Progress Update

Terraforming Moon

Humanizing Lunar Living through Human-centric Design

LA&I Graduation Studio 2024/25

Regina Tania Tan

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.

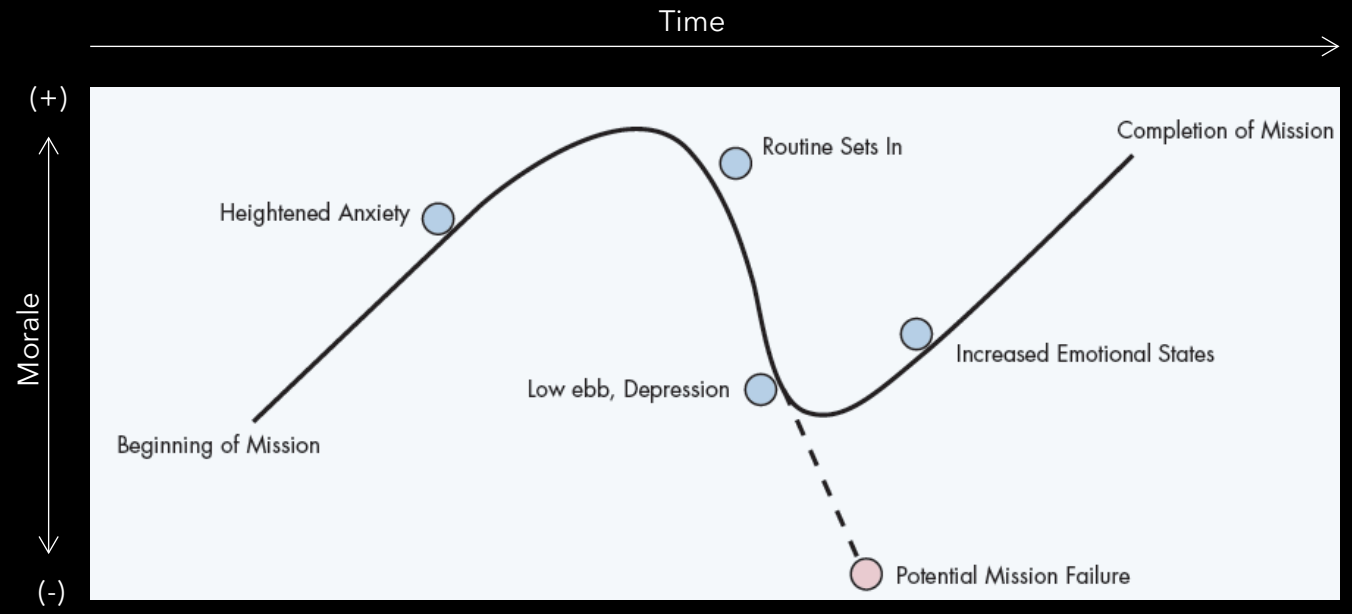
What makes a place suitable for human habitation?

Need of something familiar…human infrastructure as marker

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

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?

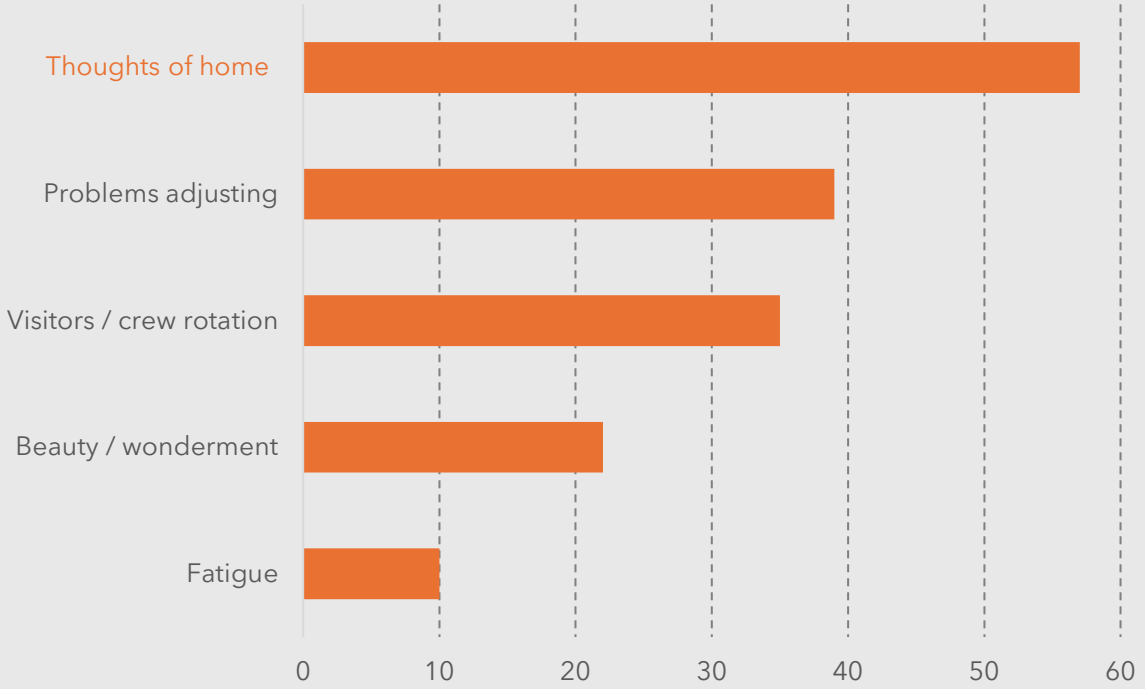
Excerpts from space missions

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



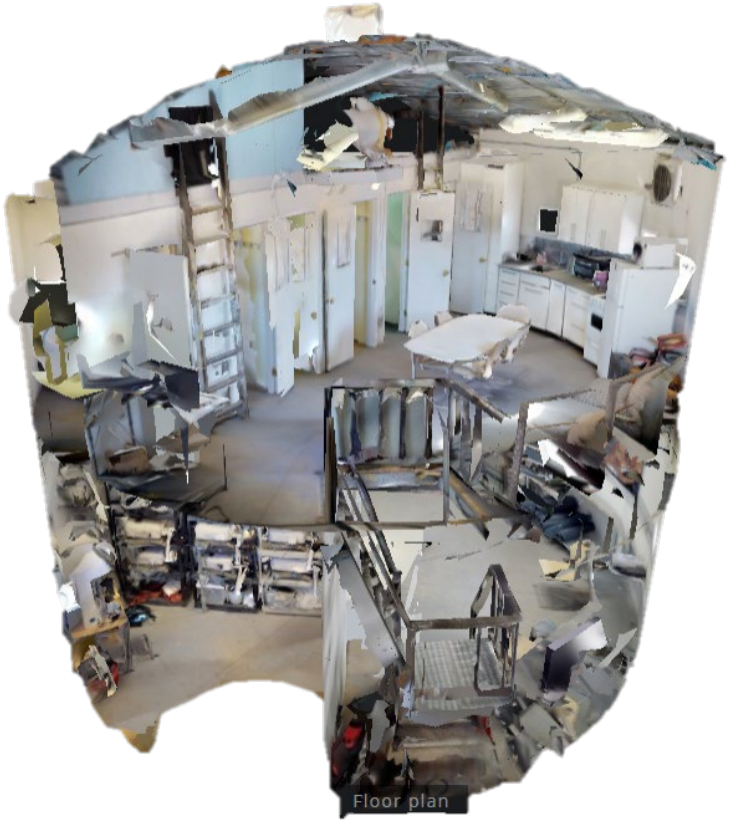
Distribution of journal entries by astronauts aboard the ISS, Olga Bannova in Space Architecture: Human Habitats Beyond Planet Earth.

"…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!"

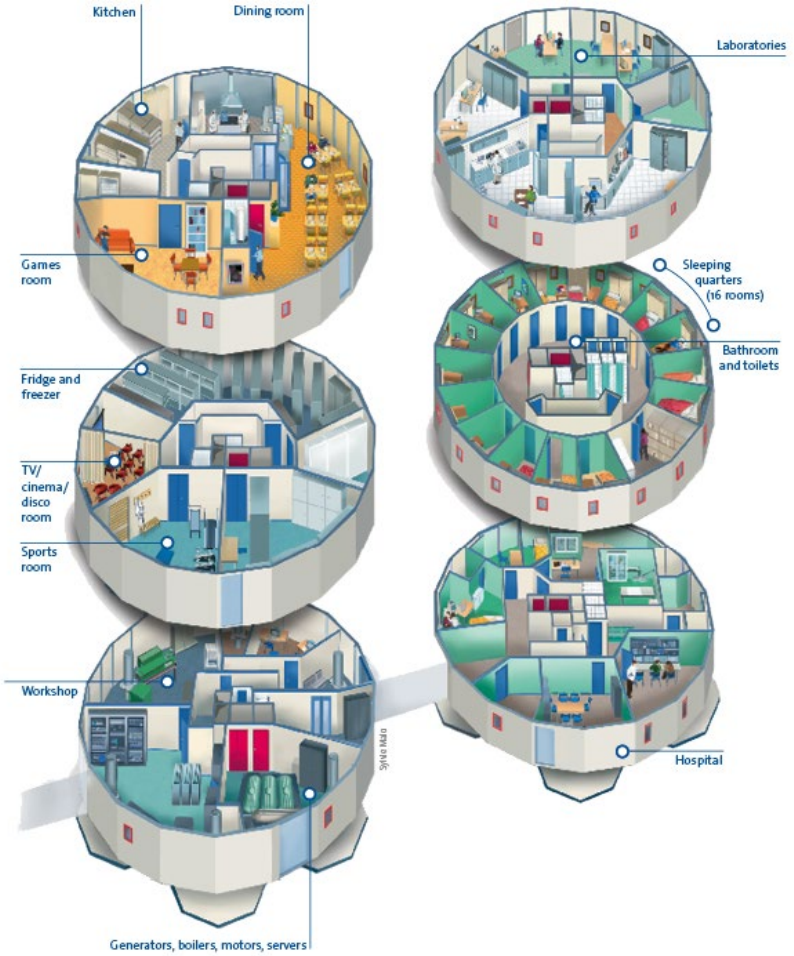
Ed Lu, ISS, Expedition 7 (185 days), NASA, 2003

Human de-centered design

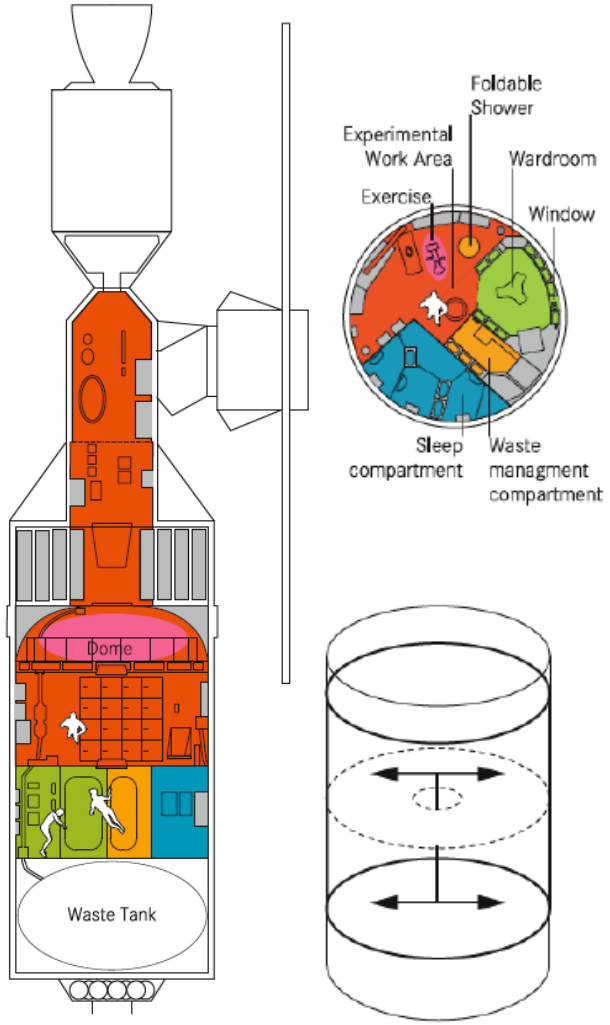
Schemes developed from functional aspect (not focusing on human behavior)



Mars Desert Research Station, Utah, USA



Concordia Research Station, Antarctica



Skylab Space Station

Human-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

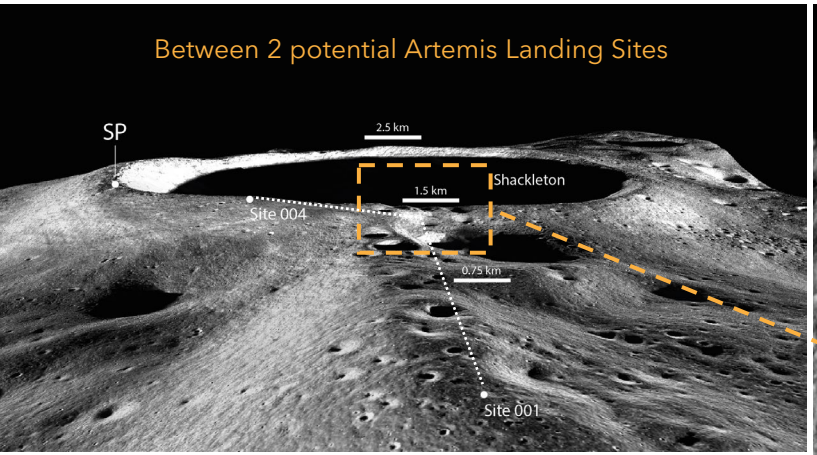
How to incorporate **user-defined spaces** based on **human-centric design principles** in designing long-term lunar habitation that **balances social interaction and private boundaries**, for the psychosocial well-being of the inhabitants?

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?

Site Selection

Lunar South Pole: Potential high human activity and abundant resource



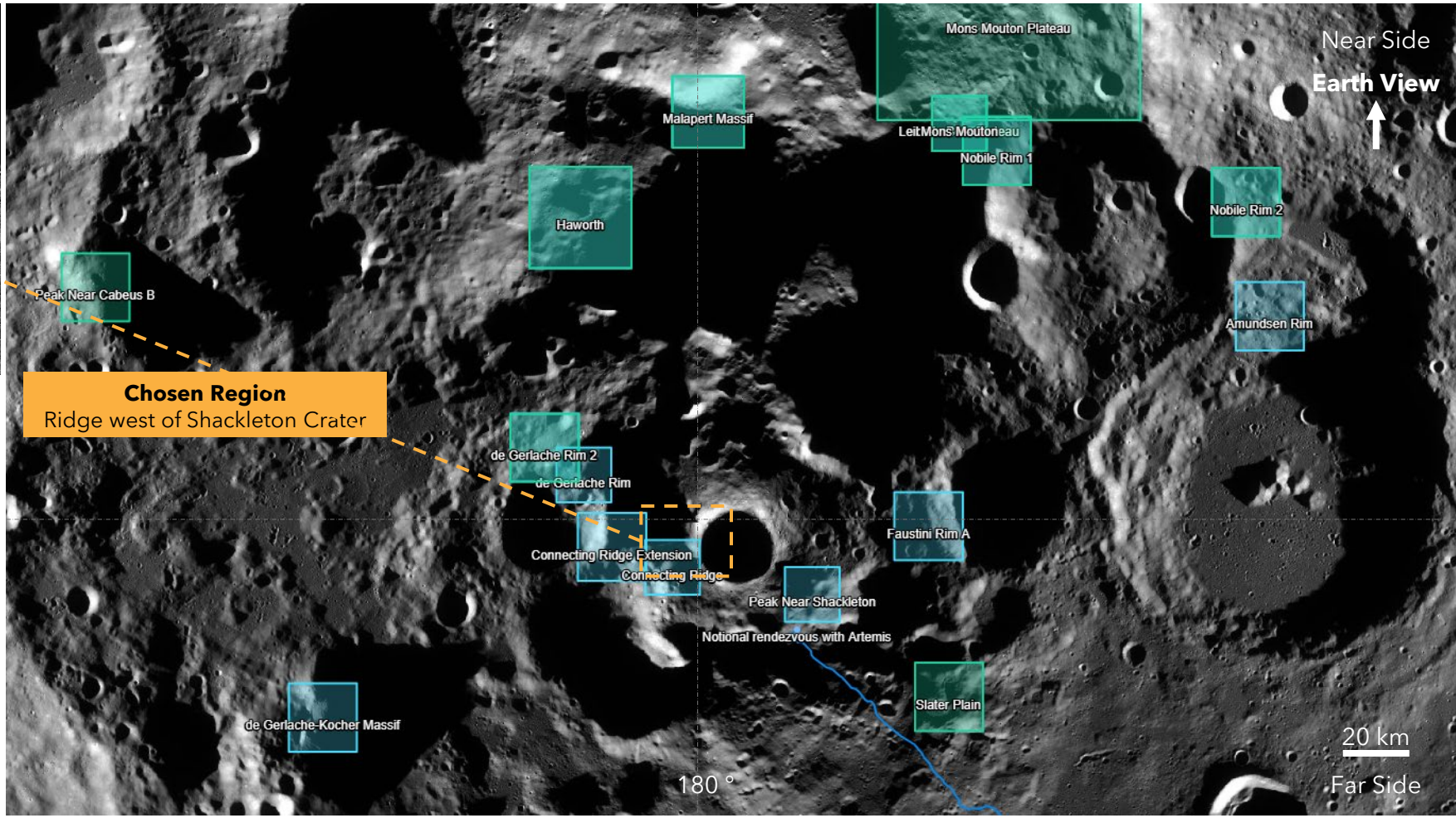
Artemis Landing Sites along Shackleton Crater ridge

High human activity potential

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

Abundant resource

- Proximity to eternal sunlit areas & permanently shadowed areas (resources & charged regolith)



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

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 → 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

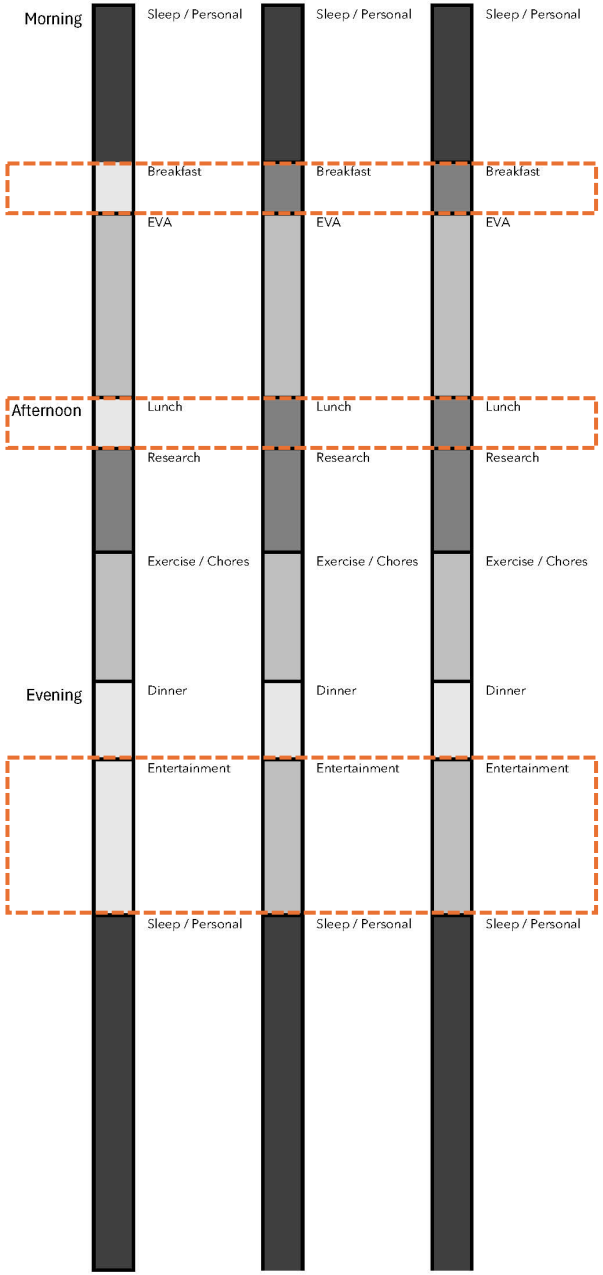
Hi-SEAS Mission NASA, various sources

Learning from analog

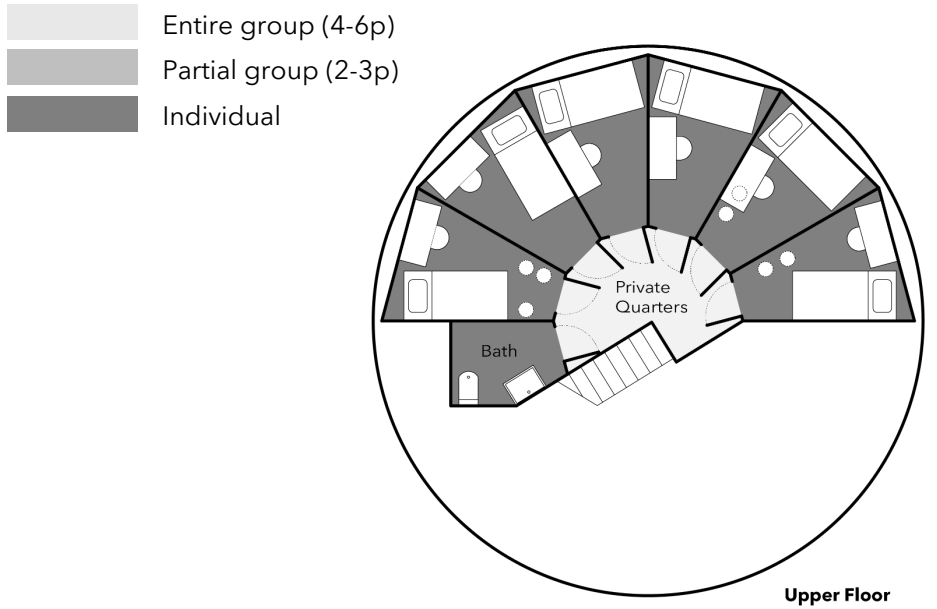
Importance of privacy gradient

Hi-SEAS Mission

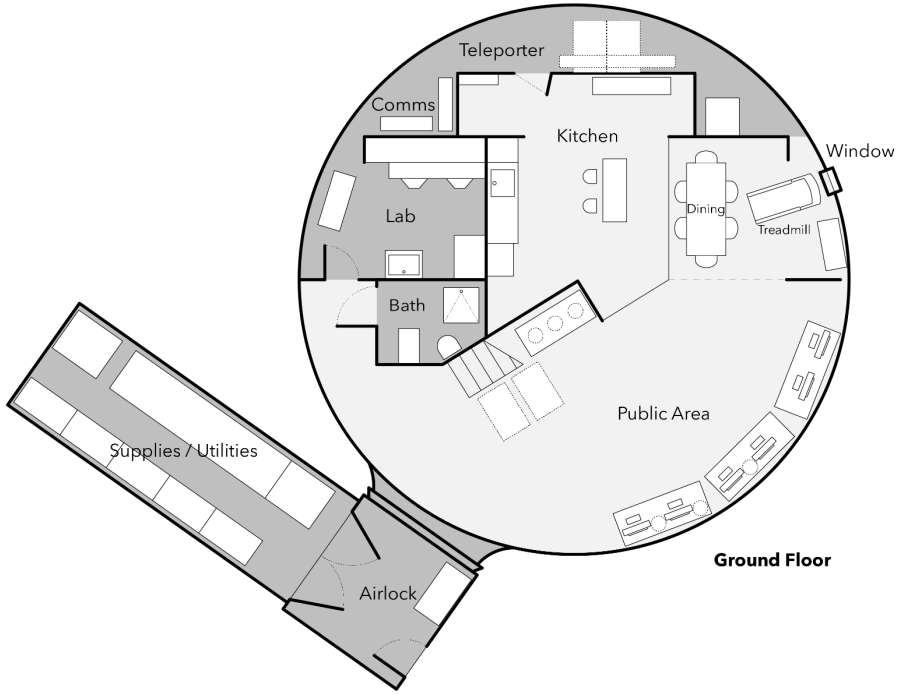
- Similar schedule even with different crew
- Declining participation in group activities over time
- Formation of social cliques over time
- Frustration: lack of semi-private space, especially auditory



Schedule based on social interaction



Upper Floor



Ground Floor

Learning from analog

"Heart" of the habitat

Greenhouse: community activator

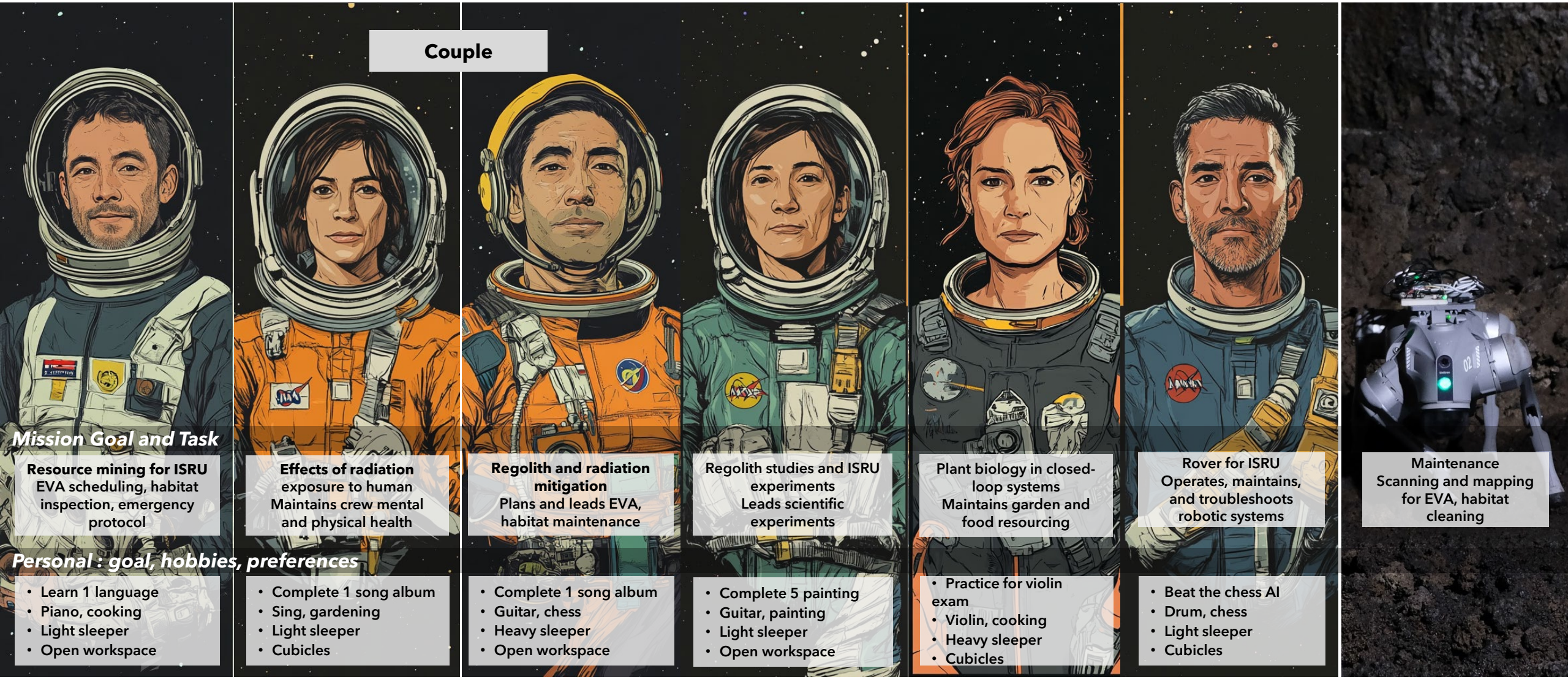
McMurdo greenhouse initiative in Antarctica, ca. 1990, Phil Sadler

First lettuce grown and eaten in space, ISS, NASA.

Harvesting plants in Hi-SEAS GreenHab

- Greenhouse as popular therapy space in McMurdo → smell of living plants and feel of warm humid environment
- Hi-SEAS IV even created "Martian" holiday to celebrate the first harvest of habitat-grown tomatoes

Personas: fictional crew members



Couple

Mission Goal and Task

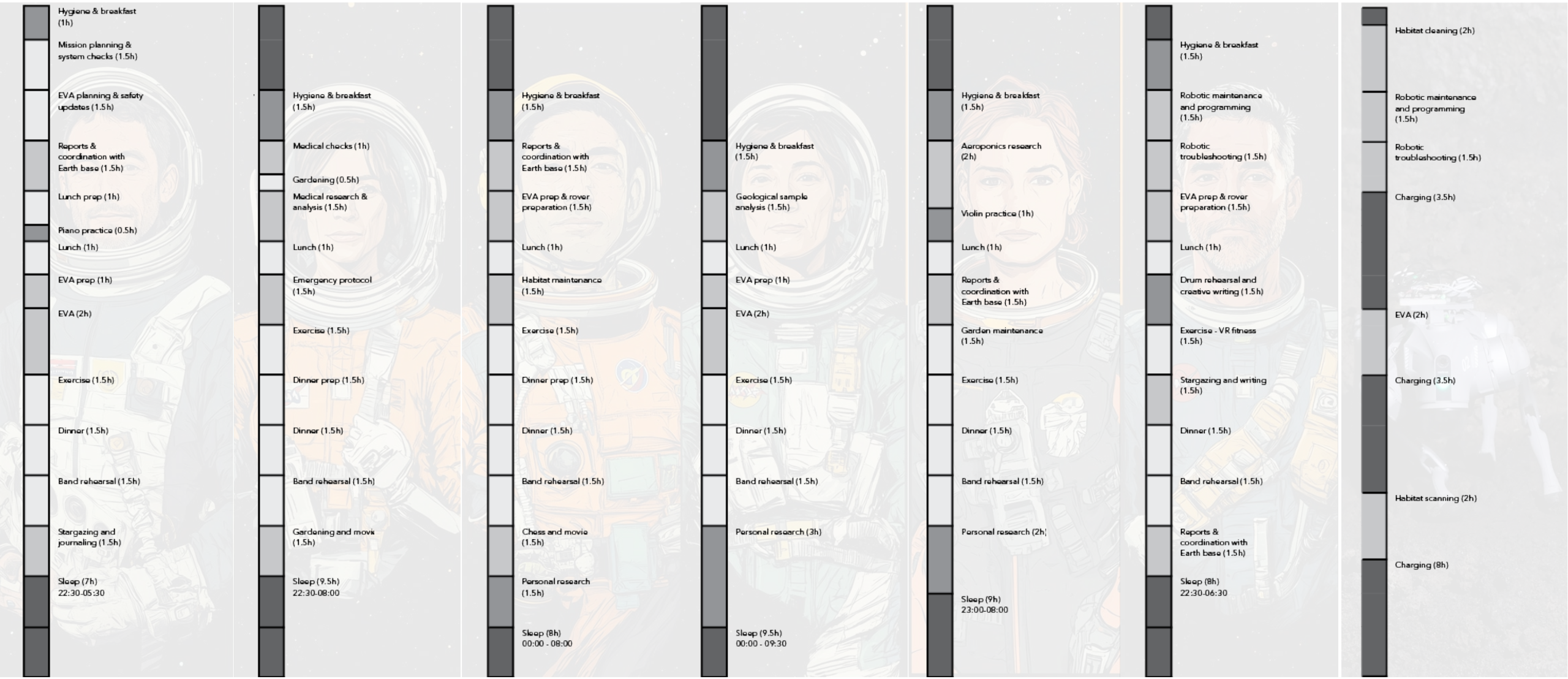
Commander, 37	Medic, 33	EVA Specialist, 35	Geologist, 32	Ecologist, 29	Roboticist, 30	Habitat Robot
Resource mining for ISRU EVA scheduling, habitat inspection, emergency protocol	**Effects of radiation** exposure to human Maintains crew mental and physical health	**Regolith and radiation mitigation** 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	• Practice for violin exam • Violin, cooking • Heavy sleeper • Cubicles	• Beat the chess AI • Drum, chess • Light sleeper • Cubicles

Persona's activity

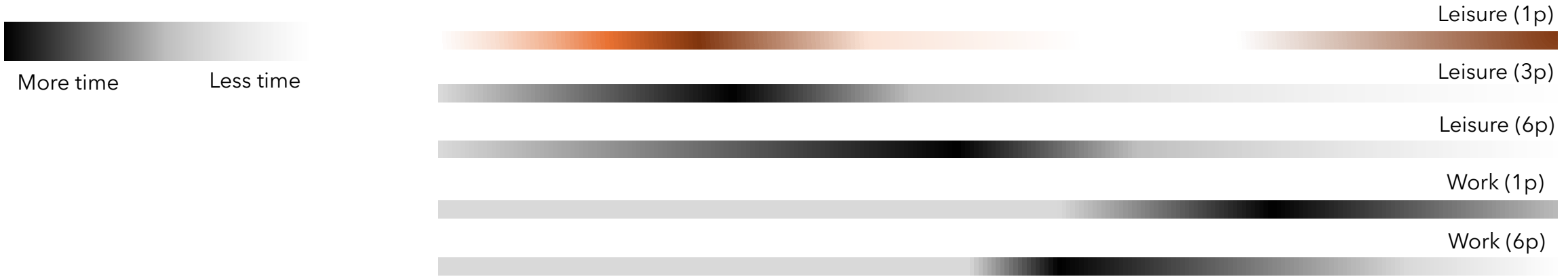
Sleep | Individual | Partial group | Entire group



Commander, 37 | **Medic, 33** | **EVA Specialist, 35** | **Geologist, 32** | **Ecologist, 29** | **Roboticist, 30** | **Habitat Robot**

Activity-space relationship

Time spent in each area, according to activity



ATRIUM / GREEN HOUSE

LIVING

WORK STATION

PRIVATE QUARTERS

multiple use ⟷ *personalization*

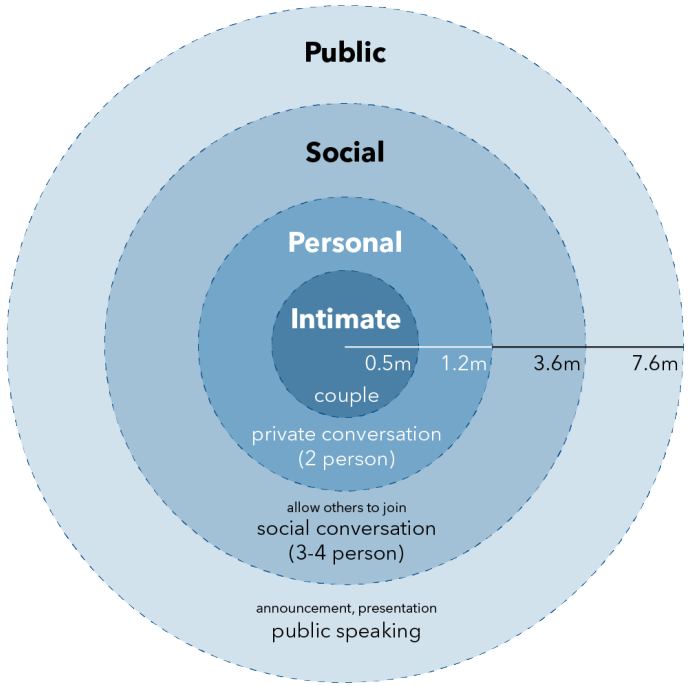
Room scale ⟷ Furniture scale

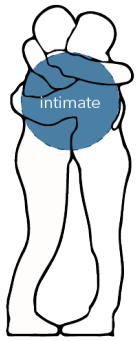
Transition space

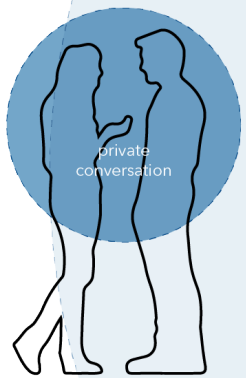
Functional space

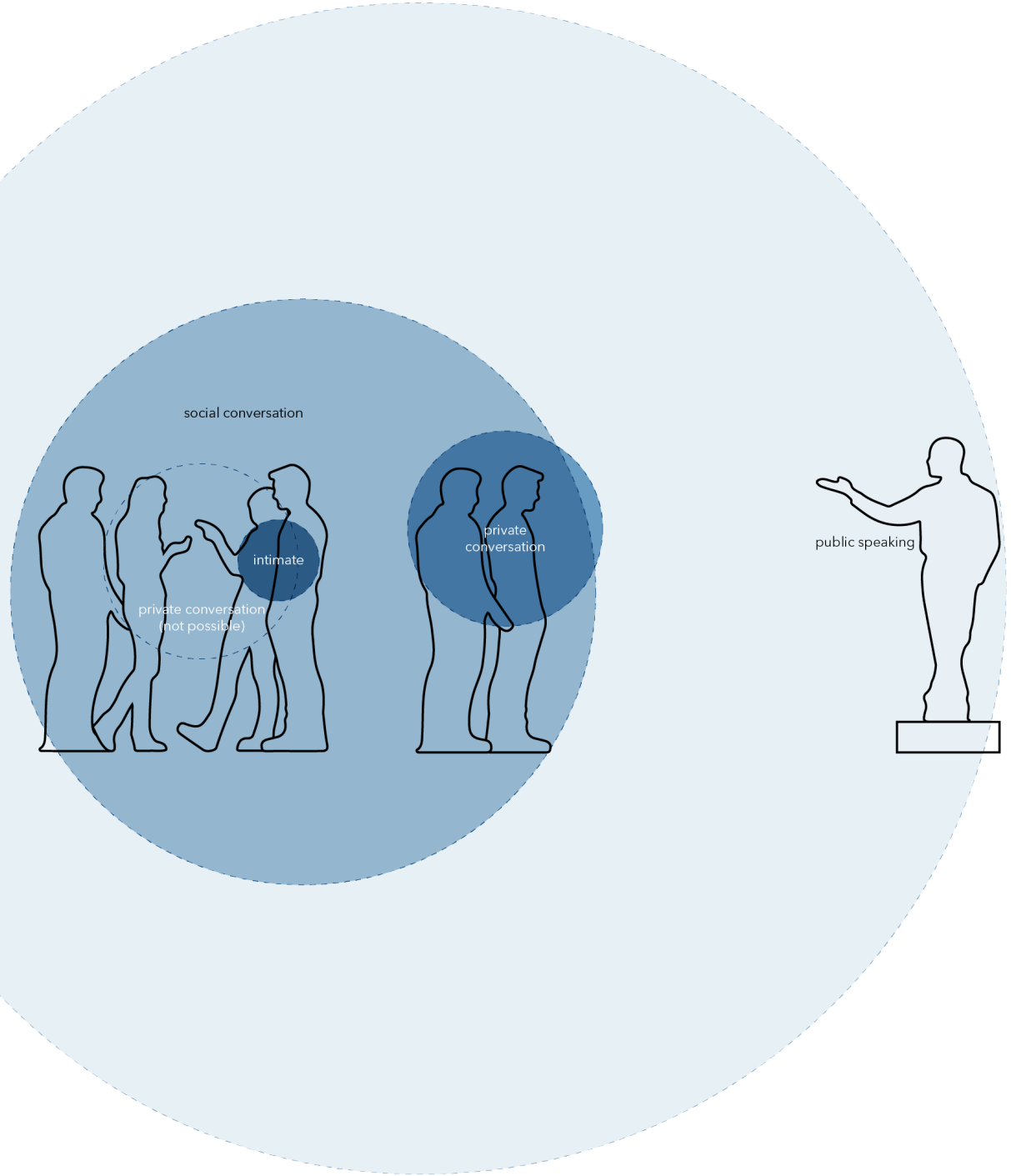
Activity-based catalogue

How do you interact?





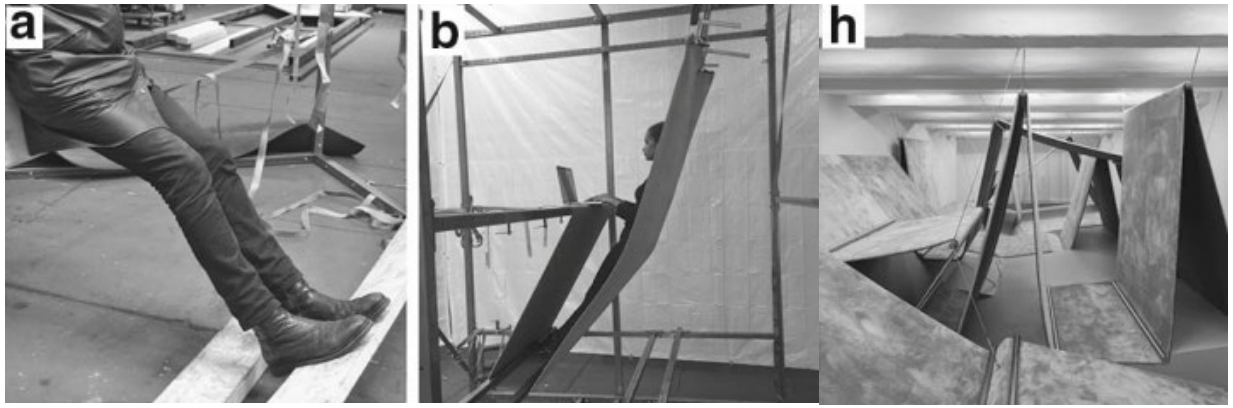




Reference_Situated Interface

Permanent: the user adjusting to the space

to enable and disable certain activity and movement

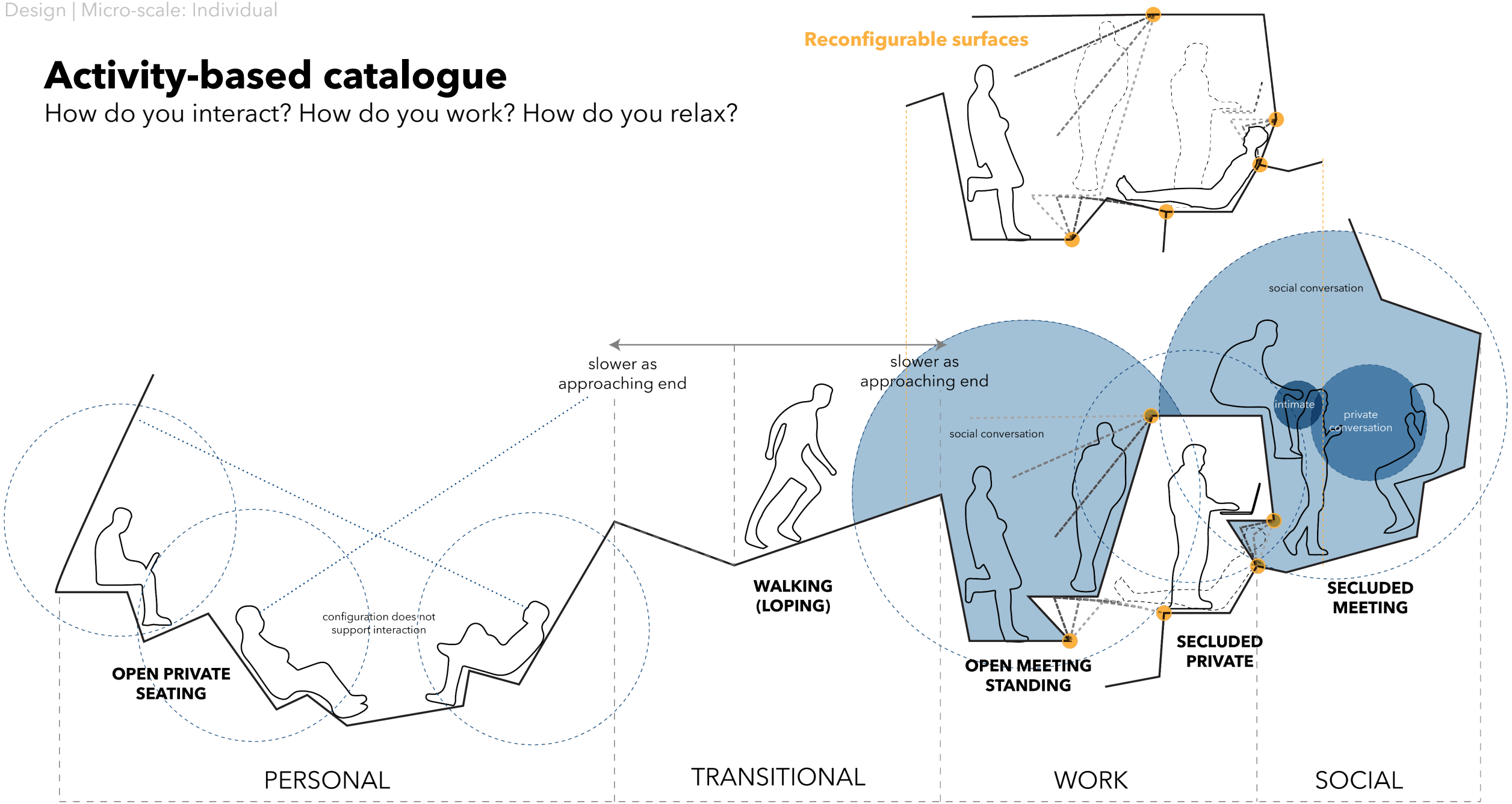


A World Without Chairs
Art installation, van Dijk and Rietveld in Situated Anticipation (2018)

The End of Sitting
RAAAF & Barbara Visser (2014)

Activity-based catalogue

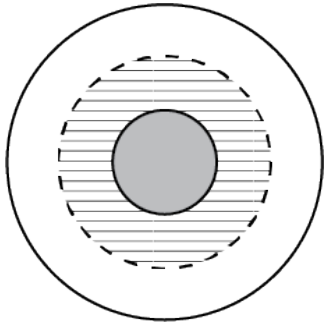
How do you interact? How do you work? How do you relax?



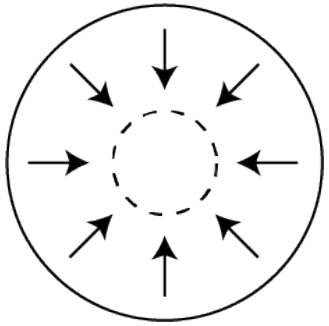
Heterogenous Space

Spatial strategies to vary social interaction

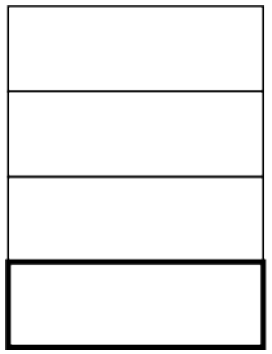
Homogenous space
Early space civilization
(short-term)



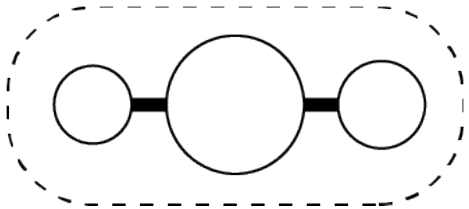
Central core



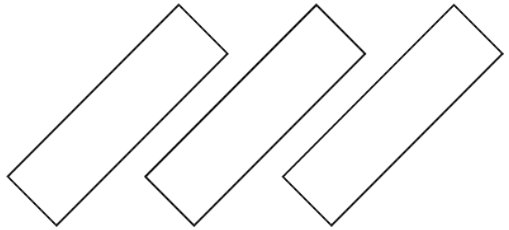
Centralized views



Uniform configuration

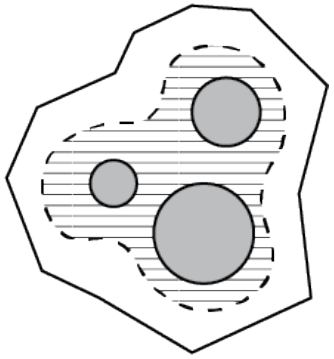


Corridors

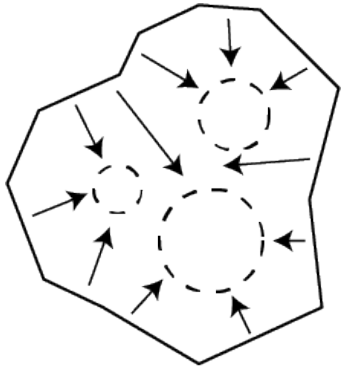


Repetitive structure

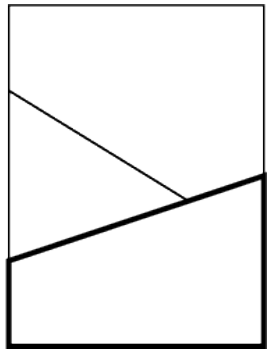
Heterogeneous space
Next generation
(long-term)



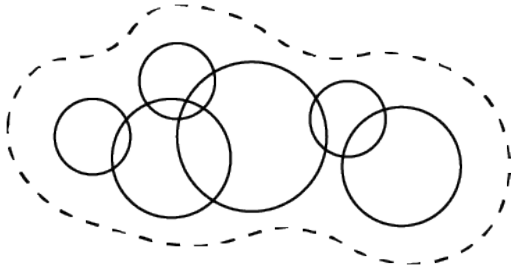
Multiple cores



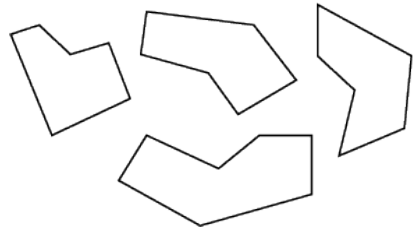
Varying views



Unique configuration



Intersection of spaces



Non-repetitive structure

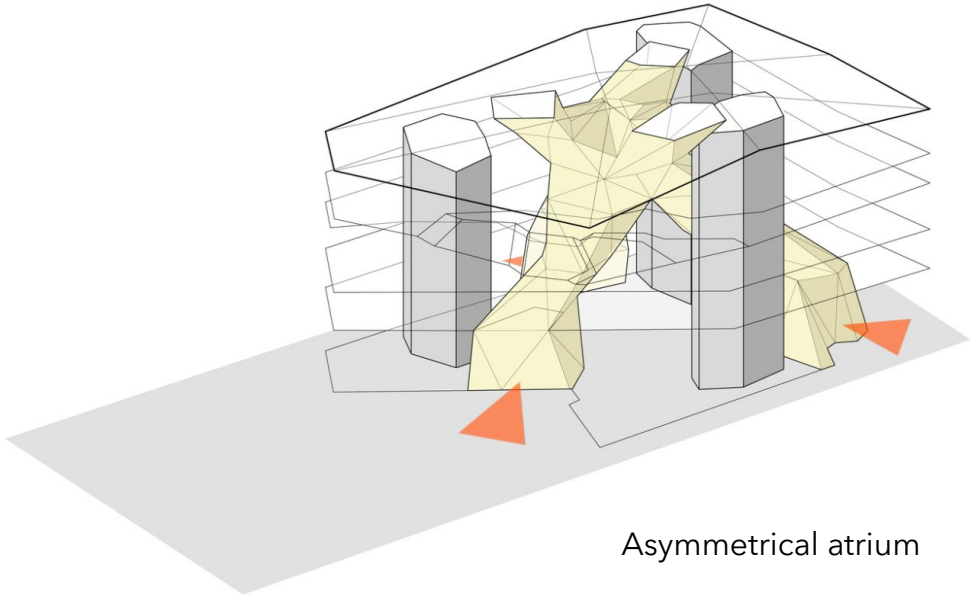
Program requirements

	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																


Design

Reference_Intersecting Atriums

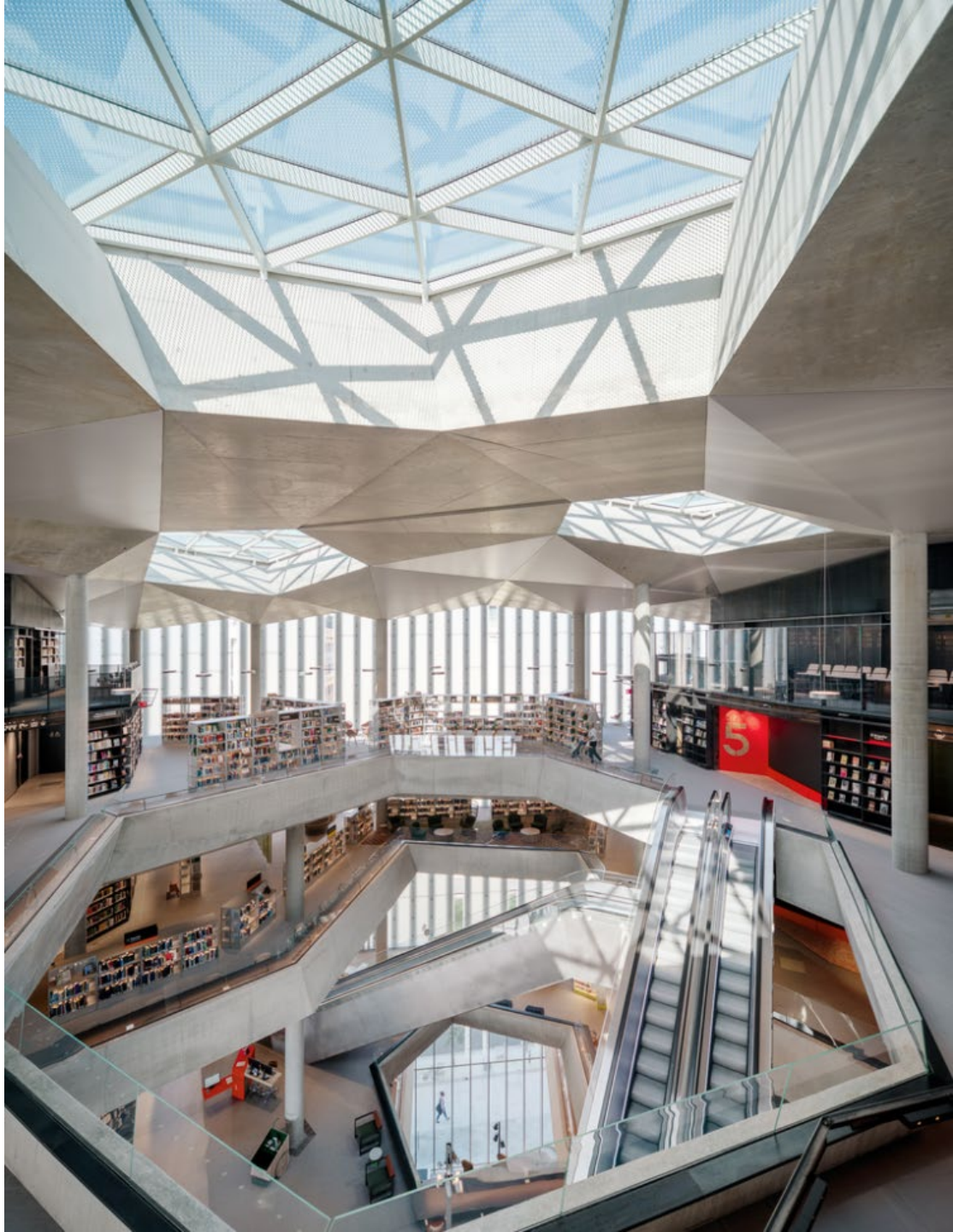
"Everyone's living room". Deichman Bjørvika, Oslo.



Asymmetrical atrium

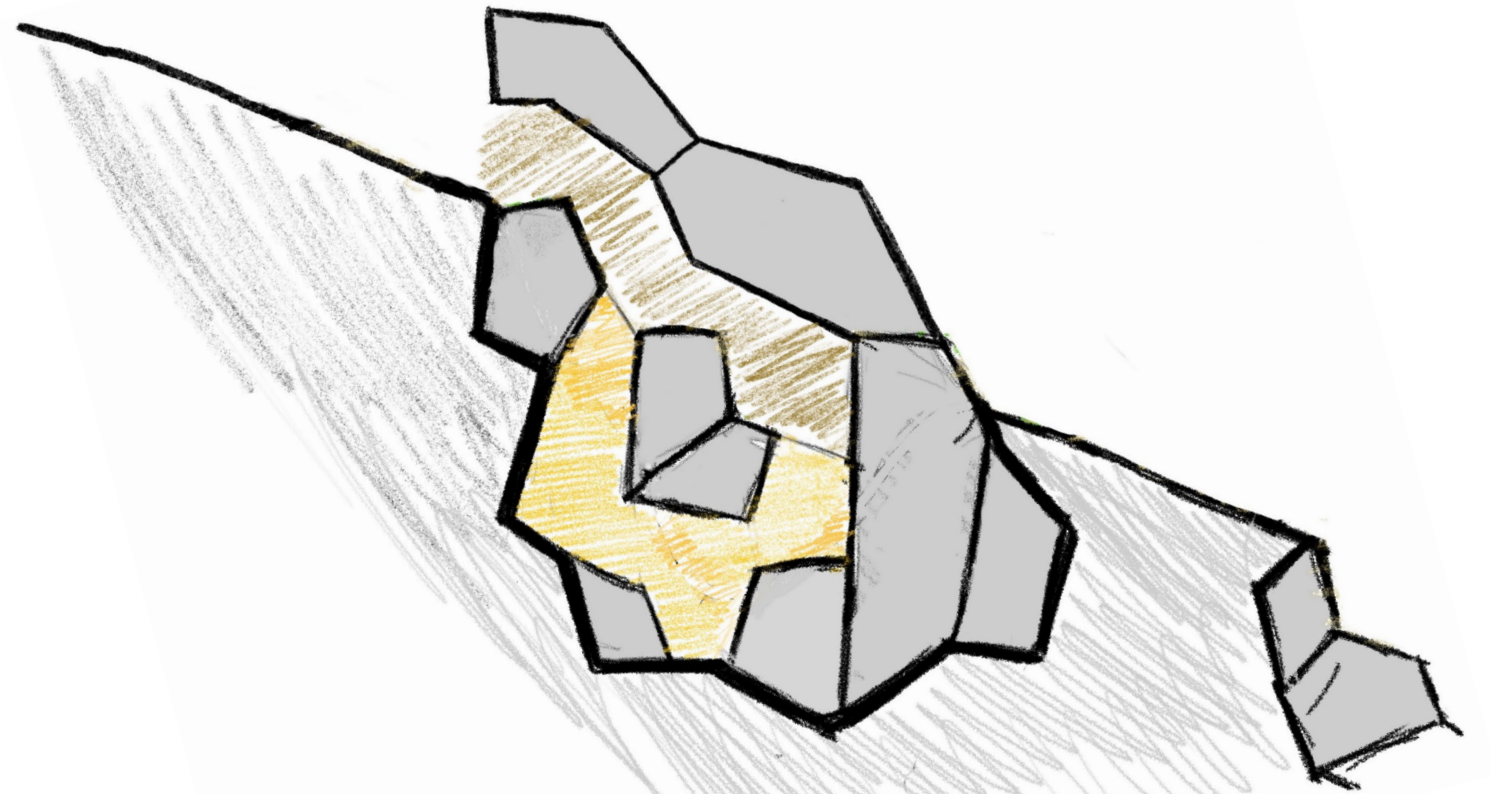
Pocket spaces

Varying vantage points



Sketch

Layered atriums



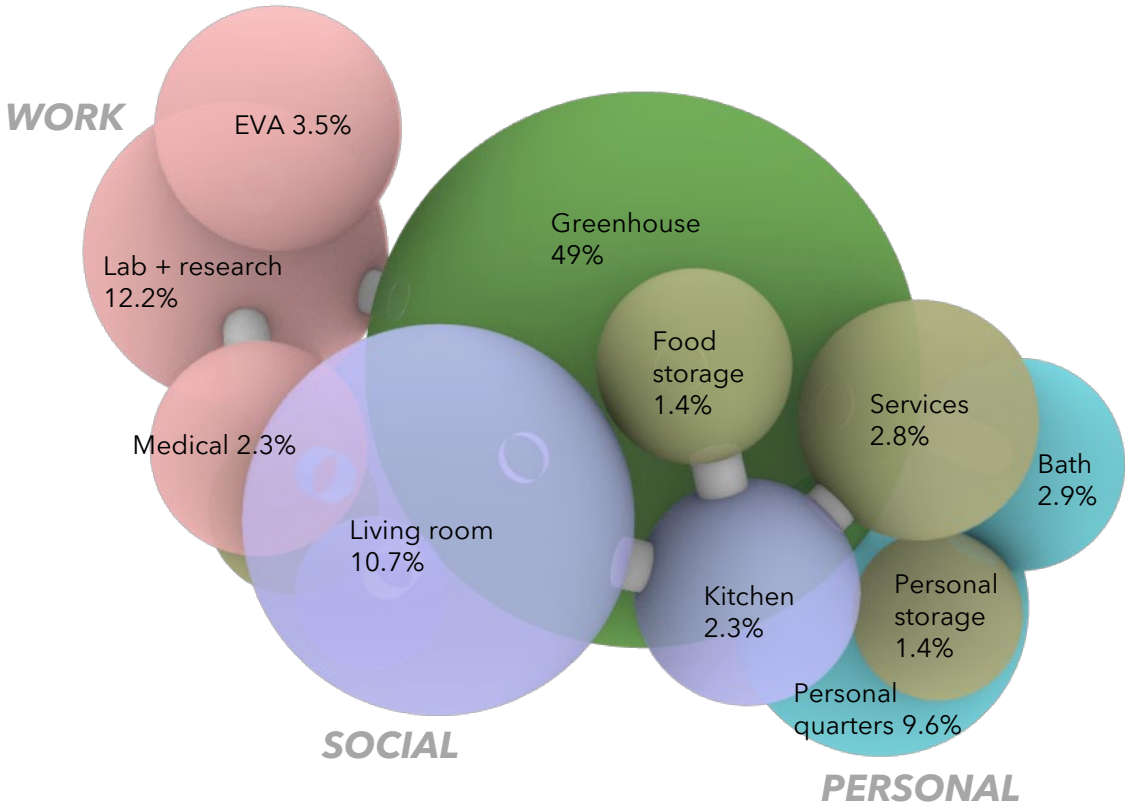
Exterior atrium (between envelope)

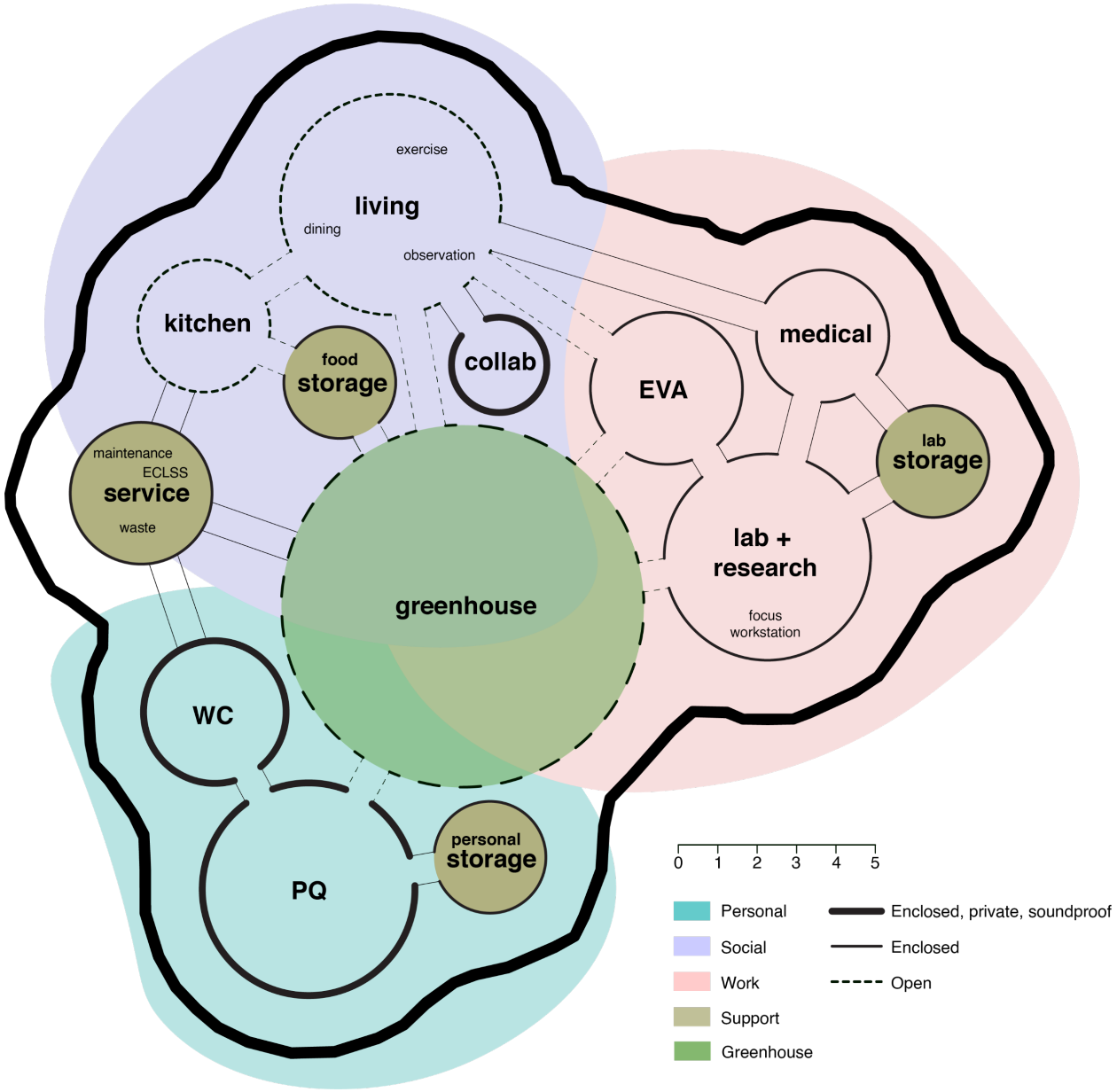
Interior atrium

5m

Program Distribution

Functional connection and basic proportion

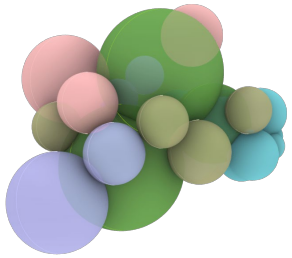


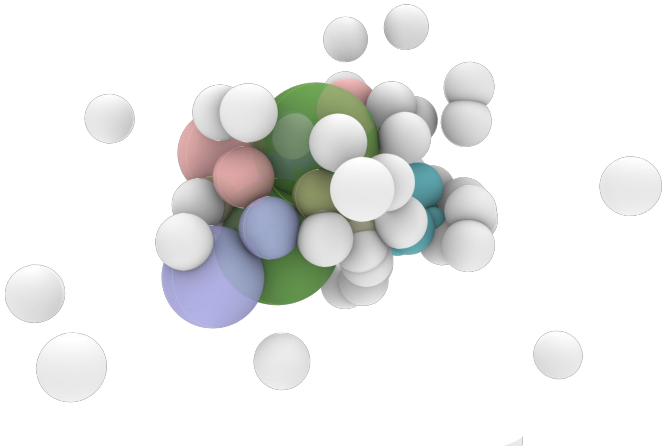


Greenhouse as atrium,
connecting 3 functional cores

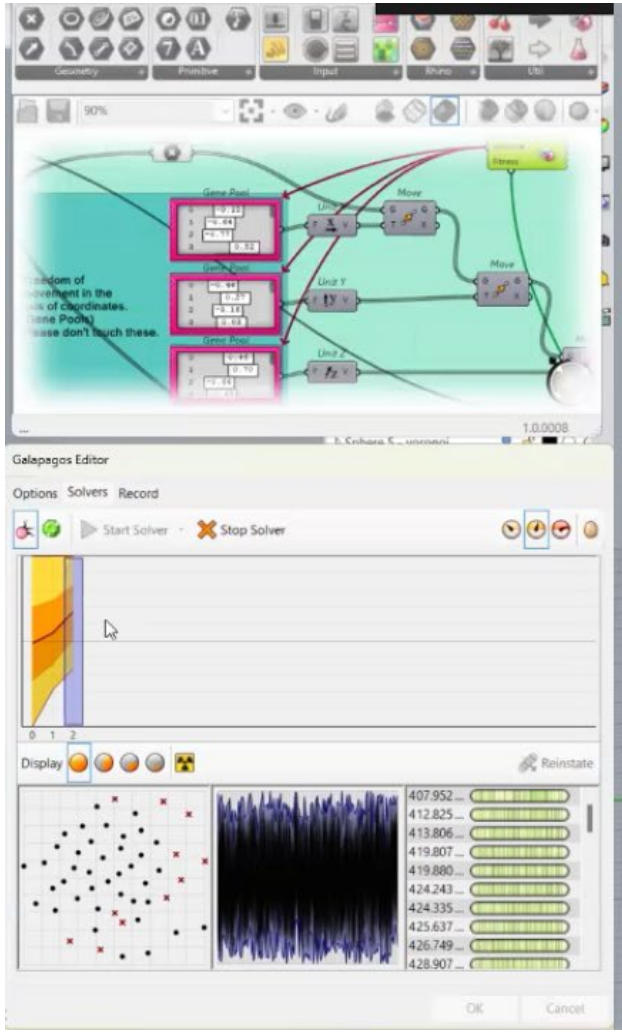
Form Optimization Process

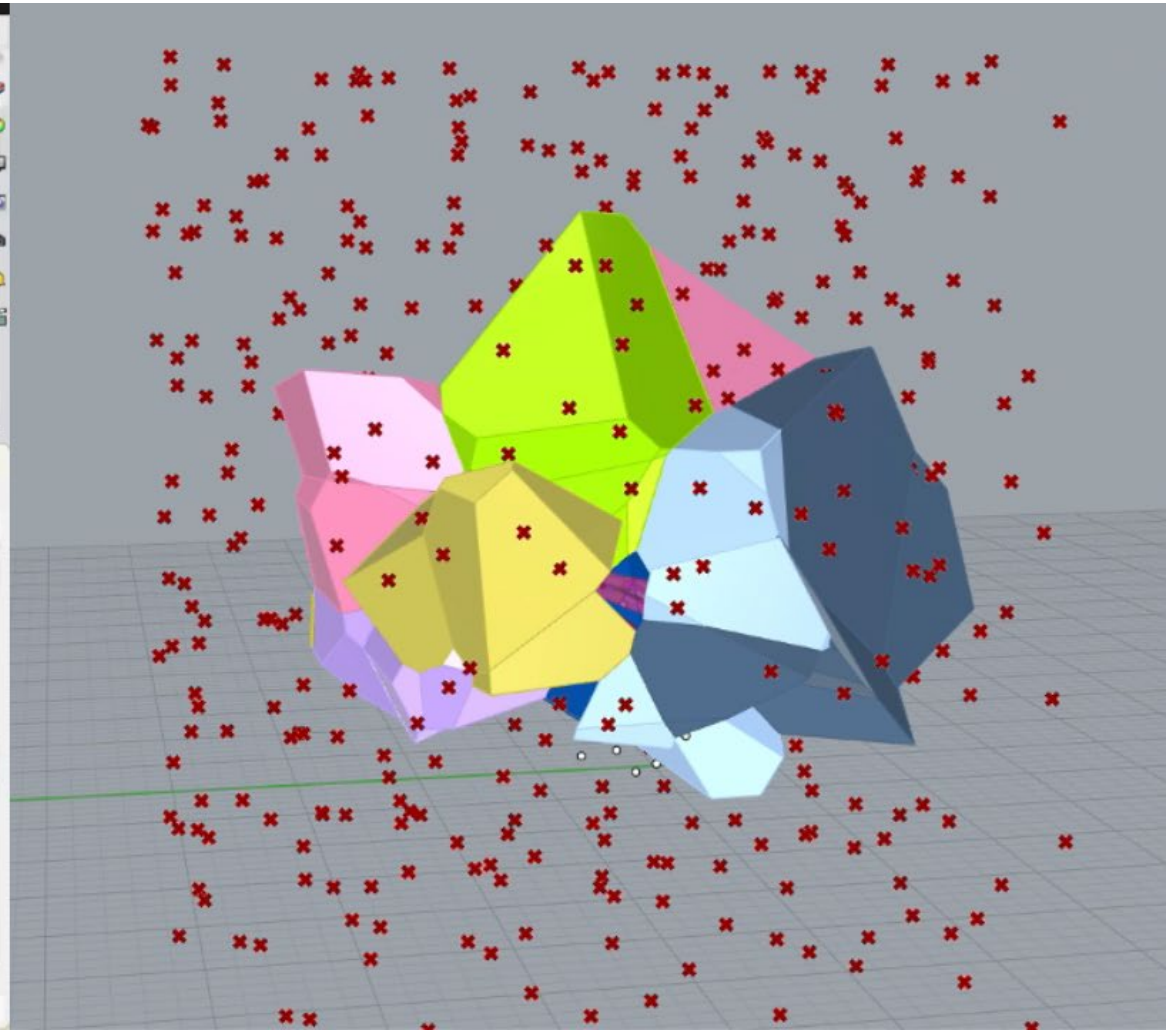
Sphere to Voronoi volume optimization using Galapagos





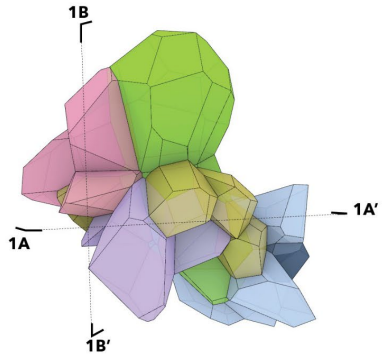
Script to optimize Voronoi control points

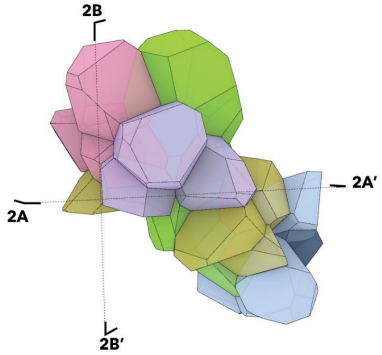


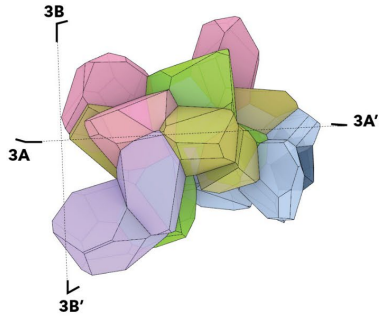


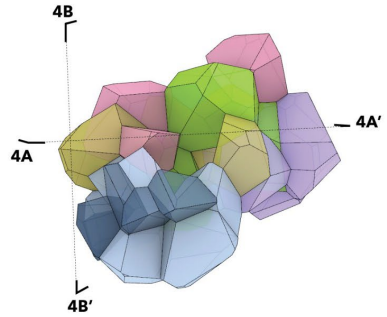
https://youtu.be/oiQ0B0b-MYM

MASSING

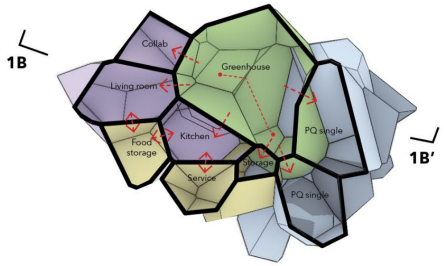


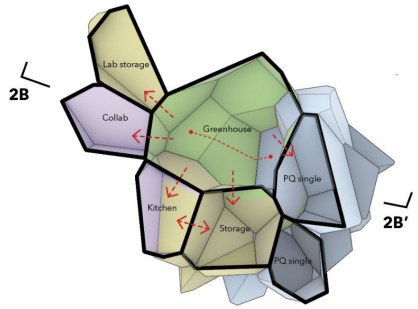


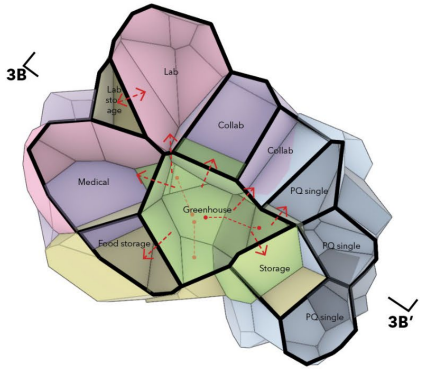


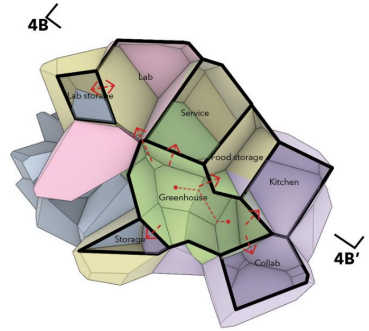


PLAN
A-A′



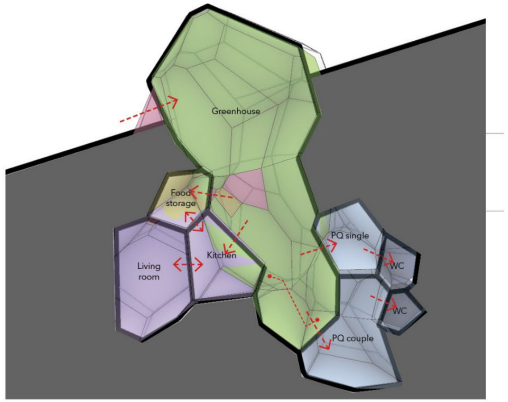




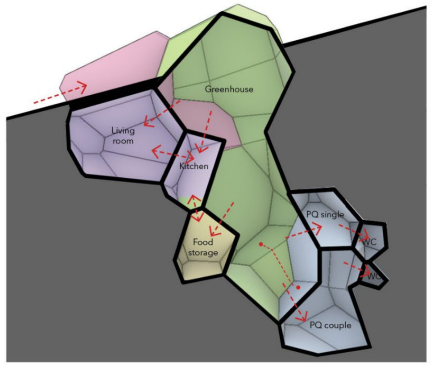


SECTION
B-B′

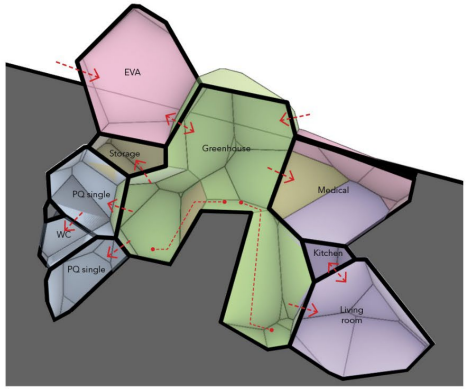
5m



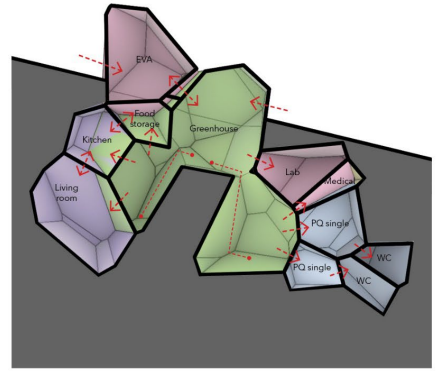
ITERATION 1



ITERATION 2



ITERATION 3

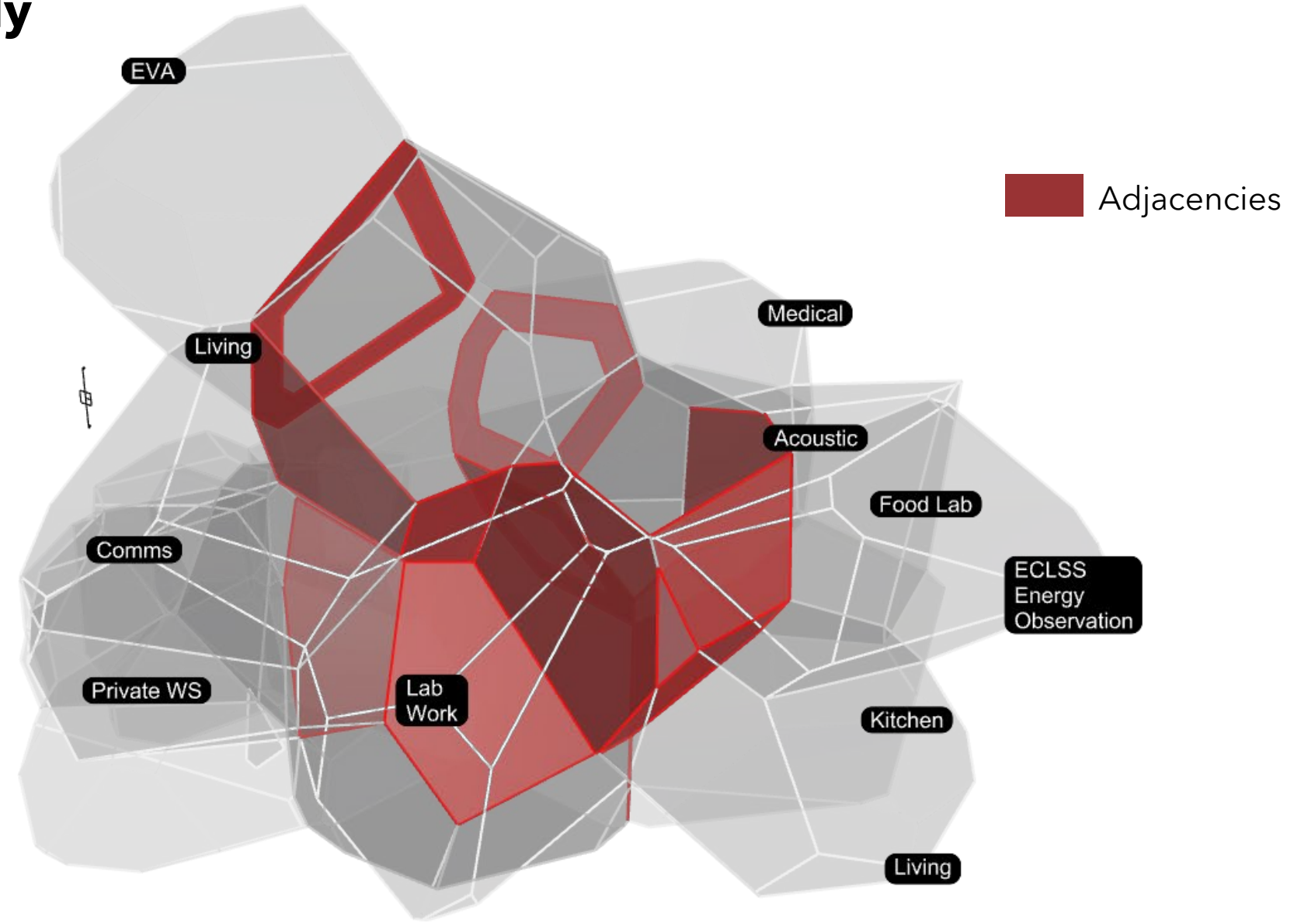


ITERATION 4

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

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

Circulation Study



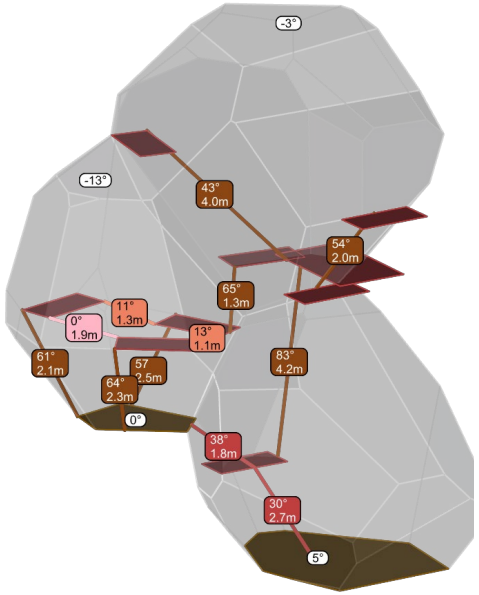
Atrium Circulation Study

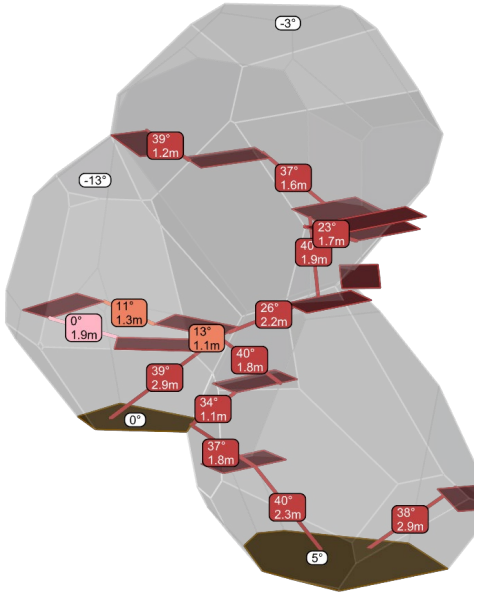
0-10° Platform (Normal walking) / ramp (comfortable)

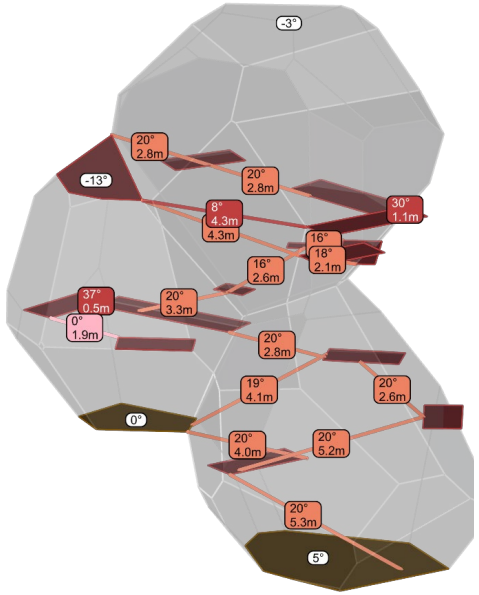
10-20° Ramp (reasonable)

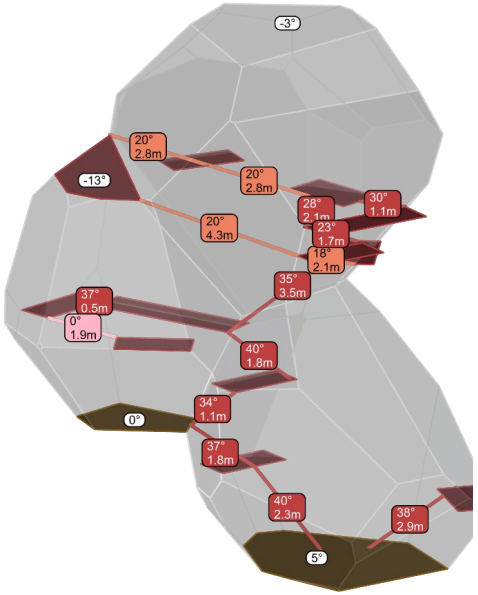
20-40° Stairs

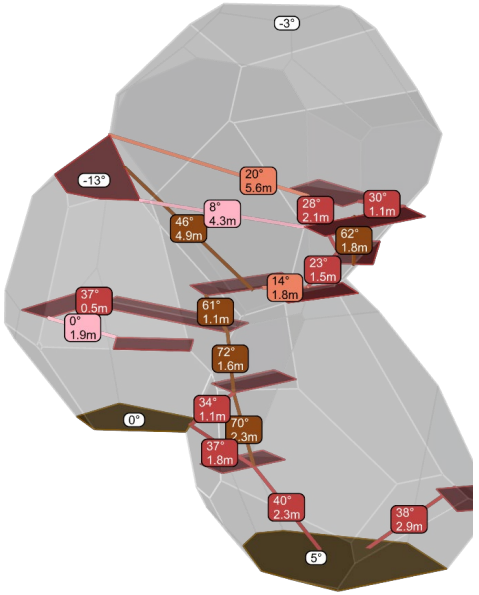
>40° Steep stairs / ladder











Moon condition

2-5° Walking/loping (normal)

10-20° Ramp

30-40° Maximum ramp / stairs

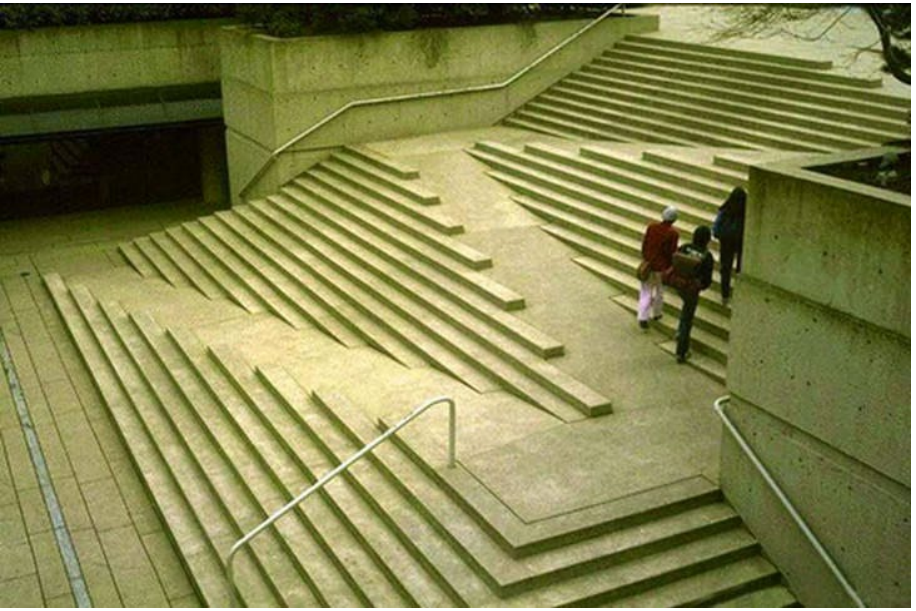
Reference_Ramp/stairs

0-10° Platform (Normal walking) / ramp (comfortable)

10-20° Ramp (reasonable)

20-40° Stairs

>40° Steep stairs / ladder



On earth - ramp/stairs combination

On earth - ramp/stairs reference, Ewha Women's University, Korea

Reference_Steep stairs

MARS Ice House

0-10° Platform (Normal walking) / ramp (comfortable)

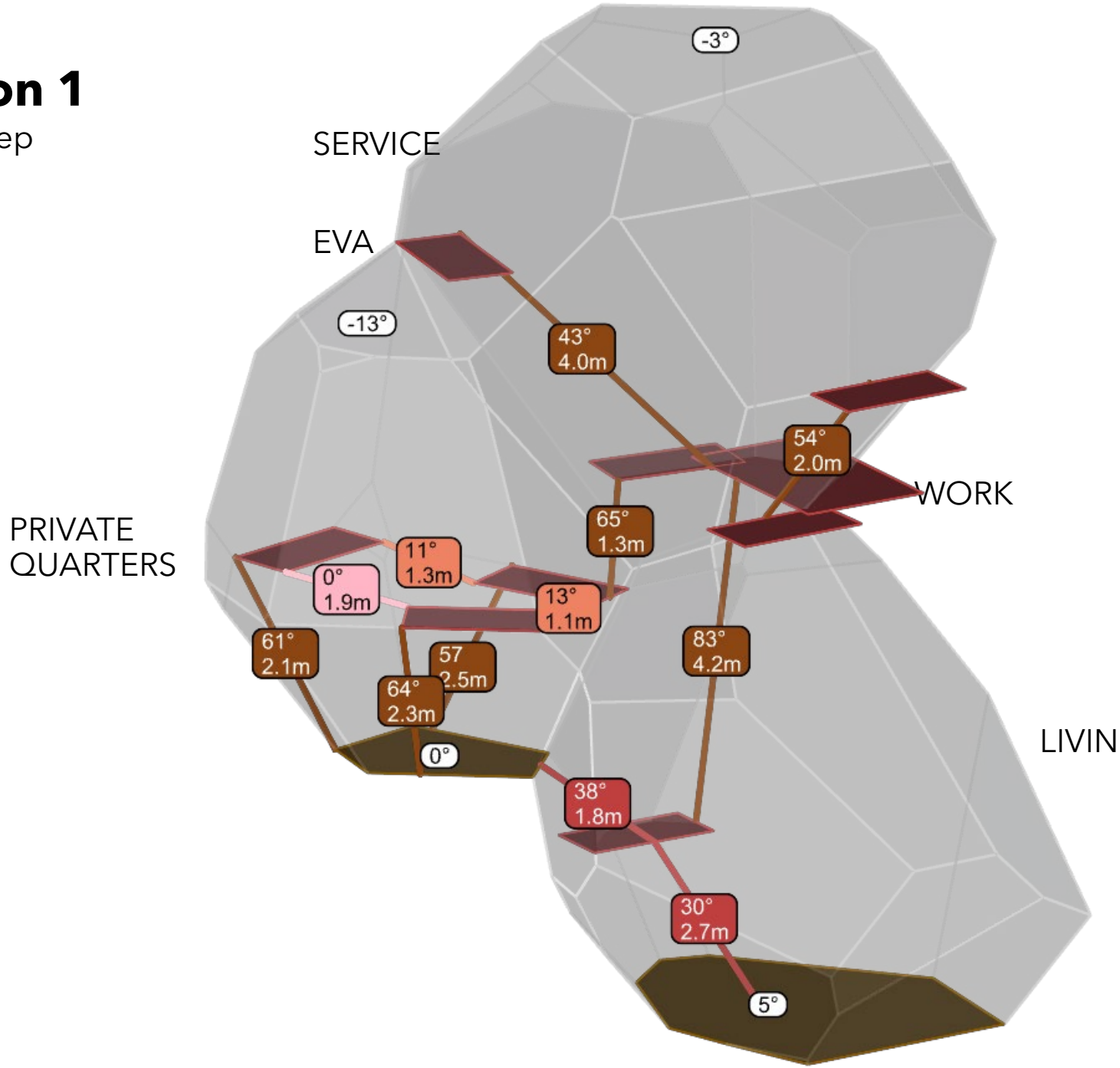
10-20° Ramp (reasonable)

20-40° Stairs

>40° Steep stairs / ladder

Atrium Iteration 1

Shortest distance / steep



0-10° Platform (Normal walking) / ramp (comfortable)

10-20° Ramp (reasonable)

20-40° Stairs

>40° Steep stairs / ladder

+ Shortest distance

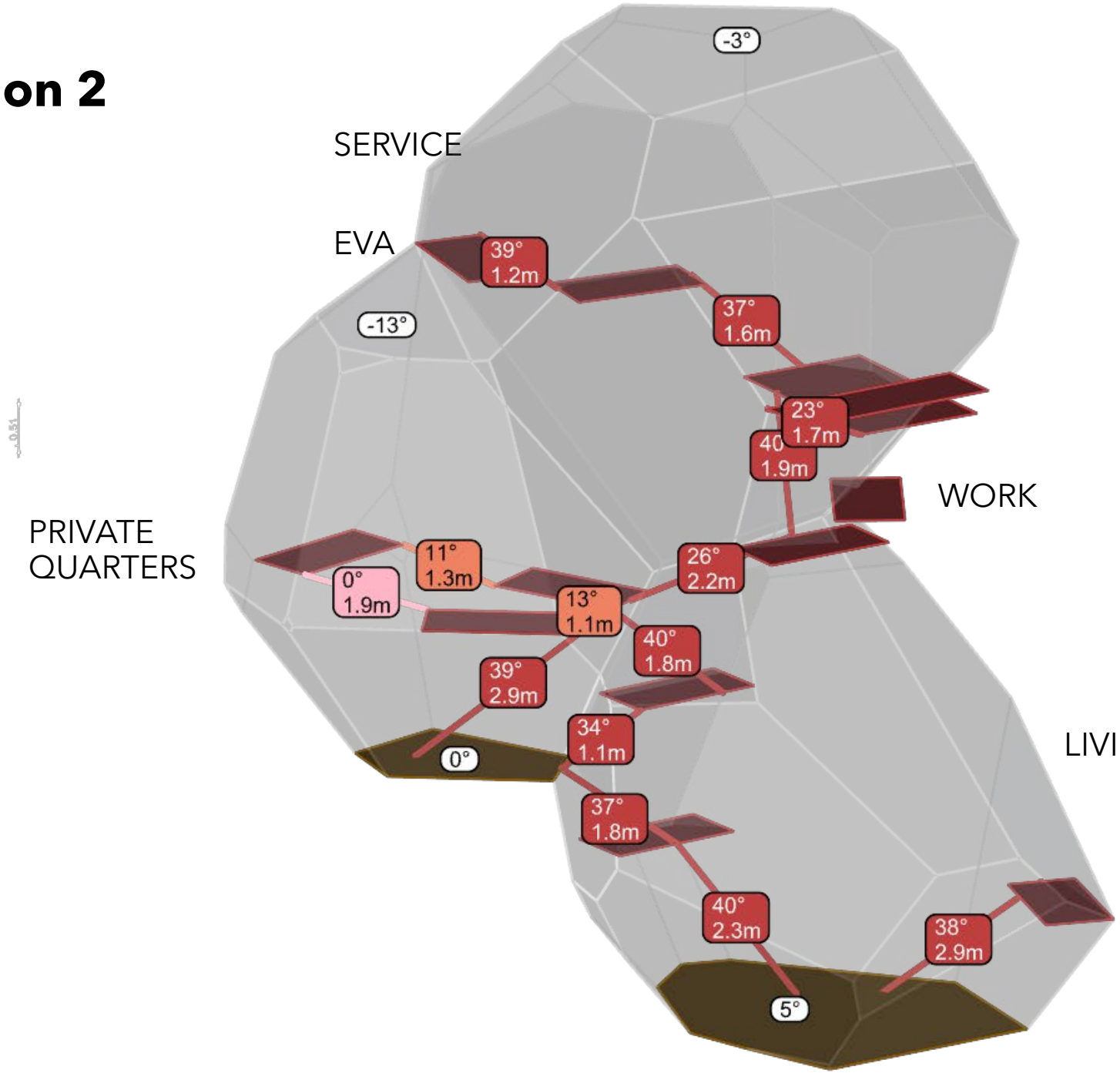
+ Less obstruction of views

+ Private quarters separated

- Steep: not comfortable

Atrium Iteration 2

Stairs



0-10° Platform (Normal walking) / ramp (comfortable)

10-20° Ramp (reasonable)

20-40° Stairs

>40° Steep stairs / ladder

+ Similar sizes

+ Less obstruction of views

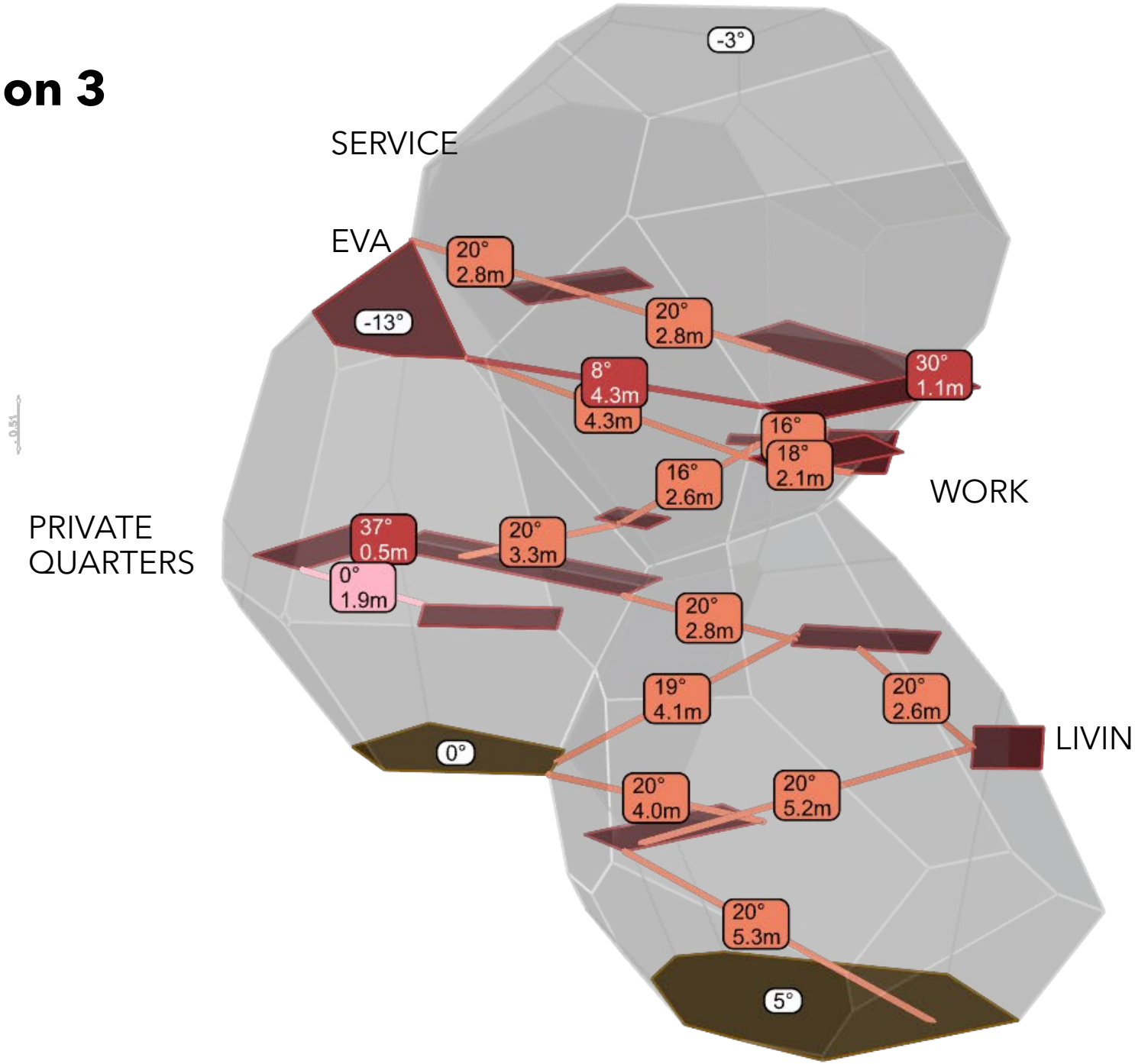
+ Framing the atrium

- Going around → long distance

- Private quarters in main path

Atrium Iteration 3

Ramp



0-10° Platform (Normal walking) / ramp (comfortable)

10-20° Ramp (reasonable)

20-40° Stairs

>40° Steep stairs / ladder

+ Ramp / less steep stairs

- More obstruction of views

- Need long span cantilevers

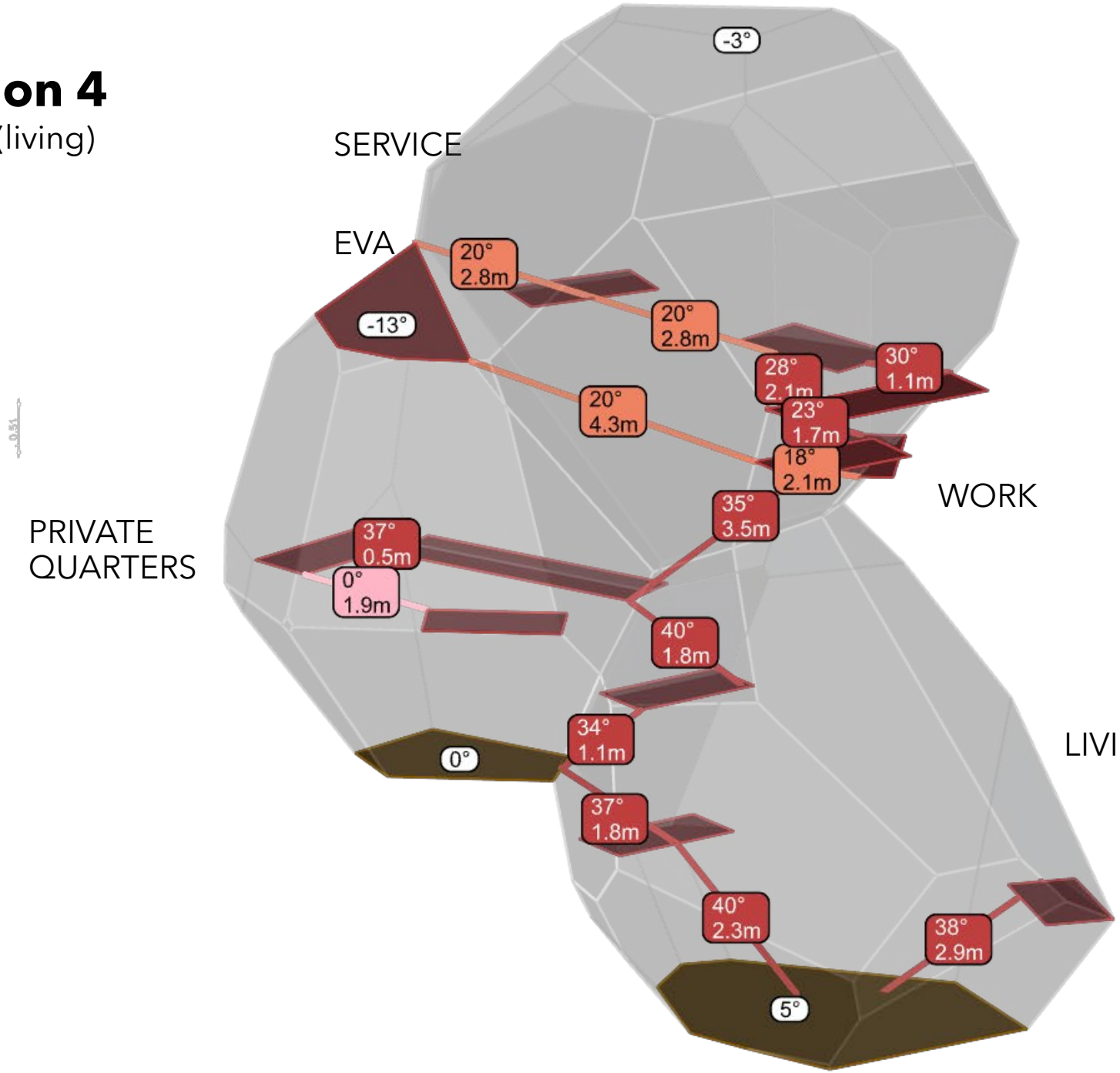
- Going around → long distance

- Private quarters separated

- Hard to get to social area

Atrium Iteration 4

Ramp (work) + stairs (living)



0-10° Platform (Normal walking) / ramp (comfortable)

10-20° Ramp (reasonable)

20-40° Stairs

>40° Steep stairs / ladder

+ Combination of circulation

+ Adjusted views

+ Mostly comfortable

+ Private quarters mostly separated

- Work in main path

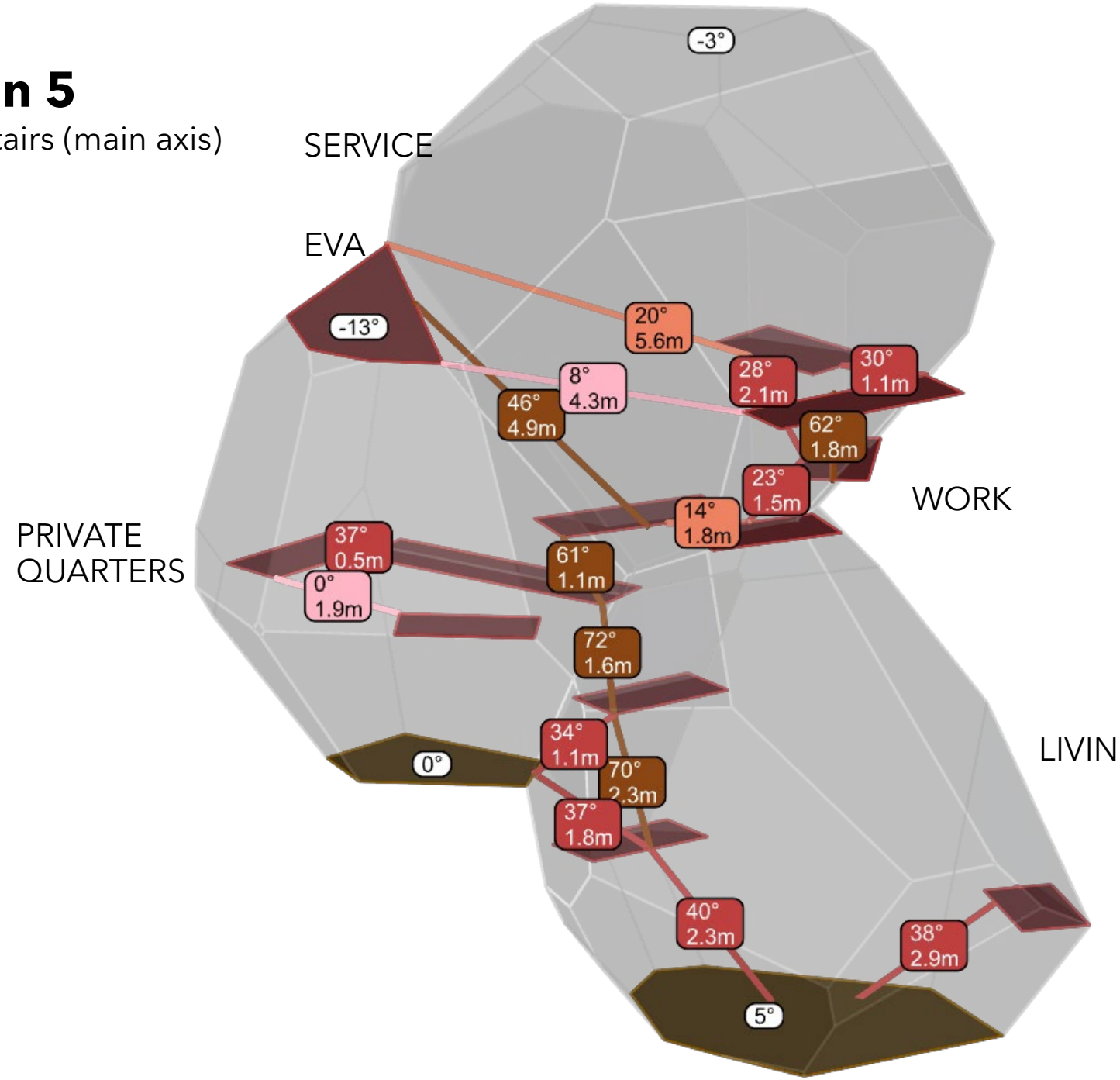
- Social area is separated

- Still need long span cantilevers

- Still going around → long distance

Atrium Iteration 5

Combination + steep stairs (main axis)



0-10° Platform (Normal walking) / ramp (comfortable)

10-20° Ramp (reasonable)

20-40° Stairs

>40° Steep stairs / ladder

+ Combination of circulation

+ Many options → variation of approaches & meeting spaces

+ Work & private areas separated

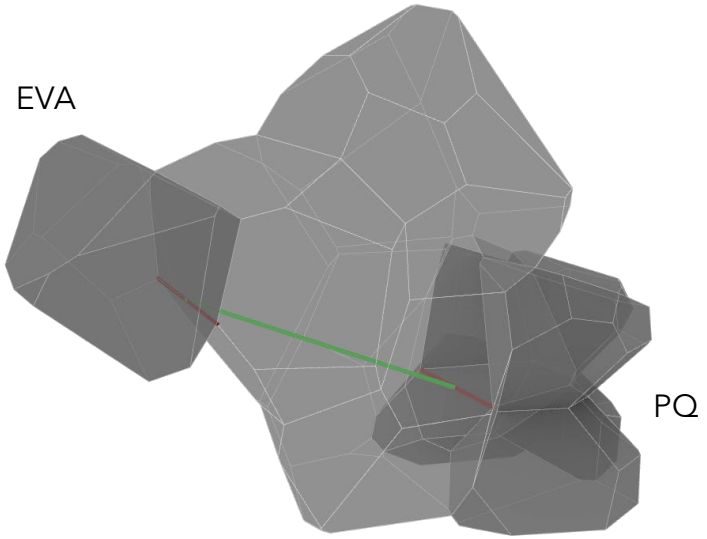
- Social areas not fully integrated with main path

- Steep stairs on main axis

- Many options → obstruct views

Paths of users

Time	Commander	Room	Connection	Medic	Room	Connection	EVA Specialist	Room	Connection
06:00	Hygiene & breakfast (1h)	PQ			PQ			PQ	
06:30									
07:00	System checks & safety update (1.5h)	Maintenance	slow						
07:30									
08:00									
08:30	EVA & Mission planning (1.5h)	Workstation	direct	Hygiene & breakfast (1.5h)			Hygiene & breakfast (1.5h)		
09:00									
09:30									
10:00	Reports & coordination with Earth base (1.5h)	Comms	direct	Medical checks (1h)	Medic	slow. Direct if emergency (alternative path)	Reports & coordination with Earth base (1.5h)	Comms	slow
10:30									
11:00				Gardening (0.5h)	Atrium	slow			
11:30	Lunch prep (1h)	Kitchen	direct	Medical research & analysis (1.5h)	Lab	slow	EVA prep & rover preparation (1.5h)	EVA	direct
12:00									
12:30	Piano practice (0.5h)	Acoustic room	slow						
13:00	Lunch (1h)	Living	slow/direct	Lunch (1h)	Living	slow	Lunch (1h)	Living	direct
13:30									
14:00	EVA prep (1h)	PQ	slow	Emergency protocol (1.5h)	Workstation	slow	Habitat maintenance (1.5h)	Atrium	slow
14:30		EVA	fast					Maintenance	slow
15:00	EVA (2h)	EVA						Atrium	slow
15:30				Exercise (1.5h)	Living	slow	Exercise (1.5h)	Living	slow
16:00									
16:30		PQ	slow						
17:00	Exercise (1.5h)	Living		Dinner prep (1.5h)	Kitchen	direct	Dinner prep (1.5h)	Kitchen	slow
17:30									
18:00									
18:30	Dinner (1.5h)	Living	slow/direct	Dinner (1.5h)	Living	direct	Dinner (1.5h)	Living	direct
19:00									
19:30									
20:00	Band rehearsal (1.5h)	Acoustic room	slow (high volume)	Band rehearsal (1.5h)	Acoustic room	slow	Band rehearsal (1.5h)	Acoustic room	slow
20:30									
21:00									
21:30	Stargazing and journaling (1.5h)	Observation	slow	Gardening and movie (1.5h)	Atrium	slow	Chess and movie (1.5h)	Living	slow
22:00									
22:30									
23:00	Sleep (7h) 23:00-06:00	PQ	slow	Sleep (9.5h) 23:00-08:30	PQ	slow	Personal research (1.5h)	PQ	slow
23:30									
00:00									
00:30							Sleep (8h) 00:30 - 08:30		
01:00									
01:30									



Threshold **Direct Path** **Indirect Path**

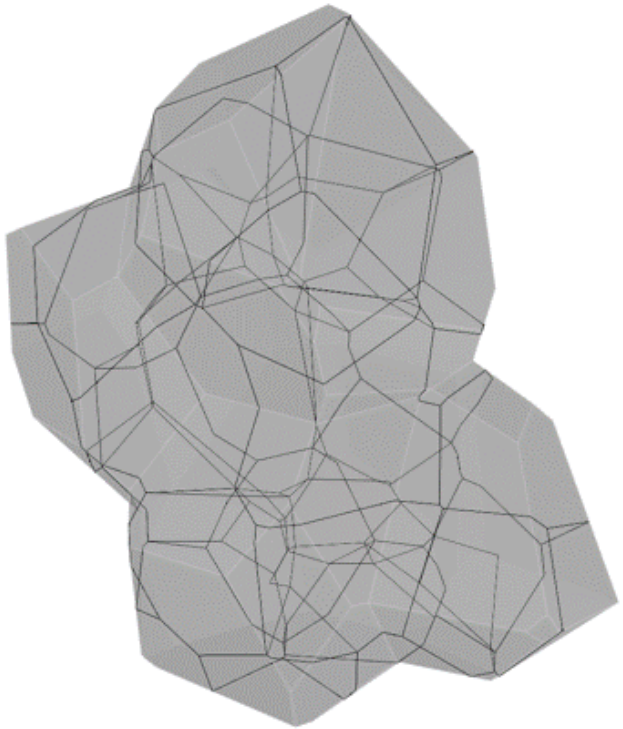
Private Quarters → Maintenance

- Slow movement
- Indirect path

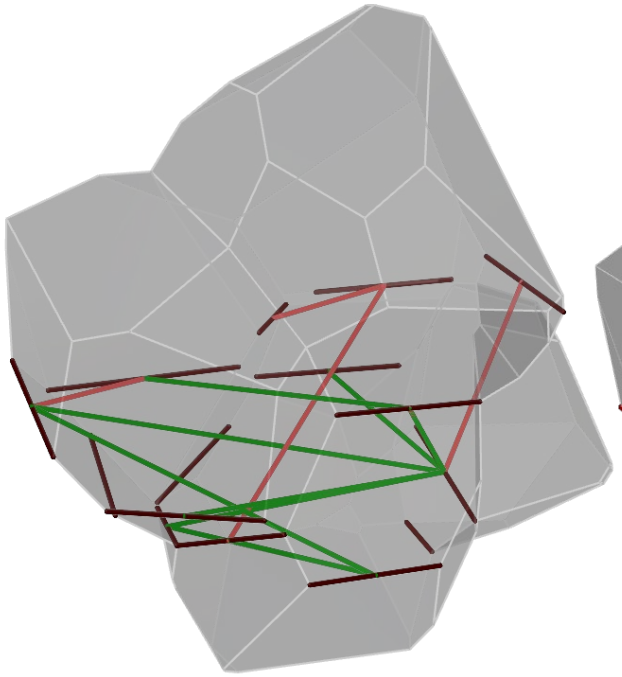
Computational method

Spatial and circulation study of atrium

Threshold **Direct Path** **Indirect Path**

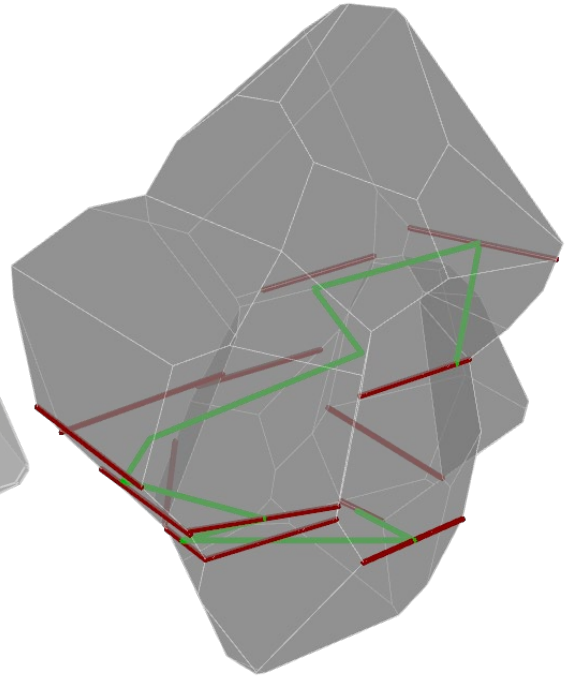


Variable porosity

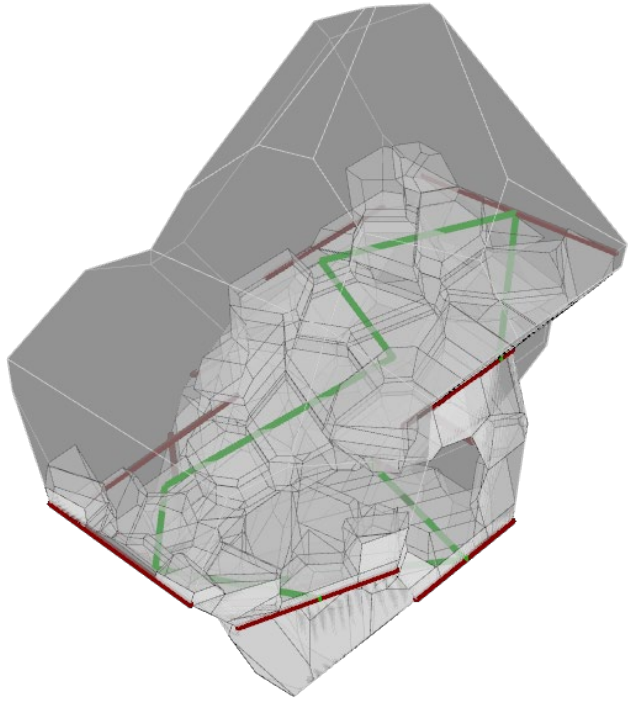


Route

Commander & Medic



Combined indirect path

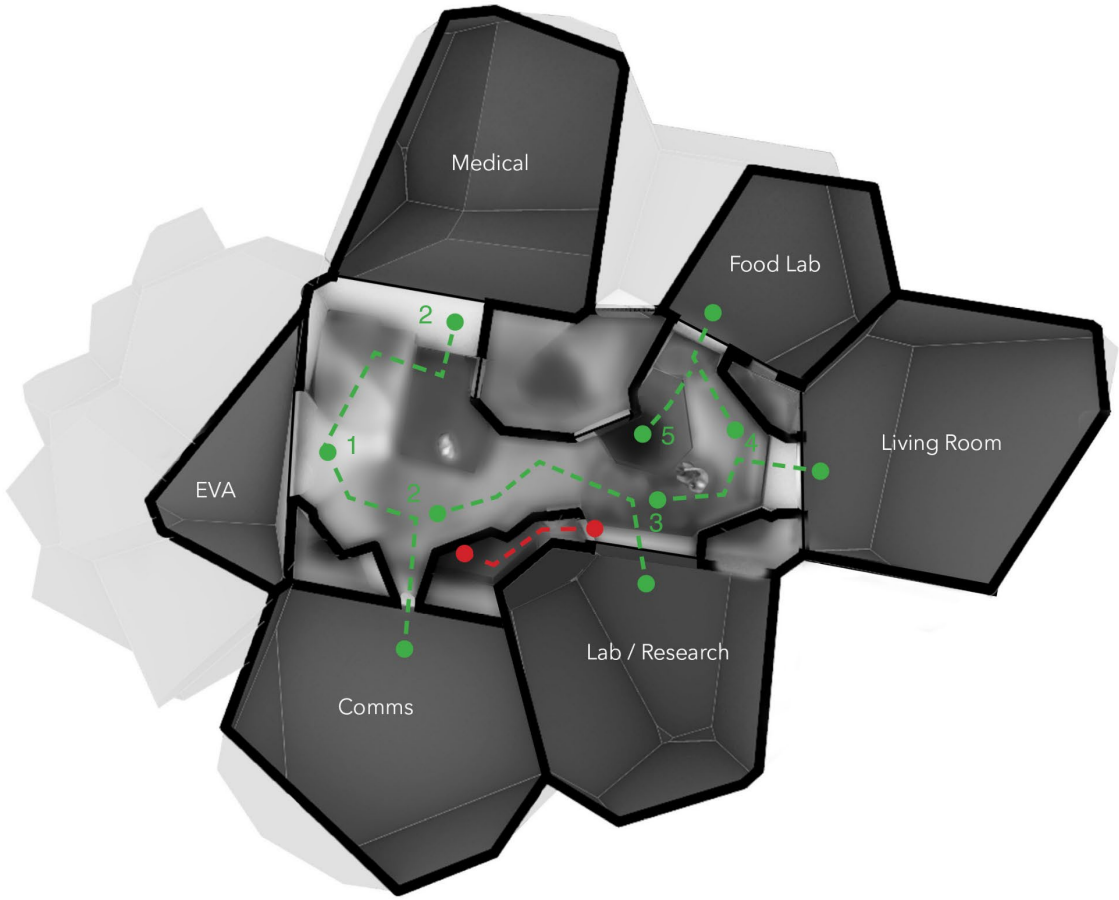


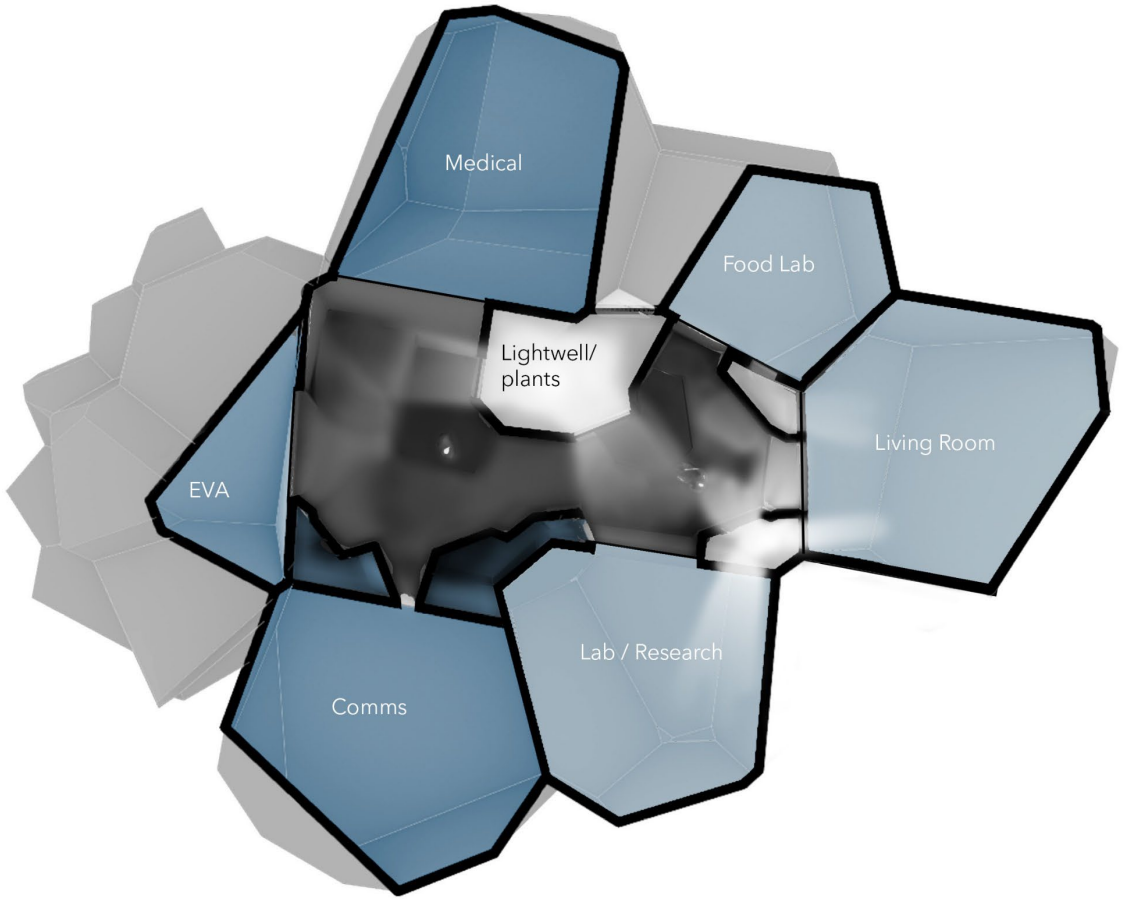
Volumes following path

Route & Function

Plan

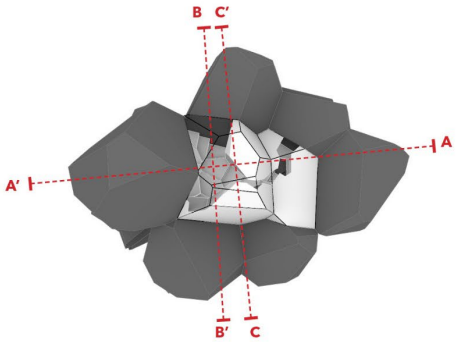
INTIMATE (1-2 p) | PERSONAL (1-3 p) | SOCIAL / SMALL GROUP (2-4p) | PUBLIC / LARGE GROUP (4-6 p)



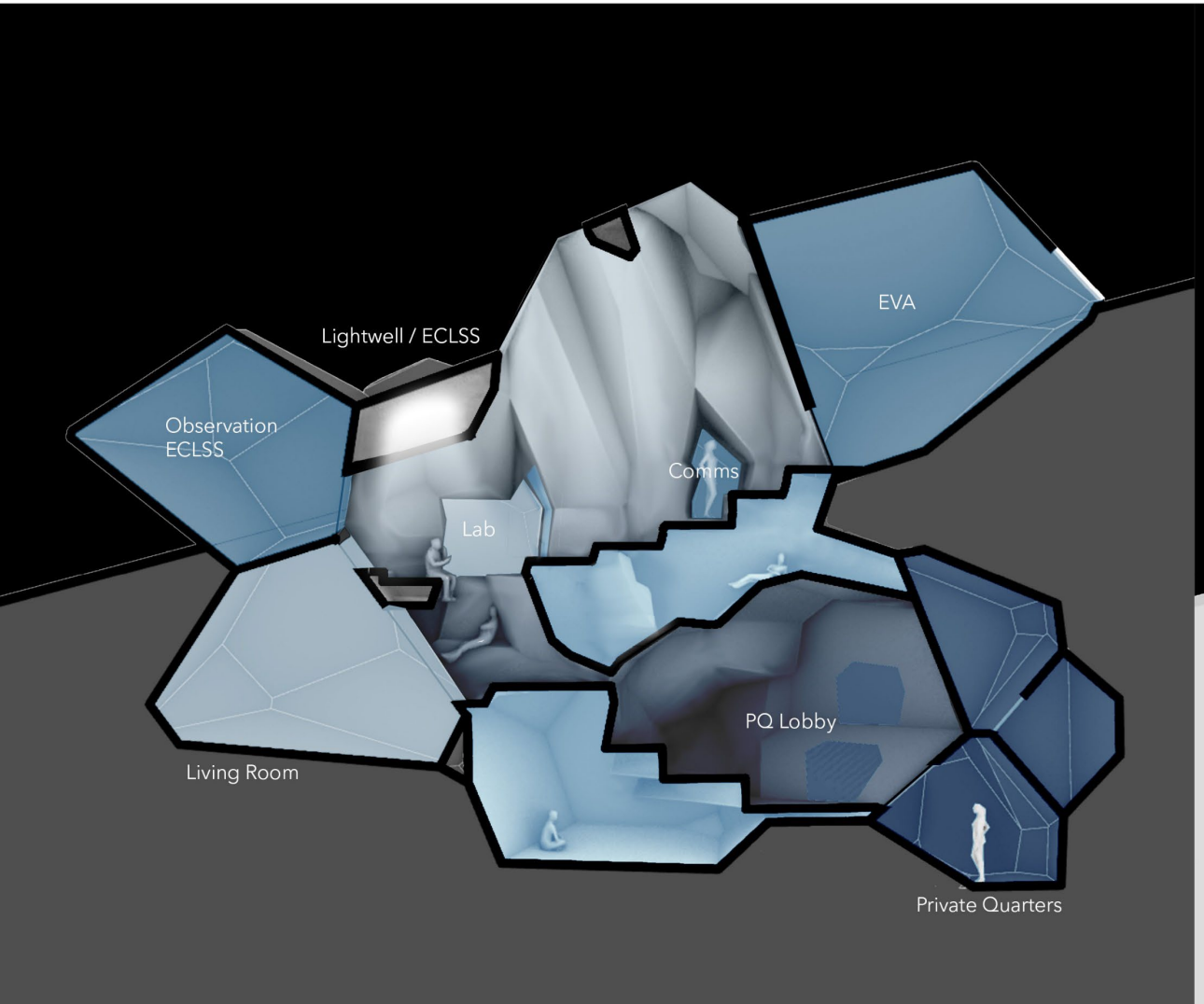


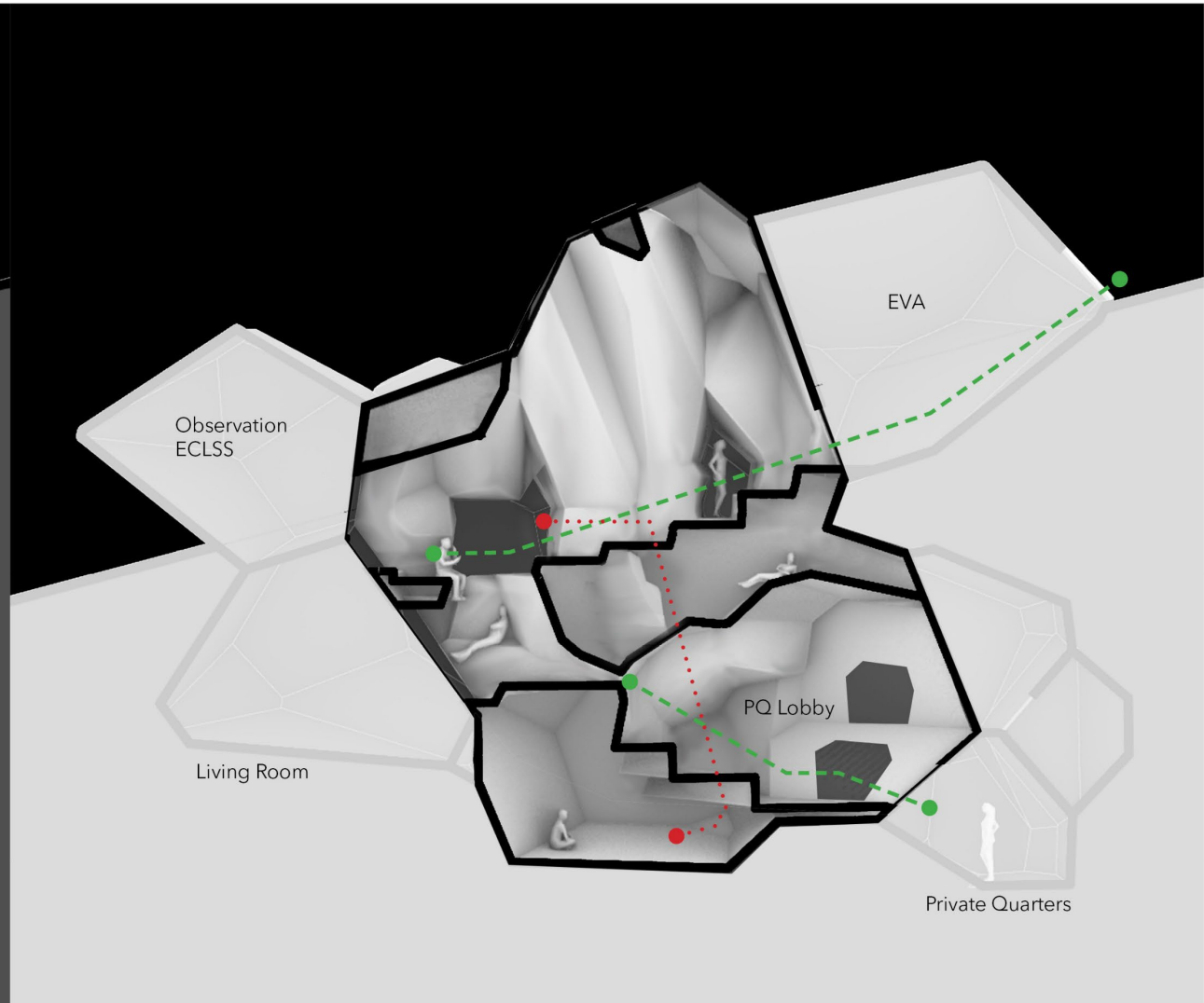
Route & Function

Section A-A’



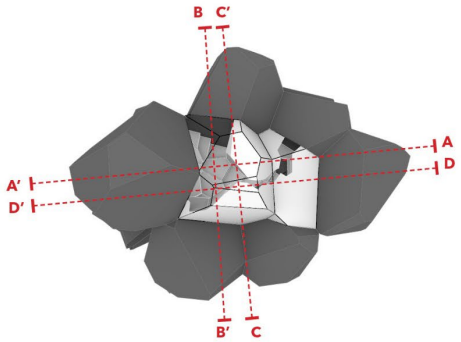
INTIMATE (1-2 p) | PERSONAL (1-3 p) | SOCIAL / SMALL GROUP (2-4p) | PUBLIC / LARGE GROUP (4-6 p)

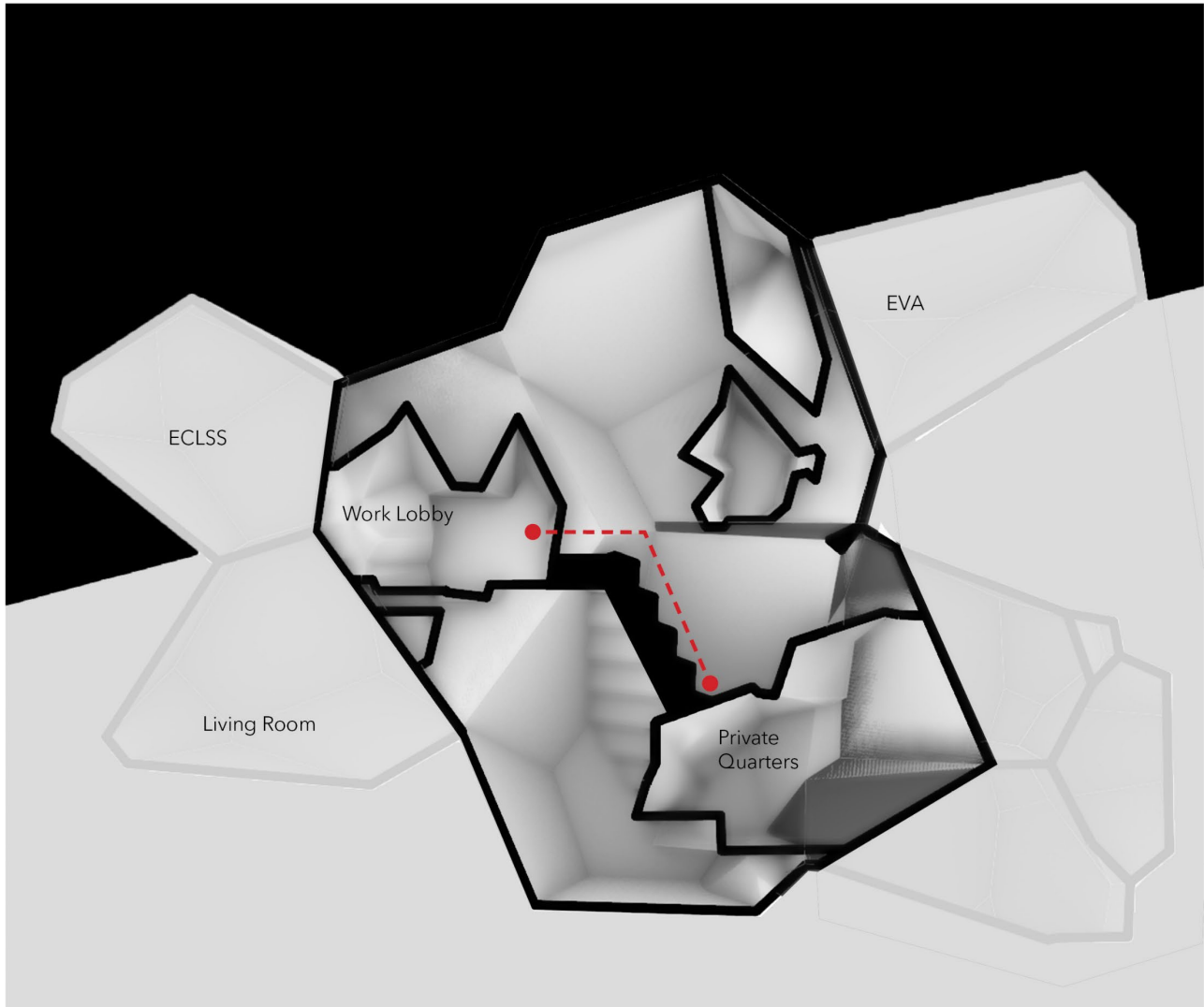




Route & Function

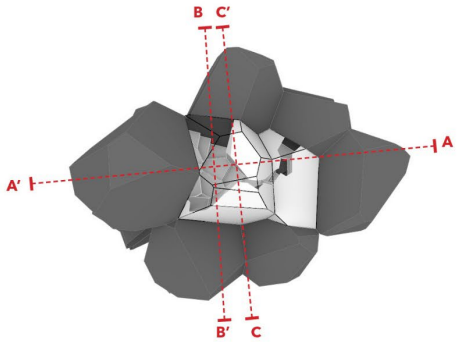
Section D-D’



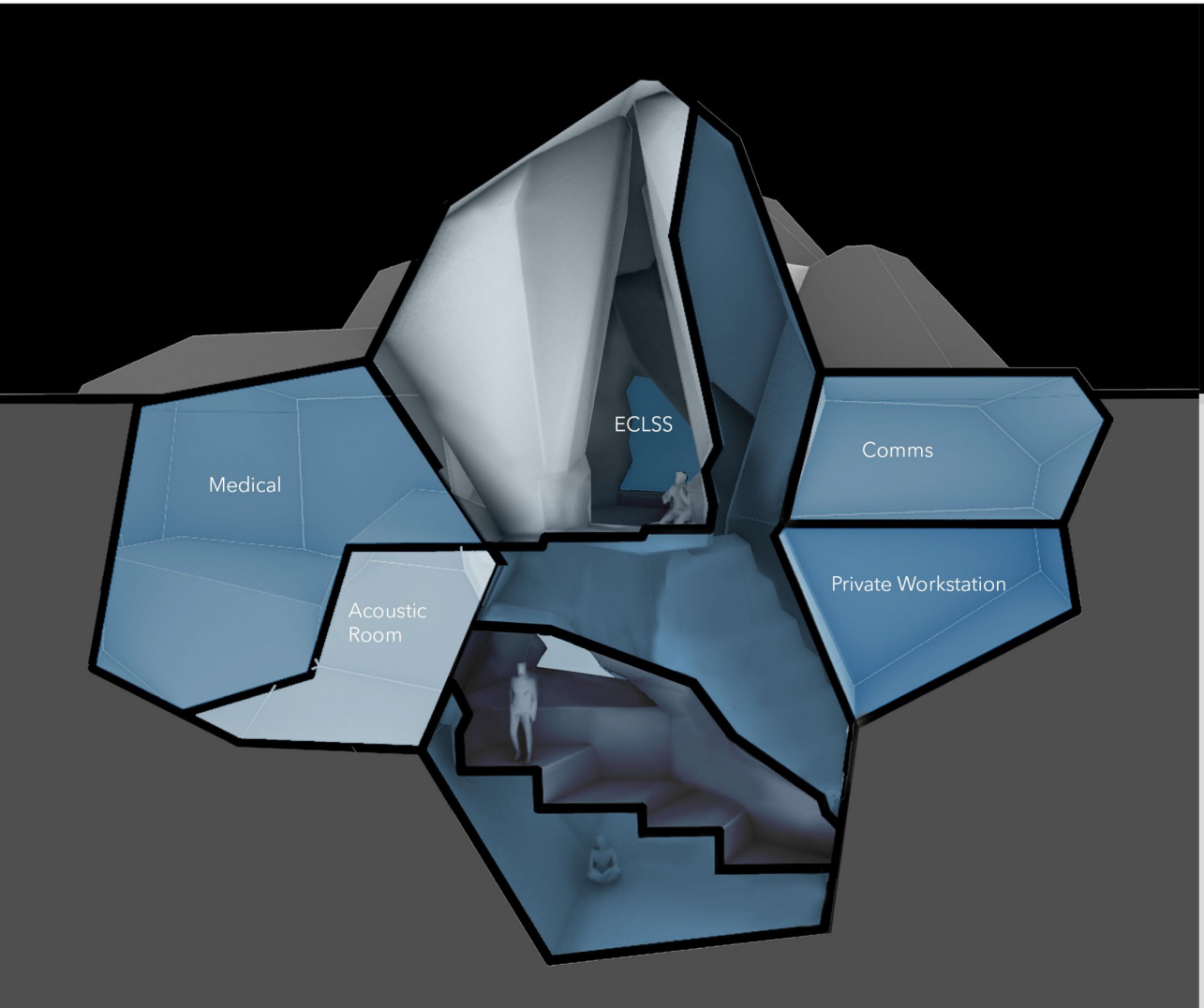


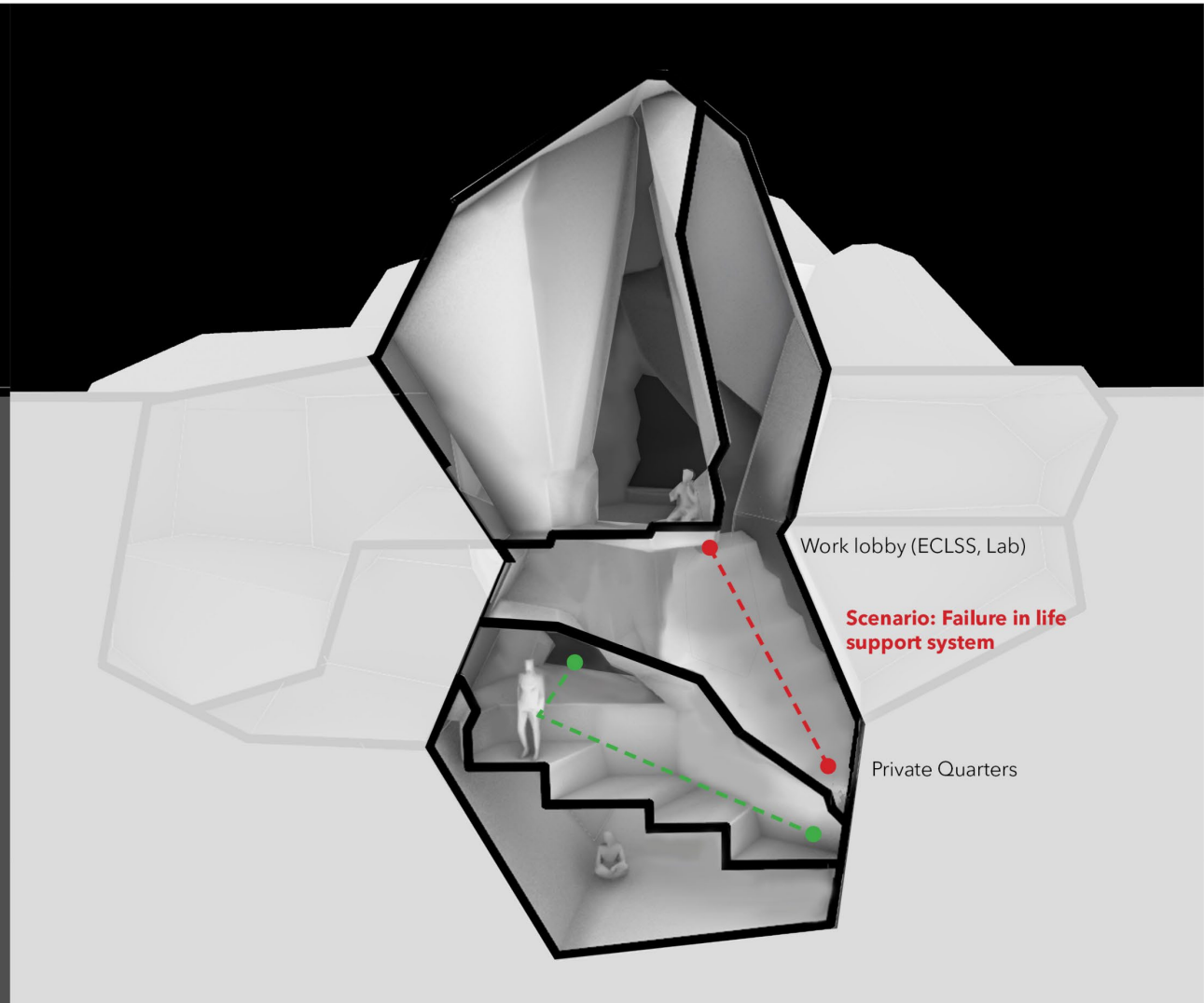
Route & Function

Section B-B’



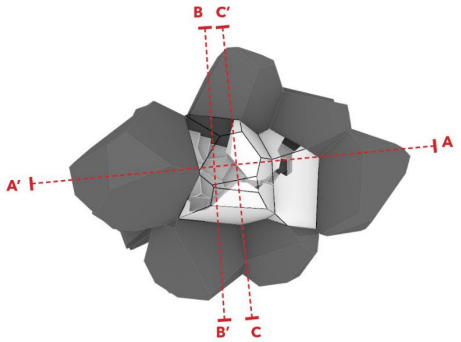
INTIMATE (1-2 p) | PERSONAL (1-3 p) | SOCIAL / SMALL GROUP (2-4p) | PUBLIC / LARGE GROUP (4-6 p)



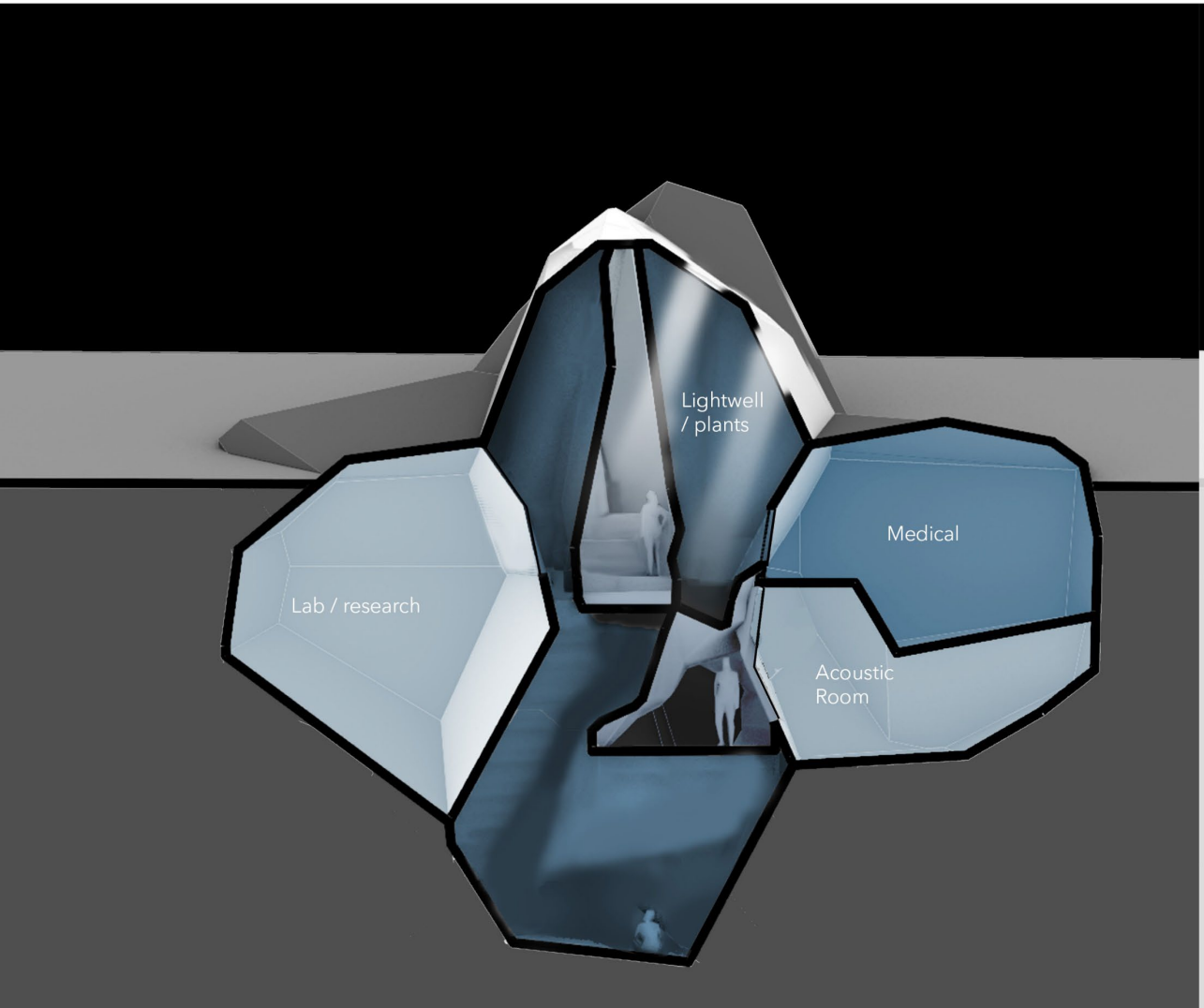


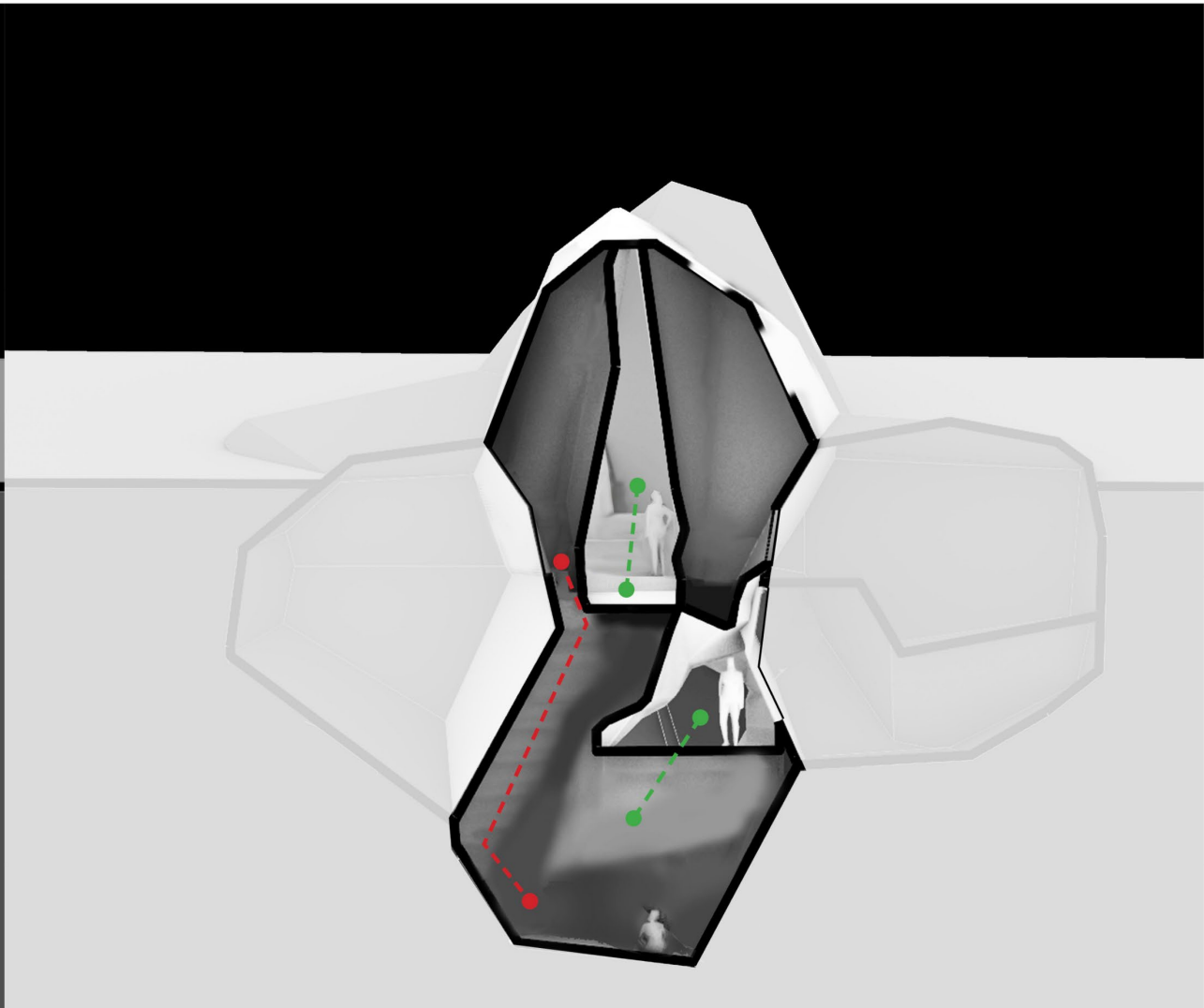
Route & Function

Section C-C’



INTIMATE (1-2 p) | PERSONAL (1-3 p) | SOCIAL / SMALL GROUP (2-4p) | PUBLIC / LARGE GROUP (4-6 p)

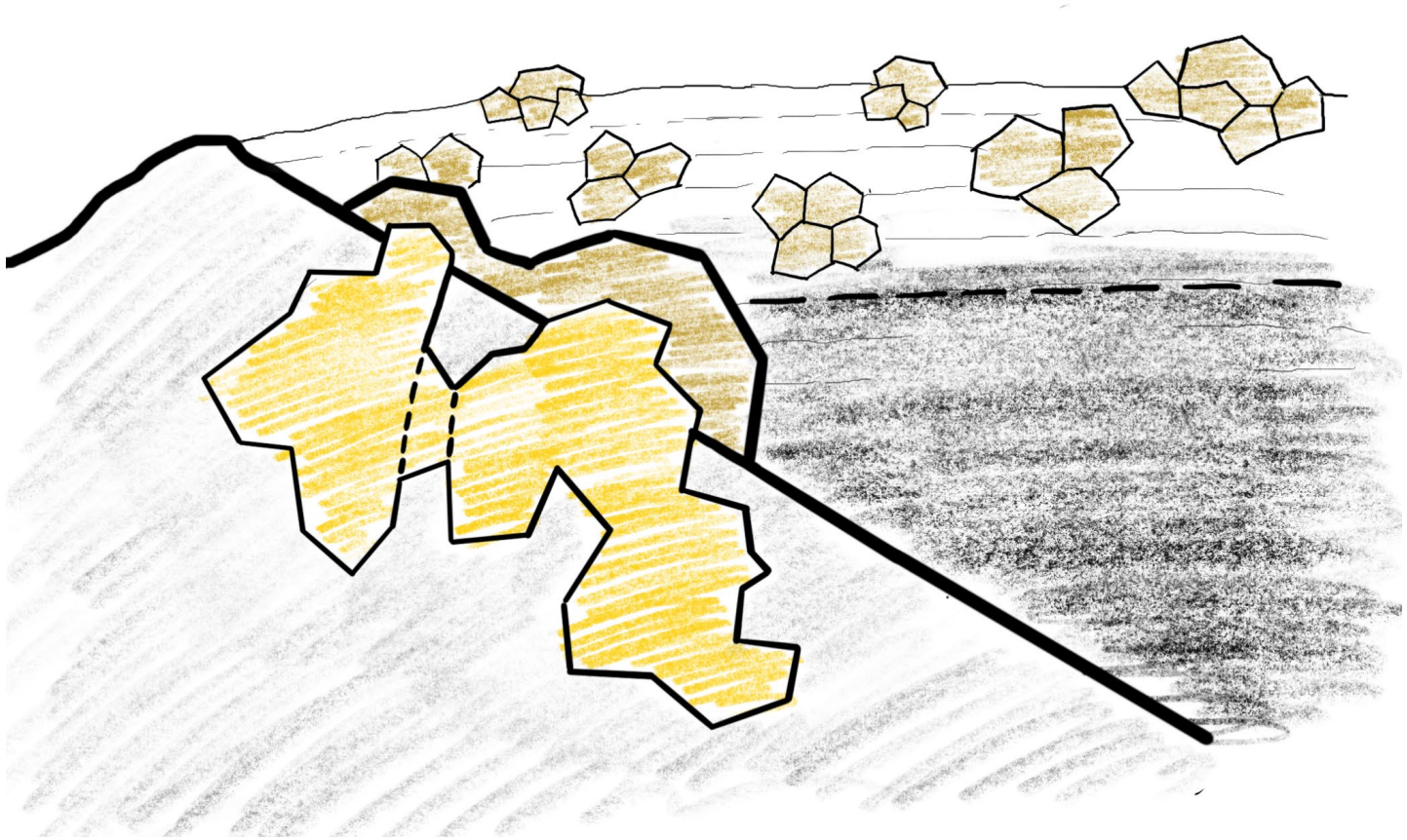




Construction & Materialization

Habitat Complex

Concept sketch, providing interior and exterior gathering space



Exterior atrium (between envelope)

Interior atrium

View to inside cave. Lava Tube Mission (2024)

View to outside cave. Lava Tube Mission (2024)

In-situ Resource Utilization

Regolith properties

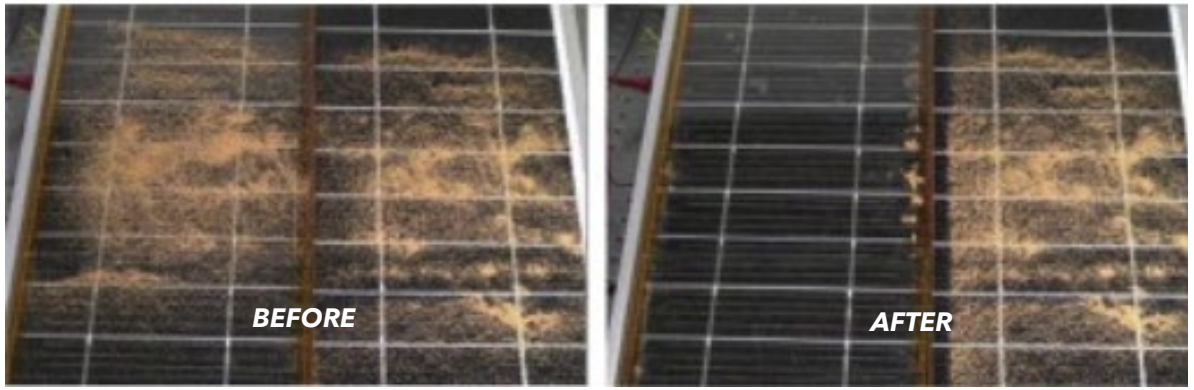
Derived materials

Regolith → Oxygen extraction → **Metal alloy**

- Water (for ISRU)
- Silica (for glass)

- **Radiation protection**
- **Rich in derived materials**
- **Electrostatically charged**
- **Geopolymer material for additive printing**

Electrostatically charged



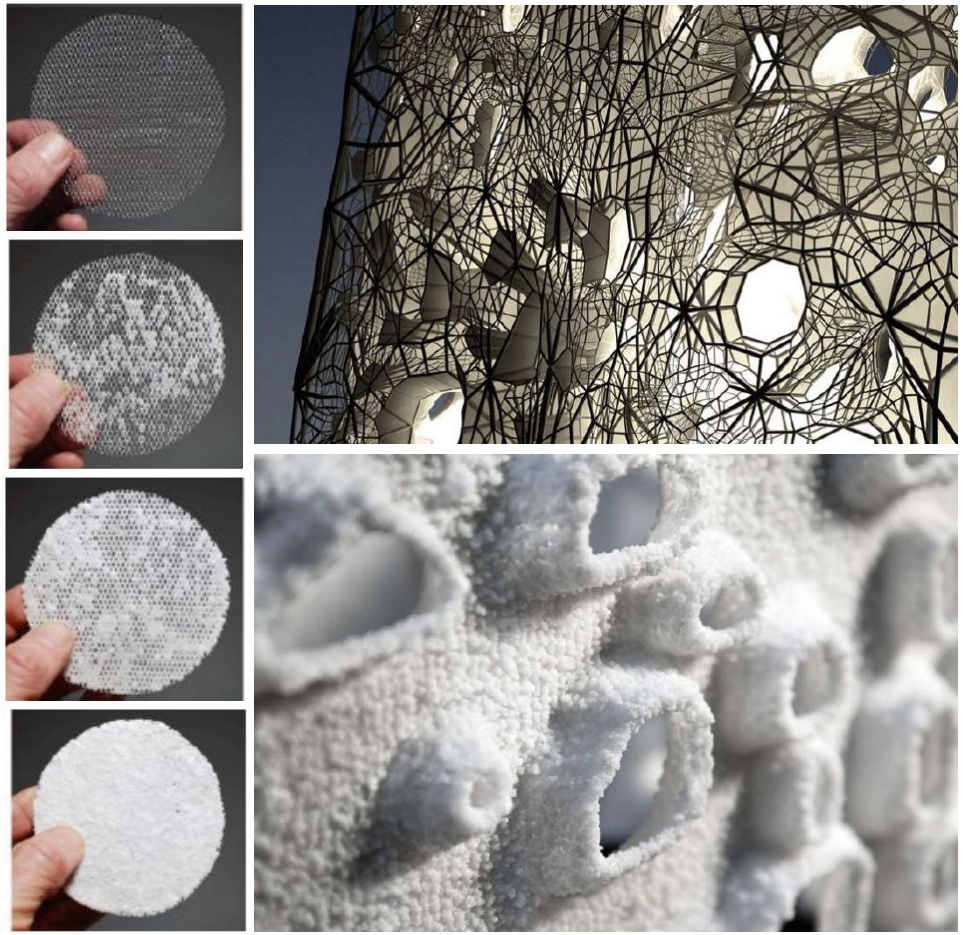
Electrostatic cleaning system for sand removal from solar panels (2015), H. Kawamoto & T. Shibata

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

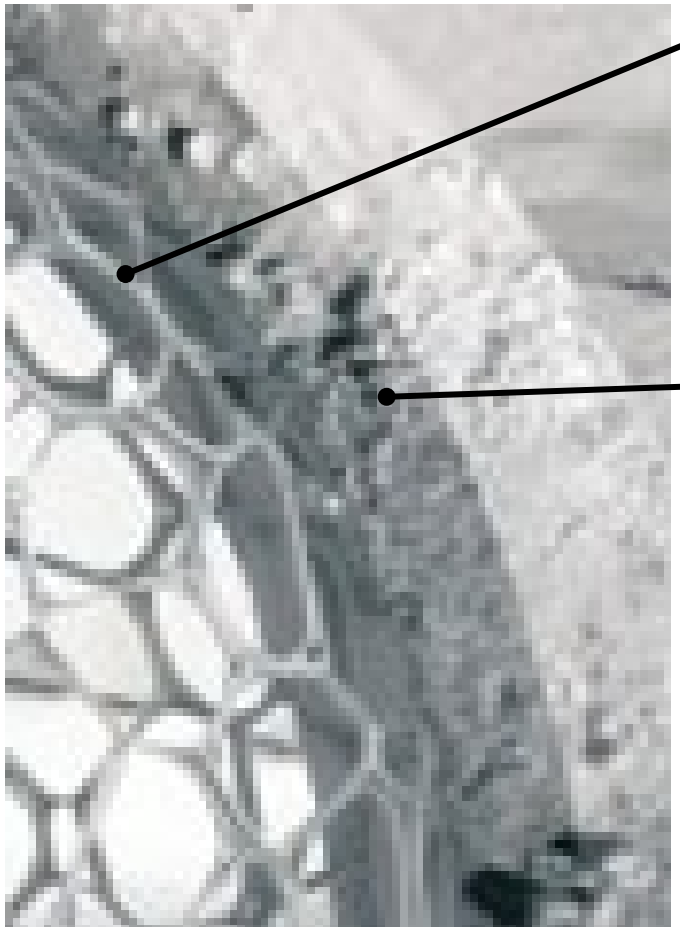
*based on in class discussion with expert

Building Method

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

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

Sintered regolith

- With laser heat

Transparent material

- Glass (silica extracted from regolith)
- EFTE, water jacket, and 3d-printed ice

Building Method

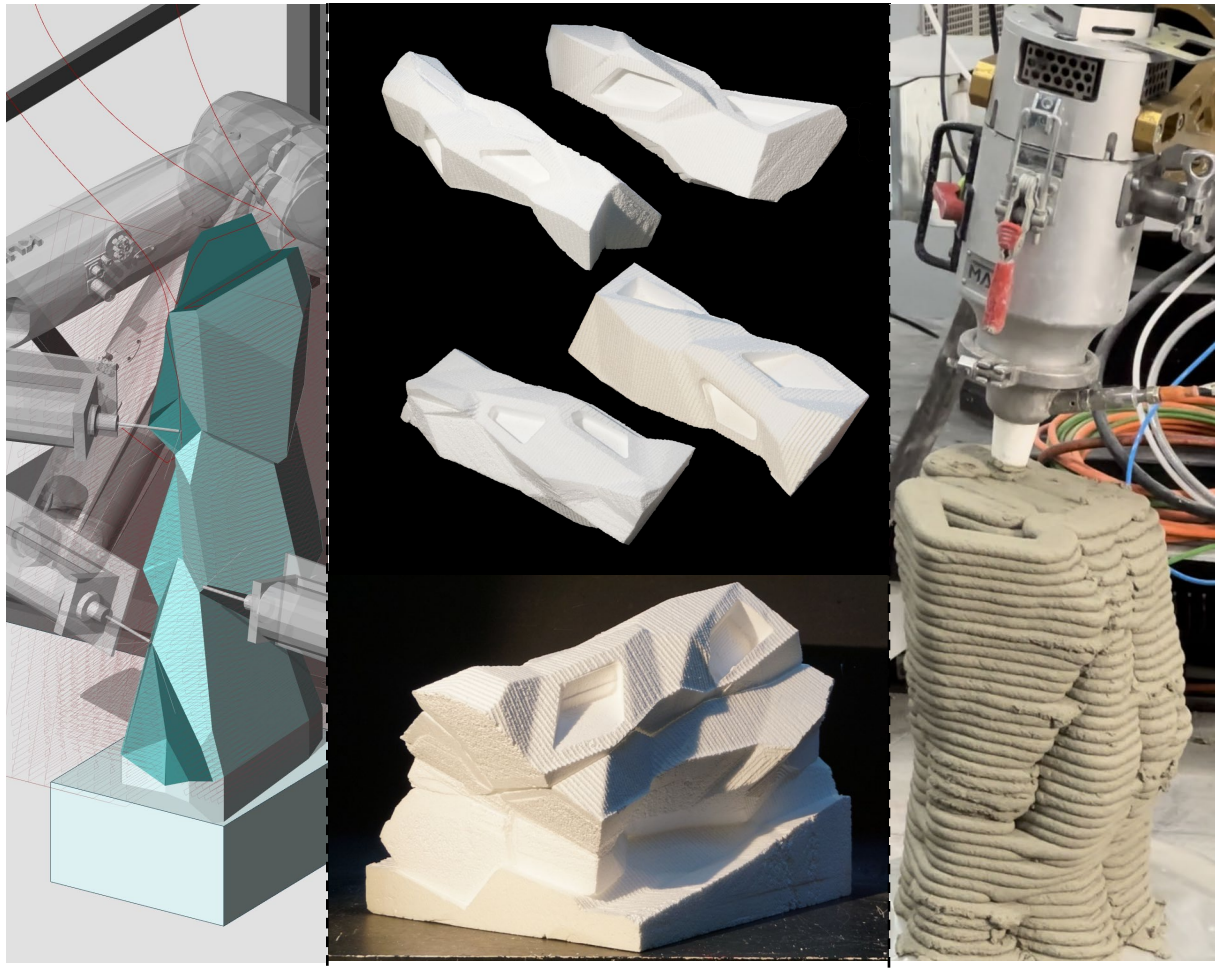
3D-printing building blocks_*Traditional*

Voronoi-based system as core

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

Suitable for heterogenous space

- Scalable from furniture to envelope scale
- Additive method suitable for mass customization



digital simulation

components assembly

additive printing

Additive Printing VS Regolith Accretion

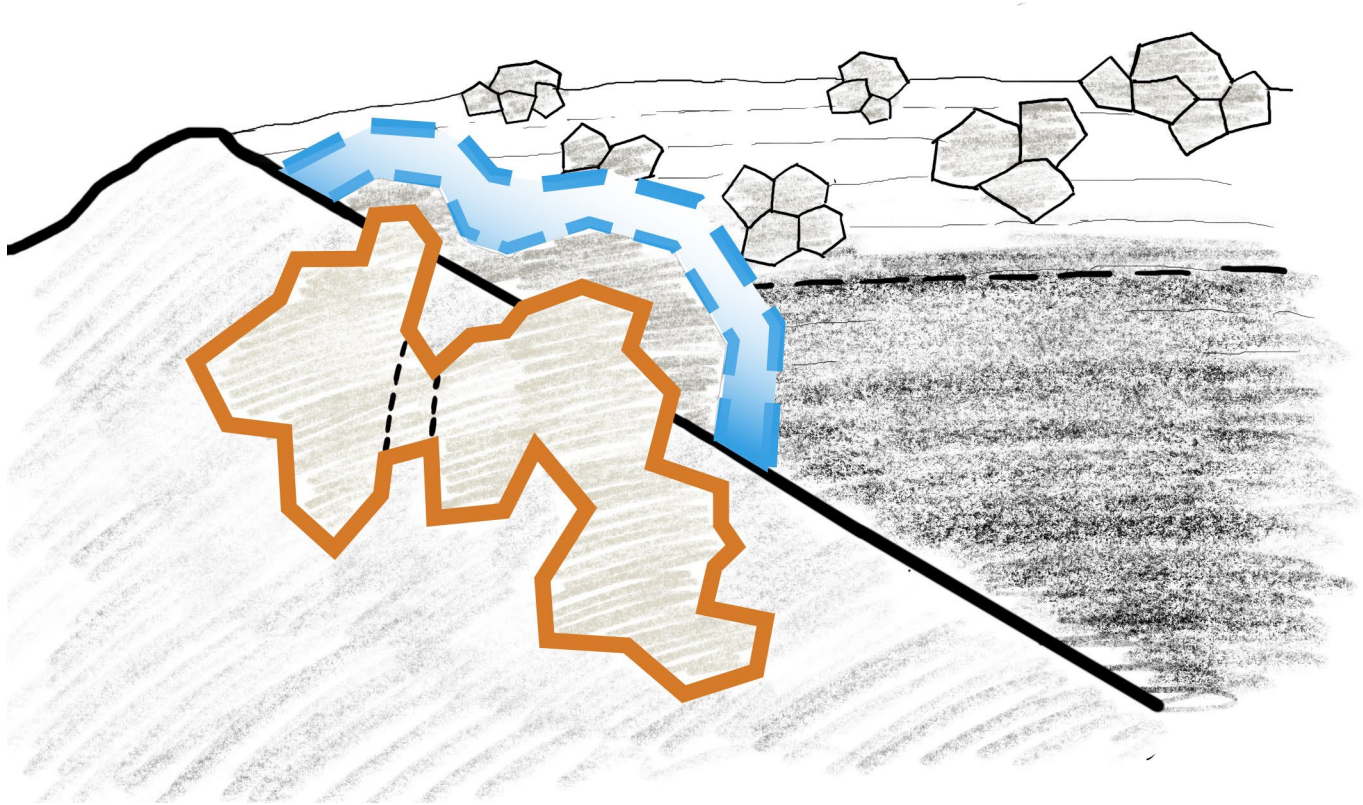
Close-up view of concrete additive 3d-printing, Vertico

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

Building Method

3D-printing building blocks + Regolith accretion



3d-printed (Core)

Regolith accretion (Supplementary)

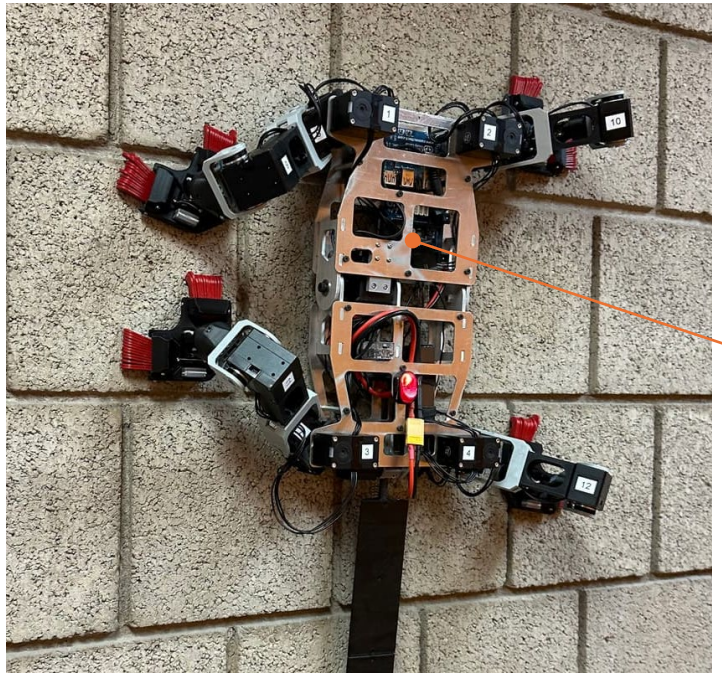
- Regolith accretion for extra shielding on windows during solar events and self-healing properties for maintenance
- Temporary radiation shielding for windows
- Protective self-healing layer from impact (i.e. micrometeorites)

Building Method

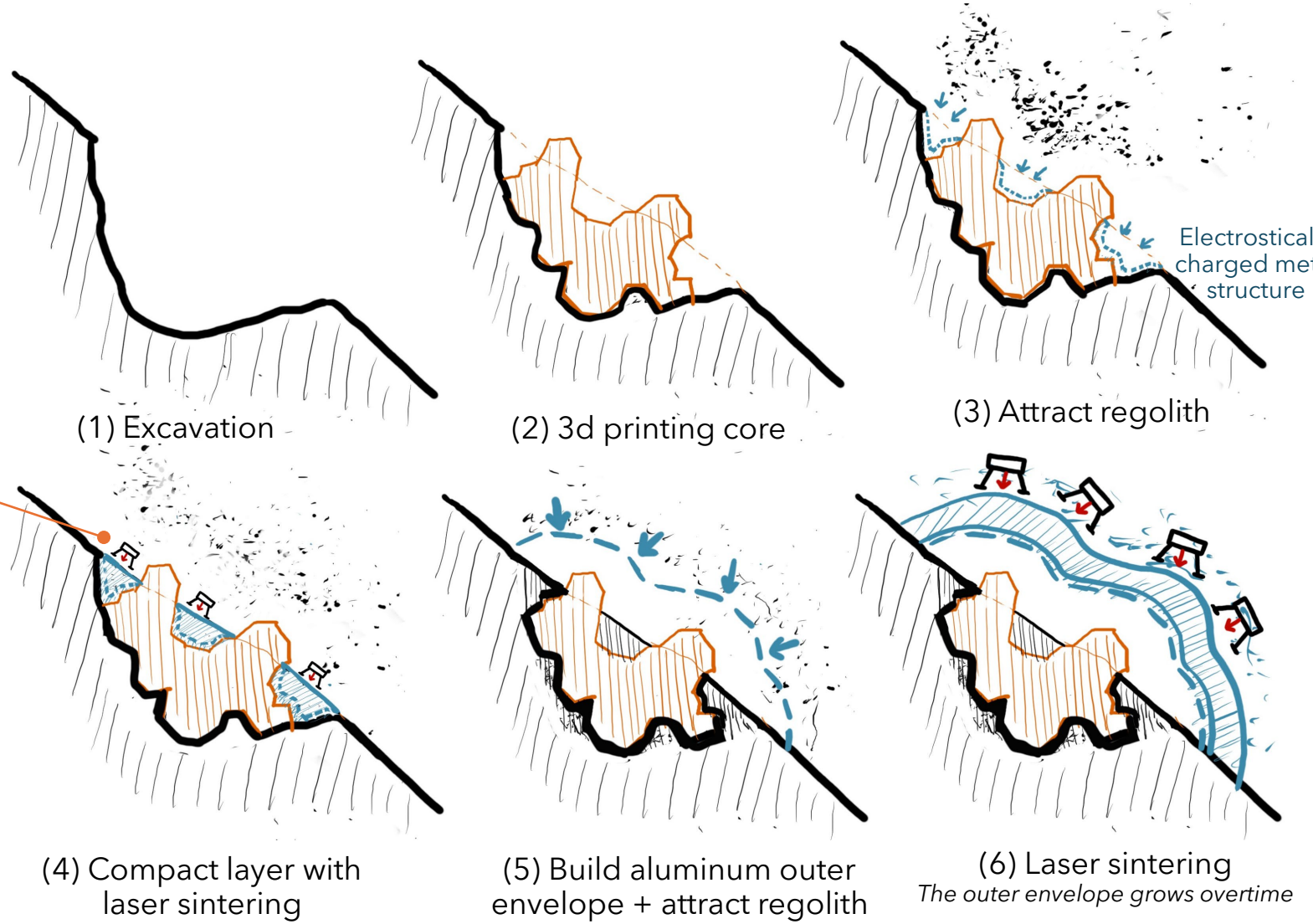
Process

Application scheme

**developed during discussion with expert*

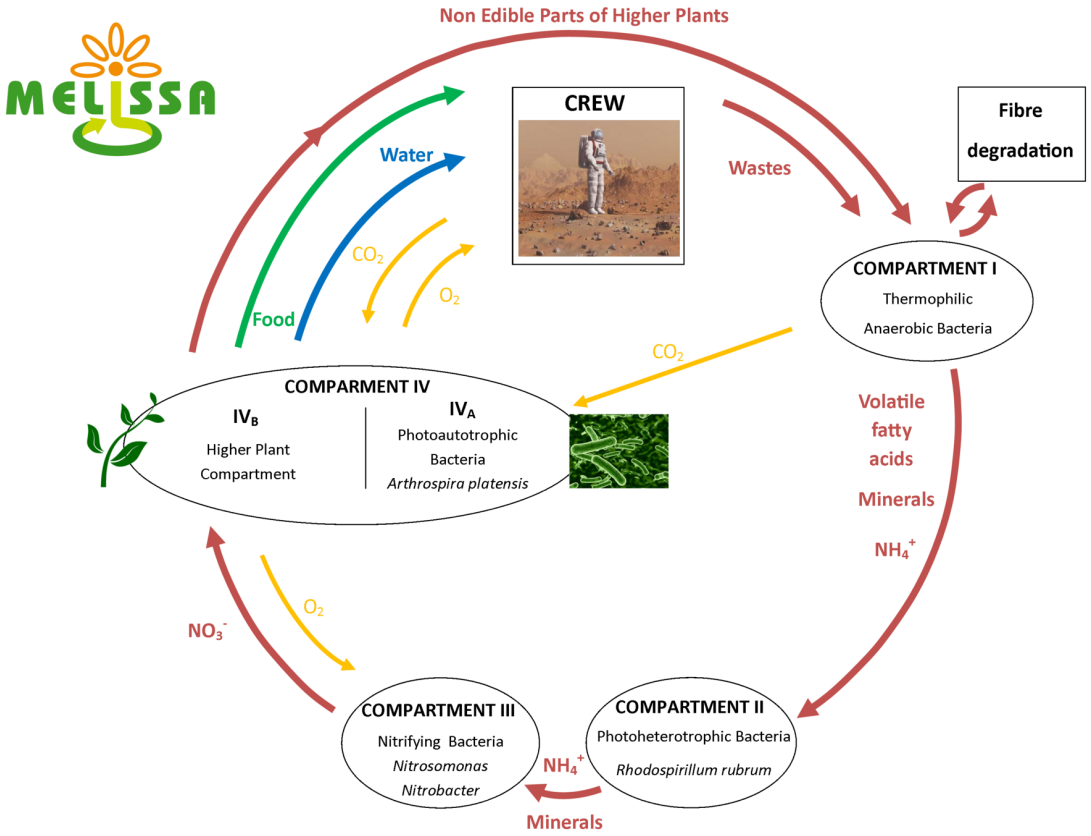


Climbing robot LORIS



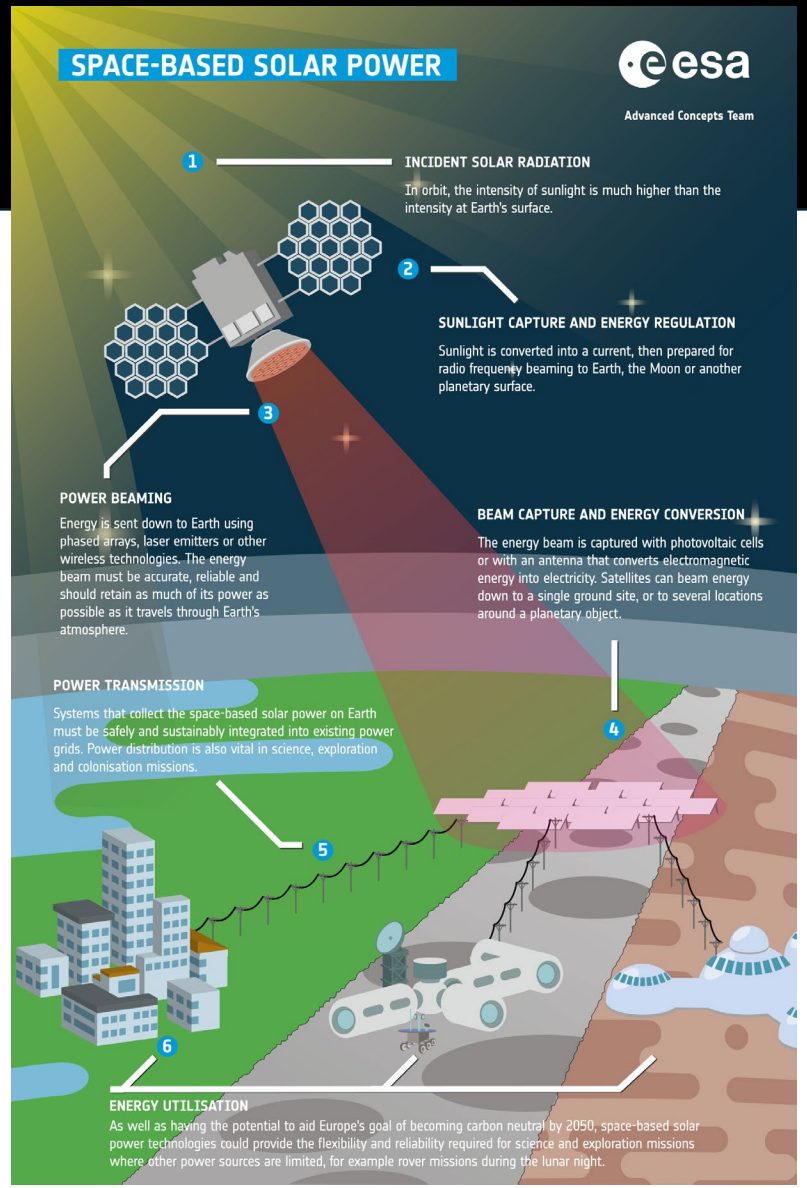
Life Support System & Energy Supply

Current projects by European Space Agency



MELiSSA

Closed-loop life support system → produce water, food, oxygen



Space-based Solar Power

Solar panels on satellites collect energy → beamed to energy conversion on lunar surface

Next steps

Next Steps

Architecture

- Design integration
- Design development of selected spaces
  - Refinement on porosity, sound insulation, speed
  - Furniture integration
- Schematic envelope and site design
- Scenario testing with personas (meteorite/radiation events, change of crew member, emergencies)

Building Engineering System (BES)

- Schematic construction and assembly system (further development)
- Schematic climate: ventilation, pressurization, airlock, energy sourcing
- Detail: fragment structure, envelope, material