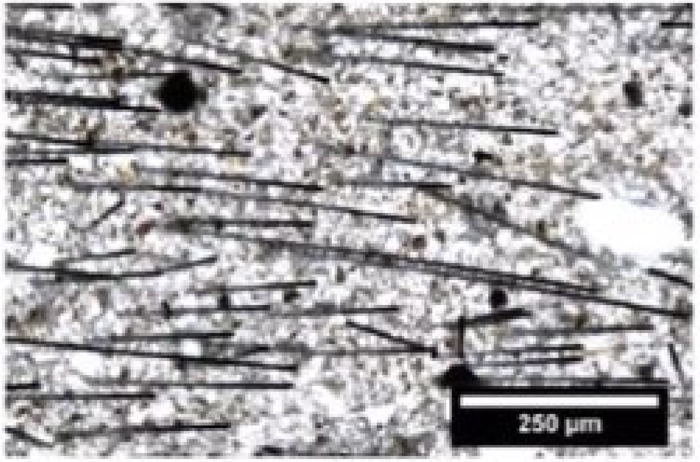


Thin sections of randomly distributed carbon fibres.

Rutzen et al., 2021



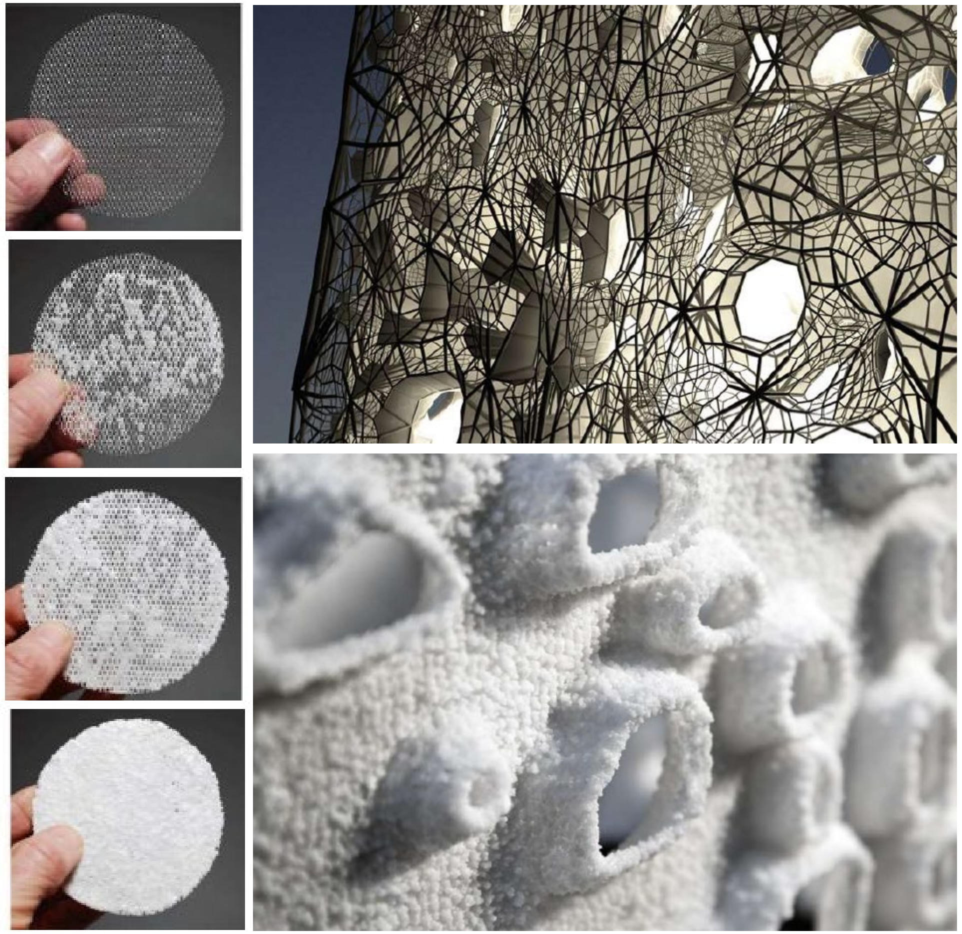
Nozzle-aligned carbon fibres at 1% by volume



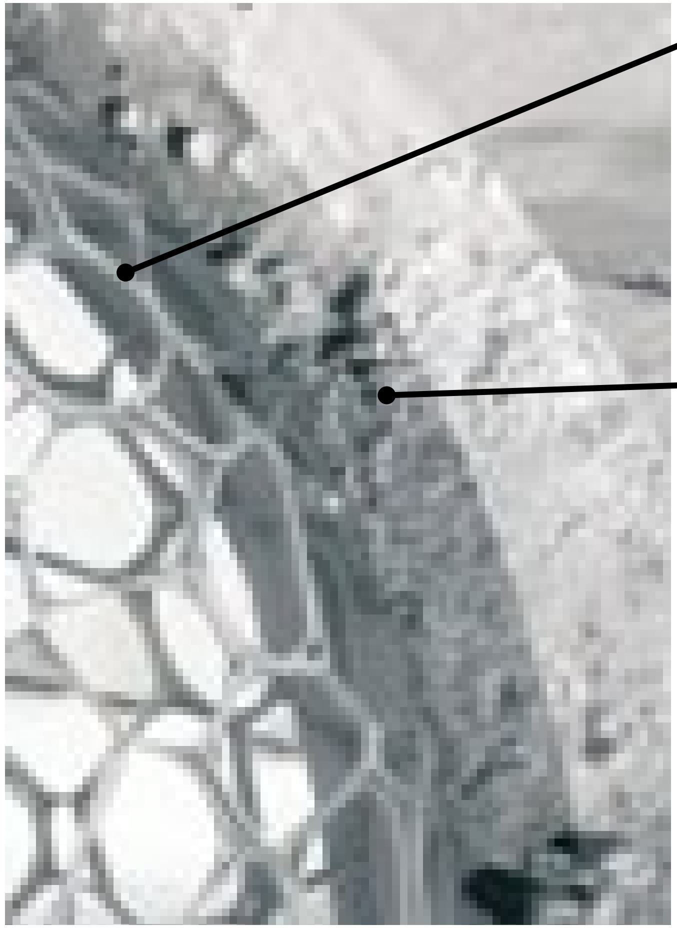
Nozzle-aligned carbon fibres at 3% by volume

Building Method: Supplementary

Regolith Accretion_*Design Potential*



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

Metallic Structure - Aluminum

- Electrical conducive property
- 2nd most abundant metal on moon
- Combine its tensile strength with regolith's compressive strength
- 3d printed

Sintered regolith

- With laser heat

3D Printing VS Regolith Accretion

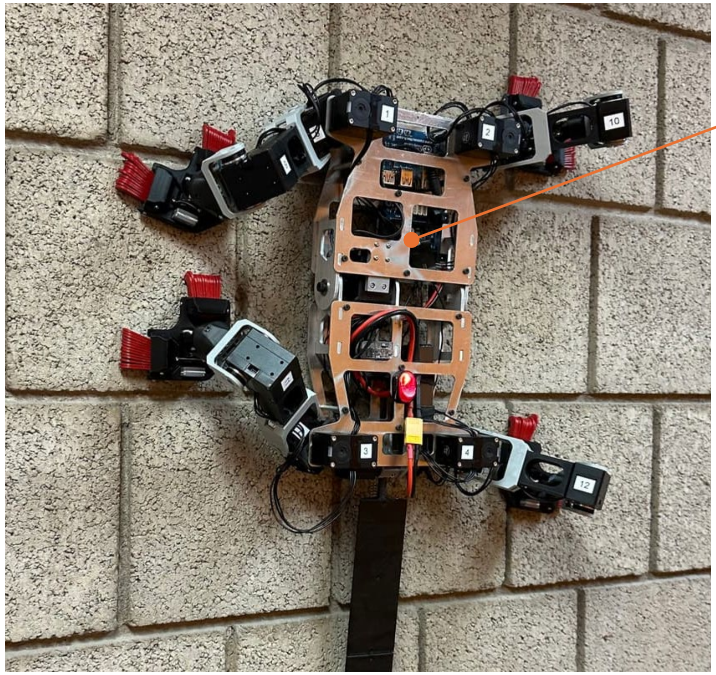
Close-up view of concrete additive 3d-printing, Vertico

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

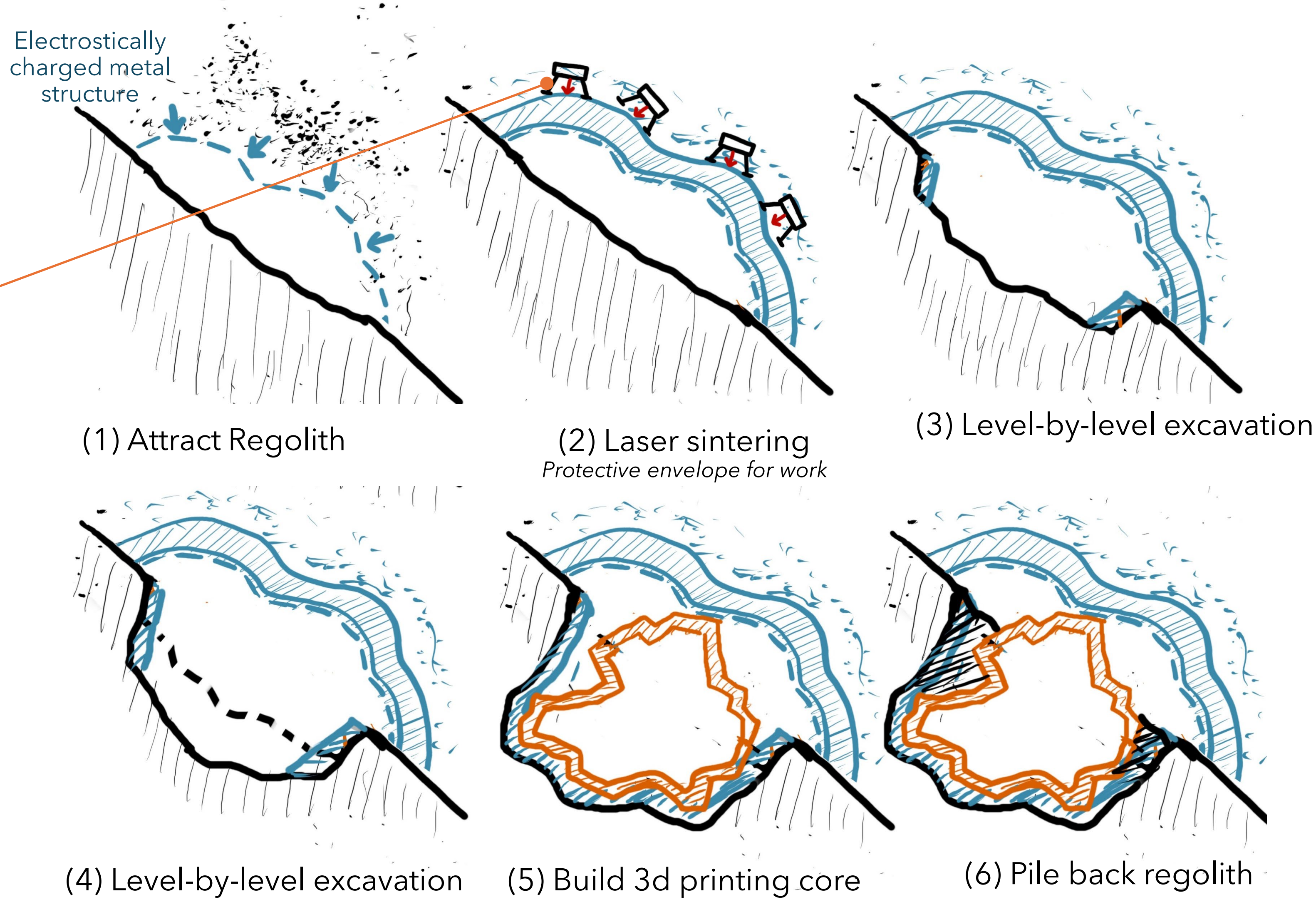
For 1m thickness	3D Printing	Regolith Accretion
Energy	~135 MWh	~72 MWh (+) consume less energy
Time	~1 day (+) faster Construction rate (1-2 meters/day)	~20 days Construction rate (5 cm /day)
Machine complexity	High (3D Printer + assembly robot)	Moderate (low energy continuous electrostatic field + 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

Building Method
Process

Application scheme
**developed during discussion with expert*

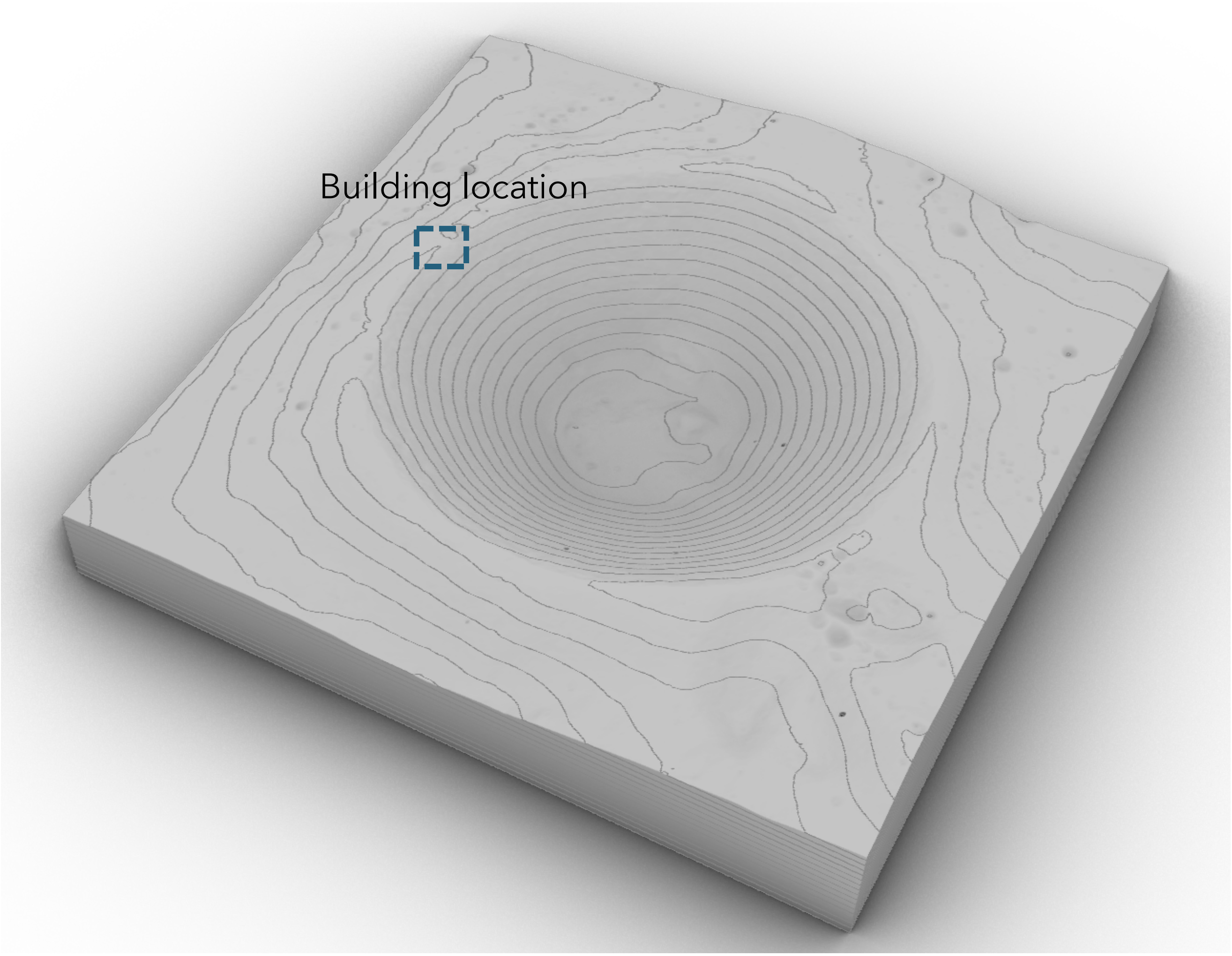


Climbing robot LORIS

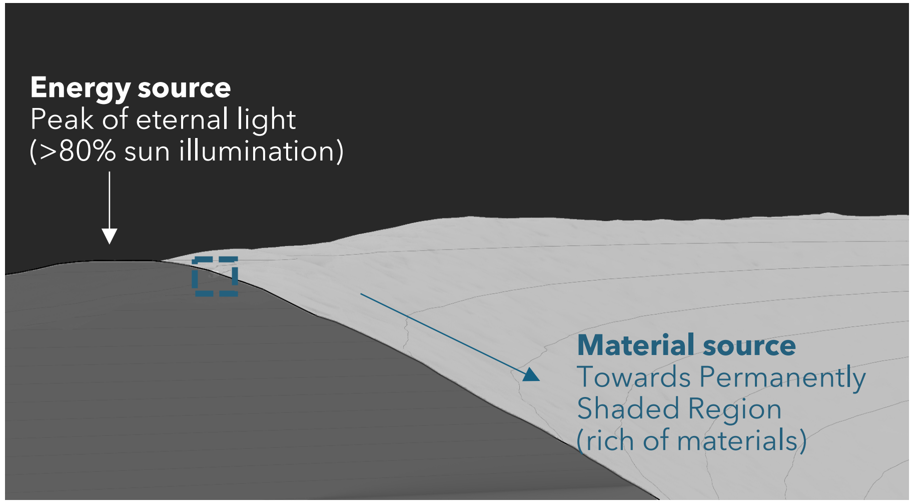


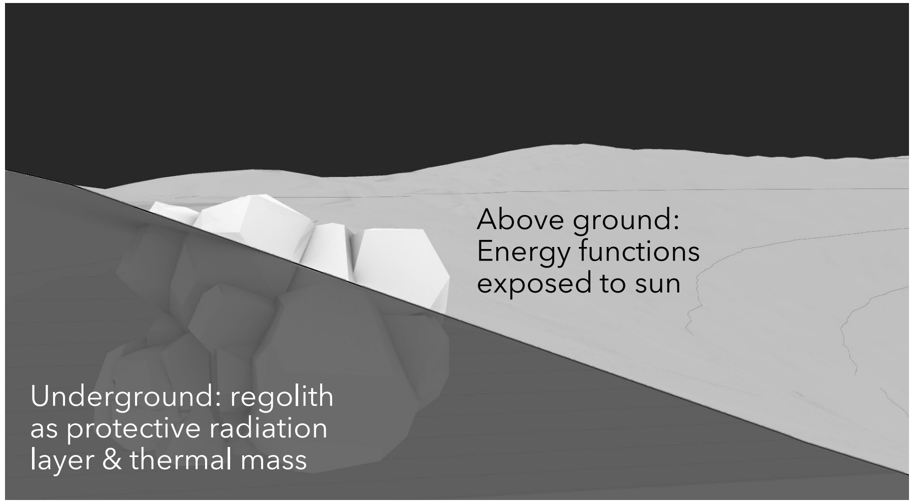
Energy Source

Utilizing site



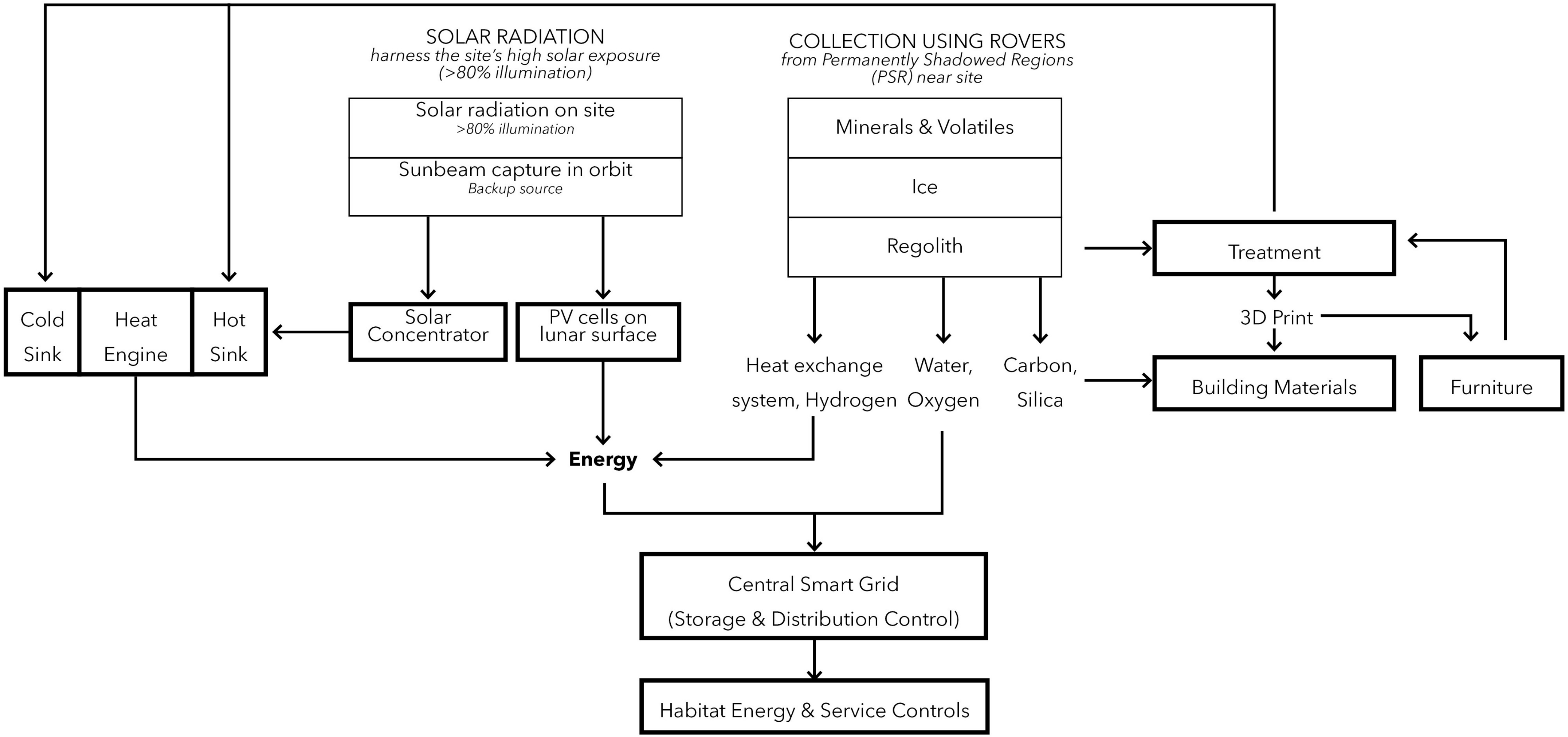
Shackleton Crater, South Pole





Energy Source

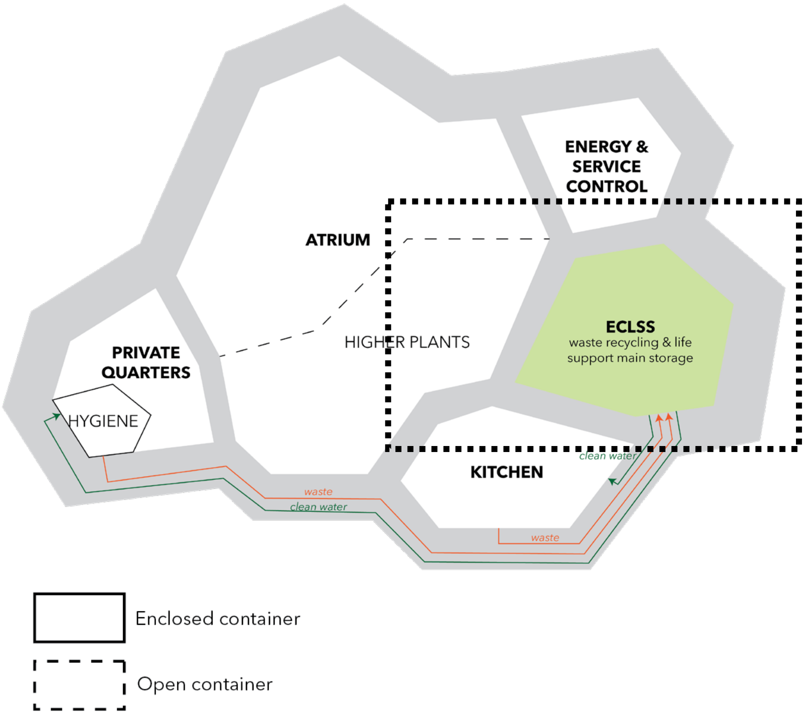
Power & Heating/Cooling

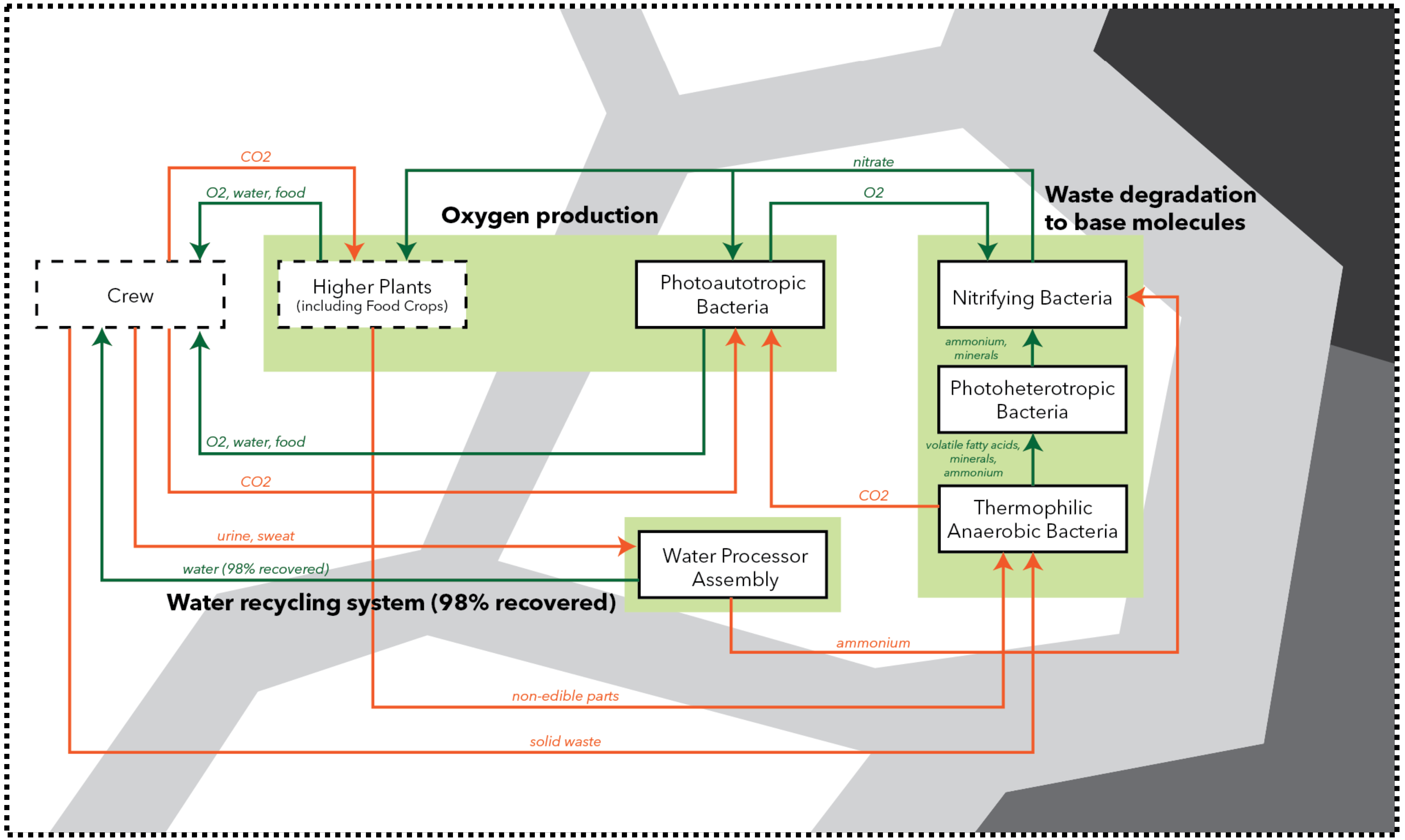


Space-based Solar Power, ESA; Heat storage and electricity generation in the Moon during the lunar night, Blai Climent et. al., Acta Astronautica; Power and Energy for the Lunar Surface, NASA; Moonshot Symposium, TU Delft, 2024; Adaptive On- and Off- Earth Environments.

Building Service System

Environmental Control and Life Support System





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

Next steps

Reflection

SOCIETAL RELEVANCE

Human-centric design: informed by experience and guided by preferences

- Minimal social context on the moon → back to basic, humans need spaces for varied social interactions
- Long-term co-living requires variety of space
- Private spaces beyond private rooms for total control of privacy

Creating transitions in Architecture for isolation

- COVID-19 saw the increase in having working & living in the same space, yet designated spaces are important for the psychosocial well-being of humans. Especially in lunar habitat where you can't simply escape outdoors.
- Limited social space force certain type of interactions, thus spectrum of interactive to solitude spaces can promote healthier relationship within crew

Ethical responsibility to minimize ecological footprint even in off-Earth colonization

ARCHITECTONIC RELEVANCE

System-based approach developed from Voronoi geometry

- Scalable: from components to spatial resolution
- Allows bottom-up approach: design from human scale
- Form, function, structure follows system
- Inherently generates variety of surface: strategy for spatial variety and enclosure
- Gradual transition in geometry size: designing for spectrum (in privacy)
- Iterative process, design by research and research by design to refine spatial logic
- Breaks away from conventional geometry allows exploration

Robotically-assisted ISRU (in-situ resource utilisation)

- Automation enables construction in extreme environments
- Making use of abundant local resources → circularity

Integrating speculative technologies

- Interdisciplinary design by research and research by design

Discussion on computational design: Methods to aesthetically evaluate iterations

- Focus on social interaction and private boundaries → openness, size, access as parameters
- Work <u>with</u> AI to help generate solutions within established framework

Next Steps

Architecture

- Refine representations (drawings, rendering, model-making)
- Develop scenarios
- Integrate greenery in atrium
- Develop openings (representation)

Building Engineering System (BES)

- Refine representations
- Detail drawing
- Refine climatization
- Detail gradual transition structure