

A night view of the lunar surface, showing a dark horizon line against a starry sky. The foreground is a light-colored, cratered lunar landscape. The text "A Visitor City" is overlaid in white, with a white horizontal bar below it.

A Visitor City

on the Moon

Giving Identity to Lunar Architecture

Department of Architecture, University of the Free State.

This extended research essay was submitted in partial fulfilment of the requirements for the degree Master in Architecture (Professional) at the University of the Free State.

The work in this document is entirely my own unless specifically stated otherwise.

Ronel van Rhijn

13/10/2023



Abstract

In an era when commercial space travel has become a reality and Lunar habitation is no longer fiction, the future Lunar visitors' city emerges. With world-renowned architecture firms collaborating with space agencies on space architecture and the ongoing developments of NASA and SpaceX, the possible identity of Lunar architecture is explored. How can biomimicry with architecture be applied to create an immersive future visitors' city on the Moon and contribute towards a Lunar architectural identity? This explorative thesis transcends the boundaries of traditional design, embracing the challenge of replicating Earth's comforts and familiarity on the Moon. It invites visitors on an extraordinary journey to a world where technology sustains life, the Earth hangs in the distant sky, and the Moon's reduced gravity offers unique opportunities for exploration. The book, *"The Image of a City"*, by Kevin Lynch, was thoroughly studied. The concept of biomimicry and relevant precedent studies were examined and applied. This was done to gain a thorough understanding of how humans perceive a new environment and how to design comfortable and relatable architecture. Furthermore, inspired by Le Corbusier's notion of architecture as a machine, this thesis conceives the Lunar centre as a self-sustaining life-support system. It delves into the intricate details of providing essential services such as food, water, oxygen, sewage management, and power within the context of the Moon. Through science and architecture, the vision harmoniously combines functionality with an immersive visitor experience, catering to both scientific researchers and adventure-seeking tourists.



Table of Contents

Abstract	ii	3.1 Architecture as a Machine	12
Table of Contents	iii	3.2 The Self-sustaining Machine	13
Introduction.....	1	3.3 Accommodation list:	15
Chapter 1: The Lunar Environment	3	3.3.1 The Business District	15
1.1 Resources.....	3	3.3.2 The City Centre.....	15
1.2 Gravity and its effects.....	4	3.3.3 Agricultural Region.....	16
1.3 The site: Lava tubes	5	3.3.4 Hotel.....	16
Chapter 2: Sustaining life.....	8	Chapter 4: Design of a City.....	17
2.1 Harvesting water:	8	4.1 Wayfinding	17
2.2 Power.....	8	4.2 The Image of the visitors' centre	17
2.3 Farming.....	9	4.2.1 Paths.....	18
2.4 Aquaponic and hydroponic systems.....	9	4.2.2 Districts.....	19
2.5 Air	10	4.2.3 Edges	21
2.6 Plumbing.....	11	4.2.4 Landmarks.....	23
2.7 Conclusion	11	4.2.5 Nodes	24
Chapter 3: Introducing the Project.....	12	4.3 Sense of the whole.....	25
Clients	12	Chapter 5: The Living Organism	27
		5.1 Biomimicry- morphological approach.....	27

Esplanade Theatre, Singapore	28	7.4 Renders	57
National Aquatics Centre, Beijing.....	29	Conclusion.....	57
Panda Tower / UDG. Atelier Alpha	29	References.....	57
5.2 Application.....	30		
5.2.1 The skin.....	31		
5.2.2 The Business District.....	35		
5.2.3 The Agricultural Region	35		
5.2.4 The Hotel	36		
5.2.5 The Restaurant	36		
5.2.6 The Tower.....	36		
Chapter 6: Landscape Design	38		
6.1 Elements of Landscape Design	38		
6.1.1 Line	38		
6.1.2 Form.....	39		
6.1.3 Texture.....	39		
6.1.4 Colour	40		
6.1.5 Visual weight	40		
6.2 Principles of Landscape Design.....	40		
Doha Airport Forest:.....	41		
Jewel Changi Airport / Safdie Architects	42		
Chapter 7: Final Design.....	43		
7.1 Floor Plans	43		
7.2 Elevations	53		
7.3 Sections.....	54		

Introduction

“Designing space architecture is no longer fiction but a reality” These are the words of UNStudio and Foster + Partners advertising their training course for space architecture in 2024. There is a new space race happening at this very moment, to design and build on the Moon and Mars.



Figure 1: Advertisement for a course in architecture for outer space in collaboration with UNStudio and Foster + Partners (YACademy, 2023: online)

For a long time, the thought of designing in space was nothing more than a figment of the imagination. However, the reality of architecture in space has never been closer. As a civilisation, we possess the technology and knowledge to make this a reality. In the words of UNStudio: “*For the first time in history, humanity is concretely being called upon to evolve as an interplanetary species. The colonization of any ecosystem or environment needs habitats and identity-giving places: it needs architecture*” (YACademy, 2023: online). Consider the following recent developments:

- In 2018, Airbus (an engineering firm) opened the ‘Moon Race’ - a contest which was supported by the ESA (European Space Agency) and Blue Origin, which funds companies to develop Lunar technology (Gibney, 2018: 474).
- The company SpaceX have recently launched a test for their complete *Starship* which is due to transport people to the Moon and back. This will enable anyone with the desire to experience space to do so without needing to be an astronaut.
- The Dear Moon project will be the first civilian mission to the Moon. They will take the civilians close to the Lunar surface and back to Earth. This is set to take place in 2024 by SpaceX (SpaceX, 2023: online).
- In 2021, NASA announced an official contract between NASA and SpaceX for the development of the Human Landing System (HLS) programme. The HLS will be the first crewed *Lunar Lander* version of *Starship*. Development for this project has already started (Foust, 2021: online).

- The company Rolls Royce has recently received funding from NASA to develop a small nuclear reactor to power future Lunar colonies. The reactor is set to be delivered to the Moon in 2029 (Dinner, 2023: online). Rolls Royce is amongst many other companies that are interested in building on the Moon and developing Lunar technology.
- It has been recorded that a Moon base is the ultimate goal of China's National Space Administration (Gibney, 2018: 474).

The Moon could act as a refuelling station for more distant travels, by mining on the Moon for oxygen and hydrogen which power spacecraft. Due to the Moon's low gravity, it would cost less to stock up for distant travels than it would to carry that load from Earth. It was estimated that a mission refuelled on the Moon could be five times cheaper than otherwise. According to Gibney, countries from around the world have talked about collaborating on a semi-permanent settlement on the Moon (Gibney, 2018: 476).

Taking all of these developments into consideration, one begins to gain an understanding of why world-renowned architecture firms such as UNStudio, Foster + Partners and Bjarke Ingels Group would partner with the European Space Agency to develop course material for architecture in outer space.

For this reason, it is imperative that space architecture be developed and all possibilities explored. Therefore, the choice of site for this thesis is on the Moon.



Chapter 1: The Lunar Environment

Designing on the Moon brings about a set of challenges that need no consideration on our planet. The conditions on the Moon are extreme, with three major concerns when considering architecture on the Moon. The first is radiation exposure, the second is temperature extremes and the third is meteorite impacts. Unlike Earth, the Moon has no natural protection from these three elements.

The Moon has no atmosphere; instead, it has an exosphere, which results in no air to breathe and therefore no wind. The exosphere is made of a very thin layer of gas. The particles in an exosphere are so few that they rarely collide with each other. It is comparable to being in a vacuum. To compare, the Earth's atmosphere at sea level contains about 100 billion billion molecules per cubic centimetre, whereas the Moon's atmosphere contains only roughly a hundred molecules per cubic centimetre (Sharp, 2022: online).

This lack of atmosphere on the Moon means that there is no ozone layer. For this reason, radiation is a major concern. Another problem arising from this lack of an atmosphere is meteorites. On Earth, most meteorites burn out before hitting the surface of the Earth due to the friction caused by the atmosphere. This is, however, not the case on the Moon. Any small meteorite heading towards the Moon does not burn up, but instead hits the surface of the Moon with tremendous kinetic energy.

Another very important consideration for designing on the Moon is that one Moon day is equal to 27.3 Earth days. This results in two Earth weeks of uninterrupted sunlight on the Moon's surface, followed by two Earth weeks of

darkness. This is one of the major contributing factors to the extreme temperatures on the Moon. The temperatures on the equator reach anything from $-130\text{ }^{\circ}\text{C}$ to $120\text{ }^{\circ}\text{C}$. At the poles of the Moon, the temperatures are even more extreme and can reach $-253\text{ }^{\circ}\text{C}$ in dark craters (Urrutia & Sharp, 2023: online).

1.1 Resources

There is no liquid water found on the Moon. There are only traces of water found in the form of ice in some dark craters at the poles of the Moon.

The surface of the Moon consists mostly of old lava flows, craters and Lunar sand. The dark spots of the Moon are large bodies of lava that have hardened and the light spots are sand or Lunar regolith. This can be seen in Figure 2.



Figure 2: Photograph of the moon, with clearly visible light and dark regions (NASA, 2023: online)

The sand particles of the Moon are not like the sand found on Earth. Because there is no natural corrosion (due to no wind) the particles have very sharp edges and the extreme heat of impact craters has turned these sharp sand particles into glass. This sand is dangerous for any human to breathe, and can damage building materials and equipment (McSweeney, 2019: online).

1.2 Gravity and its effects

The gravity on the Moon differs considerably from that of the Earth. On the Earth, gravity accelerates a falling object at 9.8 m/s^2 . However, on the Moon, gravity accelerates a falling object at only 1.6 m/s^2 . The gravity on the Moon is therefore approximately six times less than that on Earth. One's experience of weight will be much different on the Moon. For example, if a person weighs sixty kilograms on Earth, to them it would feel like they weigh only ten

kilograms on the Moon. This means that a person who can jump 0.5 metres on the Earth can jump close to 2.7 metres high on the Moon as can be seen in Figure 3.

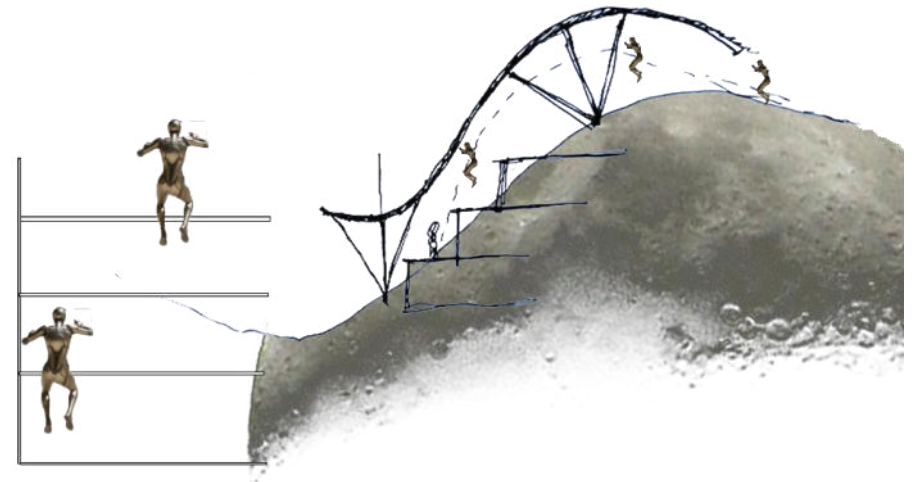


Figure 3: Differences in jumping heights of the Earth versus the Moon (author)

This has a significant impact on architecture, as this means that structures do not have to be as strong or as reinforced on the Moon. For example, a small building on Earth that has to carry its own weight of 10 tonnes, will only have to carry a weight of less than two tonnes if that same building is placed on the Moon. Therefore, that same building will not have to be as strong. This impacts cantilever designs, as cantilevers can stretch much further on the Moon than any cantilever on Earth.

Therefore, in gross terms, a structure on the Moon can bear six times the weight than on Earth, or it only has to bear one sixth of the load that is required on the Earth (Benaroya et al., 2002: 34).

It is important to note that for humans to survive, the air pressure needs to be correct, but gravity is not essential. The space suits of the astronauts are filled

with air and pressurised to be similar to that of the Earth. On the Moon base, the air pressure will be controlled to be close to the air pressure on Earth. However, the gravity will remain a sixth of that of the Earth, and cannot be changed.

The gravity of a planet is directly related to the size of the planet. The Moon is six times smaller than Earth. This results in the gravitational differences (Lunar and Planetary Institute, 2023: online). For this reason, it is impossible to alter the gravity of a planet. Therefore, there will be no differences in the gravity outside the building versus inside the building.

It is important to note that while the gravity of the Moon is substantially less than that of Earth, it is not completely absent. This means that one would not simply float around as in space. One would still be able to walk, sit, lie down, and eat. The major differences would be in how much higher and further one would be able to jump, as well as how much lighter one would feel. One would also fall down much slower.

1.3 The site: Lava tubes

Lava tubes are formed during some extraordinary lava flows caused by a volcanic eruption. As lava flows down a path, the outer layers of the lava cool down first and start to solidify into rock. The core that is still molten continues to flow, leaving behind a hollow tube-like shape under the already-solidified rock (Coombs & Hawke, n.d.: 219). This is shown in Figure 4.

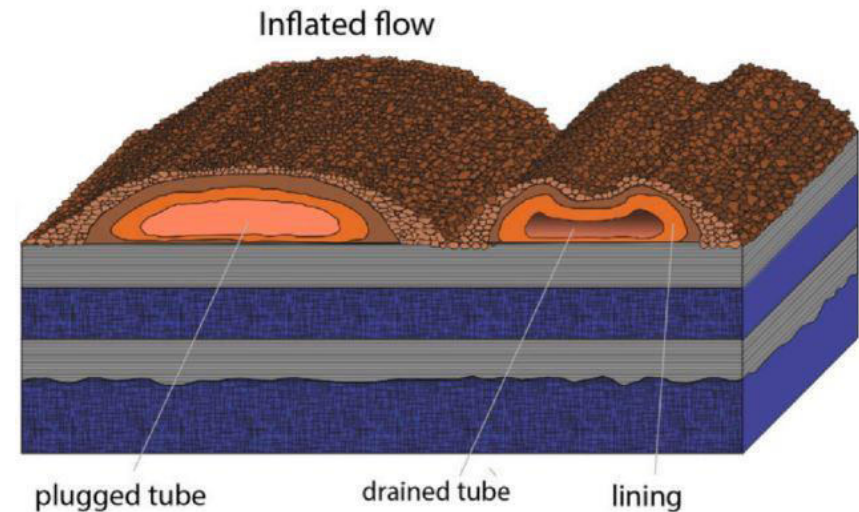


Figure 4: Basic formation of a lava tube (Sauro et al., 2020: 4).

There are several lava tubes on Earth; some are located in Hawaii and Spain's Canary Islands. Figure 5 shows images of the inside of the Undara lava tubes in Australia. However, the maximum size of terrestrial lava tubes is thirty metres in width (Theinat et al., 2019: 1- 2). On the Moon, due to the massive scale of the eruptions that took place in early times, as well as the reduced force of gravity, these lava tubes are colossal. From satellite images and through Gravity Recovery and Interior Laboratory (GRAIL) gravity scanners, some of these lava tubes are estimated to be up to five kilometres in width and hundreds of metres deep (Coombs & Hawke, n.d.: 221-222).

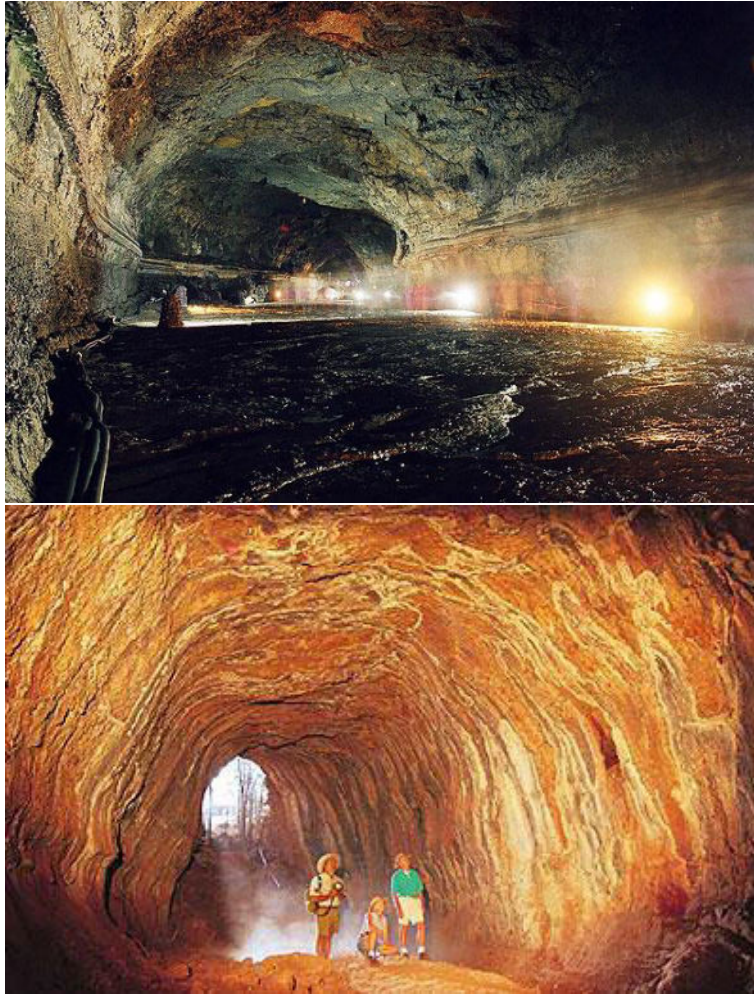


Figure 5: The Undara lava tube in North Queensland, Australia (Thala Beach Nature Reserve, n.d. online.)

The existence of lava tubes on the Moon was first speculated by scientists in the 1960s, but was confirmed in 2009 through a set of images provided by the Selenological and Engineering Explorer (*SELENE*) spacecraft. Sets of high-resolution images allowed scientists to discover a vertical hole, 65 m in

diameter, that leads to an underground network of lava tubes. This led to an additional 150 other holes that were discovered, with diameters ranging between 49 and 106 m. These indicate massive voids under the surface (Theinat et al., 2019: 1-2).

Scientists have been discussing the potential uses of lava tubes to host Lunar colonies, as these tubes would offer many safety benefits against the hazardous and harsh Lunar environment (Coombs & Hawke, 2000: 219). The lava tubes allow for much more moderate temperatures. Scientists estimate that temperatures inside Lunar lava tubes should stay at a steady and comfortable room temperature of roughly 17 °C (Atkinson, 2022: online).

Multiple studies by various groups have been conducted to determine the sizes, shapes and strength of the lava tubes and to scout for potential sites for a future Moon base. According to Theinat et al. (2019), lava tubes with a basaltic roof offer increased strength from hazards such as the impact of meteorites. Building inside a lava tube gives access to valuable resources from the nearby volcanic vents. Materials such as sulphur, iron and oxygen should be available in abundance (Sauro et al., 2020: 3).

Scientists used their expert knowledge to place an estimation on the strength of these tubes. In a study conducted by Theinat et al. (2019: 7), they found that a lava tube on the Moon, that is 300 m wide, would be stable if the smallest part of the roof was only one metre thick. This was confirmed by a study by Blair et al. (2016: 4) that was published in 2017. The shape of the lava tube plays a critical role in its stability. Tubes with a circular or elliptical cross-section with a long vertical axis would be more stable than tubes with the same cross-section but with a long horizontal axis (Theinat et al., 2019: 6). In the study, the maximum roof thickness that was tested was 500 m thick. It was concluded that a tube that stretches 5 km across experiences minimal stress and might remain stable up to 6.7 km in width. (Blair et al., 2016: 4). *Figure 6* below shows various Lunar rilles on the Moon. The Lunar rilles are formed because of previous lava flows. These rilles are what scientists look for to identify potential lava tubes. The Lunar rille forms a chain of collapsed and

intact lava tubes and originates from a source called a putative vent, where the lava initially came from. The Gruithuisen rille stretches for close to 41 km and consists of various intact lava tubes of great size. The average width of the Gruithuisen lava tubes is 858 m with a standard deviation of 300 m. This means that some of the lava tubes are more than a kilometre in width, and the widest may be close to two kilometres wide, the smallest only being 300 m wide. The average height of these lava tubes is estimated to be 200 m (Sauro et al., 2020: 12). It is possible to fit entire cities in some of these lava tubes. For the sake of this project, the smallest tube was chosen, located in the Marius B region. Satellite imagery of this region can be seen in Figure 6.

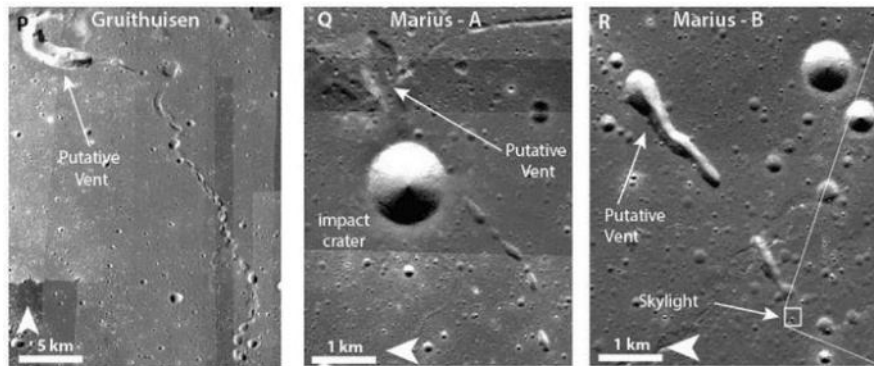


Figure 6: Illustration of various Lunar rilles, with the site at Marius B (Sauro et al., 2020: 2)

The specific site chosen for this project is located in the Marius Hills region at 13.603° latitude, -58.047° longitude. The exact size and shape of this lava tube is unknown. However, in a study conducted by Sauro et al. (2020: 12), it was determined that the average width is 527 m with a standard deviation of 197 m. For this project, the smallest possible size was chosen for the lava tube, and the site was selected close to the entrance of the tube. It is assumed that the entrance is open and unhindered. The length of the tube runs a total of 1 300

m in length and the average width is 300 m. The roof was given an average thickness of 20 m and the average height to the bottom of the lava tube roof is 80 m. This approximated topology is graphically represented in Figure 7.

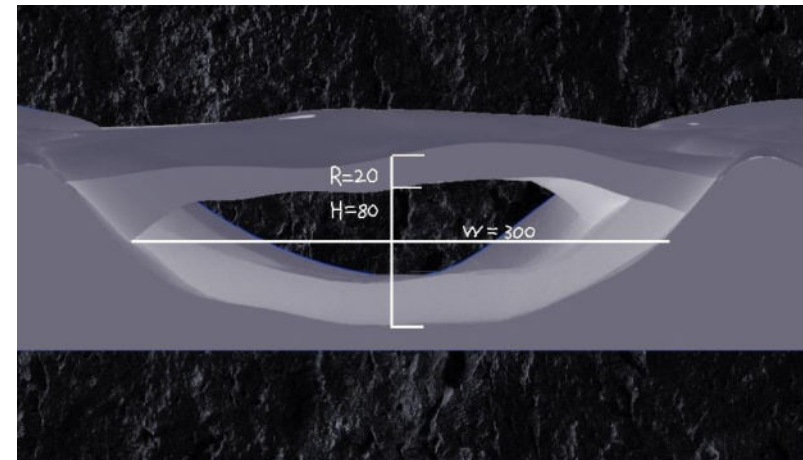


Figure 7: Chosen lava tube dimensions (author)

To work towards designing a habitable base on the Moon, thorough research was needed to understand the Moon's environment. It is clear from the information in this chapter that the Lunar environment is much different to the Earth, and presents life-threatening conditions that are unique to the Moon.

It became clear that lava tubes are the best possible sites to construct a building on the Moon, as the lava tube will shield the building and its inhabitants from most of these challenges. Now that these challenges are known, innovative ideas are required to make such a project possible.



Chapter 2: Sustaining life

Like any life form, the dwellers on the Moon will need oxygen, food and water. From the research, it is clear that all essentials needed for humans to survive will have to be provided, as these are not found naturally on the Moon. In this chapter, the novel methods that will be used to provide these essentials will be discussed.

2.1 Harvesting water:

One of the first challenges in creating a habitable space on the Moon is providing fresh water. On the Moon, oxygen and water will be the most precious commodities. Although the Moon was once thought to be an arid environment with no available water, scientists made a massive breakthrough when ice was discovered at the poles of the Moon. They found that there are deep, permanently shaded craters at the poles that contain plenty of frozen water. These places are some of the coldest places in the universe with temperatures estimated to be $-253\text{ }^{\circ}\text{C}$. It is possible that this ice can be harvested and brought to the Lunar base (Gibney, 2018: 475).

Another source of water and oxygen is the Lunar soil itself, which is called regolith. Regolith is made of 43% oxygen, silica and metallic oxides. The good news is that regolith is abundant and found everywhere on the Moon. Through solar energy and nuclear power, the oxygen could be extracted from the soil and stored as liquid oxygen. The oxygen could then be combined with hydrogen to form water. The by-products of these processes could produce valuable rare metals (Gibney, 2018: 475).

The water harvested by these methods will need to be stored in tanks inside the building. Because of the low gravity, for the water to flow to the users of the building, a pumping system will have to be implemented.

2.2 Power

The next challenge will be to provide the building with electricity to power all of the equipment necessary to support life. A renewable energy source such as solar energy could be considered for such a purpose. However, as nighttime continues for two Earth weeks, using only solar power would result in substantial downtime in power generation during nighttime.

In recent news, the company Rolls Royce have received funding to create a small nuclear-powered reactor for the Moon, funded by the UK Space Agency. The goal for Rolls Royce is to have the micro nuclear reactor ready to be delivered to the Moon by 2029. According to Rolls Royce, the micro reactor will “*develop technology that will provide the power needed for humans to live and work on the Moon*” (Dinner, 2023: online).

The nuclear reactor by Rolls Royce will be a vital part of this project, as this will make consistent power delivery possible on the Moon. The nuclear power will be in full use during the night. Essential services such as air ventilation and pumping water to residents will have to be continually operational. This will be made possible with the power this reactor will provide. Other essential services include lights and LED lights for farming and producing crops, as well as cooking and other electrical systems. Nuclear power, together with solar

power, will be available for the Moon base during the day, while nuclear power will be available during the night.

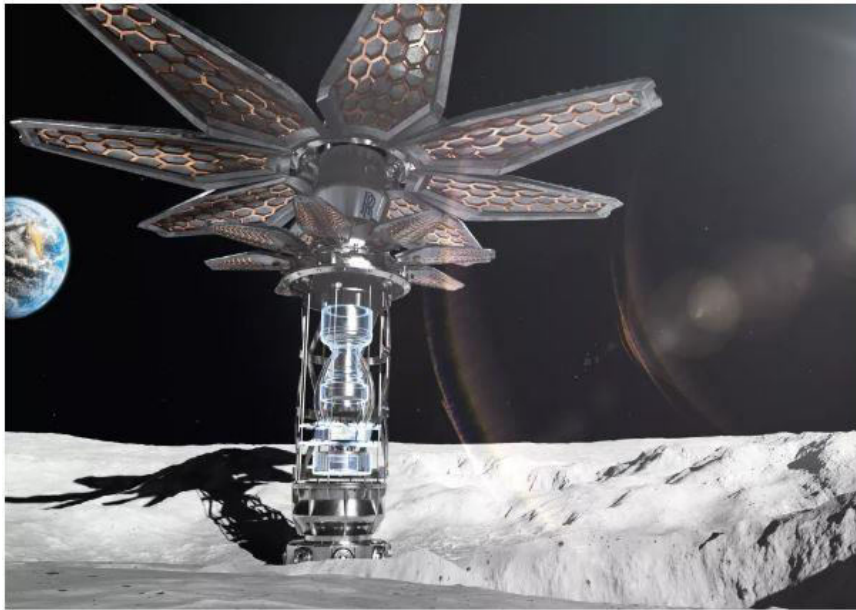


Figure 8: Artist's illustration of the nuclear reactor (Dinner, 2023: online)

2.3 Farming

Next, to provide all humans at the facility with sufficient nutrition, the production of various sustainable food sources on the Moon had to be considered.

On the Moon, different farming systems could be utilised for plant growth. The first method would be to make use of a hydroponic system. Plants can grow in water under white and red light-emitting diode (LED) lights. It has been found that tweaking the LEDs can alter the mineral composition of the plant (Gibney, 2018: 478).

The second method would be to grow the plants in Lunar regolith. Surprisingly, scientists have been able to make plants grow in poor soil. The specific plant that they have been able to grow in such poor soil was *Arabidopsis thaliana* (thale cress). This opens the opportunity for other cruciferous vegetables such as broccoli, kale, cauliflower and Brussels sprouts to be grown in these conditions. This breakthrough was key for scientists to understand how plants might survive in stressful environments (New Delhi, 2022: online).

The plants that will be considered in this project are not only essential for food, but also to develop a self-sustaining system. Food waste can be used in the soil to grow plants. The plants absorb carbon dioxide while producing oxygen. The visitors can then use this oxygen which, in turn, produces carbon dioxide for the plants to convert (Gibney, 2018: 478).

2.4 Aquaponic and hydroponic systems.

Aquaponics is an alternative method to traditional farming. It combines the cultivation of aquatic animals, usually fish, with hydroponics. Aquaponics have many benefits compared to traditional farming. The crops and the fish work together to create a closed-loop system where each provides for the needs of the other. The waste produced by the fish provides the plants with nutrient-rich water for the plants to grow. In turn, the plants break up and absorb the waste from the water, which keeps the water clean for the fish (GoGreenAquaponics, 2023: online). Figure 9 shows the working principle of a basic aquaponics system.

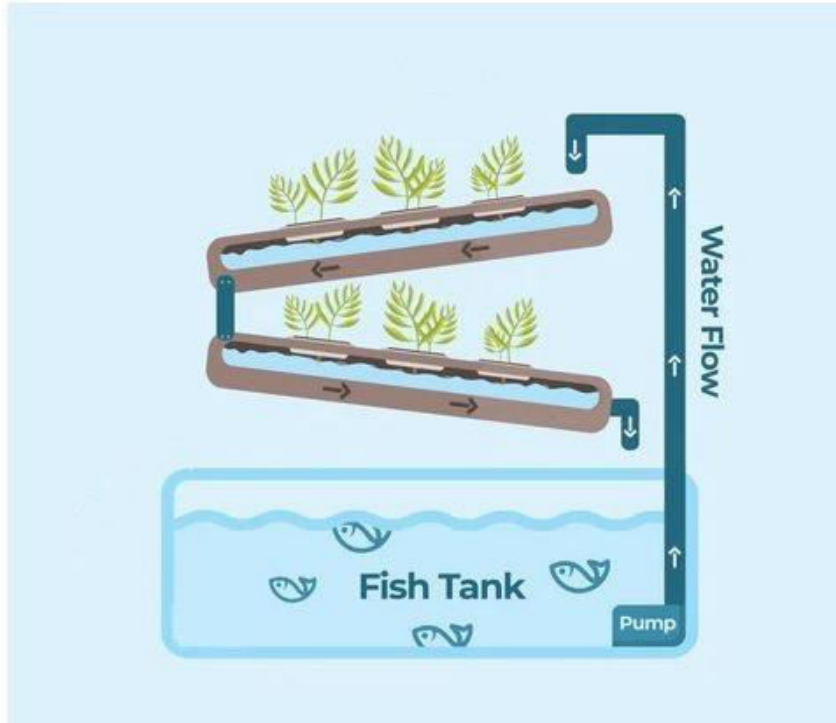


Figure 9: Illustration of a simple aquaponics system (GoGreenAquaponics, 2023: online)

Since the crops get all the nutrients in the water from the fish tank, it is not required to plant the crops in soil. The plants only require a growing bed that is either placed directly on top of the water or planted vertically with the water pumped to their roots, as shown in Figure 9. This method allows for greater production with far less space required. The fish also provides the visitors with a meaty portion.

It is important, however, to consider how water would behave on the Moon and if such a system would be possible.

Because of the lower gravity, the movements of the water would be slower. The waves of the water would be exaggerated in size and settle down slower.

However, such a system is definitely possible, as there is still gravity present that will pull the water to the surface, and prevent it from floating around in space.

2.5 Air

Three important factors need to be considered when considering the air inside the building. These are: maintaining air pressure, maintaining air composition, and obtaining sufficient oxygen.

To maintain air pressure, the building itself has to be a pressure vessel. To sustain human lives the pressure inside the vessel has to replicate the air pressure at the Earth's surface. Therefore, the enclosure must be able to withstand this pressure from the inside and also be very safe to prevent depressurisation (Benaroya et al., 2002: 35). For more technical information on this matter, the reader is referred to Chapter 1 of the technical section.

On the International Space Station, NASA uses a spectrometer routinely to analyse the composition of the air. For this project, the same spectrometer system is used. It routinely analyses the gas content of the air to make sure that the ratio of oxygen to other gases is correct. A backup supply of oxygen is always ready to be used to replenish the cabin air at the International Space Station. During an emergency, the crew can directly tap into the oxygen from the tank with their gear. This allows them to have access to oxygen while they handle the emergency. A similar system will be implemented on the Moon base (NASA, 2001: online).

However, as this project aims to produce a self-sustaining system as far as possible, the necessity of enough trees and the production of oxygen are elaborated on in Section 3.2.

Lastly, sufficient oxygen has to be obtained. As previously mentioned, Lunar regolith contains a high percentage of oxygen. Excess energy from the solar panels or nuclear reactor can be used to produce oxygen from the freely available regolith, and stored for use when required.

2.6 Plumbing

Currently, there is no official “Lunar Loo”. However, there have been a few proposals made by engineers. In 2020 NASA launched an open competition to design a Lunar loo. It was required that the toilet works in a low-gravity environment. A design by Wuelker (Neilson & Brueck, 2020: online) for a Lunar sewerage system was amongst the top three proposals. This design moves away from a conventional system that uses water to flush away waste. Instead, it uses a centrifuge system. This system relies on a centrifuge to take the waste into an underground tank. Wuelker implemented a valve and a filtration system that prevents any odours from escaping the tank. The nature of the proposed system means that it will work even during a power outage (Neilson & Brueck, 2020: online).

Since water will be an extremely precious commodity on the Moon, using a sewerage system that does not require water or uses a minimal amount of water to flush away the waste is essential. This method also reduces the amount of water that will need to be purified and recycled. The waste from the tanks can be turned into fertiliser for landscaping or agriculture. Details on the sewerage system are provided in the technical section.

2.7 Conclusion

With possible solutions in mind to provide for the needs of the Moon dwellers, the building had to be designed around these systems. Innovative engineering solutions will be imperative to make such a project possible in the future.

There will most likely be significant advancements made in Lunar technology over the next few decades. For now, the next chapter contains the proposed solutions.



Chapter 3: Introducing the Project

With an idea of how to sustain life on the Moon, the design could be planned accordingly.

As mentioned in Chapter 1, the Moon is on the radar of multiple private and government institutions to build a future Lunar base. From a scientific viewpoint, a base on the Moon would open up a whole new set of possibilities and scientific discoveries. The stars and vastness of space would be unhindered by an atmosphere, and planetary and astronomical studies would benefit greatly from a Moon base.

Other than housing researchers, the project's main focus would be to accommodate visitors. This project is to cater for those who seek an other-worldly adventure, for the curious, the science nerds and the engineering fanatics.

Through this project, the future is envisioned. It is the year 2100 and commercial space flights are a buzzing industry. It is imagined what a future visitors' or research centre on the Moon could look like. The potential identity of Lunar architecture is explored.

This project takes one on a journey to Earth's only natural satellite, with no natural drinking water, no atmosphere and no air to breathe and where life itself is sustained by machines and technology. However, the view of the stars and space will be unlike anything seen on Earth. The Earth will be seen from a distance, as the Moon is seen from Earth. The reduced gravity will give one temporary superpowers. One will have the opportunity to explore the Lunar surface and drive around in Lunar rovers.

The experience will also be educational and insightful, where the visitors can learn about the Moon's geology and study space.

The number of visitors that will be accommodated in the building will be a maximum of one hundred visitors at a time and only when it is nighttime on the Moon. This is to make exploration outside the lava tube possible for visitors without having to shield them from the surface heat and radiation of the sun.

The number of visitors is based on the Starship HLS currently in development, which will be able to carry up to one hundred passengers per flight (SpaceX, 2023: online). Furthermore, there will be space for thirty staff members who will stay on a rotational basis for two weeks at a time.

Clients

The two major clients for this project are SpaceX and NASA.

3.1 Architecture as a Machine

Le Corbusier introduced the concept of architecture as a machine, famously stating in his work *"Toward A New Architecture"* that "The house is a machine for living in" (Atmodiwirjo & Yatmo, 2015: 1). His idea emphasised the application of engineering problem-solving methods and adherence to standards in architectural design. This notion gave rise to standardisation in the field of architecture (Atmodiwirjo & Yatmo, 2015: 1).

The idea that one will live in a machine is emphasised in this particular project. Human life will be sustained through machinery, a makeshift Earth through technology. This resulted in the importance of emphasising the essential mechanical components that continuously run in the background - the heartbeat of the machine, without which the machine would cease to exist.

The logic of an engineer or standardisation should be applied to the extremely important systems of this project. Although these systems will mostly run in the background, unnoticed by the public eye, the visitors will be given a glimpse of the mechanical components that make such a project possible.

However, it is essential to note that the idea of architecture as a machine was not unique to Le Corbusier. Albert and Kendra Smith wrote, "Human dwellings are constructions of memorable machines which tell us the time of our habits" (Smith & Smith, 2005: 79).

Architecture as a machine could be seen as an assemblage of elements forming a consistent dwelling. This assemblage, akin to Le Corbusier's idea, brings together various components to create a functional whole, imposing order and organisation. Atmodiwirjo and Yatmo (2015: 2) state: "The house is something that is made up of a collection of elements which become significant when made into a whole".

This notion is extended throughout the design of this project. The machine consists of varying elements that together contribute to a significant whole, a functioning life-support machine. Not only does it support life, but it supports entertainment, hospitality and relaxation. All of these important aspects come together harmoniously with an intricate design machine.

The relationship between users and architecture involves complex interactions, encompassing spatial experience, comfort, ergonomics, and human desire. Le Corbusier's machine metaphor for architecture established functionality as its central tenet, seeking to create order in human life and living spaces (Atmodiwirjo & Yatmo, 2015: 2-3).

The approach taken for the design is focused on two major aspects; experience and functionality. The experience of the visitors takes a central focus.

To create a comfortable space, which would otherwise be impossible, Earth must in some sense be replicated, as if a piece of the globe was transported and put in place. This expands on the notion that "if architecture is to be more than simply shelter from the elements, it must be infused and inspired with meaning; it must reflect how and why humans inhabit the cosmos" (Smith & Smith, 2005: 79).

Le Corbusier's major concerns were centred around comfort and health, reflected in his emphasis on open-plan designs to allow light and air into the living spaces. However, this machine is centred around the existential experiences of the visitors as the main function. At the same time, the needs and desires of the visitors, which range from the most basic to the most adrenaline-filled adventures, are catered for.

3.2 The Self-sustaining Machine

According to the Oxford Dictionary, a machine can be defined as an apparatus that is made up of several parts, each with a definite function and working together towards a function or mechanical power.

Several functions within the building have to work together harmoniously, as a machine, to create an environment that can sustain life. The aim is to make this a self-sustaining system as far as possible.

To do that the essentials for living needed to be provided for. To sustain this project in the long-term, the dwellers on the Moon have to be as independent as possible to reduce cost and risk and ensure long-term success.

The following essential services are included in the system:

- food (sections 2.3 and 2.4)
- water (section 2.1)
- oxygen (section 2.5)
- sewage (section 2.6)
- power (section 2.2)

As discussed in section 2.4 the aquaponics system integrates fish and hydroponics. To sustain 130 people, of which 30 will be staff employed on a rotational basis, the area required to provide food for 130 people was calculated. It is estimated that with a hydroponic system, one person needs roughly 144 plants. Depending on the type of system, this requires sixty square metres if one has six layers of vertical farms (Gutierrez, 2023: online). However, the area required can be drastically reduced if more vertical layers are used for farming.

The building will host a hundred visitors only for two weeks of the month - when it is nighttime on the Moon. Thirty staff members will be hosted during the day and night. Therefore, the number of visitors can be divided in half to get to the exact number of people to feed all year round, which is fifty visitors and thirty staff members. This amounts to eighty people. The required space for the vertical farming portion of the aquaponics equates to roughly 4 800 m². The calculated area is further reduced by increasing the number of vertical layers.

Fruits:

When considering trees, apple trees were chosen. This selection was made as it is a very popular fruit that is easily grown, can adapt to any climate and requires little space. Mature apple trees can bear up to 800 apples per season (Sabin Nature, 2022: online). Other than the fruit that will be produced, the trees also produce oxygen and assist in improving the air quality.

Enough apple trees will be planted to provide 80 people with an apple a day for a year. That equates to 37 apple trees. Apple trees are usually spaced four metres apart (Agritech, 2021: online). This spacing was therefore used in the design.

Fish:

As a source of protein, the fish in the aquaponics system will be harvested and served. Plenty of flowing water and ample fish tank space will be provided to farm the fish and produce enough fertiliser for the crops.

Water:

As discussed in section 2.5, the sewerage system is water-free; only grey water will have to be reused. The grey water is collected in tanks on the service level (ground floor) and will be used to water the gardens or will be cleansed to be reused again. The water within the aquaponics system should be filtered of all ammonia before being served as drinking water. Should a shortage of water arise, additional water can be harvested (section 2.1).

Oxygen:

It is essential to plant enough trees within the building. The trees will continually filter the carbon dioxide - produced by the visitors - out of the air and produce oxygen. Too much carbon dioxide with too little oxygen can be dangerous. For this reason, the correct number of trees is calculated to keep the oxygen and carbon dioxide levels stable based on the amount of people. The amount of oxygen a tree can produce depends on its size and species, but as a rule of thumb, two mature trees can provide enough oxygen for a family of four (Arbor Day Foundation, 2023: online).

The number of trees is calculated based on the full number of visitors and staff members, to ensure enough oxygen will be produced during visiting times. The total number of people was divided by two to calculate the number of trees required. This amounts to a total of 65 trees, which includes the apple trees.

Plenty of space is provided for landscaping, to accommodate the necessary number of trees and vegetation to make the project as independent as possible.

Given the research conducted about the site and systems required for such a project, an understanding of the scope of the project was gained. From here, the following accommodation list was selected for the project:

3.3 Accommodation list:

Due to the scale of the project, the accommodation list is divided into four different districts. These are the business district, the city centre, the agricultural region, and the hotel, or residential regions. The reasoning behind creating these distinctions is discussed in Chapter 4 of this document.

3.3.1 The Business District

Ground floor

- Lunar rover hatch (Tourists)
- Equipment hatch (Research)
- Services
- Water Storage
- Food Storage
- Oxygen tanks

First Floor

- Changing rooms
- Ablution facilities
- Geological research centre
- Laboratory
- Offices
- Flight control

Second floor

- Systems control
- Agriculture offices
- Agricultural laboratory
- Medical centre

Third and Fourth floors

- Viewing deck for stargazing
- Building viewing decks
- Canopy Walk
- Relaxation areas
- Landscaping

Roof of lava tube

- Research Telescope
- Astronomical research facilities

3.3.2 The City Centre

Ground floor

- Services
- Storage

First floor

- Restaurant
- Moon bar
- Lunar bowling

Central tower

- Open-plan museum
- Conference room for welcoming
- Free-fall jump

- Entrance to canopy walk

Roof of lava tube

- Arrival and spaceship docking

3.3.3 Agricultural Region

Ground floor

- Services
- Water storage and pumps for aquaponics

First floor

- Aquaponics system
- Nursery
- Vertical farm
- Open space seating

Second floor

- Canopy walk

3.3.4 Hotel

Ground floor

- Services
- Food Storage
- Water Storage

First floor

- Hotel entrance
- Kitchen
- Dining Hall
- Staff living pods

- Ablutions
- Landscaping and relaxation
- Living pods/rooms

Second and third floor

- Additional living pods
- Circulation

The above accommodation list is provided, as this is the result of the final design. Each district and all accommodation are introduced, and described in detail, in Chapters 4 and 5.



Chapter 4: Design of a City

The visitors' and research centre can be thought of as a small village on the Moon. In essence, the project is a city with all its components and different facets. Although the project will not host permanent residents, the same basic functions may be applied. This is a multi-dimensional project that can easily become over-complicated and disorientating. The visitors' centre is an entertainment area and an office space; it has farming and accommodation. All of these different areas should be linked together systematically and in a way that is easily comprehensible.

In the book, *"The Image of the City"* by Kevin Lynch (Lynch, 1960), there are easy and practical guidelines to achieve just that. There are many lessons to be learned from small cities and villages. Although this "village" will be on the Moon, the dwellers' needs remain the same. Visitors will still want to relate to the architecture and feel at home in the spaces that are created through it.

4.1 Wayfinding

In a city, the design of space is very important. Lynch knows this and has compared the design of a city to the designing of space as an architect would design a building; only, it is done on a much larger scale. At any given moment in a city, there is an array of different sounds, more than one could fully take in in a single moment. There is much more than what the eye can see and there is so much in the city waiting to be explored. Lynch pointed out that no part of the city is experienced in isolation, but is always related to what is experienced as a whole (Lynch, 1960: 1).

To design a city, one must think of all the important aspects. Probably the most important aspect of the city is the people and their activities. The designer should always consider the people as an active part of the city and not merely as observers (Lynch, 1960: 2).

Lynch asserts that legibility is crucial in a city. Although there is no doubt that legibility is not the only important thing in a city, when it comes to the sheer size and complexity of a city, this becomes all the more important. This goes back to the fundamental needs of humans and animals to understand their surroundings. Lynch emphasised how animals use gravity, sound, smell and even magnetic fields to navigate direction (Lynch, 1960: 3). Wayfinding and orientation are therefore necessary to feel at ease and comfortable.

As straightforward as this may seem, it is easy to forget to design from a viewpoint of legibility and wayfinding. Disorientation only brings a sense of anxiety and even terror, especially in an unknown environment (Lynch, 1960: 4). Taking all of this into consideration, the layout and main paths of the visitors' centre were designed.

4.2 The Image of the visitors' centre

Lynch argues that the best way to achieve wayfinding is to use imagery that one can use to move quickly and easily (Vyas, 2011: online). This is not to say that there is no place for surprise. A surprise can create an exciting moment, but it should be in a broader context that makes sense. Alternatively, the surprise must be anticipated by the dweller (Lynch, 1960: 6).

For an image to possess value as a navigational tool within a living environment, it must fulfil specific requirements. Firstly, it should be adequate and functionally accurate, enabling individuals to effectively navigate within their surroundings according to their preferences. It does not necessarily have to be precise but should be capable of guiding someone back home reliably. Additionally, it must offer clarity and readability (Lynch, 1960: 9).

Furthermore, shared patterns of travel routes or workspaces tend to create a consistent mental image for a group by exposing many individuals to the same visual elements. Through interviews with public participants, certain features appeared to be very important in a city. Open spaces, greenery, the sense of movement along pathways, and visual contrasts, appeared to be particularly influential in shaping one's perception of the cityscape (Lynch, 1960: 16).

Enhancing the "imageability" of urban environments involves simplifying their visual identification and structure. These components are identified as paths, edges, landmarks, nodes, and regions. They serve as the foundational elements in establishing strong, distinct structures at the urban scale (Can, 2019: online).

From the perspective of Kevin Lynch's book, the Lunar city is given a very simple and straightforward map. As the project is very complex on a three-dimensional level, it is important that the plan and flow of the building are easy to read. The design follows a few axial lines heading in their own direction and crossing each other in the middle. This is the map of the Lunar city in its most basic form (See Figure 10).



Figure 10: Main paths of the Lunar city (author)

The axial lines represent the main paths of movement or circulation. All main roads therefore head towards the middle and outward with only one way to the end of each path and back. There is no way of getting lost or disorientated. One can clearly see in which direction one is heading and in which direction all the other main paths are heading. Furthermore, these paths are shared by the visitors and the staff in the building, encouraging community and bringing together visitors and researchers from all walks of life on a communal route.

4.2.1 Paths

The pathways within the "Lunar Visitors' City" represent the habitual routes of movement and influence the organisation of the entire project. According to Lynch, these key routes should possess distinctive qualities that distinguish them from other routes. This can be achieved through an abundance of specific uses or activities along their edges, unique spatial characteristics, distinct textures, peculiar lighting arrangements, distinctive scents or sounds,

specific details, or unique planting styles. These attributes should be thoughtfully applied to maintain the path's coherence. When one or more of these characteristics are consistently employed along the route, the path can be perceived as a continuous, unified entity (Can, 2019: online).

These main paths within the visitors' city are given very distinct features from the rest of the project. The first characteristic is that they are elevated above their surroundings. Furthermore, along their edges, the surroundings are soil and landscaping, which makes them stand out from their surroundings (See Figure 11). They are given the distinct material of composite wood, which in the future will most likely be a specially developed material. However, for now, composite wood is the proposed material. They are also given continuous and futuristic lighting features.

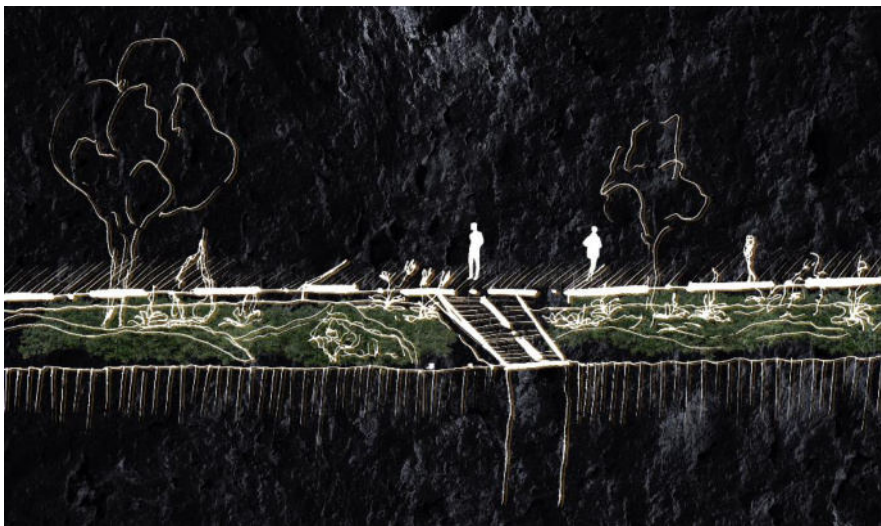


Figure 11: Main paths surrounded by landscaping (author)

The applied features mentioned above could be described as a visual and functional hierarchy of the pathways. It involves emphasising the primary channels through sensory distinctions (Filomena et al. 2019: 16). This essentially forms the framework of the city's mental image.

Furthermore, it is said that observers tend to imbue a path with a sense of direction. This occurs through a gradient or directional distinction. For instance, the gradient can be determined by the ground slope, and people are often advised to travel "up" or "down" a street. Consequently, one might describe a location as "just before the street rapidly narrows" or "on the hillside before the final ascent." This allows the traveller not only to confirm that they are heading in the correct direction but also to feel a sense of proximity to their destination (Lynch, 1960: 96-97).

This principle was applied to the design by using ascension and descension. All roads either ascend or descend from the centre where the paths cross. The contours of the site allowed such elevation differences to occur, giving distinct directions to the different paths.

4.2.2 Districts

In its most basic form, a city district is a region characterised by a consistent set of features that are present throughout the area and absent elsewhere. This uniformity can manifest in various ways, such as shared spatial attributes, like narrow, sloping streets; a common building type, like a row of houses with distinctive fronts; a particular architectural style; or similarities in topography. It can also pertain to specific architectural elements and extend to features like colour, texture, materials used, or even the type of flooring (Lynch, 1960: 103).

The more these characteristics overlap within a district, the more pronounced the perception of a cohesive and unified area becomes (Lynch, 1960: 104).

Districts are further emphasised by the clarity of their boundaries. When a district can be easily viewed in its entirety, whether from elevated points or due to the concave nature of its site, its distinct separation is reinforced. Within a district, there may be sub-districts that exhibit internal variations while still fitting within the overall character (Lynch, 1960: 104).

Districts can connect to one another through various means, such as adjacency, visibility between them, alignment with a line or axis, or via intermediary elements like nodes, paths, or smaller districts (Lynch, 1960: 104).

Lynch's concept of districts was employed in the floor plan of the project. Since there is such an extensive accommodation list, all the different functions needed to be appropriately grouped, after which, each group had to be appropriately placed in the context of the whole building, to ensure the goal of each function can smoothly operate.

The accommodation list can be divided into four groups:

1. Research/Commercial
2. Food production
3. Entertainment
4. Accommodation

Like most cities are divided into districts to group certain functions of society, the aforementioned list can be translated into the following districts of the building:

- Business district
- Agricultural region
- City centre
- Residential area

City centres are usually referred to as the main entertainment and gathering hub of a community, usually situated in the centre. The design followed that same pattern and the city centre was placed in the middle. From the city centre, one moves outward to the rest of the districts.

It was decided to place the business district, that hosts the research facilities, closer to the entrance of the cave. This seemed fitting as the researchers will have closer access to the Lunar terrain where they can conduct their

experiments and gather samples. Their position allows them to move freely without disrupting the rest of the Lunar "community".

The residential district is placed deeper into the cave in the opposite direction to the business district and in line with the city centre. The residential district is also referred to as the hotel. This is where both the visitors and researchers will stay. The hotel is placed a generous distance away from the city centre, and the rest of the building functions to enhance the sense of privacy and calmness.

The agricultural region is the closest to the city centre and also forms part of the entertainment sector. This is deliberately done so that the visitors will have the opportunity to learn and see the processes involved in conducting agriculture on the Moon. The agricultural sector employs an aquaponics system and flowing water. This creates a relaxing and beautiful environment where the visitors can linger about. The locations of the different regions are shown in Figure 12.

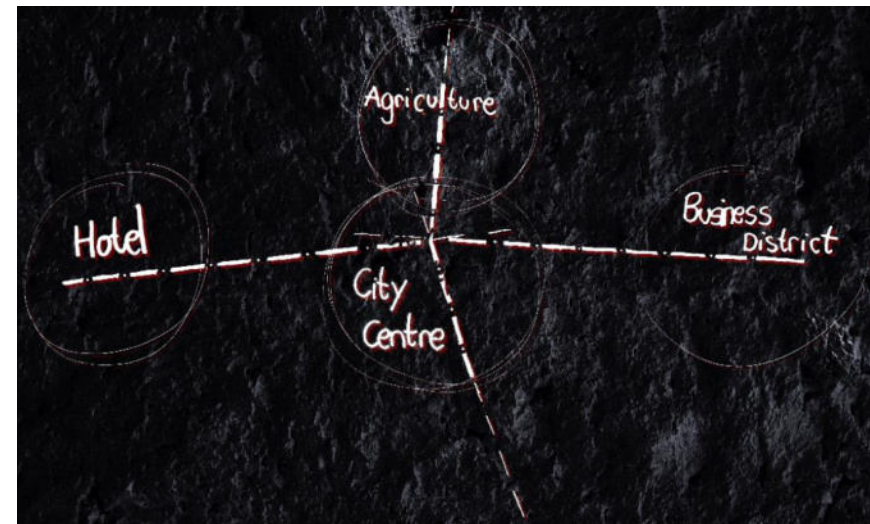


Figure 12: Different districts and their positions (author)

Landscaping is used between each district borders. The landscaping, along with the paths, also acts as the connecting media between the districts.

With each district in place, the entrance had to be established. Since the city centre will be the most public space, it was decided to have the visitors arrive directly at the city centre, without having to pass through any other districts first. This was achieved by placing the entrance at the top of the lava tube roof and having the visitors taken to the city via an elevator (see Figure 13).

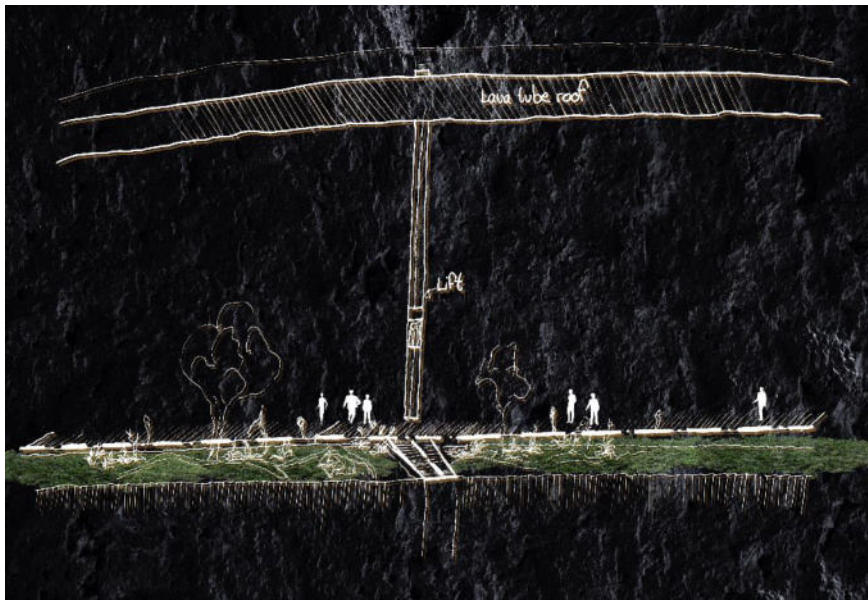


Figure 13: Elevator descending to the city centre (author)

4.2.3 Edges

Both edges (of districts and pathways) require a certain degree of visual consistency along their entire length. An edge gains additional prominence when it remains visibly continuous over a substantial distance, defines a pronounced shift in area characteristics, and effectively connects the two adjacent regions (Lynch, 1960: 99-100).

Consider the impactful visual impressions created by skyscraper apartments facing Central Park (Figure 14) or the clear transition from water to land along a waterfront. Such scenarios, where two contrasting regions are closely juxtaposed and their edges meet, naturally capture visual attention. This effect can be achieved through various means, such as contrasting materials, maintaining a consistent concave line, or using strategic planting. Alternatively, the edge can be shaped to offer orientation along its length (Lynch, 1960: 100).



Figure 14: Edge formed by skyscraper apartments against Central Park, New York (Simms, 2022: online)

An edge can serve a more dynamic role than simply acting as a dominant barrier when it allows for visual or physical saturation, effectively forming a deeper connection between the regions on either side. In this sense, it becomes a seam rather than a barrier - a line of exchange that stitches two areas together (Lynch, 1960: 100).

For the Lunar city, careful consideration was given to each district edge, so as to give a formal entrance into each function of the system. The edge that clearly defines the “business district” of the city was designed in the form of a

steep green wall that was inspired by the Jewel of Changi Airport (see section 6.2 for more detail). The steep green wall seamlessly connects to the rest of the landscaping outside the district. The main path moves through the green wall into or out of the district, announcing a formal arrival. The green wall that will be experienced on both sides of the main path as it extrudes upwards creates a memorable exit to the rest of the building (see Figure 15).

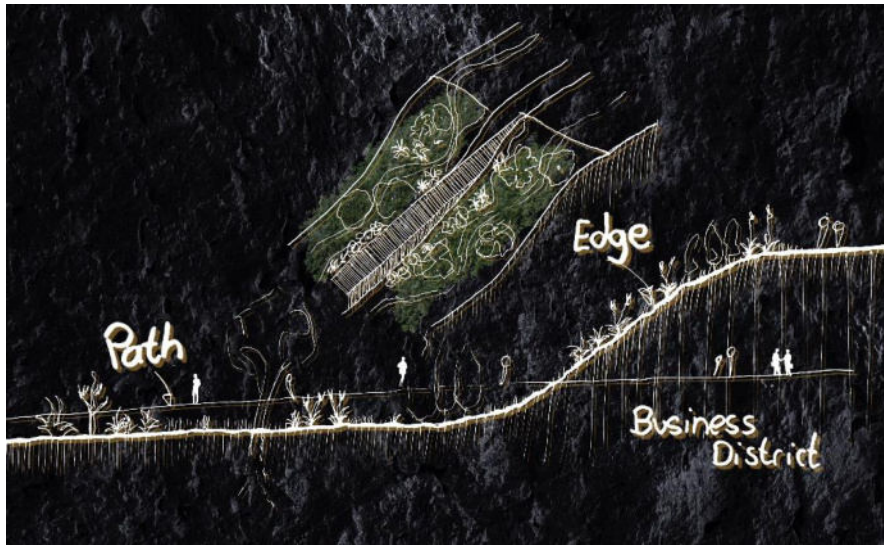


Figure 15: Sloping green edge of the business district (author)

For the agricultural region, the aquaponics system partially fulfils the role of a district edge. Furthermore, a contrast of material was used in the form of Lunar-made bricks (refer to Chapter 2 of the technical section) to form the ascending steps and to contain some of the water by forming ponds at the edge of the system. The vegetation is used, as a stark contrast was formed between the vegetation and other landscaping, as well as the walkway that leads up to that specific district. Lastly, a clear and crisp edge is formed using water. All these elements are not necessarily in the same line; this intentionally created an interactive “seam” rather than an edge. This is illustrated in Figure 16.



Figure 16: Seam of the Agricultural region through both plantation and water (author)

Lastly, the edge of the “residential district”, or hotel, is clearly indicated by a hedge of trees and immediately following the hedge are high entry walls on both sides of the path (see Figure 17). This edge does not act as a seam, but rather a barrier that enhances a sense of privacy and protection.

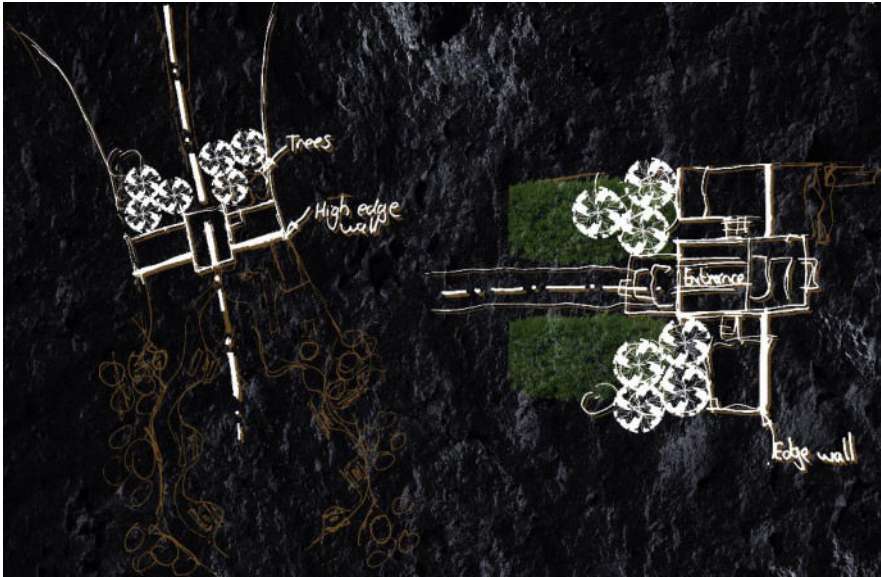


Figure 17: Edge and entrance of the hotel (author)

4.2.4 Landmarks

The fundamental quality that defines a viable landmark is its uniqueness, and its ability to stand out from its surroundings. This distinctiveness can take various forms, such as a towering structure set against a backdrop of low rooftops, flowers against a stone wall, a vibrant element within a dull street, a church surrounded by commercial buildings, or a protrusion within a continuous building facade. These spatial prominences have a strong allure that captures one's attention (Lynch, 1960: 100-101).

Furthermore, the effectiveness of a landmark is enhanced when it remains visible over an extended period or from a considerable distance. Its utility is increased when it can be easily recognised from different angles and speeds of movement, be it day or night. In such cases, it serves as a reliable reference point for navigating the complex and ever-changing urban environment (Lynch, 1960: 101).

Perhaps the most prominent landmark in the Lunar city is the rising tower of three-storeys, that elegantly frames the elevator in the middle, which takes one all the way to the roof of the lava tube. This prominent landmark announces the "city centre" and also acts as an anchor point for direction and orientation. To get to the hotel one could say "Go down and walk straight past the tower, the entrance for the hotel will be in front at the end of the path."

The second landmark, which is located inside the business district of the building, mimics the tower. This landmark forms the top and ultimate destination of the canopy walkway. This landmark duplicates the city centre, as it also frames an elevator which goes up to the telescope. Both the tower and the second landmark are made up of composite timber trusses that protrude outward in a circular pattern and form an overhead cantilever. This design takes advantage of the lower gravity of the Moon to create a structure that seems nearly impossible on Earth (see Figure 18).

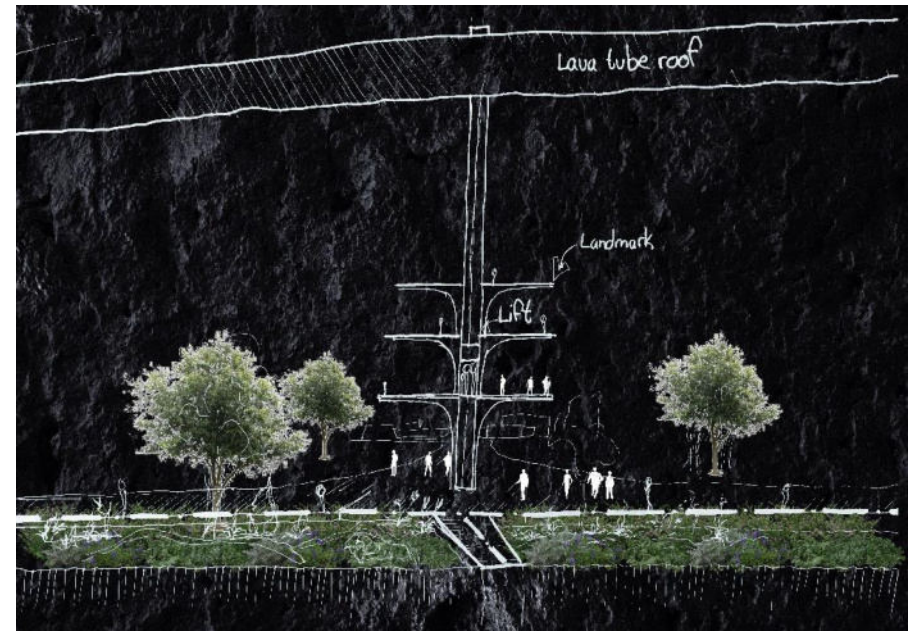


Figure 18: The tower in the city centre (author)

The third prominent landmark in the building is the perforated façade and tall entryway of the hotel. This parametric feature stands tall above the surrounding structures and clearly indicates the entrance to the hotel.

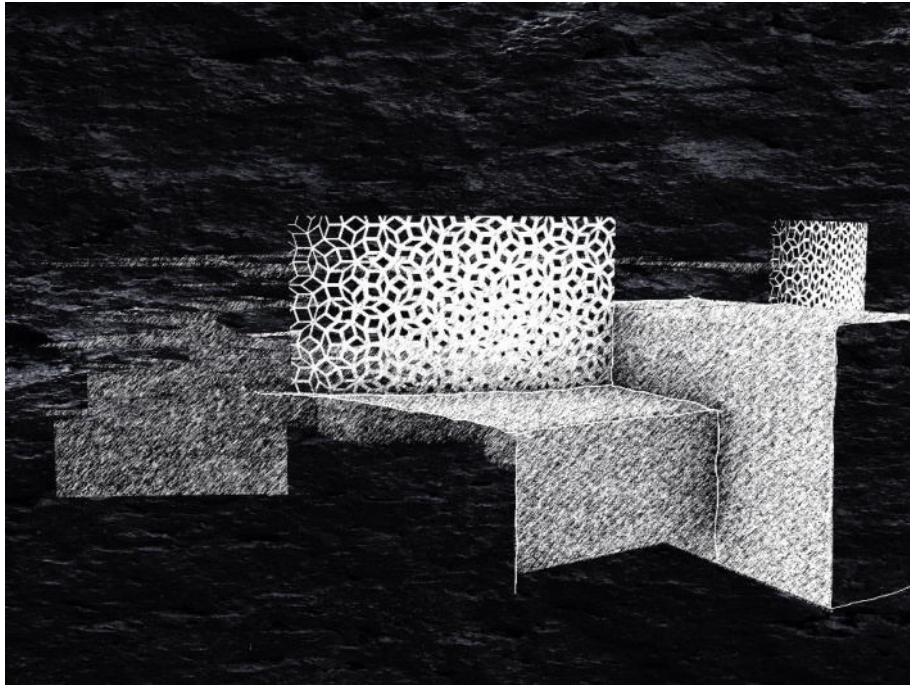


Figure 19: Parametric landmark and barrier of the hotel (author).

4.2.5 Nodes

Nodes serve as the fundamental conceptual anchor points within our urban landscapes. To establish the perceptual support for these nodes, the primary requirement is to create a distinctive and continuous quality in their walls, flooring, architectural details, lighting, greenery, topographical features, or skyline. The essence of these elements lies in their capacity to become unique, unforgettable places that cannot be mistaken for any other location (Lynch, 1960: 102).

The identity of a node is further enhanced by the intensity of its use, and in some instances, this high level of activity can even generate the node, as exemplified by Times Square. A well-defined node typically possesses a clear, well-contained boundary, rather than dissolving ambiguously in all directions. It becomes even more remarkable when it incorporates one or two focal points that draw attention (Lynch, 1960: 102).

The Lunar city visitors must be able to identify the entrance and exit of the node. They should also be able to orientate themselves within the node. These nodes can effectively organise larger urban districts if their presence is somehow highlighted in the surrounding context. Moreover, if the node possesses its own internal orientation, such as an “up” or “down,” a “left” or a “right,” or a “front” or a “back,” it can be integrated into the broader orientation system of the cityscape (Lynch, 1960: 103).

Examples of urban nodes, according to Lynch, are instances like intersections where paths cross, as well as moments when transitioning from one urban structure to another occurs. While these elements inherently suggest movement, the author argues that nodal points can serve as both connecting and gathering points. This duality is exemplified in scenarios such as a street-corner hangout or an enclosed square (Moreira, 2021).

There are three main nodes within the Lunar city. The first and biggest node is located in the city centre, where all the roads come together in a circular area. As mentioned previously, this node serves as an intersection and a place of choice-making. However, it is also a gathering area and therefore serves as a node. The second prominent node is the landscaping and gathering area under the canopy walkway within the business district. This oval space not only acts as a place of gathering but also a location for stargazing. Figure 20 shows the location of the business district node.

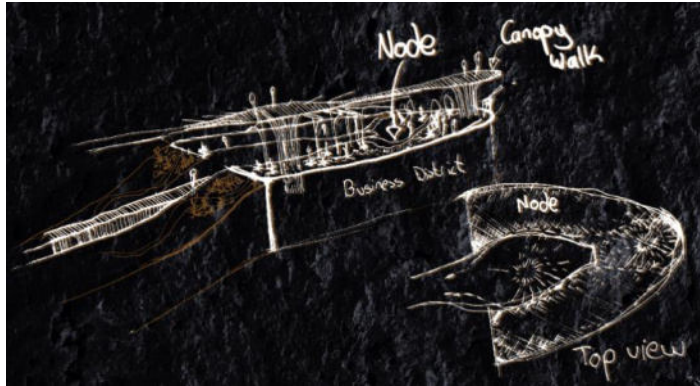


Figure 20: Node in the business district (author)

Another node lies in the middle of the aquaponics system. This node seems to cut out a very defined square in the middle of the plantation. This node will encompass a juice bar that will serve freshly grown Lunar fruit while surrounded by the sound of flowing water. Visitors can retreat to this node to be reminded of Earth and to feel anchored in an otherwise alien world. Figure 21 indicates the location of this node.

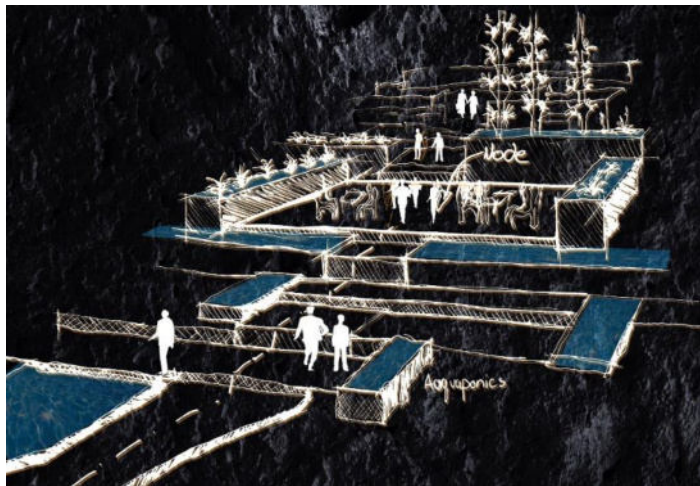


Figure 21: Node between the aquaponic system (author)

4.3 Sense of the whole.

When discussing design based on different element types, there is often a tendency to overlook the interconnectedness of these elements in creating a cohesive whole. In such a comprehensive design, pathways would serve the purpose of both revealing and preparing for the emergence of distinct districts, while also connecting various nodes. These nodes, in turn, would function to unite and demarcate the pathways, while the edges would define the boundaries of the districts. Additionally, landmarks would indicate the central points within these districts. It is the skilful coordination of these individual components that would come together to form a rich and coherent urban image (Lynch, 1960, p. 108).

It is important to view the five elements - path, edge, district, node, and landmark - as practical categories that help organise a wealth of information for designers. Their utility lies in their capacity to serve as foundational building blocks for the design process (Lynch, 1960, p. 109).

The plan of the building is brought together with all of the five extremely important elements written by Lynch. The main paths are laid out, each path leads to a district. Each district has its own respective space and defining edge. Nodes were introduced mainly as gathering spaces throughout the building and landmarks are placed at strategic positions for orientation. The image of the Lunar city has become clear with each district hosting a unique set of functions. (Refer to section 3.3).

Not only are Lynch's guidelines easy to follow and practical, but they are a fundamental organisational tool to bring together very large projects such as the Lunar city. Figure 22 shows the initial floor plans for the building; then, the building was very fragmented. Each part of the building was isolated from the next and scattered across the site. It was anything except a unified city.

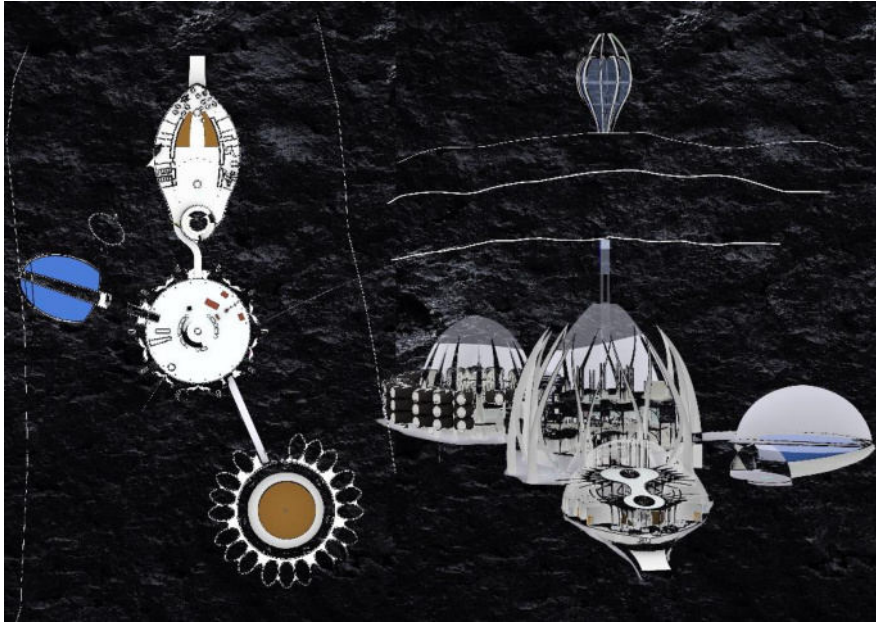


Figure 22: Previous layout and design of the project (author)

Figure 23 shows the progressive floor plans after implementing the principles found in Lynch's book. The organisational tools provided have been used to bring together every part of the building that was in isolation into a unified whole.

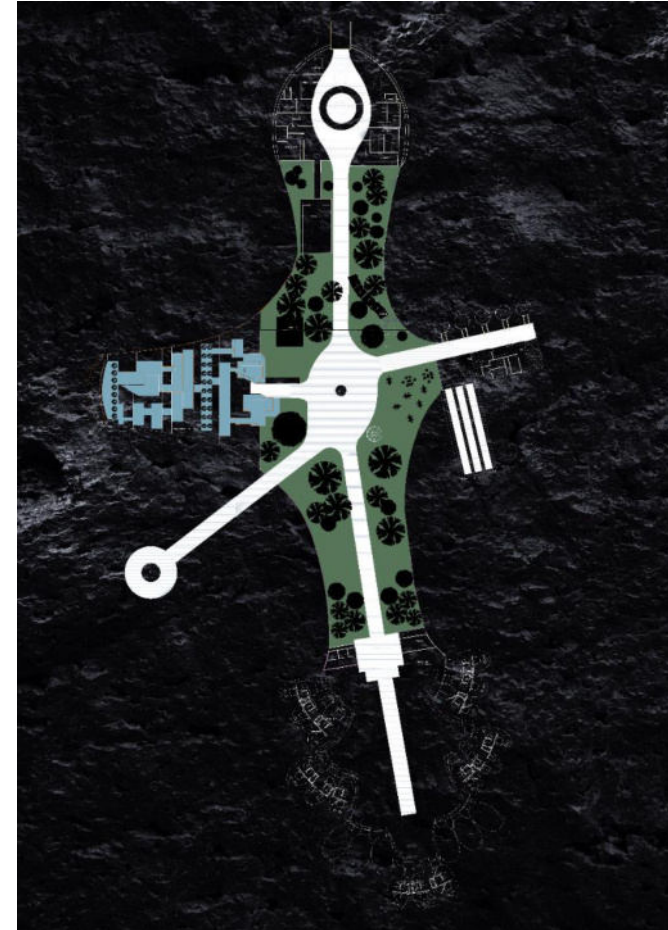


Figure 23: Floor plan development with applied principles (author)

All five elements of Lynch's book: paths, regions, edges, landmarks, and nodes have been implemented in the design. The foundation and layout of the building have been established and were designed with logic and fluidity of the functions in mind. To turn this layout into a building, the architecture emerged. The three-dimensional design of the building was inspired by the concept of biomimicry..



Chapter 5: The Living Organism

The building is designed from the visitors' point of view and how the design is meant to be experienced by them. They will most certainly go to visit this site for the adrenaline and experience of seeing a whole new world, but the architecture has to allow them to experience both the known and the unknown. If everything they see is new, unknown and alien, it might become too overwhelming and uncomfortable. For some, after being there for only one Earth day, might become homesick. For those moments, the design intends to create spaces that replicate Earth, while in other spaces one is confronted by the alien world.

By doing so, the visitors are given a choice over what they want to experience at that moment. They can go and read a book between the landscaping under the trees, or they can go to the edge of the building and stare at Earth, confronted by the distance between them and home. For the braver visitors, they can change into space suits and take a tour of the Lunar surface. However, certainly after doing so, they would want to relax in an environment that is not so strange, but feel more at home.

For this reason, biomimicry was chosen as the driving force behind the design.

5.1 Biomimicry- morphological approach

Biomimicry represents a specific scientific discipline that examines the patterns and phenomena found in nature. After these phenomena are thoroughly studied, they are replicated to tackle human challenges in a sustainable manner (Ghisleni, 2020: online).

Biomimicry stands as a promising emerging research area, which involves finding design solutions inspired by natural models, systems, and elements. Coined by Janine M. Benyus in 1997, the term is a fusion of the Greek words 'bios,' signifying 'life,' and 'mimesis,' which translates to 'imitation'. When referencing design influenced by nature, alternative terms such as biomimetics, bio-inspired, and biologically inspired are also used (Verbrugge et al., 2023: 1).

This approach perceives nature as a standard, an instructor, and a guide (Biju, n.d.). Rather than mere imitation, biomimicry serves as an inspiration for transforming the principles of the natural world into effective design solutions (Virmani, 2014).

From a conceptual point of view, the building is not only a machine that sustains life, but the building can be thought of as a living organism. Like a living organism, the building needed a shell or skin to protect that which is inside. That which is on the inside is extremely fragile, like the heart and organs of a mammal, the pressurised air and oxygen keep the heart of the project beating.

Below are examples of biomimicry that inspired the design of this project.

Esplanade Theatre, Singapore



Figure 24: Image of the Theatre's biomimicry skin (ParametricHouse, 2023: online)

The building employs a secondary lattice structure for shading. It is used with folded sunshades that can change orientation and direction. This results in a dynamic and continuously changing pattern of filtered sunlight and shadows (ParametricHouse, 2023: online).



Figure 25: Image of louvre system and durian fruit (ParametricHouse, 2023: online)

The architects took inspiration from the durian fruit, known for its protective thorn-covered exterior, to develop a cladding system. This system comprises lightweight, curved steel frames paired with triangular aluminium sun shields. The architects conducted extensive research into the local sun's path, which was one of the main determining factors of the shape and depth of the louvres (ParametricHouse, 2023: online).

National Aquatics Centre, Beijing



Figure 26: Image of building facade inspired by water and soap (Modlar, 2008: online)

The National Aquatic Centre, famously referred to as the Water Cube, is another remarkable example of biomimicry in architecture. The building served as the venue for the 2008 swimming Olympics. Its architectural concept drew inspiration from cells and the natural arrangement of soap bubbles. This distinctive geometry of bubbles allowed for an organic and unpredictable appearance. The continuous outer layer of the structure was constructed using ethyl tetrafluoroethylene (ETFE) due to its lightweight properties and excellent insulation. This cladding not only permits a higher amount of natural light to enter compared to traditional glass, but also harnesses 20% of solar energy, which is then utilised to heat the swimming pools (Biju, n.d.: online).

Panda Tower / UDG. Atelier Alpha



Figure 27: Panda Tower (Archdaily, 2021: online)

UDG Atelier Alpha designed the Panda Tower for the Chengdu Research Base of Giant Panda Breeding's new campus, creating a cultural landmark that integrates observation, exhibition, and sightseeing while symbolising the harmonious fusion of nature and technology.

The inspiration for the design originated from bamboo shoots, which are both the favourite food of the Giant Panda, and a popular ingredient in Sichuan cuisine. The tower's main structure is formed by combining floor slabs and arced units, drawing inspiration from the petals of the hibiscus flower. These pedal slabs decrease in number in an arithmetic progression from the tower's base to its top, culminating in an aesthetically pleasing display of mathematical beauty when viewed from the central courtyard (Archdaily, 2021).



Figure 28: Image of the interior of the Panda Tower (Archdaily, 2021, online)

5.2 Application

Inspired by the precedent studies, the skin of the Lunar city building will be developed using inflatable membranes and materials. Inflatable membranes have many benefits, such as easy transportation, and easy assemblage, it is lightweight compared to conventional material and adaptable, to name a few. The choice of materials and precedent studies of inflatable buildings are discussed in the technical section. There will be tremendous pressure exerted by the air inside the building (see technical section) and careful consideration is given to the shape of the 'skin' that has to contain the air.

Ideally, a sphere or a cylinder is the best possible shape to use, as the pressure gets distributed across the surface evenly (A&G Engineering, 2022). However, this does not mean that any other shape will not work. The shape must however avoid sharp edges and straight wall segments of the areas that will be inflated. A shell that curves outward and expands in the same direction as the pressure, is stronger. Such curves were applied to the design in most areas. However, in some areas, the curves bend inward towards the interior of the building to allow for variety in the shape of the architecture.

Since the design naturally requires organic shapes, applying biomimicry proved to be an invaluable foundation for the design, which is included in the floor plans and building morphology. This ties in well with the notion of replicating Earth on the Moon. The design brings "life" from Earth and also mimics the life of Earth. The shape of the building, both in plan and three-dimensionally, makes references to living organisms. The plan is specifically drawn from single-celled organisms. A comparison between a single-celled organism and a conceptual floor plan is presented in Figure 29. This concept was applied over the previous floor plan that allowed for further development.



Figure 29: Image of a single-celled organism (Wood, 2022: online), next to a floor plan concept drawing (author)

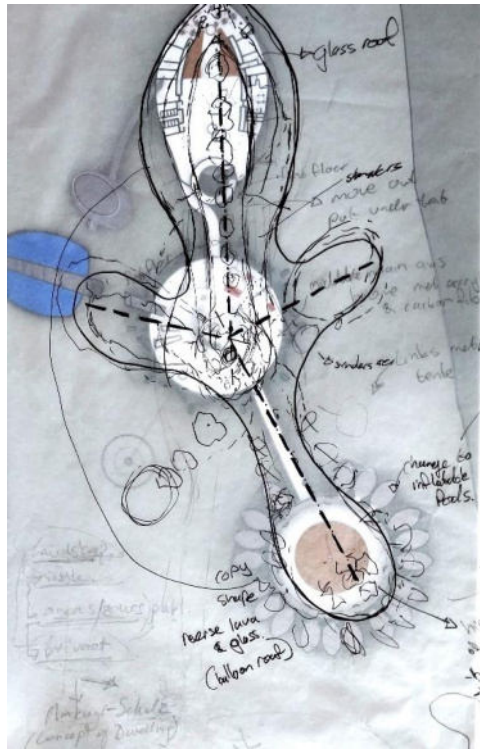


Figure 30: Progress drawing showing the development of the floor plan shape from previous floor plan (author, 20 July)

5.2.1 The skin

The inflatable membrane stretches over the entire floor plan of the building. The foundation walls of the project are 3D printed concrete and are printed to the height of the first floor-level. These walls are the boundaries of the building and form an enclosed organic shape. The inflatable membrane is attached to the foundation walls and pumped with air into a stern structure.

The inflatable membrane forms a point of hierarchy above the city centre that towers above the rest of the building like a mountain peak. Originally the shape was developed to resemble a mountain peak with lava flow, the new

developments were placed over the previous design. This was the foundational shape from which all further developments succeeded.

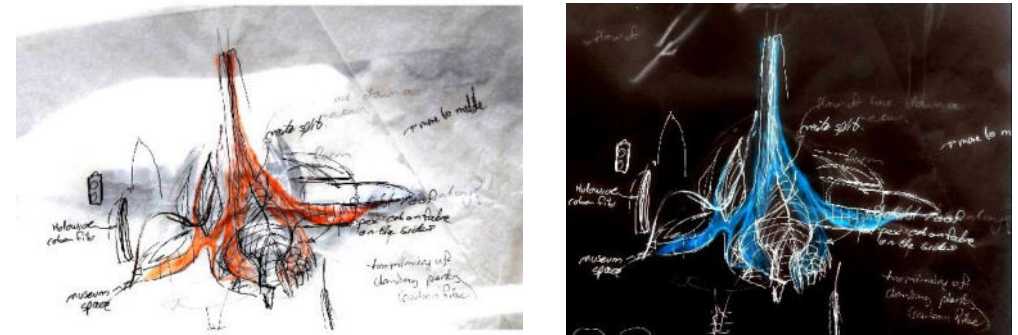


Figure 31: Development drawings placed over previous design (author)

From this point, the rest of the membrane flows harmoniously outward and covers the rest of the districts. This harmonious movement of the inflatable membrane mimics the movement of aquatic mammals, such as that of a whale. A representation of the inflatable membrane is presented in Figure 32.

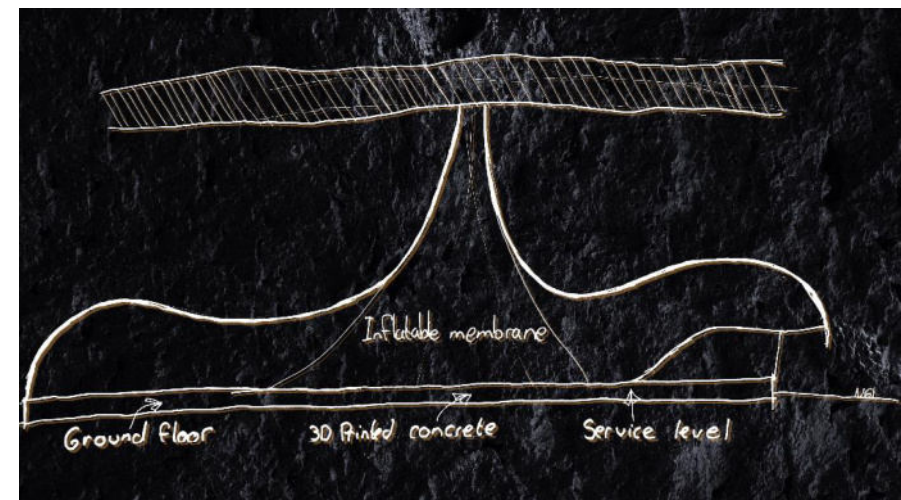


Figure 32: Basic shape of the inflatable membrane (author)

The inflatable membrane, as discussed in the technical section, is made of durable material strengthened with polyvinyl chloride (PVC). However, the material is not transparent and is usually manufactured in white. It was important to give the visitors dedicated views of the surroundings from inside the building. Therefore, transparent areas within the membrane are provided through the use of PVC plastic sheets. However, these layers of plastic are thinner and not as strong as the non-transparent membrane. To combat the loss of strength to gain transparency, a carbon fibre external structure is designed for the transparent areas. The carbon fibre external structure, referred to as an “exoskeleton” will be placed on the outside of the plastic sheets that will help contain the pressure. The exoskeleton is discussed in detail in Chapter 3 of the technical section.

The exoskeleton’s design was inspired by the intricate skeletal structure of a pufferfish. A pufferfish’s skeletal structure that also expands is made of modular bone segments that interlock, as can be seen in Figure 33. The exoskeleton is designed to be assembled of modular units that together wrap around the transparent areas (Figure 34).



Figure 33: Skeletal structure of the pufferfish (McClain, 2018: online)

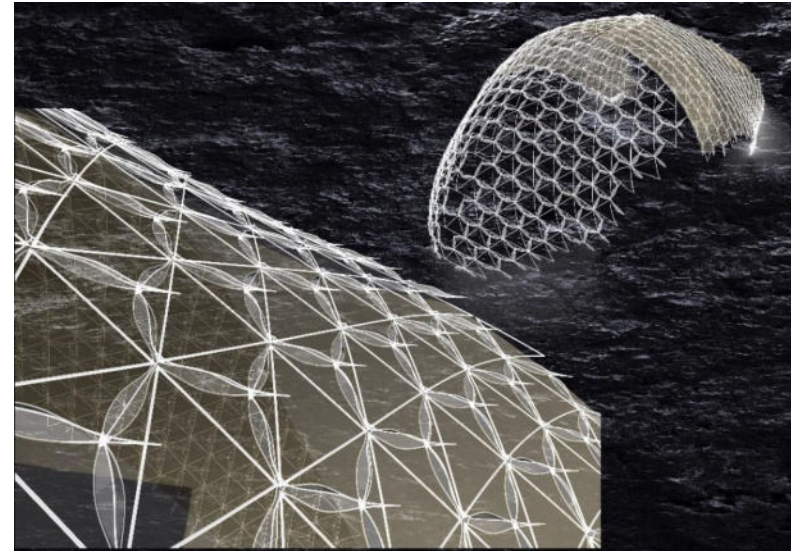


Figure 34: Diagram of the exoskeleton. Indicating the modular units and design (author)

To complete the organism, it is given a rigid structure that supports the inflatable membrane. This is referred to as the “spine” of the building. The spine is made of a durable titanium frame, to which the inflatable membrane is attached. The structure gives the skin its shape. Above the city centre, the spine is attached to the bottom of the lava tube roof and forms the tower of the building (see Figure 35).

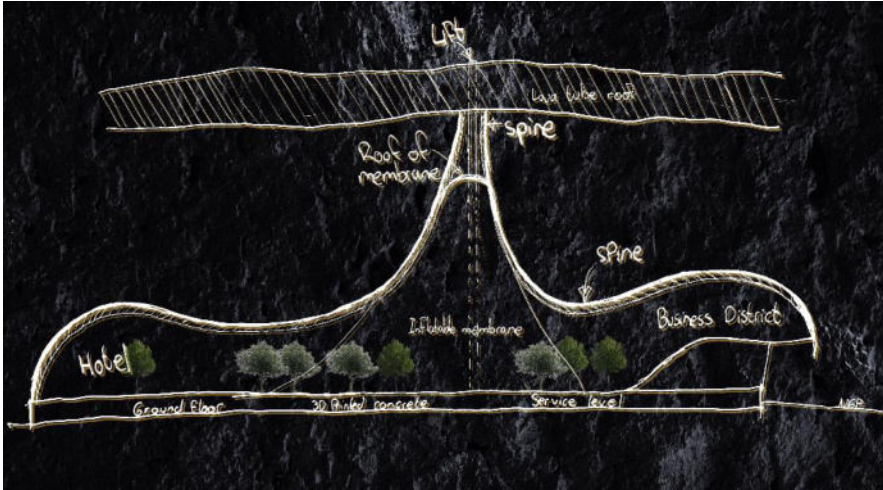


Figure 35: Drawing of the spine attached to lava tube roof (author)

This rigid structure was inspired by the fascinating spine of the Hero Shrew, one of the only mammals that has an interlocking spine. This can be seen in Figure 36.



Figure 36: Interlocking spine of the Hero Shrew (Strickland, 2020: online)

The spine of the building is designed to consist of interlocking modular pieces. Once the modular units are locked and connected in place, it makes for a rigid and sealed frame. The spine is discussed in detail in the technical section.

From the tower, the spine extends to all the other districts of the building and forms the top frame of the other districts. Not only does the spine provide the shape of the building, but it is also the support structure from which the elevated walkways inside the building are suspended. This design allows interior columns to be eliminated, which leads to the illusion of levitating walkways (Figure 37).

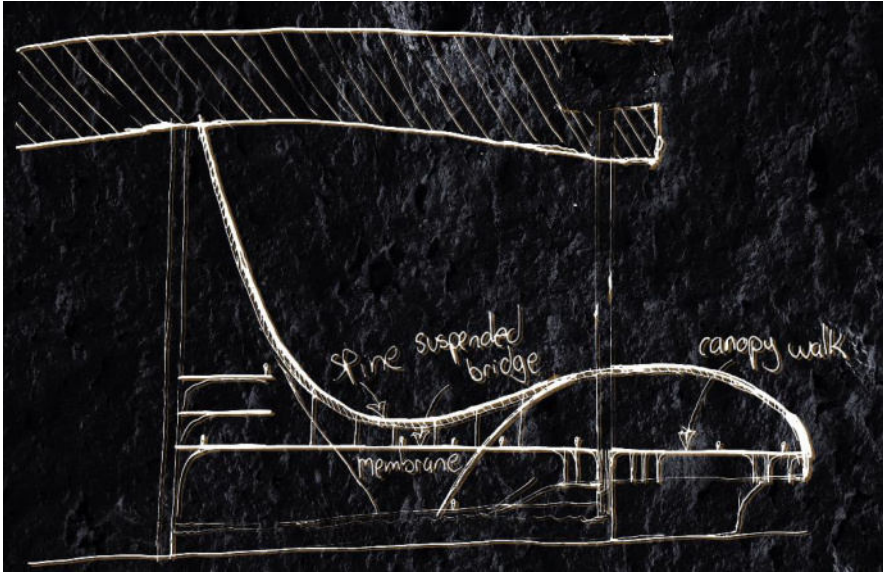


Figure 37: bridge suspended from the spine (author)

The spine also forms the creases and shape of the hotel. From the tower, the spine splits into two segments. After this split, it splits further into multiple segments that contribute to the layout of the hotel rooms. An illustration of the layout of the spine is presented in Figure 38.

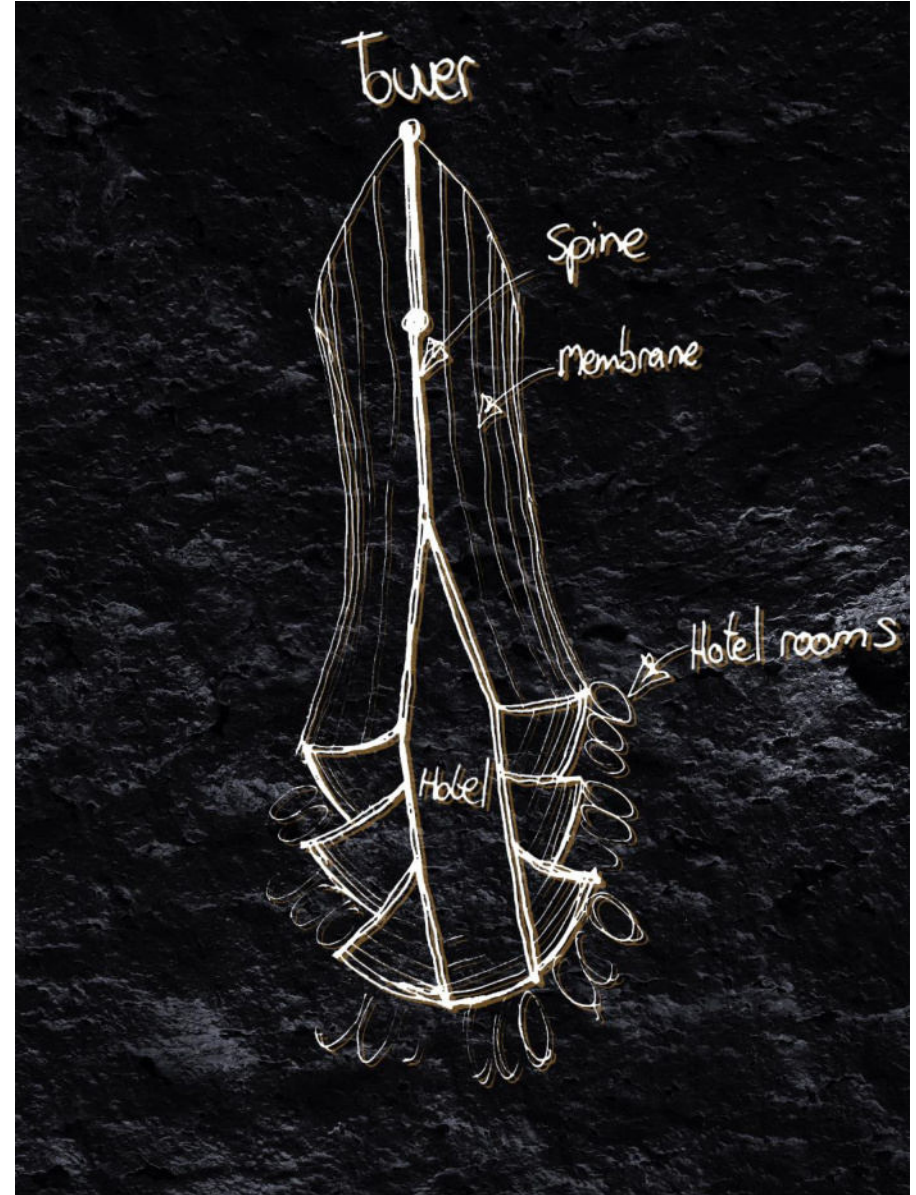


Figure 38: Top view of the spine over the hotel area (author)

5.2.2 The Business District

This part of the building is given an oval shape with an inflated dome. Placed at the entrance of the cave, the visitors will have a spectacular view of the night sky, overlooking the valley in which they find themselves. This is the “head” of the organism, barely allowing itself to be known with only a small portion visible at the entrance of the lava tube. Originally, the business district was also designed as the formal entrance to the building, before the entrance was placed at the top of the lava tube roof. This greatly impacted the shape, as the entrance was placed just above the ground level. The inflatable membrane was meant to be hoisted up in place, before that system was replaced with the spine. Figure 39 shows the progress work for the business district.

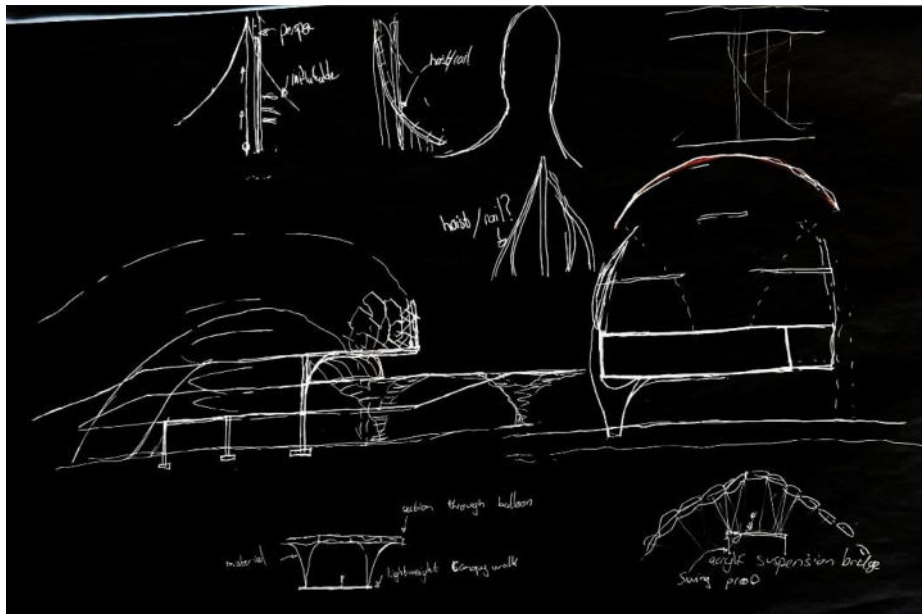


Figure 39: Progress design drawings of the business district (author, August)

The spine follows the top curvature of the dome, only from the top of the dome, it extends outwards and is attached to the roof of the lava tube at the entrance of the cave. This gesture indicates the presence of the telescope and astronomical research centre. This feature also allows the design to ‘open up’ to the rest of the Lunar surface (Figure 40).

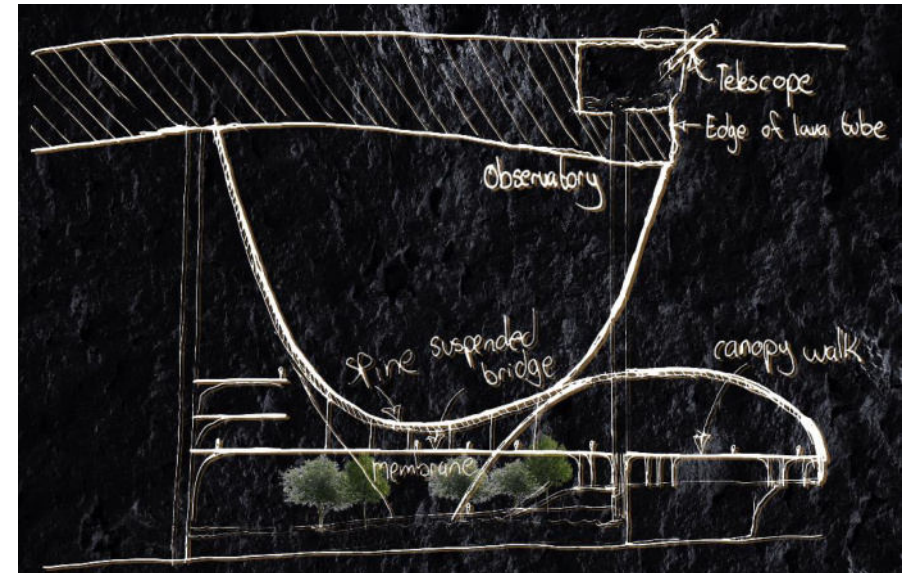


Figure 40: Spine reaching to the telescope that's imbedded in the lava tube roof (author)

5.2.3 The Agricultural Region

The agricultural region extends out from the tower and forms a tube-like shape covered with an inflated dome. There is no clear boundary of where the skin of the tower ends and the inflated dome of the agricultural region begins; the one seamlessly transforms into the other (Figure 41).

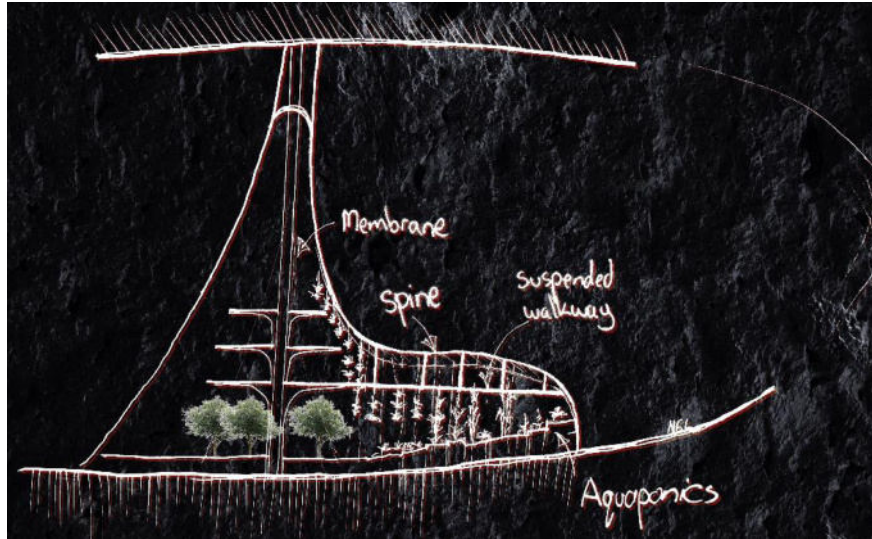


Figure 41: Form of spine covering the agricultural region (author)

5.2.4 The Hotel

The hotel rooms are oriented around a fragmented oval. The entrance to each living pod is accessible from the communal courtyard space inside the building. Outside of the inflatable membrane are the living pods, stacked on top of each other. Some living pods are larger family units, whilst others are one-bedroom units. Each living pod is oriented to have an unhindered view of the cave's interior. The design and materials of the living pods are discussed in the technical section.

5.2.5 The Restaurant

The restaurant area offers visitors a unique experience of both the gravitational difference and the lava tube itself. The inflatable membrane that stretches down from the tower extends all the way to the first floor and seems to miss covering the restaurant portion. Like a bubble, the restaurant is placed outside and seems to be placed on top of the membrane. In a transparent

globe, the restaurant is situated close to the ground and the side of the lava tube. This allows the building and visitors to engage with the surrounding rock faces. There are also dedicated seating spaces that cantilever outside of the bubble even further into the depths of the cave. These are specifically designed for the visitors who desire the full experience. The rest of the restaurant are inside the bubble with some seats moved inward under the inflatable membrane between the landscaping, for those who may feel more comfortable in an environment that reminds them of Earth.

A bowling alley on the Moon may sound strange at first, but the gravitational difference of the Moon will make for a unique and unexpected challenge in playing bowling. Everything that the visitors are used to in terms of gravity and how they know objects move will be completely different. The game will allow for such experimentation. The alleys are also adjusted, they are made broader and higher to make room for the bowling ball's potential movement.

5.2.6 The Tower

The tower offers visitors an exciting experience when entering the building. The entrance was designed from an experience point of view.

Referring back to Lynch's concept of a memorable image, this image, upon arrival for the visitors, is made vivid by having them arrive at the intersection on the first floor, directly under the hierarchy of the building. The elevator in the middle rises and pierces through the lava tube roof all the way to the top. This is where the visitors will arrive, the Starship flight will dock on top of the elevator. There will be a direct connection between the space shuttle and the elevator. Visitors will be able to get inside the lift directly from the shuttle. As the visitors slowly descend inside the lift, they would be confronted first with twenty metres of rock. Once the lift moves below the lava tube roof, the building is introduced, and one would for the first time see the vast distance and size of the cave as well as a full top view of the entire building. As the elevator descends further, it passes through another new threshold. The lift

enters the building through the inflatable membrane, and the interior of the building is revealed (Figure 42).

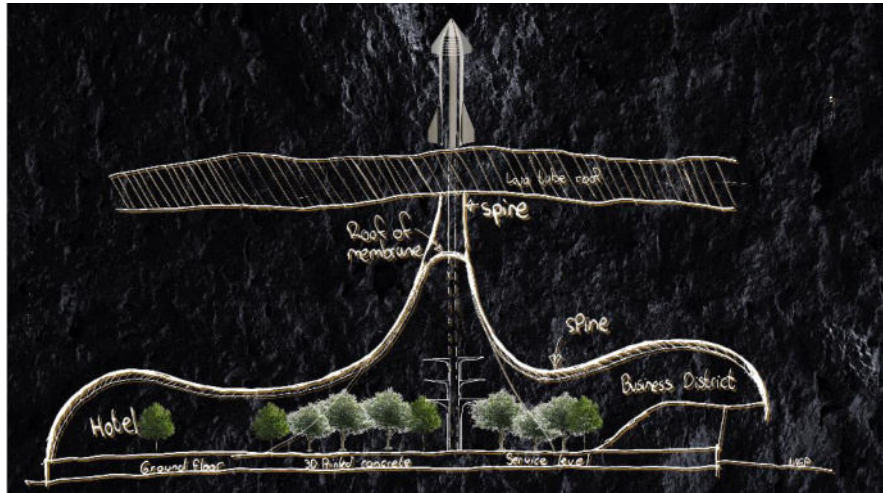


Figure 42: Starship dock connecting to the elevator over the city centre (author)

Biomimicry could be seen throughout this chapter to be an invaluable tool for design, especially with the design of organic architecture. The design, in the end, did pose as a reminder of Earth, yet unique and futuristic in its own right. With both the floor plans and morphology of the building complete, careful planning and consideration were taken to complete this project with appropriately designed landscaping.



Chapter 6: Landscape Design

The landscape design inside the building is a very important aspect of the project. Not only is it important for oxygen and food production, as discussed previously, but it is well known that people's mood and psychology are influenced by nature. Nature also contributes to the general well-being of a person (Weir, 2020: 50)

Plenty of space is dedicated to landscaping in the building. It is therefore essential to look to landscape design principles and design the landscaping effectively for relaxation. The inside of the building will mimic Earth, while the outside remains a barren inhabitable place. These two vastly different environments inside the building versus outside the building create a very stark visual contrast.

As mentioned previously, between every district is landscaping as the connecting media. The visitors will therefore always move through or in-between landscaping. The canopy walk will provide a top viewpoint of the landscaping as one moves over and in-between the tree tops.

6.1 Elements of Landscape Design

When designing landscapes, the process had to start with the intended users' needs. Plants and hardscape elements, collectively known as features, are the building blocks for landscape design. Five basic design elements were used for the development of landscape design:

- Line
- Form
- Texture
- Colour
- Visual weight

These elements are guided by principles such as proportion, order, repetition, and unity (University of Florida, 2021: online). For the landscape design of this project, each design element was considered and followed in a systematic order.

6.1.1 Line

Lines influence emotional and physical responses to landscapes.

Straight lines: Convey formality, symmetry, and direct attention to focal points, often seen in hardscape edges.

Curved Lines: Evoke informality, relaxation, natural feeling, and mystery through slower movement and hidden views.

Vertical Lines: Create upward movement, emphasising features, found in tall plants or structures.

Horizontal Lines: Horizontal lines extend along the ground, making spaces feel larger, often created by low walls, walkways, or hedges (University of Florida, 2021: online).

6.1.2 Form

This is usually the dominant visual feature that determines the style and feel of the landscape. Forms are shapes or enclosed spaces. Form is also the three-dimensional mass within spaces. Structures, plant beds, and ornamentation determine the garden's overall form theme. For the landscape design, informal forms are used such as meandering lines, organic edges and fragmented shapes. This can be seen in Figure 43. The informal garden embraces natural, organic forms that resemble nature. Form is also used to create unity throughout the garden with a coherent theme. A contrast in form at one or two strategic places is a great way to emphasise particular areas. In this case, big circles are used between the organic design of the landscaping, as a means to emphasise that space (University of Florida, 2021: online).

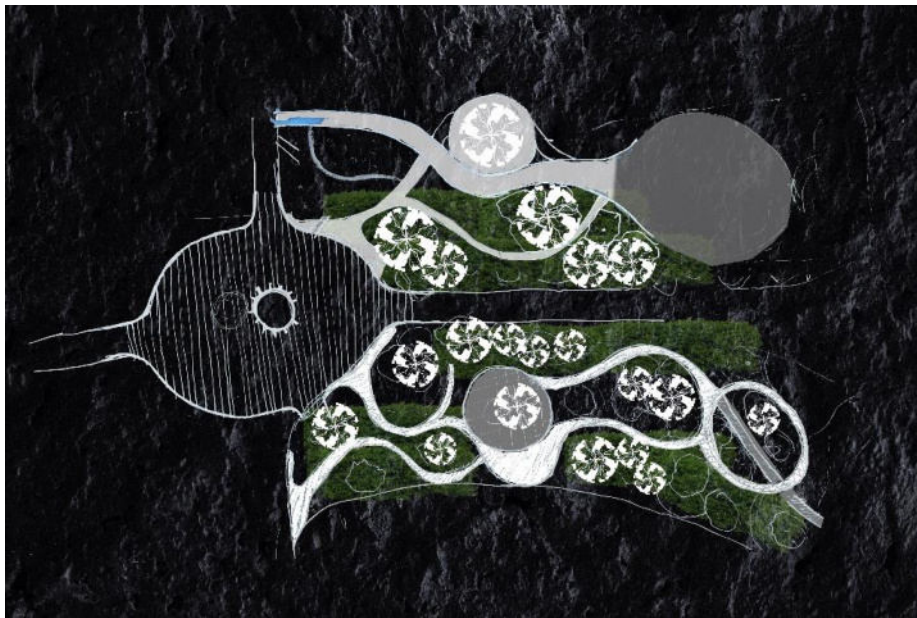


Figure 43: Top view of garden, illustrating organic, natural form (author).

6.1.3 Texture

Texture in landscape design is used to introduce diversity and contrast. A coarse texture is usually more dominant than a fine texture, whereas a fine texture tends to harmonise compositions. Coarse-textured plants draw more attention because of the contrast between light and shadow created by their rugged surfaces (The AEC Associates, 2016: online).

Plants that contribute to coarse texture are plants with large leaves, irregular leaf edges, prominent veins, variegated colour patterns, spines or thorns, as well as bold, thick, or irregular shapes. Hardscape elements with coarse textures are rough-cut stone, roughly finished brick, and unfinished wood. Weathered construction materials that retain a rugged surface also contribute to coarse texture (The AEC Associates, 2016: online).

Fine texture is characterised by traits like small foliage, slender leaves (such as grasses), thin stems, small and densely packed twigs, delicate flowers, and a sprawling form. Hardscape elements with fine texture include smooth stone, wooden or ceramic pots, and a smooth surface of water (University of Florida, 2021: online).

Most plants fall into the category of medium texture, characterised by medium-sized leaves with simple shapes and smooth edges. Hardscape elements with medium texture include standard flagstone pavers, broom-finished concrete, and finished woods.

Texture plays a significant role in the perception of distance and scale. To create a sense of spaciousness, plants with fine-textured elements should be placed along the outer edges, medium textures occupy the middle ground, and coarse textures should be positioned closest to the viewer. Fine texture, due to its small size, recedes into the landscape and appears farther away (The AEC Associates, 2016: online).

6.1.4 Colour

Adding colour to both plant material and hardscape elements enhances the landscape by introducing diversity and visual appeal. The utilisation of colour is guided by colour theory. The fundamental colour schemes include monochromatic, analogous, and complementary options (University of Florida, 2021: online).

Monochromatic Scheme: This scheme relies on a single colour. In landscaping, an all-green garden depends more on variations in form and texture for contrast and visual interest (Parnell, 2022: online).

Analogous Scheme: This scheme incorporates three to five colours that are adjacent to one another on the colour wheel. For instance, red, red-orange, orange, yellow-orange. This shared relationship amongst colours in analogous schemes creates harmony (Parnell, 2022: online).

Complementary Scheme: Complementary colours are situated opposite each other on the colour wheel and typically exhibit high contrast when paired together (University of Florida, 2021: online).

Colours possess properties that can influence emotions, spatial perception, light quality, balance, and emphasis. One such property is temperature, where colours can be perceived as either cool or warm, affecting emotions and feelings. Cool colours have a calming effect and are suitable for relaxation areas, while warm colours are more invigorating and ideal for entertaining spaces (University of Florida, 2021: online).

For the landscaping of this project, an analogue scheme of earthly browns, oranges and greens is chosen. This is to reflect the natural colour schemes of the Earth.

6.1.5 Visual weight

Visual weight pertains to the concept that certain elements in a composition hold greater significance due to their mass and contrast, making them more prominent and memorable. Background elements are no less important, as they contribute to the overall cohesion. Elements with high visual weight often possess characteristics such as bold shapes, large size, vibrant colours, and texture, while those with low visual weight include horizontal lines, fine textures, and subdued colours. It is important to have elements with lower visual weight, as they provide moments of rest for the viewer (University of Florida, 2021: online).

6.2 Principles of Landscape Design

Proportion: This involves assessing an element's size relative to others and its absolute scale, with a key consideration being how it relates to human scale.

Order: Order refers to the spatial arrangement and balance in the composition, typically achieved through symmetry, asymmetry, or perspective. Order can also be established by grouping elements into distinct clusters and arranging them around a central focal point.

Repetition: Repetition entails the deliberate use of recurring elements to create patterns, with a need for balance to prevent monotony. Repetition also contributes to rhythm in the design.

Unity: Unity is achieved by connecting elements and features to create a consistent character in the composition. Unity is akin to harmony, where everything fits together seamlessly. Unity is achieved by establishing coherence in the design through the interconnection of elements, which can be facilitated through dominance, interconnection, unity of three (or other odd numbers), and simplicity.

The Following precedent studies were referenced for the landscape design.

Doha Airport Forest:



Figure 44: Image of Doha Airport interior (Smit, 2023)

The expansion of Hamad International Airport is the focus of this precedent study. This expansion included remarkable features, such as an art gallery and a shopping area housing over 90 shops. Amongst the expansion's highlights was "The Orchard," a captivating 6 000 m² indoor tropical garden situated at the heart of the shopping area. This lush landscaped garden provides a serene retreat for the airport's 58 million passengers annually, offering a space for relaxation, leisurely walks, and rest. Adding to its allure, The Orchard incorporates moving water, contributing to the refreshing atmosphere of the design (Amusement Logic, 2023: online).

To ensure the well-being and survival of the indoor tropical forest's plant species, the garden is sheltered by a column-free canopy made of high-performance glass, specially designed to filter and regulate light (Amusement Logic, 2023: online).



Figure 45: Image of landscaping (Smit, 2023)

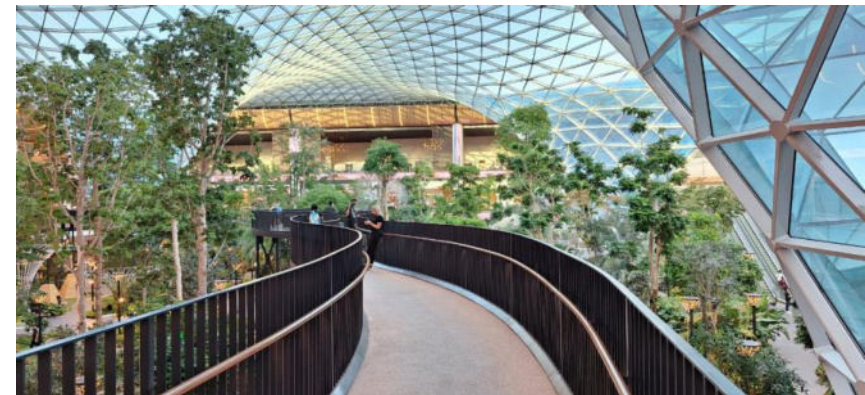


Figure 46: View from canopy bridge (Smit, 2023)

Jewel Changi Airport / Safdie Architects



Figure 47: Singapore interior forest (Archdaily, 2019, online)

Likewise, “The Jewel” is located at Changi Airport. It fulfils its purpose as a connector between existing terminals while combining two distinct environments - a marketplace and a paradise garden. At its core lies the “Forest Valley”, a terraced indoor garden offering various spatial and interactive experiences, featuring walking trails, cascading waterfalls, and seating areas. The highlight of the Forest Valley is the world’s tallest indoor waterfall, known as the “rain vortex,” descending from an oculus in the domed roof to the garden seven storeys below (Archdaily, 2019: online).

The Jewel’s design revolves around a semi-inverted toroidal dome roof, spanning 200 metres at its longest point and primarily supported along the rim of the garden, creating a near column-free interior (Archdaily, 2019: online).



Figure 48: Extended view of the interior (Archdaily, 2019, online)



Figure 49: Section view of the airport (Archdaily, 2019, online)

Chapter 7: Final Design

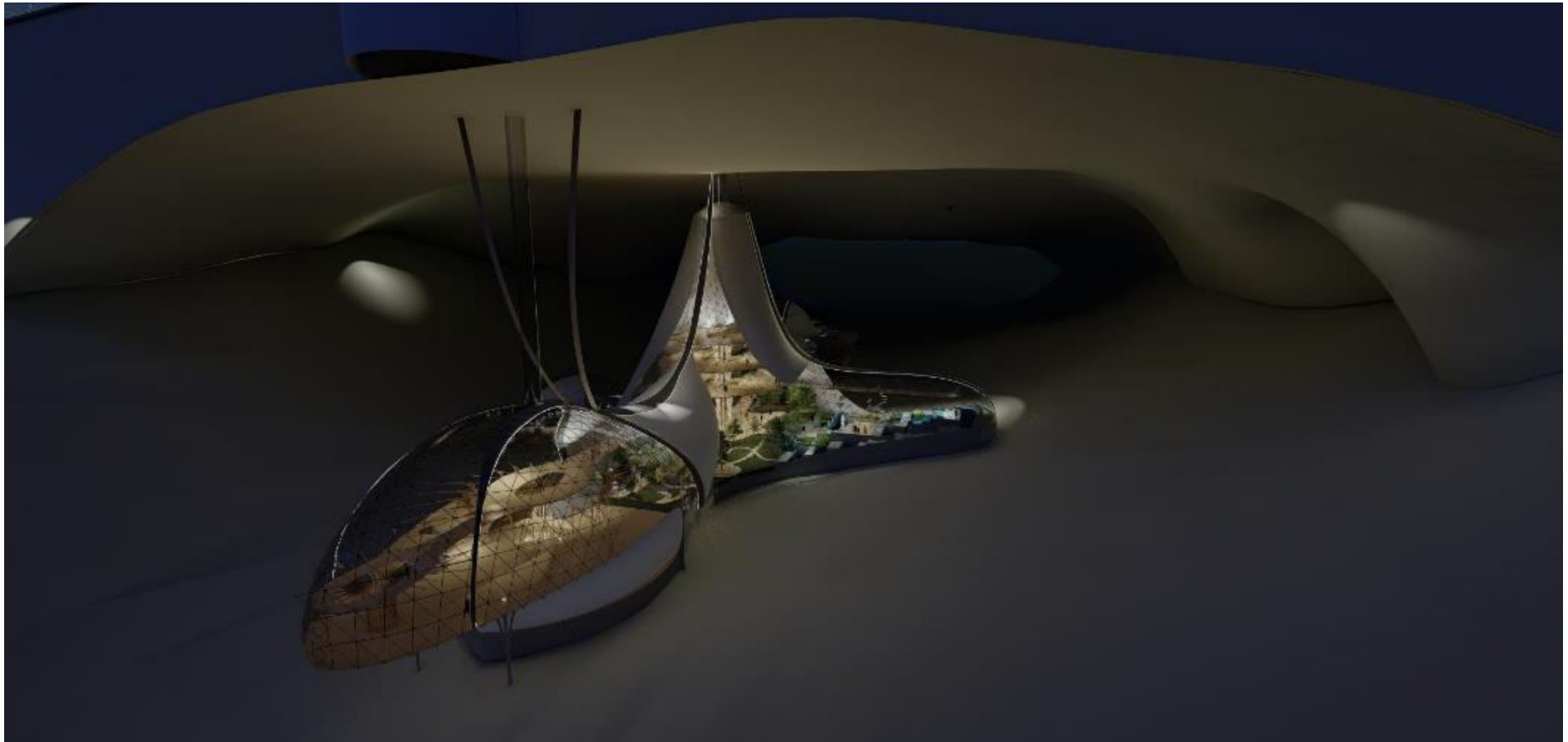
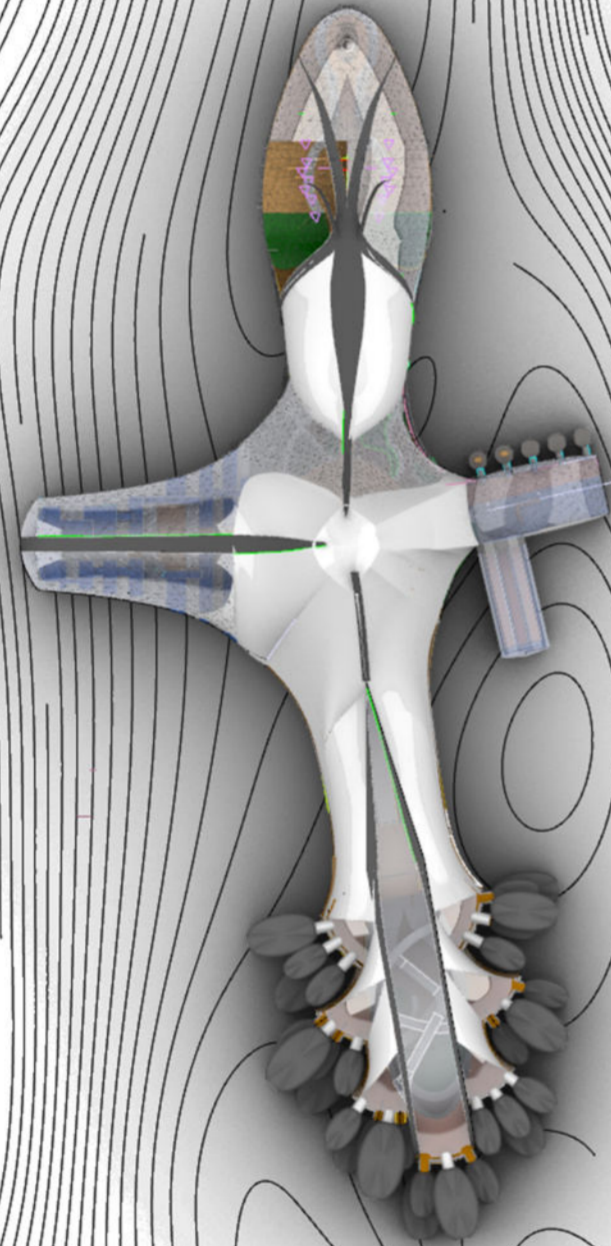
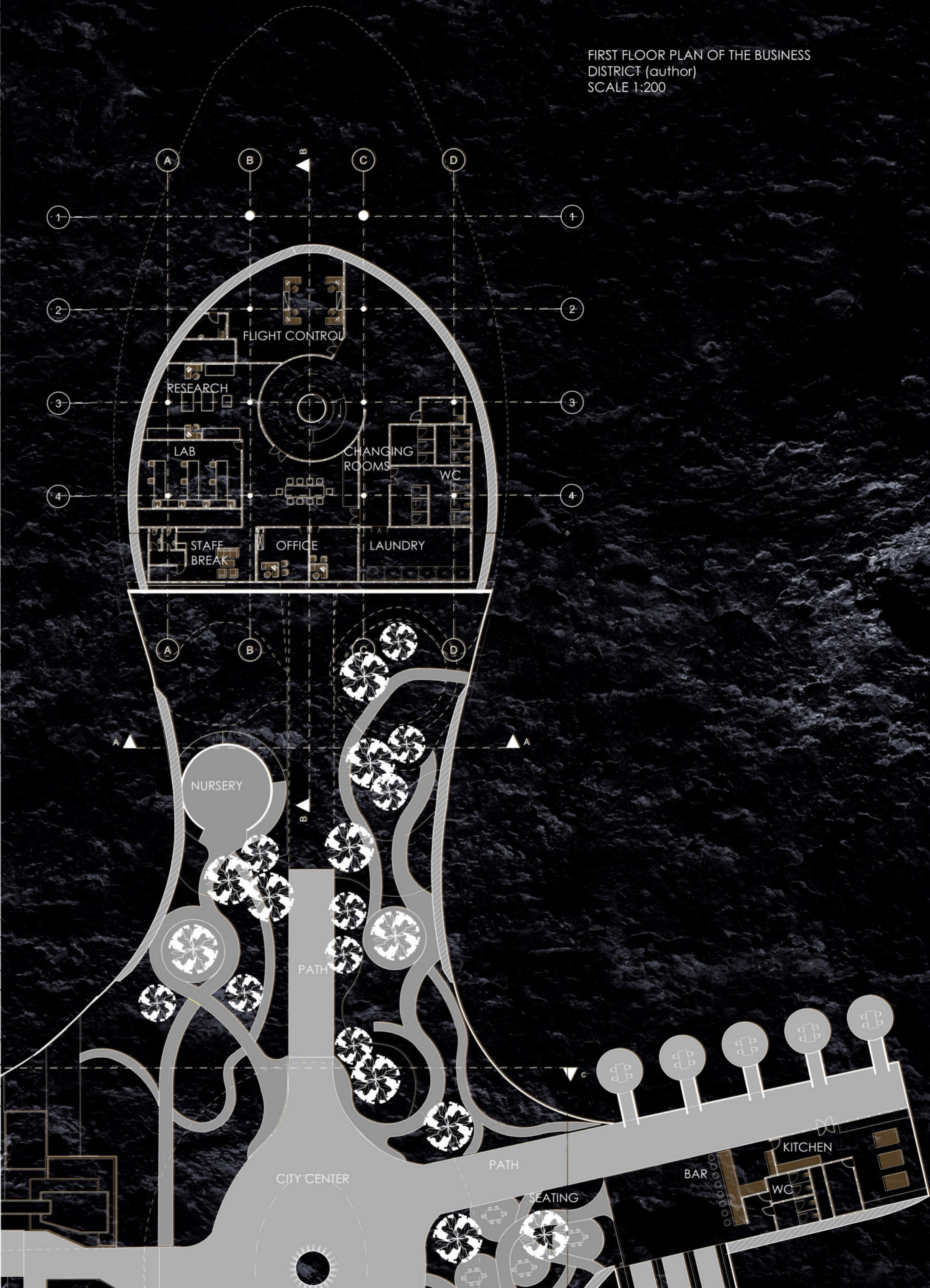


Figure 50: Rendering of building within the lava tube

IN CONTEXT PLAN (author)



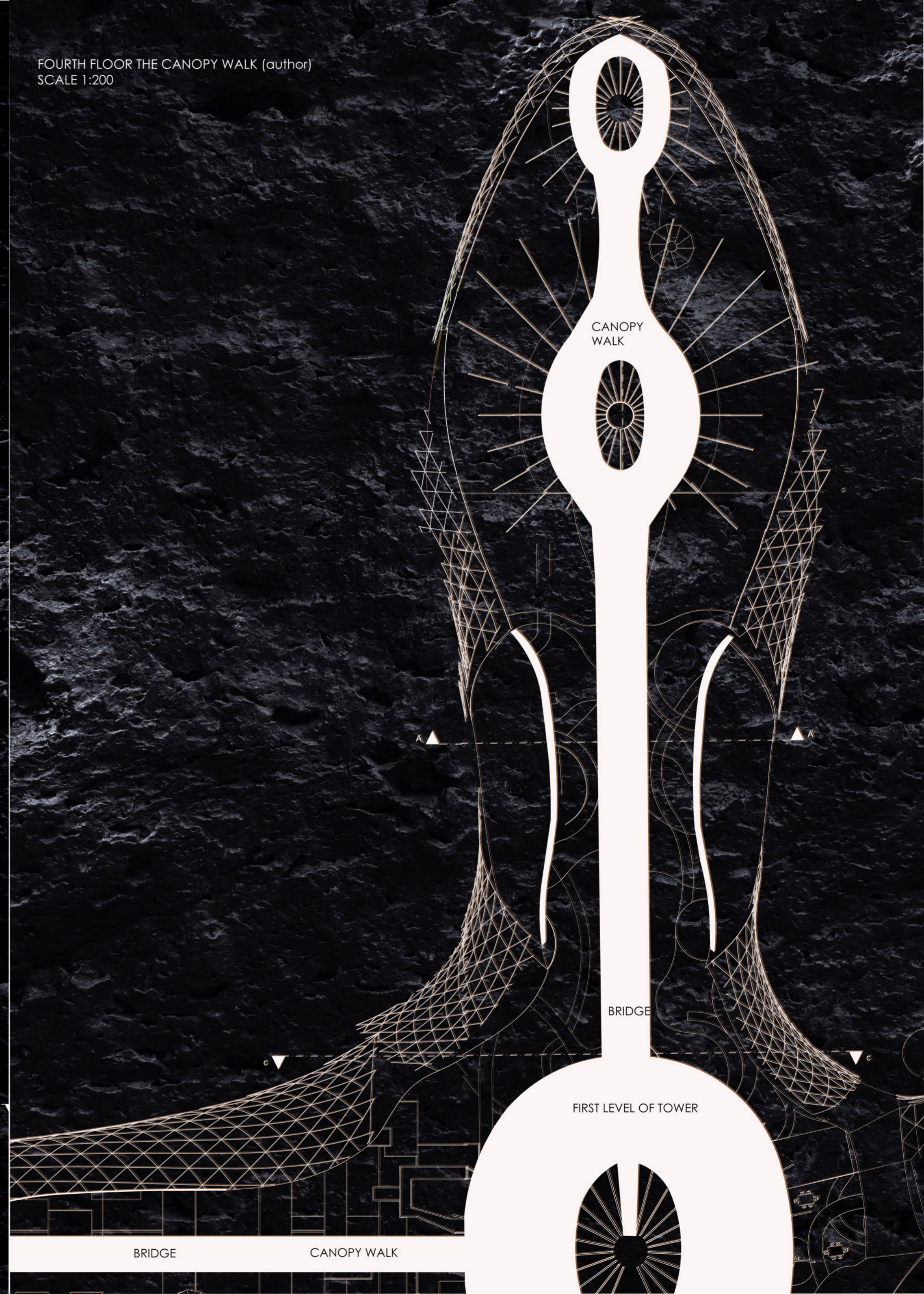
FIRST FLOOR PLAN OF THE BUSINESS DISTRICT (author)
SCALE 1:200

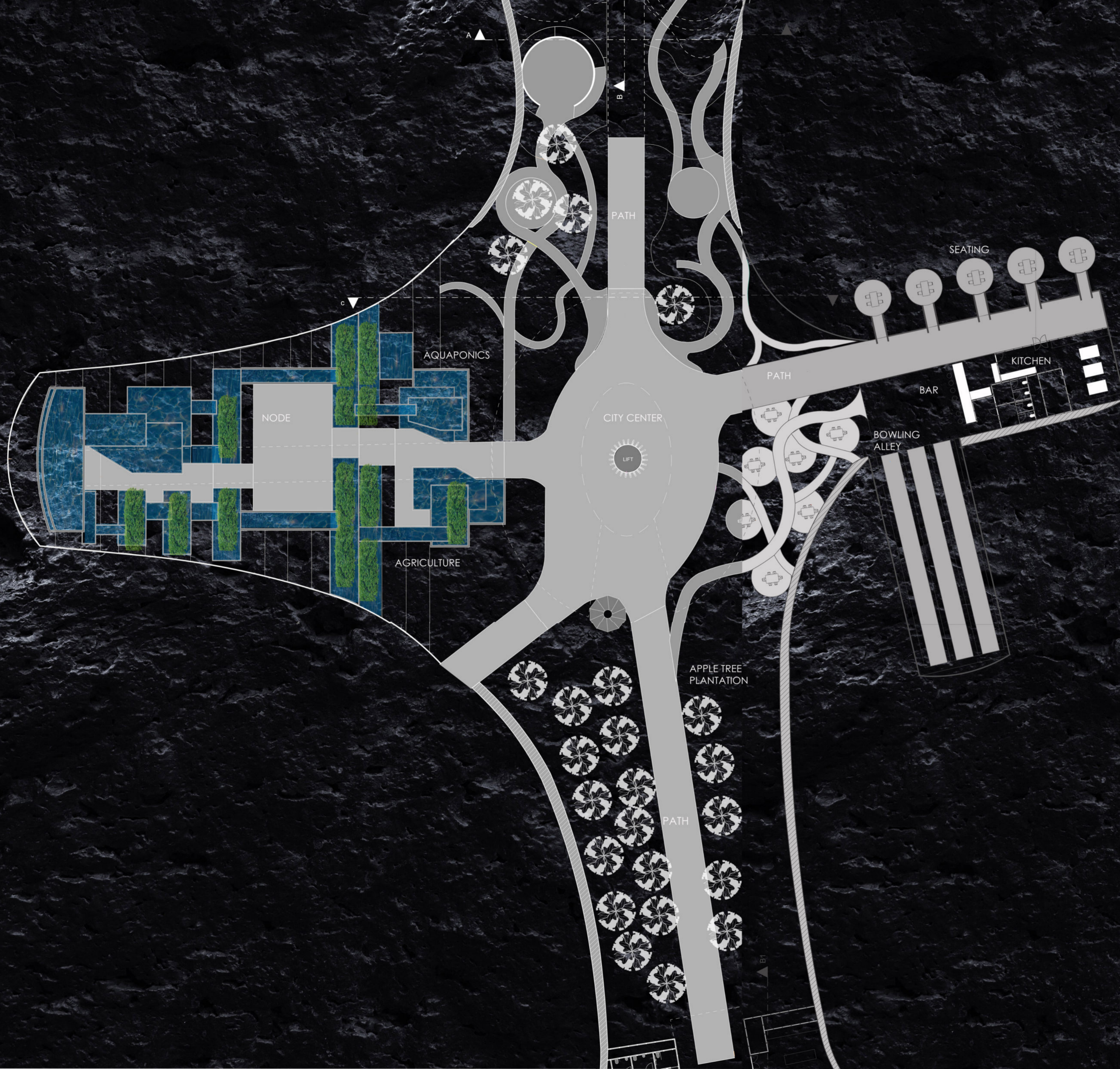


SECOND FLOOR OF THE BUSINESS DISTRICT (author)
SCALE 1:200

THIRD FLOOR OF THE BUSINESS DISTRICT (author)
SCALE 1:200

FOURTH FLOOR THE CANOPY WALK (author)
SCALE 1:200





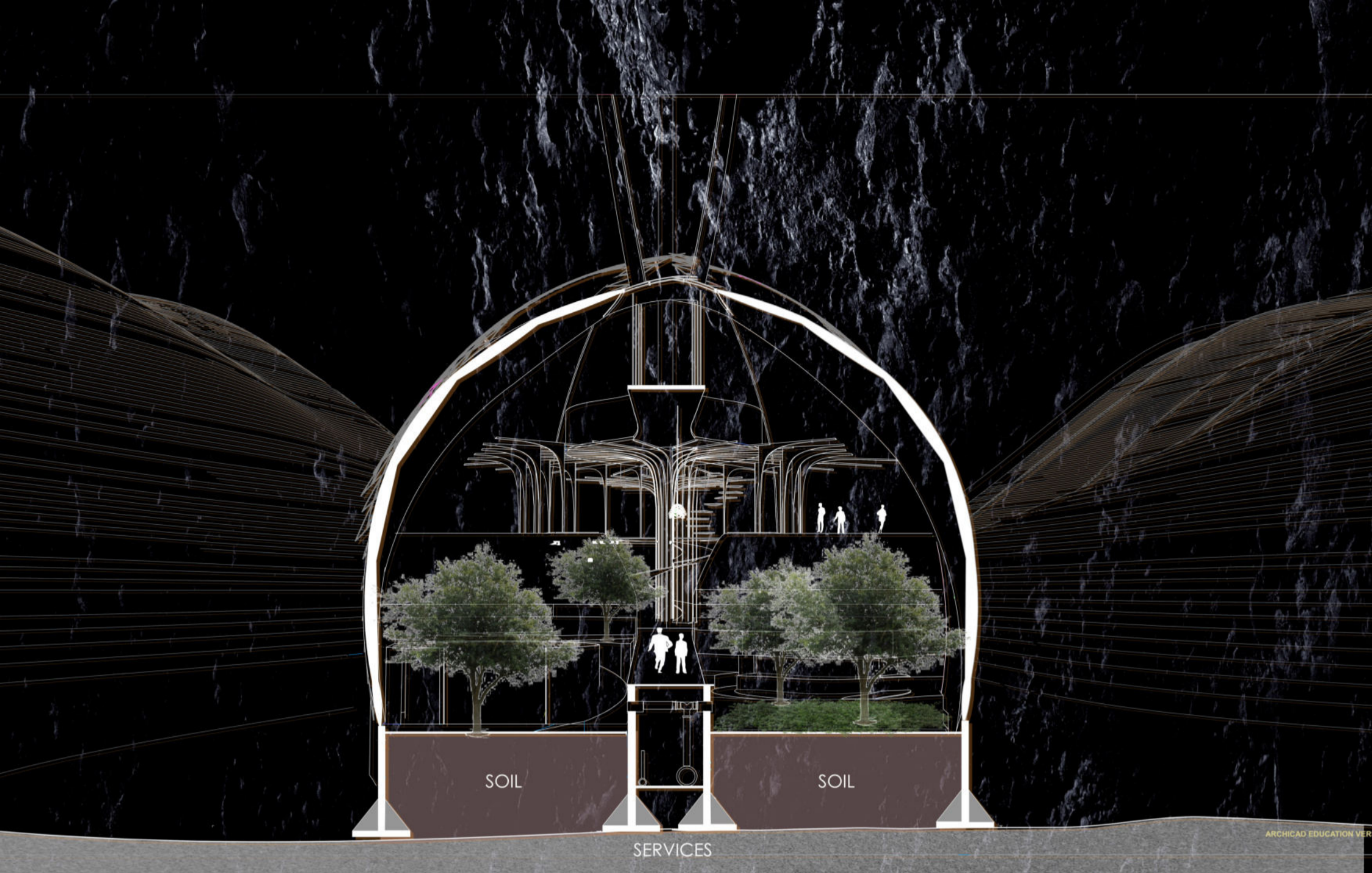
FIRST FLOOR PLAN OF THE AGRICULTURAL REGION
AND RESTAURANT (author)
SCALE 1:200



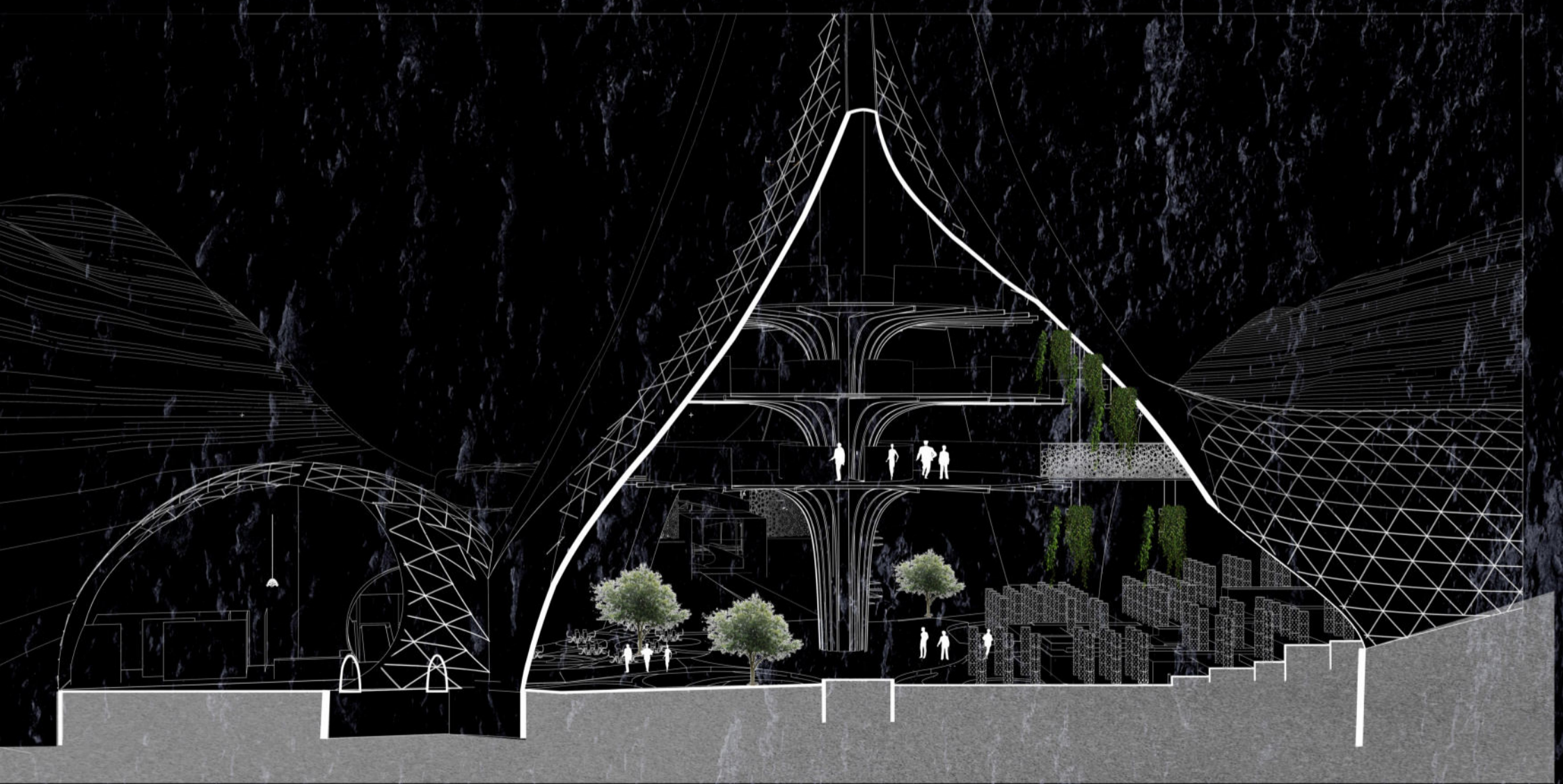
FIRST FLOOR PLAN OF HOTEL (author)
SCALE 1:200



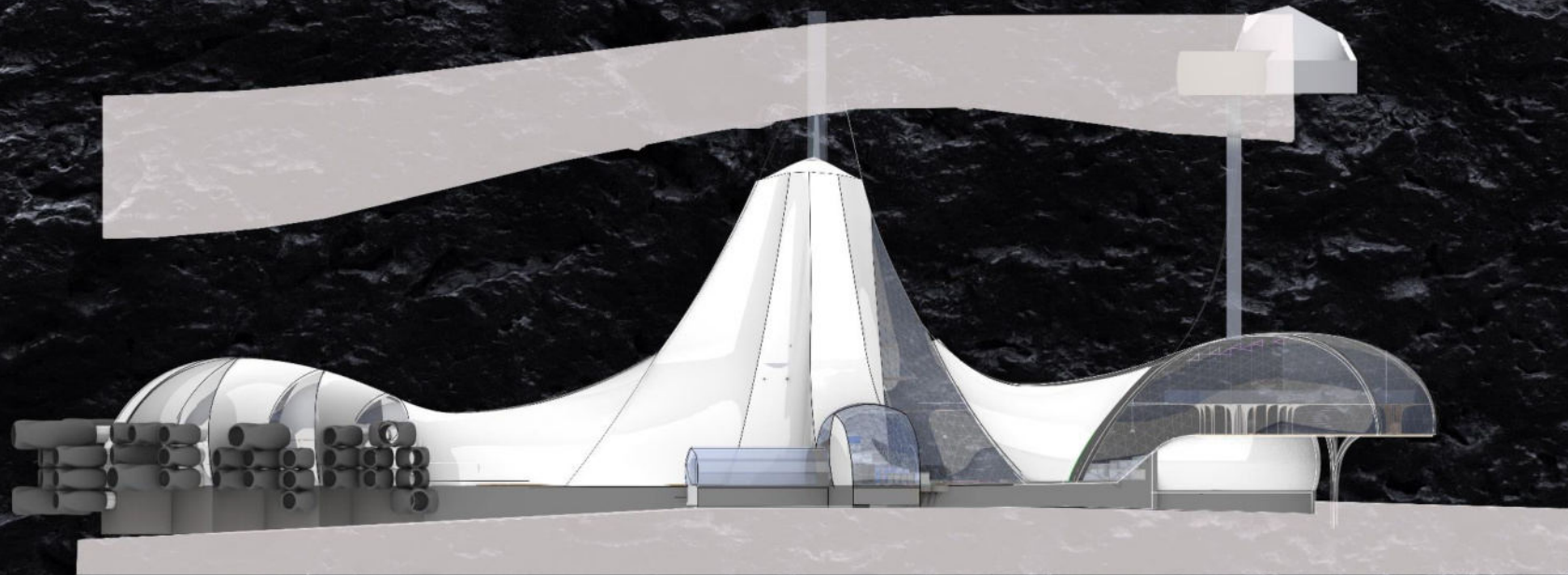
SECOND FLOOR PLAN OF HOTEL (author)
SCALE 1:200



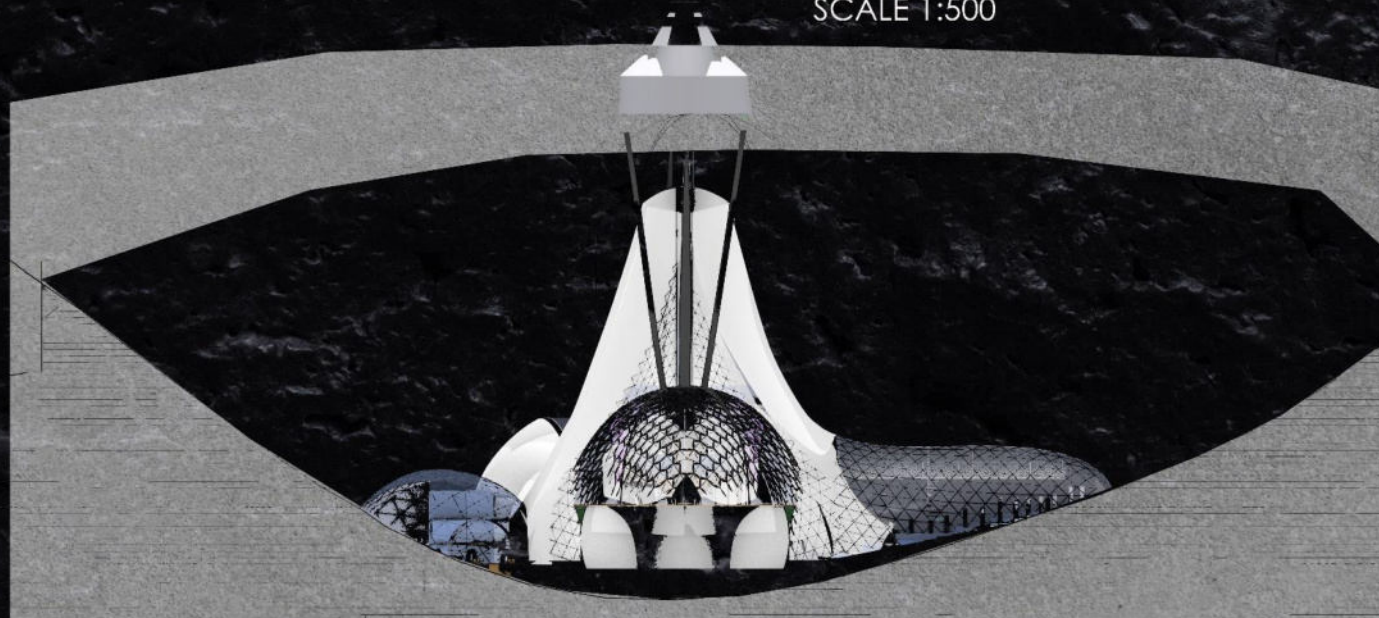
PERSPECTIVE SECTION A-A
SCALE 1:200 (author)



PERSPECTIVE SECTION C-C
(author)



ELEVATION TOWARDS RESTAURANT (author)
SCALE 1:500



ELEVATION TOWARDS ENTRANCE OF LAVA TUBE (author)
SCALE 1:500



Figure 51: Rendering of the building with Starship docked on top of the lava tube (author)



Figure 52: Rendering of the Aquaponics system and growing crops (author)



Figure 53: Rendering of the node in the aquaponics area (author)



Figure 54: Rendering of view from the first level of the tower, overlooking the aquaponics area (author)



Figure 55: Rendering of the view seen from the edges of the business district (author)



Figure 56: Rendering of the City Centre from the restaurant (author)



Figure 57: rendering of City Centre with Free Fall area and catch net (author)



Figure 58: Rendering of bowling alley (author)



Figure 59: Rendering of the view from the third floor level of the hotel (author)

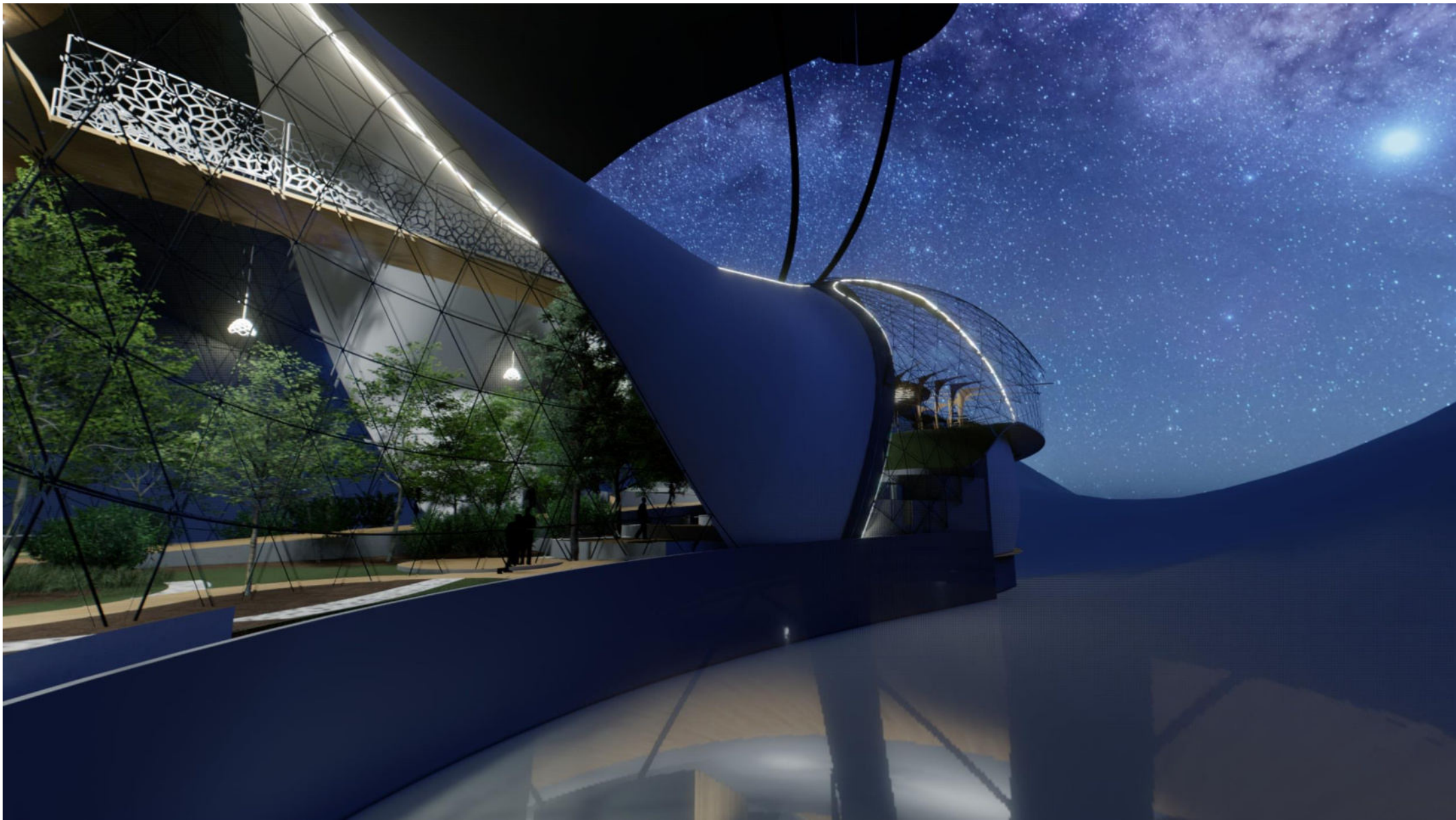


Figure 60: Rendering of the view from the 'bubble' seats of the restaurant (author)



Figure 61; Rendering of the entrance to the hotel (author)

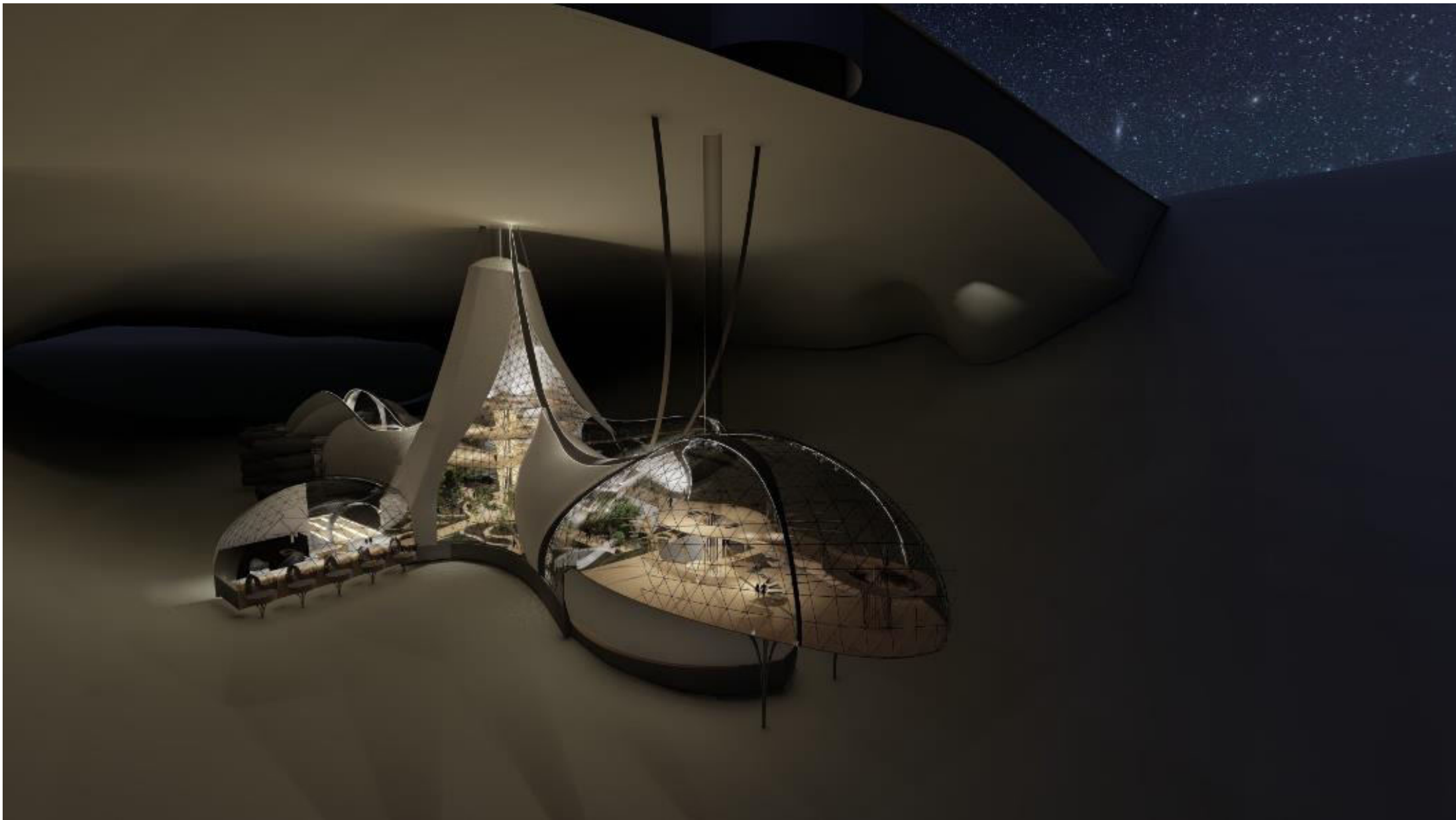


Figure 62: Perspective rendering of the entire building (author)



Figure 63: Rendering of the hotel interior (author)

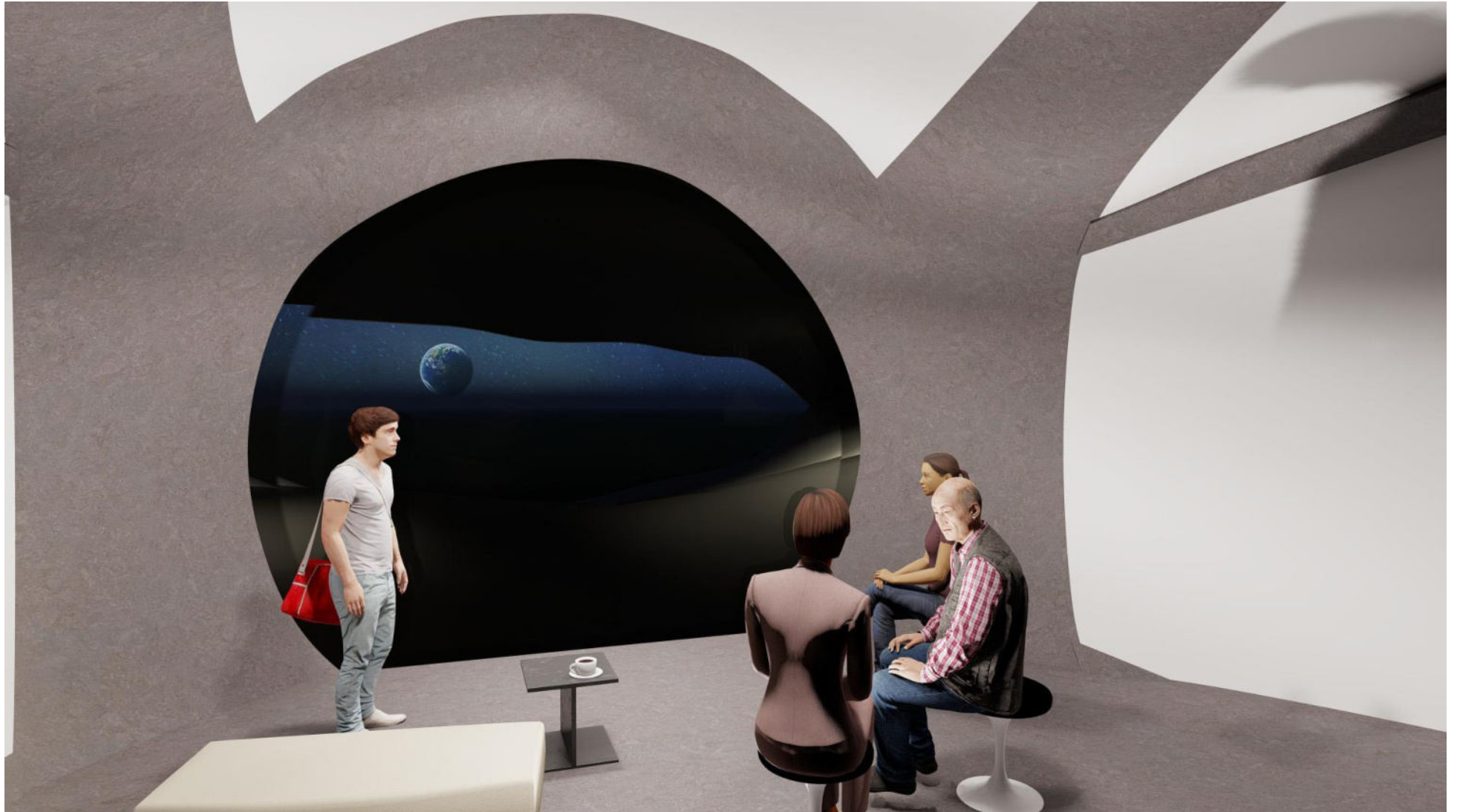


Figure 64: rendering of the view from inside the living pod (author)



Figure 65: Rendering of the path from the business district towards the City Centre (author)



Conclusion

In conclusion, this visionary architectural project, set in the Lunar landscape of the year 2100, embarks on a leap towards Lunar architecture, and architectural innovation. Through thorough planning and a synthesis of various principles, a Lunar Visitors' and Research Centre was proposed. This project not only offers an incomparable experience of the Lunar surface but also demonstrates a possibility for the future of extra-terrestrial architecture.

The concept of architecture as a machine, inspired by Le Corbusier's idea, is particularly relevant in this context. The building is designed as a self-sustaining machine, providing essential services like food, water, oxygen, sewage management, and power. These functions are the heart of the machine that mirrors Earth's functions, whilst providing a unique experience for visitors.

The Lunar city aimed to balance functionality and visitor experience, catering to the needs and desires of both researchers and visitors. This project takes one on a journey to a world where technology sustains life. Moreover, the Moon's reduced gravity offers unique opportunities for exploration and adventure.

Drawing upon Lynch's work in *"The Image of the City"* has provided one with a deep understanding of how users perceive and interact with their environment. By incorporating Lynch's principles, the floor plans were developed to clearly guide visitors through a journey of discovery, allowing them to form a meaningful image of this Lunar city.

The project mirrors the intricacies of a city, with its diverse functions and facets carefully stitched together to ensure the fluidity of the different functions. Despite the absence of permanent residents, the project includes all the essential elements of a self-sustaining community.

In his book, Lynch offers practical guidelines for urban planning and design; this project seeks to create a harmonious, navigable, and relatable Lunar environment.

The successful execution of this Lunar village relies on effective wayfinding principles based on a clear understanding of Lynch's principles: paths, edges, districts, landmarks and nodes.

The integration of biomimicry into the morphology of the building represents a very possible and viable approach to architecture in a Lunar context. This design approach, inspired by nature, has provided invaluable design solutions. In the end, inspired by nature, the design ensured structural integrity. This approach also enabled the visitors to relate to their surroundings; at the same time, it was intended that the design be unique and futuristic in style. The biomimetic principles employed in this project highlight the potential for cohabitation with the Lunar landscape.

Through biomimicry, the design further emphasises the importance of creating an environment that balances the known and the unknown for visitors.

The application of biomimicry in the building's skin, from the inflatable membrane to the exoskeleton and spine structures, reflects the organic and interconnected nature of living organisms. The design not only replicates Earth but also mimics the essence of life itself.

Furthermore, the landscaping principles applied to the interior of the building have transformed the Lunar city into a lush and calming environment for both the staff and the visitors. The landscaping not only contributes to the beauty of the project but is also extremely necessary for survival on the Moon.



References

A&G Engineering. 2022. *The Shape of Pressure Vessel Heads*. [Online]
Available at: <https://www.agengineering.com.au/shape-of-pressure-vessel-heads>

[Accessed 02 10 2023].

Amusement Logic. 2023. *A rainforest at Hamad International Airport, Qatar*. [Online]

Available at: <https://amusementlogic.com/general-news/a-rainforest-at-hamad-international-airport-qatar/>

[Accessed 25 07 2023].

Arbor Day Foundation. 2023. *The Enterprise 50 Million Tree Pledge*. [Online]

Available at: <https://www.arborday.org/enterprise/about/>

[Accessed 12 19 2023].

Archdaily. 2021. *Panda Tower / UDG. Atelier Alpha*. [Online]

Available at: <https://www.archdaily.com/979774/panda-tower-udg-atelier-alpha>

[Accessed 25 07 2023].

Argitech. 2021. *Apple (Malus sylvestris)*. [Online]

Available at: https://agritech.tnau.ac.in/horticulture/horti_fruits_apple

[Accessed 11 09 2023].

Atkinson, N. 2022. *Lava Tubes on the Moon Maintain Comfortable Room Temperatures Inside..* [Online]

Available at: <https://www.universetoday.com/156932/lava-tubes-on-the-moon-maintain-comfortable-room-temperatures-inside>

[Accessed 09 09 2023].

Atmodiwirjo, P. & Yatmo, Y. 2015. Architecture as machine; Towards an architectural system for human well-being. *Le Corbusier, 50 years later*, Volume 697, pp. 1-10.

Benaroya, H., Bernold, L. & Chua, K. M. 2002. Engineering, Design and Construction of Lunar Bases. *JOURNAL OF AEROSPACE ENGINEERING*, Volume 15, pp. 33-45.

Biju, A., n.d. *10 Stunning examples of Biomimicry in Architecture*. [Online]

Available at: <https://www.re-thinkingthefuture.com/rtf-fresh-perspectives/a952-10-stunning-examples-of-biomimicry-in-architecture/>

[Accessed 30 09 2023].

Can, S. 2019. *The City Image and Its Elements by Kevin Lynch*. [Online]

Available at: <https://semanurcan.wordpress.com/2019/10/27/the-city-image-and-its-elements-by-kevin-lynch/>

[Accessed 30 09 2023].

Coombs, C. R. & Hawke, B. R., n.d. *A SEARCH FOR INTACT LAVA TUBES ON THE MOON: POSSIBLE LUNAR BASE HABITATS*. Hawaii, Hawaii Institute of Geophysics.

David, B. M., Chappaz, L., Sood, R. & Milbury, C., 2016. The structural stability of lunar lava tubes. *Icarus*, 16(49), pp. 1-9.

Dinner, J. 2023. *Rolls-Royce gets funding to develop miniature nuclear reactor for moon base*. [Online]
Available at: <https://www.space.com/rolls-royce-funding-microreactor-moon-base>
[Accessed 24 03 2023].

Filomena, G., Versteegen, J. & Manley, E. 2019. A computational approach to 'The Image of the City'. *Cities*, Volume 89, pp. 14-25.

Foust, J. 2021. *NASA selects SpaceX to develop crewed lunar lander*. [Online]
Available at: <https://spacenews.com/nasa-selects-spacex-to-develop-crewed-lunar-lander/>
[Accessed 01 10 2023].

Ghisleni, C. 2020. *What is Biomimetic Architecture?*. [Online]
Available at: <https://www.archdaily.com/954004/what-is-biomimetic-architecture>
[Accessed 30 09 2023].

Gibney, E. 2018. How to build a moon base. *Springer Nature*, Volume 562, pp. 474-478.

GoGreenAquaponics. 2023. *What is Aquaponics and How Does it Work?*. [Online]
Available at: <https://gogreenaquaponics.com/blogs/news/what-is-aquaponics-and-how-does-it-work>
[Accessed 29 09 2023].

Gutierrez, J. 2023. *CAN YOU HAVE A SELF-SUSTAINING HYDROPONIC GARDEN?*. [Online]
Available at: <https://monstergardens.com/blog/post/can-you-have-a-self-sustaining-hydroponic-garden>
[Accessed 11 09 2023].

Lunar and Planetary Institute. 2023. *The Pull of the Planets*. [Online]
Available at: https://www.lpi.usra.edu/education/explore/solar_system/activities/bigKid/planetPull
[Accessed 02 10 2023].

Lynch, K. 1960. *The Image of the City*. 1 ed. Massachusetts: Massachusetts Institute of Technology .

McClain, C. 2018. *You Should Definitely Know about Pufferfish Skeletons*. [Online]
Available at: <https://deepseanews.com/2018/12/you-should-definitely-know-about-pufferfish-skeletons/>
[Accessed 1 10 2023].

Mcsweeney, K. 2019. *Lunar Soil Is a Dangerous Nuisance for Astronauts*. [Online]
Available at: <https://now.northropgrumman.com/lunar-soil-is-a-dangerous-nuisance-for-astronauts>
[Accessed 02 10 2023].

Modlar. 2008. *National Aquatics Centre - Exterior*. [Online]
Available at: <https://www.modlar.com/photos/225/national-aquatics-centre-exterior/>
[Accessed 1 10 2023].

Moreira, S. 2021. *Kevin Lynch's Images of the City Through Aerial Photography*. [Online]
Available at: <https://www.archdaily.com/956821/kevin-lynchs-images-of-the-city-through-aerial-photography>
[Accessed 14 09 2023].

NASA. 2001. *Design for a Lunar Loo*. [Online]
Available at: <https://science.nasa.gov/science-news/science-at->

[nasa/2001/ast03apr_2](#)
[Accessed 16 04 2023].

NASA. 2023. *Moon in Motion*. [Online]
Available at: <https://moon.nasa.gov/moon-in-motion/phases-eclipses-supermoons/moon-phases/>
[Accessed 3 10 2023].

Neilson, S. & Brueck, H. 2020. *NASA just picked a winner in its space-toilet competition. The \$20,000 prize awards the best 'lunar loo' for moon-bound astronauts*. [Online]
Available at: <https://www.businessinsider.com/nasa-picked-winner-in-lunar-loo-space-toilet-challenge-2020>
[Accessed 12 06 2023].

Oxford University Press. 2022. Success. In Oxford English dictionary.
[Accessed 12 10 2020].

ParametricHouse. 2023. *Biomimicry Architecture #3*. [Online]
Available at: <https://parametrichouse.com/biomimicry-architecture-3/>
[Accessed 1 10 2023].

Parnell, A. 2022. *How to Use Color Theory in Landscape Design*. [Online]
Available at: <https://lawnlove.com/blog/how-to-use-color-theory-landscape-design/>
[Accessed 1 10 2023].

Sabin Nature. 2022. *How Many Apples Does A Tree Yield?*. [Online]
Available at: <https://www.sabinocanyon.com/how-many-apples-does-a-tree-yield/>
[Accessed 11 09 2023].

Sauro, F., Pozzobon, R. & Matteo, M. 2020. Lava tubes on Earth, Moon and Mars: A review on their size and morphology. *Earth-Science Reviews*, Volume 209, p. 2023.

Sharp, T. 2022. *Atmosphere of the Moon*. [Online]
Available at: www.space.com/18067-moon-atmosphere.html
[Accessed 2 10 2023].

Simms, D. 2022. *The World's Skinniest Skyscraper Towers Over New York's Central Park—and It's Now Open*. [Online]
Available at: <https://robbreport.com/shelter/home-design/worlds-skinniest-skyscraper-nyc-steinway-tower-complete>
[Accessed 01 10 2023].

Smit, J. 2023. Doha Airport interior.
[Accessed 06 08 2023].

Smith, A. & Smith, K. 2005. Architecture as Inspired Machine. *Built environment*, Volume 31, pp. 79-88.

SpaceX, 2023. *The Moon*. [Online]
Available at: <https://www.spacex.com/human-spaceflight/moon/>
[Accessed 02 10 2023].

Strickland, A., 2020. *Hero shrews have strong, interlocking spines unlike any other animal, study says*. [Online]
Available at: <https://edition.cnn.com/2020/04/28/world/hero-shrew-spine-study-scn/index.html>
[Accessed 1 10 2023].

Thala Beach Nature Reserve, n.d. *Undara Lava Tubes*. [Online]
Available at: <https://www.thalabeach.com.au/undara-lava-tubes/>
[Accessed 3 10 2023].

The AEC Associates. 2016. *Importance Of Texture In Landscape Design: Architectural CAD Drafting*. [Online]
Available at: <https://theaecassociates.medium.com/importance-of-texture-in-landscape-design-architectural-cad-drafting>
[Accessed 1 10 2023].

Theinat, A., Modiriasari, A., Bobet, A. & Molesh, H. J., n.d. Lunar lava tubes: Morphology to structural stability.

University of Florida. 2021. *BASIC PRINCIPLES OF LANDSCAPE DESIGN*.

[Online]

Available at: edis.ifas.ufl.edu/publication/MG086

[Accessed 18 09 2023].

Urrutia, D. E. & Sharp, T. 2023. *What is the temperature on the moon?*.

[Online]

Available at: www.space.com/18175-moon-temperature.html

[Accessed 13 7 2023].

Verbrugghe, N., Rubinacci, . E. & Khan, A. Z. 2023. Biomimicry in Architecture: A Review of Definitions, Case. *Biomimetics*, 8(107), pp. 1-29.

Virmani, S. 2014. *Biomimicry as a tool for sustainable architectural design*, s.l.: s.n.,

Vyas, H. 2011. *Image of the City – Kevin Lynch*. [Online]

Available at: <https://archardik.wordpress.com/category/book-review/>

[Accessed 30 09 2023].

Weir, K. 2020. Psychological research is advancing our understanding of how time in nature can improve our mental health and sharpen our cognition..

Nurtured by Nature, Volume 51, p. 50.

Wood, K. 2022. *The Largest Single Celled Organism in the World*. [Online]

Available at: <https://a-z-animals.com/blog/the-largest-single-celled-organism-in-the-world/>

[Accessed 30 09 2023].

Yacadamy. 2023. *Architecture for outer space*. [Online]

Available at: <https://www.yacademy.it/educational-offer/architecture-for-outer-space>

[Accessed 24 07 2023].

A visitor City, on the Moon

Technical report





Table of Contents

Table of Contents	i	3.4 The living pods	14
Introduction.....	1	17
Chapter 1: The Lunar Environment	2	Chapter 4: Technical drawings	17
1.1 Air pressure - the vacuum of space	2	Conclusion	34
1.2 Temperature and radiation	3		
1.3 Lunar soil particles and Lunar lava tube rock	3		
Chapter 2: Construction	4		
2.1 3D Printing of Lunar Concrete	4		
2.2 Lunar bricks made of regolith.....	5		
2.3 Foundations and services	5		
Chapter 3: Material and Transport.....	6		
3.1 Inflatable membranes:	6		
Precedent studies:	7		
3.1.1 Application.....	9		
3.2 Carbon fibre exoskeleton	9		
Precedent studies	10		
3.2.1 Application.....	14		
3.3 The spine	14		



Introduction

In this technical report, one of the many possibilities for Lunar construction is presented, as well as a scientific background of the Moon's environment that influenced the construction.

The biggest challenges concerning the Lunar environment is identified and discussed in detail. The challenges identified in this report include the lack of atmosphere, the extreme temperatures and radiation exposure on the Lunar surface and Lunar sand particles.

Relevant construction methods were researched and explained. These include the 3D printing of concrete and the making of Lunar bricks.

Thereafter, possible solutions to each challenge concerning the Lunar environment is proposed. Furthermore, analysis of the different materials and their uses in the project are provided.

An important focus was given to air pressure replication, temperature regulation, and material choices. These factors are crucial for ensuring human survival, structural integrity, and the adaptability of the building to the Lunar environment.

Chapter 1: The Lunar Environment

1.1 Air pressure - the vacuum of space

The Moon has no atmosphere; instead, it has an exosphere. There is no air to breathe and no wind. The exosphere is made of a very thin layer of gas. The particles in the exosphere are so few that they rarely collide with each other. It is comparable to being in a vacuum. To compare, the Earth's atmosphere at sea level contains about 100 billion billion molecules per cubic centimetre, whereas on the Moon, the exosphere only contains 100 molecules per cubic centimetre (Sharp, 2022: online).

As mentioned in Chapter 2 of the Design Section, the air pressure in the building has to replicate the air pressure on Earth. If the human body is exposed to a vacuum, the air inside the lungs, along with water vapour, would continue to be sucked out of the body, resulting in suffocation (Kwan, 2021: online). Therefore, the correct air pressure is essential for survival.

However, to contain air inside a vacuum results in additional pressure that is exerted on the container of the air. This is not comparable to containing air inside the Earth's atmosphere, such as with a balloon. As the pressure of the atmosphere decreases, the pressure difference between the outside and inside of the container increases, increasing the force that is exerted on the inside of the container. In a vacuum, a balloon will keep expanding until it bursts. This is illustrated in Figure 1.

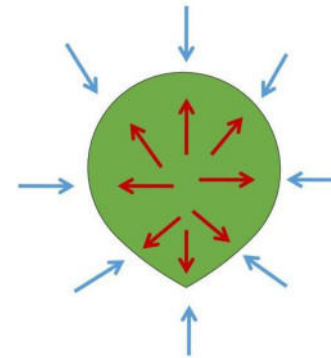


Figure 1: Figure illustrating the forces inside a balloon. The pressure of the atmosphere is represented by blue arrows (author)

The air pressure at sea level is roughly 101 kPa (kilopascals). 1 Pa = 1 newton per square metre ($1 \text{ kg}\cdot\text{m}/\text{s}^2$).

1 kPa = 1000 Pa (Stull, 2019: online). If we replicate the pressure at sea level, which is also the air pressure that is replicated inside the International Space Station (Thirsk et al., 2009: 1217), this amounts to the pressure inside the building to 100 000 Newtons = $10\,000 \text{ kg m}/\text{s}^2$. With this in mind, careful consideration was given to the choice of material and its functionality (discussed in Chapter 3.1).

1.2 Temperature and radiation

The temperatures on the Lunar equator reach anything from -130 °C to 120 °C. At the poles of the Moon, the temperatures are even more extreme and can reach -253 °C in dark craters (Urrutia & Sharp, 2023: online.)

While the surface of the Moon reaches these extreme temperatures, scientists estimate that temperatures inside Lunar lava tubes should stay at a steady and comfortable room temperature of roughly 17 °C (Atkinson, 2022: online). The more moderate temperatures inside the lava tube make the thermal expansion of materials much less of a concern.

For the most part, the lava tube will protect the building from radiation emitted by the sun. Special precautions were taken for the telescope that is situated on the top of the lava tube roof. A protective cover of anodised aluminium was provided for the exposed areas of the structure. Anodised aluminium has the benefit of being a little reflective whilst having a very low absorptivity value of 0.14 (of which 1 is the highest value and 0 is the lowest) (The Engineering Toolbox, 2011: online).

Temperatures inside the building will be regulated using the air ventilation units and electricity. However, because the Moon has no atmosphere or wind, the heat inside the building will remain constant. Heat is transferred in three ways: conduction, convection and radiation (University of Wisconsin, 2023: online). Conduction and convection both depend on molecules and air or water for heat transfer. Since a vacuum is the absence of molecules, very little to no heat will be lost inside the building. Consequently, such a building will most likely not require insulation. Radiation is the transfer of heat through electromagnetic waves, which is emitted from the sun and is thus not applicable, as the building will not be exposed to direct sunlight.

1.3 Lunar soil particles and Lunar lava tube rock

The sand particles of the Moon are not like the sand found on Earth. Because there is no natural corrosion, the particles have very sharp edges and the extreme heat of impact craters has turned these sharp sand particles into

glass. This is dangerous for any human to breathe and also damages building materials and equipment (The European Space Agency, 2018: online).

For this reason, the building's foundation, walls and columns will be concrete and will be used to elevate the rest of the structure above the surface level of the lava tube floor. There can not be any Lunar soil within the building, except in controlled environments like farms. Trees and plants throughout the building will be planted in soil brought from the Earth. There will be a protective waterproof and airproof membrane placed between the soil and the lava tube floor surface. Refer to Section A-A. prevent the Lunar soil particles from mixing with the fertile soil and to prevent the fertile soil from washing away. This can be seen in Detail Section A.

Chapter 2: Construction

2.1 3D Printing of Lunar Concrete

With the growing interest in building on the Moon, a team of Chinese engineers looked into the possibility of 3D printing concrete on the Moon. The team developed a very specialised system that is ideally suited to transport to the Moon and build as quickly and effectively as possible. They replaced the typical robot arm 3D printer with a cable-driven robot. The system is easy to transport, set up and easy to use. The cable-driven robot allows for more flexibility than the robot arm and it can achieve greater heights. The cable-driven system is also more lightweight and achieves a large printing area. (Zhang et al., 2021: 672).

Figure 1 illustrates the concept by which the cable-driven robot printer works. The frame is made of composed telescopic rods that are easy to transport and the system can be compressed to an even smaller size. When the system has been taken to the site, the frame is placed first and the telescopic rods are extended. Then the cables are tensioned between the frame. The printer does not rely on gravity and also effectively avoids collision with the cables and printed objects (Zhang et al., 2021: 672, 677).

Concrete on the Moon can be made with sulfur, instead of water, as sulfur is abundantly accessible on the Moon (Benaroya et al., 2002: 37).

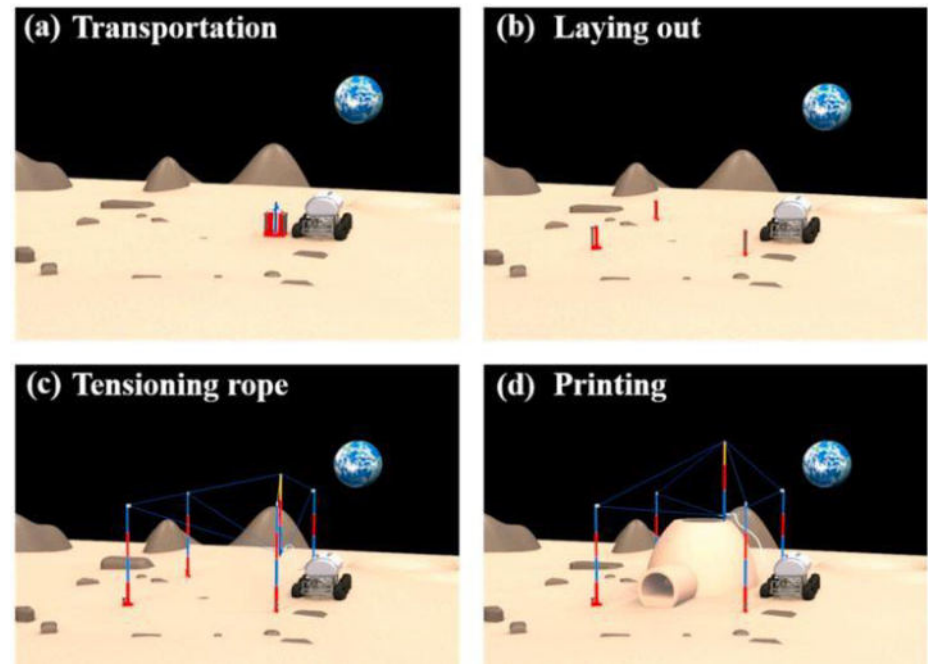


Figure 2: 3D printer for the Moon set-up (Zhang et al., 2021: 672).

2.2 Lunar bricks made of regolith

Another possibility of building on the Moon would be to use the Lunar soil. A team of scientists have recently been able to use a beam of intense light to convert Lunar soil into a small hardened brick. This method can be intensified and multiplied on the Moon to turn the Lunar sand into bricks on a large scale and can be used as building materials. The team of scientists suggested using the sun and mirrors, but solar power can also be used to turn the Lunar soil into a hardened brick. The scientists say that the layers of Lunar sand in the bricks do not bond together perfectly but they are robust enough to withstand moonquakes and bear greater weight. It is about one-fifth the strength of concrete (Gibney 2018: 478).

Lunar lava tube roofs are of hard basalt rock (Ding et al., 2022: 1). Basalt is a type of igneous rock that is formed by the rapid cooling of basaltic lava. Basalt rock usually lacks porosity and permeability (Selley, 2005: online). This means that the rock itself can be used as an airproof shield. The planetarium which is submerged into the rock does not require an additional structure other than a shield roof, as the rock will be sufficient to keep the necessary air pressure inside. This was used in the design of the planetarium.

2.3 Foundations and services

Based on how lava tubes are formed, as explained in Chapter One of the Design Section, it is assumed that one would expect bedrock at the bottom with a layer of sand on top. For this project, it is assumed that the site is mainly rock with a small layer of sand on top but the precise conditions of the site are unknown.

The foundation of the building is therefore designed to be anchored to the rock. The foundation and building are designed in such a way that minimum excavations are needed. The foundation pillars and load-bearing walls of the building will be 3D-printed concrete with a concrete footing that will be anchored securely with bolts into the rock, as shown in Figure 7: Detail Section A.

The services of the building is an extremely important part of the design. The services of the building includes the following:

Electrical systems:

- Artificial air ventilation, temperature control and filter systems,
- Air pressure sensors and regulation,
- Measuring of oxygen and carbon dioxide content in the air and the adjustments thereof,
- Electrical supply from solar plant and reactor.

HVAC

- Heating, ventilation, air conditioning (HVAC).

Plumbing

- Water storage, pumps and filtration system,
- Drainage,
- Sewer system.

These services are located on the ground floor. The entire floor will contain the necessary piping, storage, wires and electrical equipment. Along with the essential services, the ground floor will also contain fertile soil for landscaping. This is demonstrated in the detail drawing: Section A-A .

Chapter 3: Material and Transport

3.1 Inflatable membranes:

Inflatable structures have recently seen an increase in demand. Inflatable structures have some great advantages over the conventional building methods. Some of these benefits are faster and easier assembly, pre-fabricated, and not nearly as labour-intensive as conventional building methods. Inflatable membranes are strong and extremely lightweight compared to more conventional building materials.

Since transportation, assembly and strength-to-weight ratio are crucial for construction on the Moon, an inflatable membrane resolves numerous challenges of Lunar construction.

The required air pressure on the inside will not only sustain human life but will also be used to inflate the membrane and keep it in place. The semi-flexible membrane allows for the pressure force (Chapter One) to be distributed evenly across the curved surface as the material inflates. This allows for a strong and rigid structure that can contain the breathable air inside like a balloon. The inflatable membrane can be folded up and will easily fit into a space shuttle.

There are various materials and methods used for inflatable membranes. For this project, the most popular and most durable materials will be used, which are vinyl or nylon with a protective coating of polyvinyl chloride (PVC) (Miller Weldmaster, 2015: online).

Currently, many inflatable structures are made up of modular inflated arches that are knit together with ties. However, it is possible to customise inflatable structures to take any desired form (fig..) (Holstroy, 2023: online).



Figure 3: Inflatable project by Holstroy, Ukraine (Holstroy, 2023: online).



Figure 4: Holstroy project interior, Ukraine (Holstroy, 2023: online).

Precedent studies:

The Eden project:



Figure 5: Image of the Eden Project's geodesic dome (EdenProject, 2023: online).

What is so interesting about The Eden project is its bubble-like geodesic design. Although the final appearance closely resembles half of a sphere, the entire construction relies on flat surfaces with straight edges. It combines an outer shell primarily composed of hexagonal components, with some pentagons mixed in, with an internal framework of triangles. The robust design does not require any internal supports, even in the 240-metre expanse of the largest biome. Furthermore, the grid-like network of steel tubes can be conveniently transported to the site in small sections, reducing construction costs. The structure evenly distributes loads to the ground at its base, eliminating the need for substantial foundations that might otherwise be necessary for supporting such a vast enclosure (Bissegger, 2006: online).

For glazing, the project employs cushions made of ethyl tetrafluoroethylene (ETFE) transparent foil. This material is exceptionally lightweight, weighing

approximately only 1% of what glass would weigh. Additionally, its strength and self-cleaning properties make it an ideal choice for this undertaking (Bissegger, 2006: online).

ETFE air-cushions Bellewaerde Aquapark

Buitink Technology has successfully finished the construction of the ETFE air cushion roofing system for the recently established "Bellewaerde Aquapark," located in Ieper, Belgium.

The complete project involves the installation of two separate air cushion roofs, one consisting of four air cushions and the other featuring five air cushions. In total, the combined surface area of these nine air cushions amounts to 485 square metres. Each cushion is composed of four layers of ETFE foil, equating to three distinct air chambers. Notably, these cushions are entirely transparent, allowing visible light to pass through (Buitink Technology, 2019: online).



Figure 6: Image of air cushion roof system (Buitink Technology, 2019: online).

Ark Nova by Arata Isozaki and Anish Kapoor

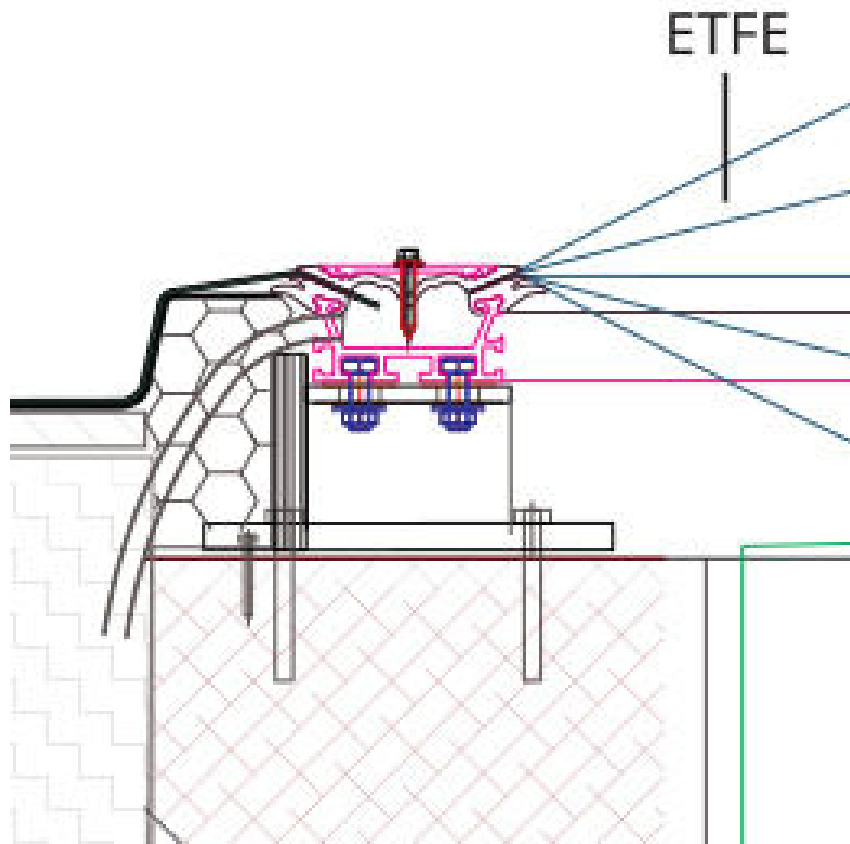


Figure 7: Drawing of connection detail and air supply (Buitink Technology, 2019: online).



Figure 8: Image of inflated Ark Nova (Frearson, 2013: online).



Figure 9: Image of the Interior of Ark Nova (Frearson, 2013: online).

Japanese architect Arata Isozaki collaborated with Anish Kapoor, originally from India, to conceive a spherical edifice inspired by the inflatable Leviathan sculptures previously crafted by the artist for an exhibition in Paris. This 500-seat performance facility is purpose-built to host various performances. The structure's walls are constructed from a flexible plastic membrane, carefully engineered to facilitate swift assembly and disassembly. When relocating the structure to a different venue, the orb is deflated entirely and then loaded onto a truck, along with the disassembled equipment (Frearson, 2013: online).

Ark Nova capitalises on this expertise but distinguishes itself as a portable structure capable of withstanding diverse weather conditions. Achieving the artistic calibre synonymous with Anish Kapoor required groundbreaking engineering ingenuity. The outcome is a striking toroidal form, fundamentally reimagining the application of inflatable tensile constructions.

The exterior shell comprises a PVC-coated polyester membrane, covering an area of approximately 2 000 square metres. It measures 0.63 mm in thickness and weighs 1 700 kg. When fully inflated, the hall boasts a volume exceeding

9 000 cubic metres, with maximum dimensions of 29 metres in width, 36 metres in length, and 18 metres in height.

The toroidal configuration of the edifice loops inward, forming a diagonal tube within the interior. This unique design offers an outward view of the sky from the building's exterior. The tensile fabric, featuring a distinctive colour scheme was custom-developed to meet the artist's specifications. As a result, the finished structure appears opaque purple when viewed from the outside and translucent red from within, delivering an unexpected and captivating visual experience for concert attendees (Aerotrope, 2013: online).

3.1.1 Application

With the aforementioned information and precedent studies in mind, the skin of the building was designed. The shape was established (discussed in the Design Section) and the desired transparent areas were chosen. It is important to note that some design adjustments to the inflatable membranes are needed to adapt to the different circumstances. The first major difference is that the air pressure will not only be provided between the layers of the membrane but more so from under the membrane. In addition, extra reinforcements in the form of carbon fibre were provided for the thinner, less durable transparent parts of the membrane.

The details of the membrane are based on the details of BuitInk Technology. The connection between the inflatable membrane and the rigid concrete foundation walls requires expert knowledge. Such a design will be produced by specialists in the field to ensure that the connection is strong and that no air can escape through that connection. This connection can be seen in Figure 8: Detail drawing of the connection between the inflatable membrane and the spine.

3.2 Carbon fibre exoskeleton

When it comes to choosing the right materials to build on the Moon, a few things need to be considered. Whatever material is used, it needs to be strong and lightweight. It has to be transported easily and assembled easily. It also

needs to be strong in tension. A lightweight material that can be prefabricated would be ideal in this scenario.

For a long time, carbon fibre has been used in the engineering and aeronautics industry because it is extremely strong in tension and also very lightweight. However, due to an expensive manufacturing process, it has rarely been used in architecture. Carbon fibre is a polymer that is also called graphite fibre. In tension, it is five times stronger than steel and twice as stiff, while being more lightweight, which makes it the ideal material to use on the Moon. Carbon fibre is used and manufactured in strands thinner than human hair. To give the material compressive strength it is used with epoxy resin or other setting plastics. On top of having a very low strength-to-weight ratio, it also has very low thermal expansion (Innovative Composite Engineering, 2023: online).

Precedent studies

BUGA Fibre Pavilion- University of Stuttgart



Figure 10: BUGA Fibre pavilion (Archdaily, 2019, online). Photo by Roland Halbe.

“The pavilion demonstrates how combining cutting-edge computational technologies with constructional principles found in nature enables the development of truly novel and genuinely digital building systems. The pavilion’s load-bearing structure is robotically produced from advanced fibre composites only” (Archdaily, 2019: online).

This unique pavilion illustrates the potential use of carbon fibre composites in architecture. The designers used carbon fibre dipped in resin in conjunction with glass fibre strands. The design, according to the architects, adopts biological load-bearing principles. Using carbon fibre and glass fibre in this unique way resulted in a very strong and very lightweight structure. The structure in total is five times lighter than a conventional steel structure. It is only 7.6 kilograms per square metre and spans more than 23 metres (Archdaily, 2019: online).

The entire pavilion is prefabricated using a robot arm with a computational design. The pavilion was then assembled using modular pieces.



Figure 11: Robot manufacturing the pavilion (Archdaily, 2019, online).

Carbon Fibre Canopy-Architectural Engineering Studio

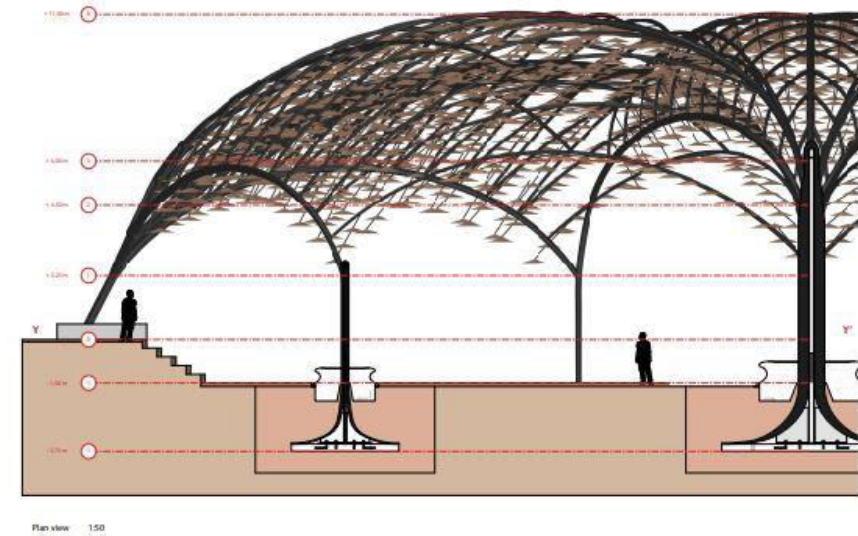


Figure 12: Carbon fibre canopy design (Volmer, n.d: online).

This canopy design illustrates another interesting way to use carbon fibre. The carbon fibre cloth is turned into tubes that are used as beams and poles. The architectural engineering studio proposed a mechanical device that would turn the carbon fibre into a circular profile using heat. Once the circular tubes are formed, the tubes are then glued to a base structure. The benefits of such a very lightweight structure enable a very small and shallow foundation. For this canopy, the designers proposed a poured concrete cone as the foundation illustrated in the figure below (Volmer, n.d: online).

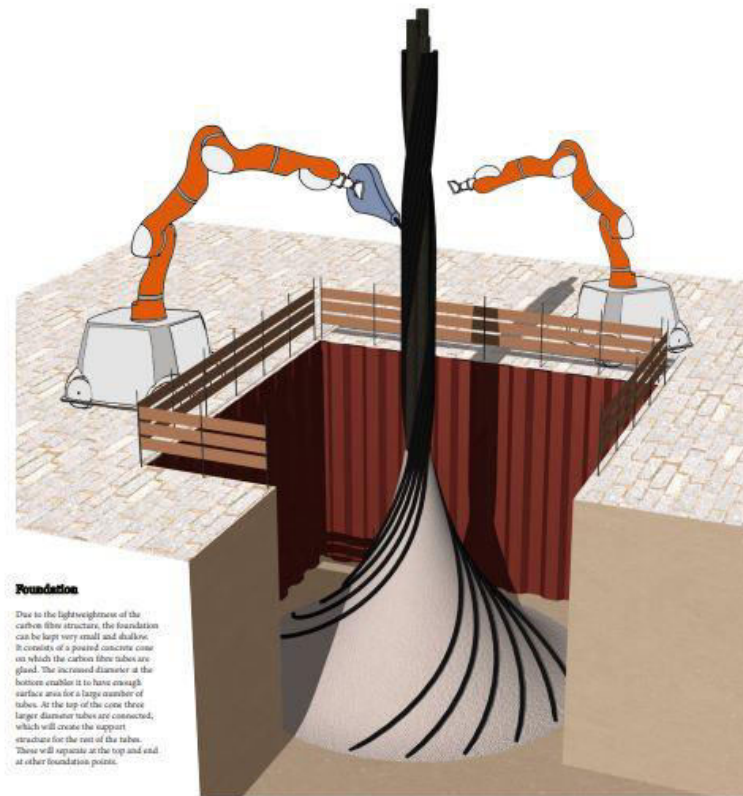


Figure 13: Concrete cone foundation and glued tubes (Volmer, n.d: online).

The canopy is built using a robot arm that pre-fabricates new tubes as the process continues. This allows for a continuous, easy workflow and no secondary connections are needed between the tubes (Volmer, n.d: online).

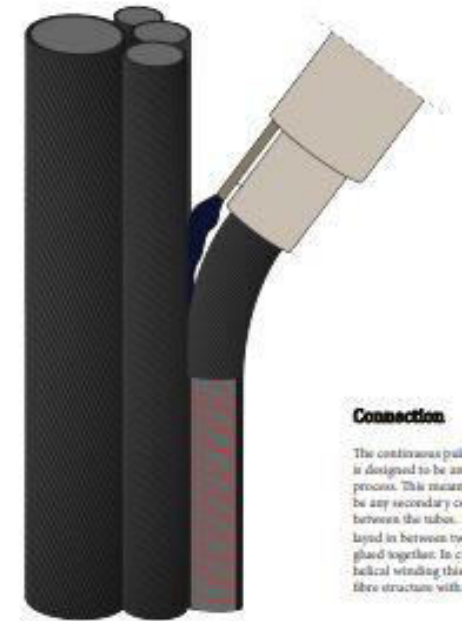


Figure 14: Tubes produced by robot and glued together (Volmer, n.d: online).

Full-scale prototype pavilion



Figure 15: Prototype pavilion (Reichert et al., 2014: 28).

The designers of this pavilion got their inspiration from bio-mimicking aspects. By studying the exoskeletons of arthropods, they produced the above design (Reichert et al., 2014: 27).

What is important in this precedent study is the designer's means of manufacturing. They first designed the base and the frame, which the robot will use to fabricate the carbon fibre sections. The entire pavilion is made of several layers that are placed on top of each other.

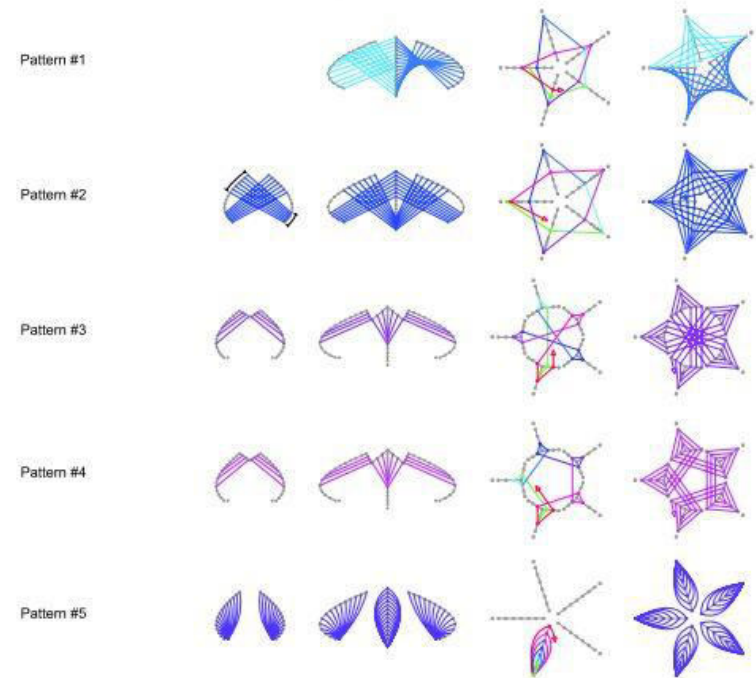


Figure 16: The different layers of the manufacturing process (Reichert et al., 2014: 36).



Figure 17: Robot arm using the frame to fabricate the pavilion (Reichert et al., 2014: 28).

A very similar method of manufacture on the Moon will be used. All that is needed to transport to the Moon is the robot, the frame and the carbon fibre in rolls. Once the robot arm is set up and the frame is in place the manufacturing process can begin. The robot will manufacture modular pieces that will be assembled to form one structure.

3.2.1 Application

As previously mentioned, there are additional forces that need to be compensated for when using an inflatable membrane on the Moon. This was done in the form of a carbon fibre and glass fibre exoskeleton. The exoskeleton is made up of smaller modular units that will be fabricated on the Moon with robotics. Thus, only the robot arm and material will have to be transported. The modular units form a geodesic dome over the PVC membrane on the outside. The pressure applied from the inside will place the carbon fibre in tension and the carbon fibre will keep the PVC membrane from deforming.

3.3 The spine

As mentioned in the Design Section, the spine was inspired by the spine of a Hero Shrew. Further analysis of the Hero Shrew shows the spine is formed through interlocking vertebrae.

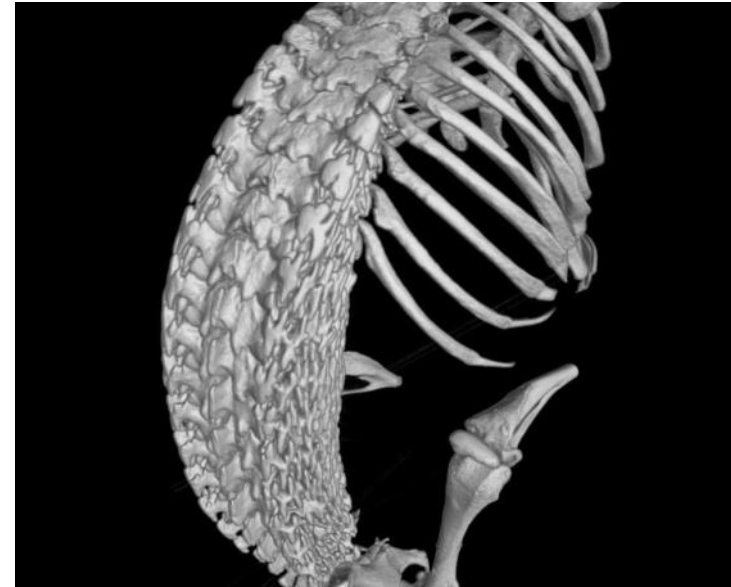


Figure 18: Scan of Hero Shrew interlocking spine (Johnston, 2021: online).

Similarly, the spine of the building is made of prefabricated carbon fibre sections. The same process for fabrication will be used here as for the exoskeleton. The inflatable membrane will be attached to these sections. As the building inflates, these sections will move with the inflatable membrane and 'lock' in place. See Detail Drawing B.

3.4 The living pods

The living pods are designed to be prefabricated on Earth and assembled on the Moon in sections. The following precedent study inspired the design of the living pods.



Figure 19: Small-scale model of SOM's inflatable Moon base design (Englefield, 2021: online).

“Moon Village”, a visionary concept for a Lunar settlement composed of inflatable modules, has been collaboratively developed by the renowned architecture studio SOM and the European Space Agency. Recently, SOM presented a detailed scale model of the “Moon Village”, following its initial announcement in 2019, during the Life Beyond Earth exhibition at the Venice Architecture Biennale.

The proposal outlines a cluster of four-level units situated in the Moon’s south polar region, intended to serve as scientific research hubs. According to SOM, “Moon Village” possesses the potential for future expansion, gradually transforming from a research-oriented establishment into a vibrant community, offering various opportunities, including tourism.



Figure 20: Close-up image of the model, exposing the structural elements of the design (Englefield, 2021: online).

For SOM, the creation of “Moon Village” revolves around designing an environment that fosters long-term human habitation and prosperity. Senior designer Daniel Inocente emphasised that their approach embodies human-centric design principles (Englefield, 2021: online).

To facilitate transportation and assembly, the modules are inflatable. The modules are compressed during rocket transportation, followed by expansion to their full size on-site. These units are constructed using a hybrid structural design, incorporating a rigid titanium alloy perimeter frame and a soft structural shell (Englefield, 2021).



Figure 21: Illustration of the interior frame (Englefield, 2021: online).

To protect the modules against small meteorites, the soft shell comprises multiple layers, including a protective layer and an insulating layer composed of open-foam polyurethane and double-aluminised Mylar. An innovative aspect of this design is the placement of structural mechanical systems outside the core, allowing for an open interior (Englefield, 2021: online).

Inspired by the precedent study, the living pods were designed in a similar fashion. The form is provided through a rigid carbon fibre frame that ties in with the rest of the building. Attached to the frame are inflatable membranes. The units are stacked on top of each other, made possible by the rigid frame of the design. Service ducts are placed next to the pods on the outside, which allows for an open interior. Space underneath the carbon fibre floor slab has been provided for service pipes and wiring. See Figure 6 for a detailed drawing of the living pods.



Chapter 4: Technical drawings

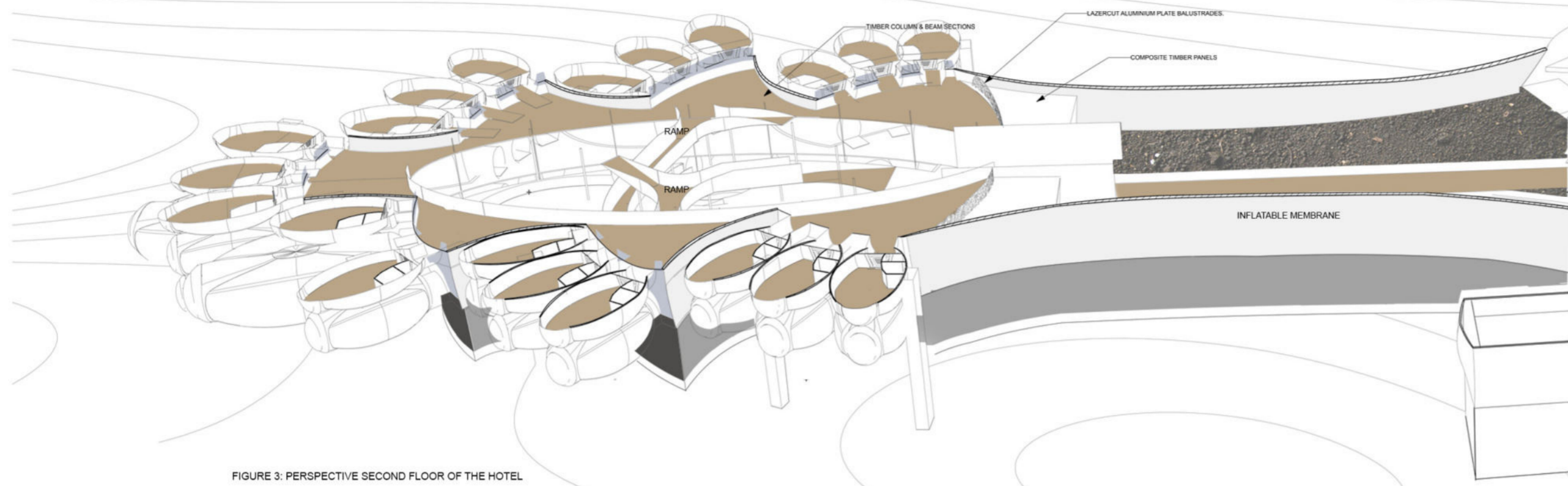


FIGURE 3: PERSPECTIVE SECOND FLOOR OF THE HOTEL

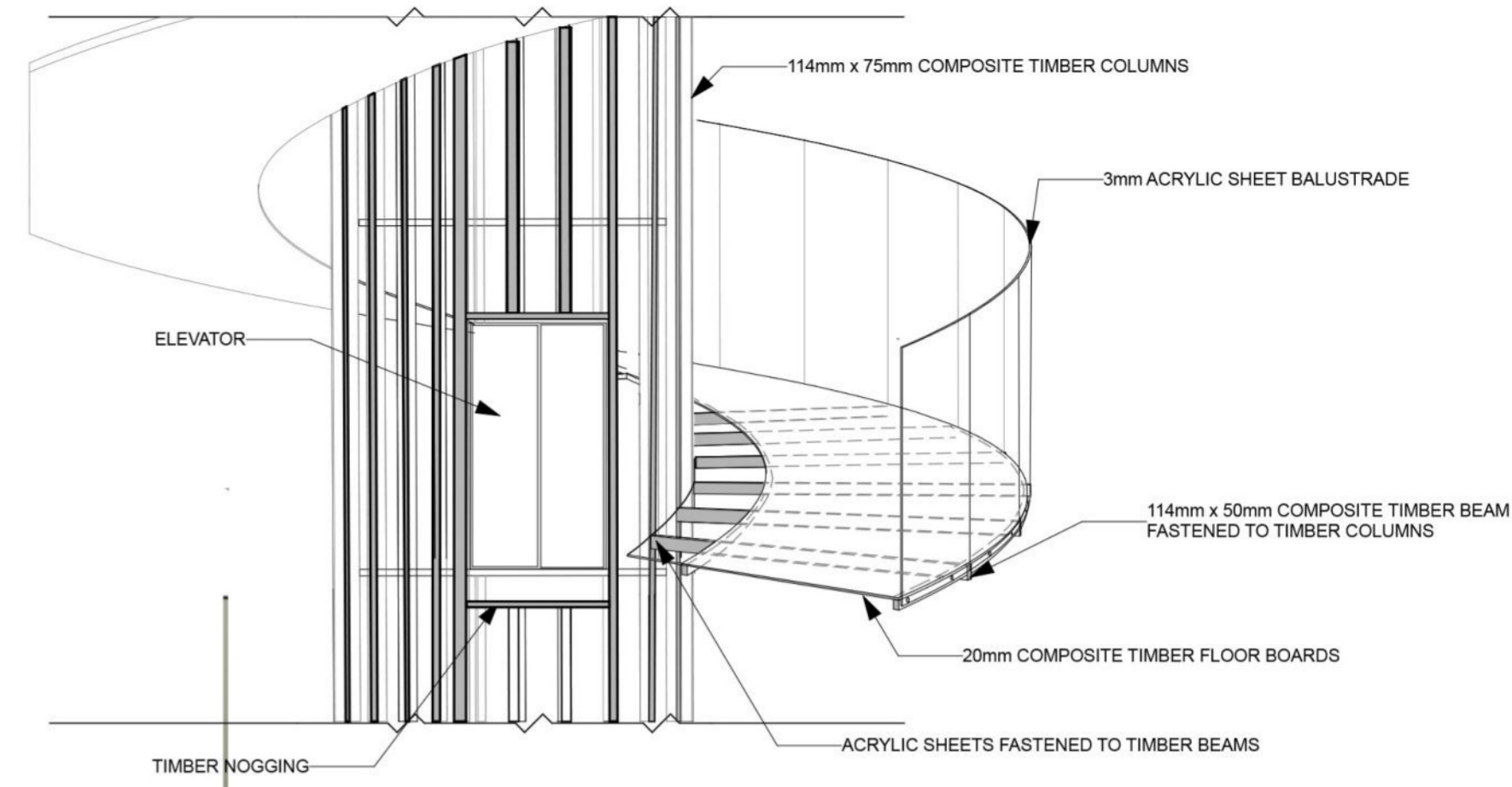


FIGURE 6: CONSTRUCTION DRAWING OF RAMP & ELEVATOR
SCALE 1:50

FIGURE 7:

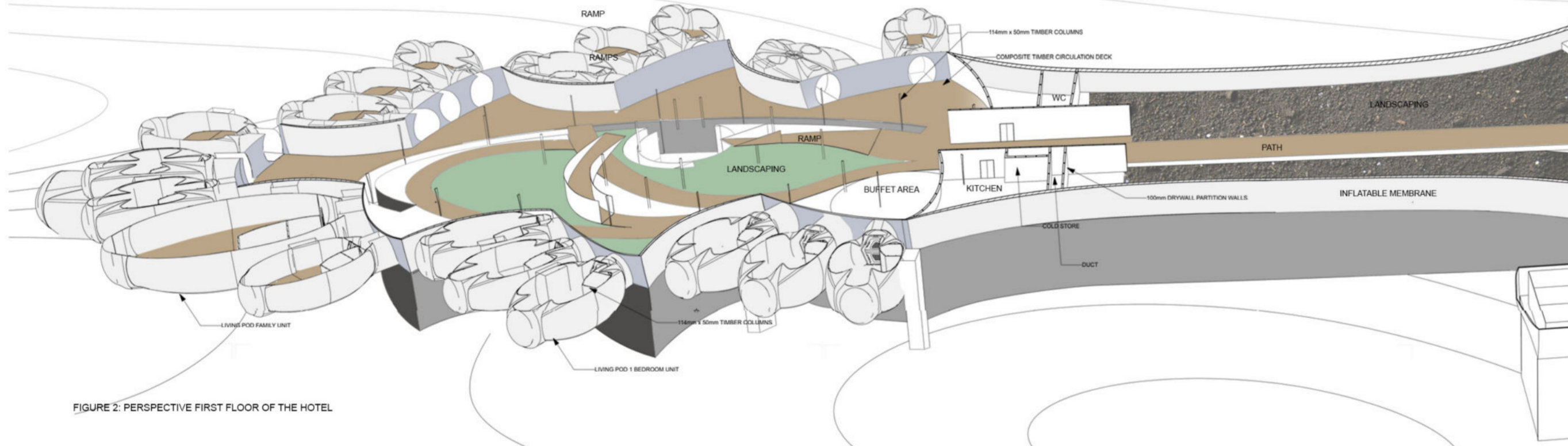


FIGURE 2: PERSPECTIVE FIRST FLOOR OF THE HOTEL

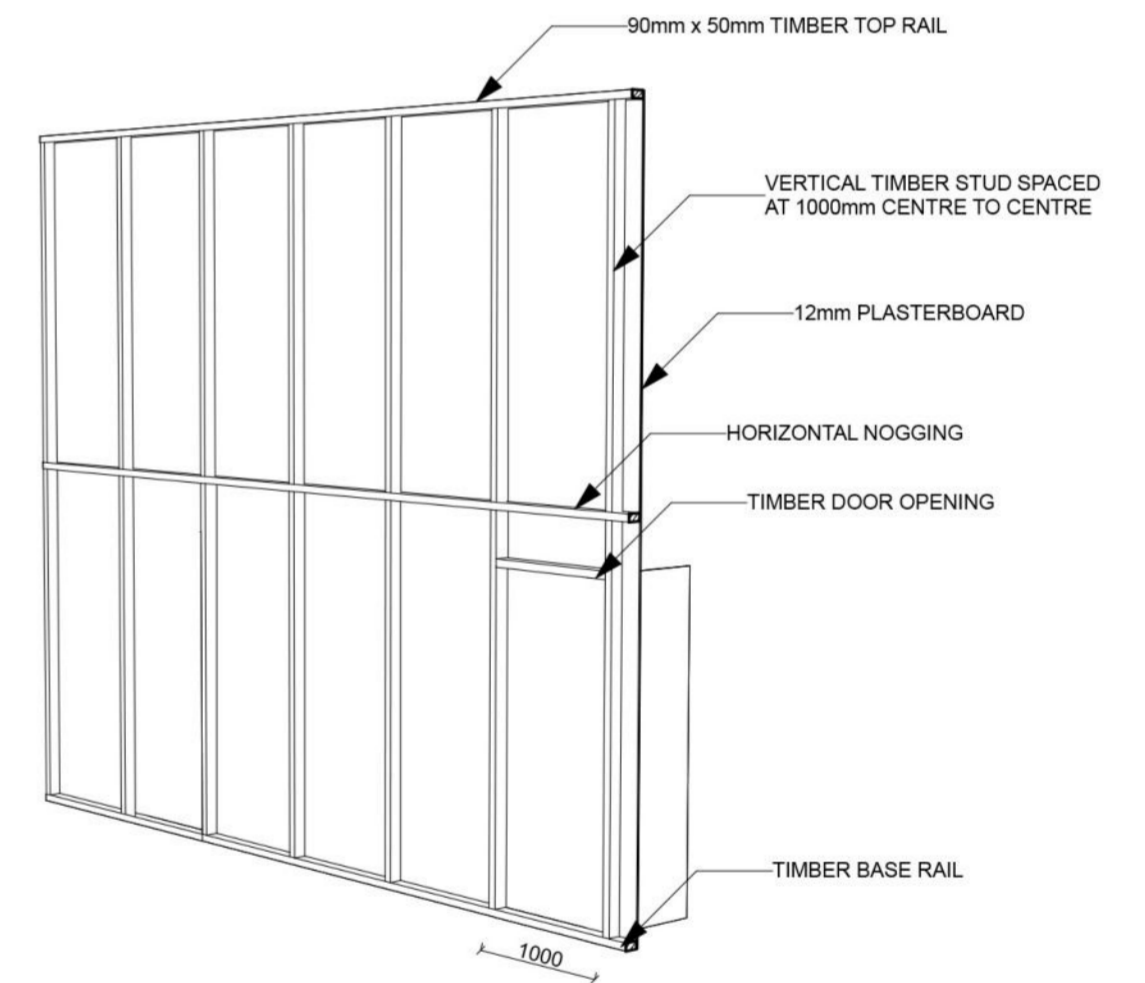


FIGURE 7: PARTITION WALL DETAIL
SCALE 1:50

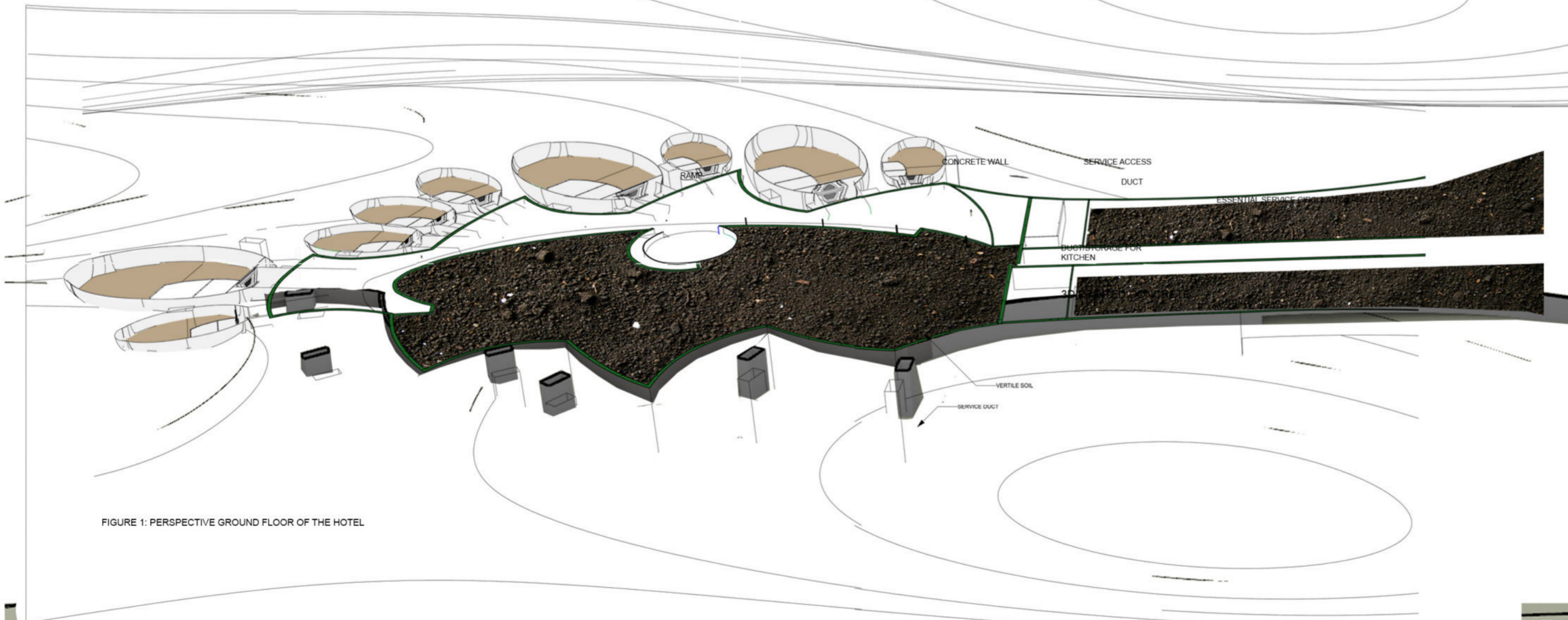
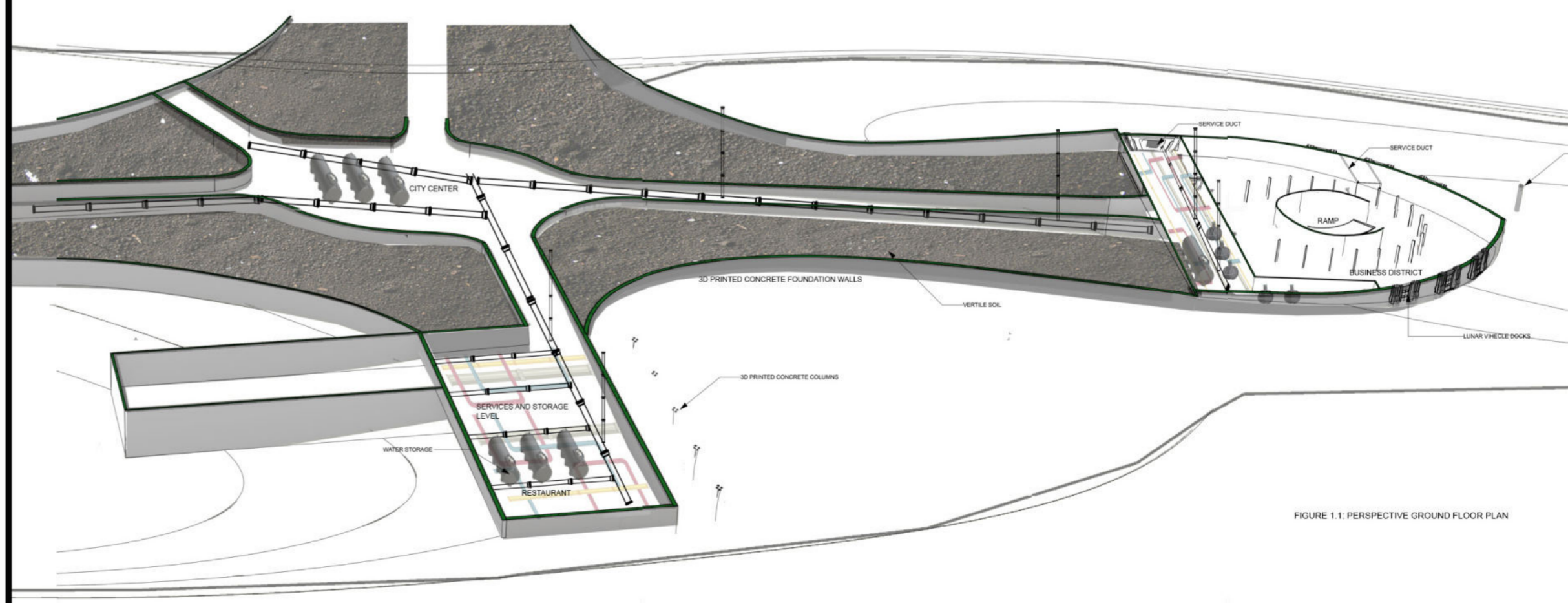
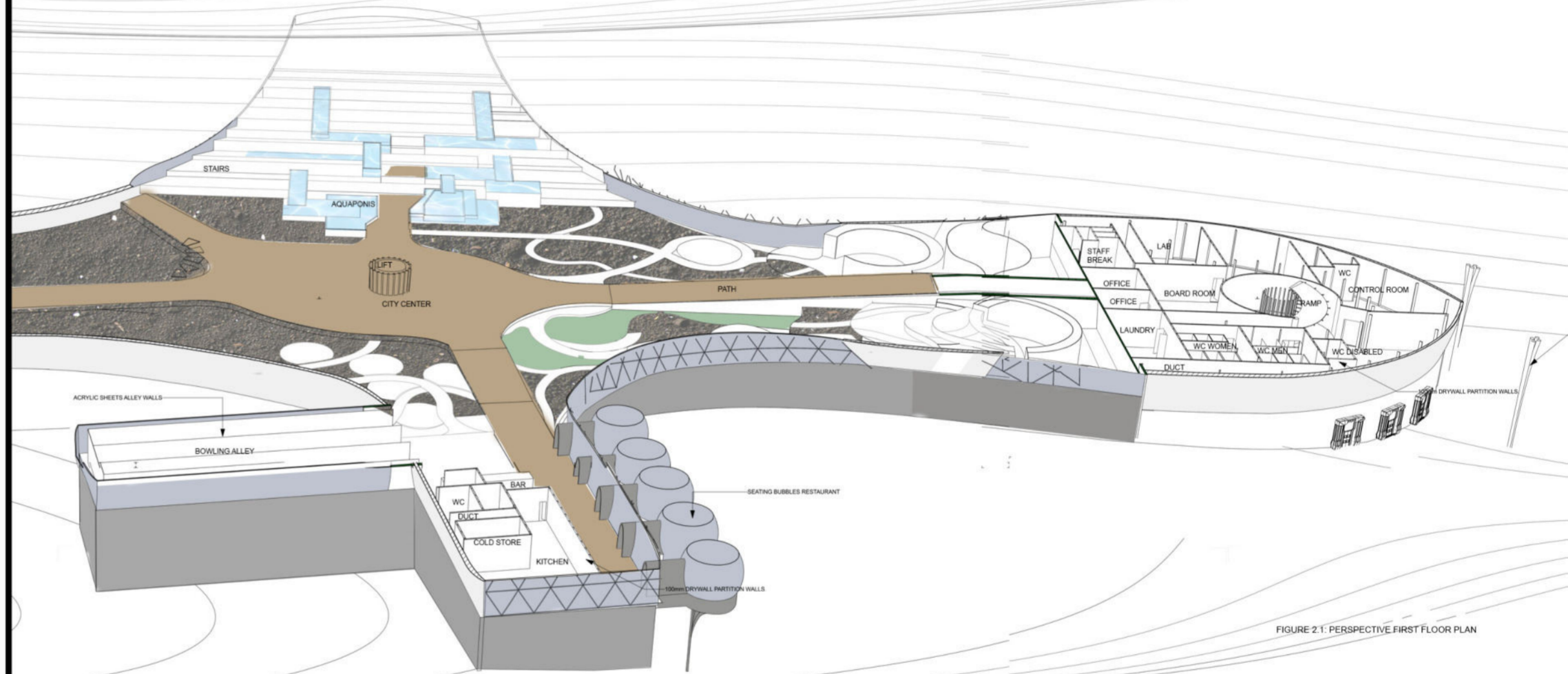
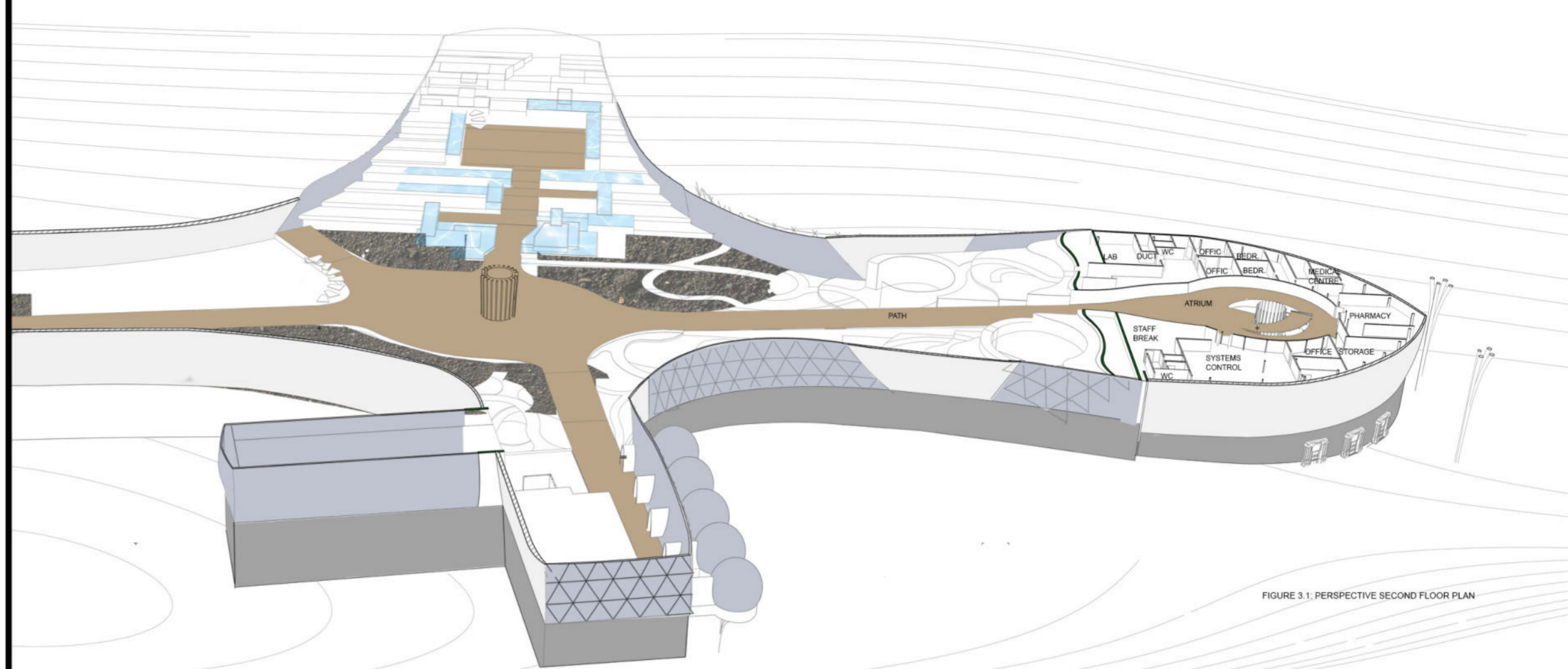
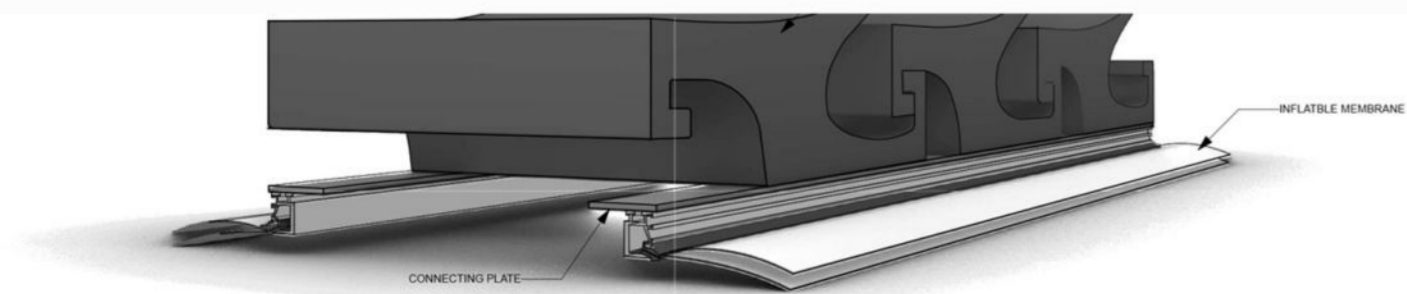
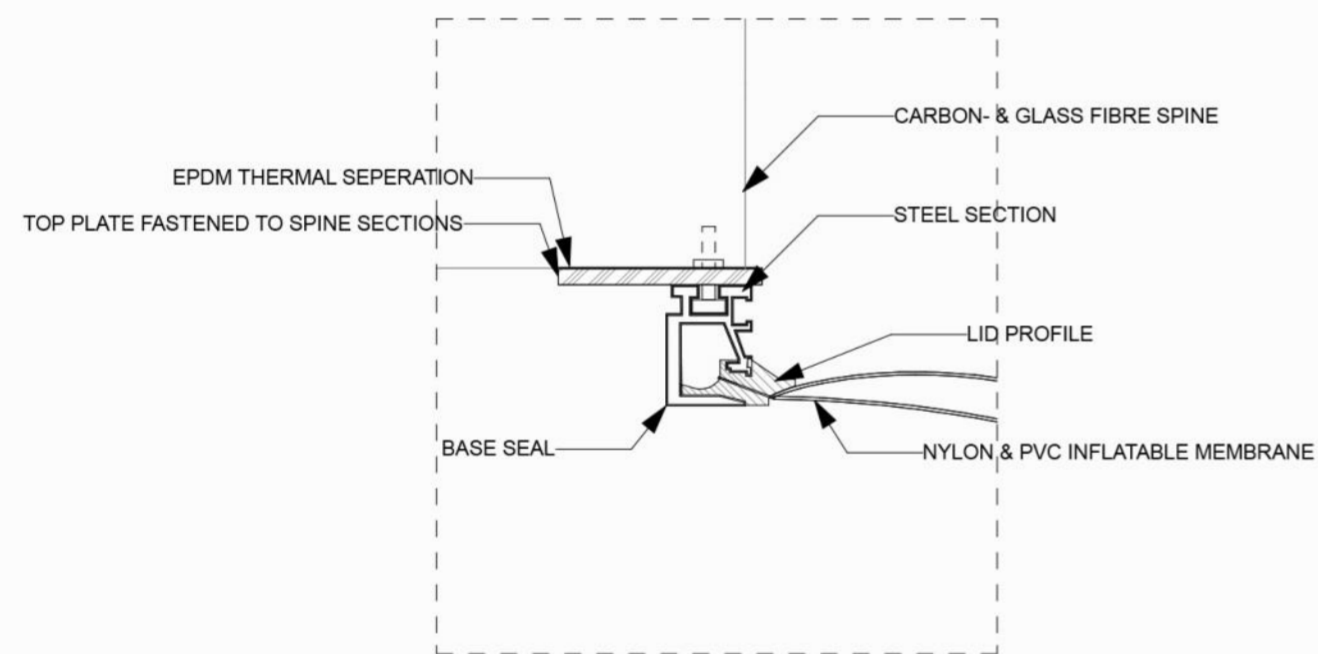
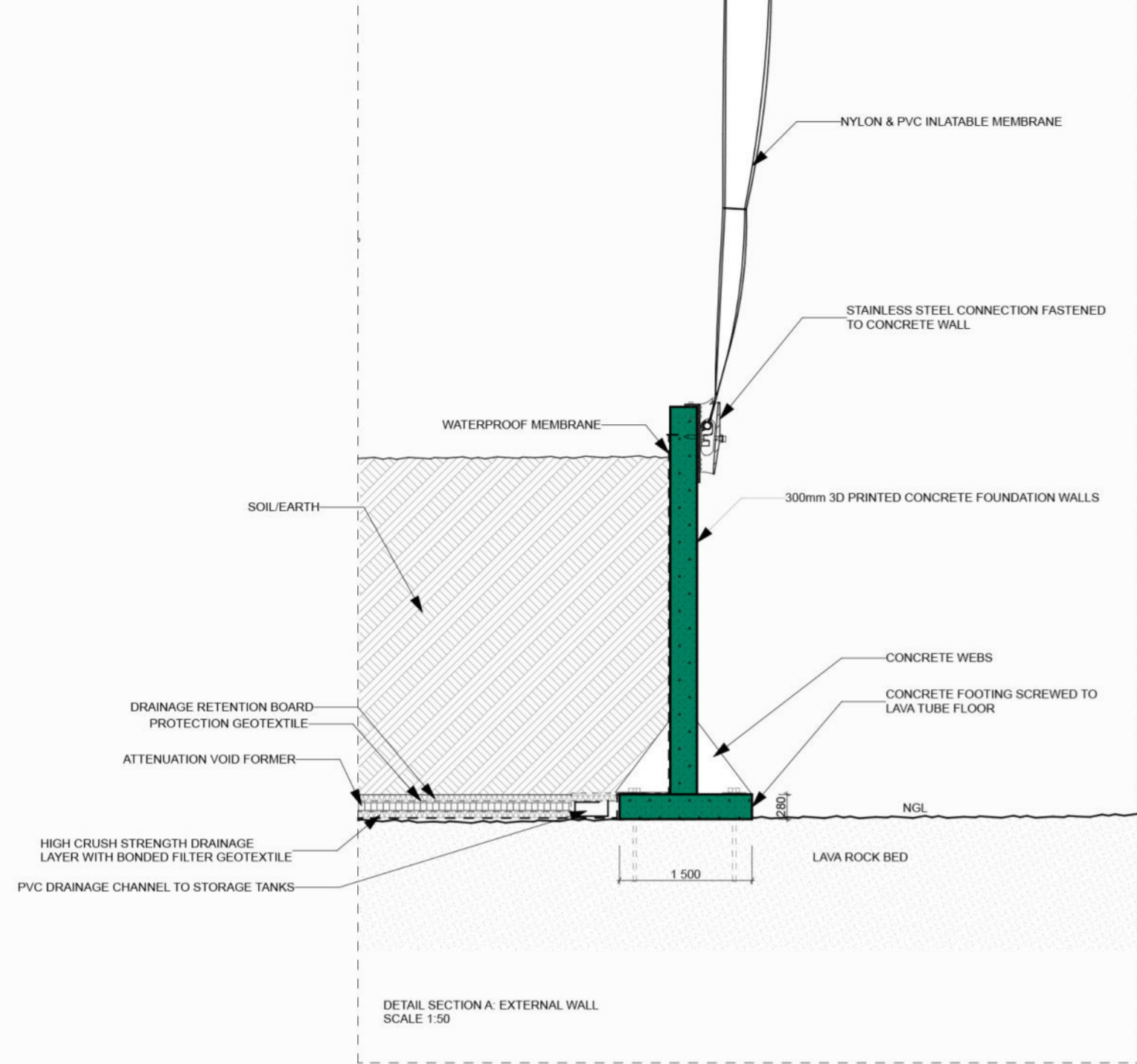
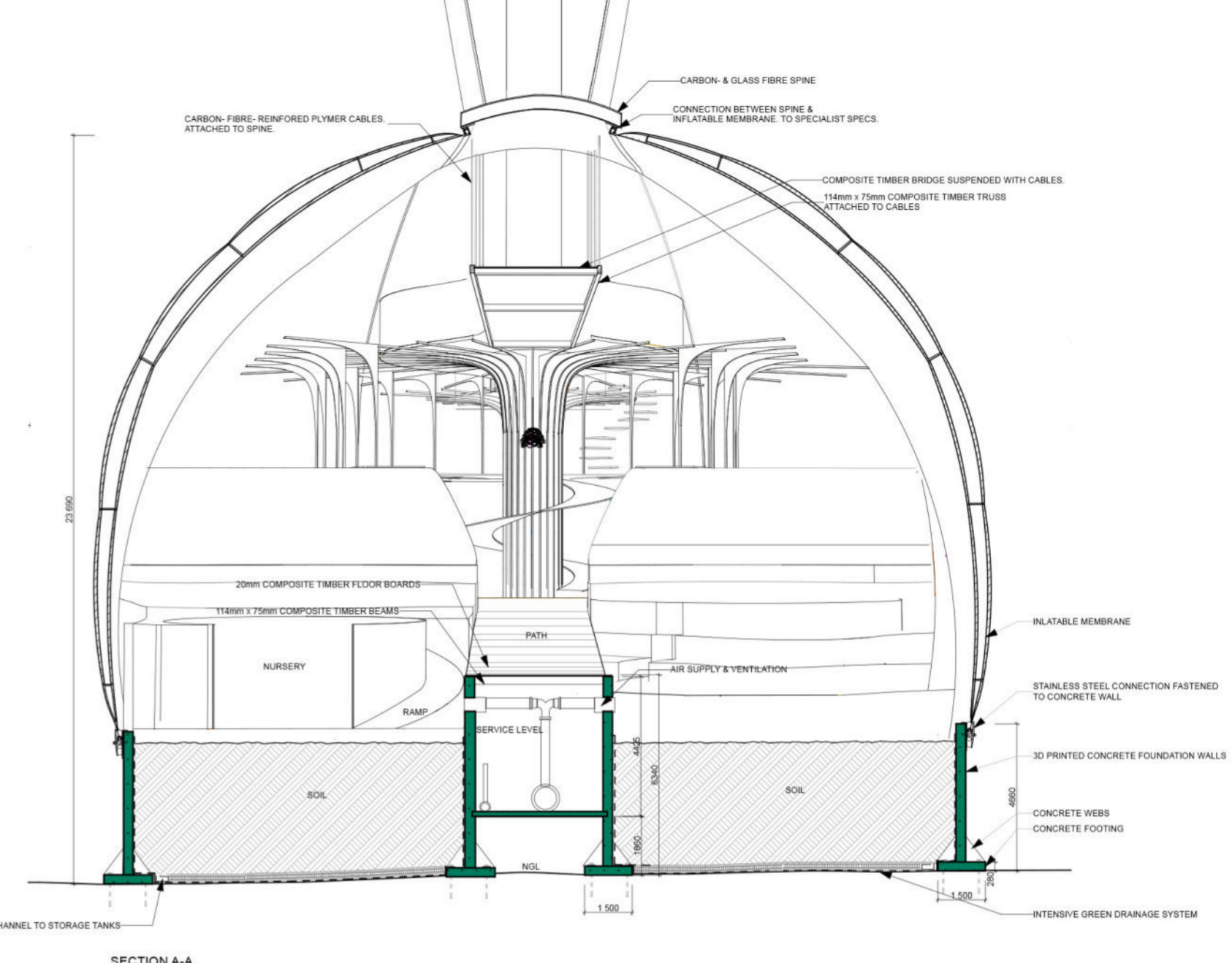
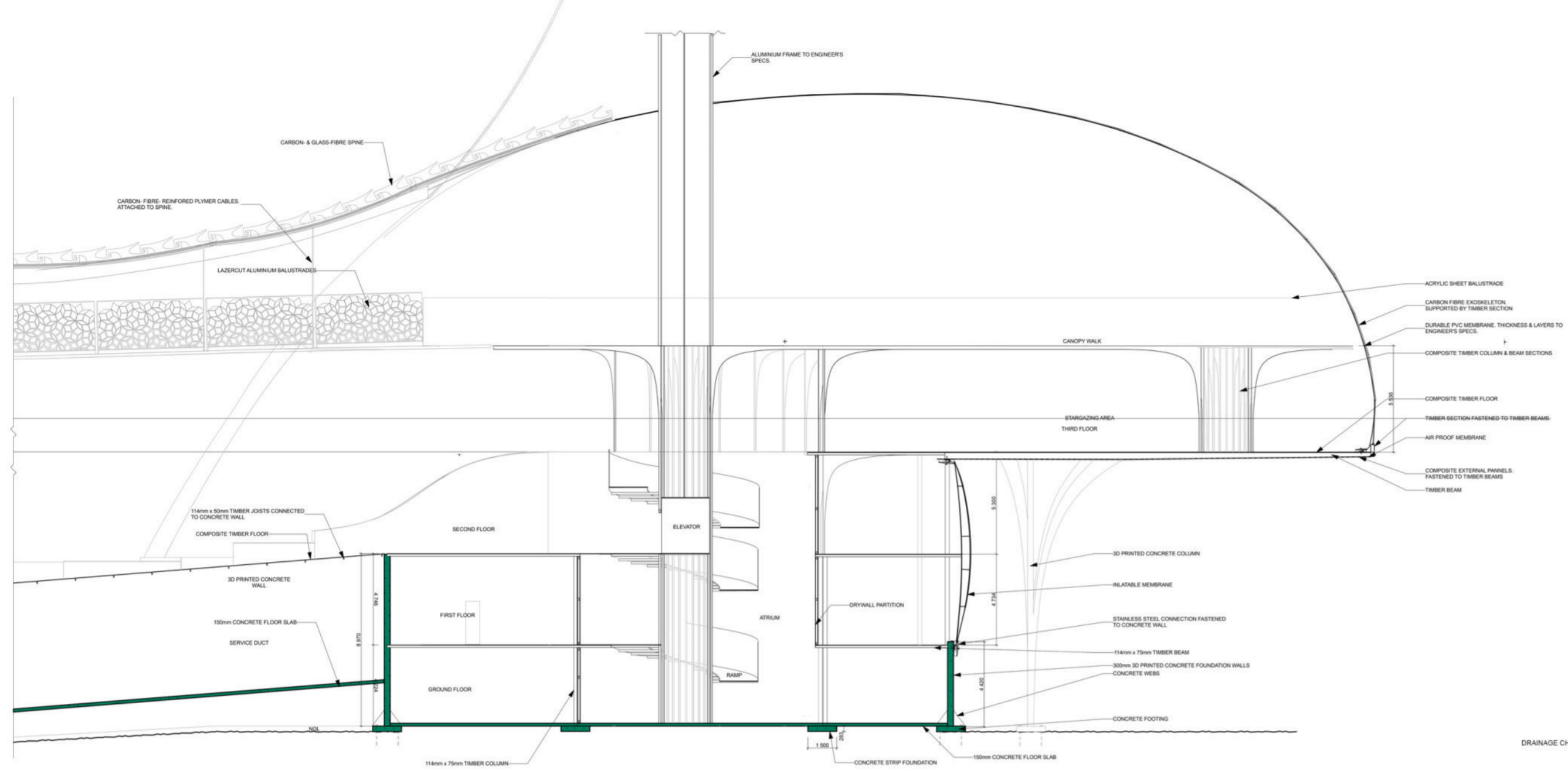


FIGURE 1: PERSPECTIVE GROUND FLOOR OF THE HOTEL





SECTION B-B
SCALE 1:100

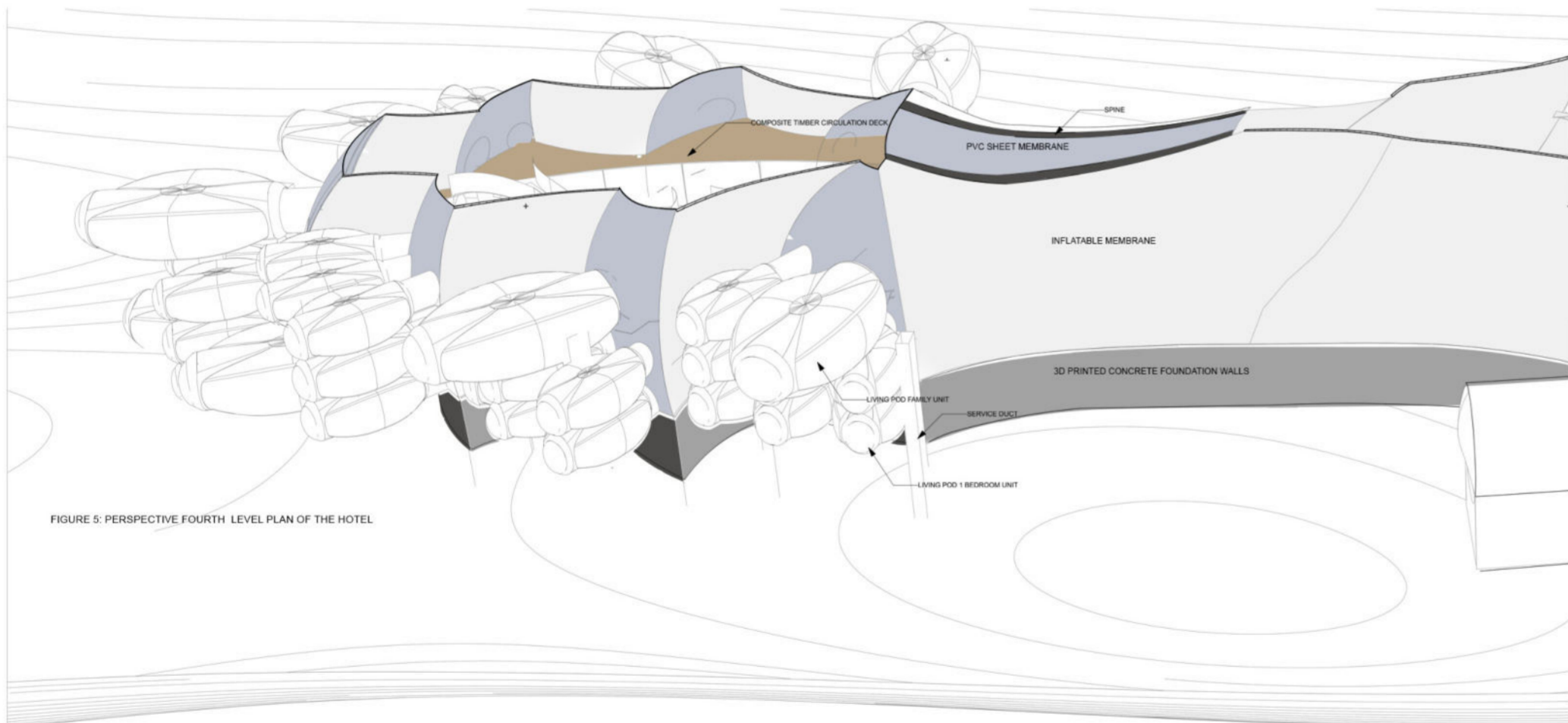
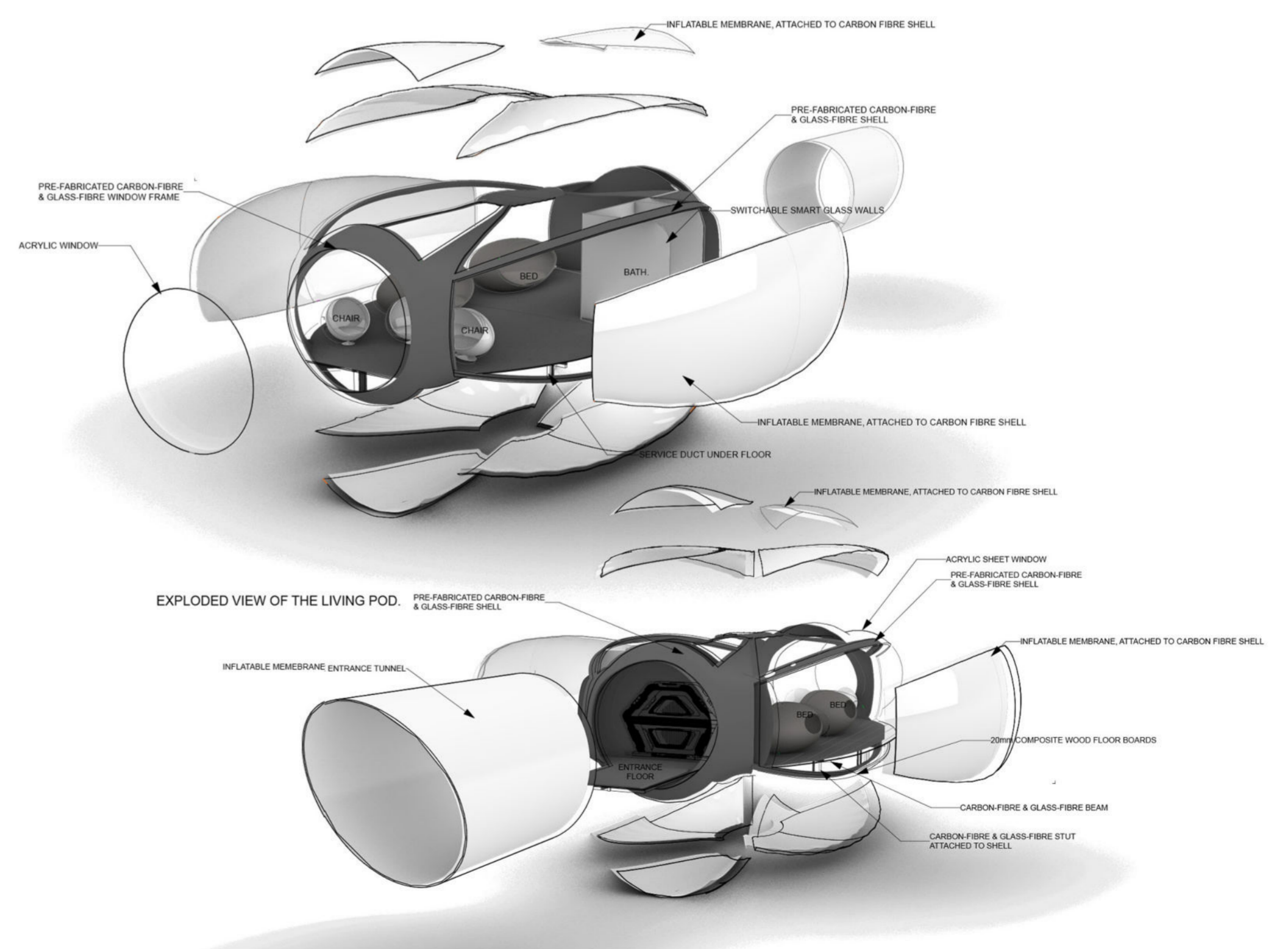
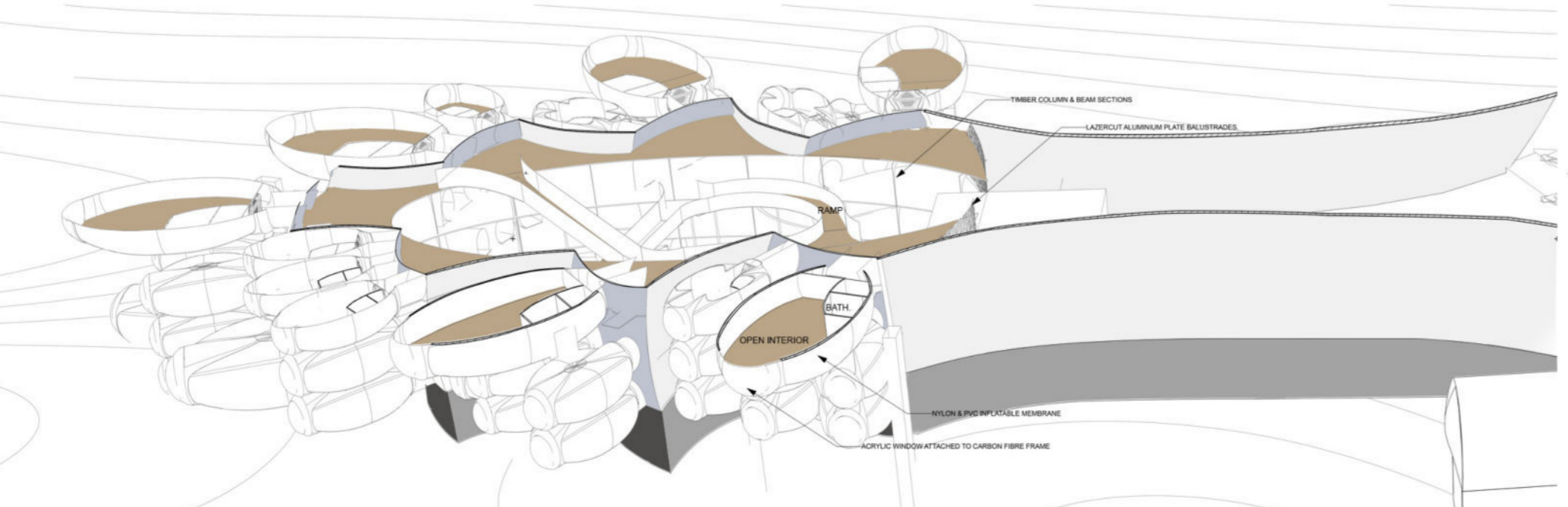


FIGURE 5: PERSPECTIVE FOURTH LEVEL PLAN OF THE HOTEL



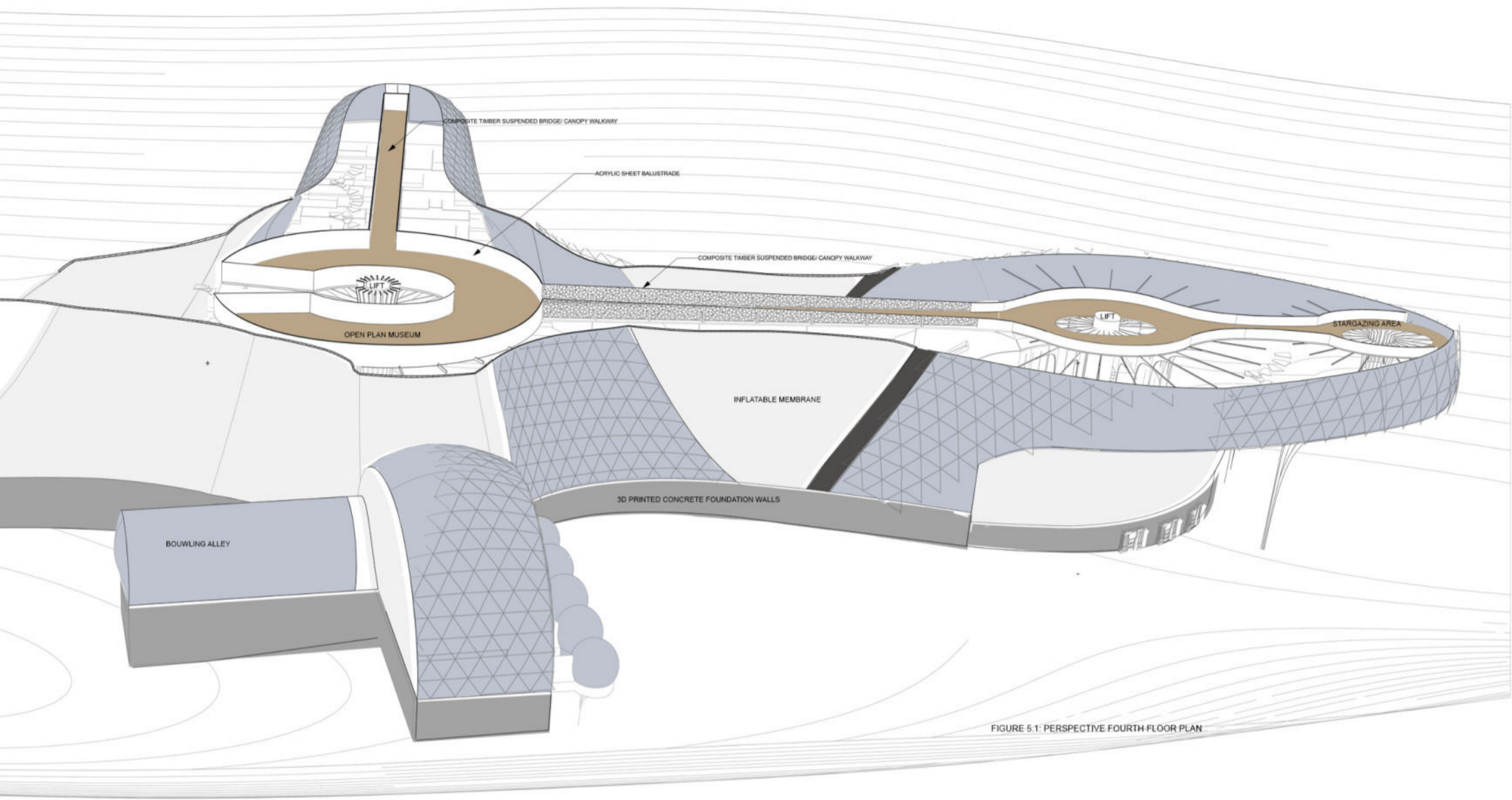


FIGURE 5.1: PERSPECTIVE FOURTH FLOOR PLAN

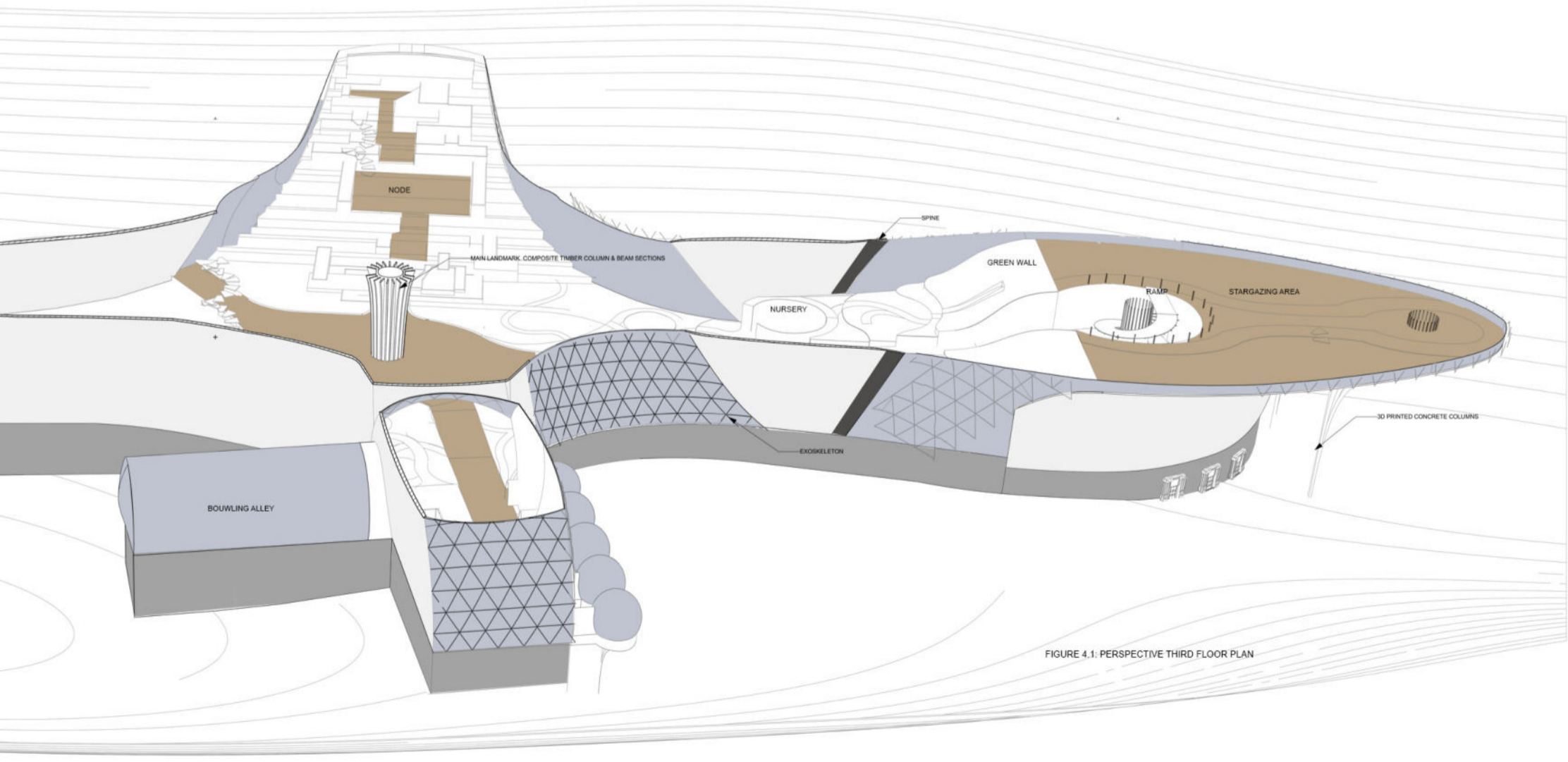
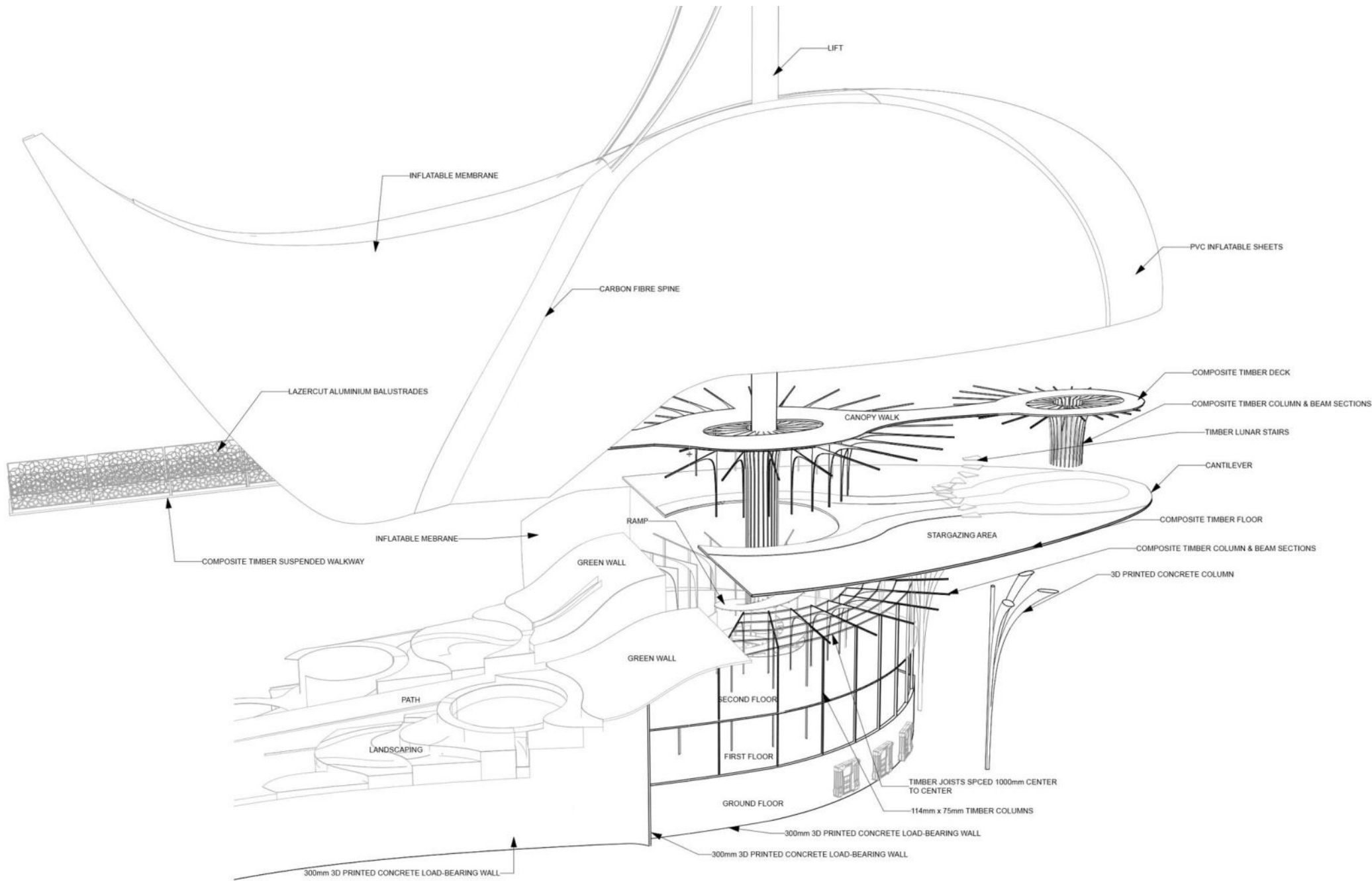
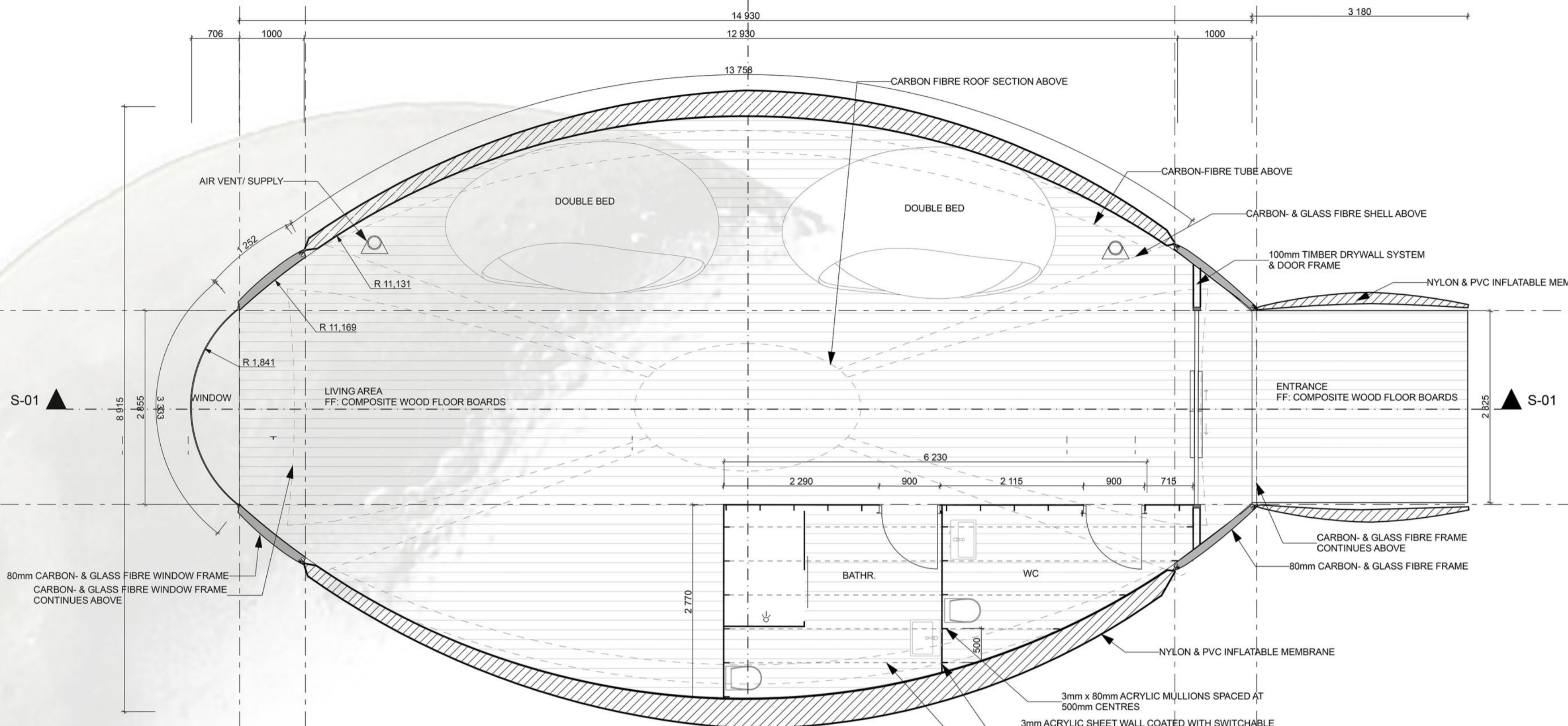


FIGURE 4.1: PERSPECTIVE THIRD FLOOR PLAN



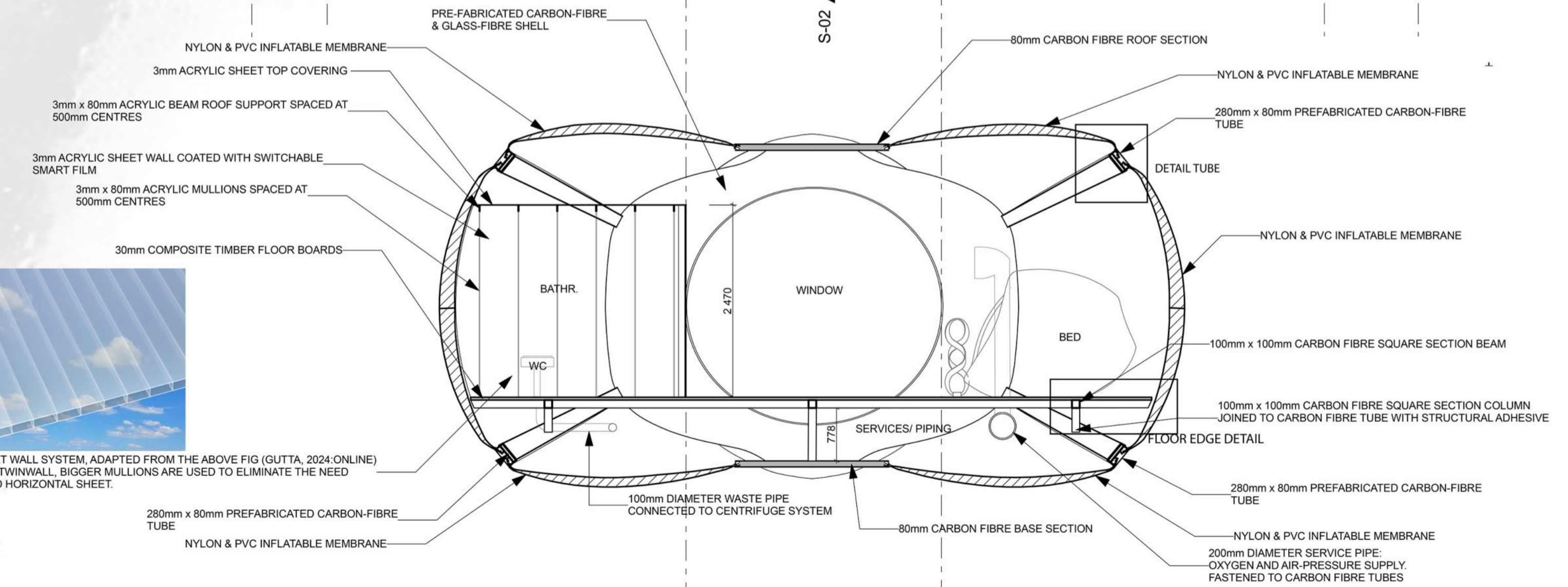
EXPLODED DRAWING OF THE BUSINESS DISTRICT. EXPOSING INTERIOR STRUCTURE.



FLOOR PLAN OF THE 4 PERSON LIVING POD
SCALE 1:50

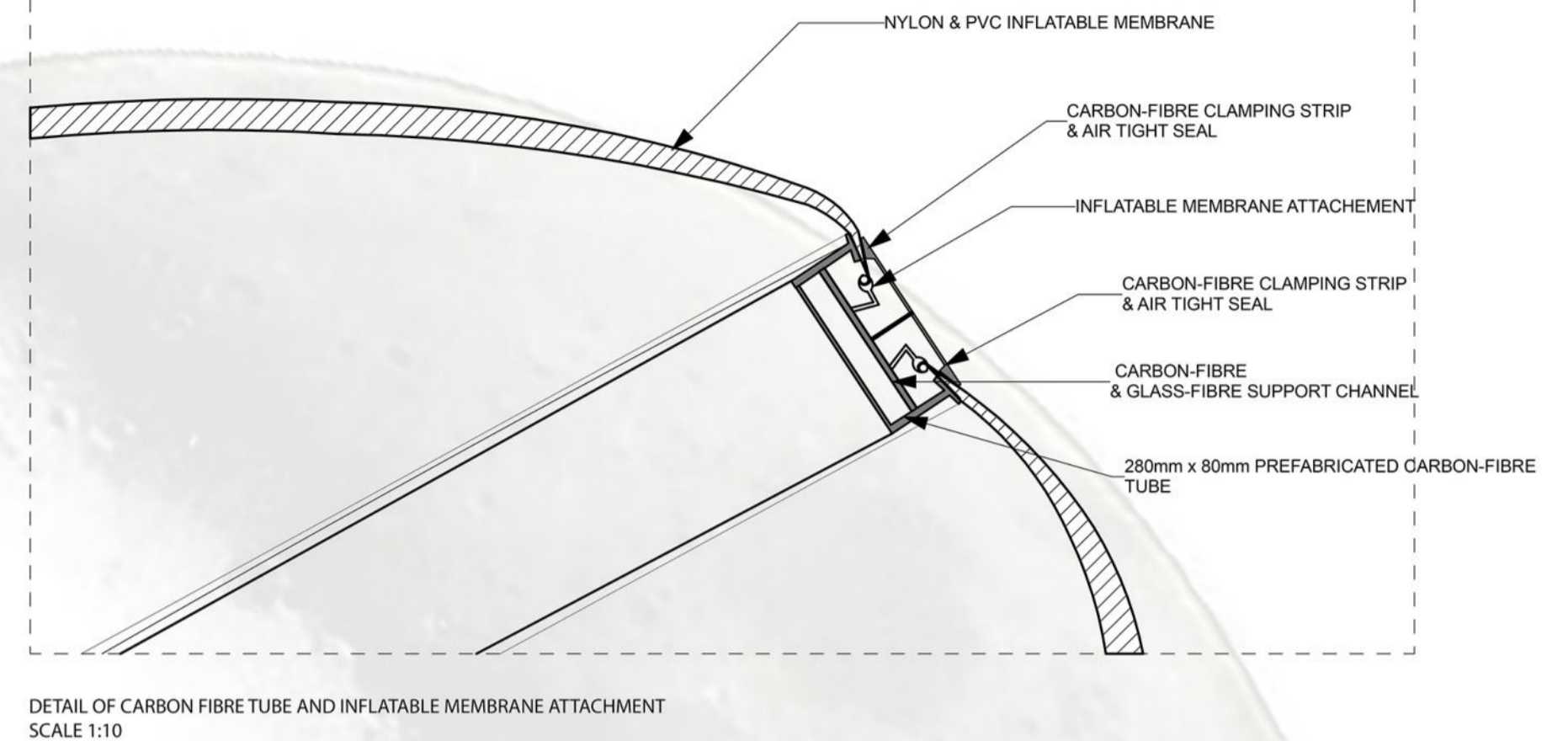
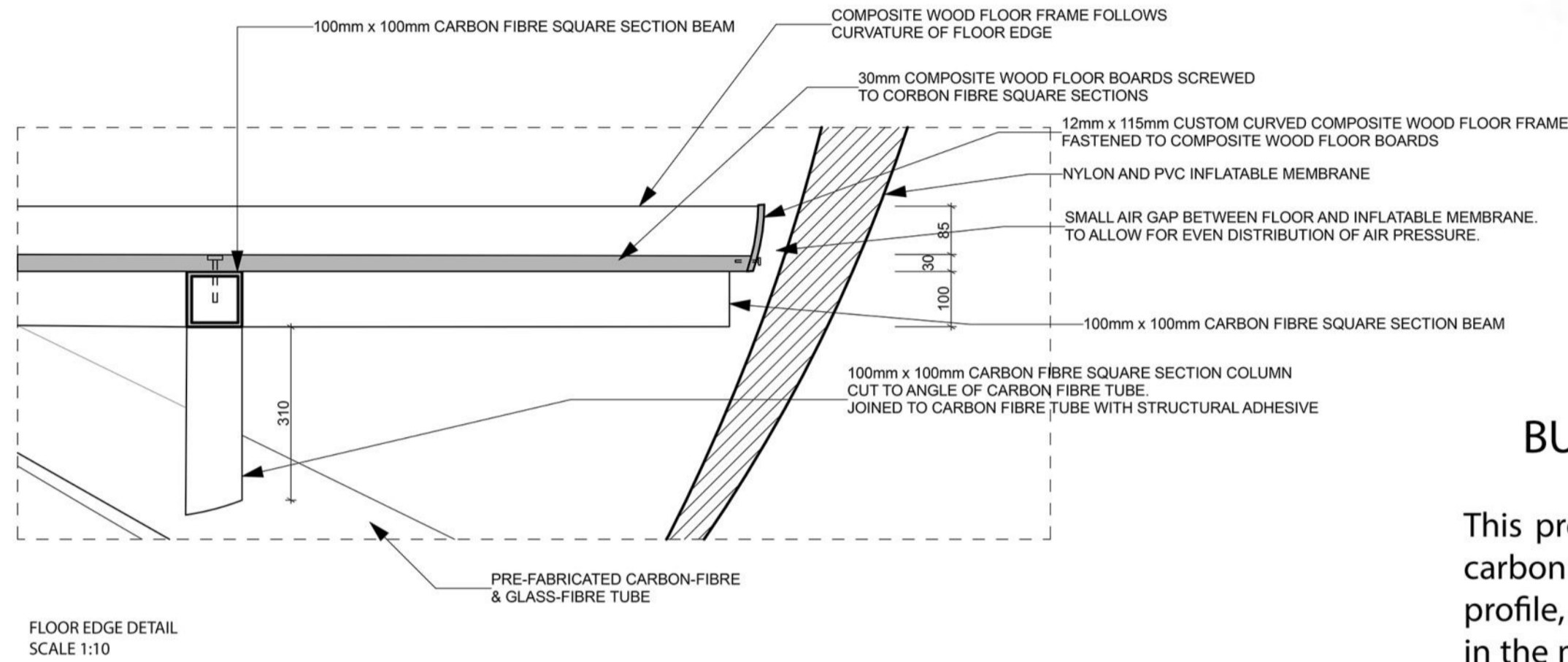


ACRYLIC SHEET WALL SYSTEM, ADAPTED FROM THE ABOVE FIG (GUTTA, 2024:ONLINE) INSTEAD OF A TWINWALL, BIGGER MULLIONS ARE USED TO ELIMINATE THE NEED FOR A SECOND HORIZONTAL SHEET.



SECTION S-02
SCALE 1:50

THE FOUR PERSON LIVING POD: CONSTRUCTION & ASSEMBLY



BUITINK TECHNOLOGY DETAIL:

This precedent study detail was adapted in the carbon fibre tube. Instead of an aluminium profile, carbon fibre is used that will be included in the manufacturing process of the carbon fibre tube as one part.

The air supply tube of the precedent study is eliminated as the air pressure from the inside will be enough to keep the membrane inflated.

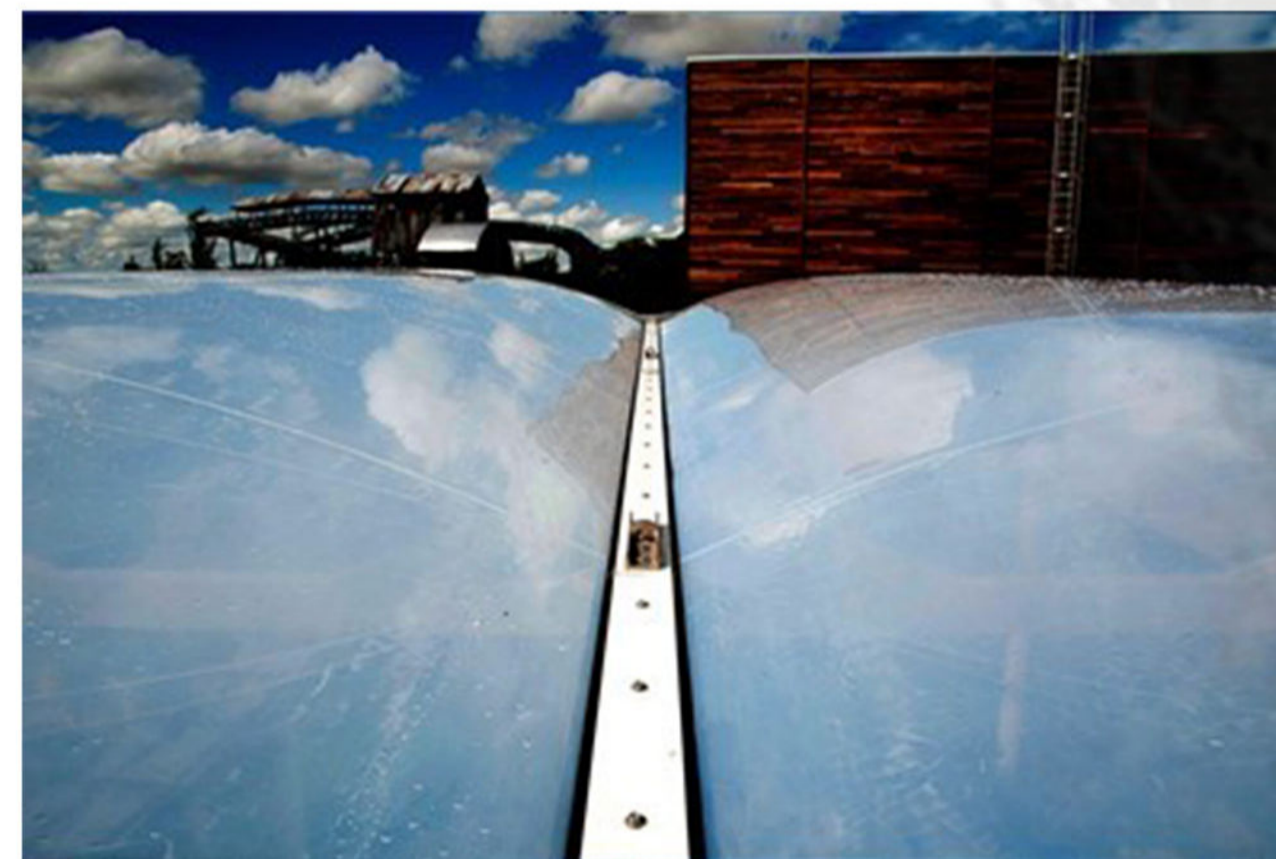
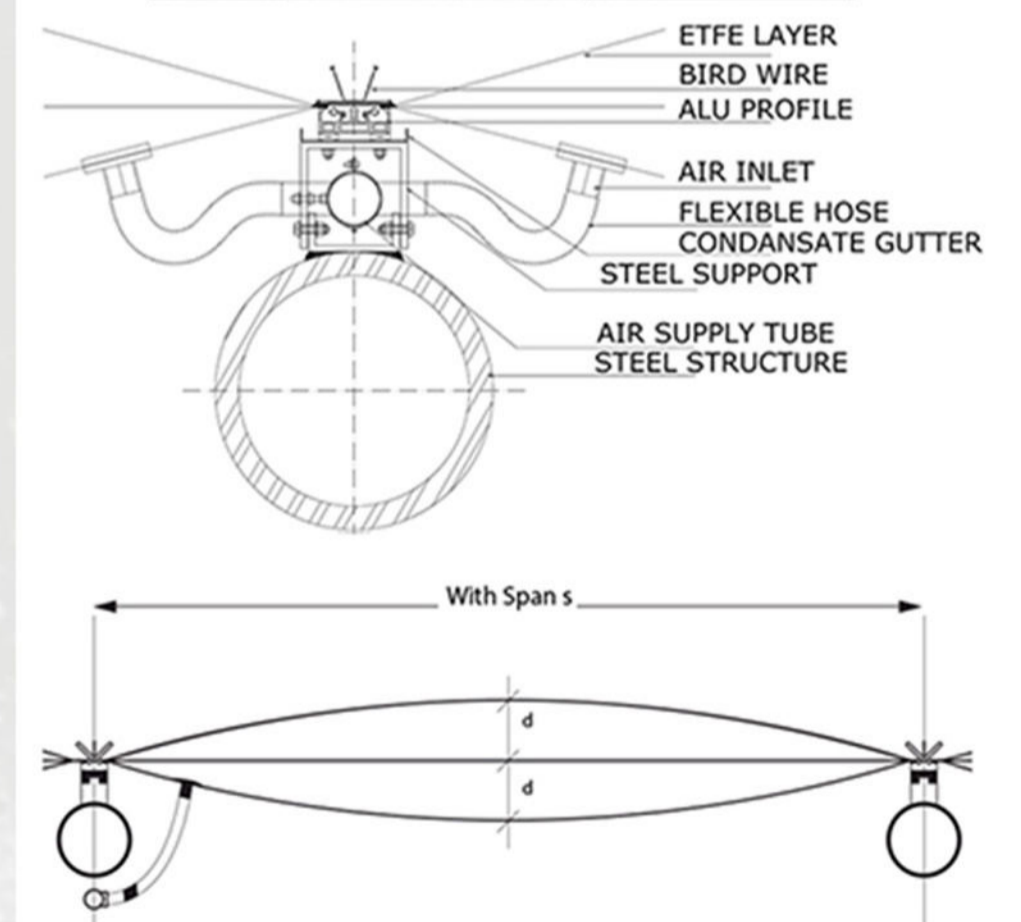
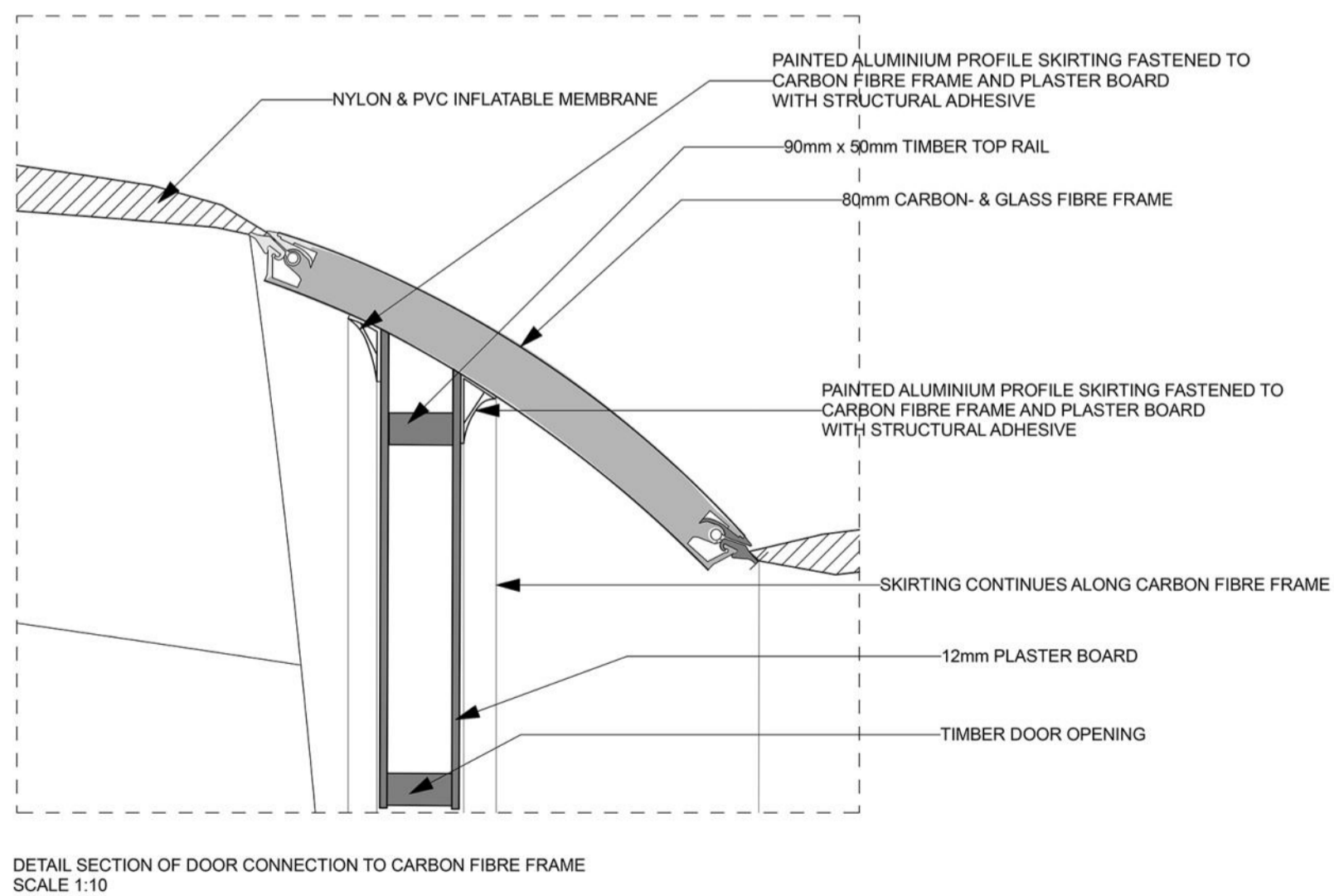
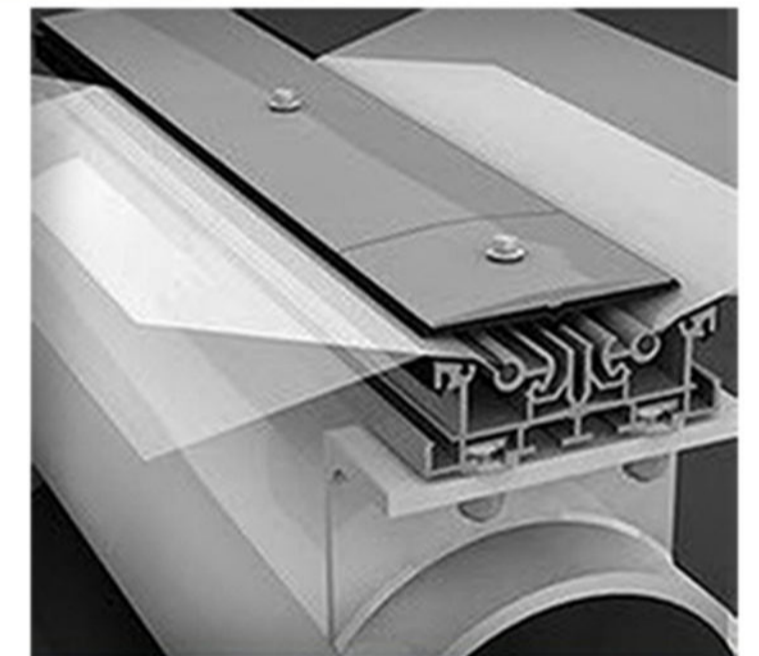


IMAGE 1: ROOF AIR CUSHION (BUITINK TECHNOLOGY, 2023: ONLINE).

IMAGE 2: DETAIL SECTION OF INFLATABLE STRUCTURE (BUITINK TECHNOLOGY, 2023: ONLINE)

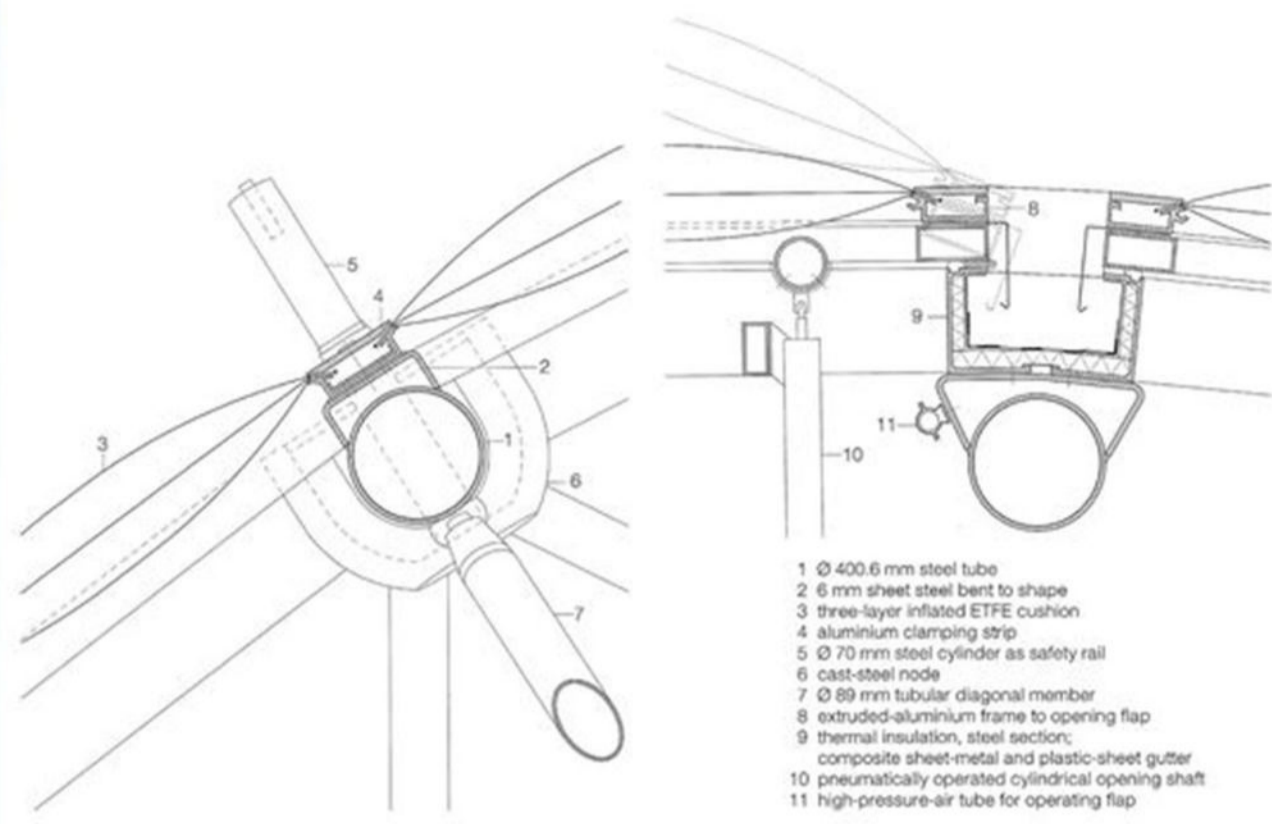


IMAGE 1: DETAIL SECTION OF THE EDEN PROJECT (WORDPRESS, 2010: ONLINE)



Figure 5: Image of the Eden Project's geodesic dome (EdenProject, 2023: online).

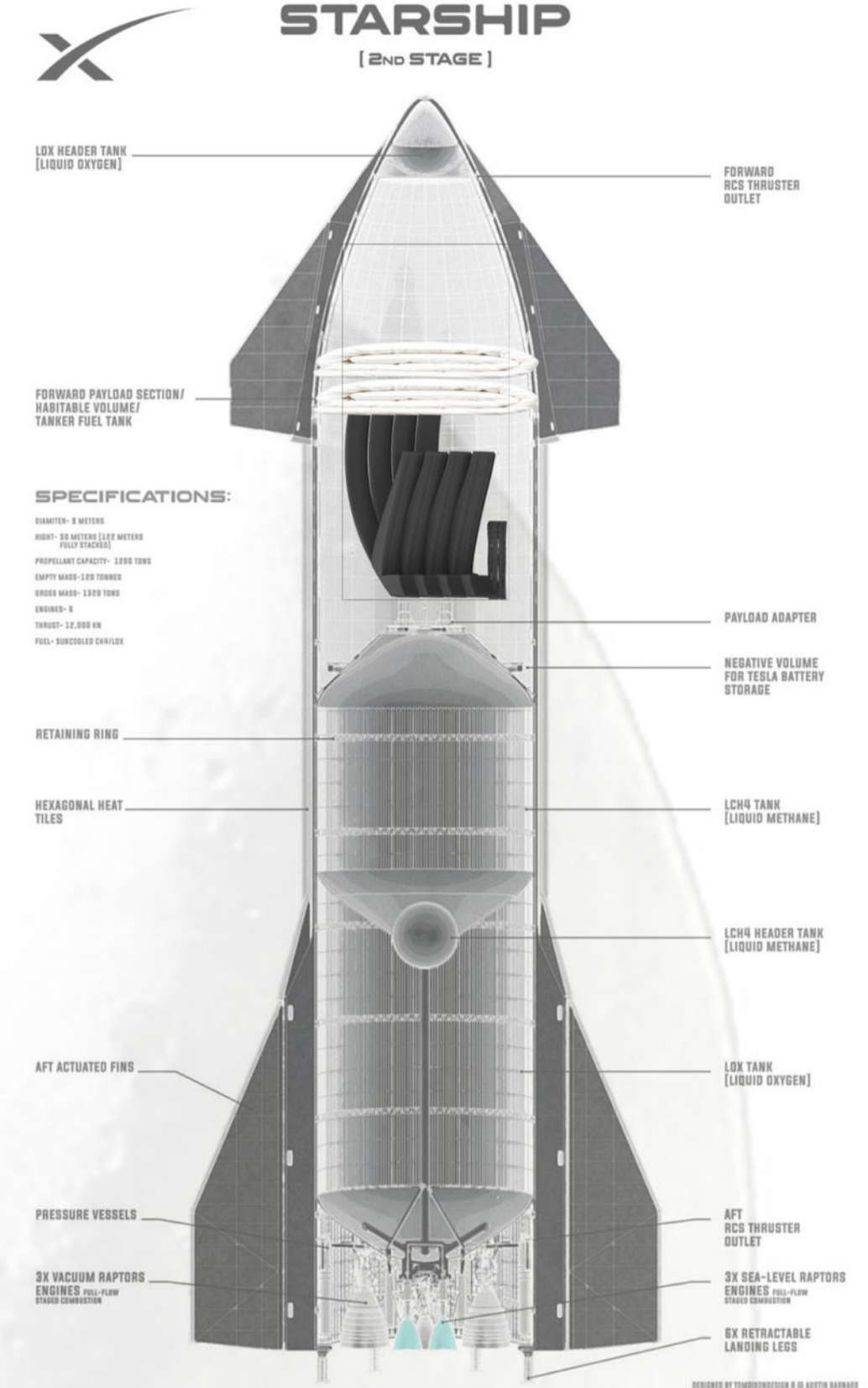
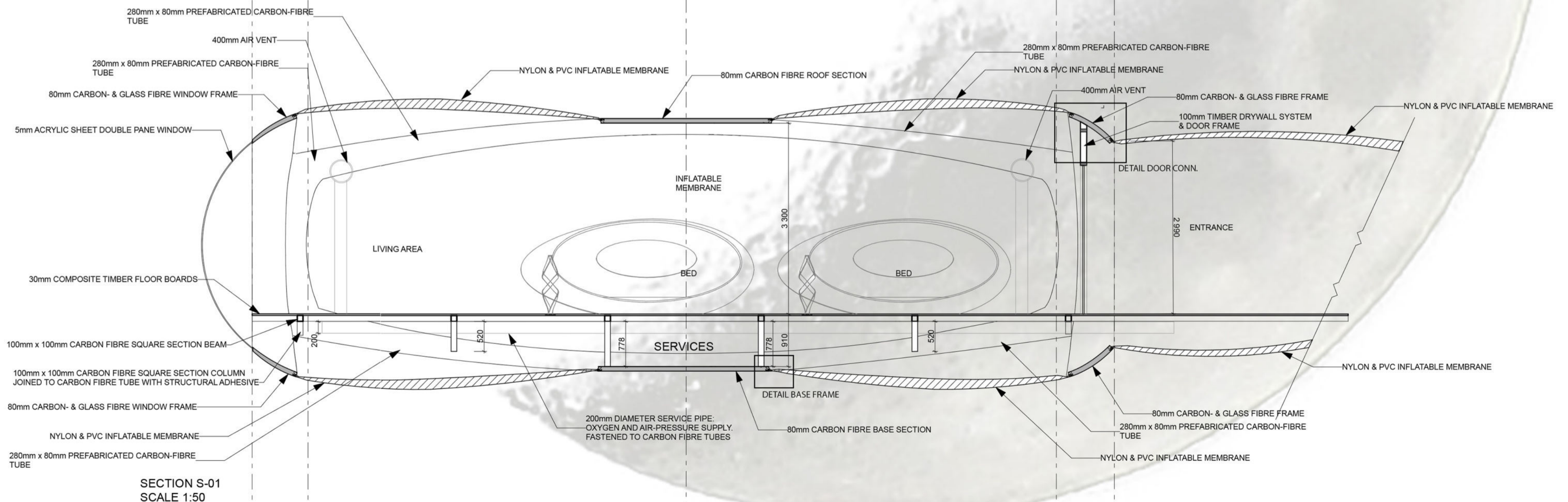
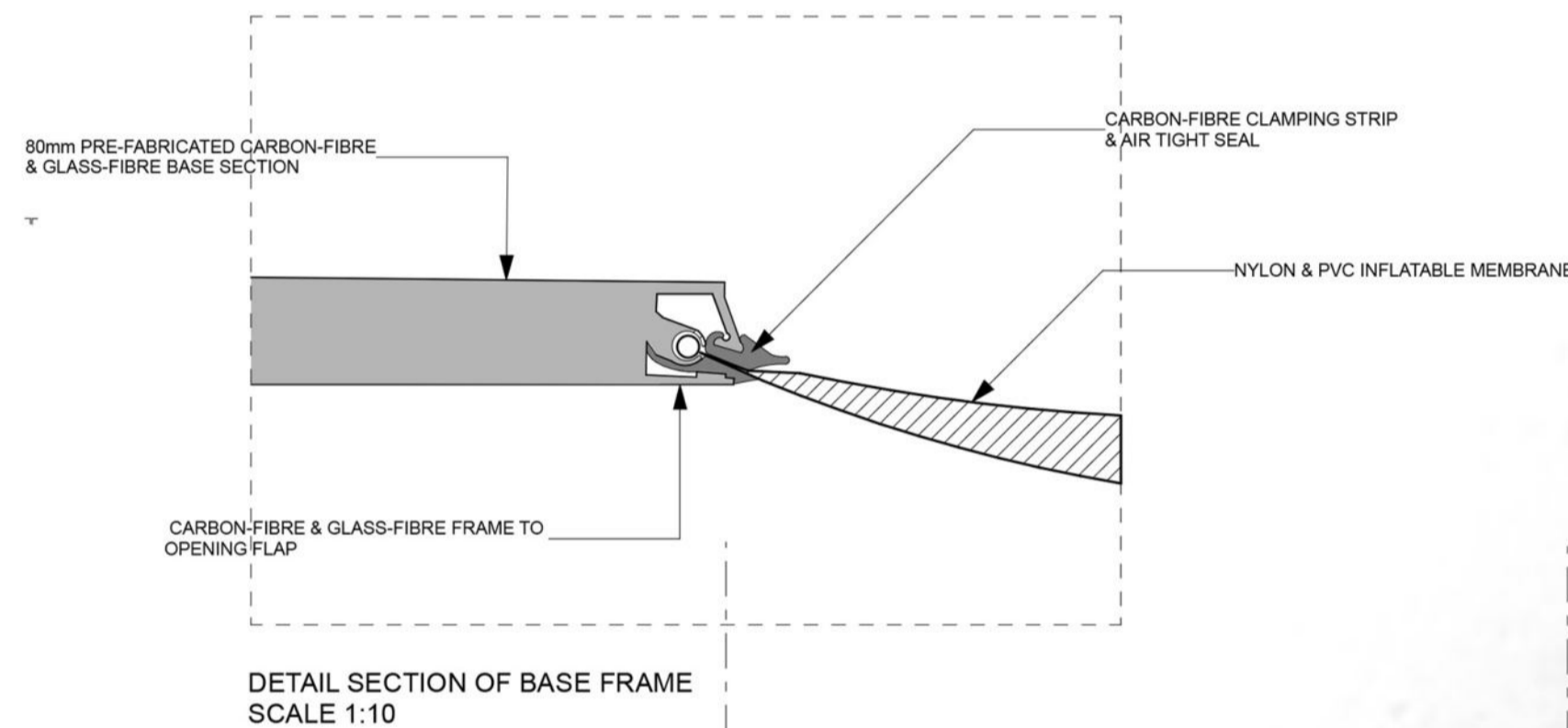


FIG 5: Illustration of pre-fabricated sections and membrane inside Straship cargo space (author)

The Eden Project present study:

This precedent study detail was adapted specifically in the base - and top frames. The detail within the frame required only a single attachment to the inflatable membrane. The detail is part of the prefabricated carbon fibre frame. This allows for the detail to be fabricated as one part. Unlike the precedent study that placed the attachment (clamping strip) on top of the structure.

The air tubes in the precedent study was also emmited as the pressure from inside the structure will keep the membrane inflated.



INSTRUCTIONS FOR ASSEMBLY: THE LIVING POD

1: THE CARBON- AND GLASS FIBRE SHELL OF THE LIVING POD WILL BE PREFABRICATED THROUGH AN AUTOMATED PROCESS WITH PROGRAMING AND A ROBOT ARM. SIMILAR TO THE PROCESSES SHOWN IN FIG 1 AND FIG 2.

2.1 : THE CARBON - & GLASS FIBRE SHELL OF THE LIVING POD CONSISTS OF EIGHT SIMILAR SMALLER SECTIONS AND TWO OVALS SECTIONS, ILLUSTRATED IN FIG 3 AND FIG 4. THE SECTION ARE MIRRORED TO FORM THE SHELL AND ASSEMBLED VIA A CLIPPING SYSTEM TO ENGINEER'S SPECIFICATIONS.

2.2: STANDARD CARBON FIBRE TUBE SECTIONS WILL BE USED ON THE INSIDE TO SUPPORT THE FLOOR.

3.1: FOR FABRICATION OF CARBON - & GLASS FIBRE SECTIONS, THE ROBOT ARM AND MATERIAL COULD BE TRANSPORTED TO THE MOON AND ALL SECTIONS FABRICATED.

3.2: ALTERNATIVELY, THE SECTIONS COULD BE PREFABRICATED ON THE EARTH AND TRANSPORTED TO THE MOON VIA THE STARSHIP FLIGHT. FIGURE 5 ILLUSTRATES HOW THE SECTIONS WOULD EASILY FIT INSIDE THE STARSHIP'S AVAILABLE SPACE ALONG WITH THE COMPACTED INFLATABLE MEMBRANE.

4: ONCE THE SECTIONS HAVE BEEN ASSEMBLED, THE INFLATABLE MEMBRANE CAN BE ATTACHED TO THE SHELL.

5: SERVICE PIPES FROM THE MAIN BUILDING ARE LAID UNDERNEATH THE FLOOR SLAB INSIDE THE LIVING POD AS SHOWN IN SECTION S-01

6: THE LIVING POD WILL THEN BE READY TO BE PRESSURIZED WITH BREATHABLE AIR.



FIG 1: Robot arm using the frame to fabricate the pavilion (Reichert et al., 2014: 28).



FIG 2: Robot manufacturing arm (Archdaily, 2019, online)

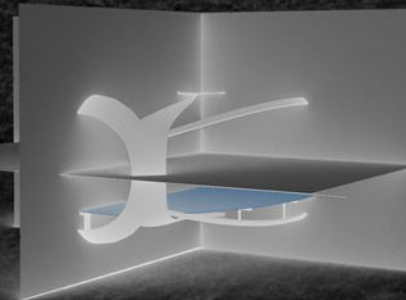


FIG 3: Illustration of similar sections to be manufactured and planes around which the sections are mirrored (author)



FIG 4: Exploded view of the different mirrored sections that form an enclosed shell (author)



Conclusion

From the given research, it is clear that every challenge needs to be addressed for such an endeavour to work. Addressing the absence of a natural atmosphere, extreme temperature variations, and the peculiar nature of Lunar soil, this project demonstrates the multitude of different factors that need to be considered. The replication of the Earth's air pressure, utilising advanced materials like carbon fibre, inflatable membranes, Lunar regolith-derived bricks and a specially developed 3D printer will make a Lunar habitat possible.



References

Aerotrope. 2013. *ARK NOVA*. [Online]

Available at: <https://www.aerotrope.com/what-we-do/art/ark-nova.html>
[Accessed 10 09 2023].

Archdaily. 2019. *BUGA Fibre Pavilion / ICD/ITKE University of Stuttgart*.

[Online]
Available at: <https://www.archdaily.com/916650/buga-fibre-pavilion-icd-itke-university-of-stuttgart>
[Accessed 12 07 2023].

Atkinson, N. 2022. *Lava Tubes on the Moon Maintain Comfortable Room Temperatures Inside..* [Online]

Available at: <https://www.universetoday.com/156932/lava-tubes-on-the-moon-maintain-comfortable-room-temperatures-inside>
[Accessed 09 09 2023].

Benaroya, H., Bernold, L. & Chua, K. M. 2002. Engineering, Design and Construction of Lunar Bases. *JOURNAL OF AEROSPACE ENGINEERING*, Volume 15, pp. 33-45.

Bissegger, K. 2006. *Case Study by Kenny Bissegger*. [Online]

Available at: https://www.academia.edu/6640725/The_Eden_Project
[Accessed 10 09 2023].

Buitink Technology. 2019. *ETFE air-cushions Bellewaerde Aquapark*. [Online]

Available at: [https://www.buitink-technology.com/uk/architecture/etfe-](https://www.buitink-technology.com/uk/architecture/etfe-cushion-roof/etfe-air-cushions-aquapark/)

[cushion-roof/etfe-air-cushions-aquapark/](https://www.buitink-technology.com/uk/architecture/etfe-cushion-roof/etfe-air-cushions-aquapark/)

[Accessed 10 09 2023].

Ding, J., Xie, G., Guo, L., Xiong, X., Han, Y. & Wang, X. 2022. Karst Cave as Terrestrial Simulation Platform to Test and Design Human Base in Lunar Lava Tube. *The Science Partner Journal*, Volume 2022, p. 2023.

Eden project. 2023. *Architecture*. [Online]

Available at: <https://www.edenproject.com/mission/about-our-mission/architecture>
[Accessed 10 09 2023].

Englefield, J. 2021. *SOM's inflatable habitats could allow people to "thrive over the long term" on the Moon*. [Online]

Available at: <https://www.dezeen.com/2021/07/07/moon-village-human-centric-inflatable-habitat-the-moon/>
[Accessed 25 07 2023].

Frearson, A. 2013. *Ark Nova by Arata Isozaki and Anish Kapoor*. [Online]

Available at: <https://www.dezeen.com/2013/09/26/ark-nova-by-arata-isozaki-and-anish-kapoor-completes/>
[Accessed 10 09 2023].

Gibney, E. 2018. How to build a Moon base.. *Nature*, Volume 567, pp. 475-478.

Holstroy. 2023. *Inflatable structure*. [Online]
Available at: https://www.holstroy.com.ua/eng_pnevmo.htm
[Accessed 10 09 2023].

Innovative Composite Engineering. 2023. *What is Carbon Fibre*. [Online]
Available at: <https://www.innovativecomposite.com/what-is-carbon-fibre/>
[Accessed 10 06 2023].

Johnston, R. 2021. *Post*. [Online]
Available at:
<https://twitter.com/DrRichJohnston/status/1371946024940544000>
[Accessed 18 10 2023].

Kwan, J. 2021. *What would happen to the human body in the vacuum of space?*. [Online]
Available at: <https://www.livescience.com/human-body-no-spacesuit>
[Accessed 09 09 2023].

Miller Weldmaster. 2015. *Types Of Inflatable Fabric (Find Out Which Are Durable And Reliable)*. [Online]
Available at: <https://www.weldmaster.com/blog/types-of-inflatable-fabric>
[Accessed 10 09 2023].

Reichert, S., Schwinn, T. & La Magna, R. 2014. Fibrous structures: An integrative approach to design computation, simulation and fabrication for lightweight, glass and carbon fibre composite structures in architecture based on biomimetic design principles.. *Computer-Aided Design*, Volume 52, pp. 27-39.

Selley, R. 2005. *ROCKS AND THEIR CLASSIFICATION*. 1 ed. s.l.:Encyclopedia of Geology.

Sharp, T. 2022. *Atmosphere of the Moon*. [Online]
Available at: www.space.com/18067-moon-atmosphere.html
[Accessed 2 10 2023].

Stull, R. 2019. *Standard Atmosphere - Pressure and Density*. [Online]
Available at:
https://www.eoas.ubc.ca/courses/atasc113/flying/met_concepts/02-met_concepts/02a-std_atmos-P/index.html
[Accessed 09 09 2023].

The Engineering Toolbox. 2011. *Surface radiation absorptivity*. [Online]
Available at: <https://www.engineeringtoolbox.com/radiation-surface-absorptivity-d>
[Accessed 09 09 2023].

The European Space Agency. 2018. *The toxic side of the Moon*. [Online]
Available at:
https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/The_toxic_side_of_the_Moon
[Accessed 09 09 2023].

Thirsk, R., Kuipers, A. & Mukai, C. 2009. The space-flight environment: the International Space Station and beyond. *Canadian Medical Association Journal*, 180(12), p. 1216–1220.

University of Wisconsin. 2023. *Unit 2: Energy Rules! Section B. Energy Transfer*. [Online]
Available at: <https://www.uwsp.edu/wcee/wcee/pd/keep-pd/energy-module/unit-2-section-b>
[Accessed 18 10 2023].

Urrutia, D. E. & Sharp, T. 2023. *What is the temperature on the moon?*. [Online]
Available at: www.space.com/18175-moon-temperature.html
[Accessed 13 7 2023].

Volmer, X. n.d. *Carbon Fibre Canopy*. [Art] (Delft University of Technology).

Zhang, D., Zhou, D. & Zhang, G. 2021. 3D printing lunar architecture with a novel cable-driven printer. *Acta Astronautica*, Volume 189, pp. 671-678.