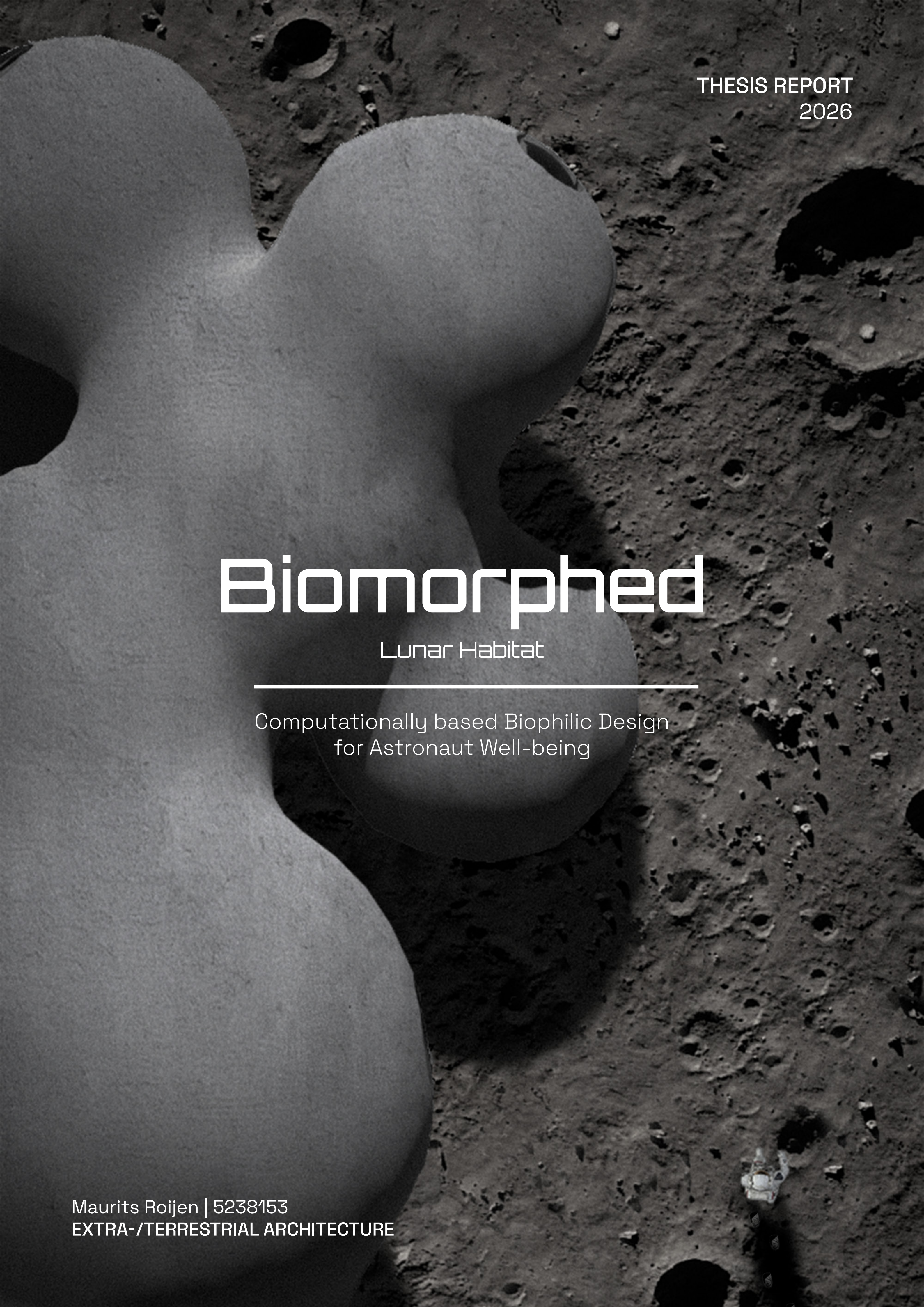

THESIS REPORT
2026

Biomorphed

Lunar Habitat

Computationally based Biophilic Design
for Astronaut Well-being

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EXTRA-/TERRESTRIAL ARCHITECTURE

Project Title
Biomorphed

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ABSTRACT

In anticipation of humanity's return to the moon and the broader pursuit of space colonisation, extra-terrestrial architecture is becoming increasingly relevant. Lunar habitat design faces significant hurdles, mainly prohibitive transportation costs, extreme environmental hazards (such as vacuum exposure, extreme temperature fluctuations, radiation and abrasive dust), as well as the significant psychological toll of long-term isolation in high stress environments. This thesis project addresses these challenges by synthesising structural resilience with inhabitant well-being.

This research explores how biophilic design principles can be integrated with In-Situ Resource Utilization (ISRU) additive manufacturing in the design of a habitat on the Lunar South Pole, with the aim of improving astronaut mental health and well-being. The habitat's structure and composition acts as a shield against the harsh environment, while ISRU through Selective Laser Melting (SLM) reduces the reliance on terrestrial resources.

The habitat's morphology is generated through computational L-systems, producing an organically branching spatial hierarchy that facilitates efficient circulation, life-support integration, and compartmentalisation for safety. This system is enclosed within metaball volumes that are optimised using Karamba3D to manage internal atmospheric pressure while providing a dynamic and organic interior landscape. Internally, the design maximises Indoor Environmental Quality (IEQ) through circadian lighting, acoustic comfort, thermal regulation and the integration of plant life in the life support systems to resemble the Earth's environment.

By synthesising biophilic design principles with additive manufacturing, this project proposes a human-centric approach to lunar habitats that prioritises astronaut well-being while carefully incorporating the technical requirements to deal with the site.

Keywords

Lunar Architecture, ISRU, 3D Printing, Biophilic Design, Mental Health, Habitat Design, IEQ

ACKNOWLEDGEMENT

A Special thank you to my girlfriend, family and friends for their support and motivation. I also want to thank my thesis tutors Dr. Dipl.-Ing. Henriette Bier, Ir. F. Adema and Ir. A. Hidding for their guidance.

AI STATEMENT

In the production of this report, AI tools like Gemini and ChatGPT were used. Their tasks include: Literature research, proofread for spelling and grammar, and improving readability and structure. These tools also provided some technical support for Rhino and Grasshopper scripting logic. However, all ideas, models, and project images are my own.

“I know the sky is not the limit
because there are footprints on the Moon”

Buzz Aldrin - Second man on the moon

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PART 1

INTRODUCTION

National Aeronautics and Space Administration. (1969, July 16). Apollo 11: View of Moon limb with Earth on the horizon [Photograph]. https://images.nasa.gov/details/as11-44-6550

PROBLEM STATEMENT

Humanity stands on the precipice of space colonisation. The NASA and ESA Artemis missions serve as a critical precursor to long-term lunar habitation (NASA, 2025). With it comes the architectural challenge of moving beyond basic habitats for survival and towards the creation of homes amongst the stars.

This transition, however, comes with an abundance of challenges. Firstly the logistics of building and maintaining lunar habitats is extremely costly. At a price estimation of $1,000,000/kg (Guccione et al., 2025), transporting material to the moon is impractical. To achieve economic viability and sustainability, we must pivot towards In-Situ Resource Utilization (ISRU). This allows us to leverage materials found on site to reduce reliance on Earth.

Secondly, the Moon’s inhospitable vacuum environment lacks atmospheric protection. Subsequently, the surface is plagued by abrasive lunar dust, moonquakes, micro-meteorites, deadly radiation, solar wind, long lunar nights and intense temperature fluctuations (Guccione et al., 2025).

While habitats can offer some shielding against some of these threats and temperature fluctuations, careful design considerations will have to be made to ensure survivability.

Lastly, the psychological toll of long-term isolation in high-stress, cramped environments poses a significant threat to mental health, necessitating a move towards human-centric design. Research indicates that long term space missions can impact mental health through emotional dysregulation, disrupted sleeping rhythms, cognitive dysfunction, etc. (Arone et al., 2021). This is where biophilic design principles can be incorporated in the architecture to help improve well being.

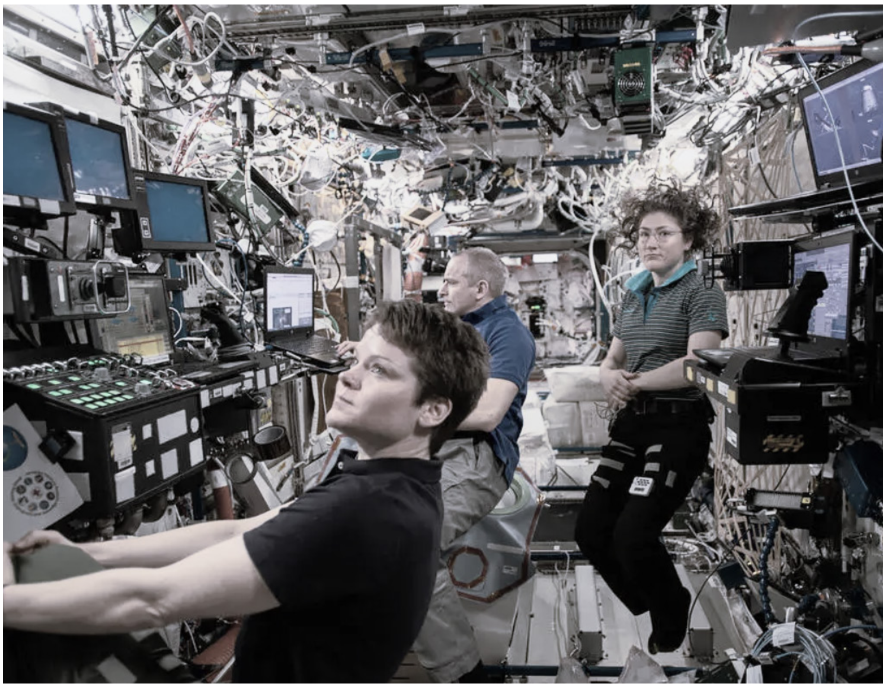


Figure 1: Interior view of the International Space Station

National Aeronautics and Space Administration. (2019, May 8). Expedition 59 crew members inside the U.S. Destiny laboratory [Photograph]. https://www.nasa.gov/image-article/expedition-59-crew-members-inside-u-s-destiny-laboratory/

RELEVANCE

International Missions

The Artemis missions (NASA, 2025) and the ESA's Terra Novea 2030+ Strategy (European Space Agency, 2022) mark humanity's long-awaited return to the moon since the first landing in 1969. Unlike the short-term exploratory sorties of the Apollo era, these missions aim to establish a sustained presence on and around the lunar surface, serving as a critical 'stepping stone' toward the eventual colonization of Mars.

To ensure we are ready when the time comes, a shift is needed in the architectural language of space habitats. Fundamentally, the ISS is utilitarian and sterile, focused mainly on survival and functionality. However, simply 'surviving' should not be the sole metric of success for a habitat, we want to create permanent homes that allow users to thrive. By focusing on wellbeing through biophilic design we develop the technical and psychological knowledge necessary for humanity to become a truly multi-planetary species.

UN Sustainable Developement Goals

Looking a little closer to home, the UN Sustainability Goals (United Nations Development Programme, n.d.) offer a lens through which the project also gains relevance back on earth. In the past innovations in space have been applied directly to everyday life on Earth.

The extreme constraints of the lunar environment act as drivers for innovations that can be implemented across the built environment and beyond. Innovations in space remain highly relevant and applicable to Earth, the ball point pen for example was originally developed for use in space.

UNSDG 3 (Good Health and Well-being): The isolation of space necessitates a mastery of biophilic design to improve indoor comfort and mental health. These design principles can help provide a framework to improve health in high-density or isolated urban environments.

UNSDG 9 (Industry, Innovation, and Infrastructure): The shift toward Design-to-Robotic-Production moves the construction industry away from manual and towards automatic construction. An innovation that could make the industry much more efficient and broaden construction possibilities.

UNSDG 11 & 12 (Sustainable Cities / Responsible Production): Using In-Situ Resource Utilization (ISRU) is the ultimate form of circularity. By eliminating the waste from transporting materials from Earth and utilising 3D-printed regolith, we model a construction philosophy that prioritizes material efficiency and zero-waste manufacturing. Moreover, the net-zero nature of the habitat ensures circularity in the resource usage during the building's use as well.

Figure 2: ESA's goal of reaching the Moon through the Terrae Novea roadmap

European Space Agency. (2022, July 4). Terrae Novae destinations: Moon [Image]. https://www.esa.int/ESA_Multimedia/Images/2022/07/Terrae_Novae_destinations_Moon

MOTIVATION

The challenge and novelty of lunar architecture is what drove me to do this graduation course. Space is the ultimate frontier and can be a driver for architectural innovations. Specifically the advancement of ISRU 3D printing and robotic manufacturing are methods that can be transferred here on Earth to help combat the housing crisis and make architecture more sustainable.

Moreover, my focus on biophilic design grounds the project in tangible design practices that are directly applicable in terrestrial projects. In the aftermath of Covid-19 the importance of healthy indoor environments has become increasingly apparent for both mental and physical health of users.

OBJECTIVE

The primary objective of this thesis is to design a lunar habitat that promotes long-term habitability and astronaut well-being through biophilic design principles. This research explores the synthesis between biophilic design robotic manufacturing and In-Situ Resource Utilization, aiming to contribute both to the future of space habitation while providing transferable insights for terrestrial projects. Some sub-objectives include:

1. Identify how organic shapes can be 3D printed on the moon and outline the construction steps related to robotic manufacturing.

2. Employ architectural biophilic design solutions to improve astronaut health and wellbeing

3. Incorporate design considerations to leverage low gravity construction and make the building’s experience dynamic

4. Design a habitat that can support a 6 astronaut team in achieving their research missions and staying both mentally and physically healthy during the mission.

5. Reduce the effect of sick building syndrome by addressing air quality, thermal comfort, lighting, and acoustic comfort

RESEARCH QUESTION

How can biophilic design principles be adapted to a lunar lava tube habitat using ISRU 3D-printed architecture to support astronaut mental health and well-being?

Sub-Questions

- What is biophilic design?
- What is ISRU and how does it relate to lunar base development?
- How can 3D printing be leveraged for biophilic design?
- How does biophilic design improve mental health and well-being?
- What are the challenges of living on the moon?
- How can the habitat offer protection against the moon's environment?
- How can computational design be applied when modeling the structure to get a more biophilic design?

SCOPE

The scope of this thesis is defined by the architectural and technical requirements of a second-generation lunar settlement, specifically moving towards long-term habitation.

Mission Context

Location: The site will be located at the Lunar South Pole near the Shackleton crater. The design is situated on the illuminated rim of the crater.

Timeline: This project focuses on long-term missions and occurs after the first lunar bases have been established. It therefore moves beyond utilitarian survival-focused design of short term missions and more towards human-centric design.

Occupancy: The habitat is designed for a 6-person crew, staggering rotation of 3-person teams to ensure continuous knowledge transfer.

Construction

Robotic Manufacturing: The design will assume a full reliance of robots for manufacturing on site. Although the project will outline the steps and design considerations for construction, its focus does not lie on robotics and their exact workings.

ISRU: The construction materials are limited to what can be harvested on-site. Therefore, the main construction material is lunar regolith.

3D-Printing: The building will be constructed using the Selective Laser Melting (SLM) of lunar regolith as its primary manufacturing process.

Architectural Design

Biophilic Design: Primary focus of the design is to integrate biophilic design principles and mitigate mental and physical health degradation

Technical Systems: The scope includes essential elements like Life Support Systems (LSS) and radiation shielding, ensuring that the habitat meets the requirements for lunar survival.

PART 2

APPROACH

National Aeronautics and Space Administration. (1969, July 20). Apollo 11: Close-up of astronaut’s foot and footprint in lunar soil [Photograph]. https://www.nasa.gov/image-detail/amf-as11-40-5880/

METHOD

To answer the research question, this report will start by collecting background knowledge through literature and case studies. Literature will be collected through recent sources due to the fast developing nature of robotic manufacturing. However, for lunar soil data may be sourced from older papers as we have not yet been back to the moon.

Once the theory is established, they will be utilized in the design stages. By exploring through sketches, maquettes, digital models and computational workflows, this project will aim to answer the research questions.

SITE RESEARCH

Lunar South Pole - Water Ice

The Artemis missions aim to land on the Lunar South Pole because of the presence of exposed water ice. Due to the tilted rotational axes of the Moon, the sun sits low on the horizon. Subsequently, crater floors become permanently shaded regions that act as cold traps with temperatures under 110 K, preventing the sublimation of water and allowing for accessible accumulations of water ice (Li et al., 2018). These deposits are essential for Lunar Missions as they are a vital resource for both life-support and hydrogen fuel.

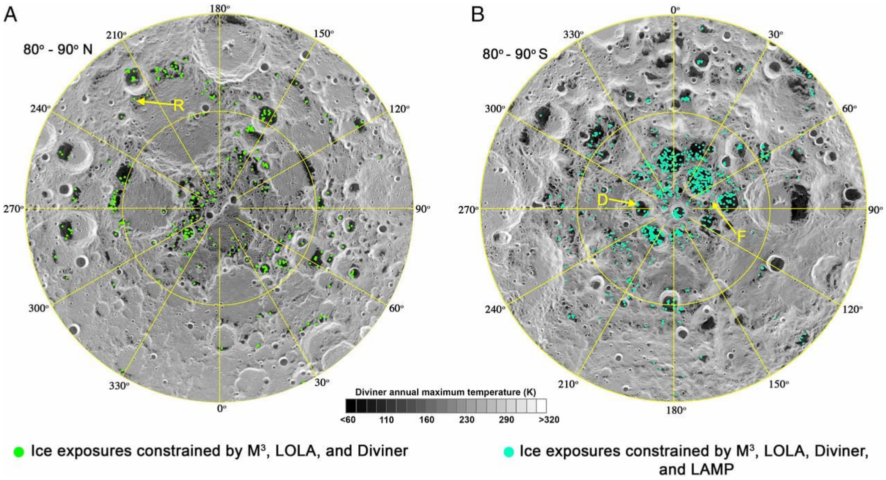


Figure 3: Distribution of water-ice-bearing pixels on the Lunar South Pole (Li et al., 2018)

Shackleton Crater - Sunlight

Another critical resource is sunlight, without it the habitat can't be powered through solar energy. However, due to the low horizon sun, there are no permanently illuminated areas in the South Pole (Speyerer et al., 2013). Nevertheless, select sites, like the rim of the Shackleton Crater, are situated high enough to receive longer periods of solar illumination. These sites are ideal for future bases and research as they have both a proximity to shaded and unshaded regions.

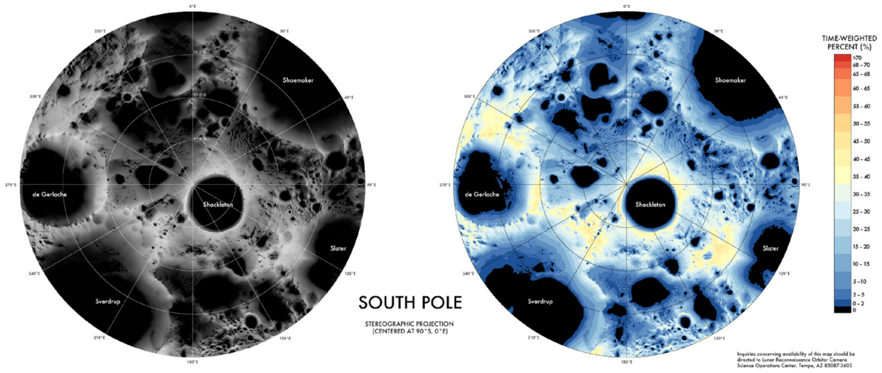


Figure 4: Illumination on the Lunar South Pole (https://lroc.im-ldi.com/images/downloads)

Site Conditions

Establishing lasting lunar habitats requires protecting the astronauts from the hostile environment.

Vacuum:
The moon does not have an atmosphere and is therefore open to the vacuum of space. Subsequently, the habitat will require pressurisation and must be resistant to the resulting forces acting on the building's envelope.

Temperature fluctuations:
Without an atmosphere to trap heat, mean surface temperatures differ greatly throughout the day. This can range from 107°C during the day, to -153°C at night (Heiken et al, 1991, p. 28). To combat these fluctuations, habitats should be designed to accommodate thermal movements. Moreover, there should be effective thermal regulation to keep a steady indoor environment.

Radiation:
Lacking atmospheric and magnetic shielding, the surface is continually bombarded by galactic cosmic rays (GLR), UV radiation and occasional solar particle events. Such exposure drastically elevates the likelihood of cancer and acute radiation sickness, making the implementation of radiation shielding indispensable. (Reitz et al., 2012).

Micrometeoroids:
The absence of atmospheric drag allows meteoroids to strike the Moon at full velocity and mass as it bypasses the ablation and deceleration that would occur with an atmosphere. This means micrometeoroids can be expected to hit large structures annually, with larger strikes occurring less frequently (Heiken et al, 1991, p. 46). The micrometeoroid impacts average a velocity 20 km/s but can be as fast as 70 km/s (Allende et al., 2020).

Seismic Activity:
Although moonquakes are long lasting, their intensity is relatively mild. Apollo mission data recorded quakes ranging from 1.5 to a 5.5 maximum on the Richter scale (Watters et al., 2024). This intensity is noticeable, but poses little risk for well designed structures.

Gravity:

Lastly, the Moon is significantly smaller in mass than Earth, meaning gravity is only about 1/6th the strength at 1.62 m/s2 (Heiken et al, 1991, p. 28). This is architecturally stimulating as it should allow for longer spans and cantilevers due to the reduced gravitational force on the structure.

ISRU

Soil Composition

In-Situ Resource Utilization (ISRU) is the practice of harvesting, processing, leveraging and storing materials found onsite. The Moon's surface contains the fundamental building blocks necessary to support long-term missions through ISRU (Zhang et al., 2023). Water and oxygen for life support, regolith, metals and silica for construction, and hydrogen, oxygen and methane for rocket fuel. Especially the top layer is of interest as it consists of a layer of unconsolidated debris caused by constant bombardment of the lunar surface (Heiken et al, 1991, p. 285). This loose top layer consists of fine dust-like particles that can be easily mined and collected.

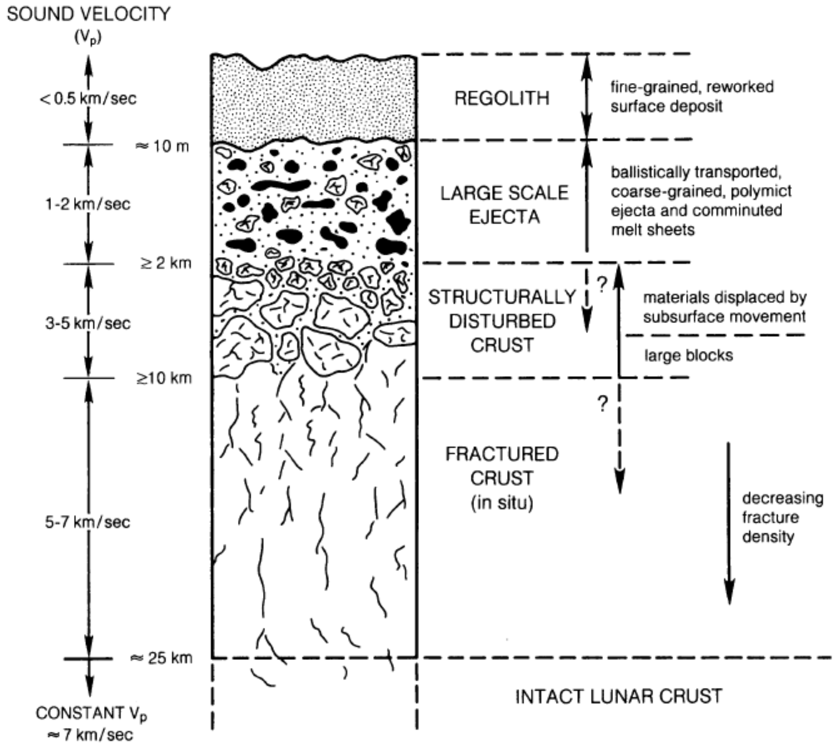


Figure 5: Lunar surface layers (Heiken et al., 1991)

Robotic Process

In order to collect the regolith top layer for processing and sintering, NASA has designed a robot with counter-acting bucket drums. The robot spins the drums and collects the regolith dust. Next, the coarse grains are filtered out while the finer grains are stored. The finer grains can then be flattened in the desired position where they are then sintered/melted together into a solid.

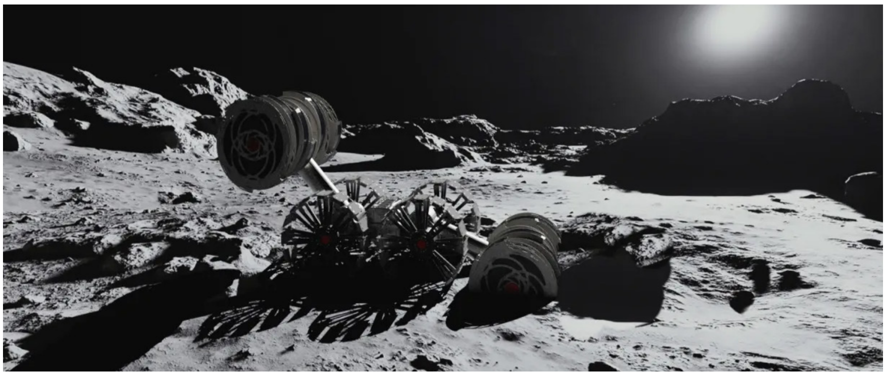


Figure 6: Render of NASA's IPEx Lunar Excavator (https://www.nasa.gov/infrastructure-pilot-excavator/)

3D Printing Method

Once the regolith is collected it can be used to 3D print structures. However, due to the vacuum conditions and ISRU nature, some additive manufacturing techniques can't be used as they require an external binding agent or a liquid paste which would evaporate in a vacuum. Therefore the best methods would be to use Powder Bed Fusion which fuses powdered materials layer-by-layer through lasers (Chen et al., 2019). This would only require the powder (regolith) and a laser that can be powered through solar energy.

There are two types to consider: Selective Laser Sintering (SLS) and Selective Laser Melting (SLM). With SLS the regolith would be heated just below the melting point to fuse its grains through sintering. However, research indicates that this method results in more porous finish when done in a vacuum, leading to reduced mechanical properties (Agapkin & Slyuta, 2025)

SLM requires significantly more energy than SLS as it heats the material above its melting point. However, the advantage of this is that it also cools more rapidly and can have multiple passes, reducing porosity. To achieve this dense, glass-like product, the regolith must be completely melted at 1500 °C, giving it a compressive strength of around 125 MPa (Guo et al., 2025).

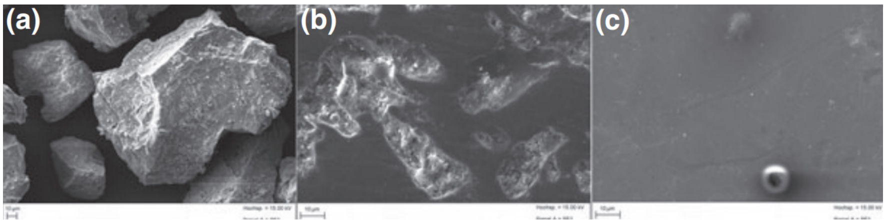


Figure 7: SEM image of lunar simulant powder, (b) Sintered part embedded within a molten zone, (c) Fully melted and resolidified part. (Fateri & Gebhardt, 2014)

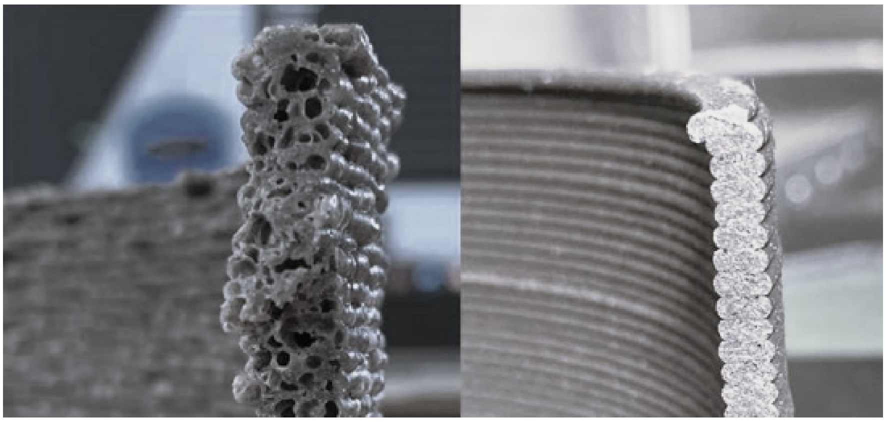


Figure 8: Porous vs dense 3D printed regolith simulant under vacuum conditions (SOURCE)

Case Study - TECLA

This 3D printed structure is an example of what can be achieved. Although TECLA by Mario Cucinella Architects used a different type of AM, it is still relevant. Note how well it achieves organic shapes and is designed to seamlessly integrate lighting.

Moreover, the design of TECLA utilised biophilic principles through its integration of nature, lighting and soft organic shaping. The large openings and indoor tree also connect it to nature. Overall, the design maximises the relationship between AM and biophilic design to give it a calming sense of refuge and rest.

Figure 9: TECLA View From Outside

Figure 10: TECLA living room with integrated greenery and lighting

BIOPHILIC DESIGN

Definition

An approach to architecture and interior design that connects people with nature within built environments, using natural elements, forms, and processes to improve human health, well-being, and productivity, stemming from our innate love for nature.

Biophilic Design as a framework can be divided into three clusters: Nature in the Space, Natural Analogues and Nature of the Space (Ryan et al., 2014,). The first incorporates nature physically though water and plants, but also sensory stimuli like light, sound, and humidity. Natural Analogues is the mimicking of nature through shapes, patterns and processes. Finally, Nature of the Space refers to experiences like prospect (view), refuge (privacy), mystery (dynamic exploration) and peril (controlled thrills).

MENTAL HEALTH & COMFORT

Astronaut Mental Health

Long term space habitation places crew in isolated, confined and high-stress environments for an extended duration. It is also monotonous living with the same small crew in an unchanging environment. For astronauts this can cause mental health and well-being to deteriorate (Arone et al., 2021)

Sick Bulding Syndrome

Sick Building Syndrome occurs when the health and comfort of inhabitants are compromised by the time spent in a building, often due to factors like lighting, air quality, temperature and noise (Rostron, 2008). This phenomenon is especially relevant to space architecture as astronauts remain confined within the habitat for the entirety of their mission duration . To prevent the habitat from becoming a source of illness, biophilic design must be integrated to help improve mental health and well-being.

Indoor Environmental Quality

In order to gauge the health and comfort of the habitat, the Indoor Environmental Quality (IEQ) will be used as a guide for biophilic.interventions. By aligning biophilic strategies with this framework the design will respond directly to the theorised causes of SBS.

Lighting:
The Moon does not follow the 24-hour solar cycle, disrupting the crew's circadian rhythm and subsequently their cognitive performance and sleep. Through the integration of lighting that changes color and intensity throughout the day, the habitat can mimic the feelings of different periods in the day to

allow our biological clock, productivity, mood and sleep to be improved (Papatsimpa & Linnartz, 2020).

Air quality:
Indoor air quality is another important consideration. Although mechanical scrubbers can filter the air and keep oxygen levels optimal, the NASA Biohome experiment (Johnson, 1990) has also shown that plants can act as natural air filters. This is especially attractive for space habitats as they require less energy, require little maintenance and can double up as food production (Wolverton & Nelson, 2020).

Acoustic comfort:
Dense, 3D-printed regolith domes behave similarly to concrete and can cause sound to create harsh echoes that reflect rather than scatter and be absorbed. An acoustic pattern can help improve indoor acoustics.

Thermal comfort:
The Moon's vacuum environment makes it difficult to shed excess heat from electronics and humans. Subsequently, the habitat can utilize thermal mass from the structure and ground as well as indoor plant transpiration to help cool the habitat naturally, reducing the cooling load of the structure.

Biophilic Integration

To improve mental health & comfort the habitat design should respond to the following properties through biophilic design:

- Non-monotomous, dynamic spaces
- Private & public area separation with the ability to retreat
- Acoustic comfort
- Thermal comfort
- Lighting Quality
- Air quality

PART 3

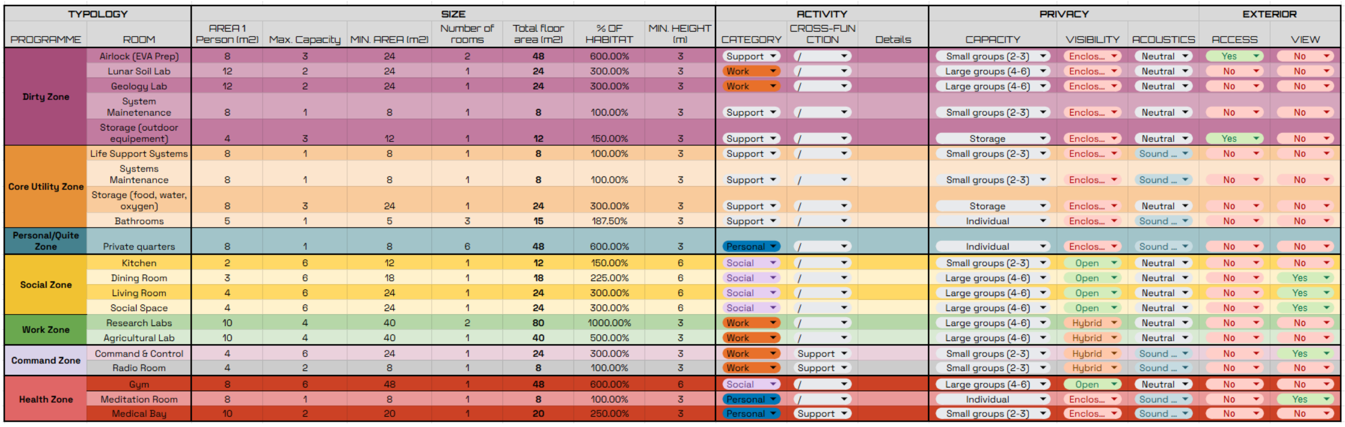
RESULTS

National Aeronautics and Space Administration. (1972, December 13). Apollo XVII extravehicular activity (EVA) - scientist-astronaut Harrison H. Schmitt - Moon [Photograph]. https://images.nasa.gov/details/S73-22871

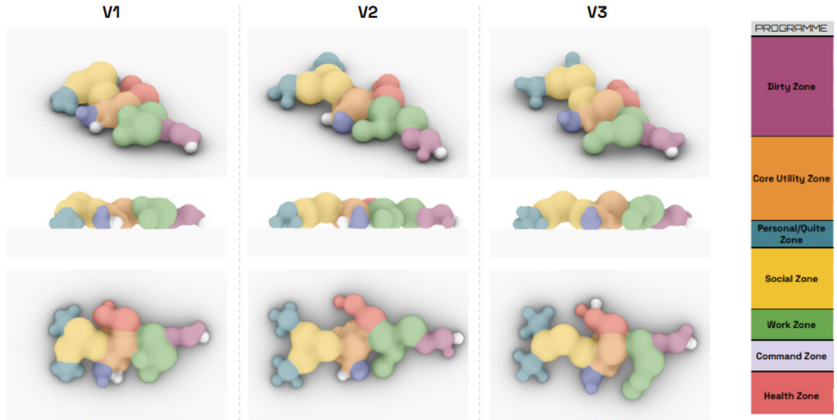
BUILDING LAYOUT

Programme

The programme of the entire building is based on requirement for a long term lunar mission focused on research. Here, the different functions have been clustered together based on function. The 'dirty' cluster contains rooms that would be exposed to regolith and therefore need to be separated from the rest to reduce exposure. The rest have been clustered based on private vs public and rest vs work, allowing for distinct experiences in each area of the building.

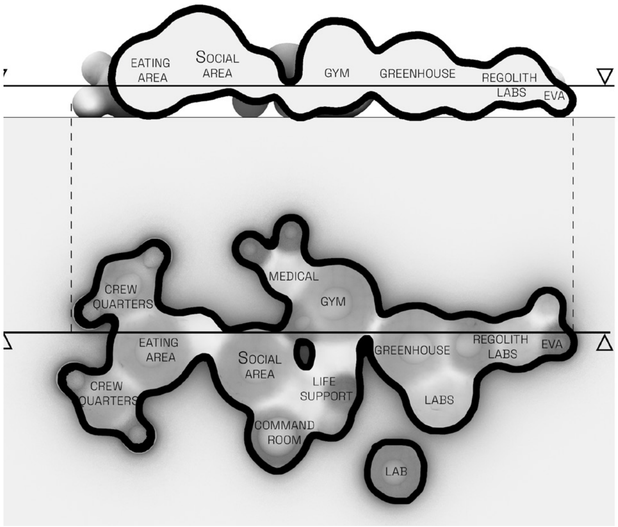


TYPOLOGY		SIZE							ACTIVITY			PRIVACY			EXTERIOR	
PROGRAMME	ROOM	AREA 1 Person (m2)	Max. Capacity	MIN. AREA (m2)	Number of rooms	Total floor area (m2)	% OF HABITAT	MIN. HEIGHT (m)	CATEGORY	CROSS-FUNCTION	Details	CAPACITY	VISIBILITY	ACOUSTICS	ACCESS	VIEW
Dirty Zone	Airlock (EVA Prep)	8	3	24	2	**48**	600.00%	3	Support	/		Small groups (2-3)	Enclos...	Neutral	Yes	No
	Lunar Soil Lab	12	2	24	1	**24**	300.00%	3	Work	/		Large groups (4-6)	Enclos...	Neutral	No	No
	Geology Lab	12	2	24	1	**24**	300.00%	3	Work	/		Large groups (4-6)	Enclos...	Neutral	No	No
	System Mainetenance	8	1	8	1	**8**	100.00%	3	Support	/		Small groups (2-3)	Enclos...	Neutral	No	No
	Storage (outdoor equipement)	4	3	12	1	**12**	150.00%	3	Support	/		Storage	Enclos...	Neutral	Yes	No
Core Utility Zone	Life Support Systems	8	1	8	1	**8**	100.00%	3	Support	/		Small groups (2-3)	Enclos...	Sound ...	No	No
	Systems Maintenance	8	1	8	1	**8**	100.00%	3	Support	/		Small groups (2-3)	Enclos...	Sound ...	No	No
	Storage (food, water, oxygen)	8	3	24	1	**24**	300.00%	3	Support	/		Storage	Enclos...	Neutral	No	No
	Bathrooms	5	1	5	3	**15**	187.50%	3	Support	/		Individual	Enclos...	Sound ...	No	No
Personal/Quite Zone	Private quarters	8	1	8	6	**48**	600.00%	3	Personal	/		Individual	Enclos...	Sound ...	No	No
Social Zone	Kitchen	2	6	12	1	**12**	150.00%	6	Social	/		Small groups (2-3)	Open	Neutral	No	No
	Dining Room	3	6	18	1	**18**	225.00%	6	Social	/		Large groups (4-6)	Open	Neutral	No	Yes
	Living Room	4	6	24	1	**24**	300.00%	6	Social	/		Large groups (4-6)	Open	Neutral	No	Yes
	Social Space	4	6	24	1	**24**	300.00%	6	Social	/		Large groups (4-6)	Open	Neutral	No	Yes
Work Zone	Research Labs	10	4	40	2	**80**	1000.00%	3	Work	/		Large groups (4-6)	Hybrid	Neutral	No	No
	Agricultural Lab	10	4	40	1	**40**	500.00%	3	Work	/		Large groups (4-6)	Hybrid	Neutral	No	No
Command Zone	Command & Control	4	6	24	1	**24**	300.00%	3	Work	Support		Small groups (2-3)	Hybrid	Sound ...	No	Yes
	Radio Room	4	2	8	1	**8**	100.00%	3	Work	Support		Small groups (2-3)	Hybrid	Sound ...	No	No
Health Zone	Gym	8	6	48	1	**48**	600.00%	6	Social	/		Large groups (4-6)	Open	Neutral	No	No
	Meditation Room	8	1	8	1	**8**	100.00%	3	Personal	/		Individual	Enclos...	Sound ...	No	Yes
	Medical Bay	10	2	20	1	**20**	250.00%	3	Personal	Support		Small groups (2-3)	Enclos...	Sound ...	No	No



Compact
Low Branching

Spread Out
Clearer Branching



L-SYSTEM

Definition and Computational Logic

L-systems, or Lindenmayers systems , are a mathematical method to model the growth process of plants (Prusinkiewicz & Lindenmayer, 2012). It defines an initial axiom and set of rules which are applied iteratively to create complex, branching structures. In this project an L-system is used computationally to serve as the primary organisational framework of the habitat.

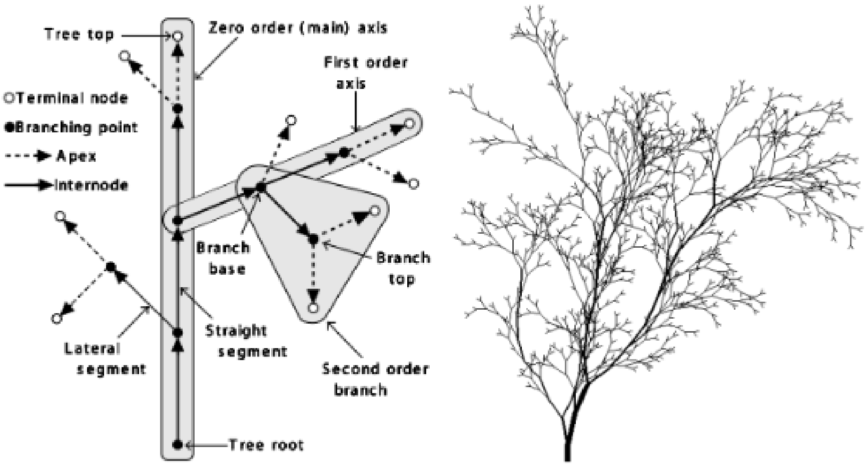


Figure 11: L-system branching behaviour and rules

Biophilic Integration

L-systems apply biomimicry to model plant growth. This is particularly relevant for humanity's long-term goal of living on the Moon. Due to the inherently recursive nature of L-systems, the habitat would be designed for modular expansion. As crew sizes expand, the habitat could generate new branches for additional living areas to form one large interconnected system.

Organizational Benefit

Organisationally, the L-system offers numerous benefits. The central branching system creates an efficient pathing for both circulation and technical piping and wiring. Moreover, the branching naturally forms sections in the design. The transition nodes between branches provide ideal locations for pressure-sealing doors to compartmentalize the habitat for safety in case of a fire or structural breach.

Lastly, the L-system also creates an intuitive spatial hierarchy as branches subdivide and decrease in scale. This facilitates a natural transition from larger social spaces to smaller private ones.

Case Study: Greg Lynn – Cardiff Bay Opera House

Greg Lynn's proposal for the Cardiff Bay Opera House serves as a precedent for utilizing L-systems as a generative architectural tool. In the design, recursive branching was applied to a set of ovals to establish the building's rough footprint. This system facilitated a clear spatial hierarchy, where the varying scales give each branch a distinct spatial quality that guide functional distribution. After some architectural refining, the resulting diversity in volume and ceiling height give the building a dynamic interior landscape.

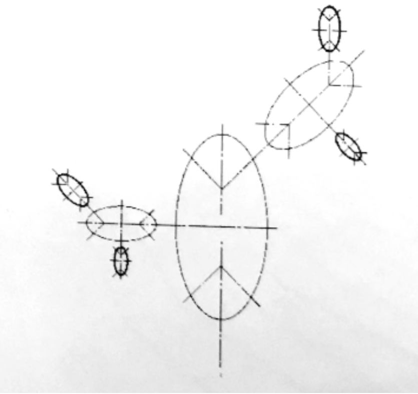


Figure 12: L-system branching using ovals Lynn, G. (1999). Animate form. Princeton Architectural Press

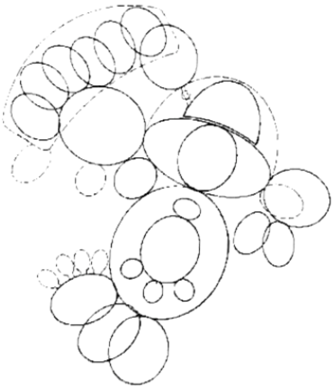


Figure 13: Adjusted L-system logic as the building's footprint Lynn, G. (1999). Animate form. Princeton Architectural Press

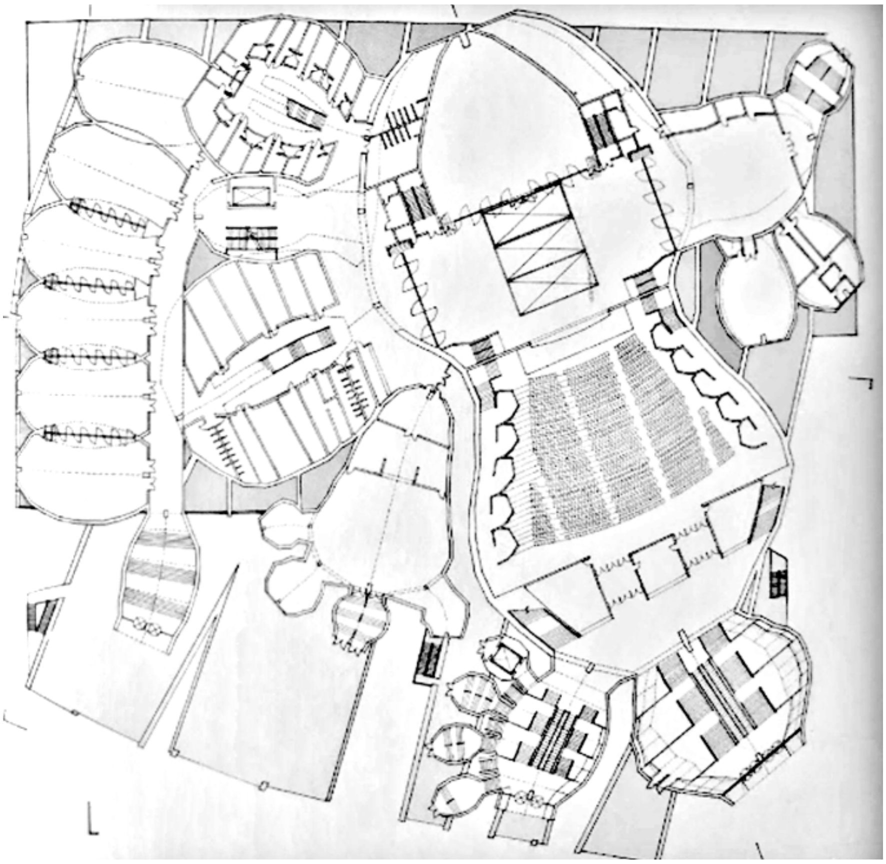


Figure 14: Architectural plan drawing of the design proposal Lynn, G. (1999). Animate form. Princeton Architectural Press

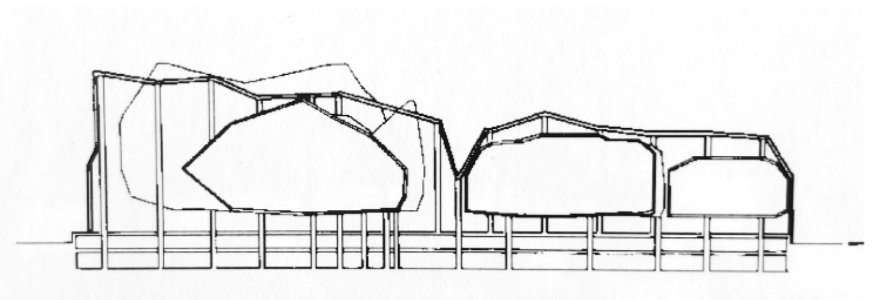


Figure 15: Section showing the varying height and room sizes Lynn, G. (1999). Animate form. Princeton Architectural Press

METABALLS

Definition and Computational Logic

While the L-system defines the pathing of the building, metaballs provide the computational system that generates the building's volume. Metaballs are defined as n-dimensional isosurfaces that are defined by a scalar field. The center points, called seed points, will be defined using nodes derived from the L-system branches. When these points are in close proximity, their fields of influence overlap, causing the volumes to merge into a continuous fluid morphology. By adjusting the strength of their influence and the proximity between seeds, the degree of merging can be controlled.

Biophilic Integration

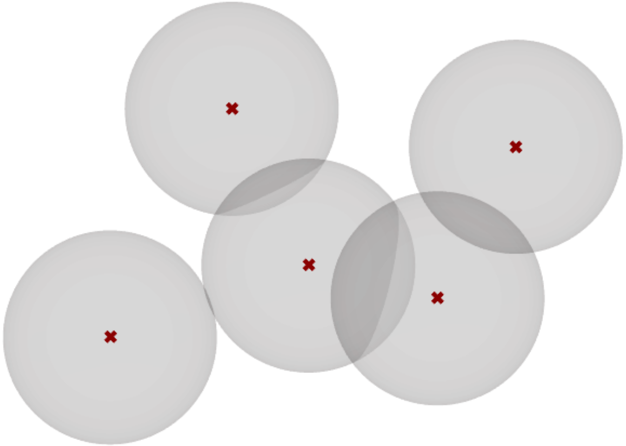
The choice of metaballs is rooted in the principle of Natural Analogues, the concept of mimicking nature.This specific morphology is inspired by water droplets and how they behave in microgravity. Without gravity, the droplet's surface tension is the dominant force, pulling it into a perfect sphere that seamlessly fuses it with any surrounding droplets. This organic fluidity results in curving, dynamic volumes that will intentionally move the habitat away from rectilinear geometries found in more traditional architecture.

Figure 16: Behaviour of water in microgravity aboard the ISS

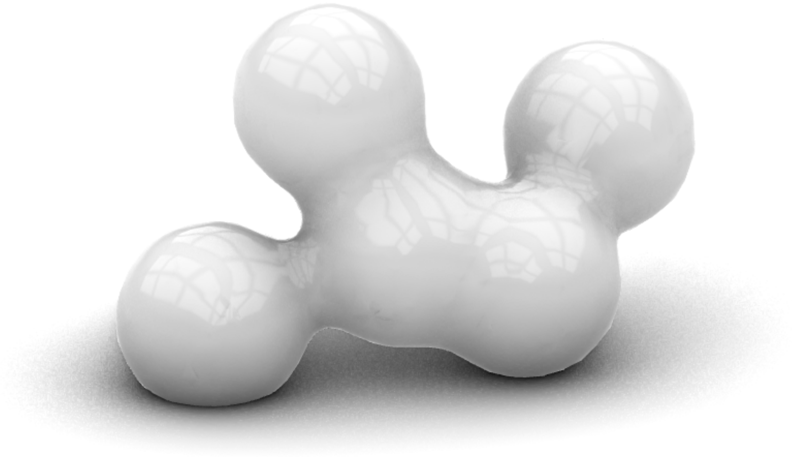
Structural Optimization

Beyond aesthetics, the metaball morphology also has performance benefits. 3D printed structures are built up in layers; the horizontal seams between layers are inherently weaker in tension. Consequently, the design should prioritise compression-based forms. The metaball system employs catenary-like arches that distribute their weight downwards through compression.

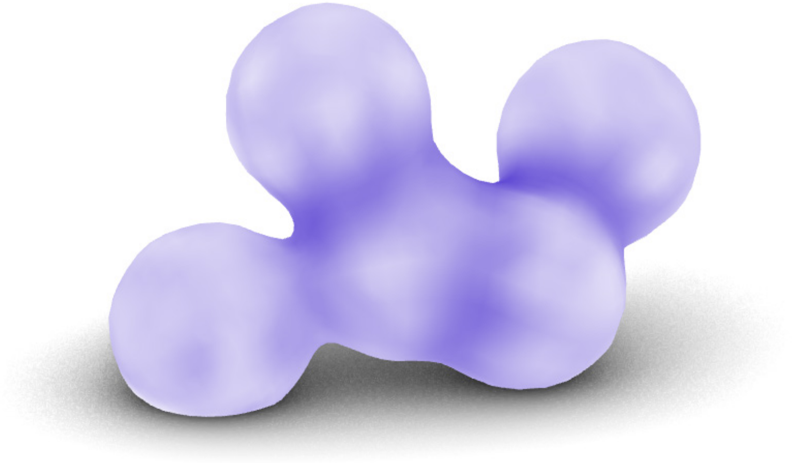
Furthermore, in the vacuum of the lunar surface, the habitat must withstand 1 atmosphere of internal pressure pushing the habitat walls outwards. Spherical and organic 'blob' shapes are more efficient at distributing stress evenly across the envelope, minimizing the risk of localised failure due to tension hotspots.



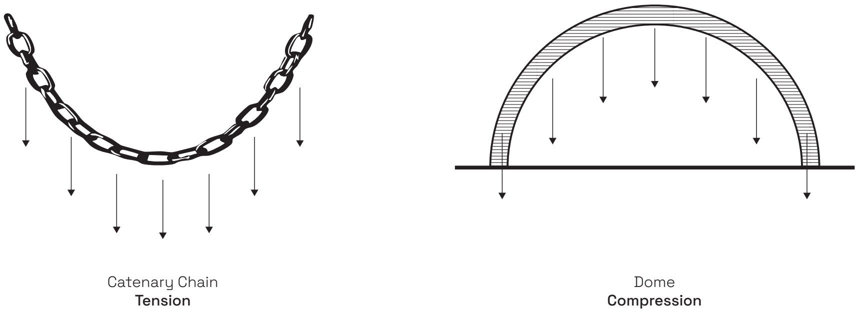
Visualisation of seed points and spheres of influence



Visualisation of the subsequent metaball morphology



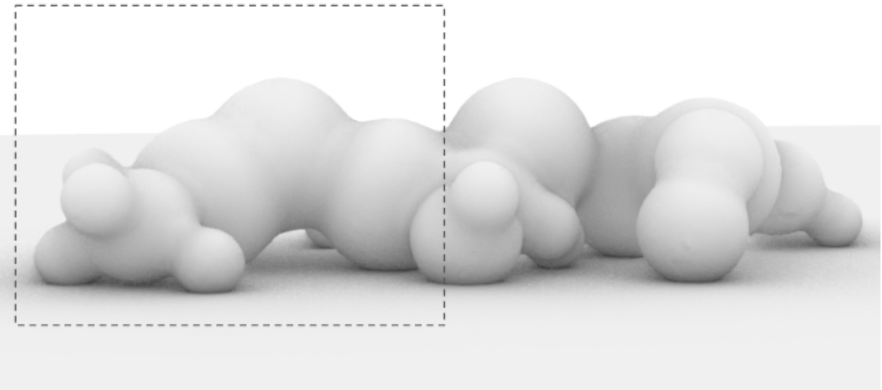
Karamba analysis of the effects of internal pressure and gravity, showing relatively equal stress distribution with some peaks in the 'necks' between shapes.



Visualisation of a catenary chain and compression dome

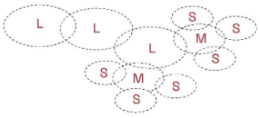
FRAGMENT

Chosen Area

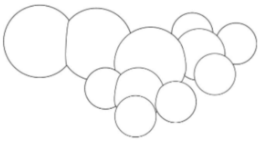


Concept Diagram

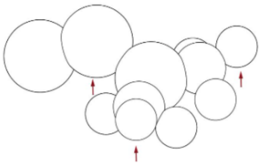
L-System



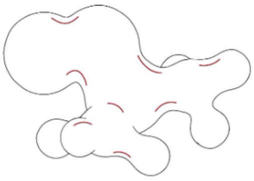
Bubble Diagrams



Volume

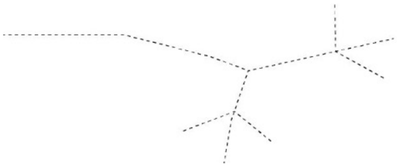


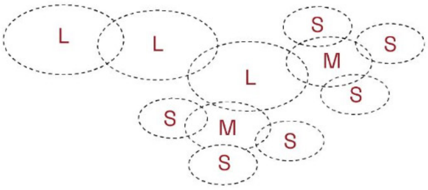
Dynamic Height Changes

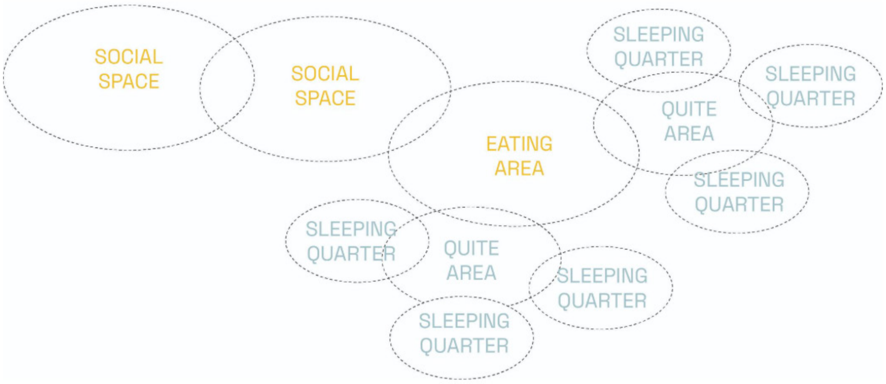


Creating Smooth Metaballs

L-system Based Bubble Diagrams

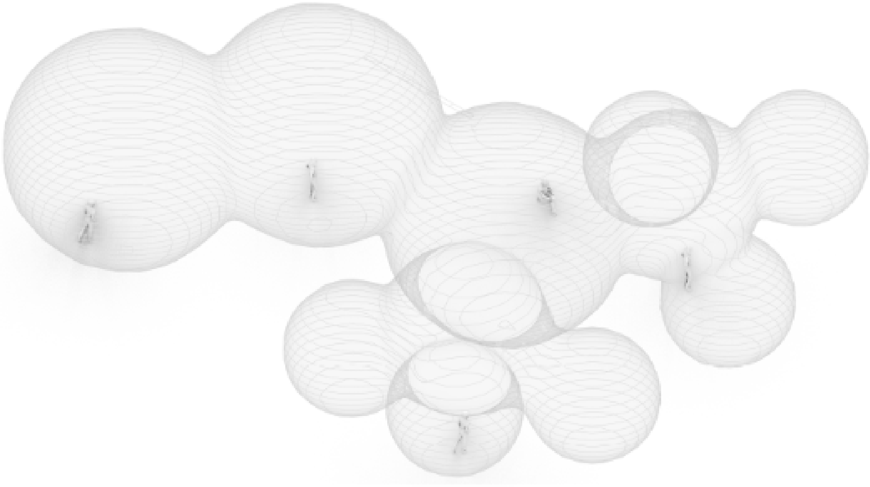






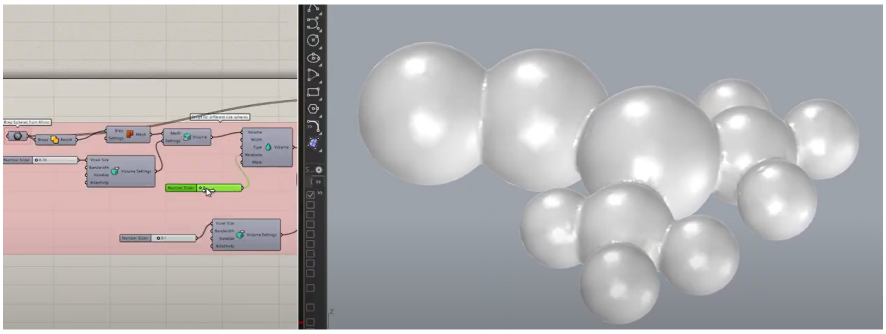
FORM FINDING

L-system floorplan combined with metaballs

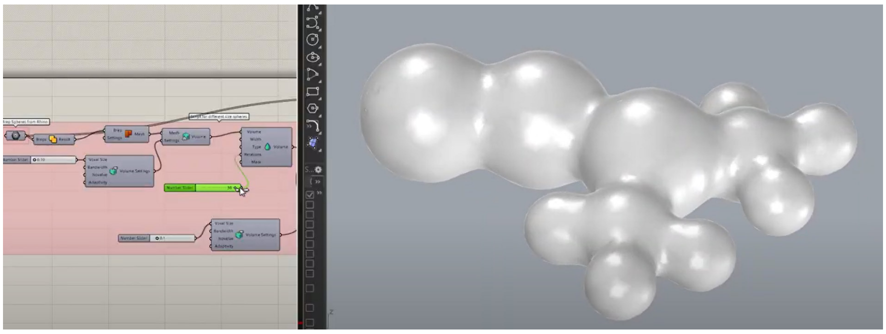


Visualisation of the L-system layour in combination with metaballs

Computationally smoothing metaballs

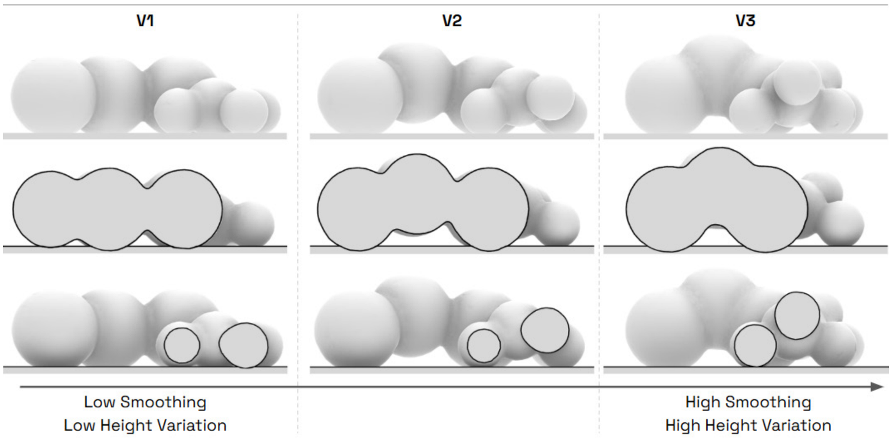


Low level smoothing, very spherical



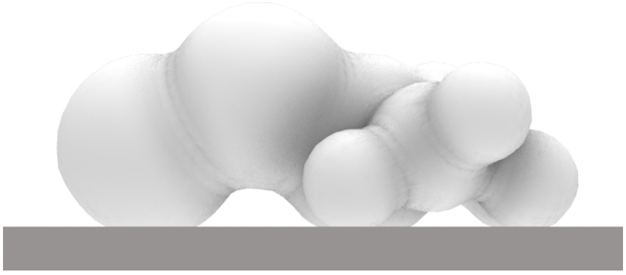
High level smoothing creates a more blended shape

Design Itterations

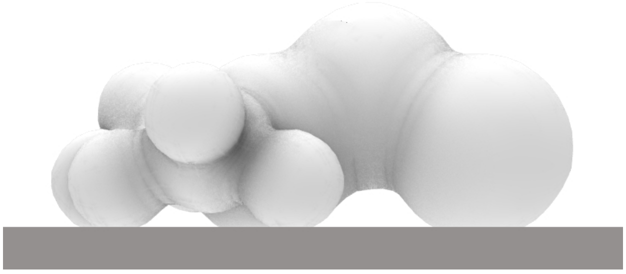


3 itterations showing their side profile and section at different depths, getting progressivly more dynamic and rounded.

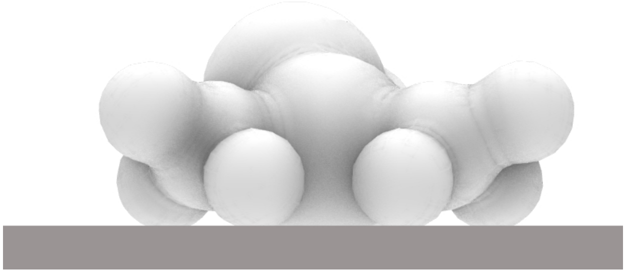
V3 Volume Elevations



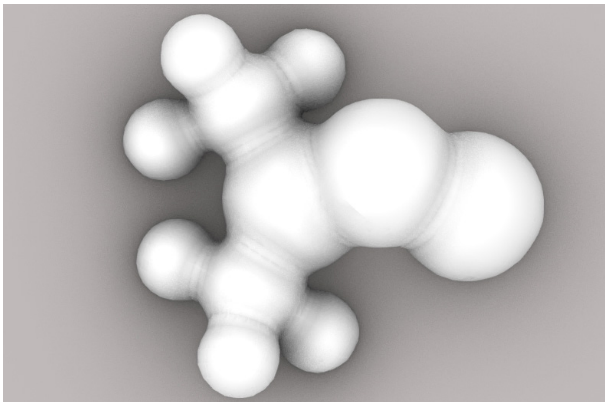
V3 left side view



V3 right side view



V3 front view



V3 top view

RADIATION SHIELDING

Radiation Safety Limits

Long term missions on the Lunar surface can only be achieved if astronaut safety is optimised. One of the main hazards of the moon is the extended exposure to radiation. On Earth the atmosphere and magnetosphere protect us, reducing the average radiation background to around 2.4 mSv/year. For reference, on the International Space Station they receive doses around 0.5 mSv/day or around 182.5 mSv/year, a significant increase (Ramos et al., 2023).

To protect astronauts from cancer and other health risks, the ESA sets a career radiation limit of 1000 mSv (ESA, 2026), while NASA allows for only 600 mSv (NASA, 2022). With radiation we generally follow the ALARA principle, As Low As Reasonably Achievable. For this reason we will aim for about half the radiation exposure compared to the ISS. This means around 90 mSv/year, thereby allowing astronauts to run missions for extended durations.

Shielding Thickness

To achieve this goal, we will need to define the required thickness of the regolith structure. The closest simulation for the regolith we will use in the habitat comes from Meurisse et al. (2020) who measured the radiation shielding capabilities of sintered regolith.

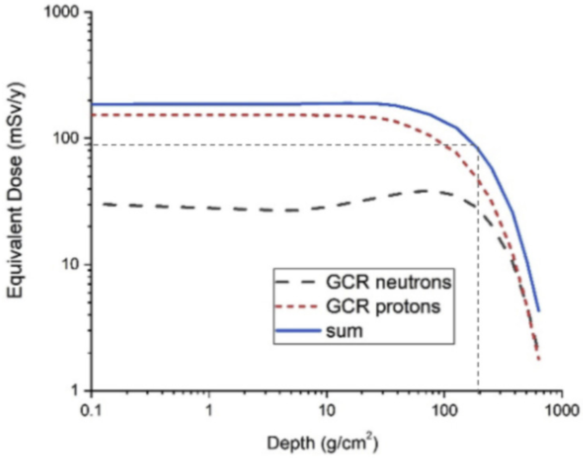


Figure 17: Equivalent dose in the lunar environment for different thicknesses of regolith shielding (Adapted from Meurisse et al., 2020)

If we aim for an equivalent dose of around 90 mSv/year, the graph indicates we need around 200 g/cm2 of sintered regolith. With a density of 2.54 g/cm3, this equates to a wall thickness of 78.74 cm which we will round up to 80 cm. Water performs even better at blocking radiation due to it predominantly being made out of hydrogen atoms, which significantly slow down the radiation particles through collisions (ESA, 2025). According to NASA's shielding requirement guidelines recommend vehicles to have at least a 20 g/cm2 aluminium shielding (74.07 mm) with an extra 20 cm water equivalent stormshelter shielding to protect against a worst case once in a thousand years of solar particle event radiation from a solar flare (Office of the Chief Health and Medical Officer, 2022).

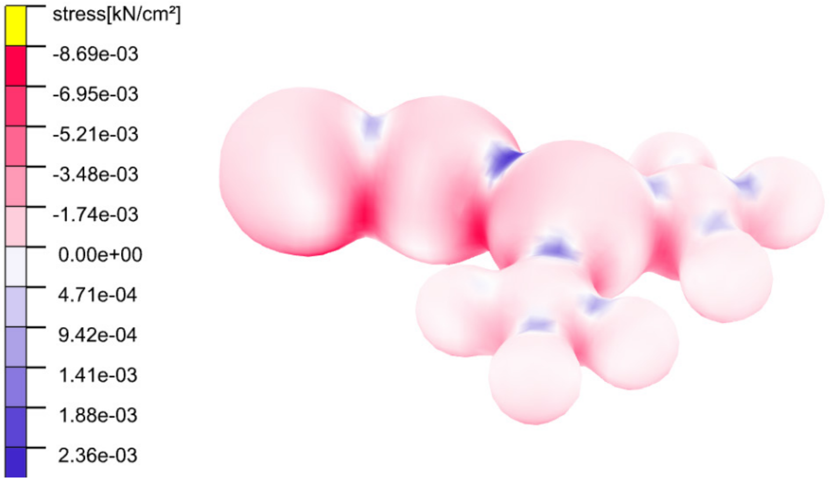
STRUCTURAL ANALYSIS

Metaball Structure Analysis

Based on the 800 mm wall thickness, the structure can be evaluated in Karamba3D and optimised. By plugging in properties of the SLM regolith, based on research by Guo et al. (2025), the design can be tested against both gravitational and pressure forces.

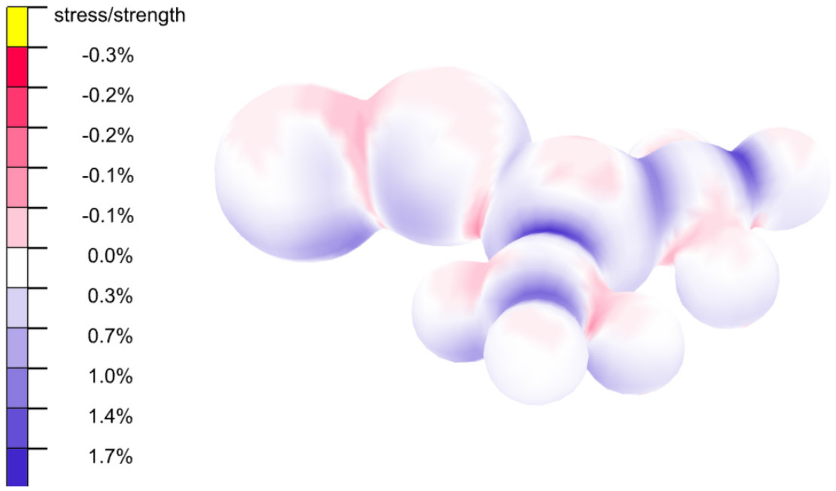
Gravitational Force

The first simulation shows the V1 design under the gravitational force on the Moon. Due to the relatively low gravity and extremely thick walls against radiation, the structure is overengineered. The red areas show compression which at no point comes close to the initial failure strength of melted regolith at 9.25 kN/cm2. It is also clear to see that the shape is mostly in compression, with a few tension peaks at the top of the bridges between metaballs. Overall the structure is very solid.

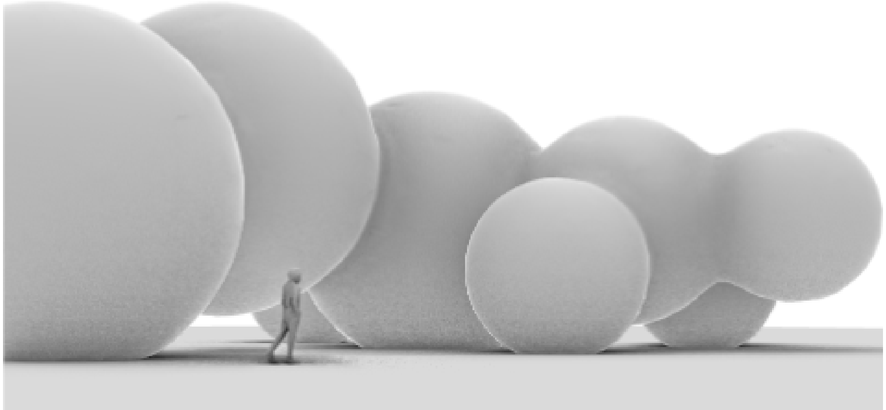


V1 gravitational stress analysis

The next simulation, V2, shows the metaballs in a cantilevered and raised scenario to facilitate the jumpy lunar movement and the goal of creating a dynamic interior experience. Again the stress to strength ration is more than able to handle the low gravitational force.



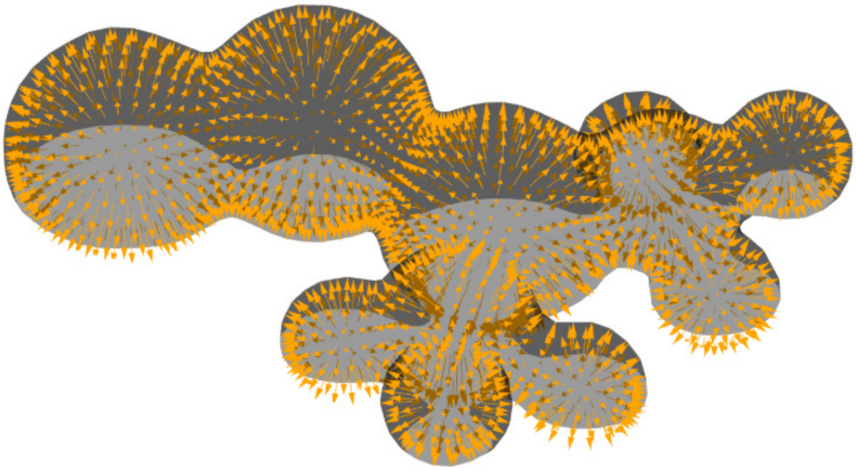
V2 gravitational stress to strength ration



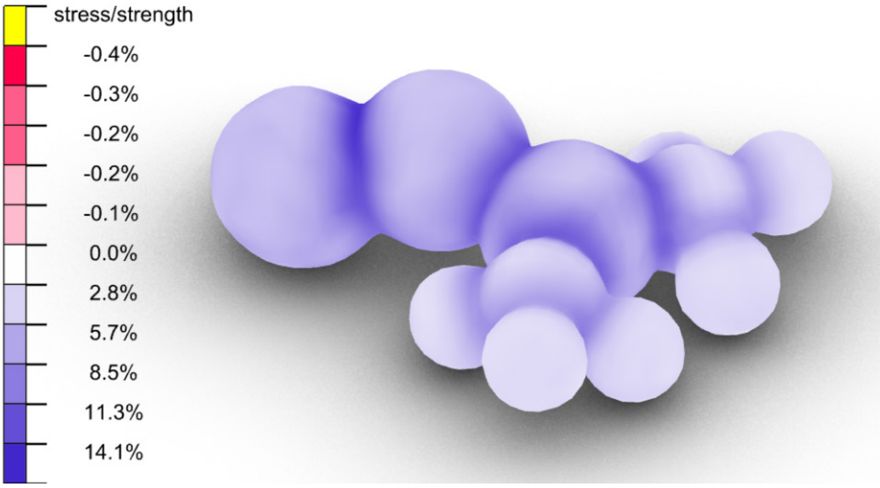
V2 design showing variable heights and cantilevers

Outwards Pressure

The most significant force acting on the design is pressure. As the Moon is in a vacuum, there is 1 atmosphere of pressure pushing the structure out in all directions and putting it in tension. This is where the metaball shape shows its greatest advantage as the force is spread across the structure relatively easily. The highest peak in tension is still well below breaking point. Compared to the force of gravity, pressure raises the peak stress/strength in V2 from 1.7% to a more significant 14.1%.



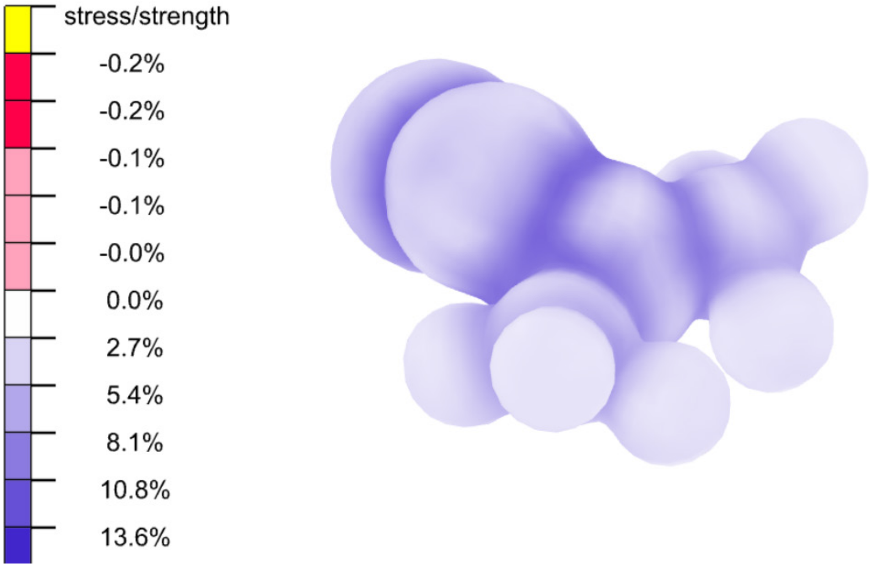
V2 with internal pressure arrows pushing the envelope outwards



V2 pressure stress to strength ration

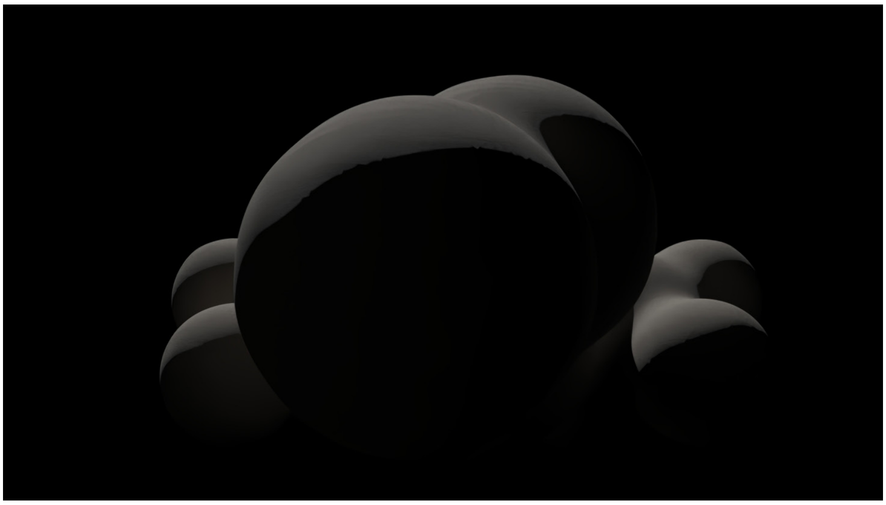
Gravity & Pressure Forces on Design

By moving the metaballs closer together and increasing the level of smoothing, V3 creates a more efficient load path and reduces the stress hotspots between individual metaballs. Allowing for a safer and more optimised structure.

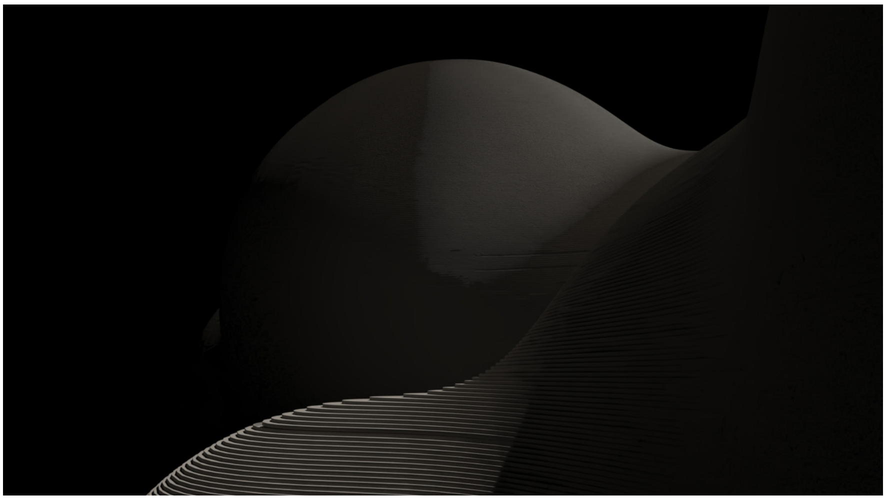


V3 pressure and gravity stress to strength ration

Impression of Resulting Structure



Impression showing the metaball smoothing



Impression showing a closer view of the smoothing with 3D printing lines visible

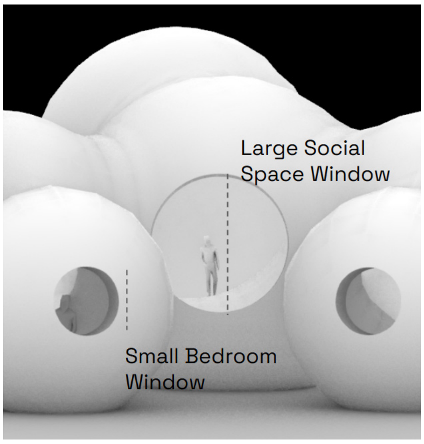
POROSITY

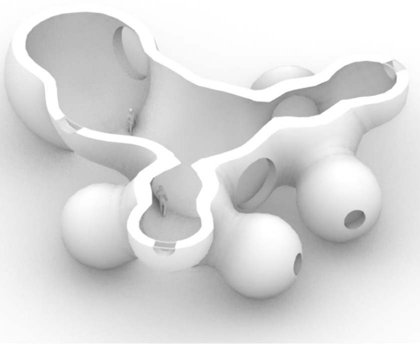
Window Typology

Experimentation with different window shapes, metaball vs circular, found that circular fits the interior the best. The sizing of the windows is based on the room's function, size and privacy.

Round

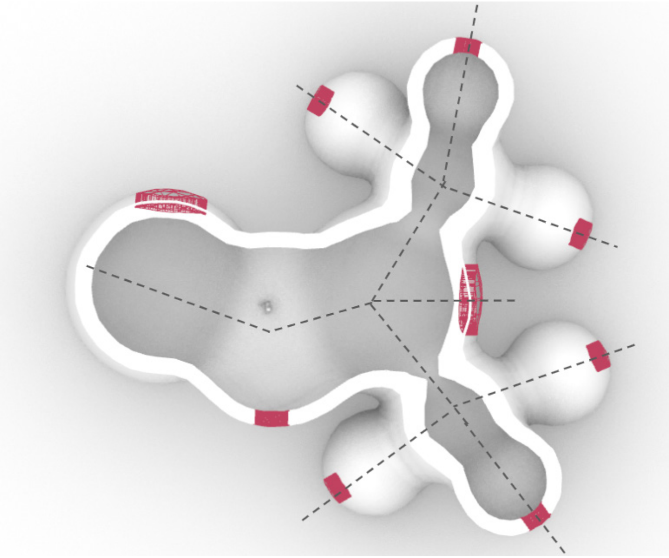
Metaball





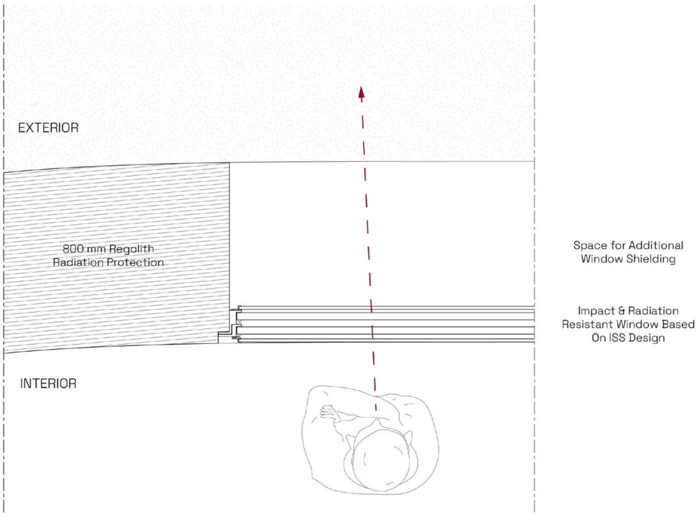
L-system Positioning

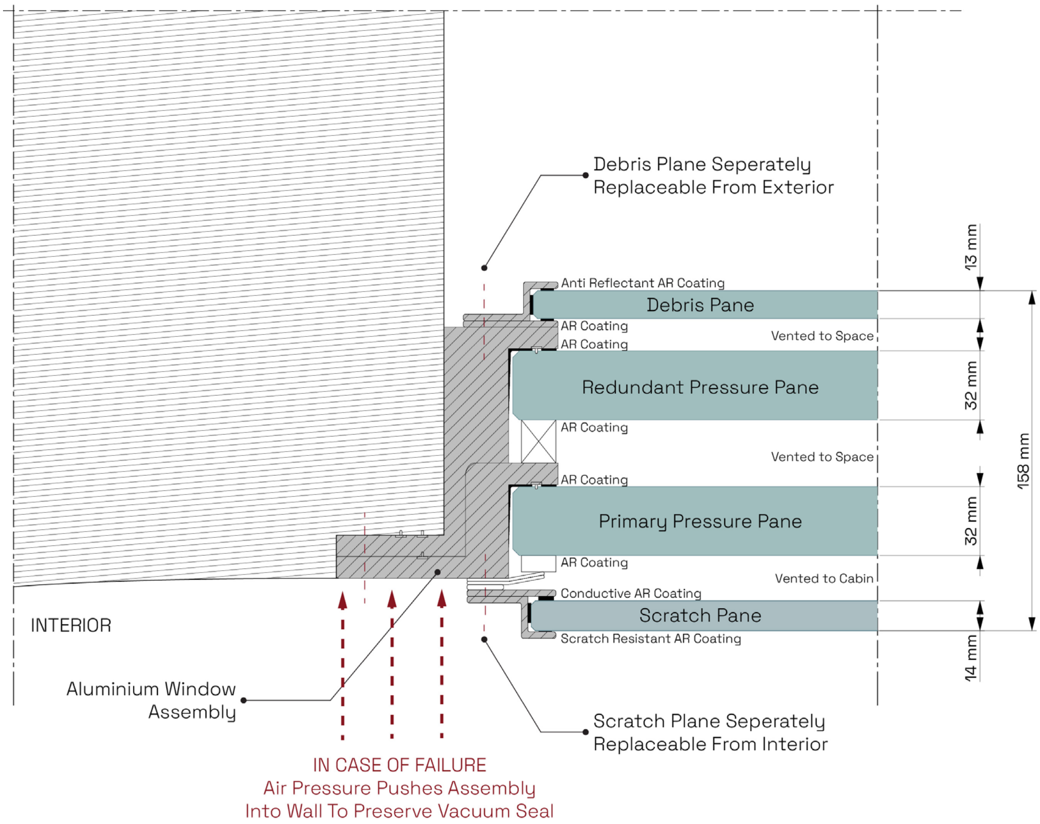
The positioning of the windows follows the L-system logic. Where possible the windows are in the extension of the L-system path, creating the feeling that the space continues on. Thereby reducing the feeling of claustrophobia.

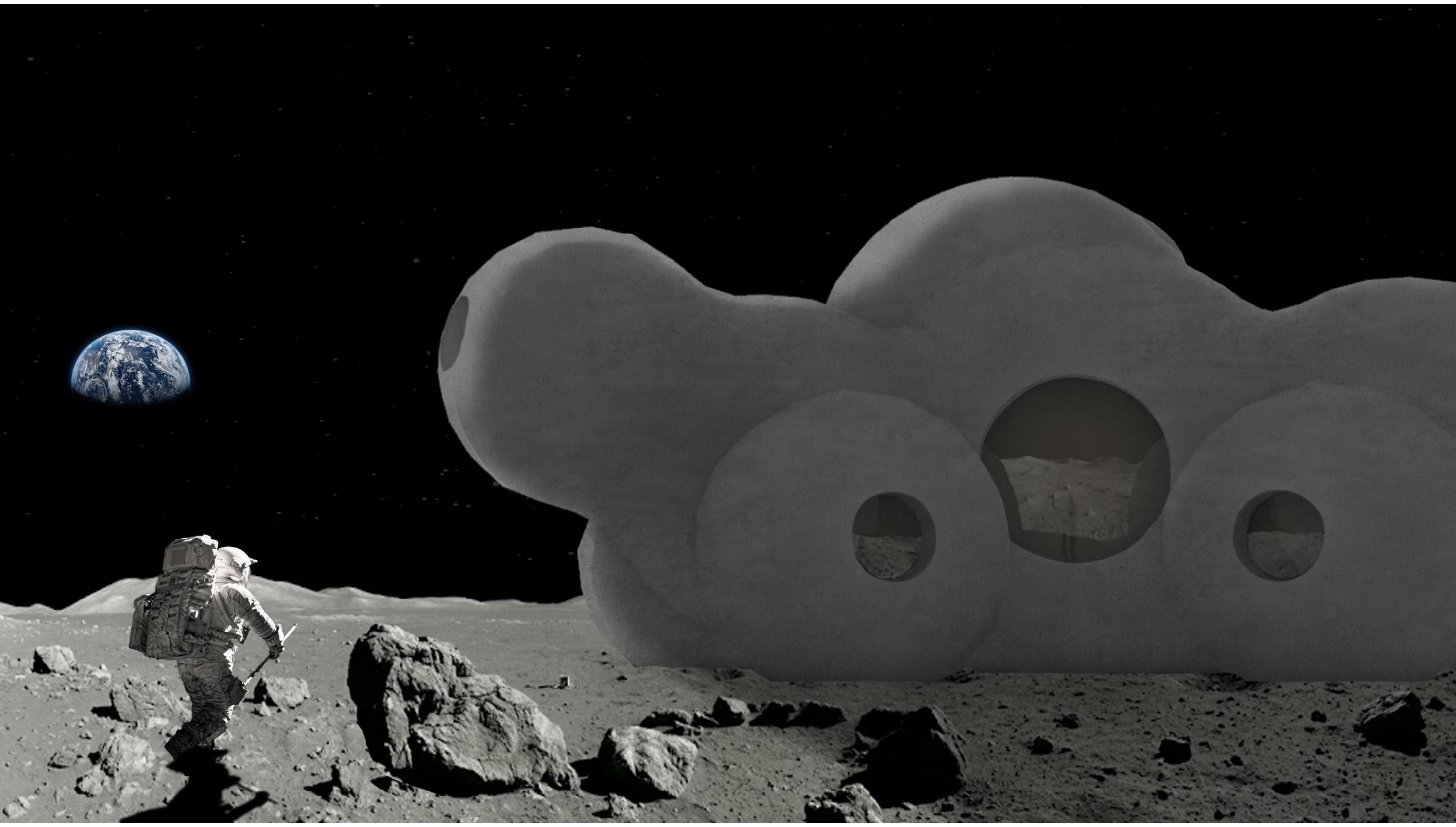


Window Detail

This window detail is based on the ISS cupola design. The exterior debris layer protects against micrometeorites and is connected in a way that is easily replaceable. Between the two main glass planes there is a 200 mm water layer for radiation protection, using a water pump system based on an existing water filled glass design built by WFG. Finally, the interior layer consists of a scratch resistant glass pane that is similarly replaceable.



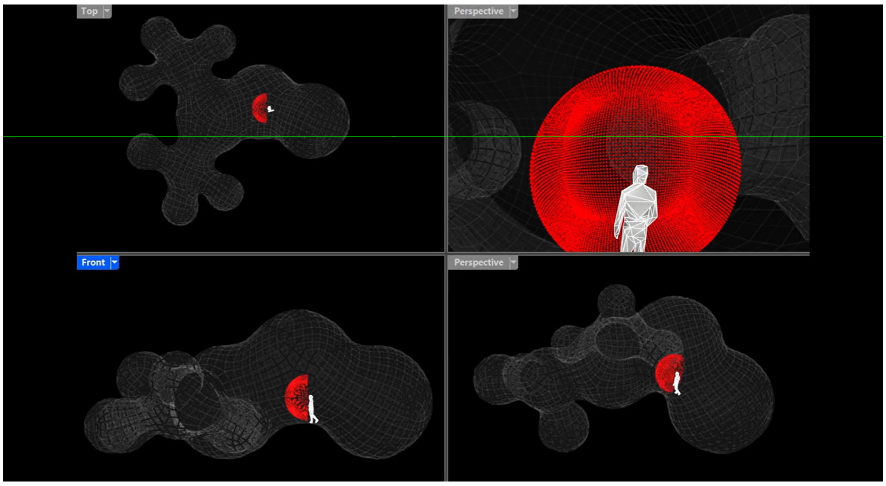




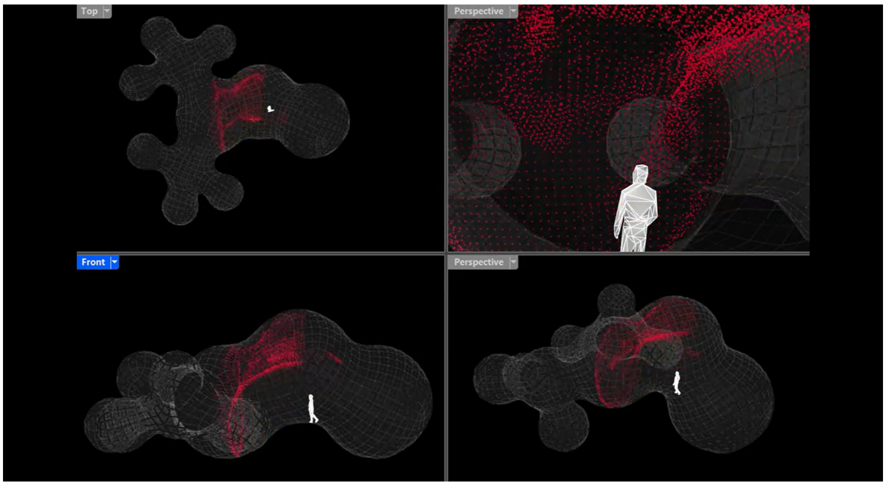
ACOUSTICS

Concave Shell

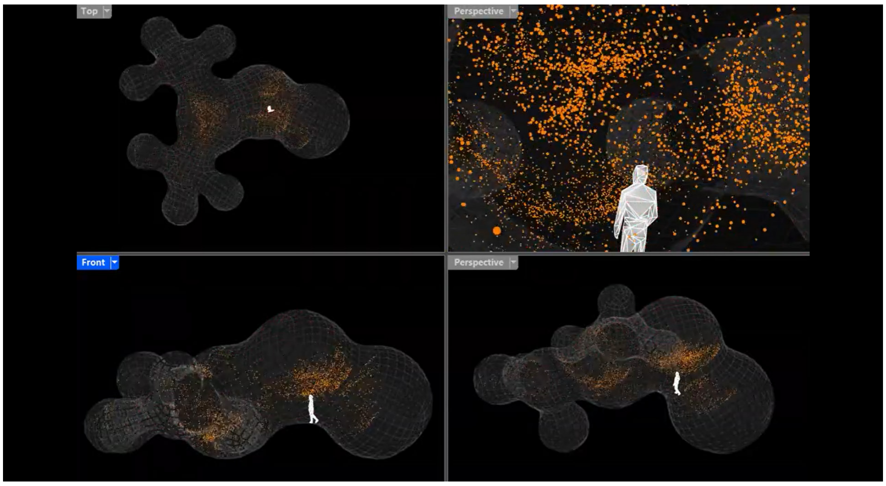
The concave shape of the metaball interior causes sound waves to reflect back towards their source. Moreover, the sound bounces around the room multiple times as it is slowly absorbed by the walls. Subsequently, without proper measures the acoustic comfort can be hindered by long reverberation times and low speech intelligibility. To illustrate this a Pachyderm simulation was run, showing the sound waves move around the fragment and slowly being absorbed.



Simulation showing sound waves emitting from a person.



Simulation frame showing sound bounding off the interior surfaces.



Simulation frame showing reflected sound returning to source.

Interior Pattern

Introducing an interior pattern helps scatter the sound waves randomly, reducing sound concentrations. A pattern can also increase the surface area and therefore the speed at which sound is absorbed.

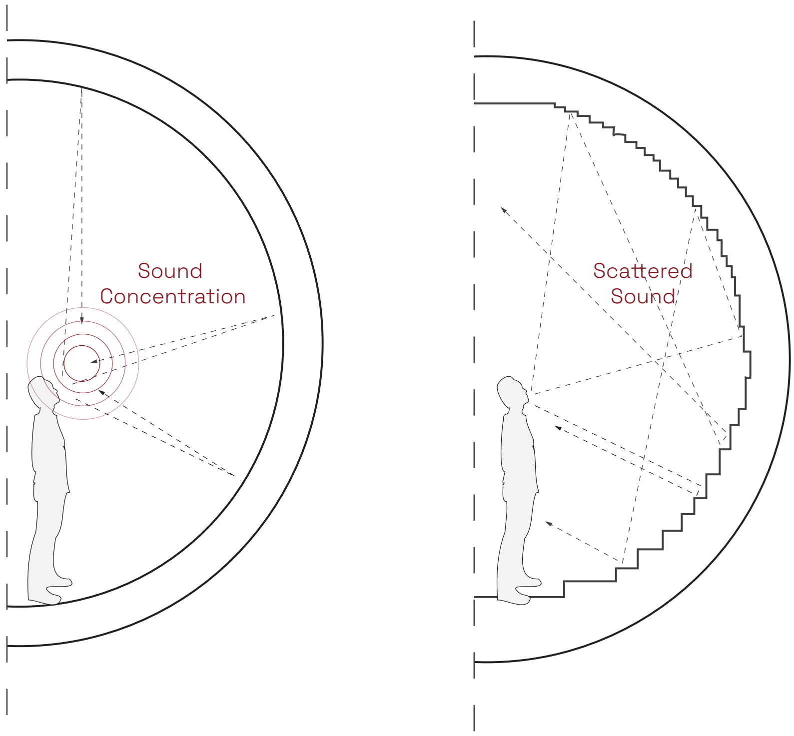


Diagram showing the propegation of sound with and without an interior pattern.

WALL PATTERN

Rock inspiration

To create the patterned surface on the organic interior, inspiration can be taken from natural rock formations on Earth. Utilizing this layered design improves acoustic comfort while adding a touch of nature to the interior.

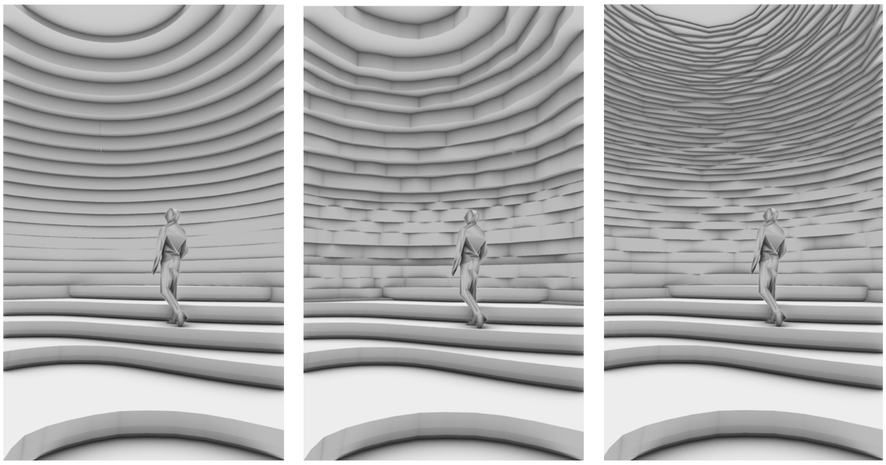
Picture of natural rock formations

Case Study - Chapel of Sound

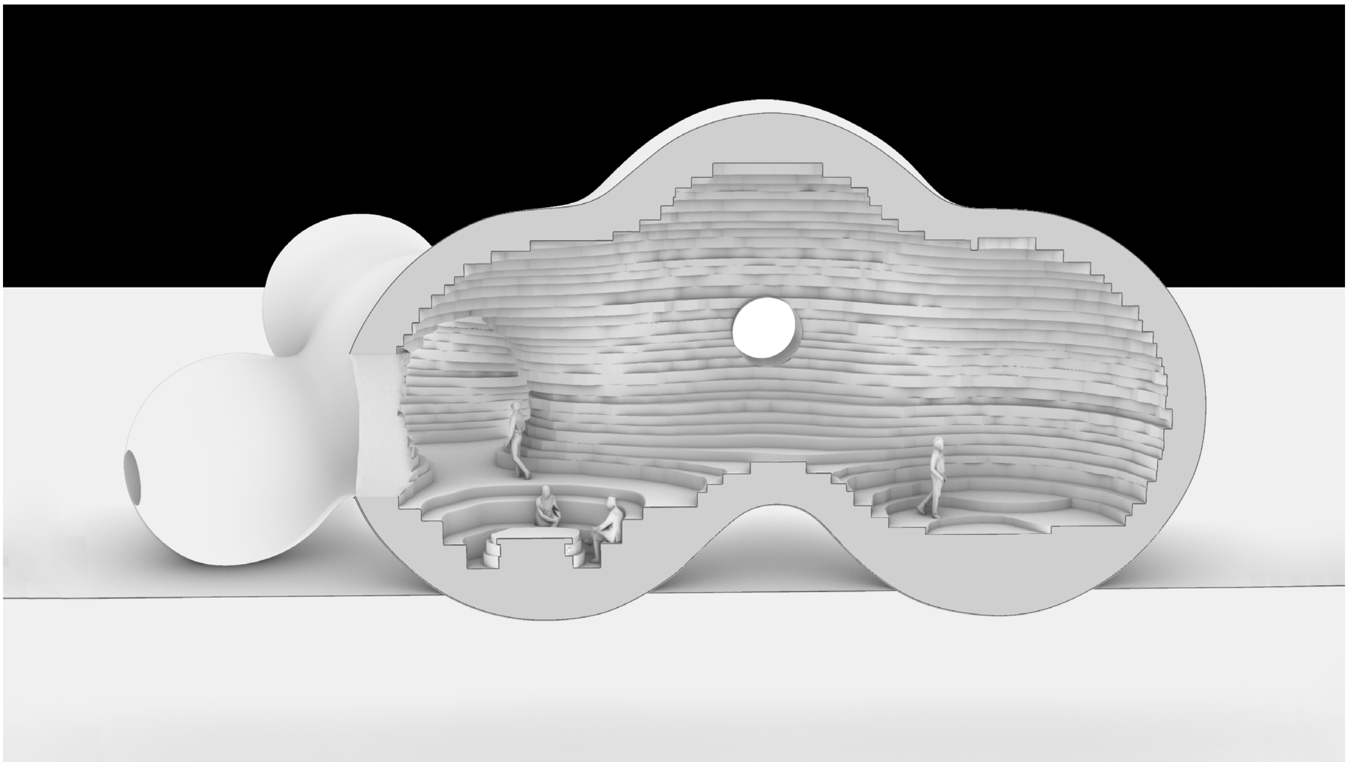
Chapel of Sound by OPEN Architecture shows how rock formations can be mimicked on the walls and floors to create seating and acoustics. Note how each layerer is extruded out at different lengths and have varying dimensions, creating a natural feel.

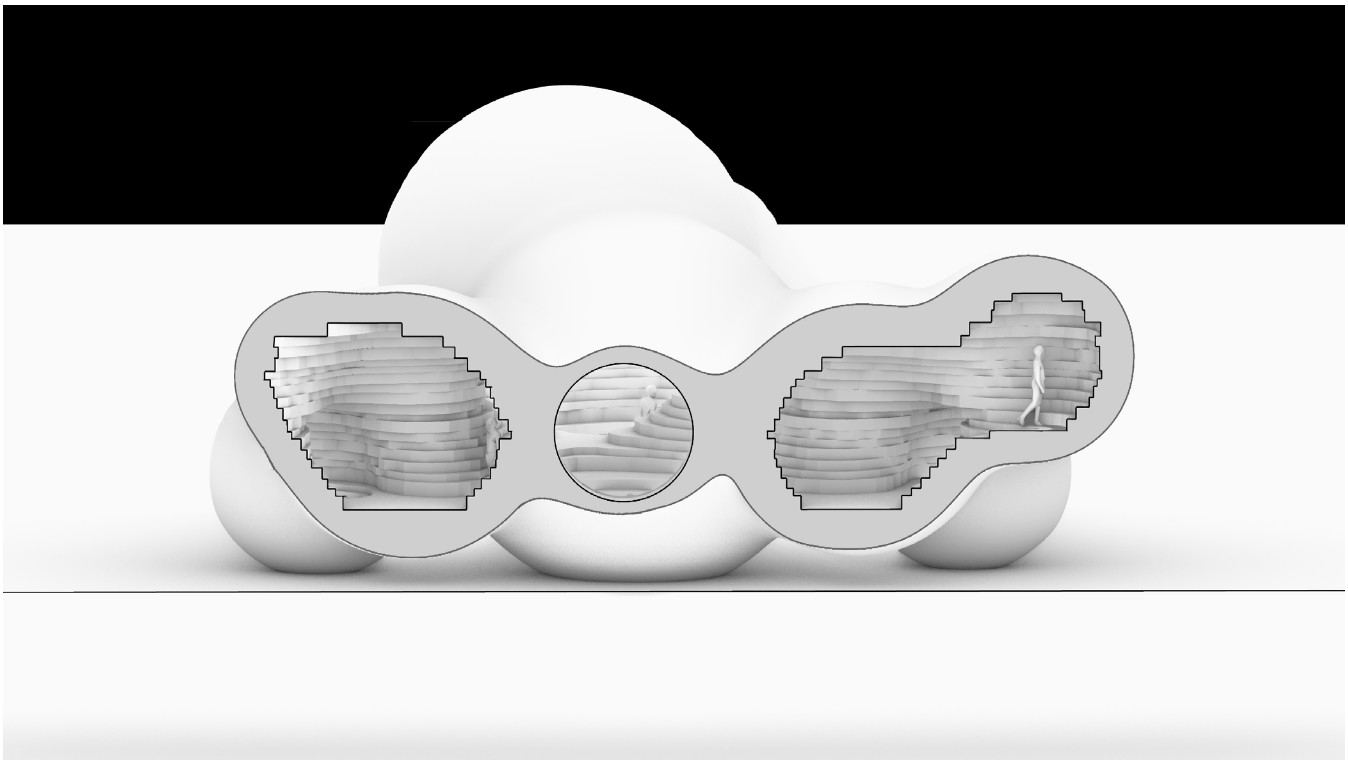
Figure 18: Interior of the Chapel of Sound (Leijonhufvud, 2021)

Pattern Itterations



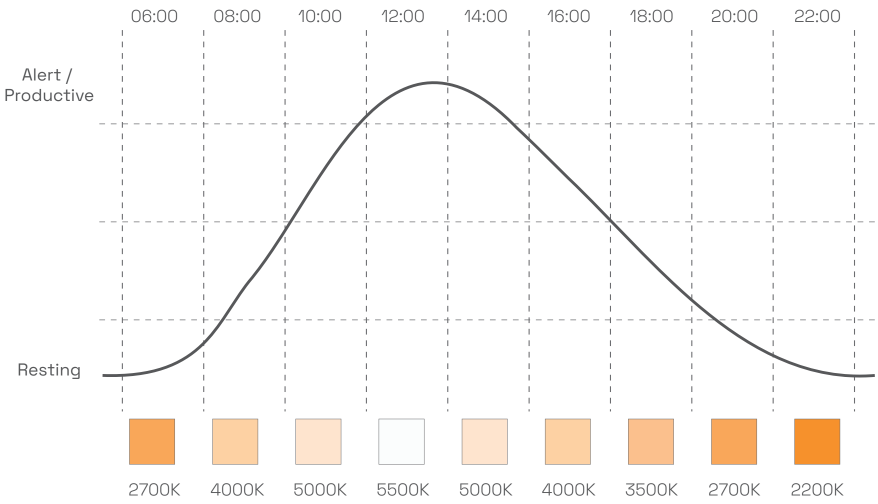
3 itterations of the interior wall pattern mimicking rock formations





CIRCADIAN RHYTHM

Lighting Throughout the Day & Effect on Body


Lighting - Circadian Rhythm

Impressions of Integrated Wall Lights

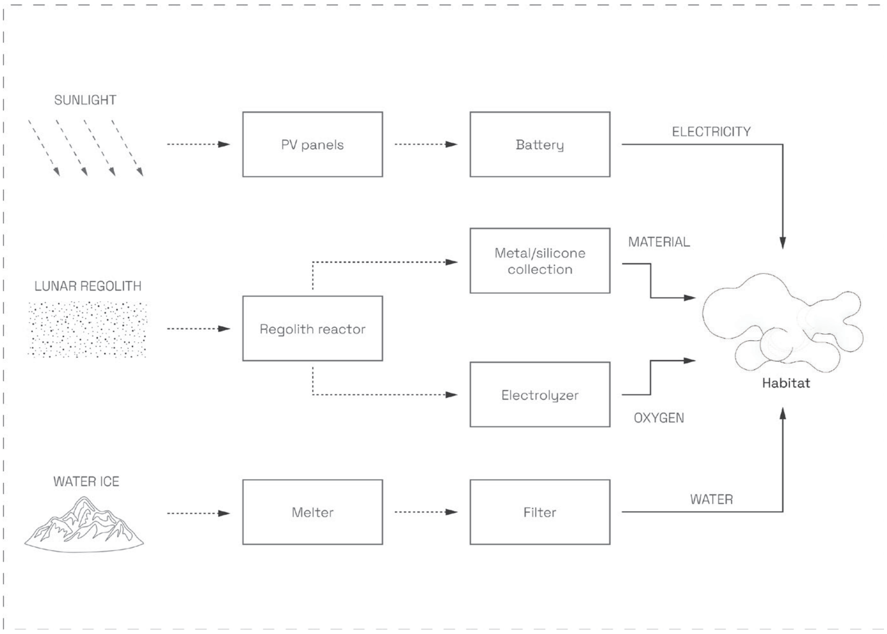
Interior lighting shifts in color, intensity and directness to mimic the natural daylight progression on Earth. This helps regulate the biological clock to improve sleep, productivity and mood.


MORNING NOON EVENING

LIFE SUPPORT SYSTEMS

ISRU Diagram

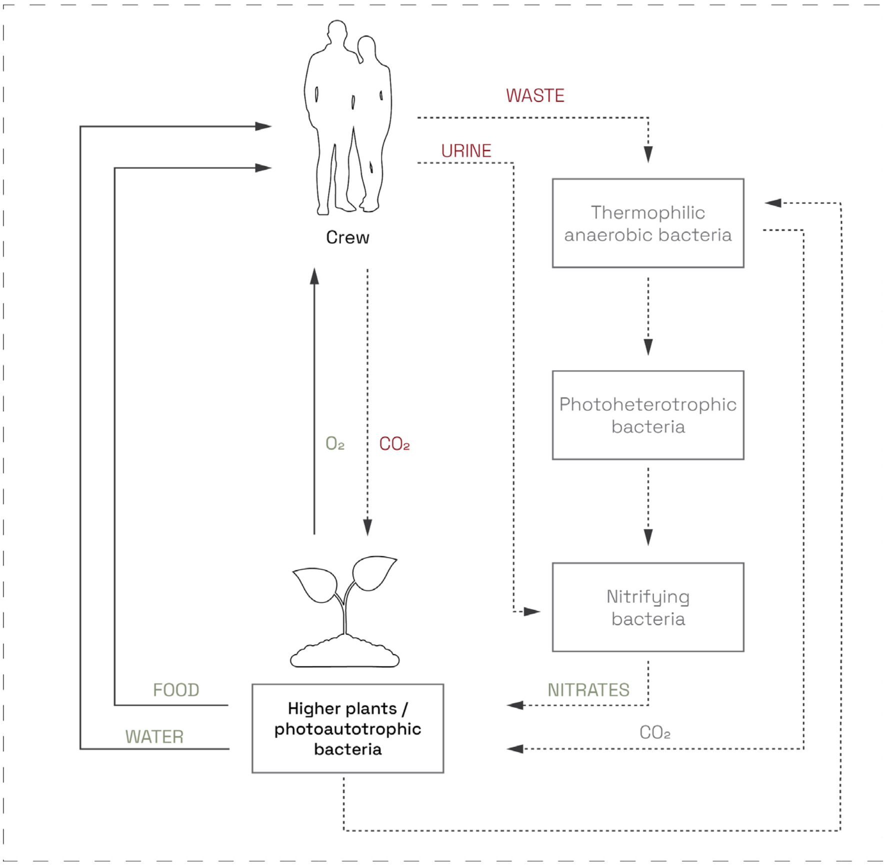
RESOURCES - In-Situ Resource Utilization



MELiSSA Loop

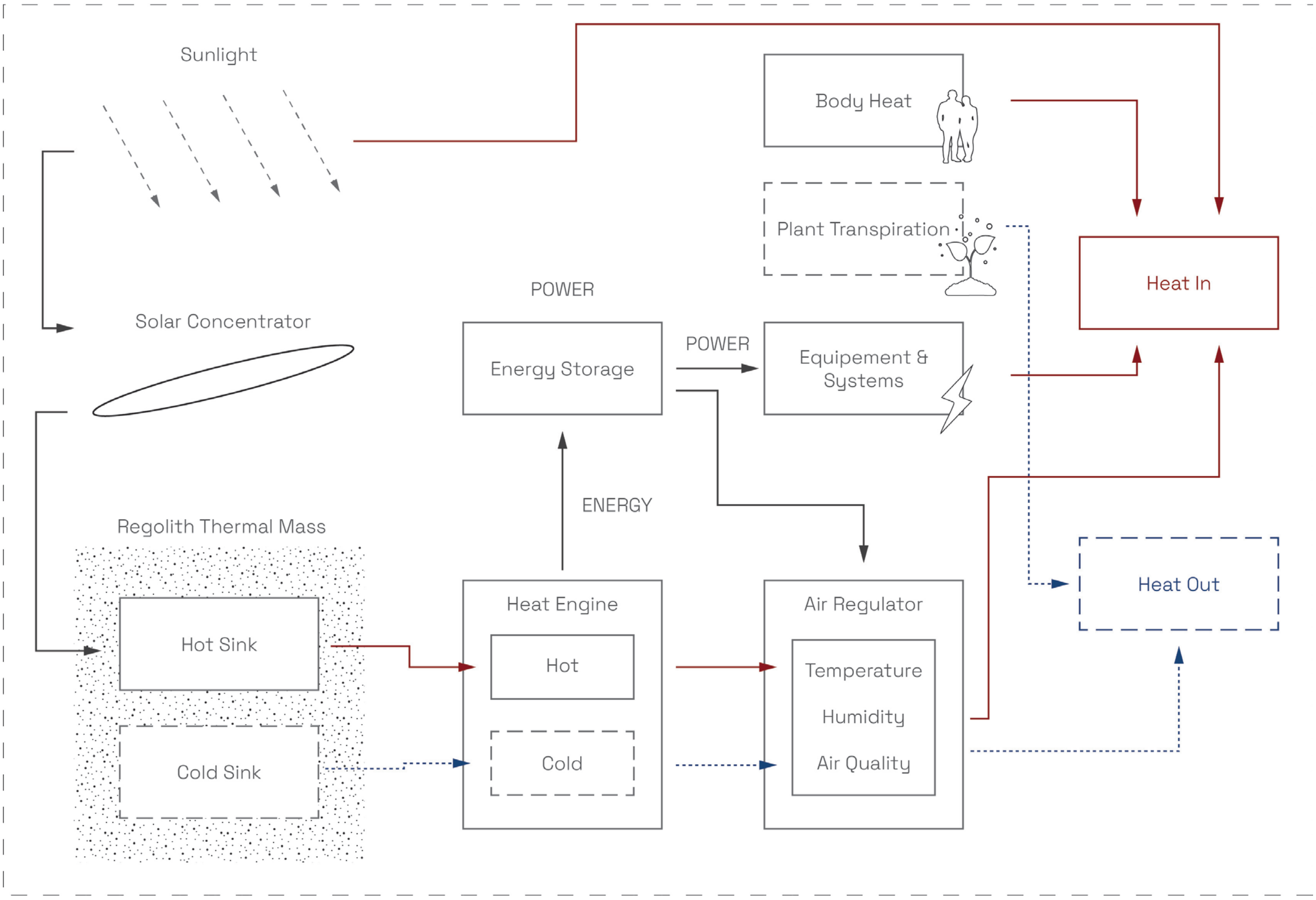
The MELiSSA loop is an ESA design of a closed loop regenerative LSS to be used for long-duration missions in space. It utilizes plants and microorganisms to create an ecosystem that filters air, provides food and filters water (ESA, n.d.).

LIFE SUPPORT - MELiSSA LOOP



Thermal Regulation

THERMAL - Heating and Cooling



PART 4

CONCLUSION & DISCUSSION

National Aeronautics and Space Administration. (1972, December 12). Astronaut Harrison Schmitt retrieving lunar samples during EVA [Photograph]. https://images.nasa.gov/details/as17-145-22165

CONCLUSION

The aim of this thesis was to investigate how biophilic design principles could be used in a ISRU 3D-printed lunar habitat design to support astronaut mental health and well-being. To answer this question, the report first identified the key challenges of lunar construction. Mainly the transportation costs, hostile environment and mental health deterioration stemming from the high stress environment and sick building syndrome.

To mitigate the transportation costs and reliance on materials from Earth, the design leverages ISRU. By harnessing local lunar resources, namely regolith, water, oxygen, silica and sunlight, the habitat can be constructed and supported with a high degree of self-sufficiency. Construction is proposed via robotic manufacturing, utilizing SLM to fuse regolith layer by layer into dense structural elements. The thickness of the envelope elements like the walls and windows are also designed to protect astronauts from radiation.

Biophilic design plays a central role in the design. From the building's initial layout, to its structural morphology and its interior detailing. Firstly, L-systems are used to establish spatial hierarchies that inform functional clustering and programmatic distribution. This system also helps with compartmentalisation for safety, efficiency in pathing and accommodates future expansion. Secondly, metaballs, inspired by water behavior in microgravity, inform the structural design. Their organic shaping is suited for additive manufacturing and has been shown to help distribute internal pressurisation loads evenly across the envelope; reducing stress concentrations. Moreover, the low gravity environment allows them to be arranged at varying elevations and angles, utilizing cantilevers to achieve a dynamic architectural experience.

To counteract psychological degradation and mitigate the symptoms of sick building syndrome, the design is optimised according to the Indoor Environmental Quality (IEQ). To achieve this the building addresses lighting, acoustic comfort, air quality and thermal comfort. Lighting mimics the temperature and intensity shifts found in regular daylight cycles on Earth. This improves the circadian rhythm and biological clock of inhabitants; thereby boosting productivity, alertness and sleep cycles. Acoustic reverberation issues stemming from the concave shape of the metaballs is addressed through interior surface patterning that mimics rock formations. This breaks up sound waves to improve speech intelligibility and reduce echos. Air quality is improved through the integration of plant life in the building and LSS, this was done through the MELiSSA loop developed by the ISS. Finally, thermal comfort was improved by leveraging the thermal mass of regolith to create hot and cold sinks that store heat energy and naturally keep indoor temperatures steady, similar to how caves maintain their temperature. Finally, spatial variability is also employed through the combination of L-system and metaball generation, allowing occupants to experience different spatial qualities with views, height differences, private areas for refuge and larger spaces for social interaction.

Overall, the design synthesises the rigorous engineering challenge with the human-centric biophilic design approach. The resulting proposal offers a viable framework for future long-term lunar habitats that prioritise astronaut health and well-being.

IMPLICATIONS

Contemporary space habitats, like the ISS, are very pragmatic engineering-focused designs. The result is a very utilitarian product where comfort is not a priority. However, the design proposed in this thesis demonstrates that human-centric design does not have to compromise the technical considerations of extra-terrestrial architecture. By successfully synthesizing biophilic design principles within the engineering challenge of the Lunar environment, this framework establishes a precedent for the architectural typology of future Lunar habitats. One that places more emphasis on astronaut mental health and well-being.

Beyond space architecture, the methodology of this research also yields implications for terrestrial architecture. The application of L-systems shows how natural growth patterns can be translated architecturally to inform spatial flow and hierarchy. Furthermore, the metaball design demonstrates how advances in additive manufacturing can facilitate a departure from traditional orthogonal geometry. Thereby establishing organic, nature inspired forms as a viable architectural standard.

Within the lens of the UN Sustainable Development Goals (UNSDG), the design offers highly transferable insights for terrestrial architecture. Goal 3 (good health and well-being) is addressed through the use of biophilic strategies to mitigate sick building syndrome in space. This is highly applicable to terrestrial interiors as we spend most of our time indoors, and increasingly important as global events, like COVID-19, highlight the necessity for healthy and comfortable indoor environments. The integration of large scale additive manufacturing in this design addresses UNSDG 9 (industry, innovation and infrastructure) and shines a light on how this industry can help catalyze a new wave of architectural typologies. Lastly, goals 11 & 12 (sustainable cities and responsible production) are linked to ISRU focus of the design. The research demonstrates how leveraging local materials can significantly reduce the reliance on long-range transportation and its associated pollution. Consequently, it is highly recommended that ISRU principles in combination with printing technology be applied to the construction industry to steer it into a more sustainable direction. Given the substantial environmental impact of building practices, minimizing the material transportation and processing this way is critical in reducing the carbon footprint of buildings.

RECOMMENDATIONS

Before Lunar habitat designs using ISRU can be realised, there is still a lot of research needed into the specific structural and material properties of 3D printed lunar regolith. This will solidify the design as it currently relies on assumptions based on few and very recent publications on SLS/SLM and lunar regolith.

Moreover, future iterations of this project should investigate the integration of flora and the finer details of how it can work in tandem with life support systems to create an Earth-like ecosystem in space. Space agencies should also formulate official policies to mandate the use of a more human centered approach to habitat design. Allowing guidelines to not only address more rigid mechanical thresholds, but also more qualitative rules on the experience of sensory stimuli like air quality, thermal comfort, lighting and acoustic comfort.

Finally, it is also recommended to investigate how the biophilic design principles and ISRU additive manufacturing approach could be transferred to terrestrial projects. Specifically in what way it can change the built environment and shift it towards a more sustainable future.

REFLECTION

Lunar architecture is a highly fascinating and multi-faceted challenge. Navigating these complexities inevitably introduced many different constraints and possible design directions, making scope creep a persistent challenge. In order to stay true to the topic, this research had to incorporate designing with and for local materials, construction methods, and hazardous conditions on the Moon. The challenge was in finding a balance between navigating these more engineering based problems, without compromising the focus on biophilic design for astronaut health and well-being.

Site selection was a challenging aspect, with iterations alternating between, and weighing the theoretical protection of, unmapped lava tubes against the hazardous exposure of the Lunar surface. Though both options had their merits and drawbacks, I ultimately opted for a surface habitat. This decision was driven by both the project's focus on biophilic design and well-being, as well as the lack of knowledge on lunar lava tubes. At the cost of extra wall thickness and radiation shielding, the habitat gained access to more expansive views, easier accessibility, sunlight and views of the Earth. This resulted in a more pleasing architectural experience that was more inline with the goals of the project.

Academically, this research fostered a highly systematic approach due to the computational tools used. By exploring the biophilic framework through grasshopper scripting of metaballs and L-systems, in combination with engineering constraints, the design follows a very methodical logic where each design step is justified and fits within the system. Subsequently, each aspect felt very intentional and logical, while still leaving some room for creative freedom and architectural expression. Overall, this made the design more structured than other projects I have worked on.

As a designer, the project pushed me to explore new modelling and simulation tools. Pachyderm was used for acoustic modeling and provided insightful visualisations into sound propagation. However, the sheer complexity of the organic geometry with a patterned interior meant that I unfortunately couldn't run a simulation of the theoretically improved interior acoustic situation. Similarly, Karamba3D was also unfamiliar to me, but proved instrumental in validating the structural reasoning behind the metaball design. Despite this, it also highlighted the current knowledge gap in the properties of sintered regolith.

Values I used were based on very recent publications that use slightly differing sintering methods and regolith simulants, meaning that there is still some speculation and assumptions when running the structural simulations.

Ultimately, this thesis demonstrates how biophilic design can be used to support mental health and well-being in indoor environments. The project taught me how technical pragmatism and human-centered design can work hand-in-hand to achieve a well rounded architectural result. Despite the technical hurdles and novel nature of lunar architecture, the project was both enjoyable and deeply instructive. I walk away from this project with my horizons broadened and a deepened design perspective, equipped with many lessons for future projects. After all, as Buzz Aldrin (2016) noted:

“the sky is not the limit… there are footprints on the Moon”.

PART 5

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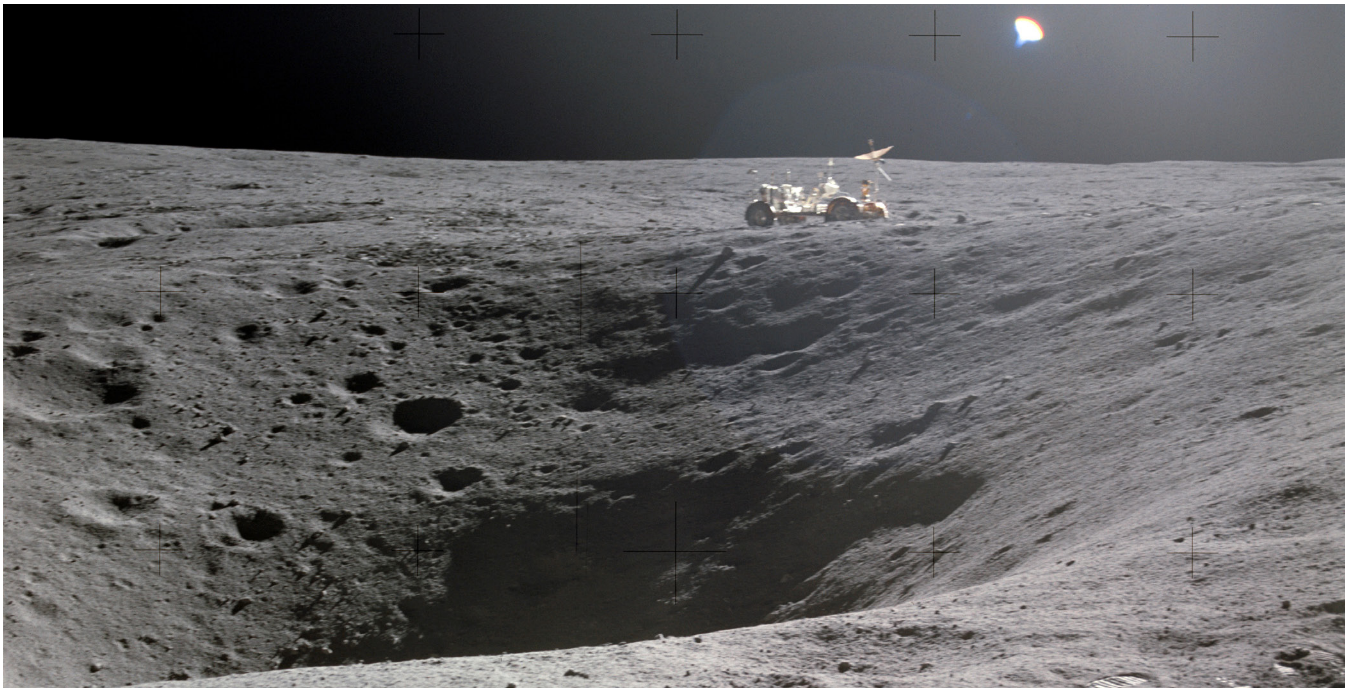

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