Graduation Report

Master of Science Architecture, Urbanism & Building Sciences

Part 1: Graduation plan P2

Part 2: Final reflection P4

Student: **Sophia Benfield**
Academic year: **2024/2025**

Architecture tutor:	Henriette Bier
Building technology tutor:	Ferry Adema
Research tutor:	Arwin Hidding

Part 1: Graduation Plan

Personal information	
Name	Sophia Benfield
Student number	5260752
Examination period	P2

Studio		
Name / Theme	**Lunar Architecture & Infrastructure**	
Main mentor	Henriette Bier	Architecture
Second mentor	Ferry Adema	Building Technology
Third mentor	Arwin Hidding	Robotics
Argumentation of choice of the studio	Lunar Architecture was the first studio to catch my eye when reviewing my options, probably because I am a big fan of sci-fi films and books. The introductory meeting confirmed my initial interest; I felt inspired and excited to be able to tackle such an unusual subject. To reach the goals of the Artemis mission (which lie in our near future) it is necessary to realistically consider all aspects of Lunar Architecture. Contributing to that future, even if it is only a little, is an amazing opportunity. Additionally, it felt like the ultimate challenge of my acquired architectural skills, to apply them to such an extreme location after being used to designing 'terrestrial' buildings.	

Graduation project	
Title of the graduation project	**MoonSane – Designing Lunar Habitats for Mental Wellness**
Goal	
Location:	The Moon, Rimae Sulpicius Gallus, LAT: 20.25645 LON:10.45098
The posed problem,	In 1969 man first set foot on the Moon, something that had seemed impossible. Now, 55 years later, we are finally getting ready to take the next step; one of the aims of NASA's Artemis Missions is to lay the foundations of lunar bases on the surface of the Moon that can facilitate human habitation for a longer period of time. Due to the dangerous conditions out on the surface, any long-term settlers will be mostly confined to the Moon base, with only their fellow crew members to interact with. This will have a great impact on their mental wellness. For example, the monotony regarding the environment and social relations can increase feelings of isolation and anxiety because they do not provide enough new stimuli. Research has identified nearly 70 stressors created by space travel, ranging from the real possibility of dying to boredom and from crew tension to isolation. On earth a lot of relaxation can be found

	outside of the home, for example, by taking a walk outside, preferably in nature. On the Moon this will not be possible as the surface environment is very hazardous and any EVA's [extravehicular activities] need to be planned meticulously. Even looking out the window will not show the varying blue and green views we are used to, but a colourless, rocky landscape similar to a black and white photograph. Solace will need to be found within the habitat itself. In the past, the design of space bases was mostly left to engineers, without consulting architects. Russian architect Galina Balashova has spoken often about being the only one with an architectural vision besides countless engineers while working on the Soviet space modules. She was the first to consider the visual impact of the environment inside the module and incorporated colour schemes and textures to help astronauts feel comfortable and help orient them in 0-gravity. Balashova even added her own watercolours on the walls, to give the astronauts a connection to home. She was the first to realise the importance of incorporating the architectural vision into space architecture. It has everything to do with habitability in the long run; creating a space where astronauts can not only survive physically, but will also thrive mentally. During his time in space, former astronaut and physician Jay Buckey realised the necessity of maintaining a good mental health as an astronaut, stating: "the psychological aspect is a really important one to deal with, because if it's done right, the missions can be truly amazing, but if it goes wrong, it's the kind of thing that can end a mission". Through various studies, it has already been established that architectural spaces can influence human emotion and mental wellbeing. On earth this theory is already being implemented in the design of new buildings, though it is sometimes still overlooked, because other factors, like the outside environment and (large-scale) social interactions, can compensate. On the Moon, when the daily visual stimuli will be mainly provided by the habitat, without a natural, external environment to compensate, these psychological aspects of architecture will be even more important and must be utilised.
research questions and	Main research question: **How can human spatial perception be used in the design of Lunar habitats, to mitigate the negative mental health effects of living long-term on the moon?** Secondary questions: ▪ What are the main psychological stressors of living on the Moon?

	▪ How can spatial geometry be used to improve mental health of inhabitants of a Lunar base? ▪ How can lighting be used to positively influence the mental health of inhabitants of a Lunar base? ▪ How can the addition of real and artificial views be used to improve the mental health of inhabitants of a Lunar base? ▪ How can the addition of a meditation/reflection space to the habitat improve the mental health of Lunar base inhabitants ▪ How can all relevant interventions be combined into a functional Lunar base?
design assignment in which these result.	The main objective is to design a moonbase that combines various spatial interventions, that have been proven to positively impact the mental health of inhabitants/users, into a fully functional Lunar habitat. These interventions will include lighting, geometry, spatial porosity and internal- and external views and need to all be implemented into a small scale Lunar base. The challenge will be to distinguish between functions within the Lunar habitat, with regards to which mental health intervention is relevant to which function and how it should be integrated; a research lab will have different requirements than a meditation space. The integration of all the architectural interventions also needs to be combined with the safety requirements of building on the Moon, considering radiation, a life support system and an adequate construction strategy with the use of in-situ resource utilisation principles.

Process

Method description

<u>Available literature</u>

The main topic will be researched by first looking into the available literature on this subject and defining different spatial interventions to research further. General information about spatial perception in architecture will be combined with relevant information about the Lunar environment and the psychological challenges of space travel. NASA has several logs in their archives, kept by astronauts during the Apollo missions, that might hold crucial information about the crews state of mind and how it was impacted by their living space, so they will be reviewed.
Besides defining the architectural interventions for mental health, it will also be important to define the criteria that will help judge each intervention on effectiveness. This will be based on available previous studies on spatial perception in architecture.

<u>Further data collection</u>

Several lectures by experts in the field will be used to gather knowledge on the location, current innovations and previous case studies relating to Lunar habitats or

off-Earth projects in general. Among the experts are architects, a radiation scientist and a participant from the HI-SEAS analogue space mission.
Additionally, the 'Moonshot Symposium' is organised to introduce new projects, for example by ESA [European Space Agency], and give an overview of recent developments.

Research by design
The main method of investigating each intervention will be research by design, which will include testing out various options through renderings and simulations. The interventions that are considered most effective will also be tested by building real life models (various scales up to scale 1:1), to test the spatiality and how it compares to the digital version.

Computational approach
To increase the efficiency of testing and combining different interventions, Grasshopper scripts will be developed based on the interventions and their variables, for example, porosity, thickness, size etc., resulting in an adjustable 3-dimensional model that will facilitate the creation of many different schematic- and design iterations.

Workshops
Workshops about robotic production and human-robot interaction will provide more detailed knowledge on off-earth construction and in-situ-resource-utilisation (ISRU) based on current research. The workshops will show the possibilities as well as the current limitations when it comes to building a Lunar base, which can be applied to the design.

Testing
As the main objective is to research the emotional and psychological reaction of people to these different interventions, a survey about a selection of the interventions will be relevant. The developed renders and models can be used as impressions that partakers of the survey can react to. To get even more accurate results, it would be helpful to create an immersive test, with the help of virtual reality, where participants can experience different spatial interventions fully. Afterwards an interview will be conducted to gauge their reactions.
How the various options perform according to the set criteria will be compared to each other, with the end result being an overview of the best design strategies and their effects.

Finally, the outcome of the research will be applied to an actual design for a lunar base.

Literature and general practical references

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Part 2: Final Reflection

Examination period	P4
Reflection	

Relation between topic, track and master programme

The goal of my graduation topic is to discover architectural interventions that improve the mental health of future Moon inhabitants, and apply them to a design of a Lunar habitat. The Lunar Architecture studio is all about creating a Lunar habitat that will be successful long term and maintaining good mental health of astronauts is necessary for accomplishing this.

Building on the Moon is a matter of life and death, as the habitat will literally be protecting astronauts from the lethal external environment. Providing shelter, both physically and emotionally, is the most fundamental reason architecture exists, and can be traced back to the first human settlements on earth. This studio takes the field of architecture back to this core principle, while applying the most advanced technology to achieve its goals.

The master programme of AUBS prides itself on being an multi-disciplinary study programme, for example, applying social sciences to the built environment as well as more technical aspects. This graduation project adheres to this way of working by incorporating both the physical and the psychological to create a built environment where currently there is none (the Moon!) and also by working together with students and teachers from other faculties, like Robotics and Aerospace Engineering. This provides an opportunity to broaden the knowledge beyond architecture and apply their research, so the project, which remains speculative, can stay as close to reality as possible.

Academic and societal value

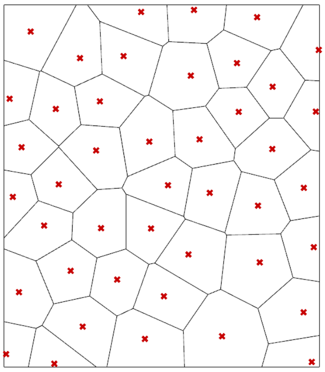
With the start of the Artemis project, the creation of a permanent Lunar base has been set as a goal, which has made it relevant to explore and consider all aspects of this new form of architecture. Most of the architecture until now has been adapted to the Earth's environment, both physically and conceptually. Building on the Moon will require a whole new set of criteria, adapted to this unfamiliar, hazardous landscape. It is important to address all aspects, including the psychological impact of living in Lunar architecture.

Improving our mental health has become a broad, societal concern over the past few decades, not only in The Netherlands but all over the world. The pandemic increased this awareness even more, with many people noticing their mental health declining after being confined to their rooms during lockdown. Providing an architectural toolset to create spaces that are beneficial for the mental wellness of human beings could, for example, help prevent and mitigate these situations in the future. Creating architectural interventions that decrease stress could also be useful for locations where stress is most

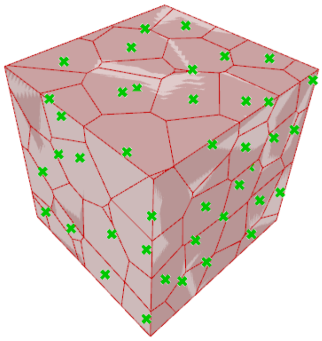
experienced, for example in the work- and study place, as well as in hospitals and clinics. This is already being applied sporadically, but it should become a regular practice.
The challenges provided by this extreme Lunar environment will also help develop architectural practices and technologies that can be relevant for on-Earth projects, by pushing the boundaries of current technologies further. For example, the principles of making the components with in-situ-resource-utilisation (use of local materials) with the help of robotics, is a practice that should be implemented on Earth as well. This could reduce transport cost and emissions significantly, and would make it possible to help build houses in extreme environments or very isolated areas, like the desert, which is comparable to the barren Lunar landscape.
The principles of the life support system developed by MELiSSA, which aims to close the waste loop, could help reorganise the amount of sewage waste on Earth. The system can also be applied to purify water for areas where clean drinking water is already scarce.
Why only use it off-Earth, when it could improve our own lives down here?

Influence of the unusual location

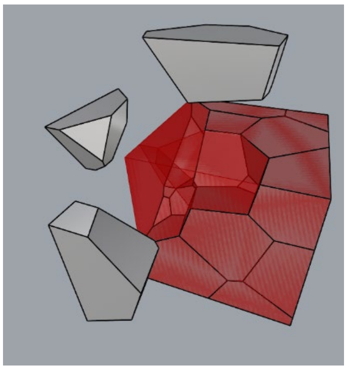
Interesting about this project, compared to more traditional design briefs, was that the façade was the least important part of the building, because the inhabitants would be mostly confined to the interior, not even seeing the outside of the building on a daily basis. Additionally, with no current built environment present on the Moon, there was nothing to relate it to, besides the grey, dusty landscape and a black sky. Usually while designing you either relate your design to elements of the direct environment, or even actively rebel against it by doing the opposite of what building styles are already there. On the Moon these strategies become less meaningful, because your design is more related to the basic needs of the inhabitants. However, it did provide an opportunity to break through some terrestrial rules; in conversation with our mentors, we decided early on that the alien landscape of the Moon required architecture that looked like it belonged there and not like it belonged on Earth. Orthogonal approaches are very terrestrial and it was preferable to create another form-language that would be distinctly Lunar.
With the introductory workshop about the component based construction method, we were also introduced to Voronoi. This is a randomised, point based pattern, derived from patterns found in nature. It creates lines (2D) or surfaces (3D) at the exact halfway point between all points in a point cloud (usually randomly generated) and thus creates irregular polygons/ poly-surfaces that fit together seamlessly (figure 1). This form language felt appropriate to the landscape and provided the base for our designs. It also turned out to be beneficial for the component stacking structure we used for constructing.



Voronoi 2D



Voronoi 3D



Voronoi cells have an angular, irregular shape

Figure 1: Voronoi geometry from 2D to 3D

This unusual geometry did mean that defining the spaces became more difficult, because on Earth, we are used to see rectangular rooms, using the corners for orientation. When these spaces become more faceted, they also become less recognisable as spaces. The choice of views and sections were crucial, with every line and shape weighed carefully, to not confuse the viewer. A lot of feedback from the our mentor was about this visual understanding of the space. Going back and forth with visuals, sometimes even the smallest adjustments could improve the readability of the spaces.

Feedback loop between research and design

The speculative nature of this design project did provide some difficulties along the way. A lot of the research is still being done and the reality of the situation is that no actual moonbase has been built so far. This required a lot of research into the possibilities and theories currently being tested and we needed to evaluate how plausible and relevant they were in regards to our own project.
When the certainties of an urban master plan and direct environment, either urban or natural, are taken away, you feel a little lost as a designer… Especially in the beginning, it was important to completely immerse ourselves in the unfamiliar environment and its characteristics, to regain some grip on the project. The many lectures that were provided by the studio, about innovations in the field, did help us discover alternatives to the terrestrial methods and materials we had previously worked with. Our mentors provided feedback on the acquired information, as their experience with the topic was more extensive than ours, which helped steer our topic in the right direction.
The component based construction method, provided by PHD research from our own faculty, influenced all our designs from the very start. The workshop about this topic showed us our parameters and how it would affect our design before we had even thought of designing, for example, the walls would probably need to be over 1 meter thick (for stability and radiation protection) and a flat roof would be inadvisable due to the inability

of the Lunar Regolith material to deal with tensile forces. Somehow, though it was limiting, it was also grounding, providing rules to follow. Every time we made a design decision, it was important to go back to these ground rules to see if what we wanted was actually possible.
My specific research provided elements that had direct implications for the architectural design, for example the spatial geometry and permeability and the meditation room with an Earth view. However, while implementing them it was difficult to know where to start. The vision was not yet clear. My mentor urged me to first find examples of how the geometrical elements had been integrated into architecture in the past, to get a definitive idea of what it would look like. The examples were scarce, but findable through extensive research. Fortunately, the examples did align with the idea created by the initial research. Especially the asymmetrical, angular rooms resembled the digital examples used in the research experiments. For example, the *St. Joseph House* by Wolfgang Tschapeller ZT GmbH had a strong resemblance to one of the virtual test spaces (firgure 2 & 3).

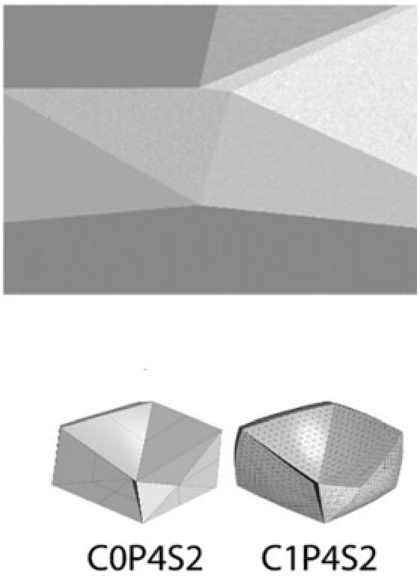


Figure 2: Test image from Shemesh, et al., 2021

Figure 3: St. Joseph House interior (Archdaily, 2012)

These references provided a more clear image of what the end product should look like, which then informed the design strategy. It also provided a sense of reality, to know that building with this kind of complicated geometry was possible. It also provided a feedback loop for my own design, to compare iterations to these examples and evaluate if a space needed more adjustment or not.

Value of approach

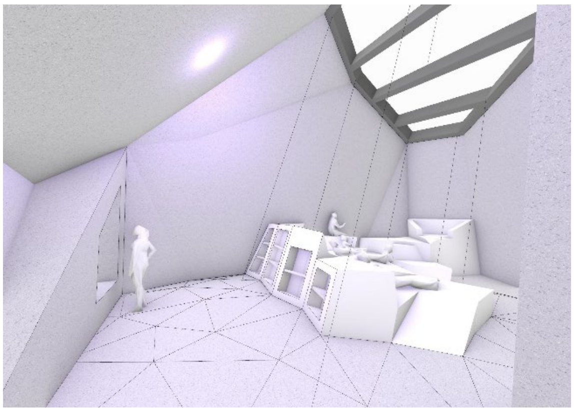
Integrating the geometry and permeability turned out more challenging than I expected. Especially the curvilinear geometry that I planned to use in the more socially oriented rooms proved difficult. It showed the limitations of computational software, in which it is easier to generate angular geometry than curvilinear. With help from one of my mentors, a script was developed to transform the angular rooms into curvilinear geometry, implementing it also on an furniture level proved too intensive within the time that was left. At P2, the main feedback of my mentor was that I should focus on one or two interventions, instead of everything I had gathered during the research stage and we discussed that perhaps the curvilinear should be left for what it was and could only implemented when there was time leftover (surprise, surprise, there was not).

This requirement to focus on only one or two interventions in the end led me to develop the spatial permeability script the most and focussing on integrating the all important Earth view into the meditation space. It felt like a slight failure not to be able to incorporate everything I had initially wanted, but luckily, my mentor steered me into that direction, because otherwise I would have gotten lost. Sometimes it is better to do one thing well, than many things half-heartedly.

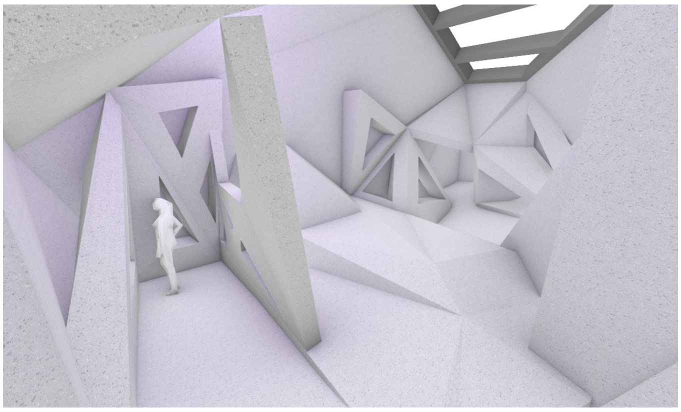
In the graduation plan I had expressed the wish to do some testing with VR, using the visuals created of my meditation space to get feedback from test subjects. When I included this in the graduation plan, I already suspected it might be optimistic in the time that I had left (at that stage, the visuals were yet to be developed). Unfortunately, this prediction turned out to be correct. However, it turned out that the feedback from my mentors every week, also served as a good evaluation of the effectiveness of my space, with us discussing in depth the 'feel' of the space. Although, of course, not as immersive compared to using VR.

At P3 I was advised to pick one room in the building where I would go into detail with the integration of my spatial interventions. At first I thought the big atrium and garden space would be the best choice, but it turned out to be too big a space to effectively show the integration of furniture. While reflecting on this problem, I was reminded what my project was actually about; the meditation space. This proved the perfect space to tackle, with both the colour projection and spatial permeability present in that space. By now I had developed the permeability study already, but for the garden/atrium. Fortunately, because it was computationally developed and automated, the permeability script could easily be applied to the meditation space, showing the added value of using the computational approach.

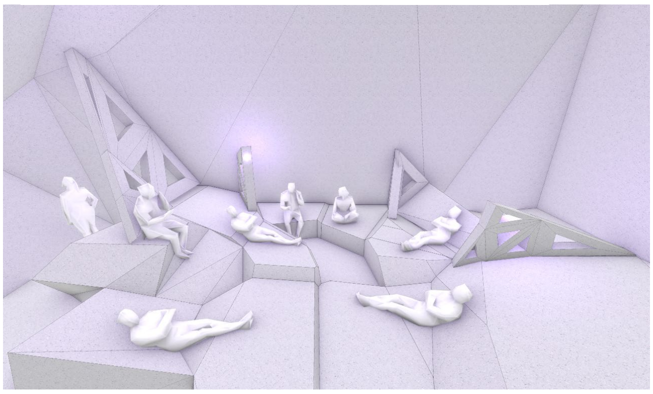
Choosing the meditation space turned out well for the development of the interior and furniture strategy. It was small enough to get into the nitty gritty, with my mentor suggesting adjustments that could be easily integrated by the Grasshopper script. Below there is a progression showing a few iterations (figure 4).



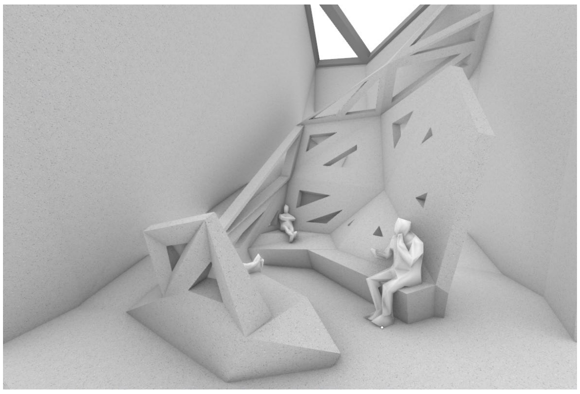
Iteration 1



Iteration 3



Iteration 5

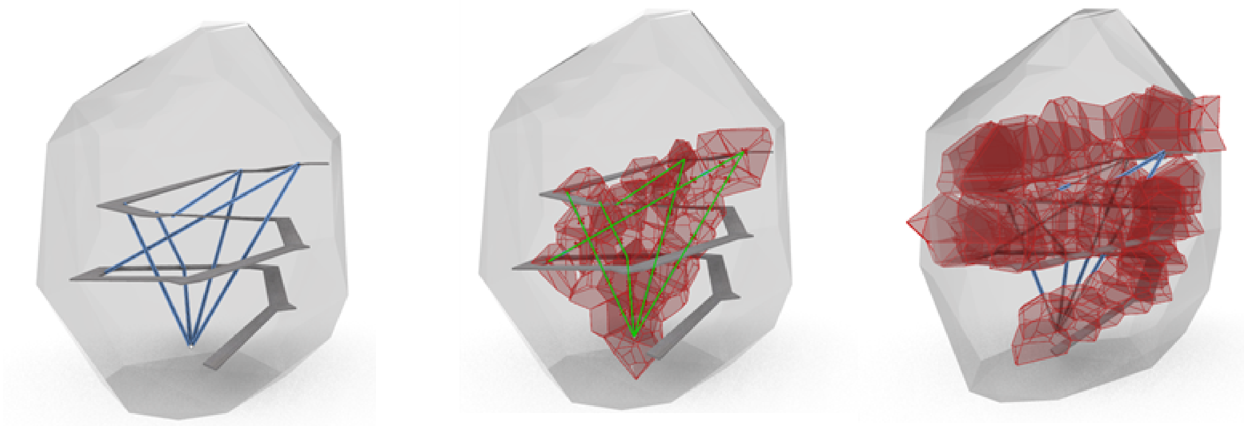


Iteration 8

Figure 4: Various design iterations for interior of the meditation space

At first the placement of furniture was very random, leaving a lot of the space unused. Through feedback the plan was developed to create multiple spaces within the one room, dividing them into degrees of privacy.

Before landing on the permeability study as a strategy for the interior, other studies were done. For example, a study was done using 'negative space' to create the interior, starting with each room as a solid shape and then hollowing out the usable space, based on walking paths and functions. I started this study by developing the large garden/atrium. This was to be a multilevel space, connecting several rooms in one long ramp. First the connective walking paths from space to space were mapped out and then the views that were favoured throughout the space (see figure 5).



Step 1: mapping walking paths (grey) and views (blue)

Step 2: generating Voronoi along the view paths

Step 3: generating Voronoi along the walking path

Figure 5: Mapping the path and view in 3D and creating geometry along these lines

Generating solid Voronoi along these lines and subtracting them from the basic volume I had started with, provided an interior space. The resulting space looked interesting, but my mentor rightly noted that the many faceted surfaces were disorientating and overstimulating, something I had actually wanted to avoid. Additionally, the solid Voronoi cells made the room look cluttered and 'chunky', for lack of a better word. My mentor advised to conduct a smoothing study of the interior space, to see if this would solve the problem. One of the results is shown in figure 6.

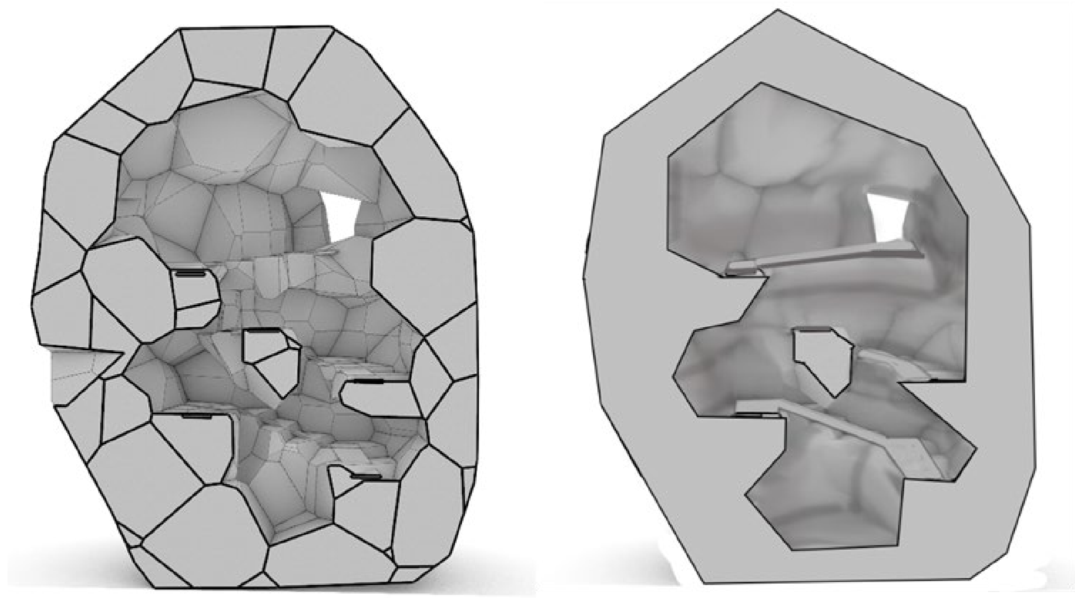


Figure 6: Result of the subtraction method, before and after smoothing

Even with the smoothing the interior spaces where not what I had in mind, also relating back to the examples I looked at during my research.
It was difficult to admit this strategy was not working at all, with the initial urge being to tinker away at it until it worked. My mentor suggested that I try a different strategy, more similar to a permeability study I had done before, on a larger scale. I was reluctant. Abandoning this strategy, after putting a lot of work into it felt like a failure and a waste of time, but in the end it was just another step that brought me towards the permeability study I ended up using. It was a classic example of 'trusting the process', and trusting my mentor…
During the process I had a tendency to get lost in research about less important parts of my project and with her feedback, my mentor helped me to regain focus on what was the essence of my project. Without this, I might not have finished as much of the project as I would have liked. This feedback loop was very helpful, and after I while I started to recognise myself when I was getting sidetracked by an unimportant detail.

Transferability of the project results

Within the field of extraterrestrial habitats, the design of this base was not meant to be location specific. Though a general area had to be identified based on resources, in principle, this design can be built wherever there is a flat or lightly sloped surface on the Moon. The only element that changes with every location is the position of the earth in the sky. To receive this important view, the orientation of the meditation room window will need to be adjusted accordingly. Because the near side of the Moon always faces the Earth, even though the Moon itself is orbiting our planet, the Earth seems fixed in place in the Lunar sky (though in reality it makes a slight looping motion). This makes the mapping of the Earth view easier. The diagrams below show how this would work, relating to the latitude and longitude of the viewers position on the Lunar surface; the longitude provides the orientation related to North, while the latitude informs the positioning angle of the window. Only at the Lunar poles this might be problematic, because the Earth is only visible sometimes, while other times it drops below the horizon.

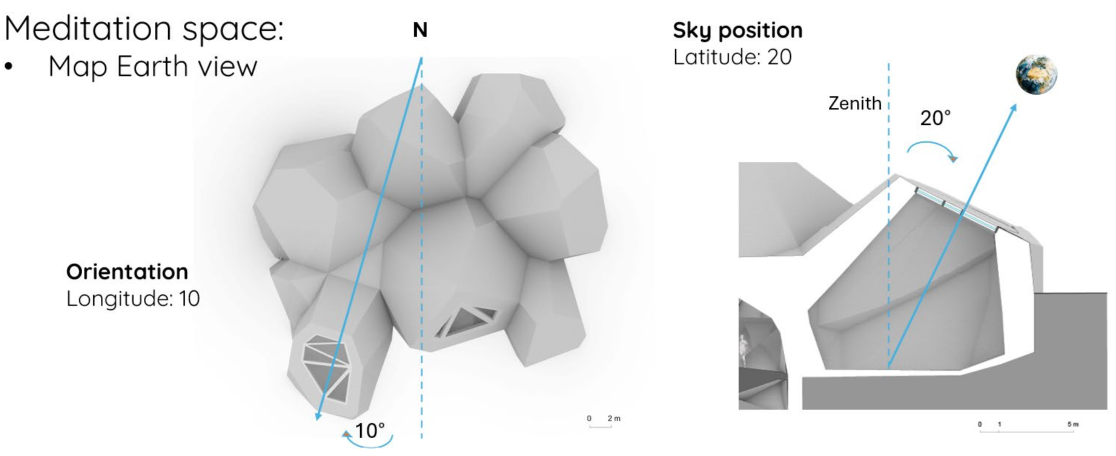


Figure 7: Earth view mapping for the meditation space

More generally speaking, the elements identified and applied in this design project, like the geometry, permeability gradient and mood lighting can be applied to any room, regardless of the location. On Earth there is also need for the integration of mental health-friendly architecture. Our mental health being is being held in high regard these days by society, especially in the work- and study place (for example, at the Faculty of Architecture a contemplation room has recently been opened). The design of the mediation space can be integrated wherever it is wanted and I believe it would be especially important to add similar sanctuary spaces to high stress environments, like offices and colleges/universities, but also to hospitals and (dentists) clinics, where the benefits of relaxation can improve the experience for users/ visitors.

The only thing that will not be able to be recreated on Earth is, of course, the Earth view providing the overview effect. Perhaps with screens it can, but research has shown this will not have the same effect as the real thing. However, as the installations of James Turrell have shown here on earth, these meditation rooms can still have an emotional impact with the use of colour and a sky view.

With regards to structure, on earth the interventions I have identified and implemented will be easier to apply to architecture, mainly because there is less limitation in the use of materials.

Using computational scripts to design

During this project, we were encouraged to develop computational script that automated our design strategy so we could apply it to any part of the building if we wanted. This choice was informed by the similar approach used for the development of the structural components. The main program used for this was Grasshopper in combination with Rhino. My lack of experience with Grasshopper made me reluctant to use this as a design tool in the beginning, but more skills were easily acquired and I found that using Grasshopper scripts provided consistency in the design. The spatial permeability study that I developed for the interior could not have been done as easily without a computational script (if at all) and it ended up being the most important element of my design.

Similarly, the Voronoi geometry that was chosen to create the initial shape of the building would be impossible to create without a computational script and that played a pivotal role in the base shapes of my design.

It was important to find the balance between what the computational scripts provided and the architectural qualities I had in mind. It would have been easy to let the Grasshopper script work their magic and take what they gave me as 'final', but often it lacked finesse, with odd corners and ill-adjusted seams. It required manual tweaking of the input geometry as well as the output geometry and it resulted in many iterations of the design, often based on feedback given by my mentor. Some iterations are shown in figure 4.

Towards P5

It will be important to test at least a fragment of the space in a scale model, preferably the meditation space. Trying out the mood lighting with changing lighting and seeing how it transforms the space in reality will be very beneficial to test the concept. It will be interesting to see how the space will translate from a digital model to reality.

The visuals taken from my mediation space are the most important for my concept and they could use more refinement, going into more detail. It is interesting to compare them from visuals taken from my physical scale model as well.

Another next step will be to develop a pattern strategy for the projections/visuals in the solitude room of my meditation space; defining what factors the colours and patterns are based on (heart rate, temperature etc.) and generating an example projection.

References:

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