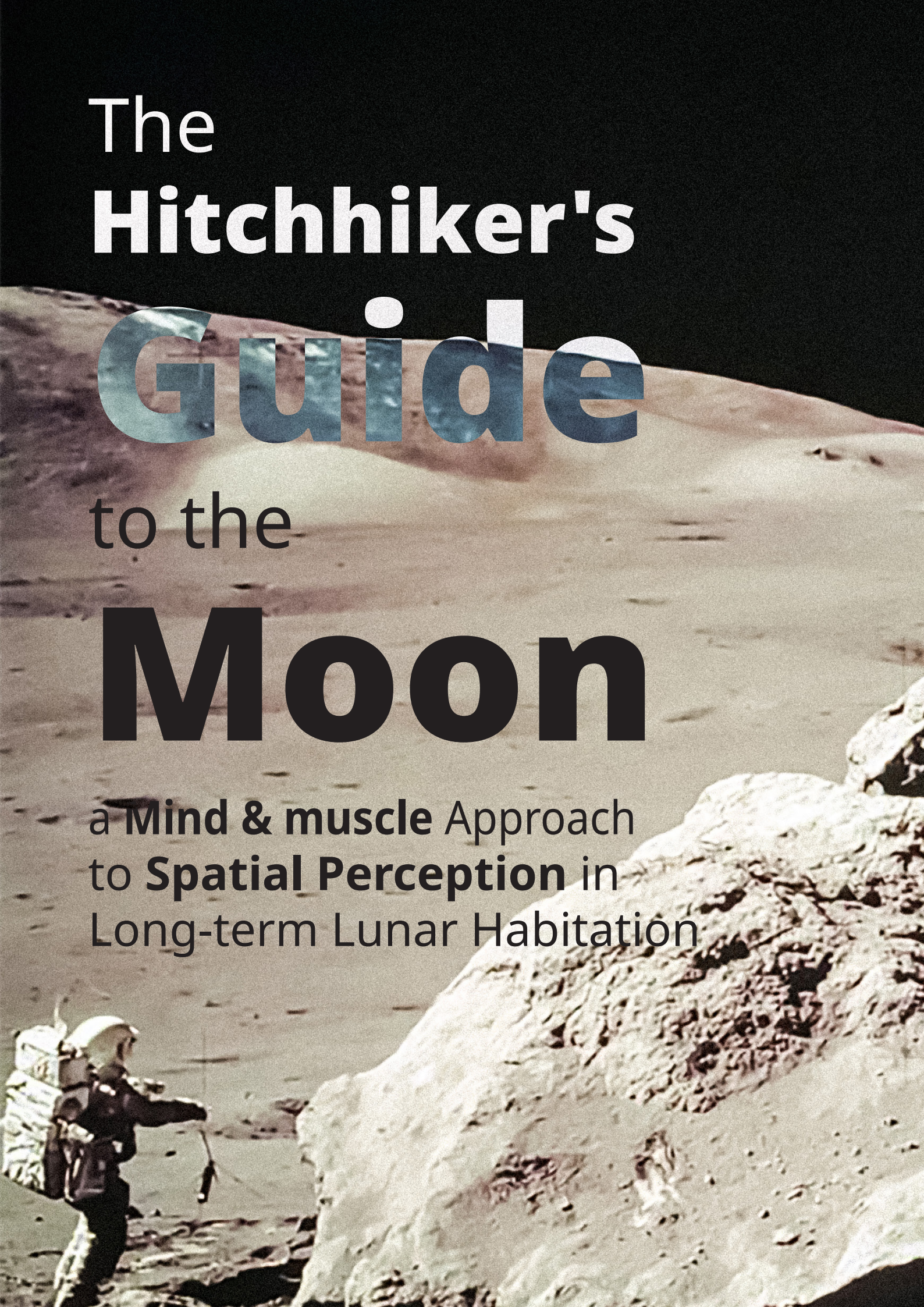
The Hitchhiker's Guide to the Moon

a **Mind & muscle** Approach to **Spatial Perception** in Long-term Lunar Habitation



The Hitchhiker's Guide to the Moon
A Mind & Muscle Approach to Spatial Perception in Long-term Lunar Habitation

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Abstract

As humanity transitions from temporary lunar cells to permanent colonization, the fundamental challenge of space architecture shifts from basic survival to mental well-being. While current space engineering prioritizes life support over the qualitative mental experience, this research instead proposes a mind-and-muscle framework for spatial perception in lunar habitation that specifically addresses the "Missing Plumb Line", the chronic cognitive dizziness caused by the absence of Earth's gravity vertical.

Based on human-centred design approach, this study investigates how to keep the mind strong as part of space resilience. This resilience is fostered through the implementation of 'Visual and Muscle Anchors'—deliberate geometric visual and force cues that provide the brain with an artificial sense of orientation and verticality, preventing the spatial flips and illusions that are common in low gravity conditions.

The design utilizes the *Oblique Function* to replace traditional floor-wall hierarchies with sloped and continuous surfaces. These surfaces engage habitants through muscular tension, providing them with a constant sensory alternative for the plumb line. The volume is generated through computational design that follows Voronoi, and Point Charge (influence of charge strength) logics, which optimizes both structural integrity and sensory complexity. Gyroid isosurfaces were tested as comparative explorations alongside the Voronoi streamline. Finally, the structural realization of this environment employs 3D regolith printing with In-Situ Resource Utilization (ISRU).

More than designing the habitat itself, the project also aimed to indicate a guideline for lunar lifestyle, a consciousness that the built environment is more than physical entity but also users' cognition.

Key words:
Low-gravity, Visual cues, Spatial perception, Human-centred design, Robotic building, 3D printing, In-Situ Resource Utilization (ISRU)

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1.0 BACKGROUND

1.1 Context

From ‘surviving’ to ‘living’: Now we landed on the Moon, then what?

Space engineering determines how to ‘survive’ in outer space. When it comes to habitation, would it be like in the spacecraft Orion -- Astronauts need to live in 9m^3 of habitat volume for 10 to 21 days for Artemis II mission. It seems bearable to live in such small area for 10 days, but what about longer missions?

The design of the Mir space station represented space architecture in Low Earth Orbit. By carefully design modular functions, the station achieved certain efficiency in survival and research. Architect Galina Balashova focused on the psychological well-being of crews on long-duration missions, by defining “up” and “down” with dark green carpet floor and white ceilings, but forced the crew to spend nearly all their time on housekeeping (Balashova, 1980).

As astronauts having trouble recognizing ceilings and floors, maybe the concept of “up” and “down” should not be defined in the first place.

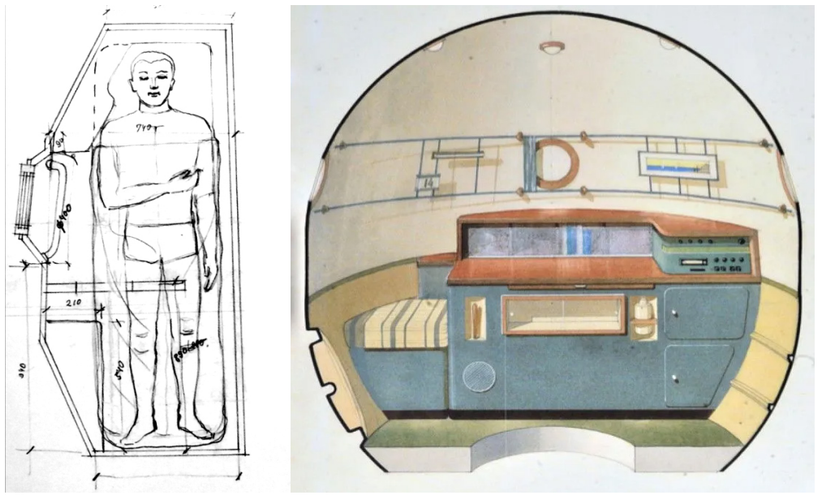


Fig.1.1 Sleeping pod
[Galina Balashova, 1970-74]

2.0 PROBLEM STATEMENT

2.1 Main problem

Missing of ‘Plumb Line’: Cognitive disorder due to lack of gravity vertical

In order to define the problem, I looked back at the fundamental difference between earth and moon. Gravity is one of the major issues. Morfoisse (2024) investigates how gravity influences our brain’s internal ‘map’ of three-dimensional space, and challenged traditional views with the idea that this 9.8G gravity is exclusive and fundamental to the earth that affects all interpretation in all sensory inputs.

As a result, Due to low gravity, the human vestibular system (in inner ear) becomes disordered, and the brain can no longer rely on gravity as an absolute reference for ‘below’ (Morfoisse et al., 2024). The Apollo 11, 12, and 14 astronauts also reported multiple serious visual misjudgements while walking on the lunar surface, that their perception of ‘far’ and ‘close’ failed to match with their own previous cognition on earth (NASA, 1971). Later research indicates that brain often defaults to mind and muscle vector: Down is simply measured by eyes or wherever your feet are pointing, regardless of the actual slope.

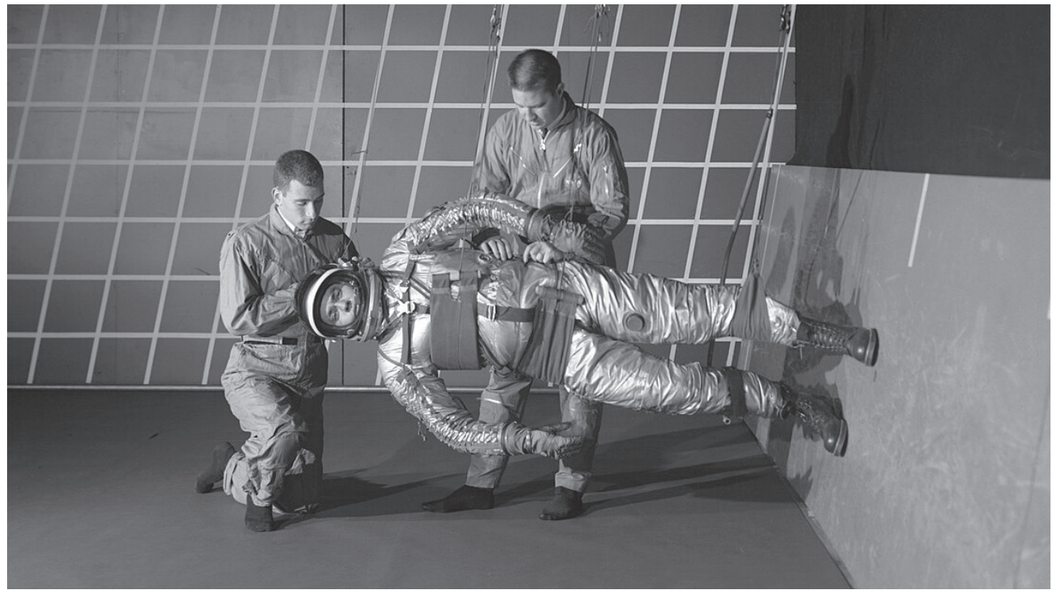


Fig 2.1: NASA testing moon gravity cognition, in a horizontal way [NASA, 1963]

3.0 OBJECTIVE

3.1 General Objective

Space exploration has always been fascinating, yet the reality is very different from what we've seen from Sci-fi movies. In 2001: Space Odyssey (1968), we are impressed by the spacecraft Discovery One, the Djinn chair, and the prediction of AI "HAL 9000" computer. The lasting impact goes beyond filmmaking, involved in Space Age Design, fashion industries and even the invention of iPad (Medium, 2018). People's lifestyle had already been changed without going to space. However, in reality, the design for lunar habitat is heavily technology driven, yet is necessary, to meet the minimal requirement of survival on the moon. But to actually live there, humans need more than just the basics.

Architectural objective: Space colonization

Indicating a guideline for about lunar lifestyle more than just survival, and bring technological consciousness where space can be determined more than merely volume but also minds

Usually, we think of lunar base is a life-supporting machine. But in this guideline, moon habitat is also about expanding human consciousness into the outer space. On the Moon, the technology keeping you alive, and the goal of designed space is to make our minds work together so that we feel connected to our environment, rather than scared of the "vacuum" outside.

Technical objective: Space-resilience

Embodying cognition researches to spatial cues when designing lunar base, and being able to 3D print with ISRU technology in Robot building.

4.0 RESEARCH QUESTIONS

4.1 Main Research Question

How can architectural spatial design in extra terrestrial environment collaborate technology with perception, to deal with low gravity cognitive changes in movement and perception in maintaining mental well-being of future lunar habitants?

4.2 Sub Research Questions

1. Premise: Physical survival challenge

Design must be based on conscious research of physical ICE conditions in constructing and inhabiting lunar bases with ISRU (Oman C, M. et al., 2006)

2. Design: Sensing spaces

Based on visual cues and movement study, how can the furniture, room, and lunar habitat dealing with sensory deprivation and monotony due to loss of gravity vertical?

3. Sequel: Mind over matter

Between interactions of individuals and objects, how can the built space and architectural expressions cope with imbalance between privacy and social needs?

5.0 APPROACH & METHODOLOGIES

5.1 Site

Location: Lunar South Pole. On sunlit peak point of rim at Shackleton Crater

The location choice is mainly resource driven: Because of how the Moon tilts, the sun is always low on the horizon at the poles. Sunlight hits the rim of the crater but can never reach the bottom. At the Permanently Shadowed Regions (PSRs), water may exist because of the freezing temperature, along with other resources that are trapped by ice (NASA, 2022).

On the other hand, the perk received solar energy for 90% of the (earth) year. The advantage include solar energy, thermal radiation and the ability to see the earth (NASA, 2022). This combination of resources is why NASA and also other space agencies see this specific crater as the best place to build the first permanent lunar city.

Apart from the universal challenge of life-support, the specific challenge for this peak location at the rim is 10% time at low degree (average -53°C) and cosmic radiation (Leonard, 2022).

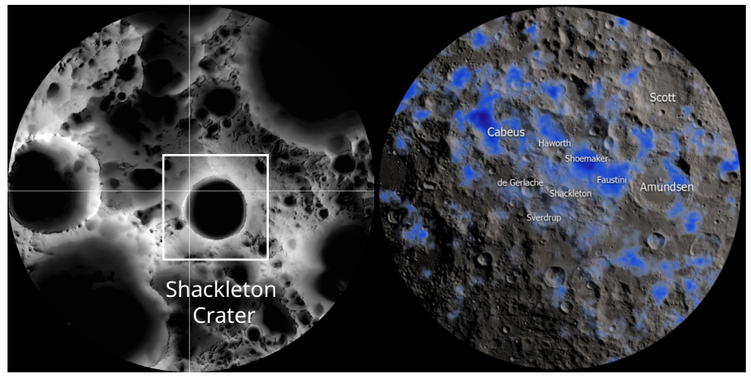


Fig 5.1.1: Lunar illuminated days [NASA, 2010]

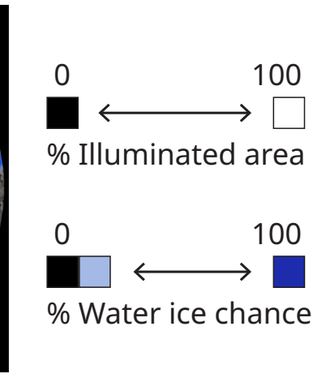


Fig 5.1.2: South pole water ice [NASA, 2010]

5.2 Scope

Strategic technology and timeline

ISRU extraction workflow: NASA's Plan.

According to NASA's research, ISRU in lunar south pole is primarily water ice trapped in PSRs. Extracting from water ice dirt, the resulting materials are breathable oxygen, gas and metallic by-products that can be used for 3D printing (Kleinhenz and Paz, 2020).

Apart from water ice, lunar rock consists of metal oxides. NASA also use extreme heat to strip oxygen from the minerals (NASA, 2015). The residue is a highly valuable mixture of raw metals prepared for lunar 3D printing in micro-scale, like electronics and hardware. While the leftover non-metallic waste can be mixed with lunar regolith as filaments for 3D printing in constructing habitats (NASA, 2015).

The regolith is already an in-situ resource on the Moon, but the binding material like polymer is a problem. Unlike earth, moon surface lacked carbon that can be extracted for organic materials. Nowadays, scientists are actively recycling binder from bio waste, as well as looking for inorganic substances inside regolith that can be used as alternatives, like using micro-ware melting and fusing powder materials to bond lunar dust (ESA, 2020; 2021).

However, diving deeper into this topic is not helpful for this thesis. It is time to look into the larger picture: After successful landings of multiple short-term lunar modules, this habitat is considered to be self-maintaining, lasting over a generation while developing to form their own space colonize culture. According to the space habitation plan by NASA, the context of this lunar base is settled in the 2080s, after humans have successfully harvest energy and material from PSRs of Shackleton Crater.

Threfore, there are three targets in construction of a moon base: Survivable, sustainable and operational (ESA, 2019), and this project is aimed at all three phases.

Survivable: Include fundamental protection of 3D print in-situ elements, design for swarm robots and investigation pods for autonomy installation

Sustainable: Accommodate researches in fabrication and preparation for future habitation

Operational: Expand the habitat for long-term and self-sufficient living and working on the moon

Temporalities

Crew members

8

6 visiting, 2 long term maintenance crew

To ensure continuous operation and diverse research capabilities, the habitat is designed to sustain an 8-person crew: 2 long-term maintenance members and 6 visiting members. Because the lunar base serves multiple programmatic goals, these inhabitants operate on distinct temporal rhythms, shifting between external lunar resource cycles and artificial circadian routines.

The crew is divided into three functional categories:

Long-term Crew: Dedicated to habitat maintenance, infrastructure operations, and technical upkeep. Their routines bridge both external environmental monitoring and internal life-support management.

Visiting Scientists: Focused on laboratory research, in-situ resource utilization (ISRU), and biological farming. Their schedules are heavily dictated by Lunar Time, aligning with external operational windows, solar illumination, and resource extraction cycles.

Mars-transit Tourists: Utilizing the habitat as a low-gravity training facility and behavioural research ground. Shielded from the external lunar environment, their schedules strictly follow Internal Time—a simulated 24-hour circadian rhythm designed to maximize physiological adaptation and mental well-being before deep-space transit.

Spatial design

Programmes

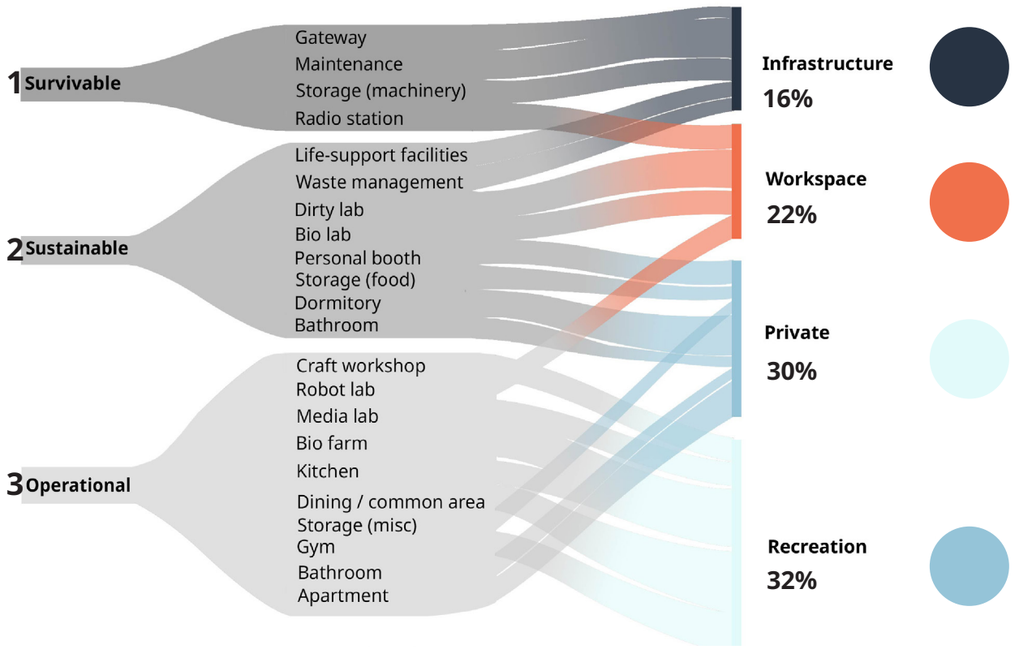
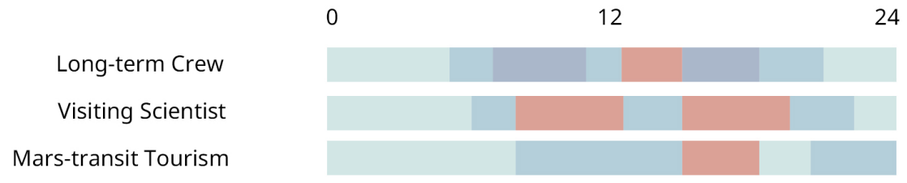


Fig 5.2.1: Programmes



The visualization Categorize the expansion of a moon base: Survivable, sustainable and operational. Each phase then form spaces to required functionality required by ESA.

Moreover, these three phases also show the transition from the focus of Lunar time to internal time: At phase 1, lunar habitat requires mineral and radiation energy to survive, so programme functions directly relate to lunar time and condition more than habitant's well-being. At phase 2, programmes are focused on utilise moon resources for human self-sustain life-support. At phase 3, programmes only deals with lunar habitants' living quality, regardless of external lunar time but form an internal time that best suits the well-being of habitants.

5.3 Research Design

How can we design without the ‘plumb line’?

To improve cognition in a monotony environment where the brain gradually abandons the ‘plumb line’ of the earth, the research looks at what people rely on instead.

In 2016, an experiment titled *Visual Gravity Contributes to Subjective First-person Perspective*, investigated how the brain uses visual “gravity” cues to determine where you are located and from what direction you are looking at the world. The conclusion points out that gravity is a *multisensory anchor*. We don’t just feel gravity with our inner ear; we 'see' it in the environment. When visual gravity conflicts with physical gravity, the brain can actually relocate the subjective first-person perspective, providing a scientific explanation for out-of-body sensations or the spatial flips experienced by astronauts in orbit (Pfeiffer et al., 2016).

Threfore, This research will employ a combination of literature study, case studies, workshops, as well as movement and visual studies to explore the logic behind human’s physical receiving information and mental interpreting of space perception.

Muscular perception in experiments

Experiments show the essence behind moonwalk is body's adaptation to 1/6G lunar gravity. The sense of space and 'down' is reclaimed by paying attention to keep body steady, as you need to know how you are going to fall based on the surface you touch.

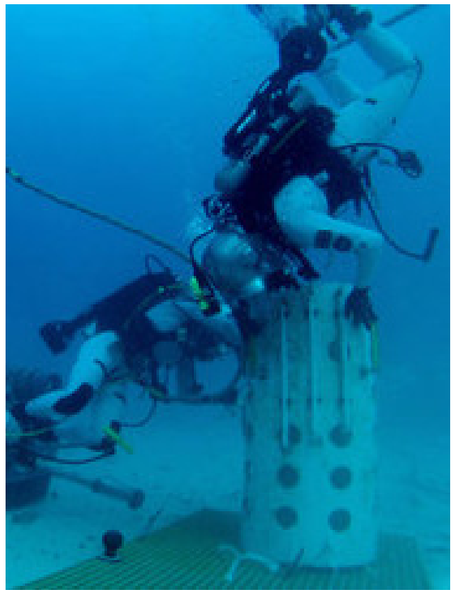


Fig 5.3.1: Moonwalk practice
[David L. Akin, 2023. Video clip]



Fig 5.3.2: Moonwalk by Apollo 17 astronaut
[NASA, 1972. Video clip]

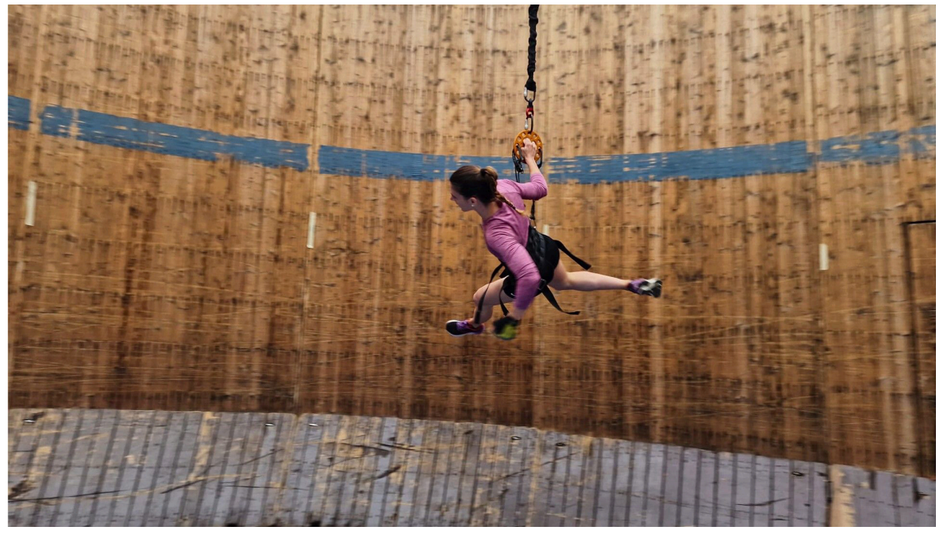


Fig 5.3.3: Simulate force on a sloped wall that counter-balance gravity
[Prof. Alberto E. Minetti, 2024. Video clip]

Muscular perception in architectural theory

Moreover, the movement study is based on theory of Oblique Function by Claude Parent (architect) and Paul Virilio (philosopher). The study examines the strength increase in muscular tension and compression in relation to human experience in different activities.

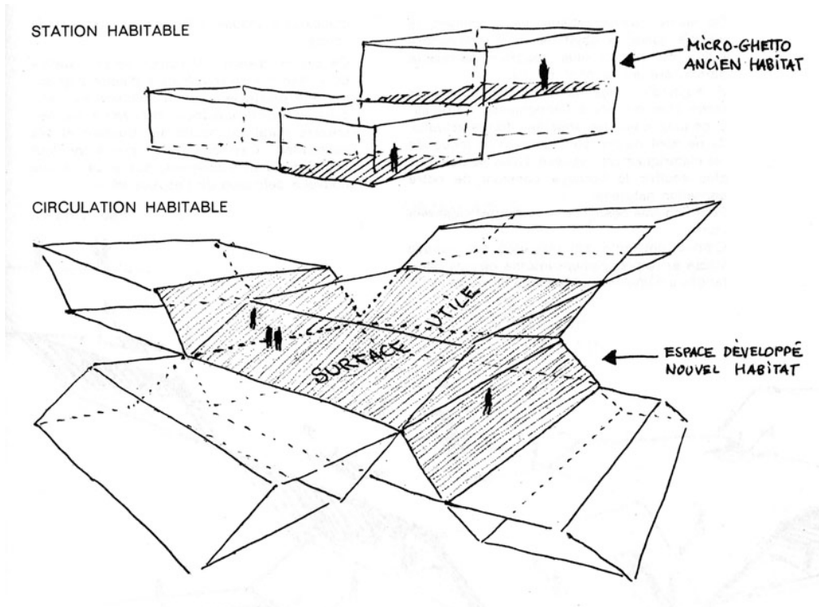


Fig 5.3.4: Oblique Function
[Claude Parent and Paul Virilio, 1970]

Visual perception in psychological research

The study of space perception are carried out primarily developed from visual cues, but also combining information from other senses in hearing, touch, and balance, under subject area of “space perception”.

To design without the “plumb line”, the study of human response to difference geometry is also conducted. In the research of Talmon, et.al. (2016), by simply ask the question “Does the shape of a room change how you feel?”, the researcher used Virtual Reality (VR) in experiment to prove geometry is a tool for the mind. This is helpful to determine rooms with different level of safety and functions.

Gibson (1979; 2014) also points out in ecological field that, the meaning of vision is that we don’t just see geometry, we see what an object affords us. In his theory, visions can be translated in abstract patterns of *Fields of affordance*, which then is helpful in abstracting the geometry of vision that move beyond the unmesurable sight seen to sight encountered.

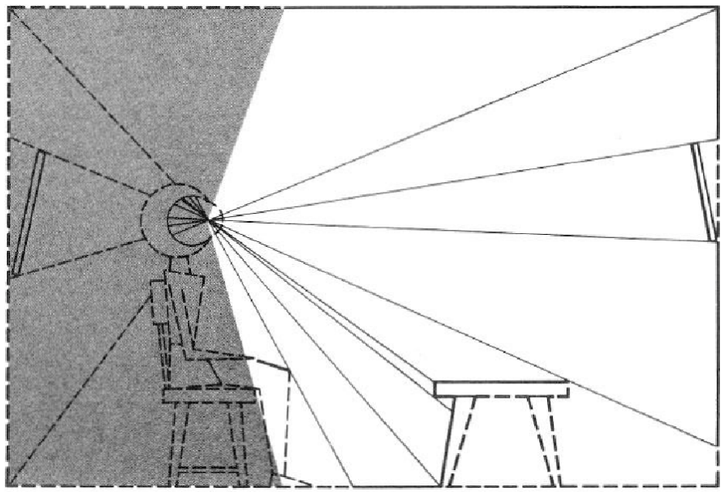


Fig 5.3.5: Figure from The Ecological Approach to Visual Perception
[James. J. Gibson, 1979]

Visual perception in architectural theory

Similar approaches are already taken place in architectural field, but without mentioning the name of ‘spatial perception’. Dated back to Bauhaus in 1930, the original diagram emerged from Bayer’s work and his interest in psychology and ergonomics. He argued that the traditional “picture on a wall” approach ignored the natural range of human sight. His theory and later 1935 exhibition shifted the definition of an exhibition from a collection of objects to a designed experience. By acknowledging the 180 vertical and 360 horizontal potential, he proposed that display surfaces should be angled to meet the eye perpendicularly, regardless of where they are placed in a room.

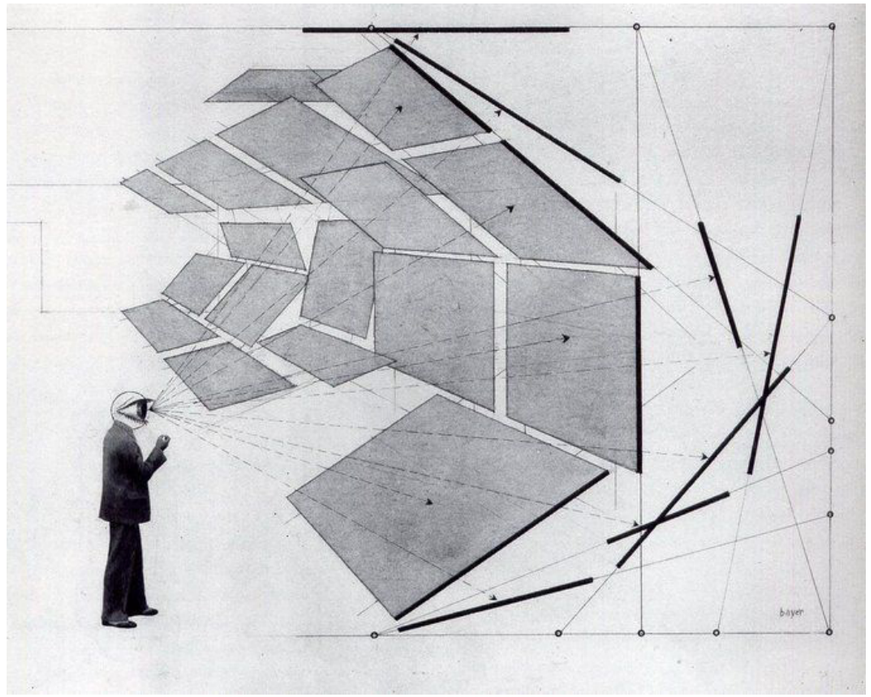


Fig 5.3.6: Diagram of the Extended Field of Vision
[Herbert Bayer, 1930]

Spatial attractors

By analysing current designs and changes in space station in an archaeological way, we can get an impression of what are contributing to muscular perception and to visual perception (Walsh, 2021).

Visual anchor

- Lighting
- Monitors, indicator lights
- Rail (visual geometric protrusion)
- Signs, customization

Strength anchor

- Positioning
- Working plane
- Buttons, panels
- Decking

Force anchors are charge points and visual anchors appear as a series of leading lines that draws the eye, balances the layout, and creates emotional harmony in an originally harsh-looking environment (fig 5.3.7 and 5.3.8)



Fig 5.3.7: Space station interior, factory new with few indicators
[St P Walsh, 2021]

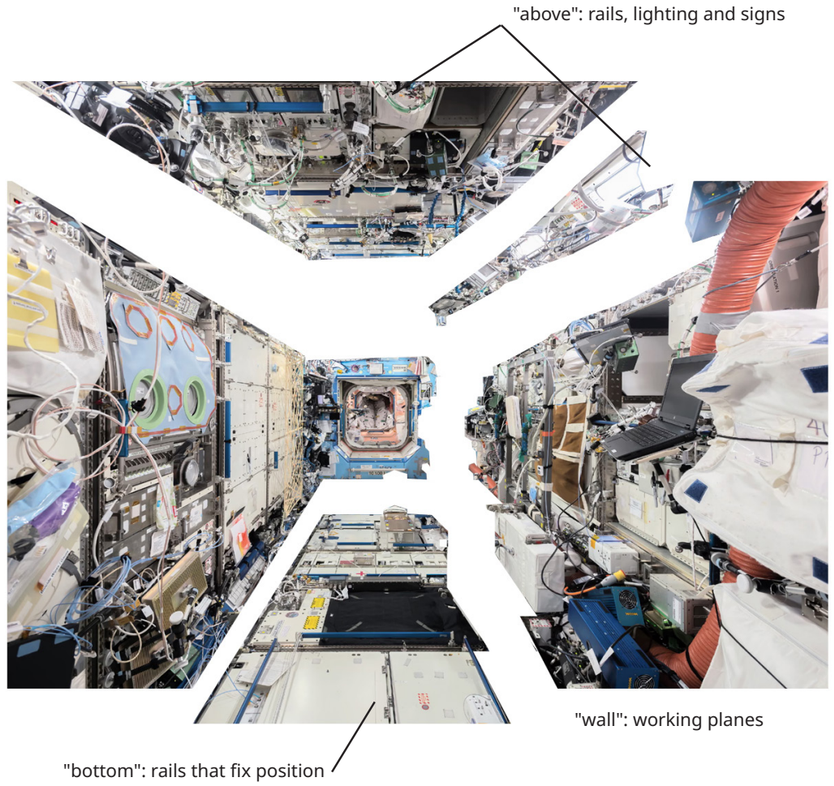


Fig 5.3.8: Exploded analysis of attractors

5.4 Interpretation of anchors

People react differently according to ambient environment, but in an opposite way, the space can be defined for convenience so that users can quickly understand the different ambient by experiencing themselves in certain mode of vision and body position. Before defining the actual boundary and geometry, the correspond body position is analysed and divided into multiple anchors and attractors.

External focus:	Reception, interaction of space and outcome
Internal focus:	Pay attention to keep body steady
Clear Zone:	Visually isovist-clear zone that allows interaction
Supporting area:	Physically connecting area for muscle respond
Visual anchor:	Horizontal extension of vision
Force anchor:	Perpendicular force applied to surface

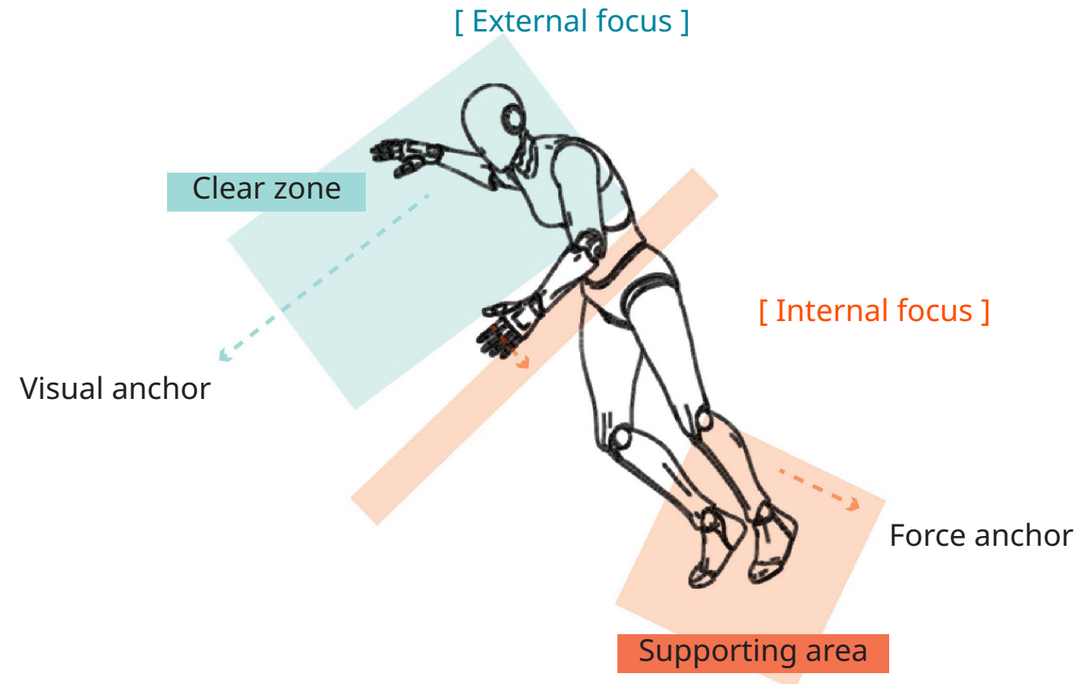


Fig 5.4.1: Analysis of visual anchor and force anchor

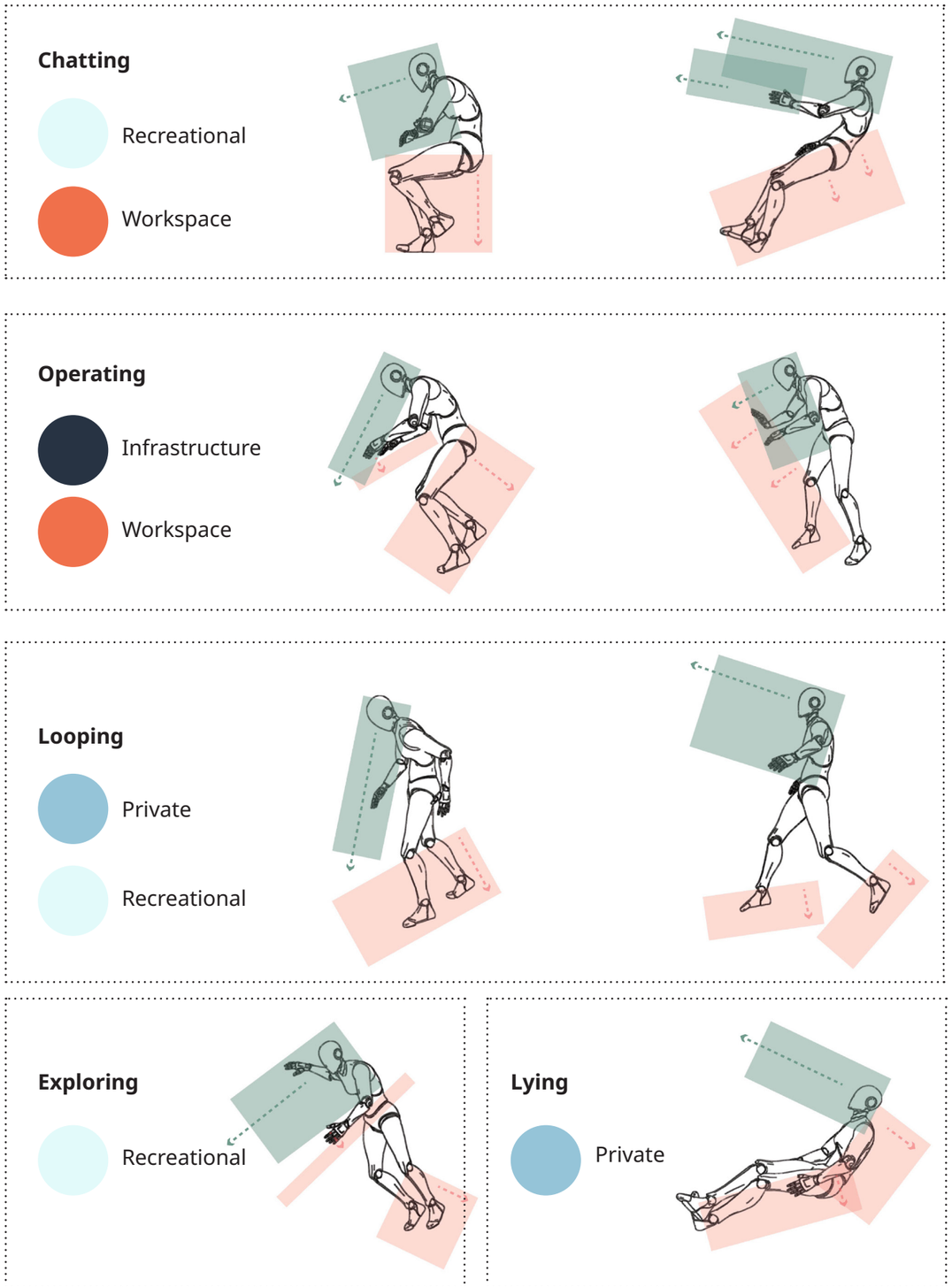


Fig 5.4.2: List of different modes in gravity interpretation

5.5 Case Studies

The End of Sitting Amsterdam

RAAAF

It is an experimental architectural installation designed to completely eradicate traditional chairs and desks from the workplace. Instead of prescribing behaviour through singular pieces of furniture like chairs or desks, the design provides an open landscape of affordances.



Fig 5.5.1: Gyroid climber

Ku.Be House Frederiksberg

MVRDV + ADEPT

Instead of defining levels , architects use labyrinth, trap and net to move “upward”



Fig 5.5.2: Ku.Be House

Jewish Museum Berlin & Denmark

Daniel Libeskind

In standard architecture, we expect 90-degree angles. Libeskind systematically eliminates them. Every room and corridor is composed of sharp, “stabbing” corners or wide, “stretching” walls. This forces the eye to constantly adjust to unpredictable perspectives.

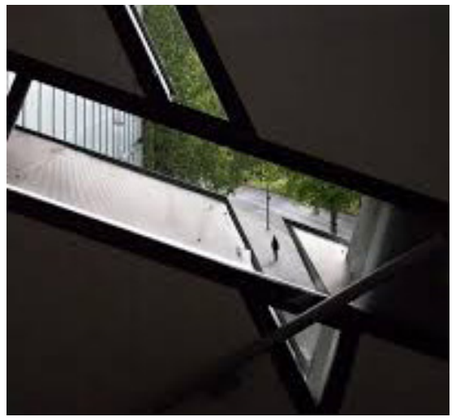


Fig 5.5.3: Jewish Museum Berlin

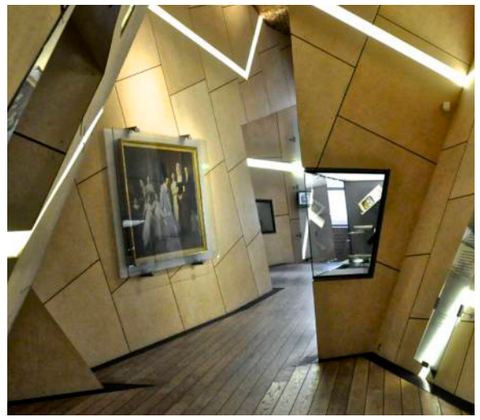


Fig 5.5.4: Jewish Museum Denmark

Chapel of Sound Chengde

OPENarchitecture

Move further than slopes and geometry, this project communicate audiences with ambient created by layered patterns and material finish.



Fig 5.5.5: Chapel of Sound

6.0 DESIGN

6.1 Planing concept (macro)

Independent gravity

Based on researches and analysis, Each programme can be influenced by lunar time and internal time, resulting in each programme having its own unique ‘gravity’. Moreover, habitants’ behaviour is influenced in designed gravity when coping with tasks that require certain focus of visual anchors and force anchors.

Further breaking down habitants’ perception in low gravity environment, David (2023) points out in the underwater simulation tests that gravity sensation was amplified at different slopes. Thus, the planning concept is to distinguish gravity change when entering or exit to different modes.

Based on the degrees of gravity variation required for different functions, the zoning concept falls into three different level categories:



0 - 10°
Flat
Stable surface

10 - 35°
Slope
Room change

35 - 57°
Stair
Level change

Zoning in bounding box

According to gravity perception preferences, iterations are tested based on which category being the dominate gravity level.

In the mild sloping model, flat, stable surface is preferred, resulting in bounding box being flattened.

If the habitants have no preference in gravity change, a square bounding box is created for agents to explore relationships freely.

If the bounding box expands vertically, fewer programmes will stay on similar levels, with more level change expected.

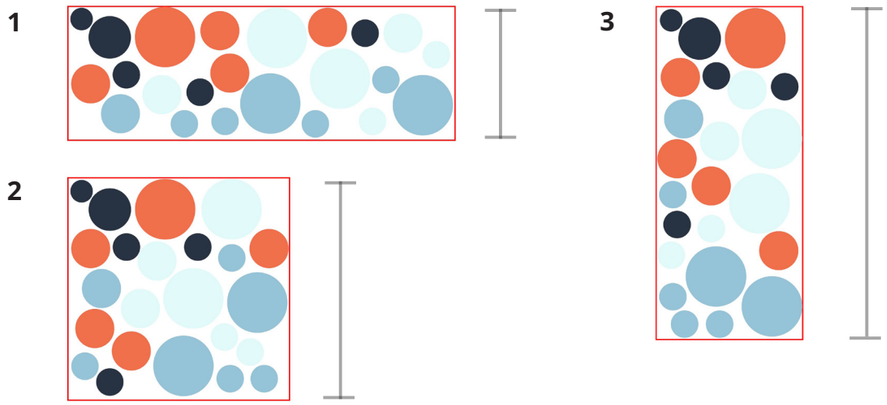


Fig 6.1.1: Bounding box iterations

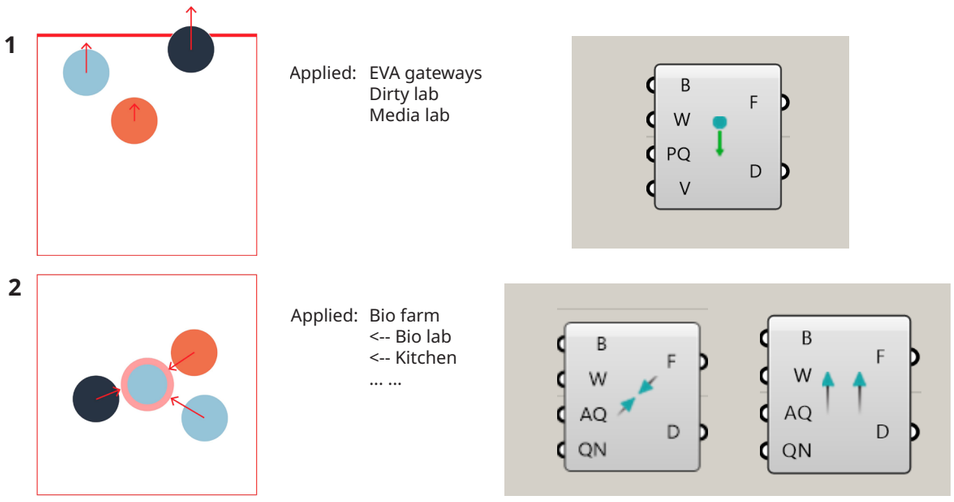
Agent rules

The behaviour of each function will affects its placement, and the behaviour includes:

1. **Pull**. Lunar time preference, strength pulled to lunar surface.
2. **Attraction**. Functions have logical or narrative relationships connect with each other. [**Align** applied at relations with linear narrative]
3. **Cohesion**. Programmes with shared internal time clustering together.
4. **Separate**. Functions that need privacy or equal distribution.



Agent: Quelea



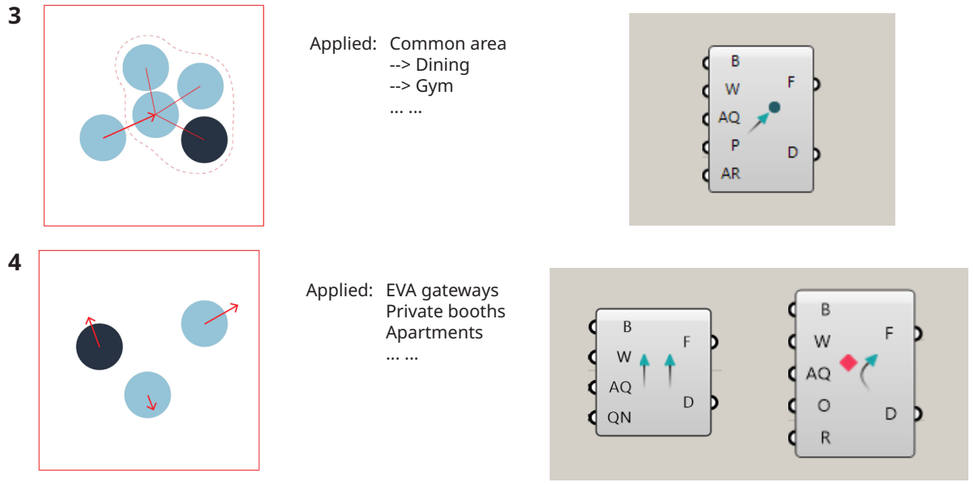


Fig 6.1.2: Agent rules

3D agent based modeling

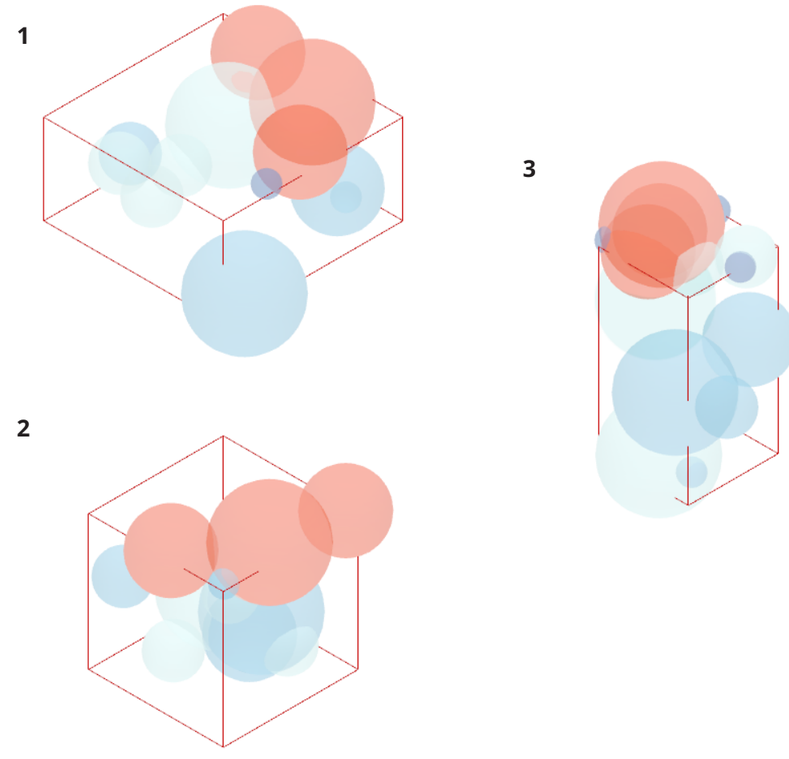
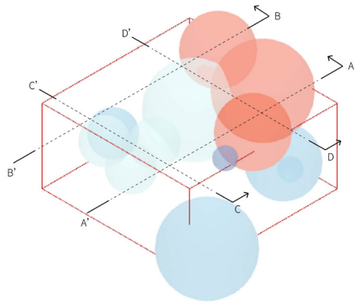


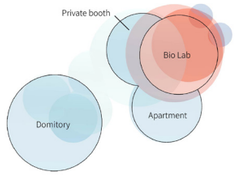
Fig 6.1.2: Clip from modeling animation

1 Evaluation of iterations

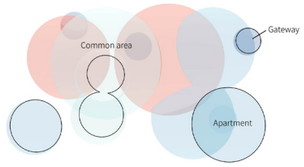
Sloping: Bubble diagram



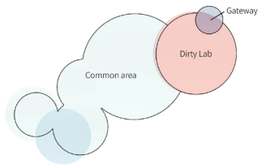
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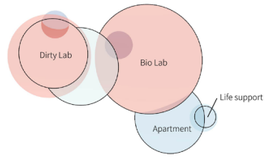
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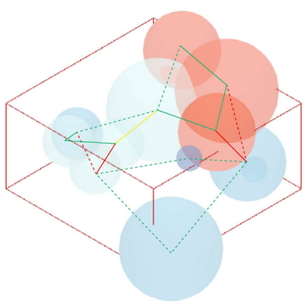
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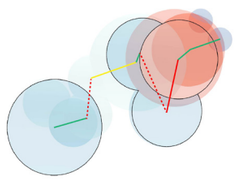
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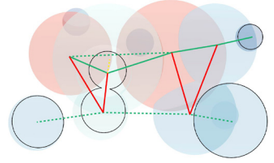
Sloping: Circulation analysis



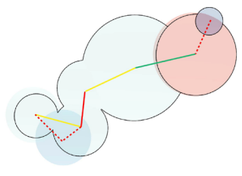
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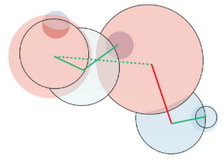
Section CC'



Section BB'



Section DD'



Flat

Slope

Level

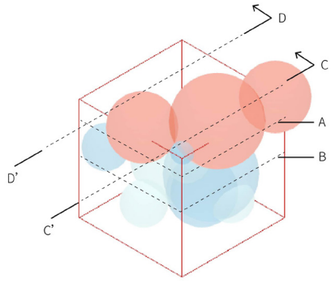
Fig 6.1.3: Outcome evaluation (1)

Because of larger flat surface area, functions that required lunar time distributed evenly on top surface, resulting related functions connect on similar levels, while unrelated functions zoning on another level. The hierarchy between lunar & internal time is clear. However, the inter-relationship between related functions is not enough to differentiate because the gradient is too subtle to notice a change in low gravity environment.

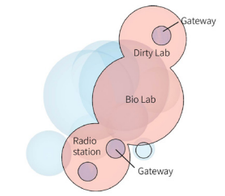
Moreover, flat distribution will cause more unwanted zones to be exposed under radiation, as the hierarchy is arbitrarily distinguished by lunar time or internal time without smooth transition.

2 Evaluation of iterations

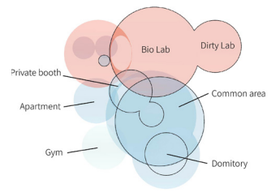
Neutral: Bubble diagram



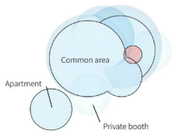
Plan A



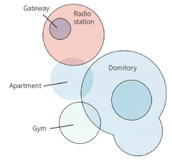
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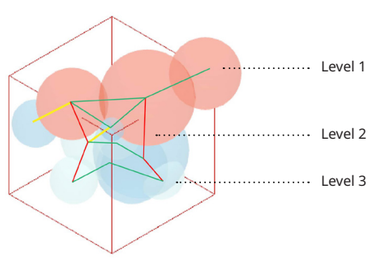
Plan B



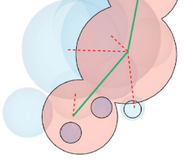
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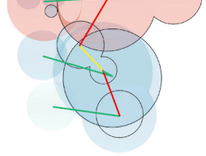
Neutral: Circulation analysis



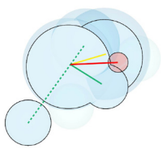
Plan A



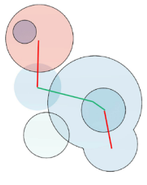
Section CC'



Plan B



Section DD'



Flat

Slope

Level

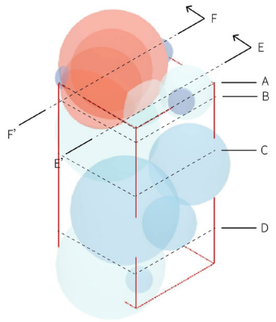
Fig 6.1.4: Outcome evaluation (2)

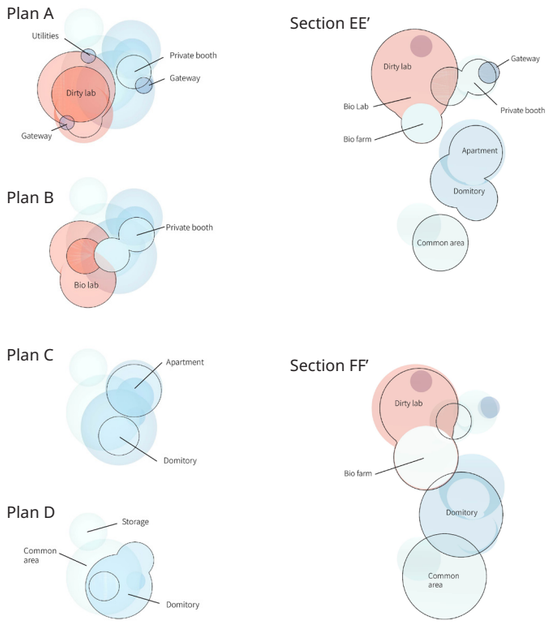
When no preference of bounding box is given, functions tend to gather together, and align equally under service functions and labs (survivable and sustainable functions that require lunar time). This results in a more compact zoning that minimize travel time.

However, equal levels cause less dynamic of the same function and segregation between layers. The static views, same-old routine and accumulating CO2 levels will harm habitants' mental well-being.

3 Evaluation of iterations

Vertical: Bubble diagram





Vertical: Circulation analysis

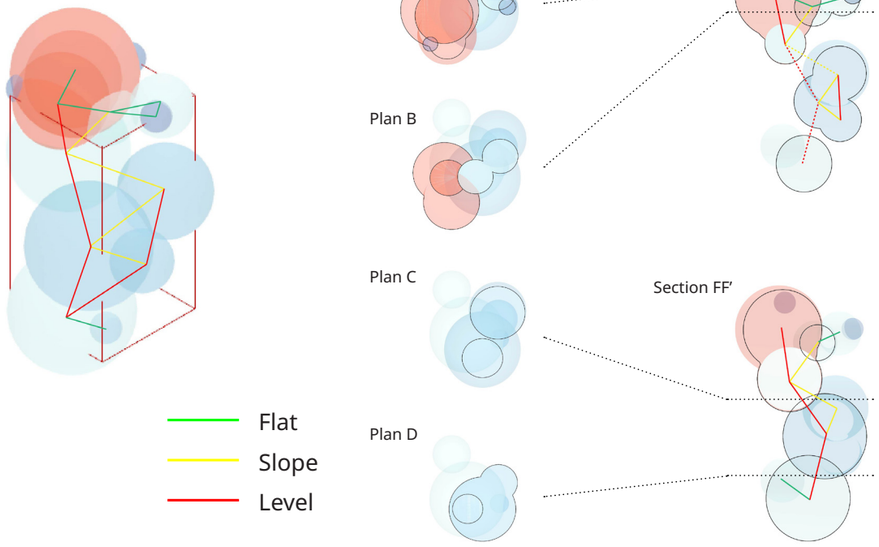


Fig 6.1.5: Outcome evaluation (3)

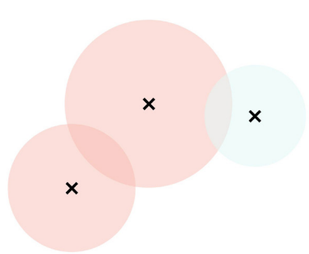
With fewer similar functions stay on the same level, this model shows rich variety of slope degrees and thus indicate more interrelationships. Operational functions that function with habitat's internal time is placed downwards and free from direct impact of space radiation.

6.2 Computational translation

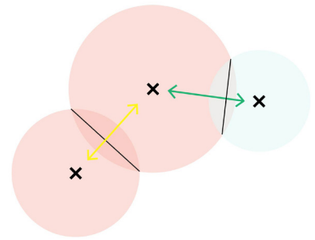
This approach translates from non-standard impressions to measured attractors and vectors, contributing rooms with individual gravity.

Voronoi

While bubble diagrams indicate size and gravity relationships, Voronoi not only helps to define wall (and floor) boundaries that independently to gravity direction, but also generates contacting surfaces between each rooms. With standing surface, working surface and wall surfaces defined, the bubble diagram can be translated to actual volumes with individual gravity.

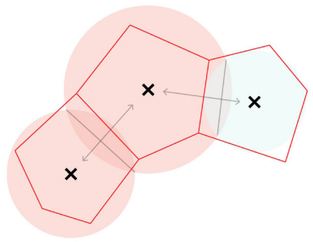


1. Bubble example

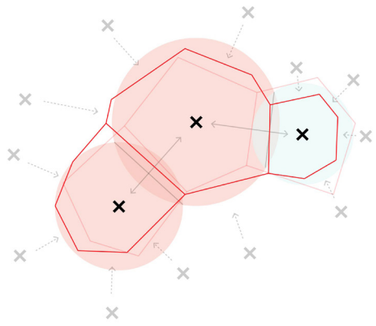


2. Boundary indication

Defined by each bubble's centre point in relation to other bubbles



3. Voronoi boundary

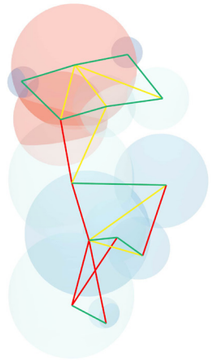


4. Weighted boundary

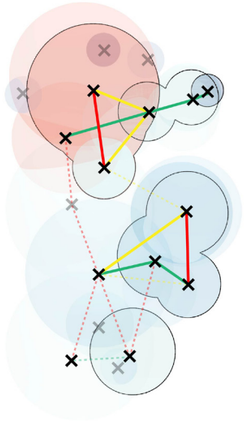
Defined by neighbouring points and distance

Fig 6.2.1: Voronoi analysis diagrams

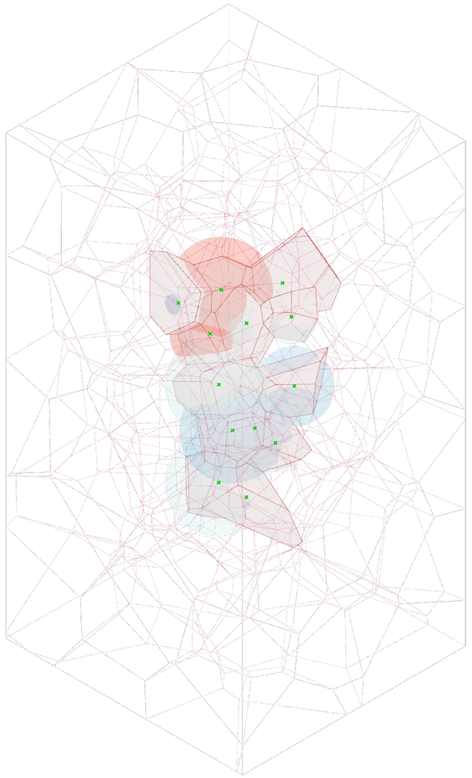
Voronoi application



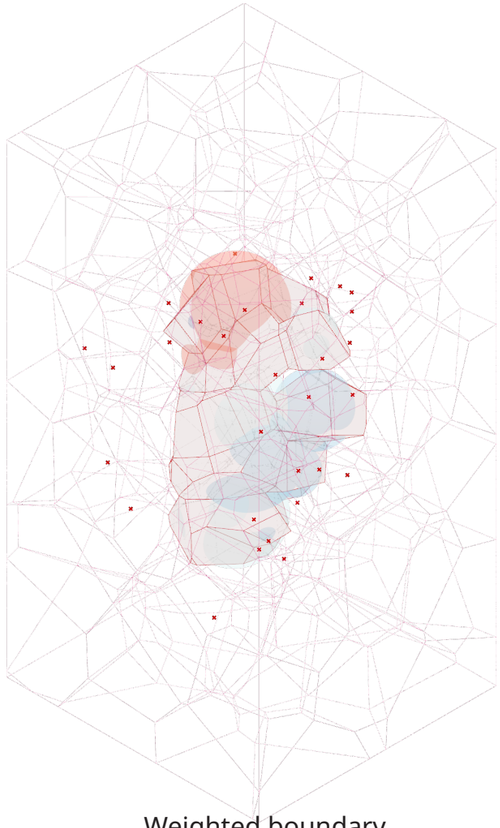
Circulation



Zone centroid



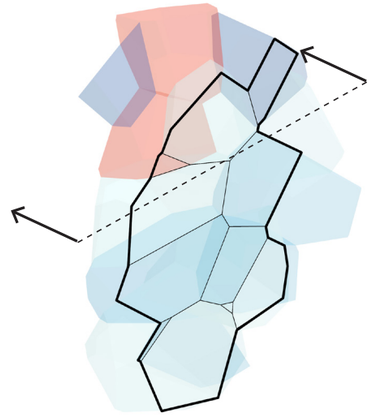
Voronoi boundary

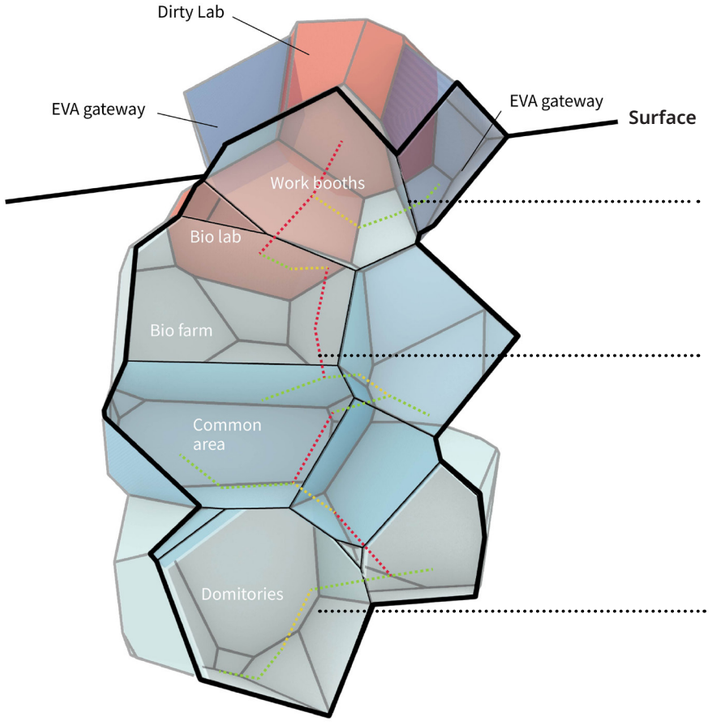


Weighted boundary

Fig 6.2.2: Voronoi application

Section (macro)





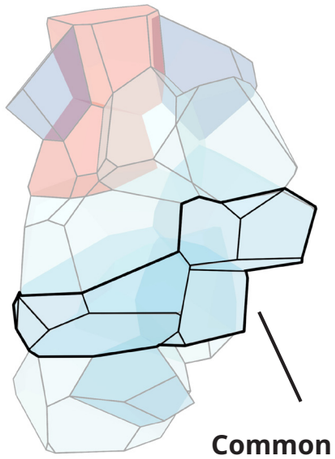
Gentle slope (0-10):
Indicate similar gravity, used for same or related move and function

Steep slope (35-57):
Indicate change of gravity, used for level change and function differentiation

Mid slope (10-35):
Indicate function change within same hierarchy, used for transition space of gravity changes

Fig 6.2.3: Voronoi macro section

6.3 Architectural exploration (meso)



Common area

As the main transition space between lunar time and internal time, common area connects Bio-farm, workstations and private space like dormitories.

Previously in the macro scale, each zone is defined by a dominant perception of gravity, distinguished by primitive diagram of slope gradient and relations.

In this sector, landing space is further explored as relationships between individual gravities inside one zone.

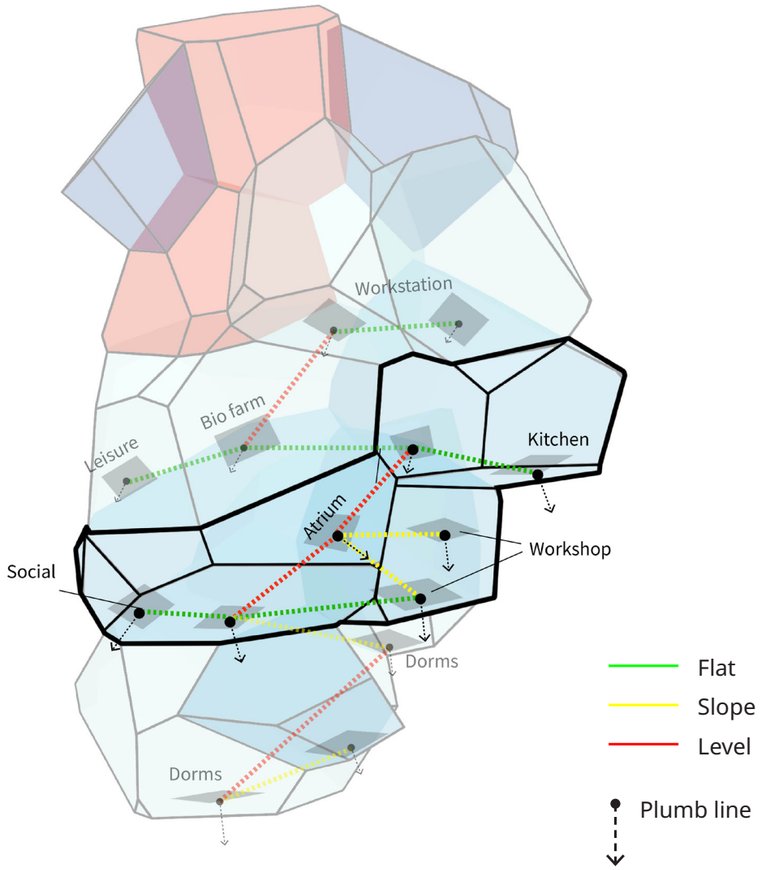


Fig 6.3.1: Common area circulation

Activity Inside Common area

Because the common area bridges upper workspaces and lower dormitories, its spatial usage shifts across the 24-hour cycle depending on the routines of three distinct user groups:

Crew: Travel for maintenance

Scientist: Travel to and from labs

Tourism: Train in gyms, for research

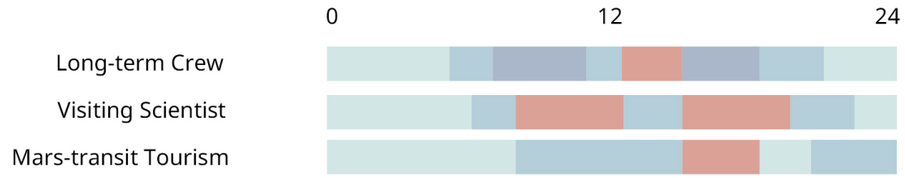


Fig 6.3.2: Timeslot allocation

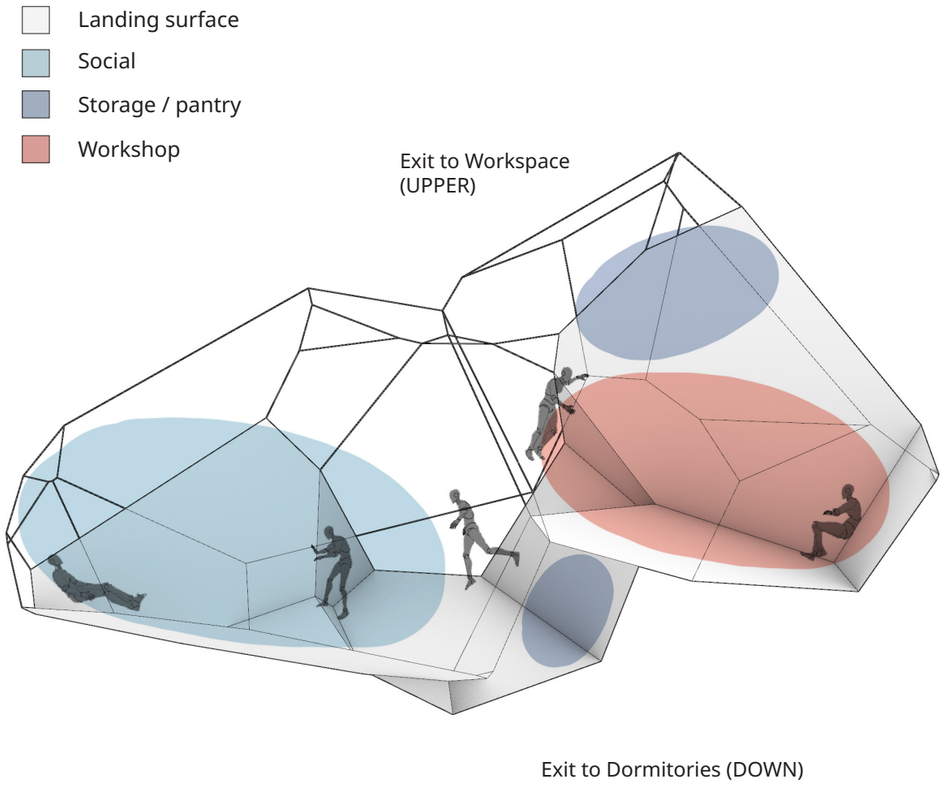


Fig 6.3.3: Primary movements

Space optimization

Standard 3D Voronoi tessellation often produces acute intersections that result in dead volume and awkward posture zones. To maximize habitable volume and ensure safe movement in low gravity, the cell boundaries are geometrically optimized so that all interior corner angles remain greater than 75°, eliminating sharp, unusable spaces

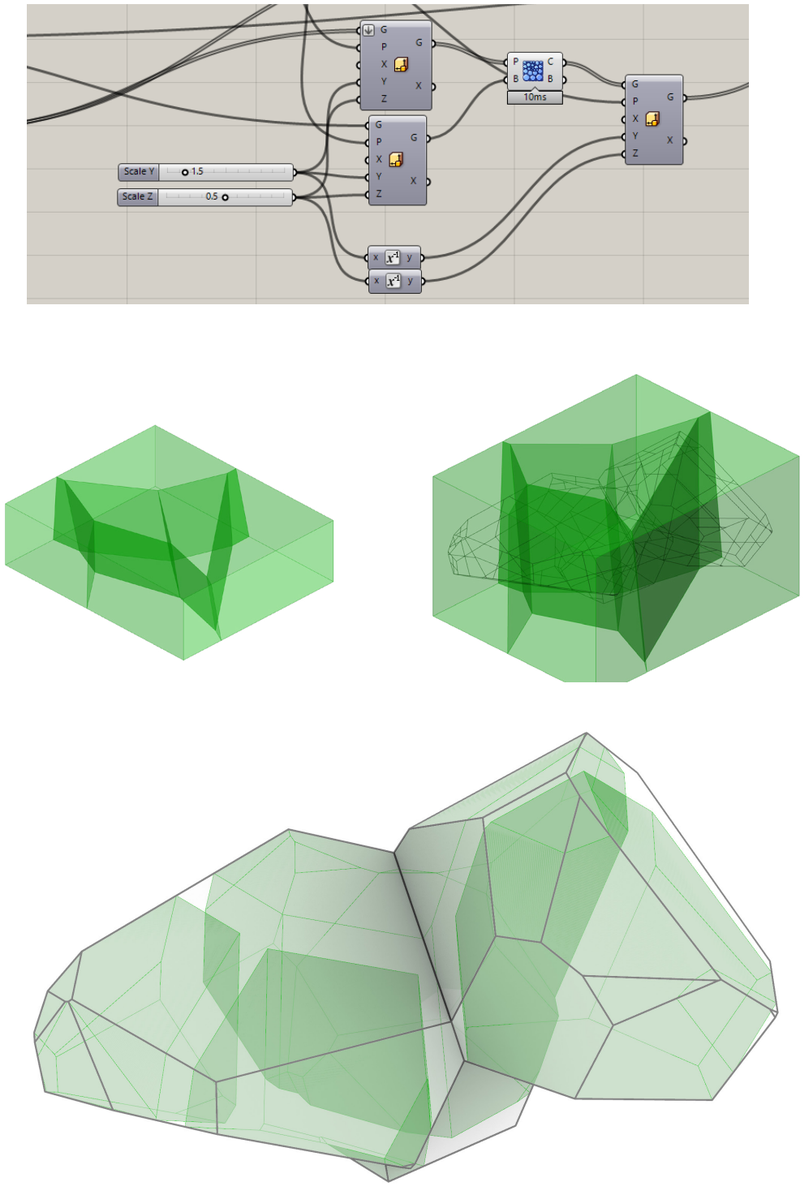
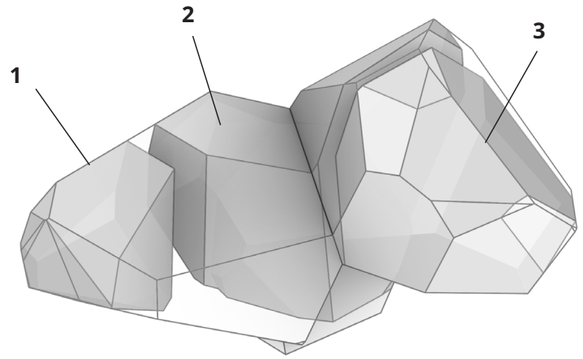


Fig 6.3.4: Partition definition

Voronoi

By applying 3D Voronoi within the common area, the volume is subdivided into three interconnected sub-zones—the Booth, Transition Hallway, and Workshop—each with its own localized gravity. Rather than relying on a fixed horizontal floor, the faceted Voronoi boundaries simultaneously define room enclosure, spatial openness, and the specific slope gradients required for each activity.

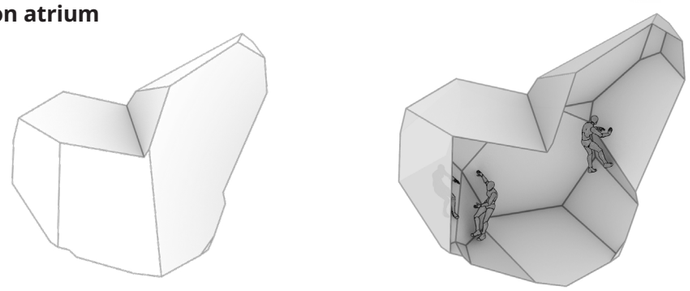


Space Openness

1. Booth



2. Transition atrium



3. Workshop

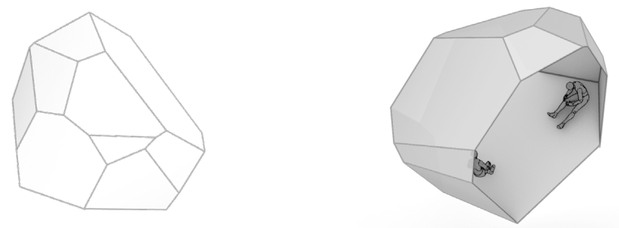
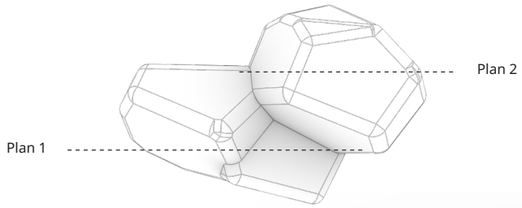
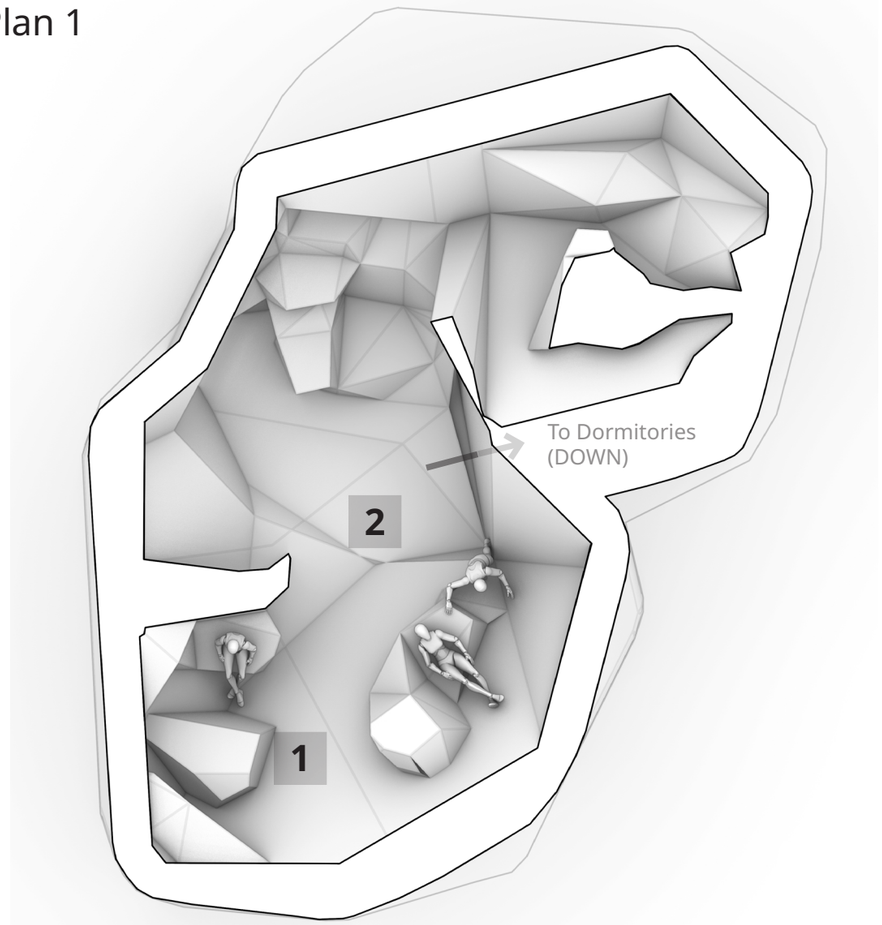


Fig 6.3.5 Subdivide zones

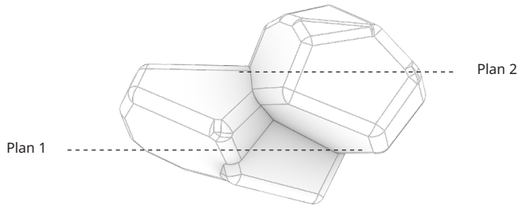
Plans



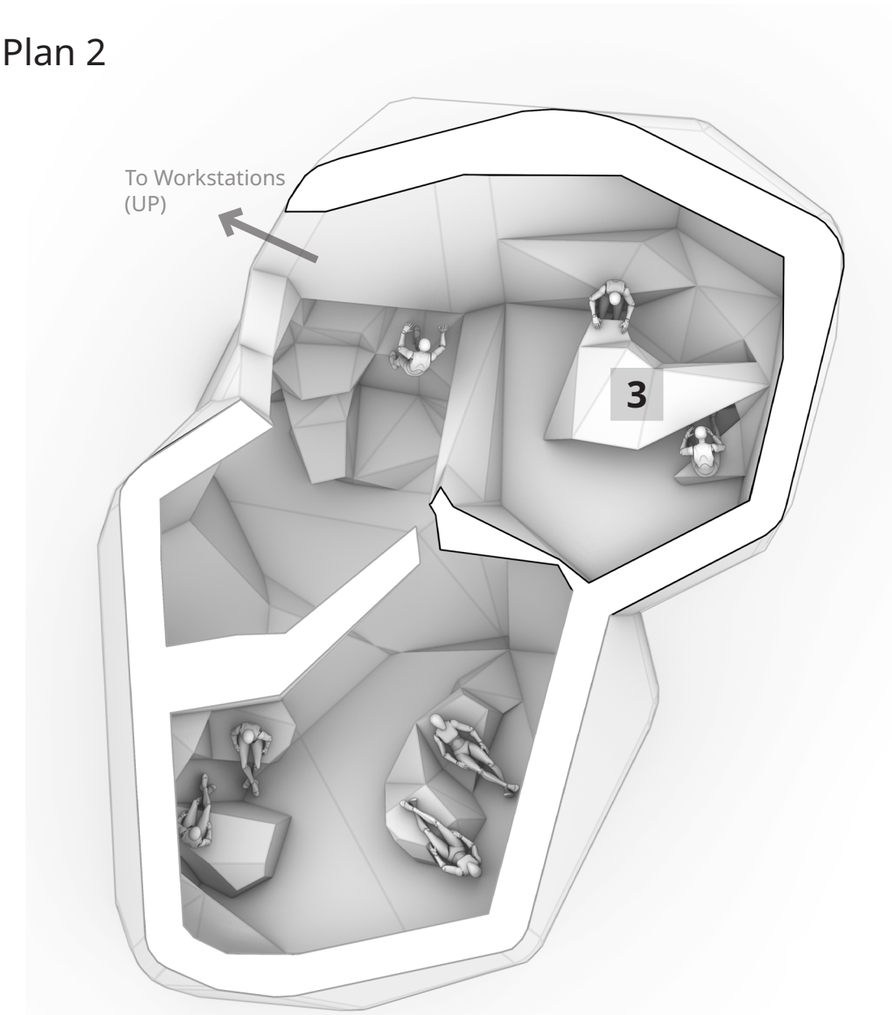
Plan 1



1. Booth
2. Transition atrium
3. Workshop

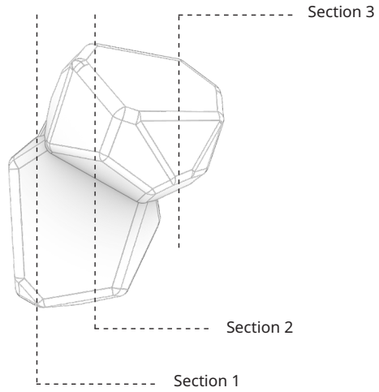


Plan 2

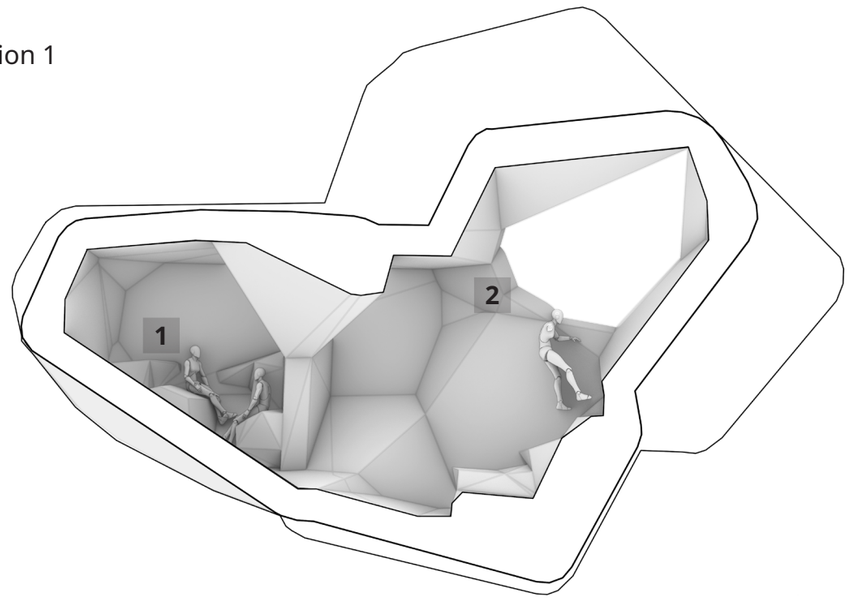


1. Booth
2. Transition atrium
3. Workshop

Sections

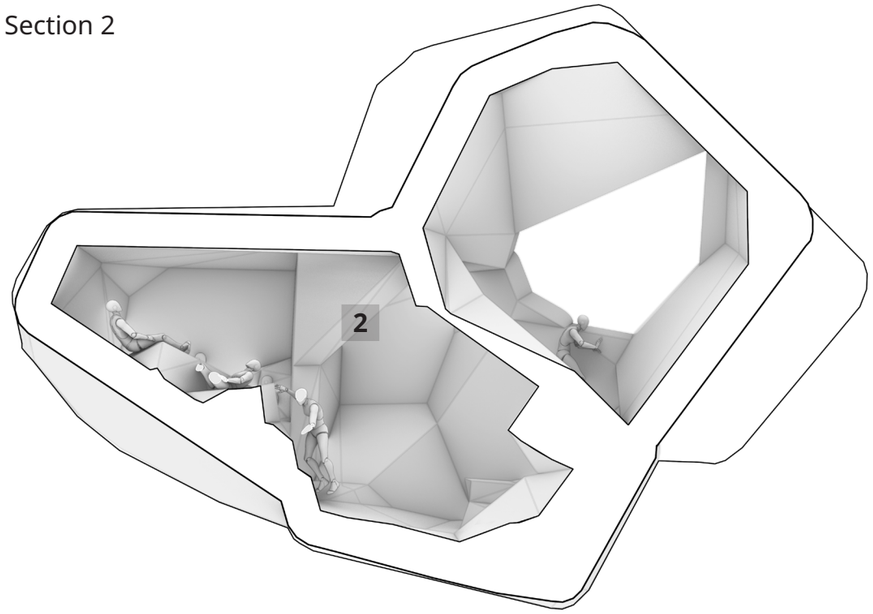


Section 1

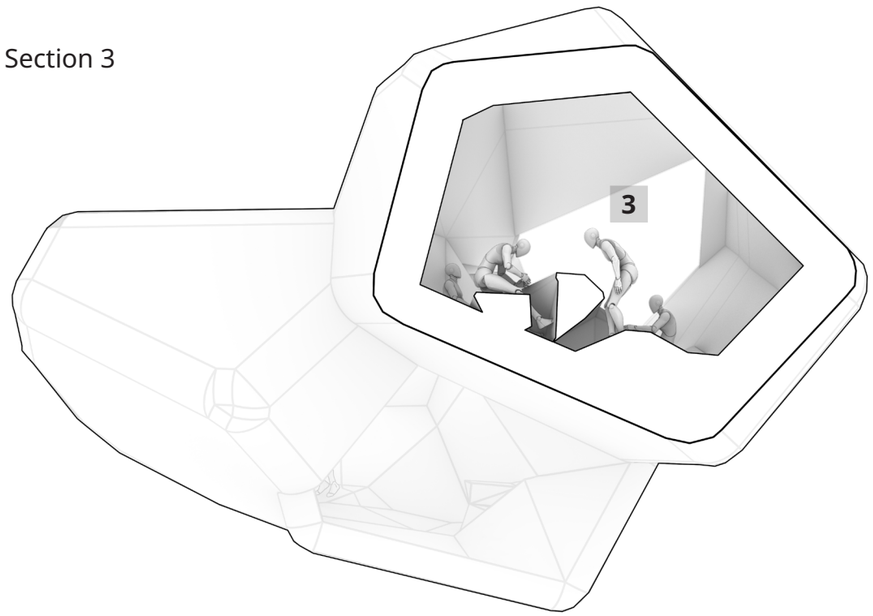


1. Booth
2. Transition atrium
3. Workshop

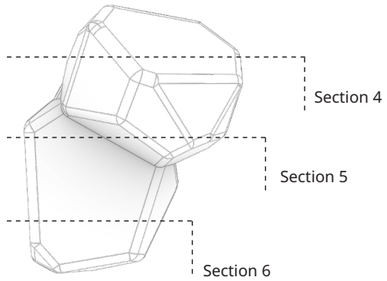
Section 2

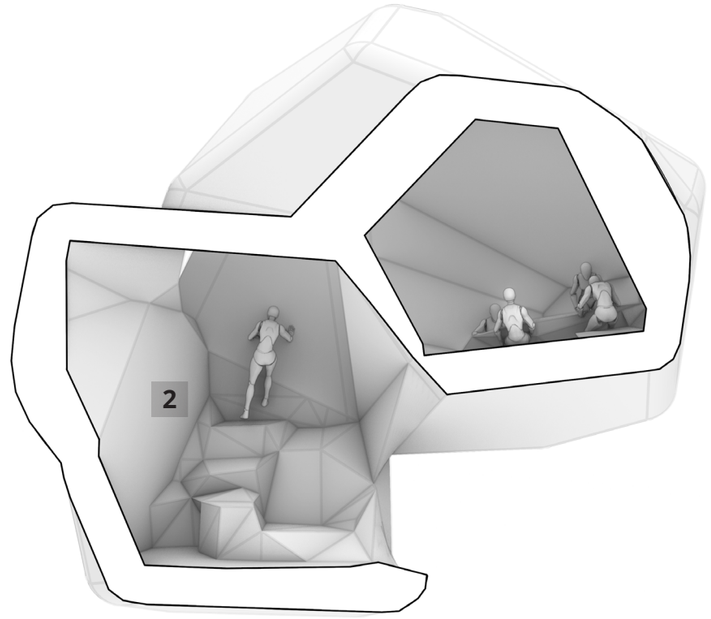


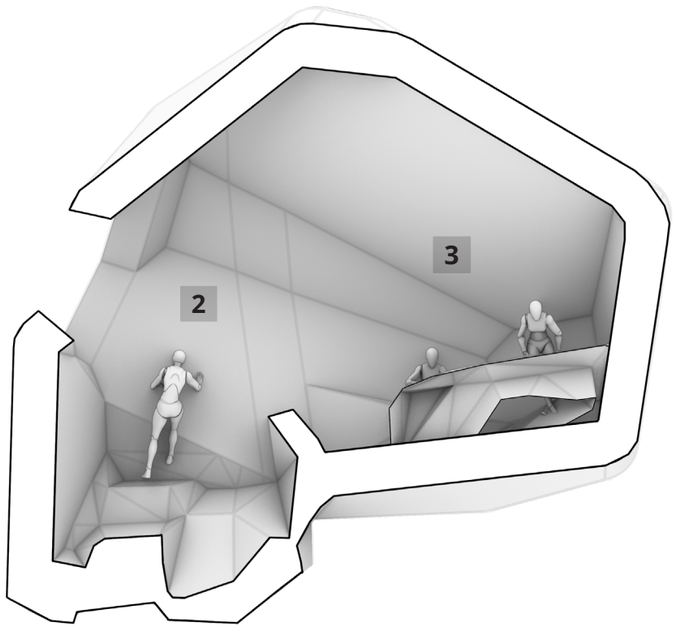
Section 3

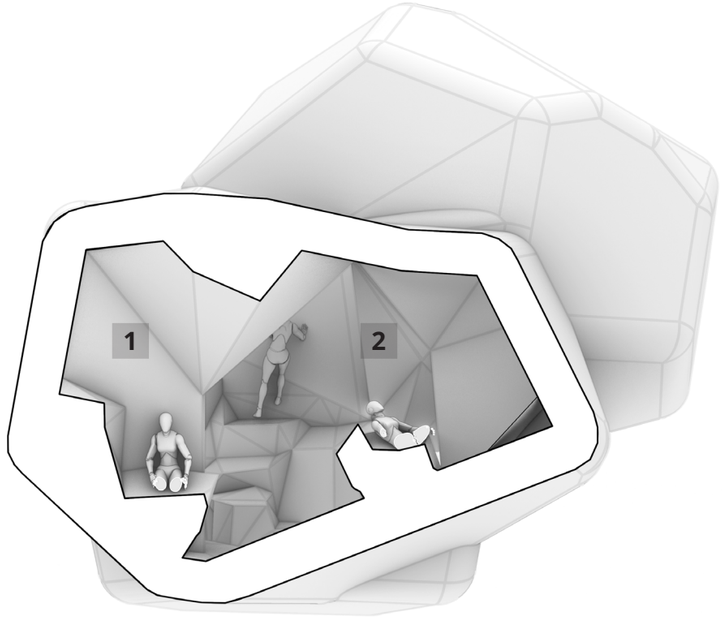


Sections









1. Booth
2. Transition atrium
3. Workshop

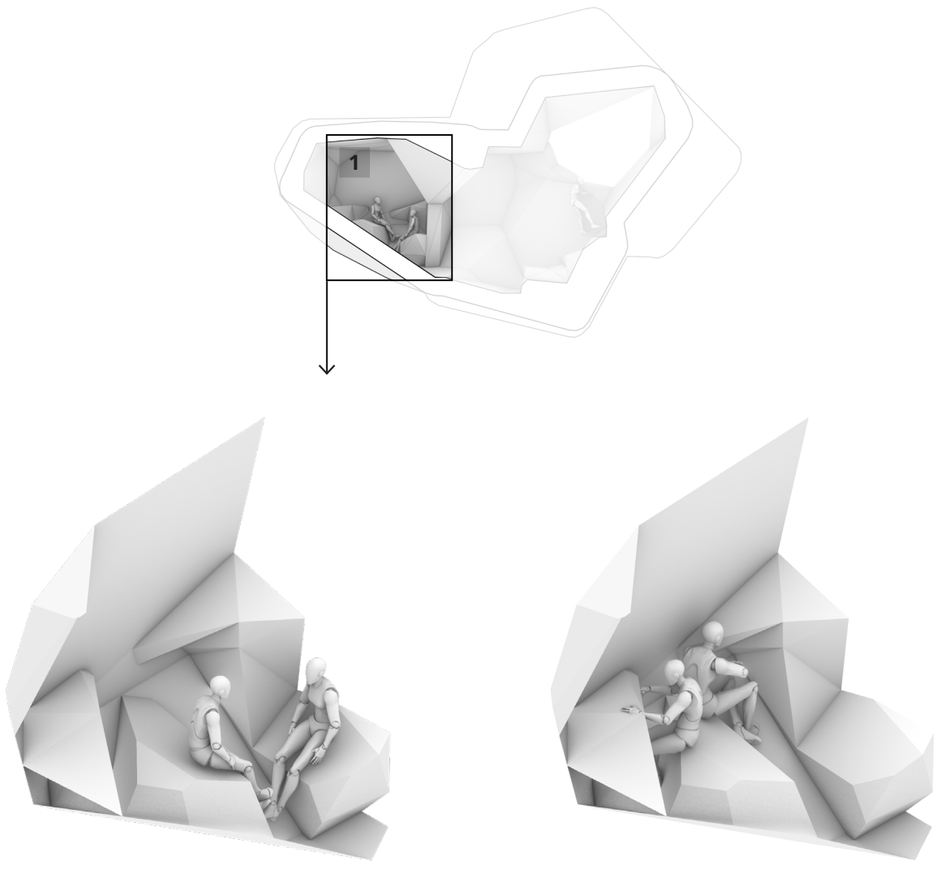
Furniture integration

Rather than adding loose furniture into an empty room, the Voronoi surfaces are subdivided to form integrated seating and tables, directly shaping how habitants perceive gravity in each sub-zone.

Booth: Meet & Eat

Gravity: Slope degree; change difference
Resolution: Space specification; stable surfaces
Body perception: Muscle intensity; visual synchronization

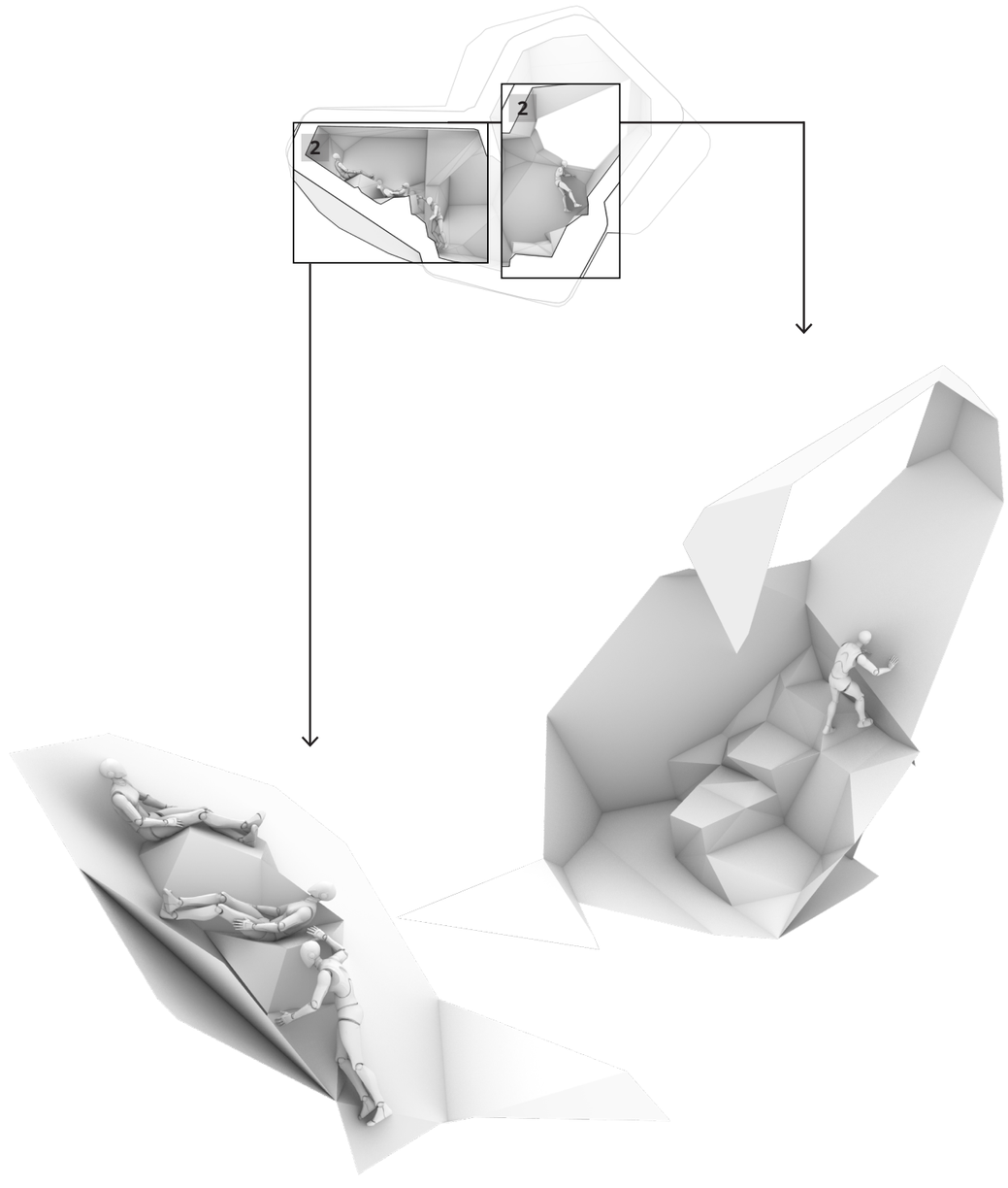
In the Booth, opposing mild-to-medium slopes (10-35) fold inward to create a contained zone of localized gravity. The boundary transitions into integrated stable surfaces. This geometry stabilizes the body with minimal muscular tension while aligning seated habitants face-to-face, establishing a shared visual horizon for eating and conversation.



Transition atrium: Rest & Go

Gravity: Slope degree; change difference
Resolution: Space specification; stable surfaces
Body perception: Muscle intensity; visual synchronization

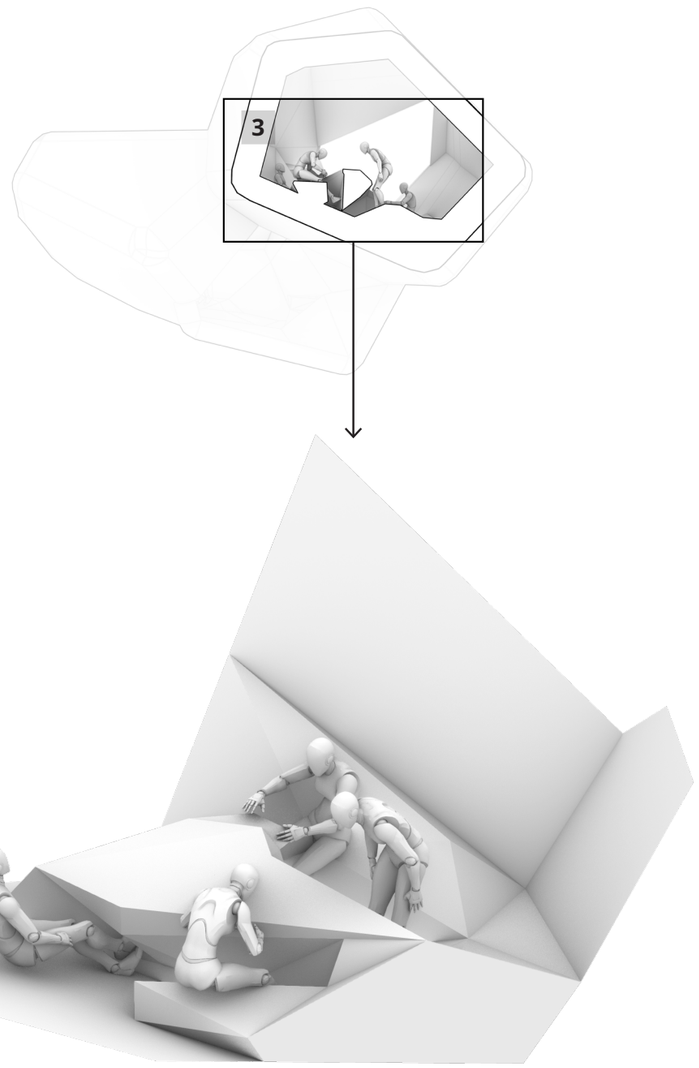
The Transition Atrium combines medium to steep slopes to accommodate both circulation and brief rest. On one side, steep steps require active muscular compression to ascend or descend; on the other, elongated inclined planes allow habitants to recline against the slope, shifting their visual anchor open toward the atrium while resting



Workshop: Work & Discuss

Gravity: Slope degree; change difference
Resolution: Space specification; stable surfaces
Body perception: Muscle intensity; visual synchronization

In the Workshop, localized gravity is centred around a work island. Gentle slopes and steady footholds brace the lower body, allowing habitants to lean forward into the workbench with steady muscular tension. Because all working planes tilt toward the centre, the table itself becomes the shared visual and physical anchor, dominating the group's orientation around their tasks.



Lighting

Visual information can be deliberately organized to influence how inhabitants interpret and navigate a space. Research on visual perception suggests that spatial experience depends not only on physical geometry, but also on how the environment is visually interpreted.

In this project, lighting is therefore considered a visual anchor that helps establish spatial orientation in the absence of a reliable gravitational vertical. Studies of visual ambient suggest that the distribution of light influences how people perceive safety, attention, and direction. Talmon et al. (2016) explored the relationship between room geometry and emotional responses, while Gibson (1979; 2014) emphasized that vision helps us understand how to act within a space. Pfeiffer et al. (2016) further examined the role of visual cues in the perception of gravity.

Building on these findings, the project explores three lighting placements:

Head light: to create a sense of enclosure and arrival

Point light: to emphasize specific activity areas

Light stripe: to provide directional cues along a route

In corresponding to exhibition design by Herbert Bayer at the Exposition des Artistes Décorateurs, Deutscher Werkbund exhibition display (1930).



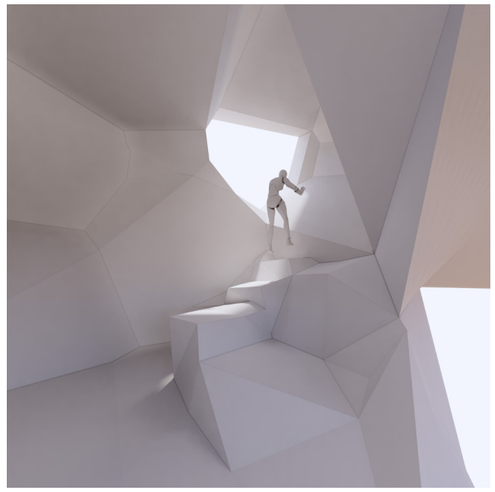
Fig 6.3.6 Museum lighting at the Exposition des Artistes Décorateur



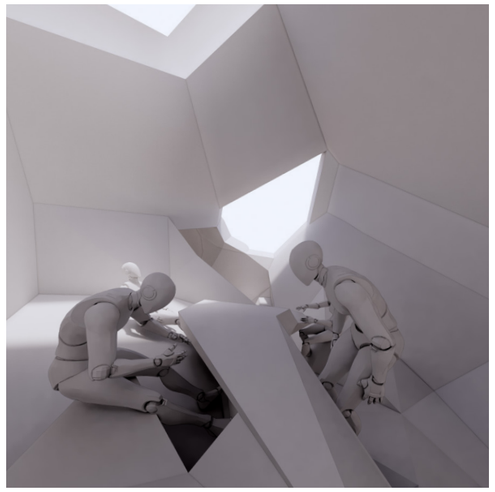
Head light above sofa



Head light above booth



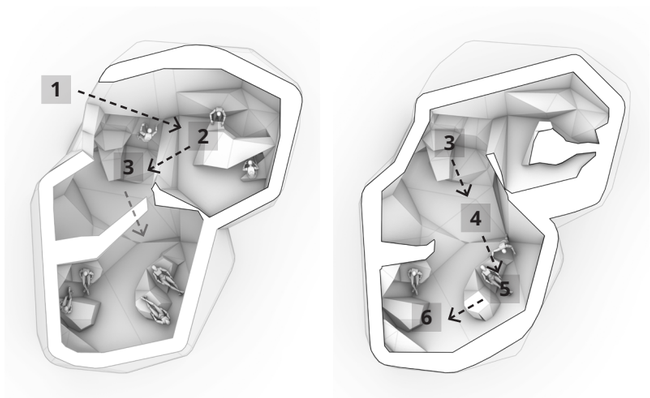
Directional lights at stairs

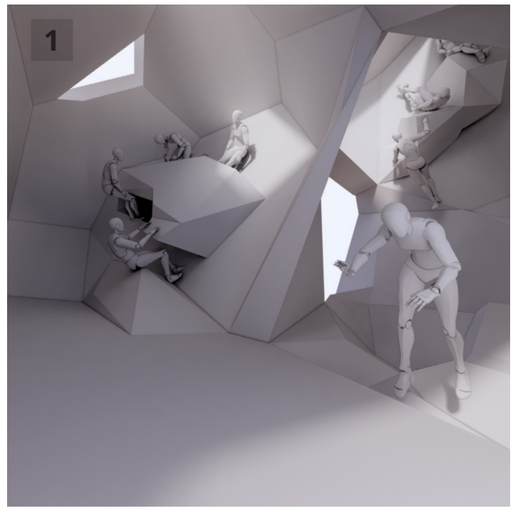


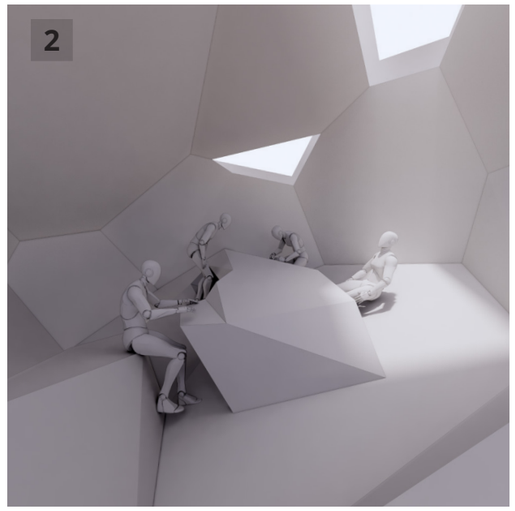
Point lights at working table

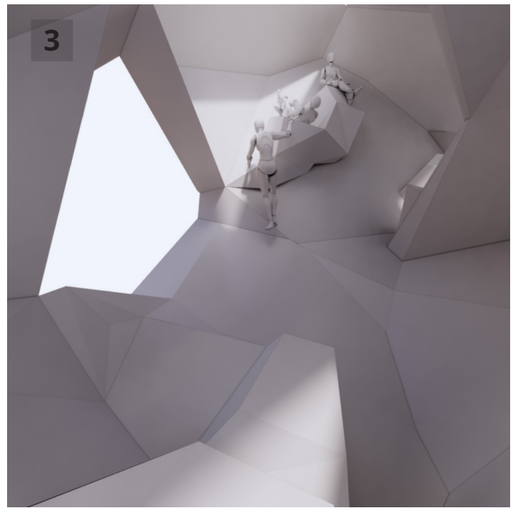
Fig 6.3.6 Lighting experiments

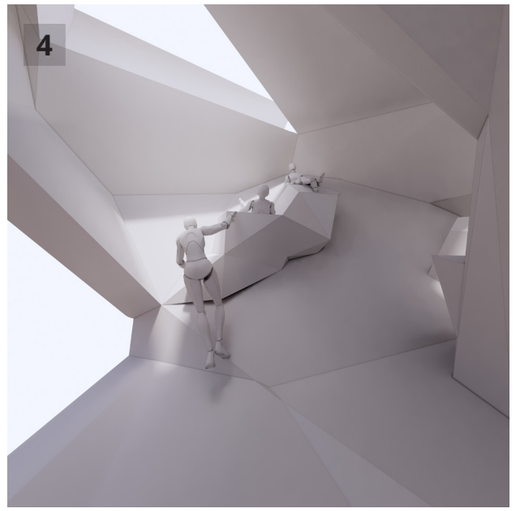
Journey



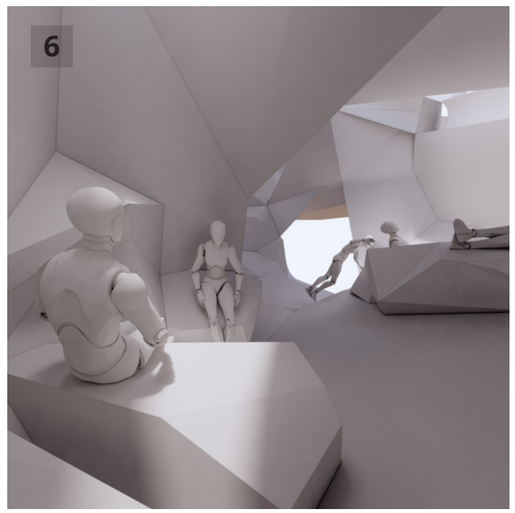










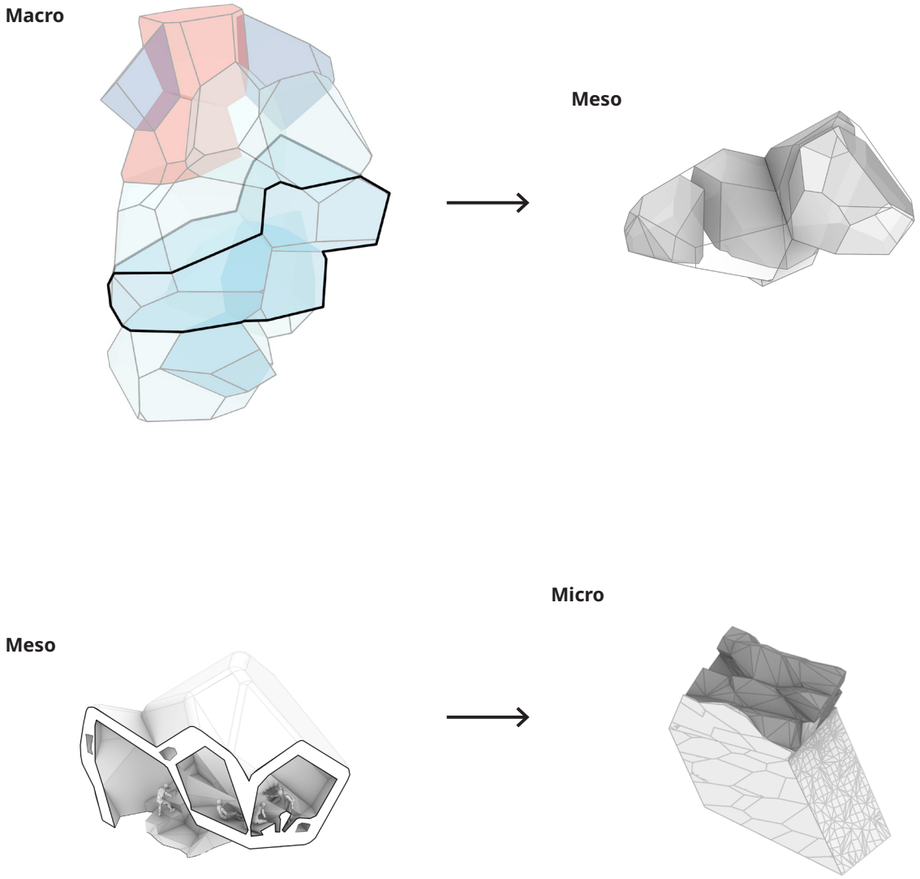


6.4 Proof of concept (micro)

To validate the theoretical and structural viability of the habitat, this section extracts a single micro-scale architectural fragment to construct and analyze in detail.

Voronoi streamline

Voronoi tessellation serves as the continuous computational design strategy across all scales of the project. It translates seamlessly from defining macro-level programmatic zoning to shaping meso-level room boundaries, and finally generates the precise micro-level structural facets required for robotic fabrication and physical assembly.



Material properties

Lunar regolith
According to NASA (2015), Lunar regolith, together with binders, can be used as construction filaments for lunar habitats. Although there are debates about the type of binder should be used on the moon, the direction of FDM printing is an understood rule.



Fig 6.4.1: 3D printing lunar regolith, NASA, 2019

Shielding

To ensure long-term mission viability, the habitat relies on a vertical radiation shielding strategy. Because radiation exposure decreases significantly with depth, programmatic zoning is directly aligned with safety requirements. The upper workspaces, protected by the 80 cm 3D-printed sintered regolith shell, are designed to receive approximately 110 mSv/year (roughly half the exposure of the International Space Station). Conversely, as the habitat descends, the lower dormitories leverage the overlying structure and natural lunar terrain to drastically reduce exposure to < 1 mSv/year, establishing a highly protected safe haven for extended human habitation.

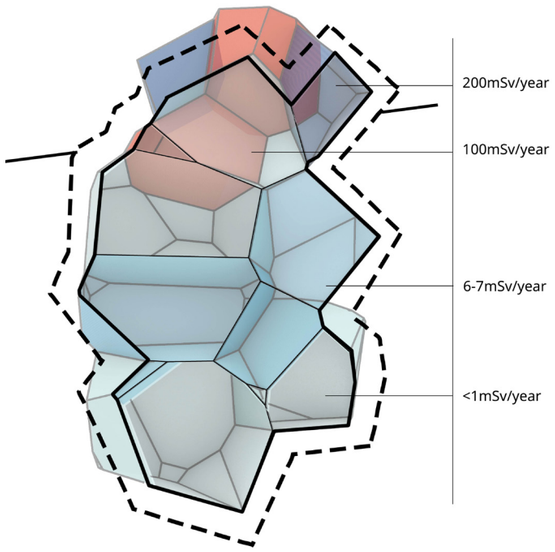


Fig 6.4.2: Radiation Shielding

Structure

The structural integrity of the 3D-printed regolith relies on the principles of the inverted catenary. Just as a suspended chain naturally assumes a curve of pure tension, inverting this curve creates an arch that operates entirely in pure compression—an optimal structural model for unreinforced 3D-printed materials like lunar regolith.

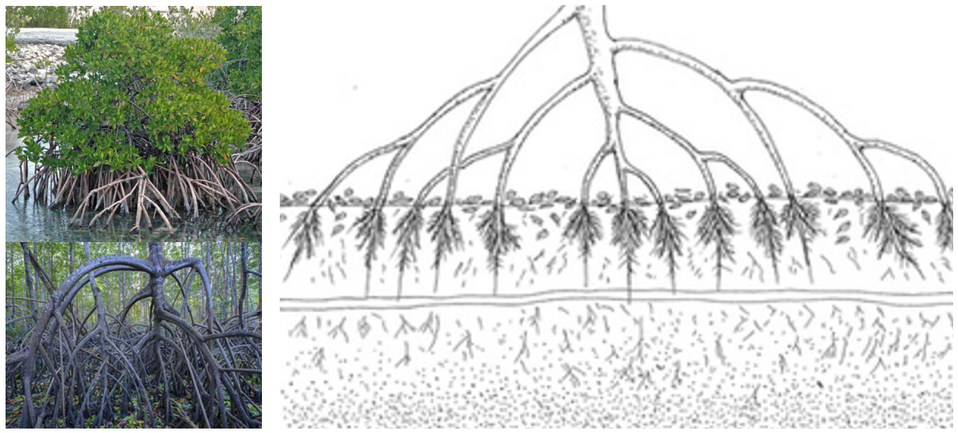
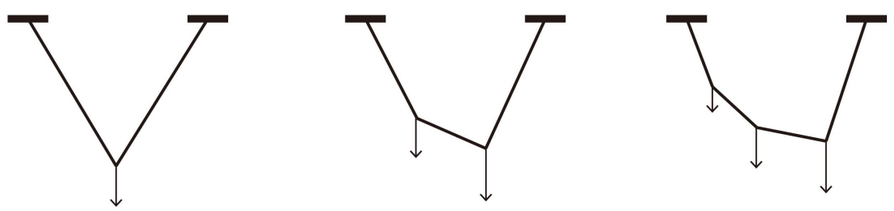
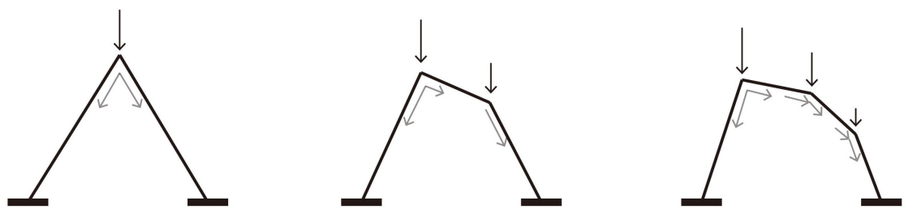


Fig 6.4.3: inverted nested catenaries in nature
[Proceedings of the National Academy of Sciences, (2016)]

Hanging Chains (catenary)



Inverted Catenaries (voronoi thrust forces)



(Inverted) Nested Catenaries

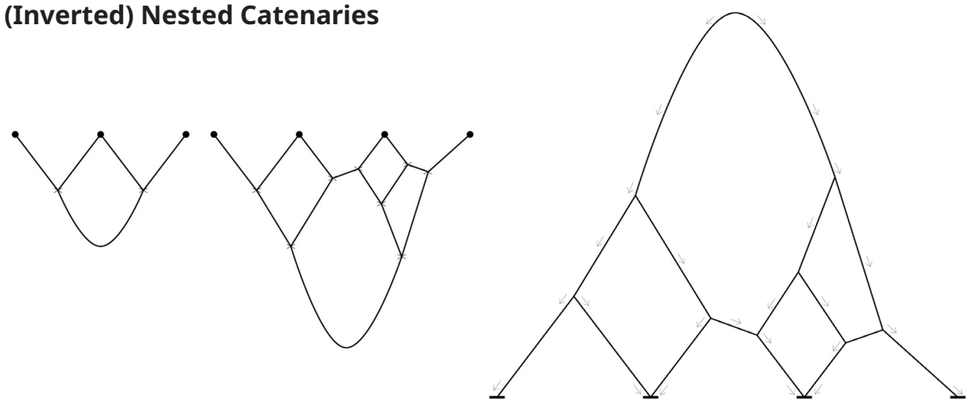


Fig 6.4.4: Inverted catenaries and voronoi relations

Fragment

By mimicking this logic, voronoi boundaries spread downward thrust forces and dead loads into lower ground, minimizing bending moments and tensile stress across the habitat shell. This ensures the interior spaces (such as the workshop and transition atrium) remain structurally stable and fully open, without requiring intrusive central support columns.

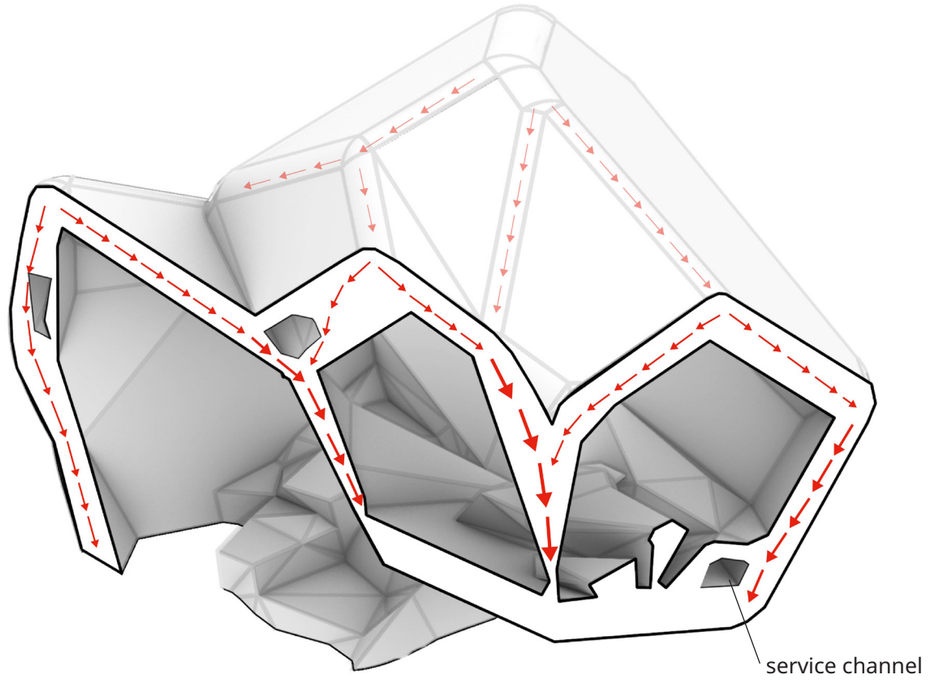
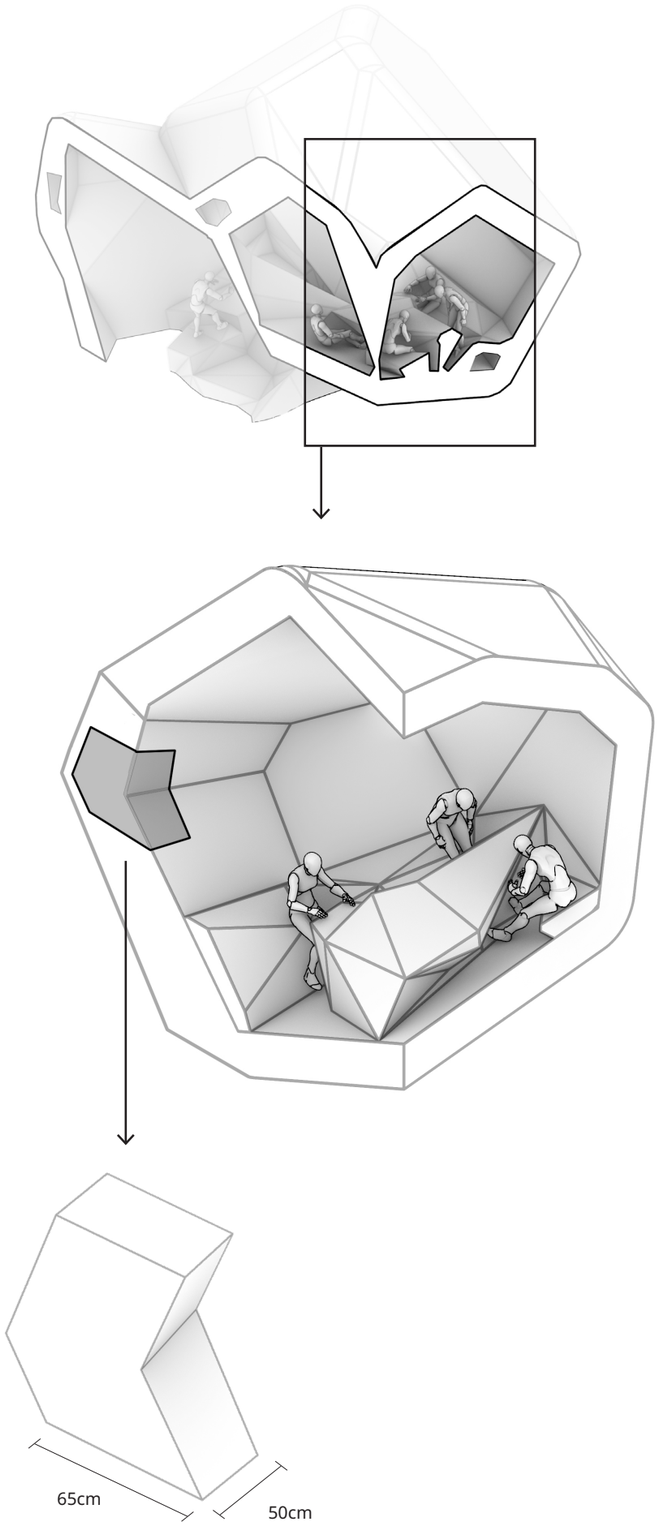
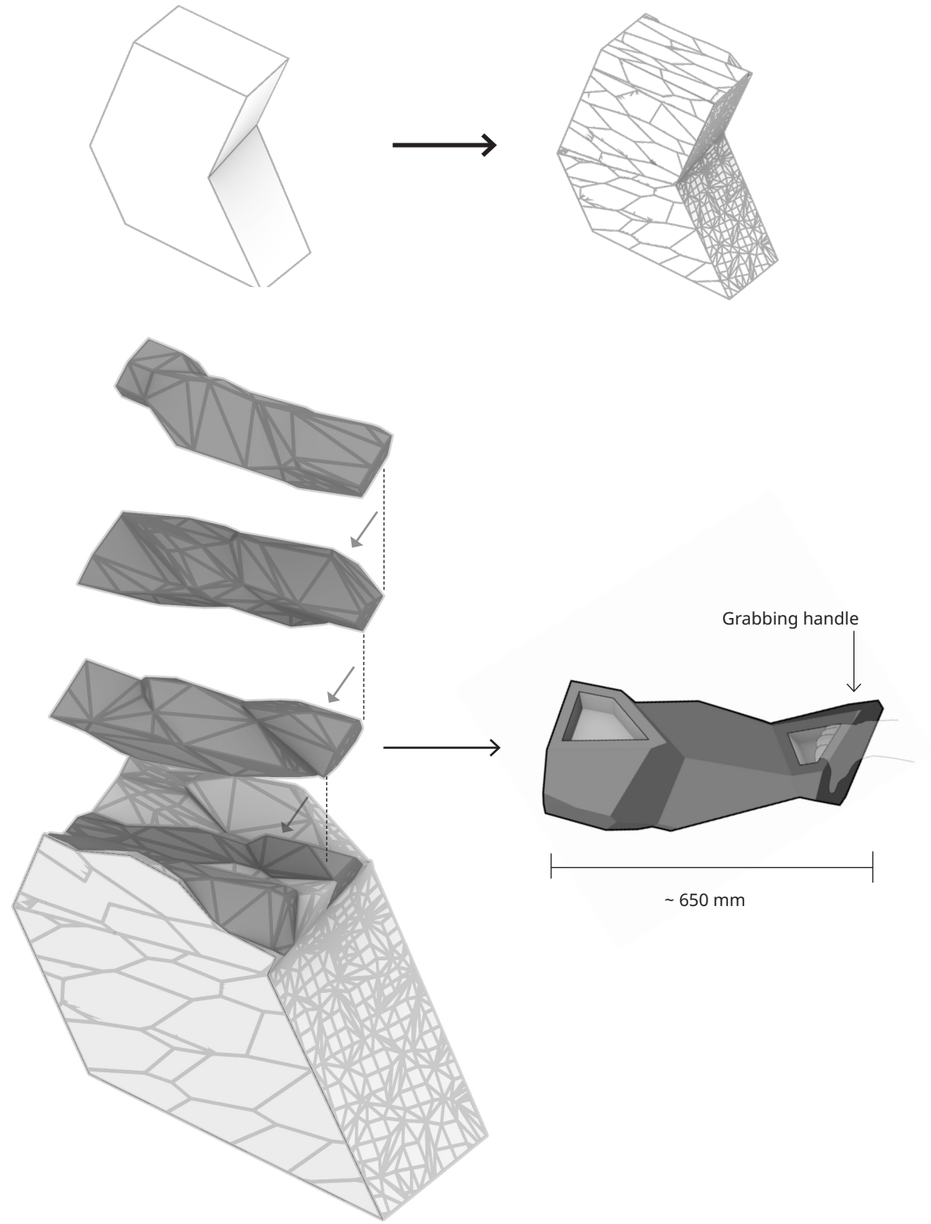


Fig 6.4.5: Structural logic



Assembly

Through computational design, the continuous Voronoi walls are subdivided into blocks (approximately 650 mm in length) optimized for 3D printing and robotic handling. To join the pieces, the interlocking faces of the blocks are geometrically calculated using the same inverted catenary principle. As the robots stack the components, the angled joints wedge together under their own weight, utilizing pure compression to lock the individual units into a continuous, self-supporting structure.



Robot to Design Production

To physically validate the computational design and assembly logic, a robotic workshop was conducted using EPS foam mock-up components. A robotic arm was programmed to execute the precise movements required for construction, testing the feasibility of the generated grabbing handles and interlocking geometry.

EPS mock-up components



Fig 6.4.6: Milling workshop

Assembly mock-up



1. Approaching component
2. Picking component (assisted)
3. Transporting component
4. Adjusting Component
5. Placing component (Assisted)

Fig 6.4.7: Assembly workshop

3D printing components

Parallel to the robotic assembly tests, physical 3D printing trials were conducted to verify the material extrusion process. These physical prototypes demonstrate that the complex, multi-layered patterns generated by the computational model can be successfully translated into continuous robotic toolpaths, simulating the layer-by-layer deposition of the regolith mixture.

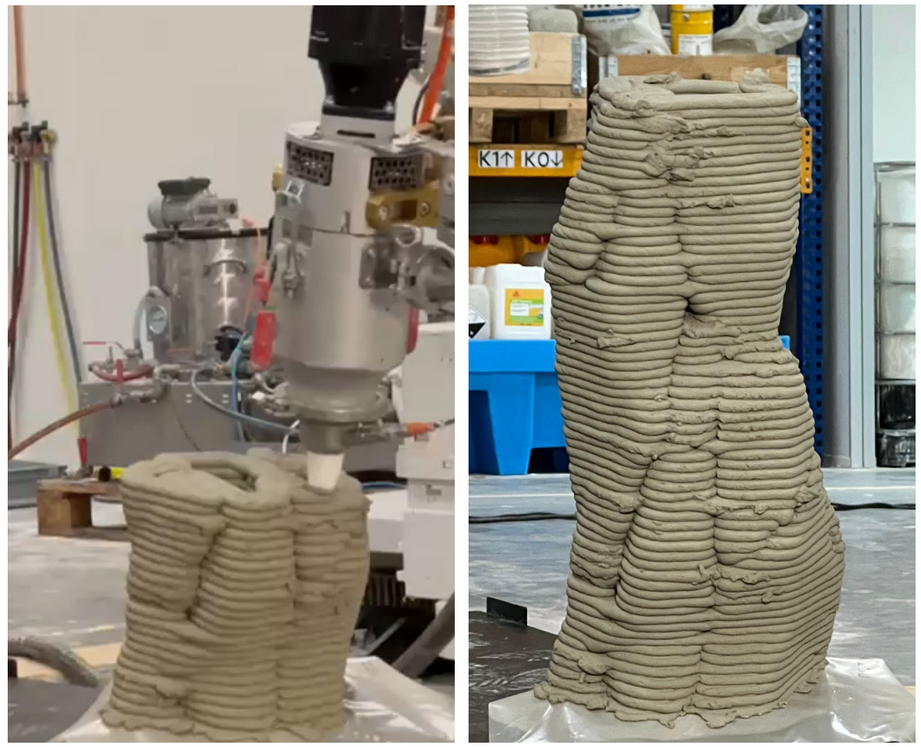


Fig 6.4.8: 1:1 3D printing part

Proposed System for lunar condition

The habitat construction relies on swarm robotics, utilizing multi-limbed systems modeled after NASA's LEMUR (Limbed Excursion Mechanical Utility Robot), which was field-tested in Death Valley, California.



Fig 6.4.9: Swarm robot
[NASA]

Sloped voronoi blocks serves a dual purpose during assembly. As the components are stacked, the surfaces naturally generate a stepped topography. This creates an integrated, walkable path that allows the climbing robots to traverse the exterior shell and continue building upward. (Cheng, F. C. et al., 2026)

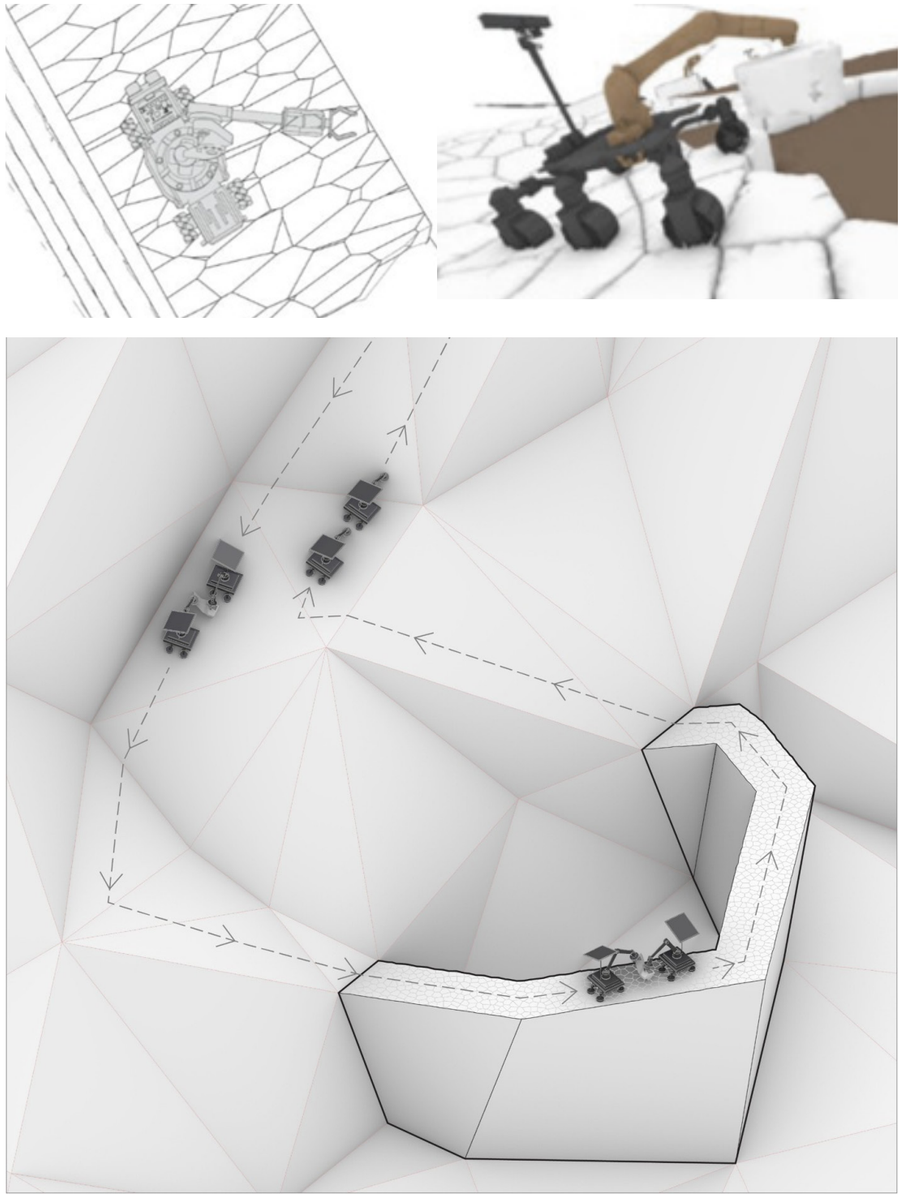
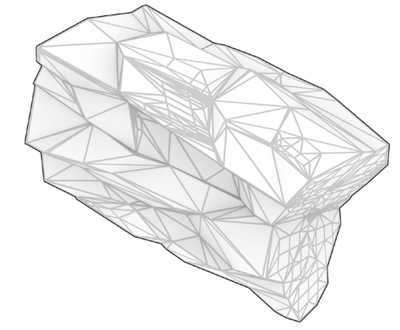


Fig 6.4.10: Construction process assisted by swarm robots
[Cheng, F. C. et al., 2026]

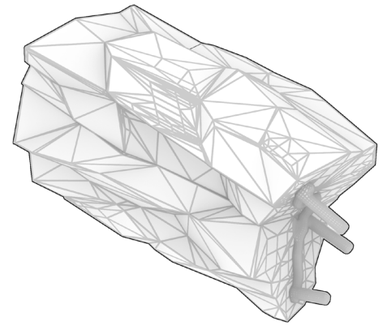
Light integration

Based on the lighting workshop, artificial illumination is embedded directly into the physical components to establish clear visual anchors.

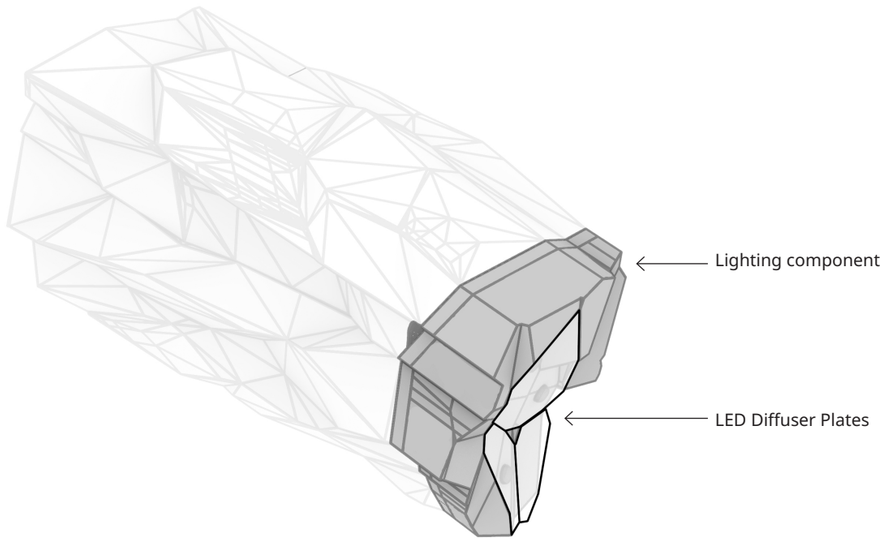
The LED panels are designed to perfectly follow the faceted geometry of the voronoi surfaces, to maintain continuous aesthetic of the habitat. Cables are routed internally through structural channels that could be left out during R2DP component design stage, keeping the habitable surfaces entirely unobstructed.



1. Designed components



2. Inner cable routing preset



3. Attathed lighting panels that follow geometry

7.0 RELEVANCE

7.1 Off-earth Relevance

Prevent illusion and maintain well-being for Lunar habitants

In Gibson's (2014) "The Ecological Approach to Visual Perception", he argued that poor spatial perception design can lead to severe cognitive load, or even illusion. While on earth, the effect of seasickness may provide a better description for this illusion. Seasickness occurs when the brain's "plumb line" and its "visual vertical" stop agreeing with each other. By aiming very far away, people regain visual anchor and thus the dizziness stopped.

While in moon EVA missions, low gravity worsen the situation of "plumb line", while the monotony environment provide few visual vertical, astronaut's motion may cause sickness, as stated in the report of Apollo 14 (NASA, 1971). The picture also shows the perception on the moon is less clear whether there's a hill or a pit in the distance.

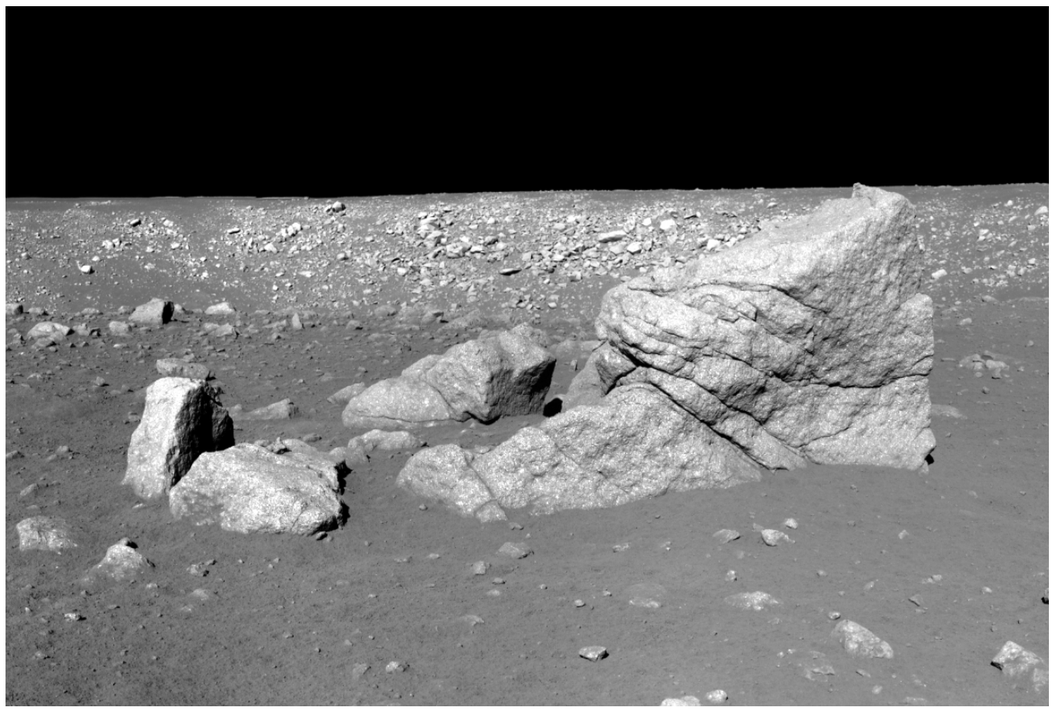


Fig 7.1: lunar surface (2020)

7.2 On-earth Relevance

Everyday of visual & object vertical

Coincidentally, in the last century, De Stijl movement also tricks people's visual vertical of gravity. Buildings on Earth are mostly built with hierarchy (or floors), but when there's no or less "below" or "above" hierarchy, people's cognition, habits, ... will inevitably change as well. Even without gravity, we can still obtain cues for spatial perception because geometry triggers our visual and muscular responses.

Improve spatial perception

Spatial research could improve design process by taking individual's perception into consideration, encourage design for specific purposes or functions as well as reduce cognitive load. For example design for dementia, or "Neuroarchitecture", enhancing cognitive performance in workspaces.

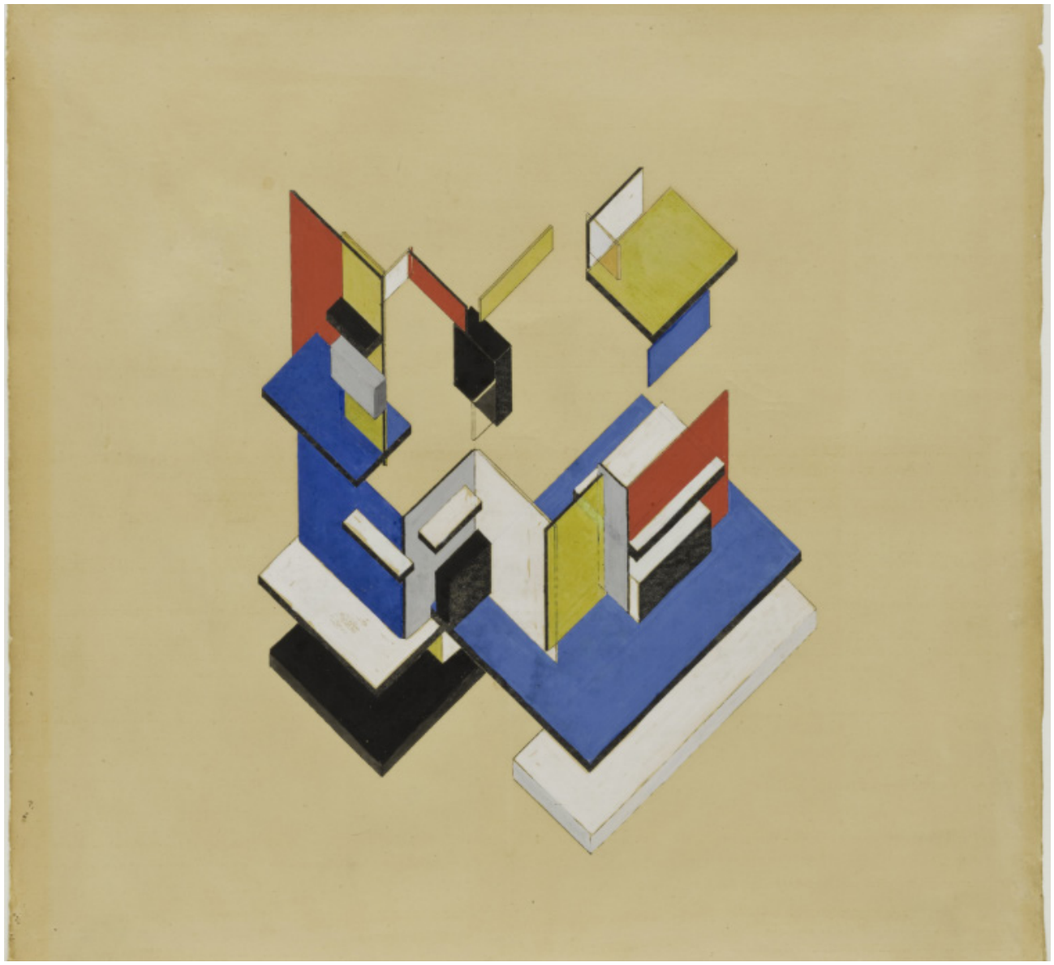


Fig 7.2: De Stijl movement (1923)

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9.0 REFLECTION

Space Efficiency and Individual Gravity

The transition from Earth's 9.8G "plumb line" to the moon's 1/6G environment fundamentally redefines spatial efficiency. By abandoning traditional horizontal floors and vertical walls, the habitat maximizes habitable volume through the integration of individual, localized gravities. Instead of stacking homogeneous floors, the design utilizes continuous, multi-faceted surfaces that act as distinct visual and force anchors. This mind-and-muscle framework ensures that every architectural plane serves an ergonomic or cognitive purpose—whether it is a mild slope cradling the body for social interaction or a steeper gradient demanding muscular compression for vertical transit.

Consequently, spatial efficiency is no longer measured by square meters of flat floor space, but by the density of usable affordances. This prevents the cognitive dizziness common in low gravity and reclaims "dead" volume, creating highly functional, 3D-navigable interiors.

Computational Logic: Voronoi vs. Isosurface

The computational journey initially explored isosurfaces to define these non-standard volumes. However, isosurface generation typically relies on the marching cubes algorithm, which discretizes 3D space into a uniform volumetric grid of voxels. As the design scales down from macro-zoning to micro-components, the necessary grid subdivision increases exponentially, leading to immense computational complexity and rigid grid-based volumes that cannot translate to smooth architectural expressions.

Voronoi tessellation, conversely, proved to be a highly consistent and scalable strategy across all scales of the project. Because voronoi is a vector-based mathematical framework, it calculates boundaries based on point-to-point proximities rather than arbitrary grid subdivisions. For form-finding and spatial zoning, this proximity logic optimally translates programmatic agent behaviours (pull, attraction, cohesion) directly into dynamic geometric relationships.

For physical construction, the resulting voronoi topology is inherently structurally optimized; its faceted boundaries naturally mimic nested inverted catenaries. This geometric configuration operates in pure compression, efficiently channeling the massive dead loads of 3D-printed regolith shielding downward without the need for internal support columns, making it perfectly suited for robotic fabrication.

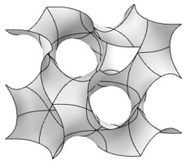
Technological Limitations

Despite these structural and perceptual optimizations, the project operates within the anticipated limitations of 2080s technology. The construction timeline relies entirely on the assumption that autonomous LEMUR swarm robots and large-scale In-Situ Resource Utilization (ISRU) regolith extrusion will function reliably in extreme lunar conditions. Furthermore, the architectural freedom is inherently restricted by non-negotiable life support parameters, including the rigid spatial demands of closed-loop environmental systems (such as the MELiSSA loop) and the material required to maintain radiation exposure.

Academic Reflection

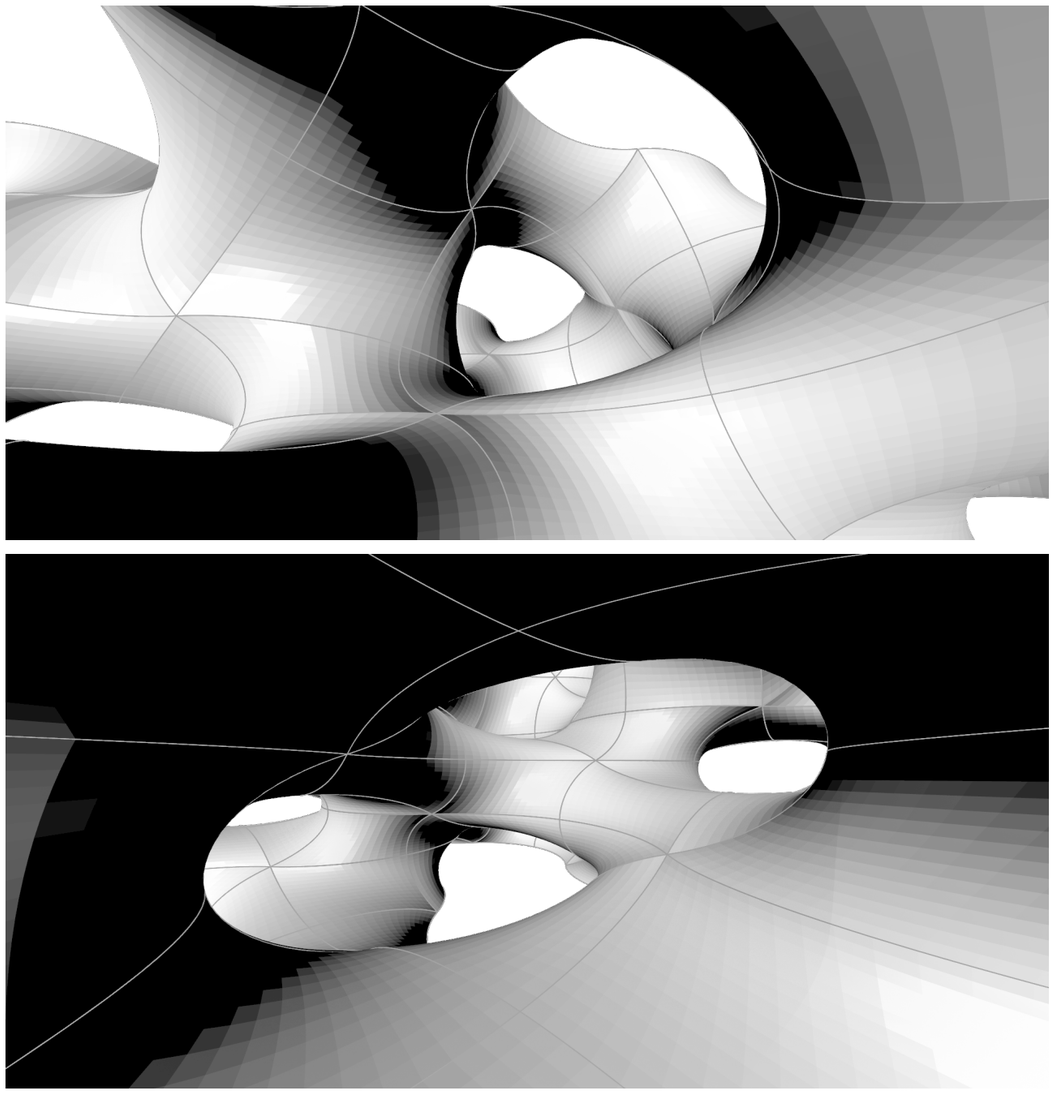
Ultimately, this research implies that as humanity moves from surviving to living in space, the aesthetics and typologies of architecture will change enormously. By translating the extreme physiological and perceptual shifts of lunar habitation into built morphology, the designer's role expands beyond generating protective, engineering-driven shells. True extraterrestrial architecture emerges only when we abandon Earth-bound geometries and allow human cognition and physics based on different gravities to directly shape the built environment.

10 APPENDIX



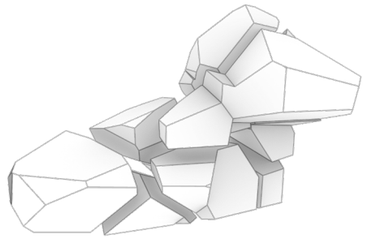
Gyroid experloration

First impressions



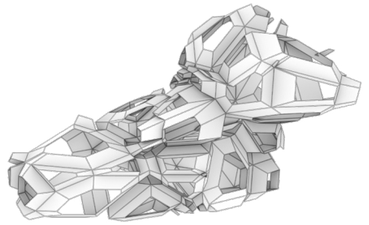
Iso-surface transformation (meso)

Take advantage of Voronoi approach, faces can be extracted and categorized to landing surface (force vector) and visual receiver (visual vector)



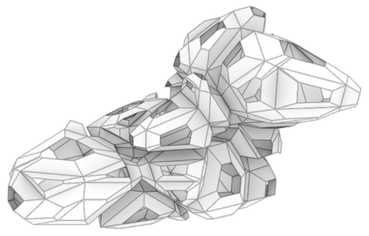
1. Define volume

Determine the bounding volume of every partition and room



2. Extract landing and visual surfaces

Within the voronoi cell, there are landing surfaces and visual surfaces. In this step, they are set open from iso-surface calculation (no floor defined)



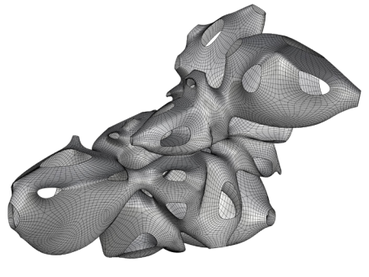
3. Select opening and closures

With open and closure analysis, these surfaces can serve as different purposes:

- Full close: landing surface

- Full open: inter-connection

- Scaled open: visual vectors connect to visual perception: wall-mount devices, faux windows, lights



4. Iso-surface calculation

Method applied: Millipede & Weaverbird

Compute & weld iso-surface meshes

Fig 6.3.13: Iso-surface transformation

Revisit common area (meso)

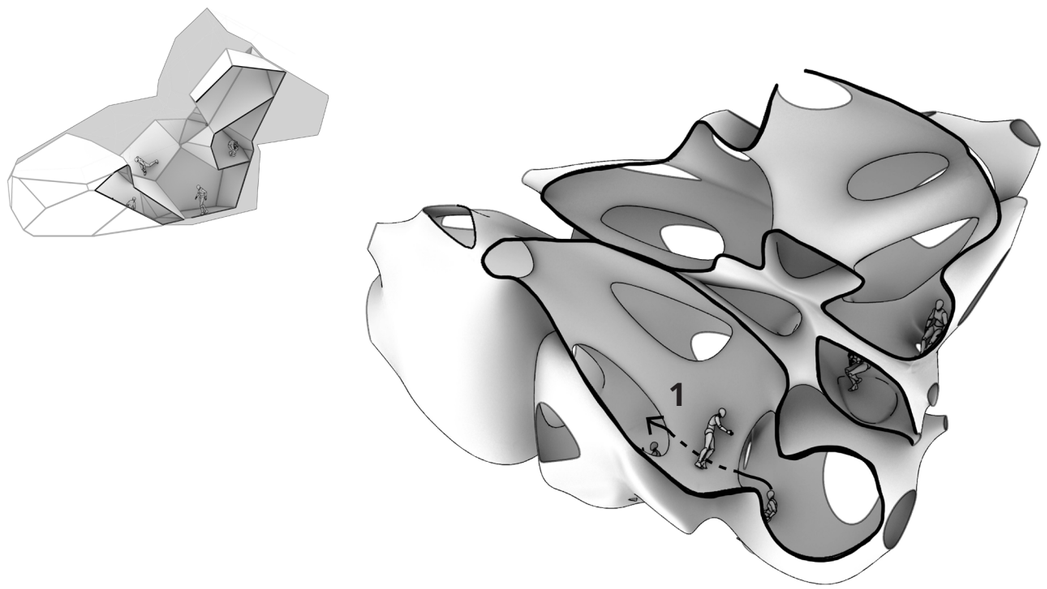


Fig 6.3.14: Section 2 (iso-surface)

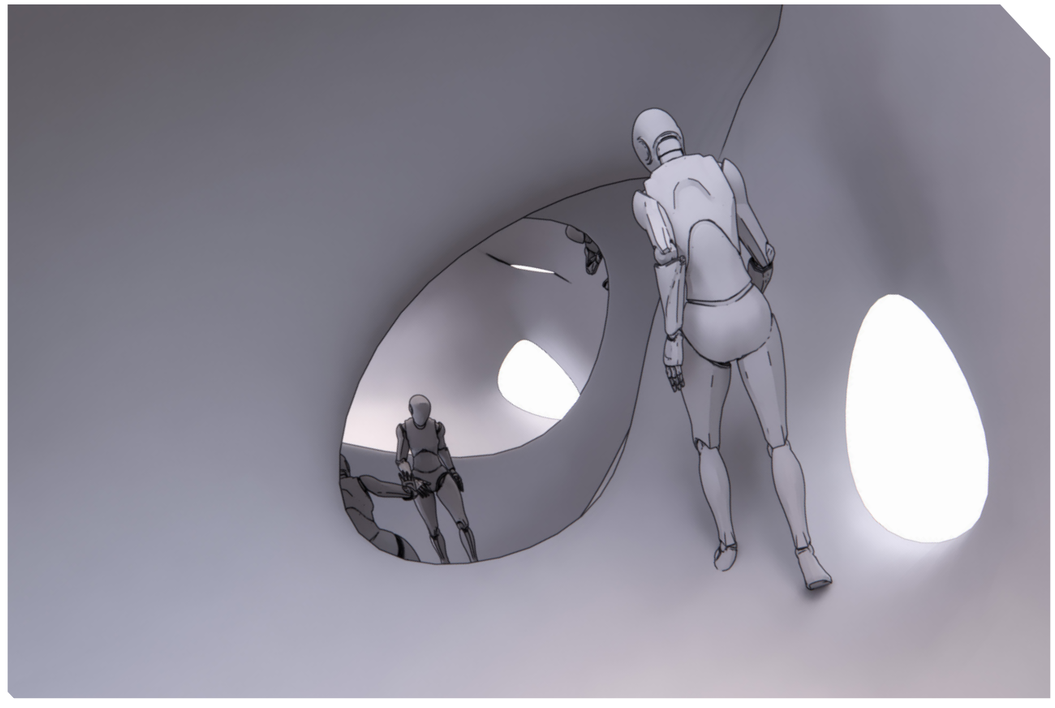


Fig 6.3.15: View 1: From workshop to common area

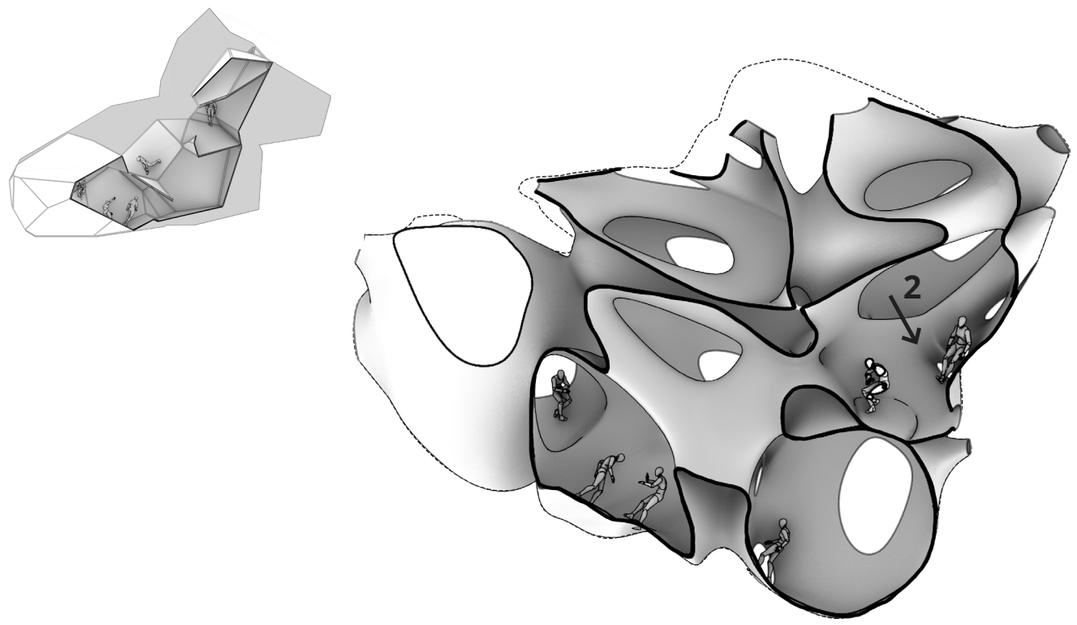


Fig 6.3.16: Section 3 (iso-surface)



Fig 6.3.17: View 2: Inside small workshop

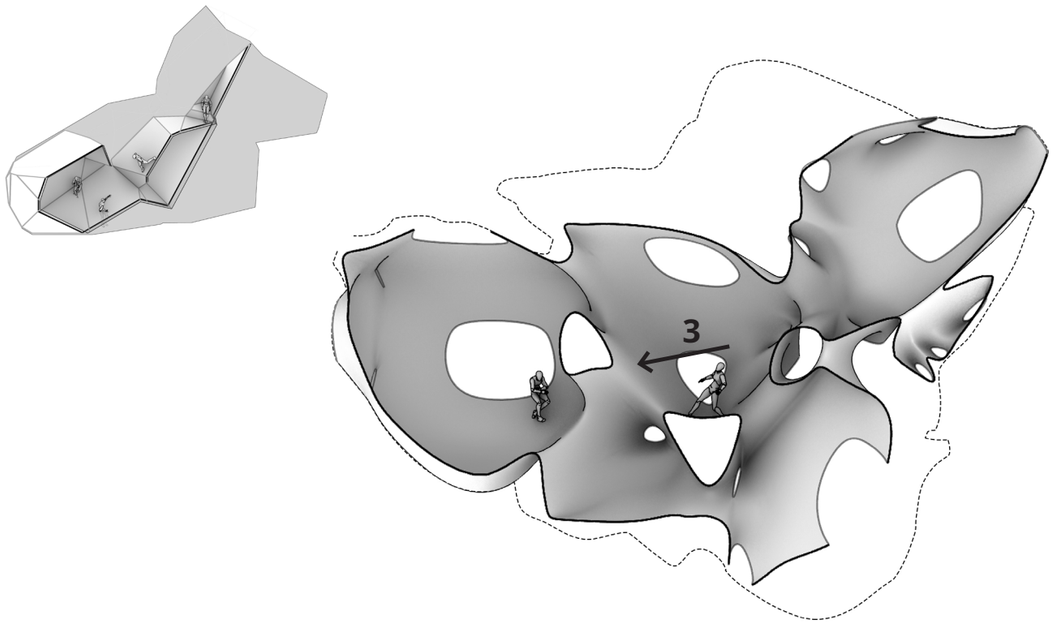


Fig 6.3.17: Section 4 (iso-surface)

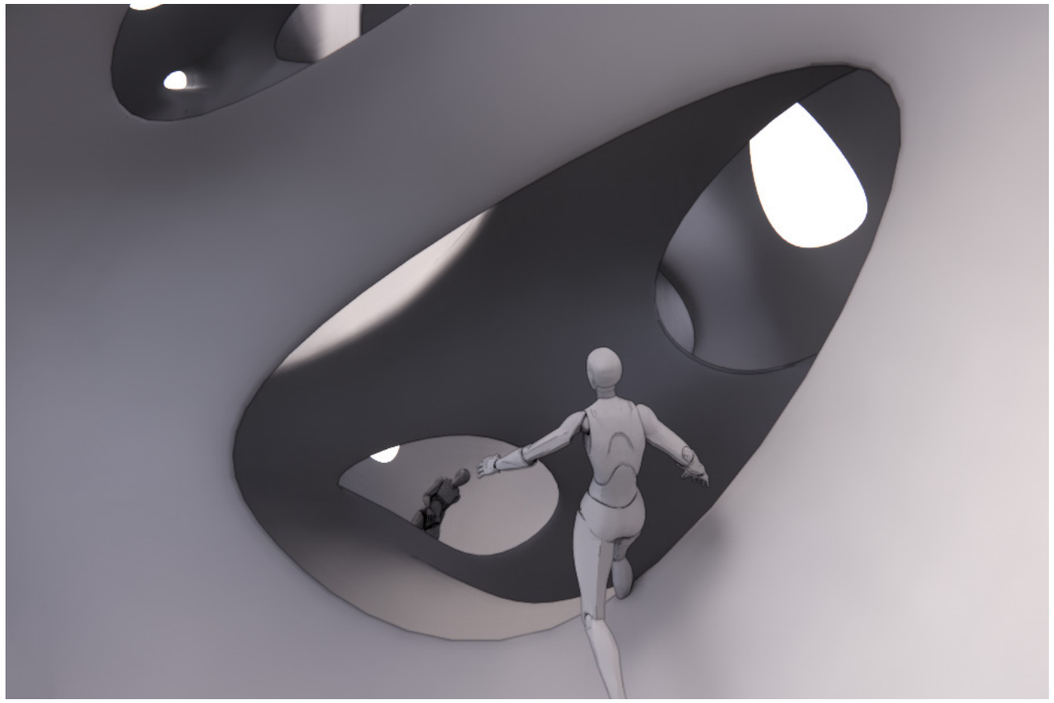


Fig 6.3.18: View 3: From ramp to common area

Revisit common area (meso)

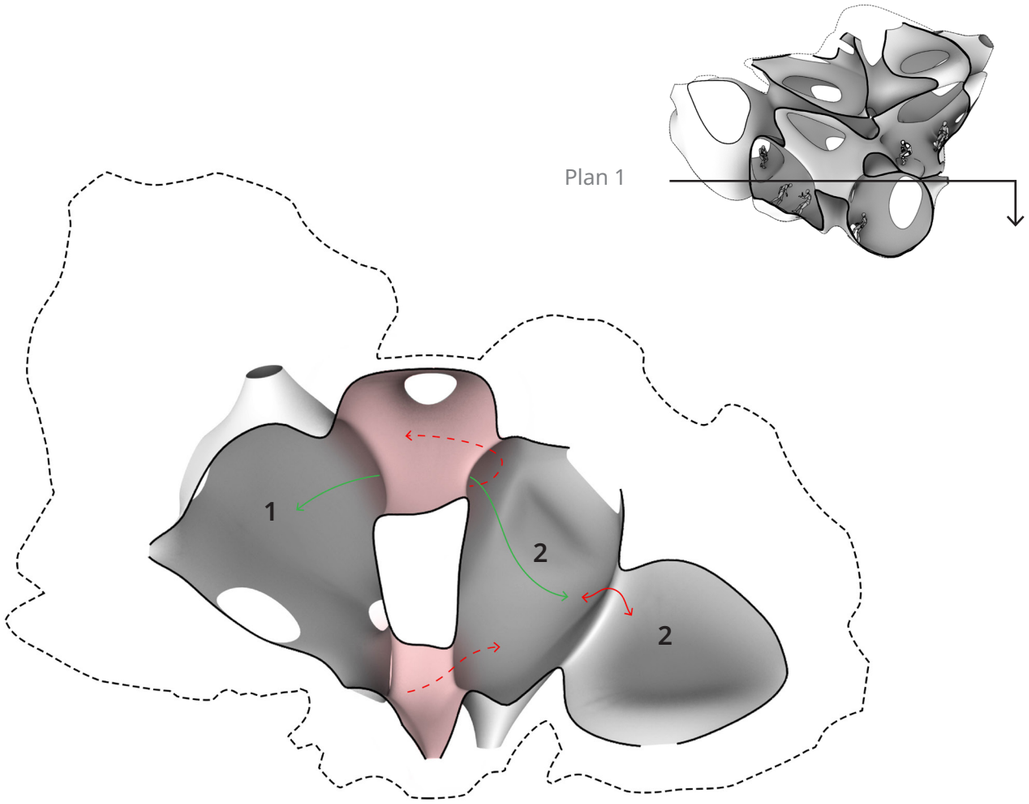


Fig 6.3.19: Plan 1 (iso-surface)

1. Workshop (large)
2. Common social area

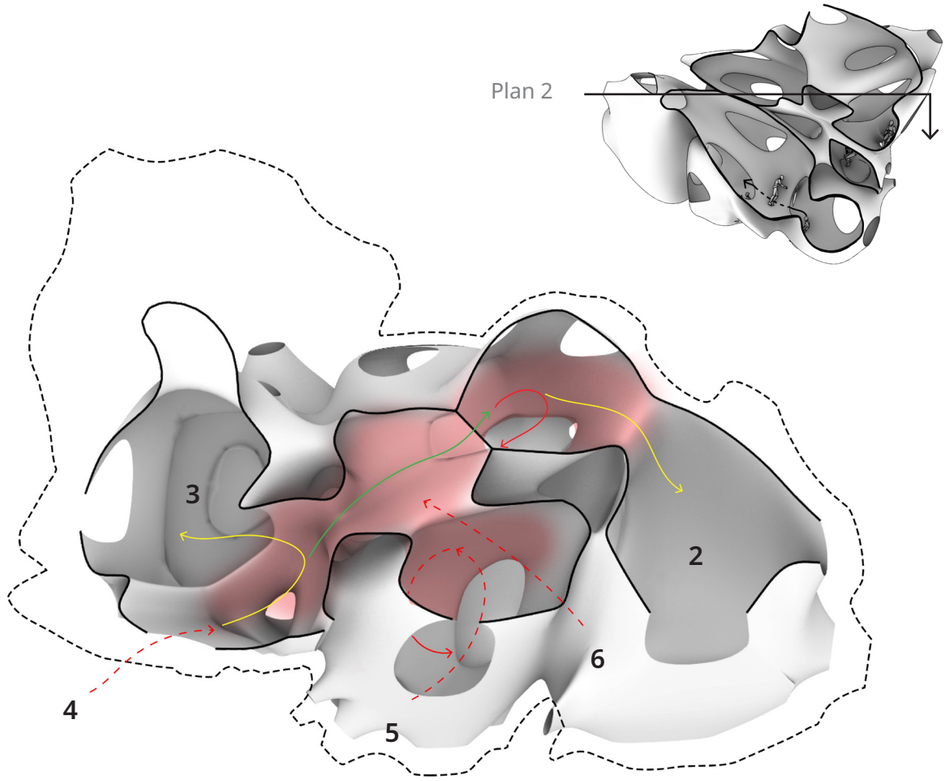


Fig 6.3.20: Plan 2 (iso-surface)

Flat
Slope
Level
Circulation

1. Workshop (large)
2. Common social area
3. Workshop (small)
4. Connection to workstation
5. Connection to Bio farm
6. Connection to leisure garden

6.4 Proof of concept (micro)

In order to test whether certain IsoValue would house sufficient volume and address user's reclaiming of the individual 'plumb line', the original visual and force anchors are implemented in a segment.

Micro space: private workshop

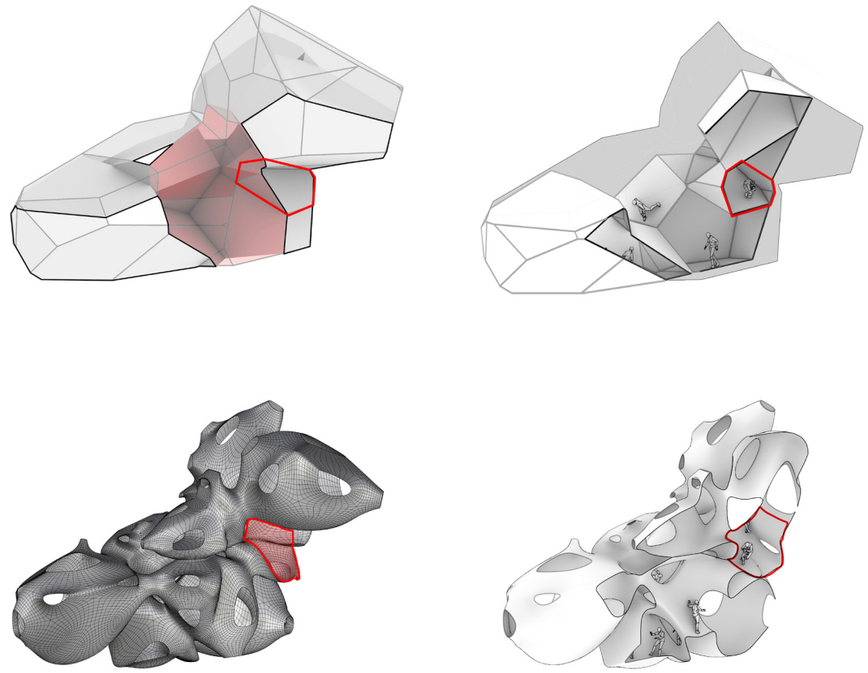


Fig 6.4.1: Micro (voronoi) up; (isosurface) down

Micro space: workshop table environment



Fig 6.4.2: Force & visual vectors

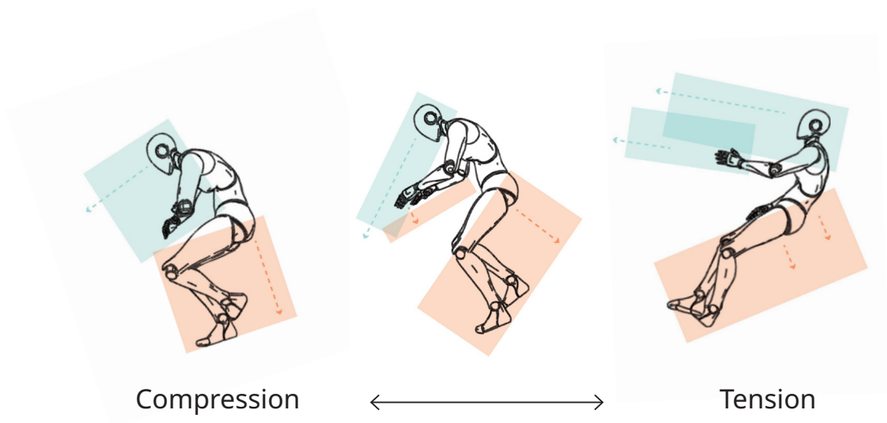


Fig 6.4.3: Body movement sequence

In the case of small workshop, habitant's perception of gravity can be object vertical: the chair, the working surface, lights... Again, we feel gravity from ambient environment rather than the weak 1/6G moon gravity.

Object gravity

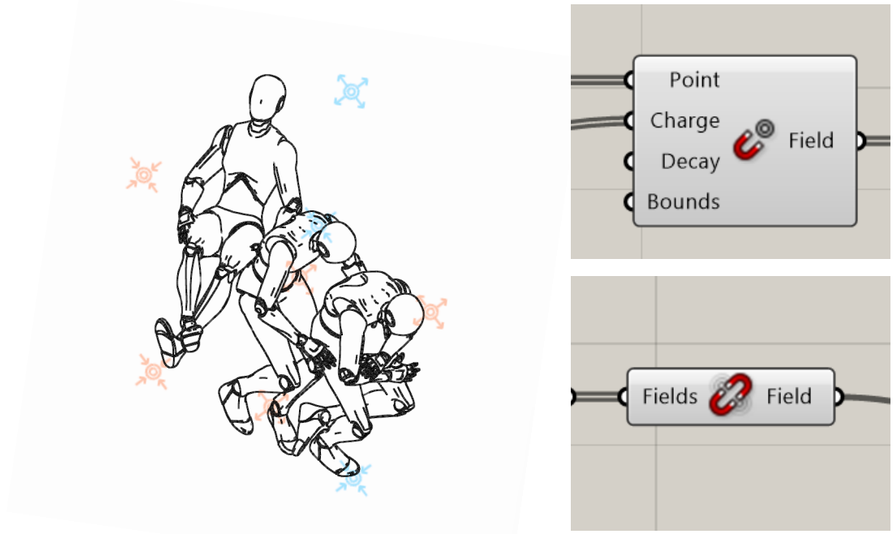


Fig 6.4.4: Charge points

Anchors either charges as compression or tension, trigger interior surfaces catering to habitant's perception of gravity.

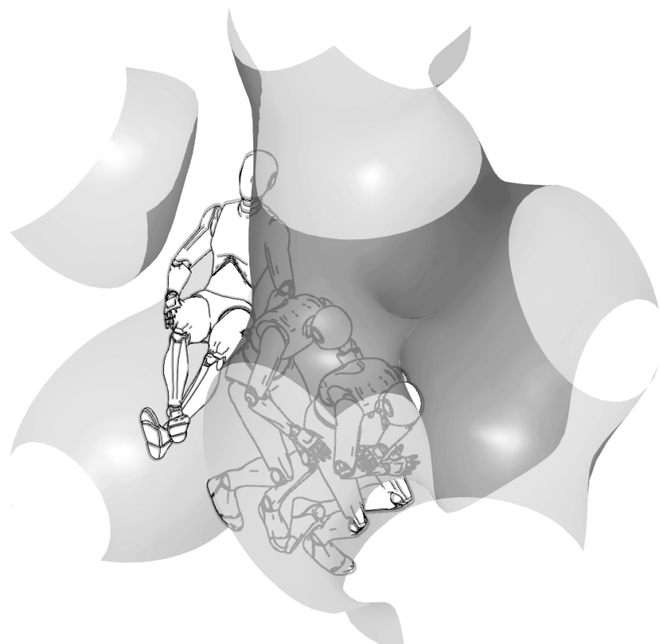


Fig 6.4.5: interior gravity cues setup

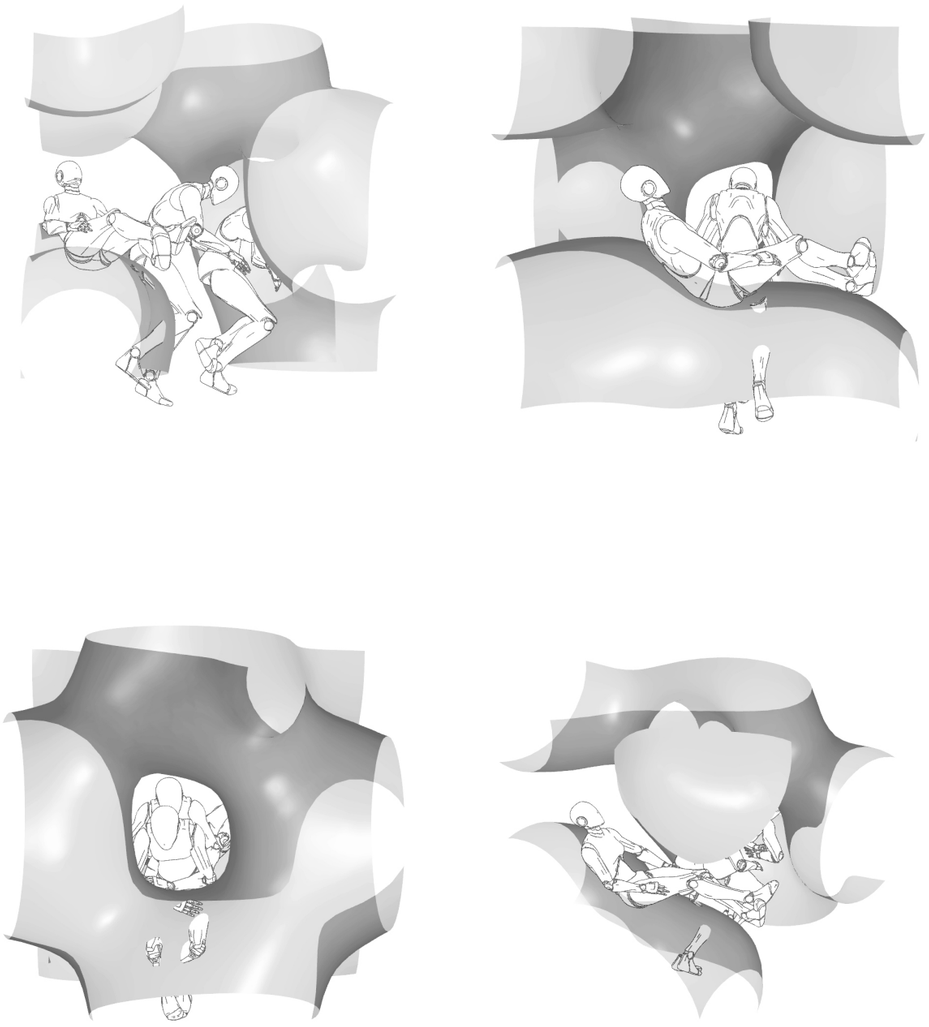


Fig 6.4.6: Evaluate output