Biomimicry as a Design Tool for Sustainability in Burning Man

by

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Contents

Abstract

The architecture developed in this thesis explores how to use biomimicry for an integrative architectural element for a harmonious relationship between the building, its users, and the environment.

The Black Rock Desert suffers from the carbon emission and wastes from the Burning Man Festival, where participants intensively use air-conditioners. Three infrastructure was proposed to provide electricity and water. An infrastructure provides natural heating, ventilation, air-conditioner and water collection by emulating the processes and functions of cacti, termite mounds, and prairie dog burrows.

The circular economy was developed by recycling the waste from Burning Man to grow cellulose and chitin for building materials for 3D printing, and by using the locally abundant wind, sunlight, and geothermal to operate the Hydration Room.

This thesis demonstrates a regenerative and sustainable built environment by integrating a circular economy for building life cycle and operation, and HVAC mechanisms from organisms for design principles.

Acknowledgements

I would like to express my gratitude to my committee, James Forren and Brian Lilley, for your timely guidance and encouragement during this process, as my thesis topic is one that I was not initially familiar with.

I would like to thank my parents, who supported me over the past four years.

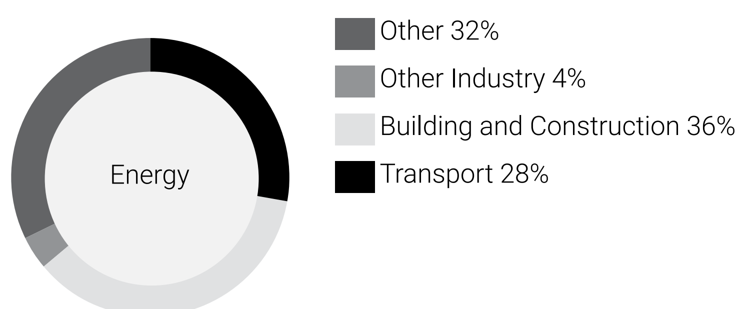
A special thank you to Quinn, Valerie, Jialin, and Yan who supported me to push through this thesis.

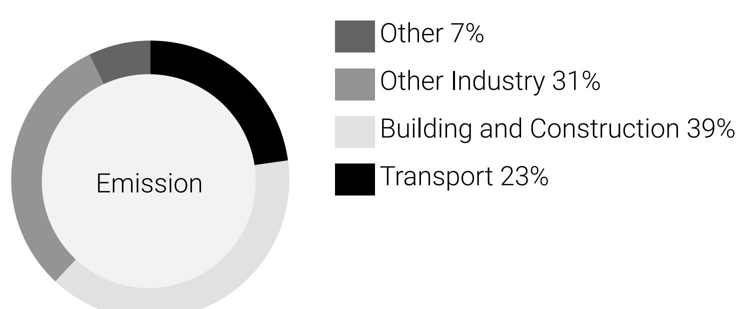
Chapter 1: Introduction

This thesis explores the potential sustainability of biomimicry as a design tool for architecture.

Architecture and Environmental Impact

Buildings are responsible for a great portion of global CO_2 emission as well as energy consumption. Combined, building construction and operations accounted for 36% of global final energy use and 39% of energy-related CO_2 emissions in 2018. With no indication that these numbers will be relieved in the near future, it is fair to say that architecture drastically deals with the environment. Currently, many countries are working on policies to adapt the environmental impact (GlobalABC, IEA and the UN 2019, 1-18), which calls for designers to address sustainability in their design.





Global energy use and carbon emission (GlobalABC, IEA and the UN 2019, 1-18)

Biomimicry and Sustainability

Sustainability in this thesis refers to the act of doing less harm to the environment in building operation and construction. Biomimicry, the concept of taking inspiration from flora, fauna, or ecosystems being emulated as a design method is a growing interest of research in the field of architecture. This is not only because it is an innovative method, but it also offers the potential to create a sustainable and regenerative built environment.

Approaches and Dimensions of Biomimicry

This thesis explores three approaches of biomimicry: organism, behavior, and ecosystem and their potential sustainability. The organism approach emulates the morphological or physiological features of an organism; the behavior approach studies the thermal regulation mechanism of animal nests; the ecosystem approach aims to create a circular economy for both finite and renewable material and energy. Since each approach addresses different dimension of nature, this thesis argues that three approaches combined can lead to greater sustainability.

Material and Construction

Technology advancements in material and 3D printing can enhance the sustainability of biomimicry. Developing non-toxic and multi-functional materials with 3D printing has been a growing trend in the architectural realm. The mix of cellulose and chitin, the two most abundant biomaterials on Earth, displays immense structural strength. Controlling the concentration of chitin can create transparency difference, which can be used for lighting. Also, the Hydroscopic Aperture project displayed how a window can operate autonomously by using the inherent material behavior of cellulose responding to moisture.

Biological Models for Energy Management

Biological models were selected in this thesis to develop a strategy for architecture in terms of the form, material layering, and HVAC system. This thesis studied the following precedents by the approach and dimensions of biomimicry:

- Geometrical and physiological features of barrel cacti for dealing with the desert climate in terms of heating and cooling, wind-resistance, and water collection.
- Termite mounds and prairie dog nests for their natural ventilation mechanism by utilizing the wind energy and the sun.

Demonstrator Project - Burning Man

This chapter analyzed the ecosystem of Black Rock City as well as specific sources of pollution from Burning Man for the resources available to support a regenerative cycle for architecture and the master plan. Burning Man is an annual festival held at Black Rock Desert, Nevada, US. It was selected as the testing site for its huge negative impact generated during its 10-day period. The crowd reached 80,000 people in 2019, effectively becoming the third largest city in Nevada for the duration of the festival. Burning Man direly needs to make changes in order to host the event without harming the desert, not only to satisfy its own sustainable policy to protect the area, but also to appease the requests of the local government and nearby residents (Donnelly and Jones 2019).

Thesis Question

How to develop integrated strategies based on biomimicry with the currently technology to create a sustainable and regenerative built environment?

Chapter 2: Biomimicry

This chapter details the various forms of biomimicry and the potential sustainability inherent in each approach. Pedersen Zari, a proponent of biomimicry, suggests that these different approaches will likely lead to different results in terms of overall sustainability . It is assumed that a biomimetic approach to architectural design with an understanding of the ecosystem can be a tool for creating a regenerative practice where the built environment becomes a vital element in the integration with natural ecosystems (Zari and Storey 2007, 3). In addition to Pedersen Zari's point of view, this thesis argues that the combination of all three biomimetic approaches can lead to a greater sustainability.

Definition

Biomimicry is the emulation of nature to create efficient or sustainable design solutions, as opposed to merely exploiting the resource of nature (Pawlyn 2016; Fisch 2017). This concept studies nature's models and mirrors their functions, processes, and behavior in order to mitigate the environmental impacts, or at least attempt to (Aanuoluwapo and Ohis 2017, 1). The term biomimicry was first coined in 1982 and popularized by scientist Janine Benyus in her book *Biomimicry: Innovation Inspired by Nature* published in 1997. Benyus suggests looking to nature as a "Model, Measure, and Mentor," and emphasized sustainability as an objective of biomimicry by studying nature to solve human problems.

Biomimicry, Architecture and Sustainability

Architecture has long used nature for inspiration. How people use biomimicry is constantly evolving. During the first century BC, the Roman architect, Marcus Vitruvius Pollio, opened a new dimension in biomimicry by comparing the propositions of temples with the dimensions of the human body. Copying figures and proportion was the only application of biomimicry in architecture until the end of the 19th century (Mahmoud 2010, 1; El Ahmar 2011, 15). In the 20th century, Frei Otto, Antoni Gaudi, and others mimicked forms, structures and material behavior, opening a new chapter for biomimicry (Mahmoud 2010, 2). The sustainable benefits of biomimicry are gradually being uncovered – finding structural inspirations from organisms results in a reduction of material usage for structural performance; mimicking the form can tune architecture for better energy management.

In recent years, researchers of biomimicry advocate not only to mimic the form and structure, but also to emulate the processes and functions of organisms or ecosystems to fully explore the sustainability potential of biomimicry. Since organisms in nature have developed a concerted way to work with their environment over millions of years; they interact with the environment in a sustainable way, without depleting natural resources or polluting the environment. This coordination of organisms and its surroundings can be compared to the relationship between a building to its surroundings (El Ahmar 2011, 2; Mahmoud 2010, 2).

Approaches of Biomimicry

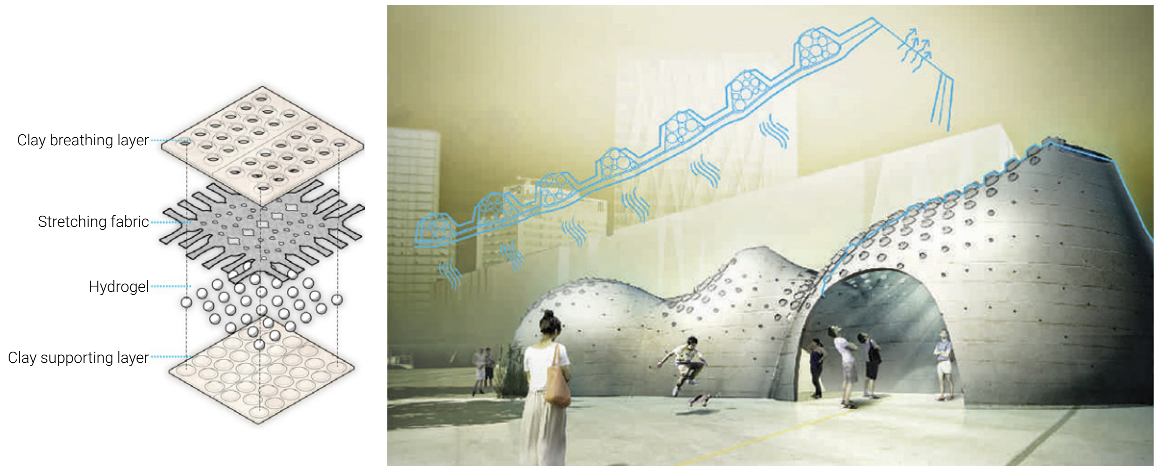
Pedersen Zari is a professor at Victoria University of Wellington in New Zealand who studied and created the basic theories of biomimicry with the connection between biology, nature, and architecture. By examining the biomimetic ideologies and implementations from other scientists, designers, and writers, Pedersen Zari was able to break down biomimicry into three different approaches as below (Maglic 2012, 11):

- Organism approach: The emulation of morphology and physiology of plants or animals.
- Behavior approach: The emulation of the actions of animals.
- Ecosystem approach: The emulation of the process and functions of elements in an ecosystem.

Organism Approach

The organism approach refers to mimicking a specified organism, such as a plant or animal. The focus of study can be the entire organism or only a portion of the organism (El Ahmar 2011, 14). Two dimensions of an organism can be observed: physiology and morphology.

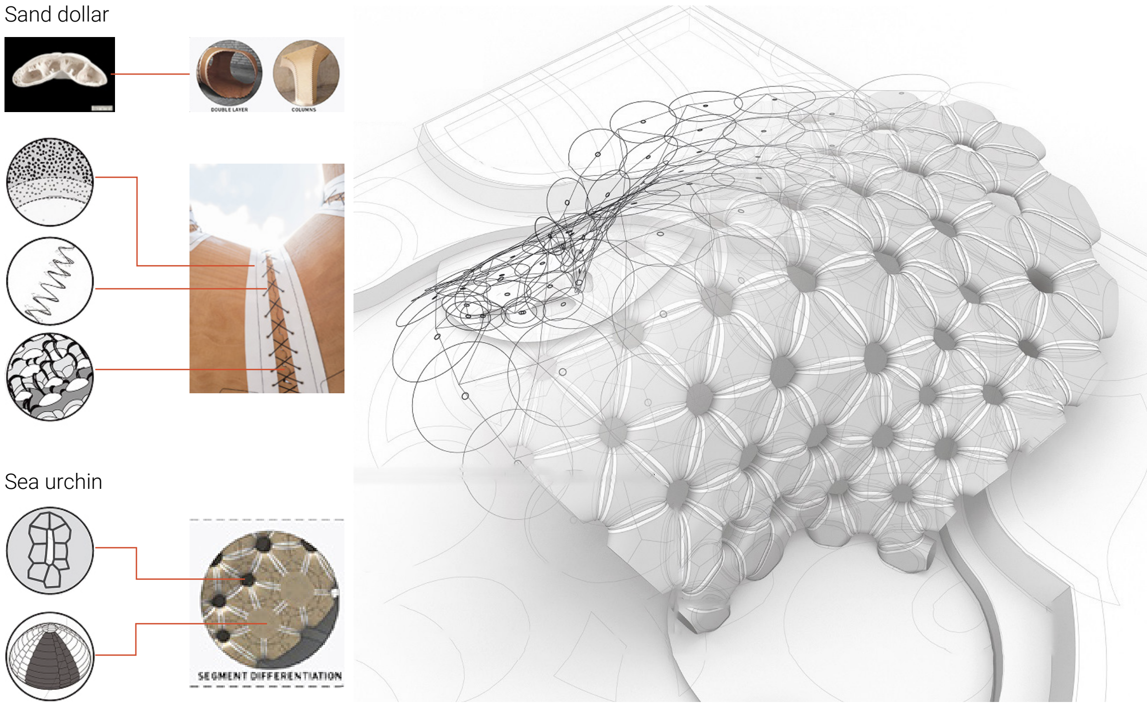
Physiology refers to the internal response of an organism to an external stimulus to maintain homeostasis, such as the skin of mammals sweating to cool down. For example, The Hydroceramic Pavilion is a design of sandwich panel that implements evaporative cooling with hydrogel, ceramic and fabric, a composite material responsive to heat and water. The proposed solution is a passive system able to lower the temperature of an interior space by 5°C. Hydrogel holds the moisture for evaporative cooling, with the fabric as the water channel, and the ceramic aids the cooling properties of said hydrogel. The system works with a water channel that consistently supplies water, and a base material that holds the water. As the hot air hits the hydrogel, the water absorbs the heat thereby causing it to evaporate (IAAC Blog 2014).



The Hydroceramic mimicks human skin sweat for evaporative cooling. (IAAC Blog 2014)

Morphology is the structural or geometrical feature that enhance the adjustment of an organism to a particular environment and enables better functionality for survival, this has realized in size, form, and pattern (Badarnah 2017, 5).

For instance, ICD/ITKE Research Pavilion 2015-16 is an emulation of the constructional morphology of sand dollars and sea urchins. The procedural principles of growth was simulated for an integrative design process for the structure. The performance of these modular lightweight structures relies on both the arrangement of individual plates, and the geometric feature of a double-layer system. The plates are connected through fibrous elements along with the finger joints, and the researchers hypothesized that this multi-material connection is vital to maintain the integrity of the sea urchin's shell during growth and exposure to external forces. The material system was developed as a double-layered structural unit, which consists of extremely thin wood strips. (ICD/ITKE University of Stuttgart n.d.)

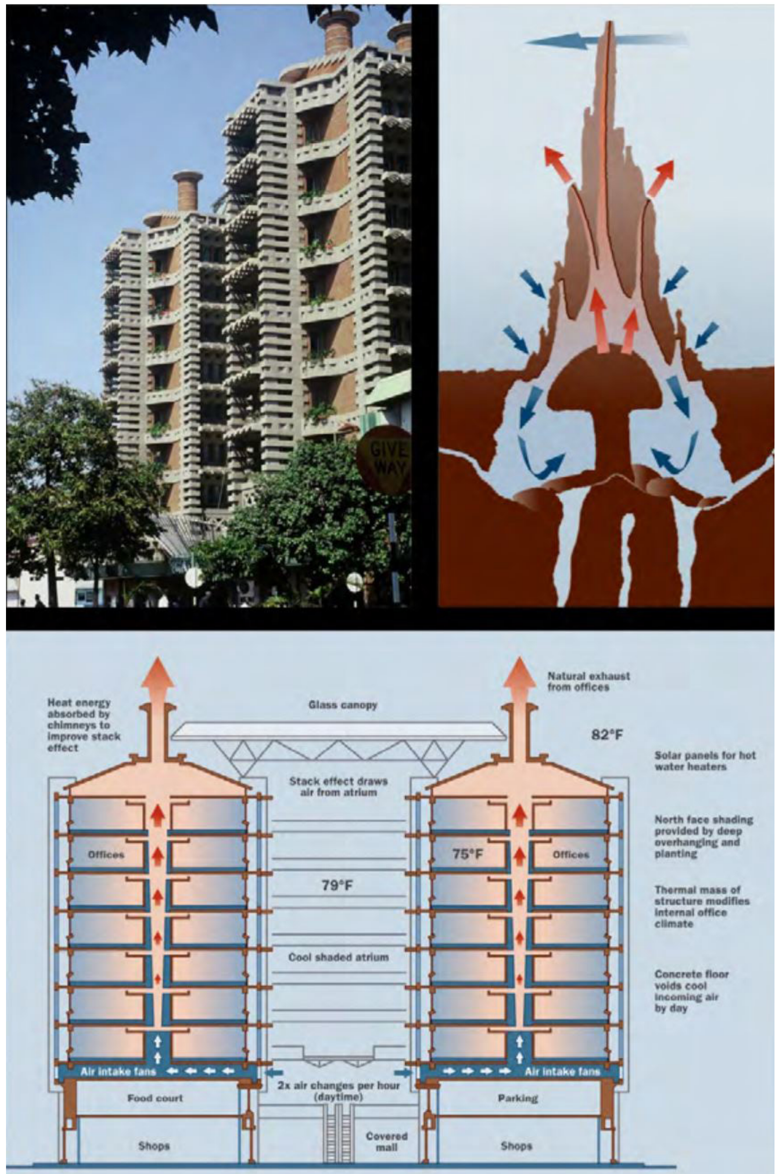


ICD/ITKE Research Pavilion 2015-16 (ICD/ITKE University of Stuttgart n.d.)

Behavior Approach

The behavior approach refers to imitating a specific type of behavior or action that an organism performs in order to survive (Maglic 2012, 32; El Ahmar 2011, 14). The Eastgate Center is an example of echoing the mechanism of termites building their nests, for a passive HVAC system.

The designers studied termite mounds for a possible solution for the problem of heating and cooling a large structure for the Eastgate Center in Africa. The termite habitat is climatically extreme, ranging from as high as 40°C in the day to as low as 1.7°C at night. To protect their royal areas and maintain food sources, they developed a way to preserve the temperature of their nest to be exactly 30.5°C at all times. To achieve this, the termites open and close specific vents in the mound to create convection currents for thermal regulation. Air is absorbed at the lower part of the mound, down into the center of the muddy walls, and up to the peak of the termite mound (Maglic 2012, 21).



The Eastgate Centre. Inspired by termite mounds that maintains comfortable conditions close to the equator in Zimbabwe without mechanical cooling. (Pawlyn 2016, 45)

Ecosystem Approach

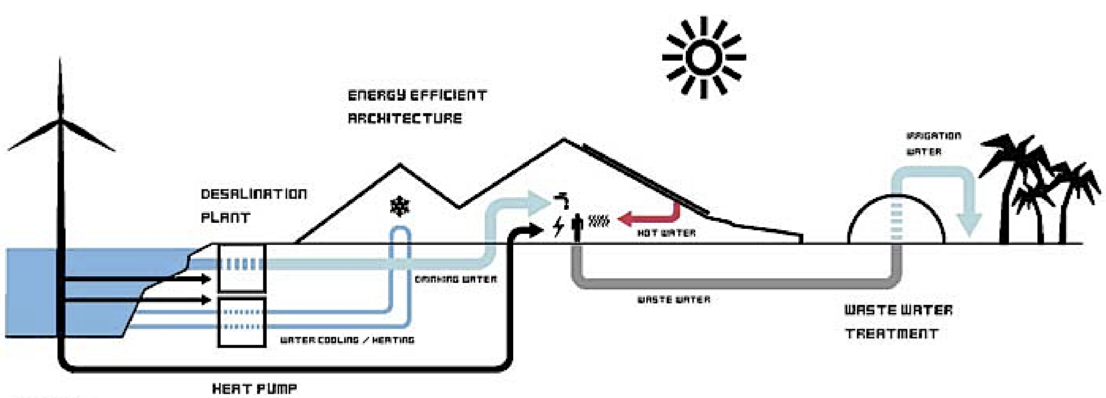
The ecosystem approach of biomimicry refers to emulating an ecosystem for its functions and the required elements and principles for the success of operations. (Maglic 2012). Pedersen Zari suggested that if biomimicry is to increase sustainability for architecture, the principles of ecosystem should be integrated into the design at the earliest stage (Zari and Storey 2007, 8).

Circular economy is the spine of ecosystem approach in regards to material and energy regeneration. Biological systems have evolved to thrive in closed loops, in which there is no concept of “waste,” such that everything is considered a nutrient (Pawlyn 2016, 67). Circular economy maximizes the value of available resources and has distinctive principles as below (Pawlyn 2016, 43-79):

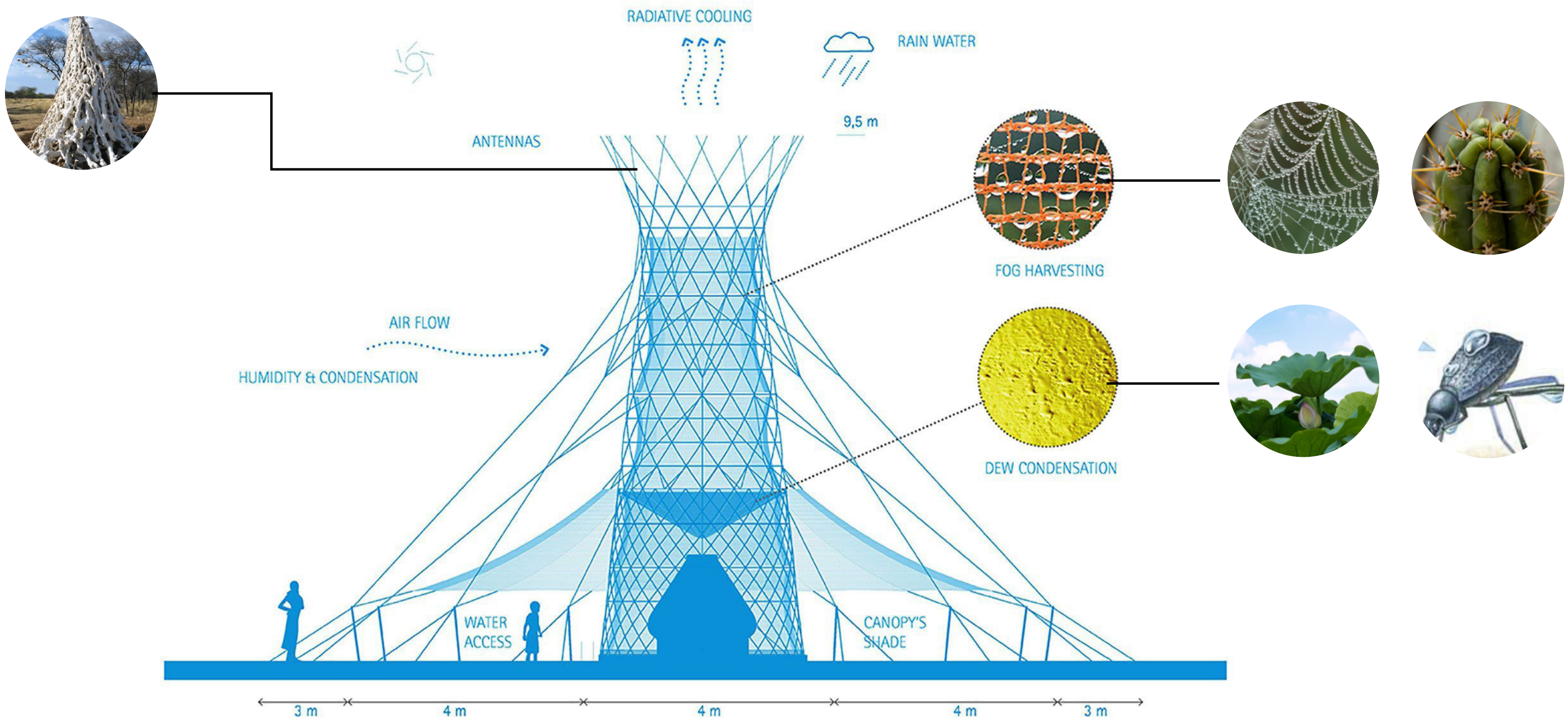
- Dividing materials into finite and renewable categories, such as metal belongs to the former and wood to the latter. Closed loops can be created by recycling and repurposing finite materials and regrowing renewable materials.
- Encouraging the use of renewable energy, such as wind, water, sun, and geothermal.

Two ecosystem examples the Zira island and the Warka Tower were analyzed here. The Zira Island was designed to be a Zero Energy entertainment city on an existing island. The designer of Zira Island proposed to transform the island from a place with no vegetation, water, or resources to a self-sustaining ecosystem. In order to power the entire island, a combination of various technologies to was proposed; wind energy from the Caspian Sea was harnessed to power desalination plants, and these plants were incorporated to convert sea water into fresh water for drinking. Collected water was also used for heating/cooling the buildings and waste water was dispersed throughout the island so vegetation could grow. Additionally, storm water was collected and recycled for irrigation. The waste produced during the processing and filtering were saved to be fertilizer for the vegetation (Maglic 2012, 23).

The Warka Tower is a water-harvesting infrastructure serving several rural communities in Ethiopia. There, the villagers live in conditions often without running water and electricity. The Warka Tower is a lightweight, easily constructed, and independent infrastructure system that provides a social place for the community, where people can gather under the shade of the canopy. The project was designed from the study of insects and plants to develop the capability of collecting water from the air in one of the most arid environments on earth. The designer also studied local craftsmanship and construction techniques from African vernacular architecture, and applied his studies by integrating a bamboo frame that supports a mesh polyester material inside to collect water from fog and dew (Climate Action Challenge n.d.).

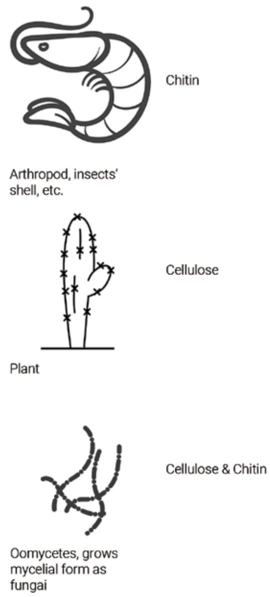


BIG Architects, carbon neutral master plan (Maglic 2012, 23)



Warka Tower (base drawing from Climate Action Challenge n.d.)

Material and 3D Printing



Sources of cellulose and chitin

As an additional part of biomimicry approaches, technology advancement influence how designers implementing biomimicry and enhance the sustainability potential of biomimicry. Developing multi-functional and biological material in 3D printing is a growing trend in the world of building materials as well as construction methods. Cellulose and chitin are the first and second most abundant polymers on Earth; they are consistently a topic of research for their potential application in manufacturing. Cellulose is usually found in plants, and chitin in arthropods, but the occurrence of both biopolymers as structural components are largely found in eukaryota and bacteria. Despite their abundance, they rarely appear together in the same organism. Only certain species of oomycetes have both cellulose and chitin; oomycetes grow in a mycelial form like fungi (Sanandiya et al. 2018, 1).

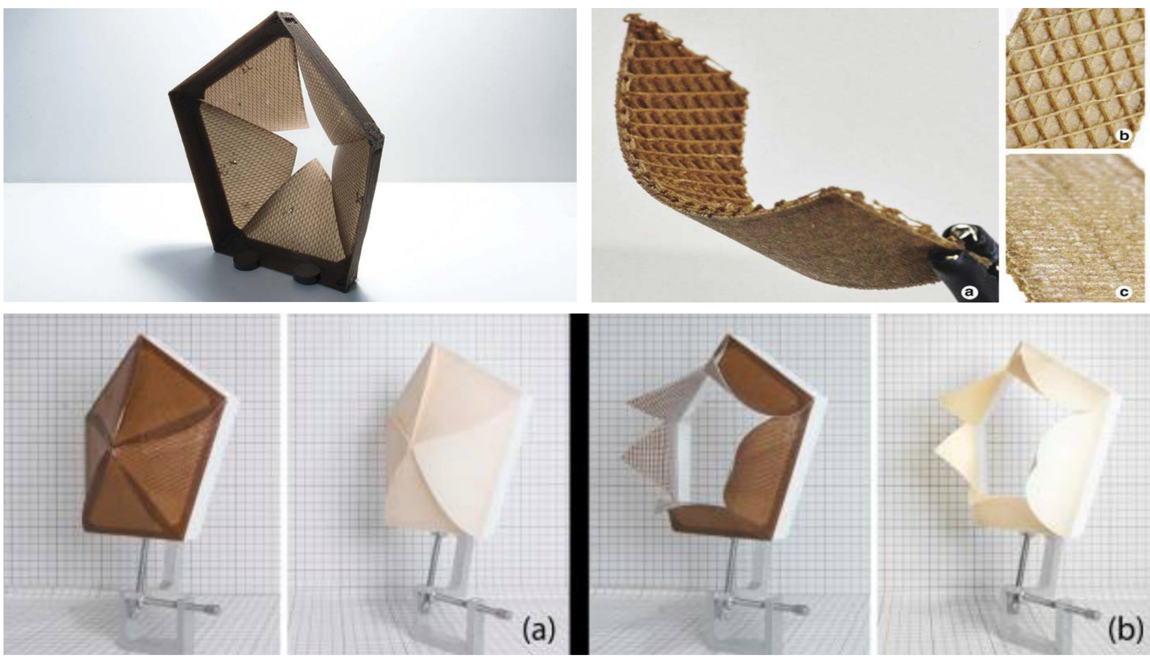
3D printing technology is an additive manufacturing technique in contrast to conventional manufacturing techniques. Traditional techniques can be summarized as subtractive (carving wood), moulding (clay pottery) and forming (bending and forging metal). Three features of 3D printing are (Pawlyn 2016, 48-49):

- Able to print mixed raw materials in nanoscale particles, as the minuscule scale of the material allows low-energy bonds to assist in assembling the particles.
- The direct translation from digital model to physical model requires a less laborious process for construction and allows for the bottom-up manufacturing that occurs in nature, which in turn uses less material compared to conventional construction methods.

- Able to print functionally graded material in one piece.

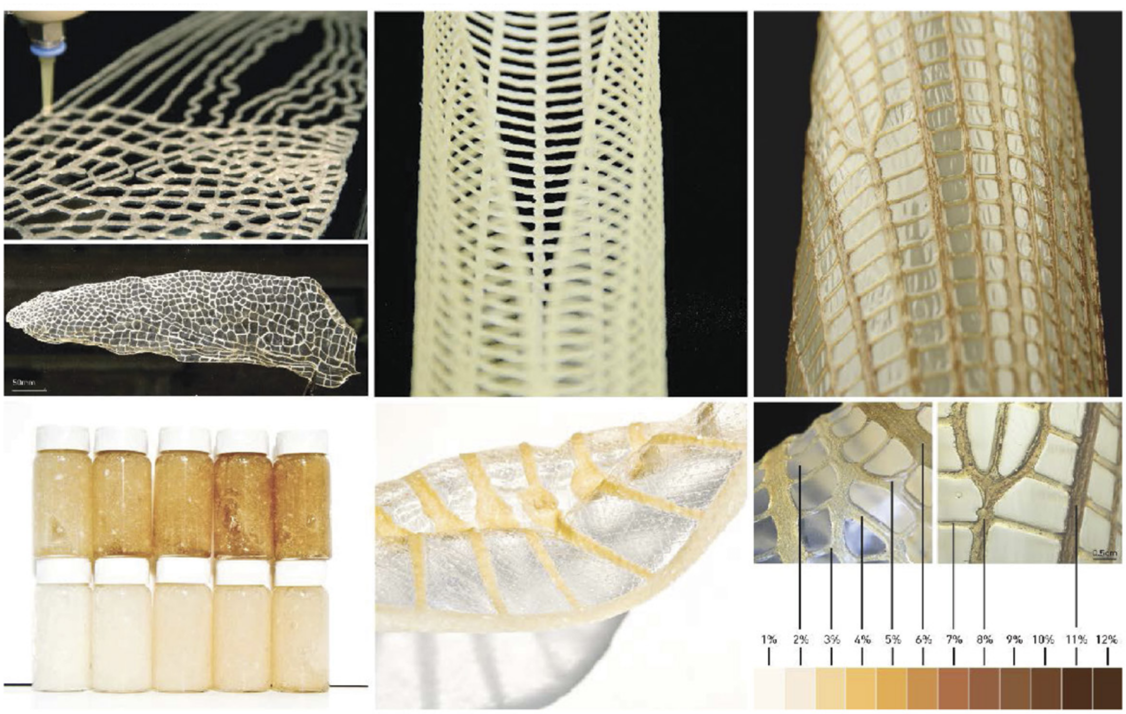
Three projects show the promising development of using biomaterials with 3D printing in architecture, The Aguahoja Pavilion, The FLAM, and The Hydroscopic Aperture.

The Hydroscopic Aperture utilizes the inherent material behaviour of cellulose to operate window opening. Cellulose is hydrophilic and absorbs moisture, and the designers took advantage of this. The window system consists of five cellulose petals and when exposed to moisture, the petals bend to a different extent according to the moisture level (Correa Zuluaga and Menges 2015, 4).



The Hygroscopic Aperture (Correa Zuluaga and Menges 2015, 4)

The Aguahoja Pavilion demonstrated the fabrication of a paneling system using cellulose and chitin with the use of 3D printing technology, and the result displays mechanical, biodegradable, and optical properties. The combination of cellulose members and tensile chitin membrane shows high structural performance in both bending and tensile strength. Chitin-only depositions can be mechanically and optically graded. For example, by using chitin gels of different concentration in acetic acid aqueous solution (from 1% to 12%) tocreate transparency difference.. Structural strength gradients can be accentuated by using various thickness extrusion path arrangements, or by using different nozzle sizes for each extrusion path (Mogas-Soldevila and Oxman 2015).



The Aguahoja Pavilion . 3D printed panel system in cellulose and chitin demonstrated structural strength and transparency property. Left Column: Chitin and sodium alginate (extract from algae). Middle Column: Chitin and cellulose. Right Column: Chitin and acetic acid. (Mogas-Soldevila and Oxman 2015, 6)

The FLAM project also used cellulose and chitin to create a load-bearing structural piece by 3D printing the element, which demonstrated the capability of using biomaterial for large-scale manufacture. The uniqueness of this project is that the printed result can be processed or molded with woodworking techniques (Sanandiya et al. 2018).

The FLAM project, 3D printed panel system in cellulose and chitin in large scale manufacture (Fernandez 2018)

Conclusion

Biomimicry is materialized in various forms, it is suggested that mimicking organisms alone without emulating how they participate in the ecosystem has limited sustainability. Replication of organisms tends to be of a specific feature rather than an entire system that relegates biomimicry as a secondary technology, often added as an afterthought, rather than being integral to the process (El Ahmar 2011).

b)For example, the ICD/ITKE Research Pavilion 2015-16 demonstrated the benefit of mimicking organisms, which increase sustainability by using fewer materials to achieve structural performance. However, this project shows that using one approach alone only addresses a few dimensions to achieve sustainability. This thesis believes that adapting all the three approaches to make architecture in every phase of its life cycle, from manufacturing, design, construction to operation can achieve greater sustainability.

Each of the three approaches studies different aspects of an organism or ecosystem; the dimensions of each approach as applied in this thesis can be summarized as follows:

- Organism approach: Physiological features to maximize the characteristics of materials and morphological features to develop architectural form to reduce energy consumption.
- Behavior approach: The natural HVAC system from the nest of animals.
- Ecosystem approach: A regenerative economy by maximizing the value of both finite and renewable resources, integrating the uses of natural resources into architecture, and implementing construction and material processing methods that impart less harm to the environment.

Chapter 3: Biological Models for Energy Management

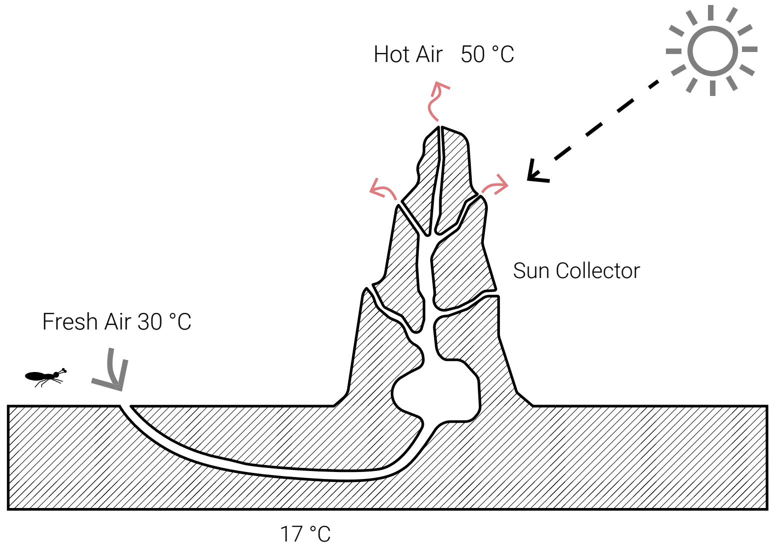
This chapter documents the studies of cacti, termite mounds, and prairie dog burrows to better understand how these biomimetic principles operate in nature. In addition to scholarly research, this thesis conducted research by dissecting and physical analyzing of barrel cacti. The behavior approach was used to study the passive ventilation of termite mounds and prairie dog burrows. Organism approach was used to analyze the morphology and physiology of cacti for their capability to deal with the desert for thermal regulation, wind resistance, and water collection. Bedouin tent is an all biomimetic approach example, which demonstrates a possibility for making a regenerated living environment.

Buoyancy-Driven Ventilation in Termite Mounds

Buoyancy-driven ventilation is the air flow that results from temperature differences between the interior and exterior. It is known as the stack effect, and solar energy is widely used to drive it (Walker 2016). Termite mounds utilize the buoyancy of air to induce air flow, using its central chimney

Termite mound (Mining Magazine 2017)

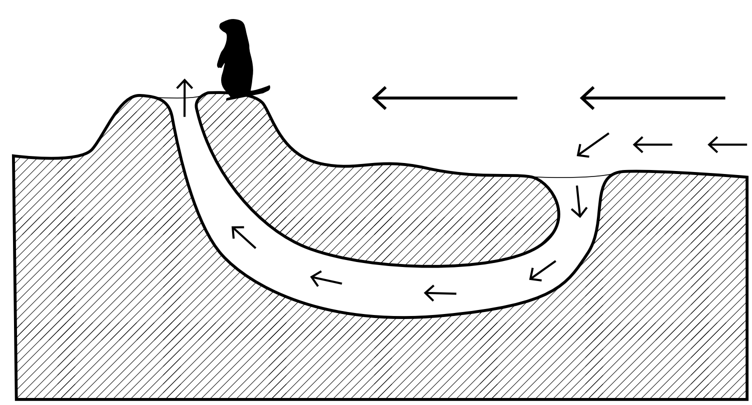
to collect solar energy to take in fresh air and release the exhausted air. (Tuner and Soar 2008, 3).



Air ventilation in a termite mound (illustration based on the diagram from Shenoy Innovation Studio 2011)

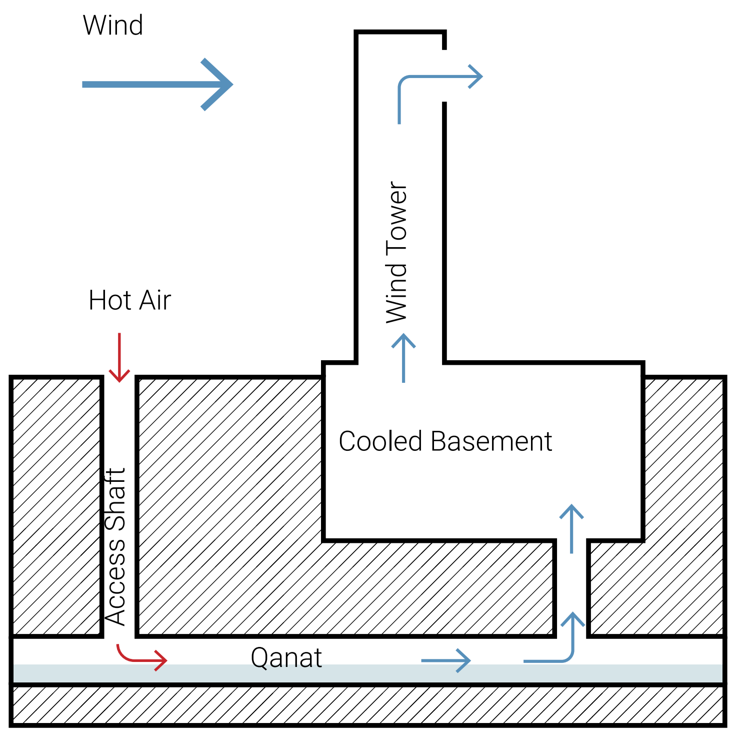
Wind-Driven Ventilation in Prairie Dog Burrows

Wind-driven ventilation is the flow of air caused by pressure differences of wind; wind causes a positive pressure on the side of buildings that faces the wind and a negative pressure on the other side (Walker 2016). The prairie dog builds a mound with an elevated opening upwind and a mound with a lower opening downwind. The wind velocity is faster over



Wind Pressure of Prairie Dog (illustration based on the diagram from Spatial Experiments 2016) the elevated opening than over the lower opening, which creates a pressure difference. This difference between the two openings creates one-direction flow through the burrow as air is swallowed into the lower opening and exists through the elevated opening (AskNature 2018).

A wind tower is a traditional Iranian architectural element to create natural ventilation. It comes in various design forms, where one design is similar to the ventilation of the prairie dog, which uses the air pressure difference to move the air flow (Pour 2011, 56).



Wind tower (illustration based on diagram from Bailey 2009)

Cacti

Cacti in the desert have unique mechanisms to regulate thermal conditions and collect water, from the material characteristics to the organs in multiple scales. Cacti were studied in these categories: material characteristics, water collection, thermal regulation, wind resistance, and organization.

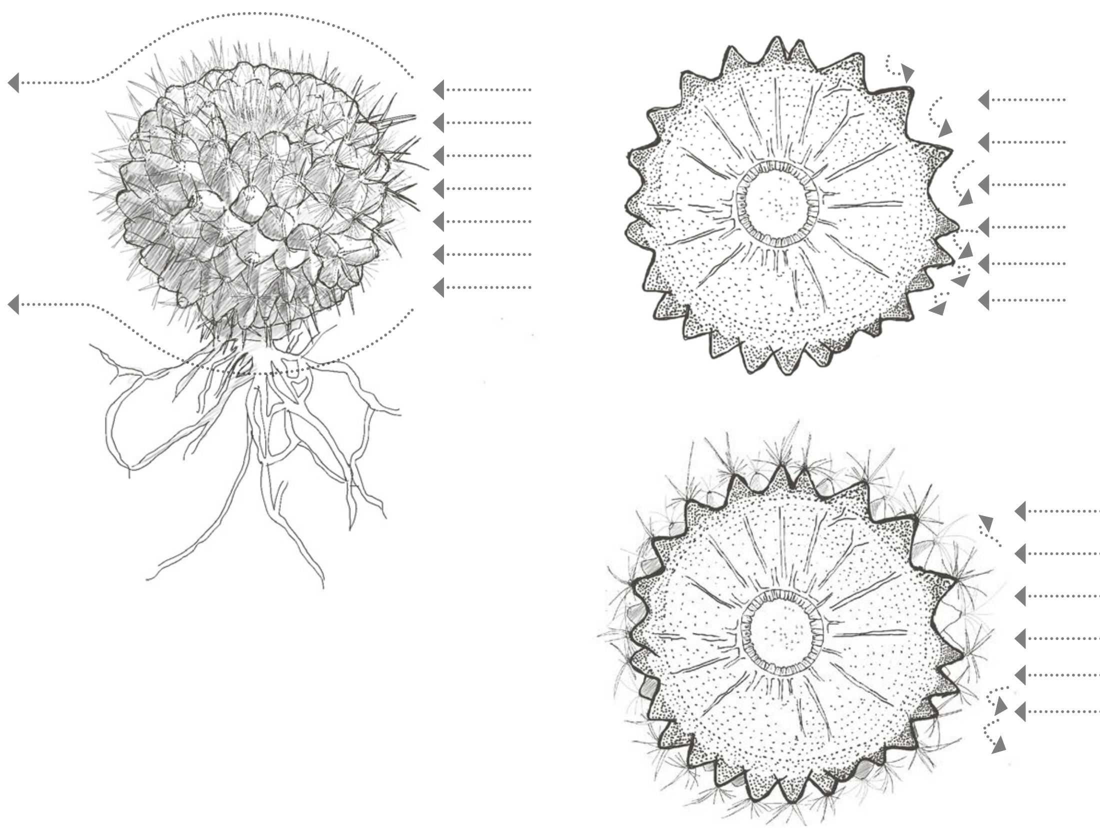
Material Gradient of Cacti

The colour gradient (from the darker green to the lighter green of the section) shows a material gradient as well as functional gradient (the lighter colour indicates softer texture, meaning higher deposits of water, resulting in weaker structural integrity). The darkest green is made of cutin, a waxy and translucent material. A hydrophobic polymer protects cacti from dehydration and disease. The light green is made of mucilage, a hydrophilic material to deposit water. It is a gooey and gelatinous material secreted by the plant cells.

Photos of the two dissected barrel cacti

Wind Resistance

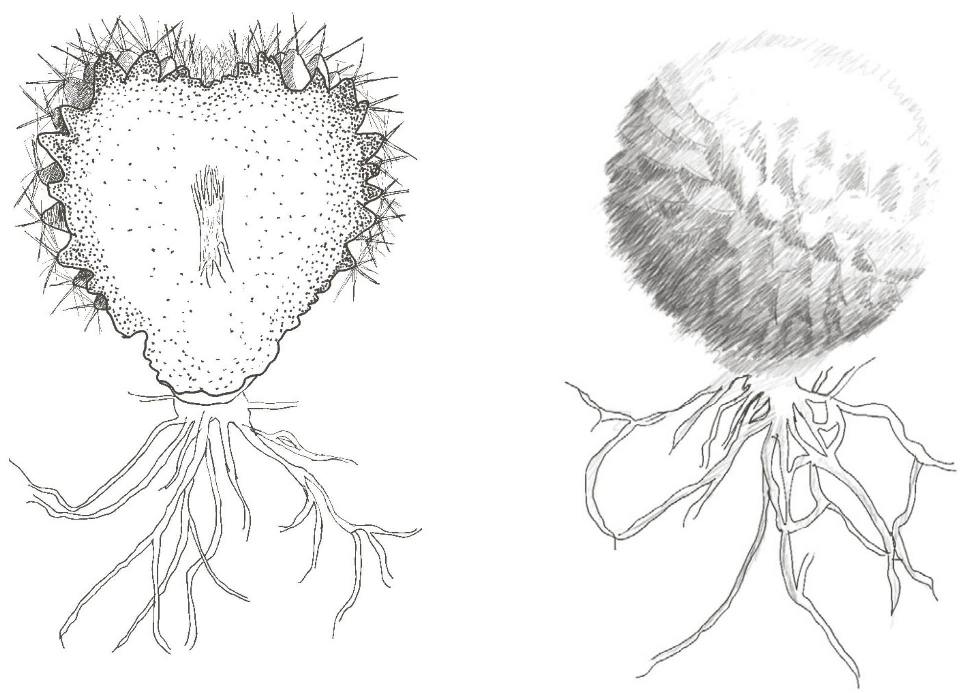
The stem of cacti can contain up to 95% water and they have little hard wood tissue which makes their structural strength low. However, this in combination with a root system displayed the ability to withstand high wind. The shape of the cactus is excellent to handle wind loads - the peak and the valley of tubercles, the spines, and the round shape assist in reduction of the wind load at high wind velocities (Babu and Mahnesh 2008).



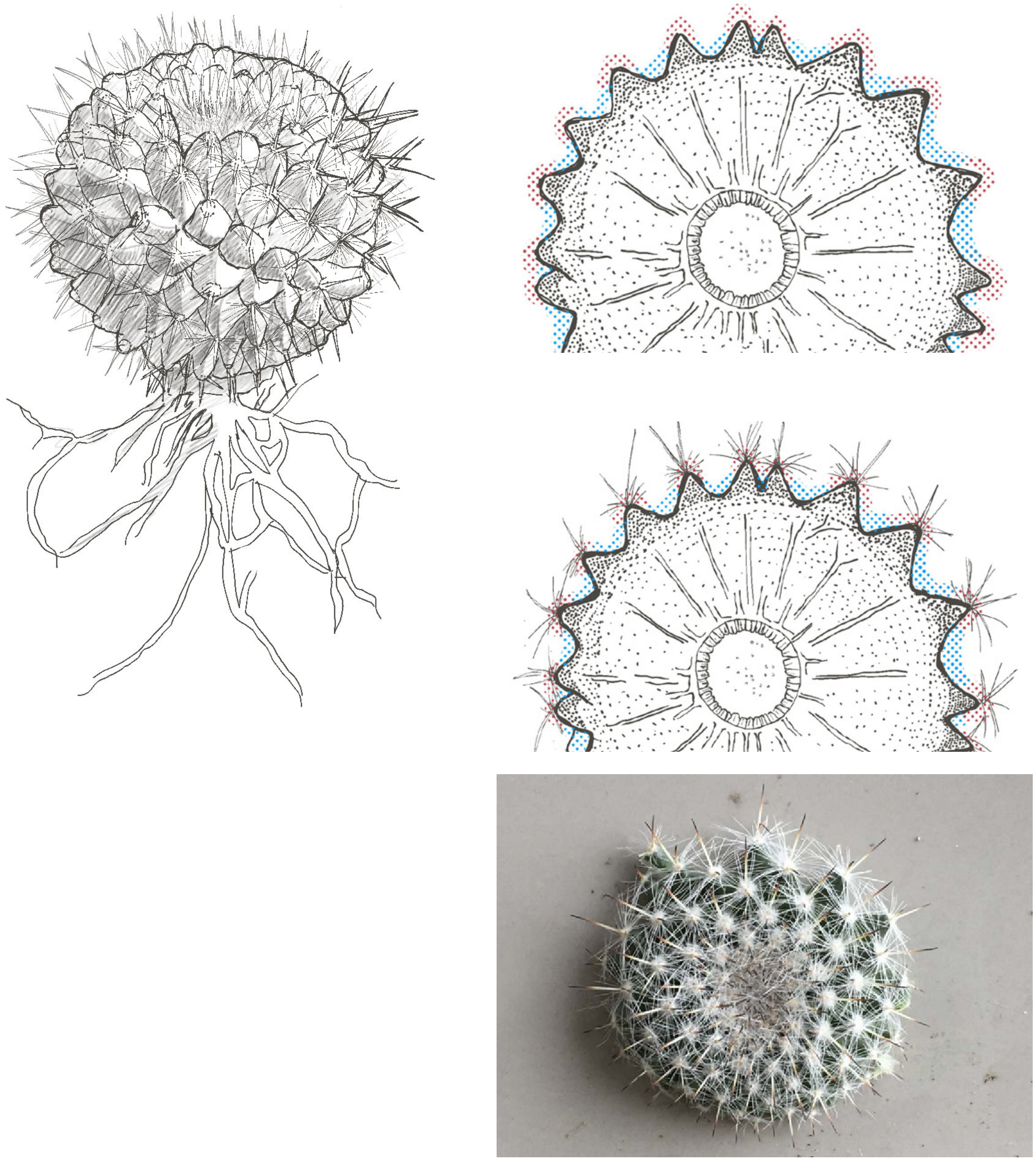
Left: Round shape reduce wind impact.
Top right: The shape of cacti is excellent for handling wind loads. The plants have cavities and peaks along the stem assist in reduction of the fluctuating aerodynamic loading.
Bottom right: The spines also helps to reduce the aerodynamic loading.

Thermal Regulation

The cooling mechanism is embedded in the spines, tubercles, and the overall shape, same as the geometry developed for wind resistance. The spines and tubercles create micro air currents, which facilitate the radiation of heat (Krulik 1982). The light color of trichome and spines reflect sunlight (Williams Jr. 2005, 11-13). The tubercles provide self-shading and the round shape of the cacti reduces the area of sun exposure and heat gain. The spongy stem of cacti stores water, effectively making cacti thermal masses, keeping them warm at night and cool during the day (Krulik 1982).



Left: The spongy stem deposits water thus the entire cactus is a thermal mass.
Right: Round shape reduce surface area for heat gain and direct sunlight.

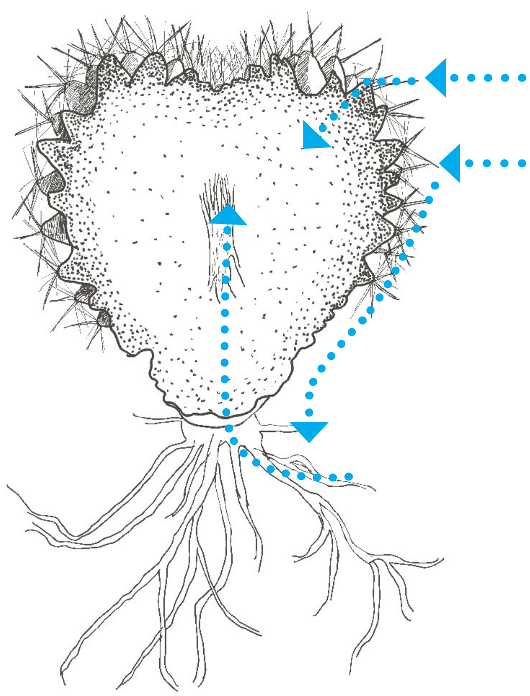


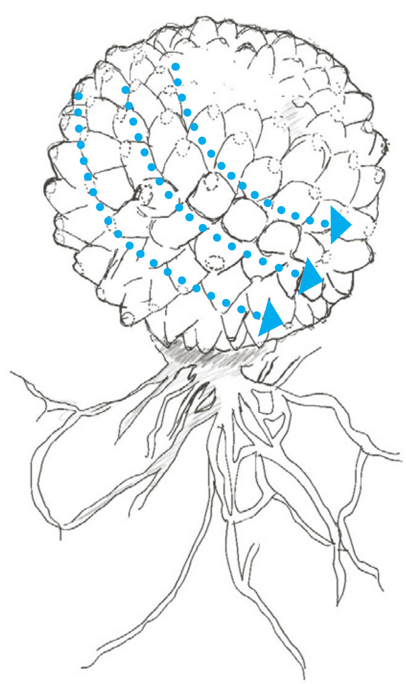
Left: Tubercles create shadows for shading.
Top right: Tubercles or ribs create temperature difference on the peak and the valley to create air current to radiate heat.
Middle right: Spines help to trap air current to radiate heat with ribs or tubercles.
Bottom right: Light-colored spins and trichome reflect light and heat.

Water Harvest

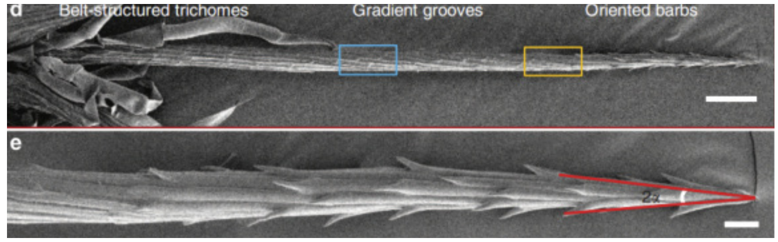
Cacti harvest water from the root and the spines. The shallow root is developed to absorb water as soon as the water touches the ground, and certain geometries and material combination demonstrated the capability to accelerate water flow so it is absorbed before the it evaporates.

Cacti have multiple mechanisms in various scales for collecting water from fog and dew to ensure they are sufficiently hydrated in the arid environment in which they live. They have three structures crucial for fog collecting: the conoid shape structure of the spines, the oriented barbs, and the grooves on the spines. The trichomes at the base of the spine quickly absorb water due to the capillary force formed by the trichomes and the spines. These geometries within the trichomes create a pressure gradient from the top of the spine to the bottom, which direct the droplets from the peak to flow into the body of cacti (Ju et al. 2012).

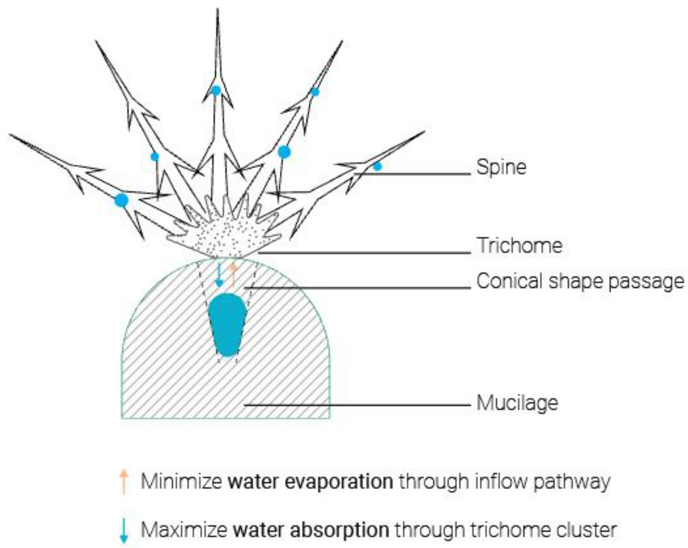




Left: Two ways for cacti to absorb water, through the spines or the root.
Right: Helical pattern accelerate water flow.



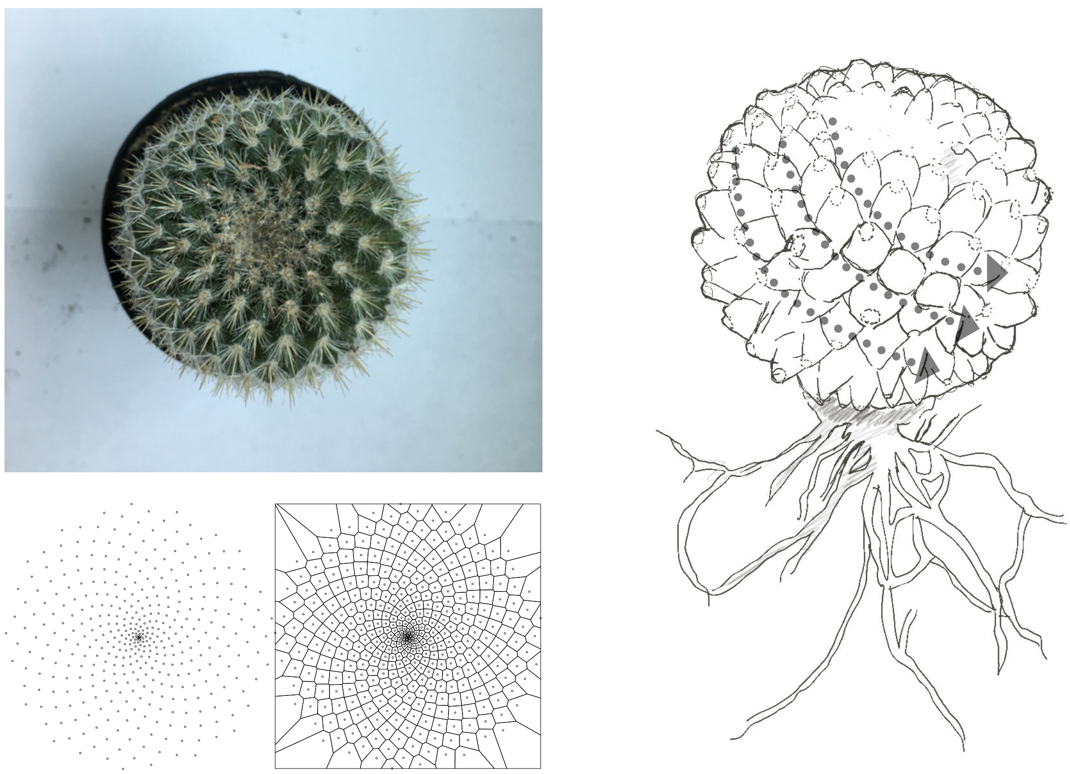
Barb and grooves in microscale (Kim et al. 2017, 2).



The layering of hydrophilicity and hydrophobicity of spine-trichome-cortex creates a directional flow from the top of the spine towards to the stem. Additionally, the cone shape of the water passage accelerate the water flow (Illustration based on the diagram from Ju et al. 2012, 2).

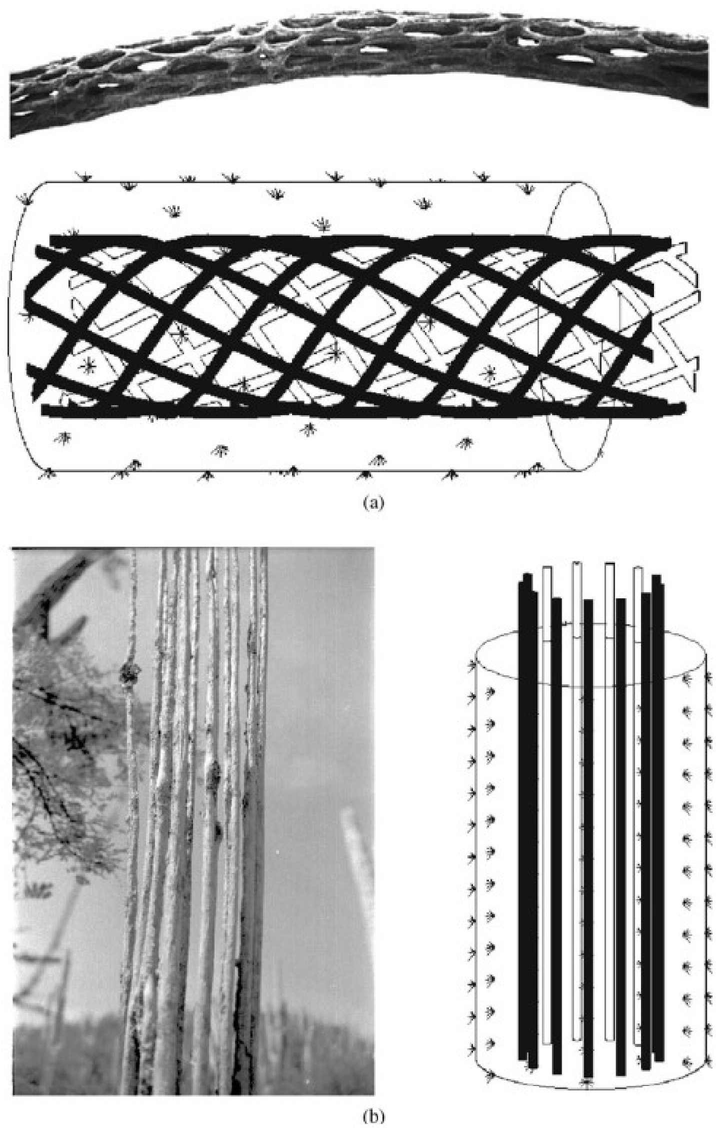
Helical Pattern in Tubercles and Vascular Bundles

Cacti has helicap arrangement of the tubercles, in many plants helical patterns has different functions, here it might speed up water flow towards the root (Pawlyn 2016, 84-85). Voronoi diagram is a common pattern in nature to distrubute space evenly. In cacti, the evenly packed tubercles are in voronoi diagram, along the helical pattern, thus to evenly cover the cactus for self-shading.



Top left and right: Helical pattern in cacti.
Bottom right: Helical pattern and voronoi diagram for water acceleration and space distribution.

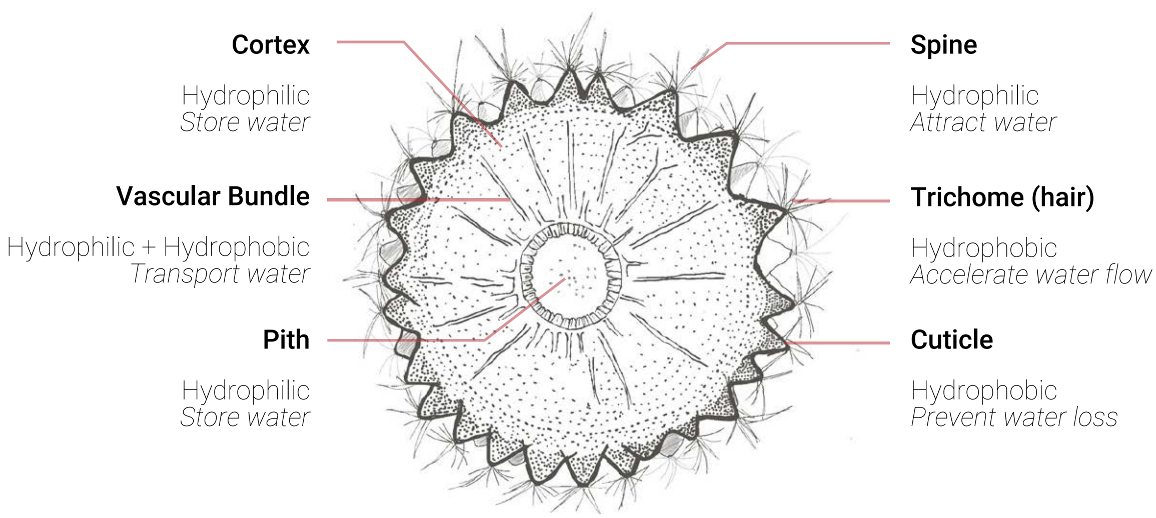
The helical pattern happens not only on the surface of tubercles but also in the structure, resulting in a vascular bundle. In addition to that, the pattern also facilitates water absorption and flow of the vascular bundle (Altesor and Ezcurra 2003, 565).



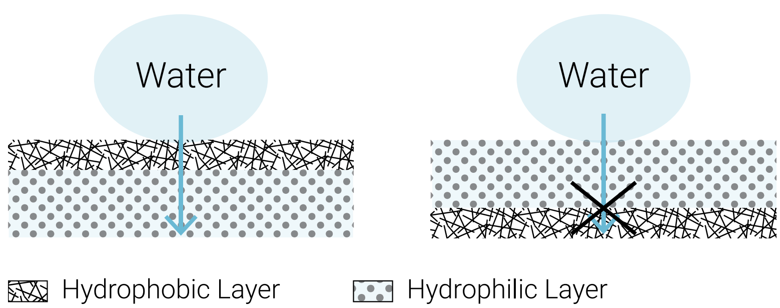
The section cut across the stem of vascular tissue.
This woody material has a structural function and forms the supporting skeletons of many cacti. (Altesor and Ezcurra 2003, 564)

Material Characteristics

The material characteristics of organ layering are particularly effective to facilitate direct water flow, by alternating hydrophilic and hydrophobic substances (Kim et al. 2017). This feature does not only show on the spines but throughout the entire system of the cactus.



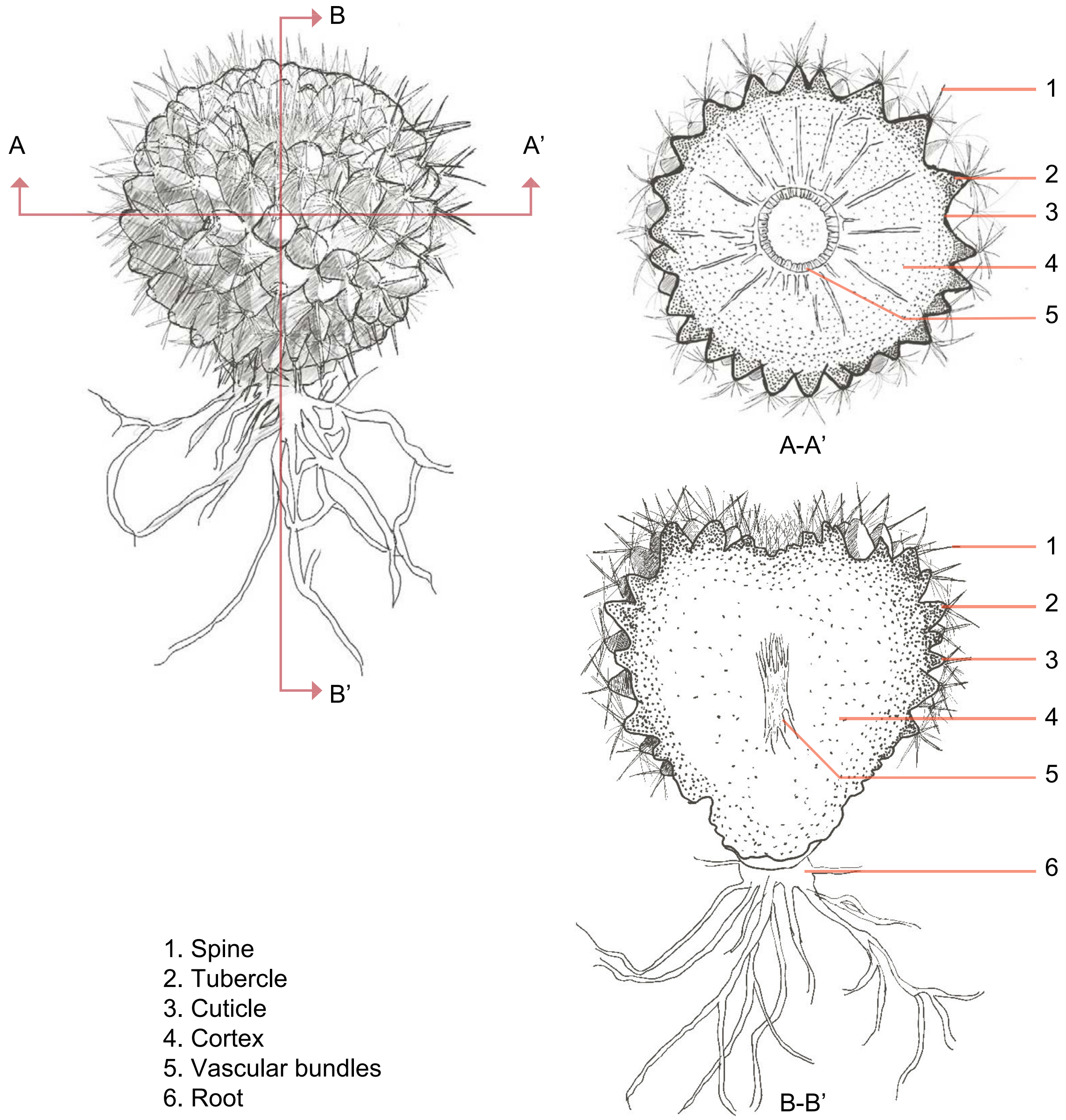
Material properties of a catus (data from Cactus Art. n.d.a. and Cactus Art. n.d.b.)



Material layering of hydrophobicity and hydrophilicity creates directional water flow and speed up the transportation (illustration based on the diagram from Tian et al. 2014, 6023)

The Conclusion of Cacti Study

The cacti deal with wind, heat, water scarceness with geometrical features in multiple scales, from the conical shape of spines and barbs, extruded tubercles and helical pattern, to the overall round shape. The material characteristics is specialized in water collection by alternating hydrophilic and hydrophobic layer. The study demonstrates that maximizing the morphological and physiological features is how the system of a plant work, which will be applied to the design in this thesis.



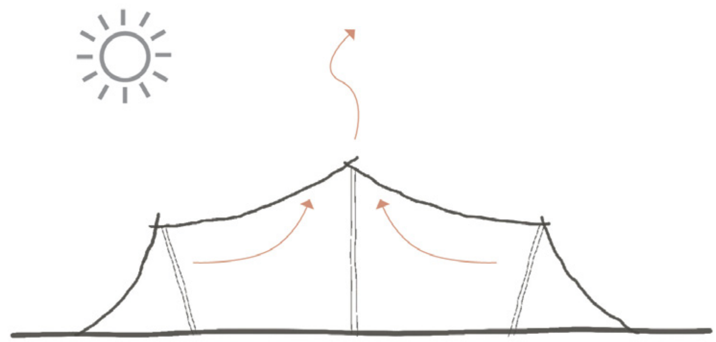
The organization of a barrel cactus. The organs of the cactus work indepently to collect water.

An All Approach Realization: Bedouin Tent

The Bedouin tent is an example of utilizing all three approaches of biomimicry. The Bedouin tent is an Arabian desert dwelling for Bedouins without any sort of active heating and cooling devices. The tent is called Woollen House and is in full contact with the exterior environment (Attia 2014, 1) The traditional tent is made from goat hair or a mixture of sheep wool and camel hair. The wool is a heat absorber, which traps heat inside. The tent creates natural ventilation with its open sides for air exchange and top openings for air escape. Inside the tent, stack effect is powered by the buoyancy of air. The wool (goat, camel and sheep wool) absorbs and retains considerable amounts of moisture from the atmosphere which is then distributed in capillary spaces between fibres, acting as thermal mass (Marwa & Ahmad 2015, 6). The biomimetic approaches the tent has can be summarized as below:

- Organism: Use of material characteristics to aid thermal regulation.
- Behavior: Buoyancy-driven ventilation.
- Ecosystem: Use of renewable resource solar energy and wool.

An all biomimetic approach example, Bedouin tent (Attia 2014, 2)



Stack effect in Bedouin Tent, powered by solar energy for ventilation and thermal regulation.

Conclusion

From the behavior approach, one can learn that termites and prairie dogs take advantage of the sun and the wind to create airflow for their nests. From the organism approach, one can see the geometry and material characteristics of cacti work in multiple scales to deal with the climate. The Bedouin Tent is an example of the integration of all three approaches, by using renewable materials wool, solar chimney for ventilation and material characteristics for thermal mass. The dimensions learned from these studies can be considered to be integrated to architecture for better performance in energy management and a closed-loop life cycle.

Chapter 4: Burning Man and Black Rock Desert

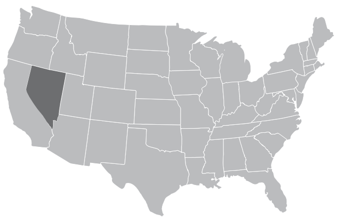
The Burning Man Festival held in Black Rock Desert, Nevada, USA is chosen as the testing site and event to employ biomimicry because it encapsulates many of the global environmental issues . The carbon footprint in one week of Burning Man is 1400 pounds per person which outweighs the weekly average of 846 pounds per person in the US (Burning Man Journal 2018). Burning Man has negatively impacted the local environment and has caused concern among the local residents. There have been negotiations between the organization of Burning Man and the local government, with both parties hoping to produce solutions to protect the desert.

This chapter analyzes the ecosystem of the Black Rock Desert Playa, as well as the impact from Burning Man to gain the insight for intervention and mitigation. The major issues of the festival are CO_2 emissions, waste contribution to landfills (Donnelly and Jones 2019), and disturbance on the local ecosystem (U.S. Bureau of Land Management 2012). The sources of pollution from Burning Man were identified and the current mitigation actions from the Burning Man organization are presented. The study of the ecosystem includes the climate of the desert, organisms, and biodiversity on the playa.

Burning Man

Burning Man is an event held annually in late August to early September in the United States at Black Rock City (BRC), a temporary city that is erected in the Black Rock Desert of northwest Nevada. The late summer event in BRC is an experiment in community and art, influenced by ten main principles: radical inclusion, radical self-reliance, radical self-expression, communal effort, civic responsibility, gifting, decommodification, participation, immediacy, and leave no trace. The event takes its name from its highlight piece, the symbolic ritual burning of a large wooden sculpture, “The Man” (Burning Man n.d.a). The festival is celebrated with temporary structures including theme camps, installations, an effigy, and a theme temple for exploration. Participants, who are called Burners, play and interact with the installations as a form of socializing and celebrating. The most common transportation method to reach the site is driving, as people pack a lot of supplies to camp for 10 days, whereas the most common mode of circulation within the site is biking (Burning Man n.d.b). The number of participants is growing annually; 20 people attended in its inaugural year 1986 and in 2019, that number reached 80,000. This increased population and the extravagance of the activities have brought more environmental concerns to the desert (Donnelly and Jones 2019).

USA (base map from Google Maps, n.d.a.)

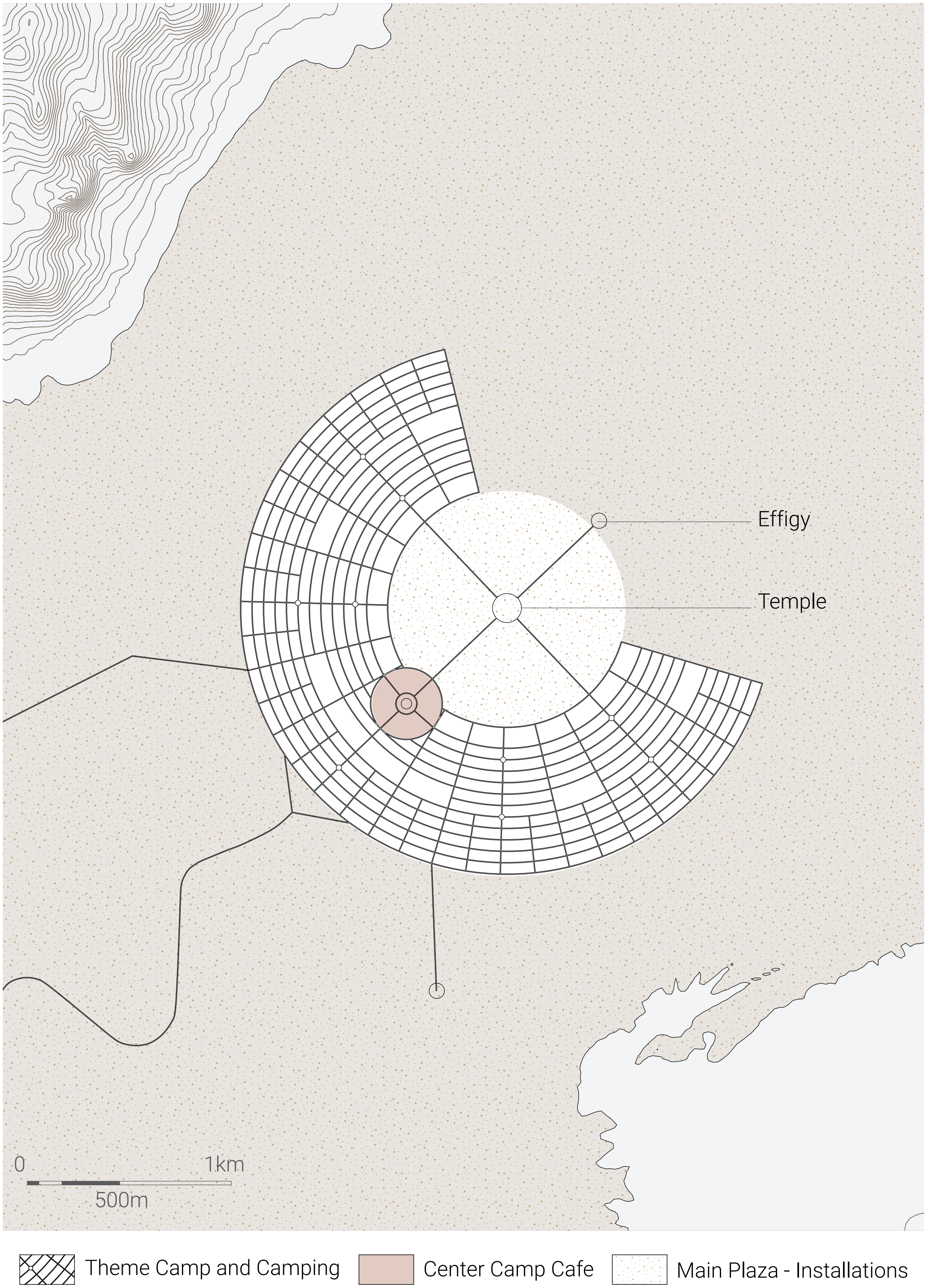


Black Rock Desert, Nevada (base map from Google Maps, n.d.a.)

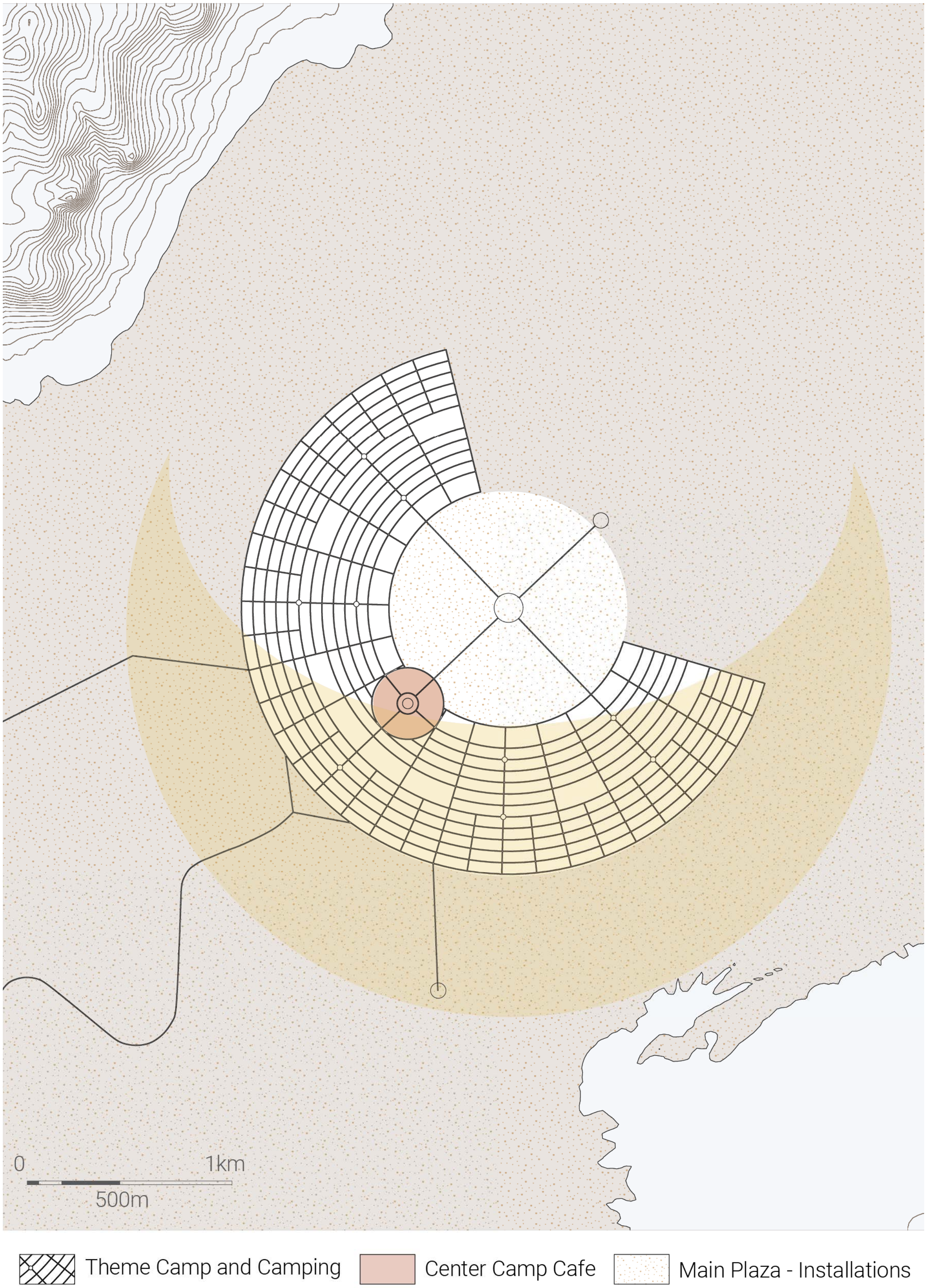
Satellite image of Burning Man (Goolge Maps, n.d.b.)

Activities in Burning Man (London 2017)

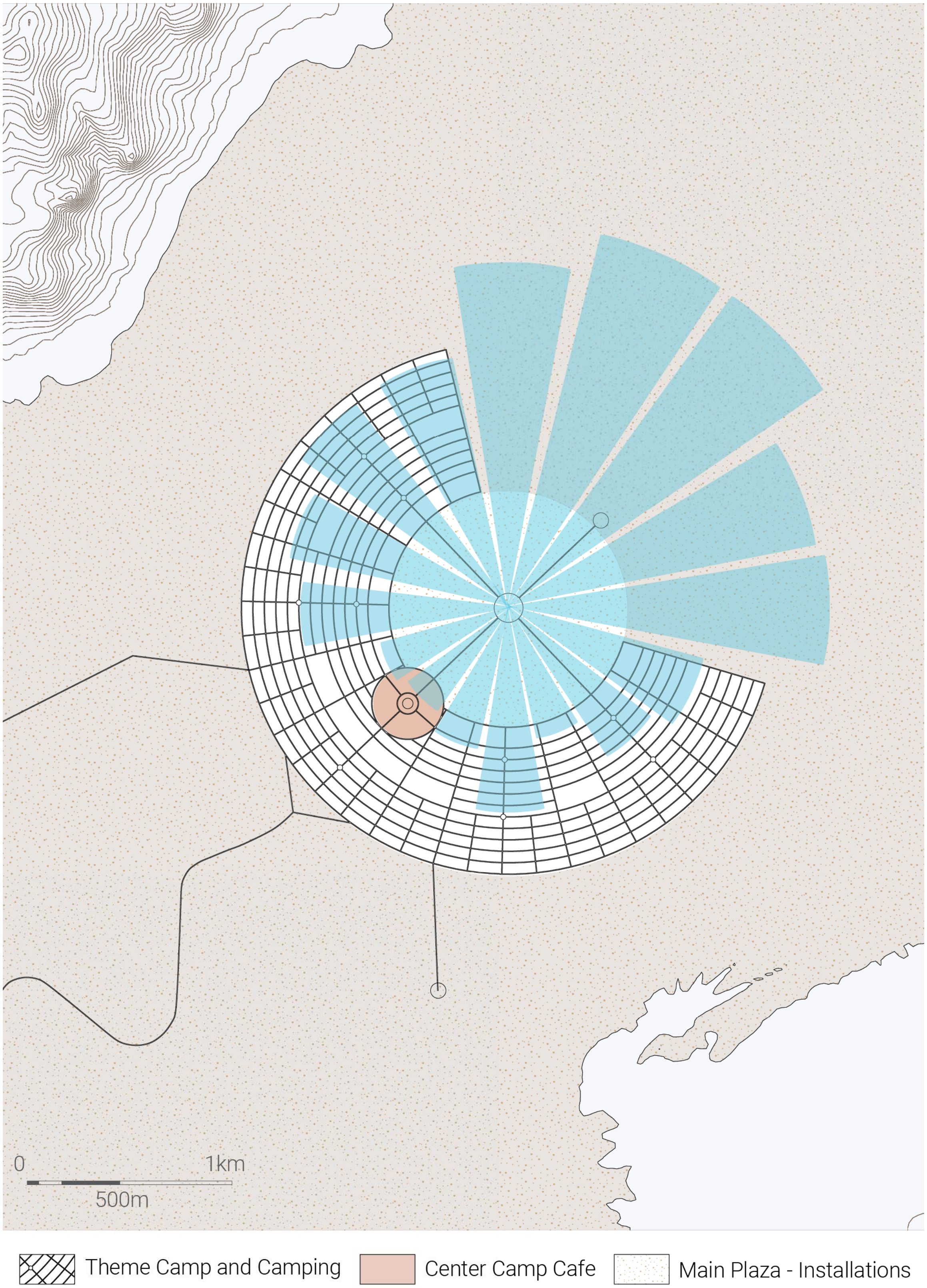
Activities in Burning Man (Huey 2016)



The zoning of Black Rock City (data from Burning Man n.d.c)



The sunpath of Black Rock City (data from Time and Date n.d.)

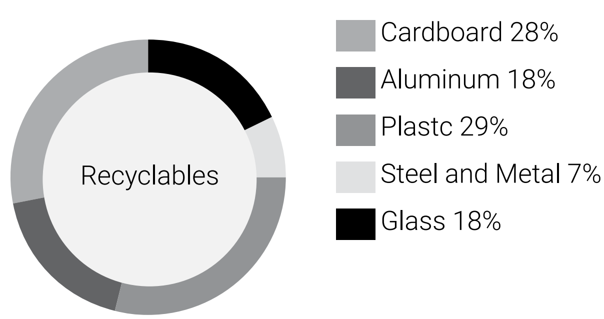


The wind direction of Black Rock City (data from Time and Date n.d.)

Waste

A plethora of waste is produced every year from Burning Man - waste that may be repurposed, such as recyclables, compost, and wood. In 2013, they collected 74 cu. yds of aluminum; 124 cu. yds of plastic; 74 cu. yds of glass; 30 cu. yds of steel and scrap metals; and 118 cu. yds of cardboard. Burners also tend to over-pack food, resulting in an exorbitant amount of organic waste. (Burning Man n.d.d).

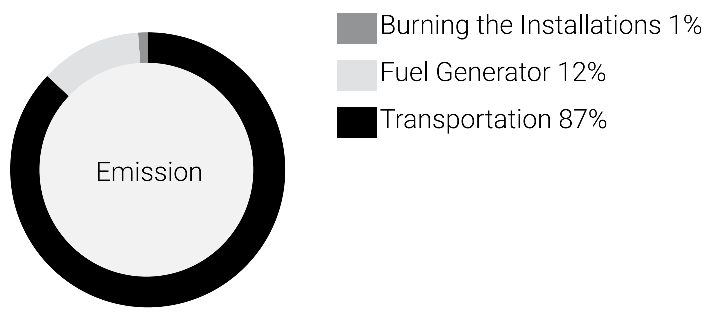
Burning Man organizers have implemented some sustainable initiatives. After the event, whatever is recyclable is shipped to various recycling facilities. Starting in 2013, organizers have been collecting wood every year at the end of the event, stored them at the Burning Man warehouse, called The Burning Man Work Ranch, which then gets used throughout the festival of the following year (Burning Man n.d.d).



Category of the recyclables of Burning Man (data from Burning Man n.d.c.)

CO_2 Emission

Three major sources that contribute to CO_2 emission and air pollution are: transportation, air-conditioning, and the burning of installations. Traffic alone contributes more than 80% of the pollution, from flying and driving to and from the site and the transportation of water and supplies to the site everyday. Although beverages are offered at the event at the Centre Camp Cafe, participants are responsible for their own potable water and other use of water from the nearest town, Reno. Burners also haul a great deal of art and equipment to the site for their installations (Donnelly and Jones 2019). The second largest contributor towards carbon emission is the multitude of fuel-powered generators for air conditioning and electricity. The festival activities do not stop at night, thus a high amount of electricity is used to power up theme camps and installations to continue the celebration. Burning the installations only contributes to 1% of the carbon pollution (Wenzel 2007).



Sources of carbon emission of Burning Man (data from Wenzel 2007)

The Sustainable Culture of Burning Man

One of the policies of the event regards environmental protection. The organizers have been asking participants to strictly follow Leave No Trace (LNT) and Matter Out Of Place (MOOP) to protect the environment. However, LNT and MOOP only prevent leaving pollution on site after the festival, and carbon emissions during the event are not even addressed. Estimates show that in the next few years, the participating population will reach 100,000 people, therefore, the next stage of Burning Man should keep its spirit alive but also reduce harm to the desert (Donnelly and Jones 2019).

The Ecosystem of Black Rock Desert

The desert ecosystem is first and foremost defined with the scarcity of water, secondary are heat and limitations of food and nutrient resources (Holzapfel 2008, 879-880). Black Rock Desert is a semiarid desert with annual precipitation of approximately 200mm. Precipitation in deserts in general varies randomly between years and is therefore not predictable, and water is the control factor for biological processes. In Black Rock Desert, maximum summer temperatures can be over 35°C, and minimum winter temperatures are often below freezing.

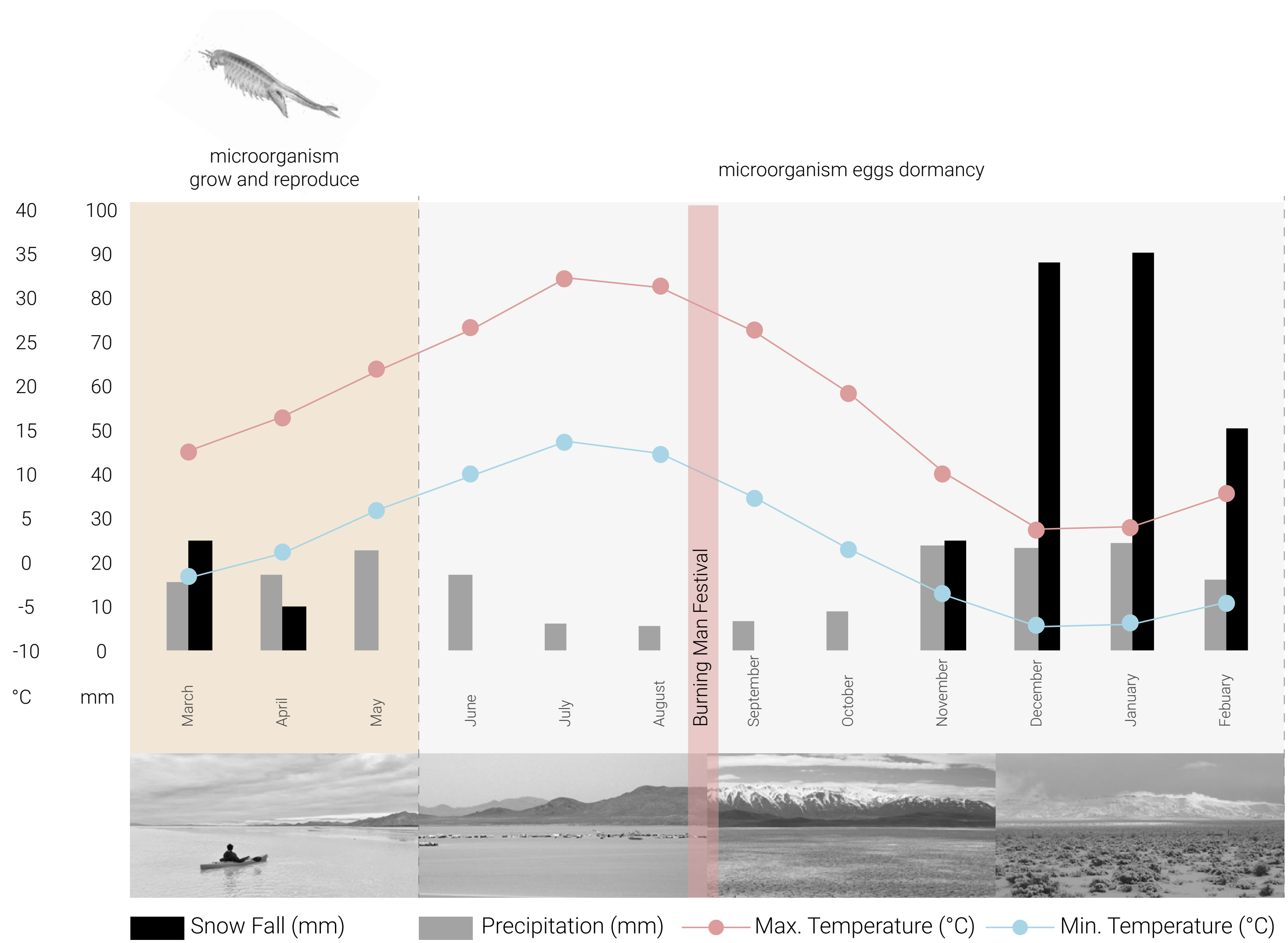
During Burning Man, average temperatures range from 9°C at night to 33°C in the day. Wind and sunlight are abundant, with prevailing wind from the southwest and an average of 13.5 adaylight hours. Humidity is low, hovering around 28%-33%, while the comfortable humidity for human is within the range of 50%-60%. Precipitation levels is approximately 5.8~7.1mm monthly.

The Black Rock Desert Playa is the depression of a prehistorical lake. Depending on the rainfall and temperature, the playa can be flooded and resemble the former lake. The playa is characteristically wet during winter and early spring, even during years without rain or snow. When the playa has no flood for a few years, the surface can transform from a hard and durable surface to soft and loose (Friends of Black Rock High Rock. n.d.).

Deserts are low in water, nutrients, and energy resources, therefore adaptations to cope with the scarcity of water are predominant to most of desert organisms. Water and heat stresses are usually coupled, thus many of the adaptations cope with both (Holzapfel 2008). For example, the study of cacti from the previous chapter demonstrated the strategies of cacti to reduce heat and to collect water.

Although BRD is home for many wildlife and plants, the Black Rock Desert Playa is devoid of animals and vegetation due to lack of stable water resources, and highly alkaline soils, respectively. However, the area is rich in microorganisms. When the playa is flooded, it supports phytoplankton, bacteria, crustaceans, and other microbes. Most of the aquatic species in the Black Rock Playa are branchiopods. Their eggs lie encased in dry playa soil and do not hatch until the playa is flooded for long enough for adults to grow and reproduce. Four types of branchiopods are shown here, two types of fairy shrimp, tadpole shrimp, and water flea (U.S. Bureau of Land Management 2012, 98).

The most intense activity that occurs on the playa is the annual Burning Man Festival, which operates on 3% of the playa in area. The intensity of human enterprise varies across the playa, one this is certain, all the foot traffic, camping, and heavy vehicle traffic that takes place for a minimum of six weeks every year leaves drastic impact the local ecosystem. The traffic and long-term camping decreases branchiopod egg abundance (U.S. Bureau of Land Management 2012, 129).



Cycle of Black Rock Desert Playa (data from Friends of Black Rock High Rock n.d.)

Conclusion

The analysis of Burning Man and the ecosystem of Black Rock Desert Playa can be summarized as below:

- The strength: Rich in microorganisms.
- The weakness: Unstable water resources.
- The opportunities: Snow for water resources and waste can be recycled for building materials.
- The threats: water scarceness, high heat in the day and low temperature at night, low humidity, and pollution from Burning Man causes the decrease of microorganisms.

The investigation of the ecosystem and pollution sources is applied to create a circular economy for the Burning Man festival and its hosting site, the Black Rock Desert.

Chapter 5: Burning Man Design Proposal : Circular Economy and the Infrastructure

After analyzing the available resources from the ecosystem and pollution of Burning Man, the architectural intervention is to create infrastructure that keeps Burners comfortable day and night with natural HVAC, potable water harvested locally, and to serve different spatial needs for public gathering in open-air or enclosed spaces. The infrastructures are made from locally collected waste to grow cellulose and chitin. The life cycle of the infrastructure aim to coordinate the schedule of the local ecosystem.

The Master Plan

The Hydration Room

The Hydration Room is an enclosed and self-sustaining pavilion designed for the Burners who are at risk of dehydration or heat stroke, which provides locally collected water and natural air-conditioning to encapsulate humidity inside, thus creating a cooling paradise to rescue the Burners.

The Hydro Pavilion

The Hydro Pavilion is a covered open space which provides natural air-conditioning for the Burners away from scorching sun.

The Tree Pavilion

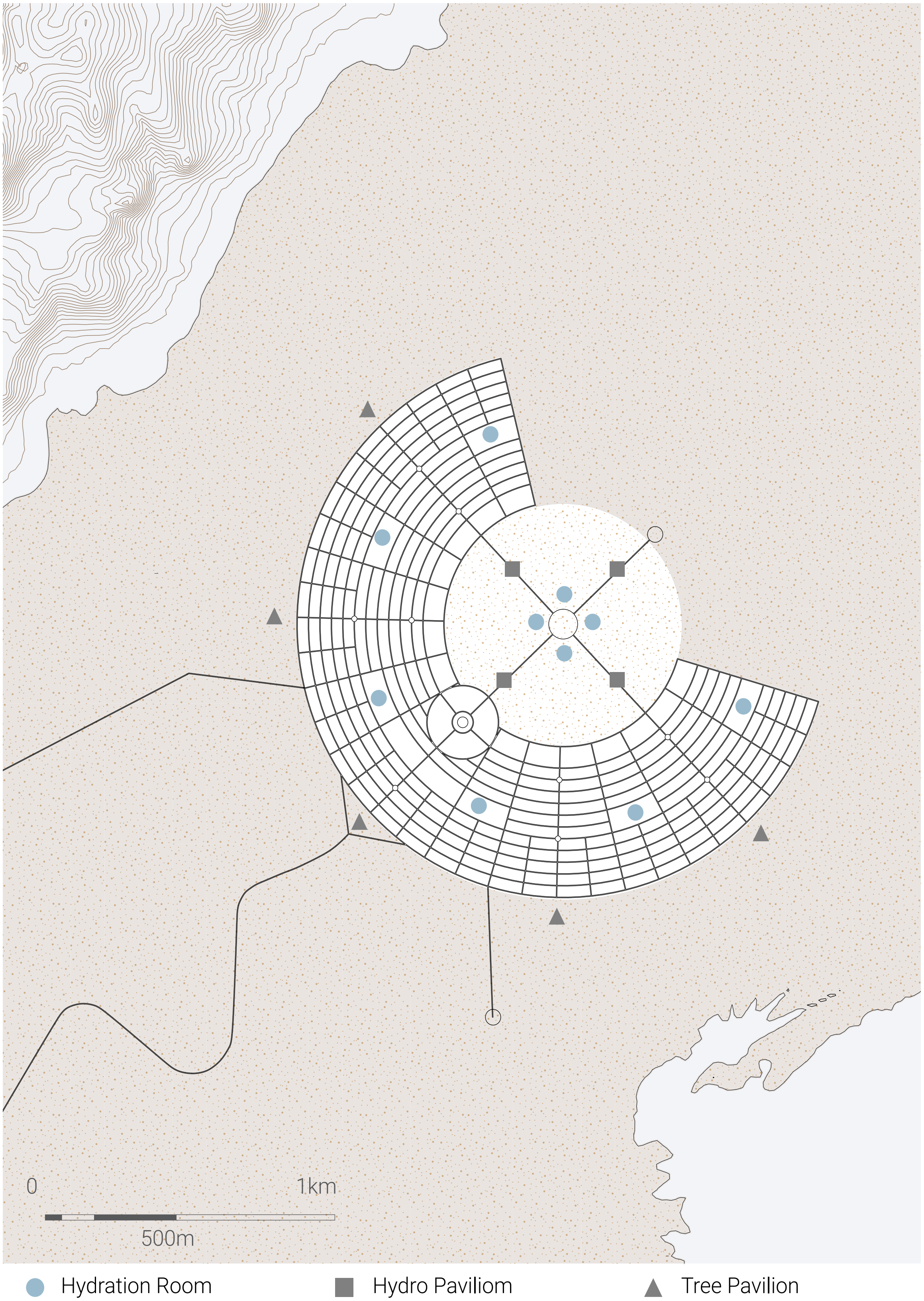
The Tree Pavilion collects solar power and transforms it into electricity, to power the water pumps and provide electricity for general use, while also being an open-air space for public gathering.

Circular Economy: Waste, Ecosystem and Life Cycle

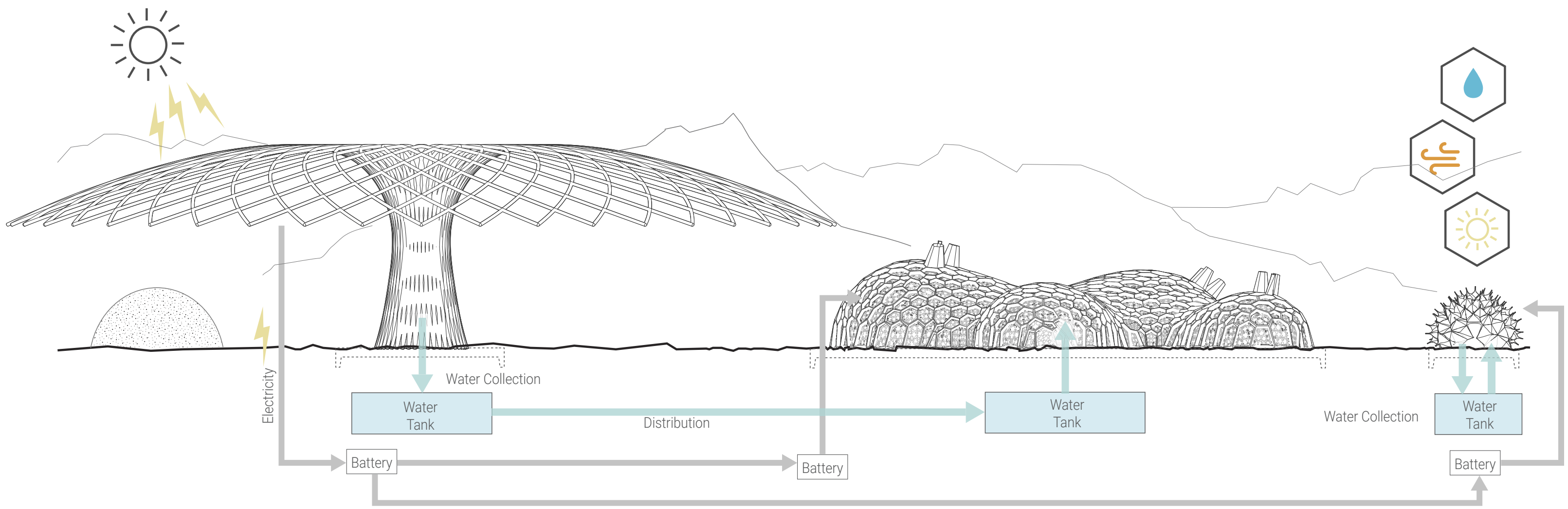
Currently, only wood is recycled and reused from the event. Expanding the recycling initiative to other waste material can reduce the environmental impact. Two streams are proposed to repurpose the waste from Burning Man: the organic and non-organic waste. The non-organic stream recycles and washes glass, metal, and plastic bottles and repurpose them into building materials. The organic stream recycles wood, compost, and cardboard; the potential lies in extracting biomaterial to achieve full degradable material. Two biomaterials can be derived from the organic stream, cellulose and chitin, and repurposed for 3D printing.

In addition to recycling the waste from Burning Man, the infrastructures also work with the ecosystem of the Black Rock Desert Playa. By collecting water in spring and winter, and store the water for the summer festival use.

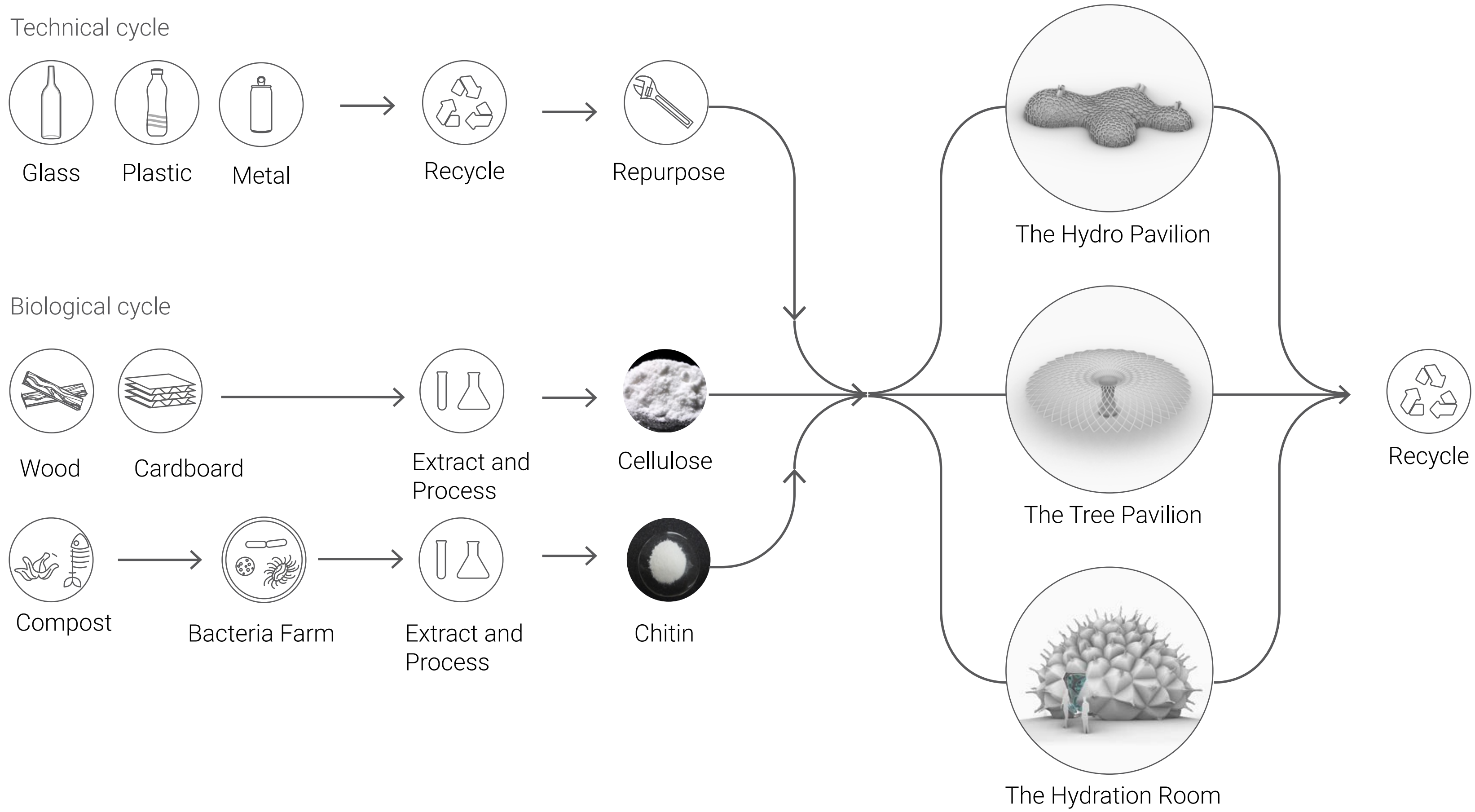
The life cycles of the infrastructures are designed to correspond to the schedule of the local ecosystem. The festival starts construction work in summer, and after Burning Man the infrastructures are turned into bacteria farms to grow plants, microorganisms, or fungi for building materials . The organisms in the bacteria farms grow and reproduce in spring after snowy winter. Thus, an organism-like life cycle for the building can be created and maintained to regenerate on an annual basis.



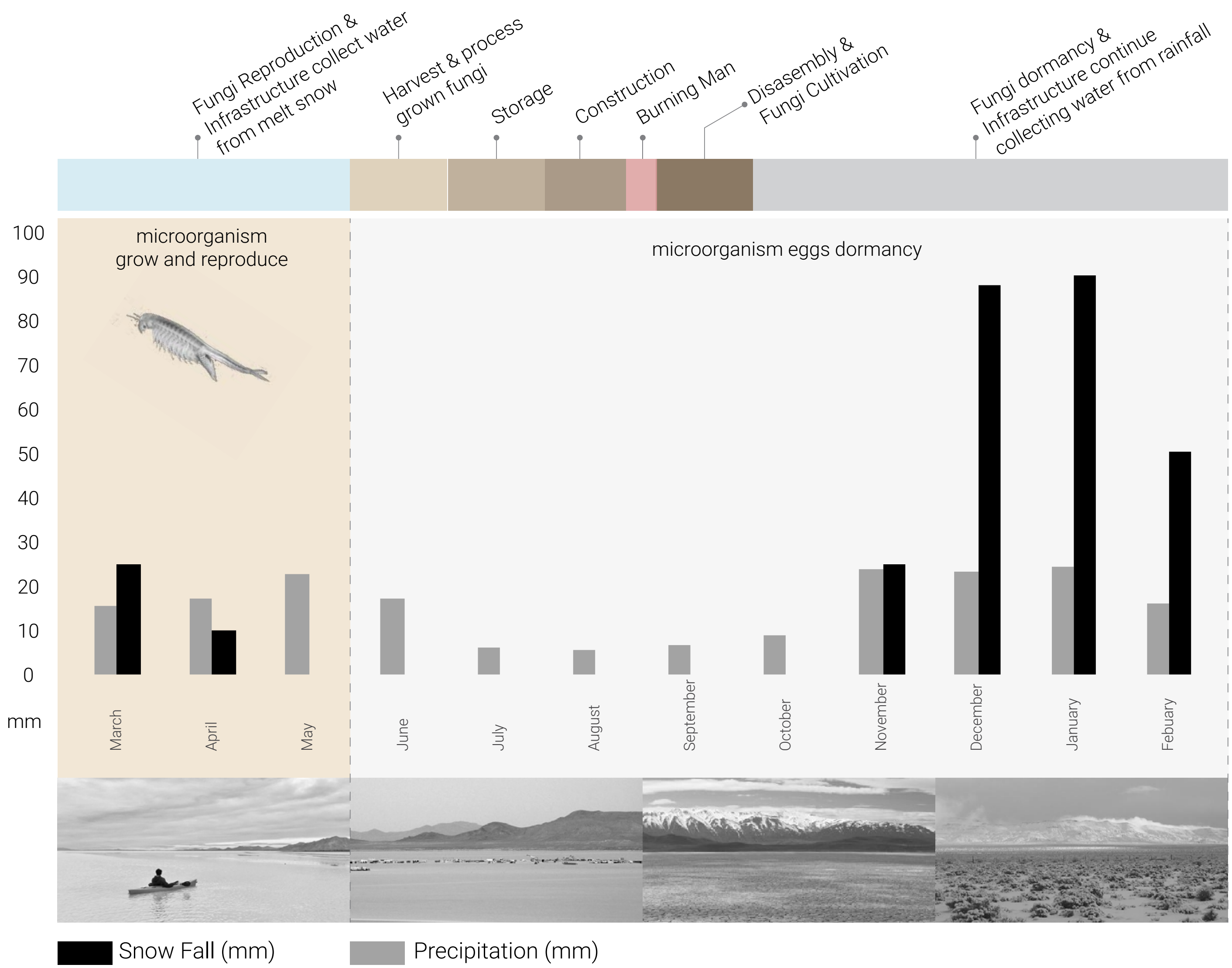
The master plan for Burning Man.



Site section



Waste recycle for building materials



Life cycle of The Hydration Room and other infrastructures, follows the ecosystem schedule of Black Rock Desert Playa.

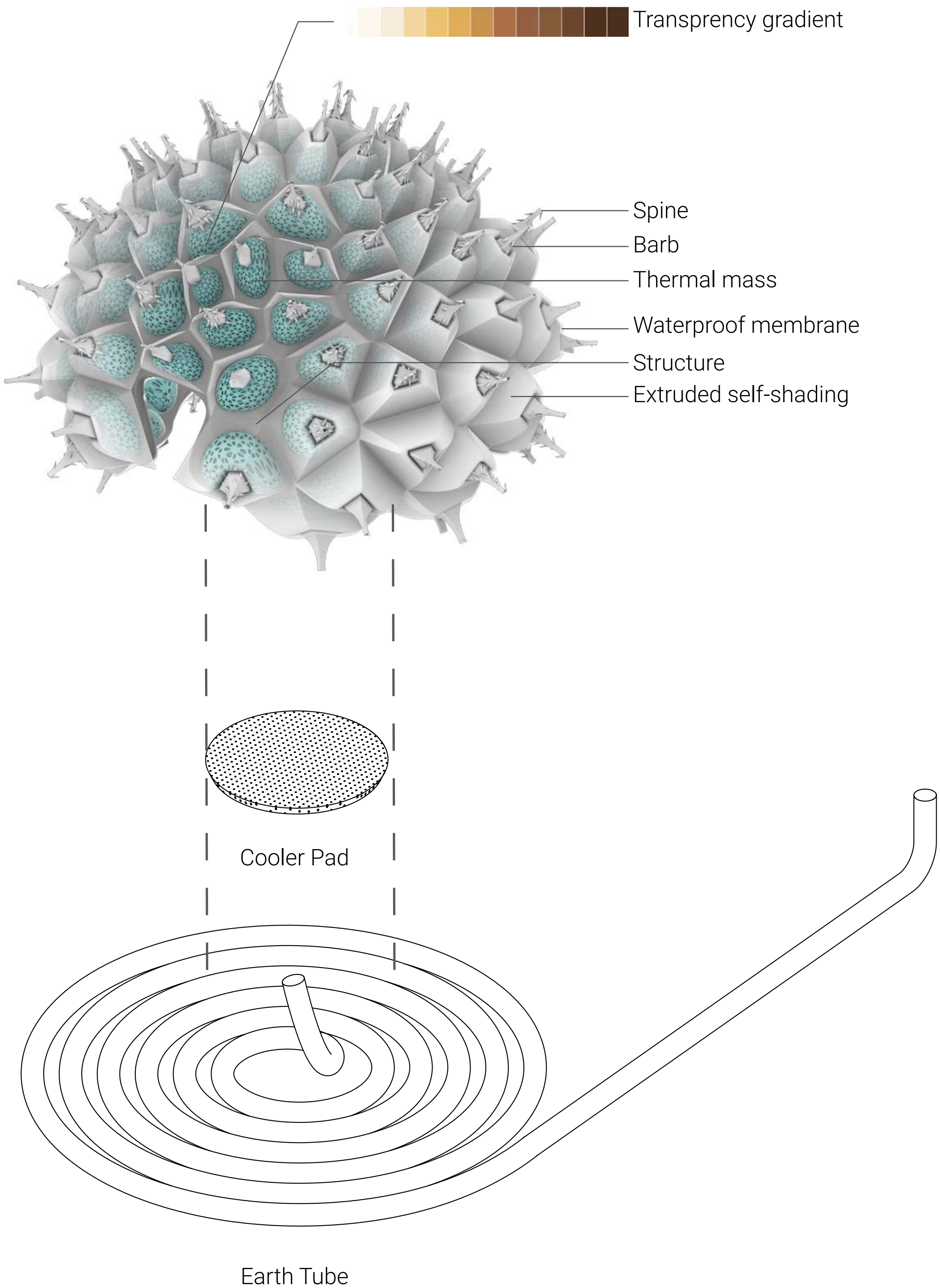
Design

The Hydration Room is designed from the inspiration of cacti, prairie dog, and buoyancy-driven ventilation using solar energy along with biomaterials and 3D printing technology.

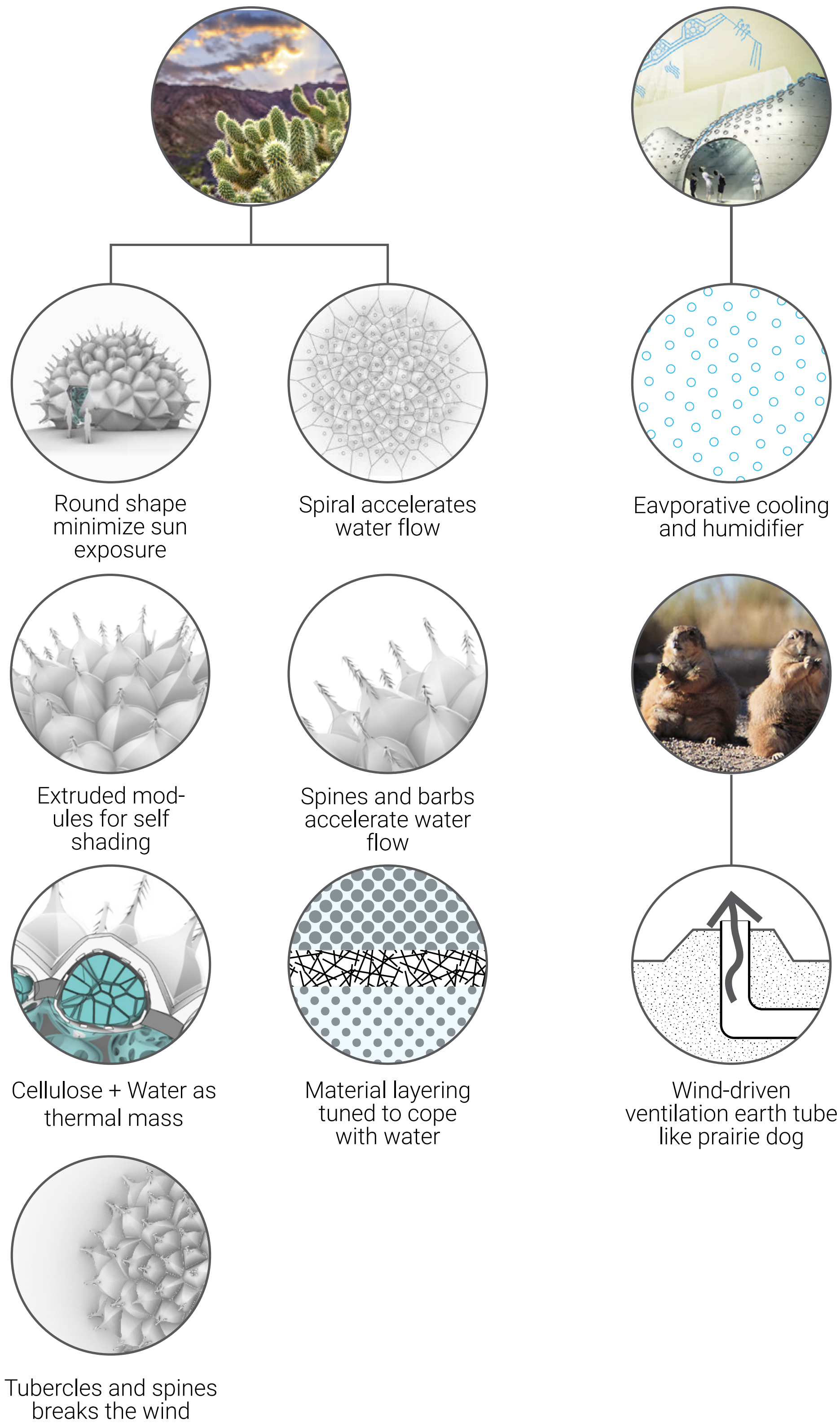
The design intention is to translate the geometry and the material characteristics of the cactus to cope with heat and water to rescue the Burners from dehydration and heat stroke. Additionally, evaporative cooling and wind-driven ventilation are integrated for cooling, humidifying, and circulating fresh air.

Form and Material Assembly

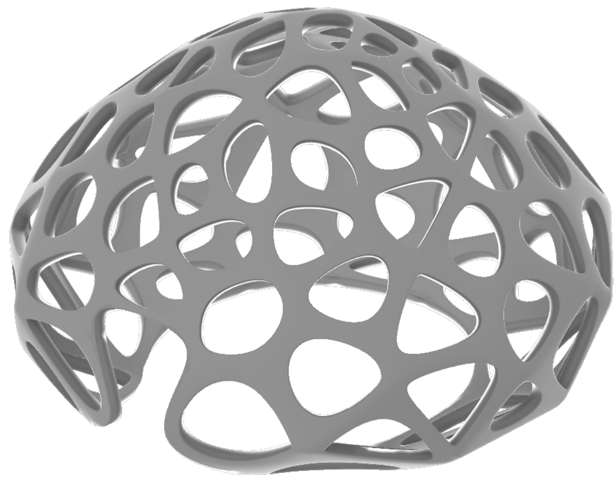
The geometrical features to cope with wind, thermal regulation and water are combined together in multiple scales from the spines, extruded self-shading units, to the overall round shape. The layering of the design also emulated cacti for their material characteristics to capture water, accelerate water flow, prevent water loss, and thermal regulation. The design concept is a large cactus containing many smaller cacti.



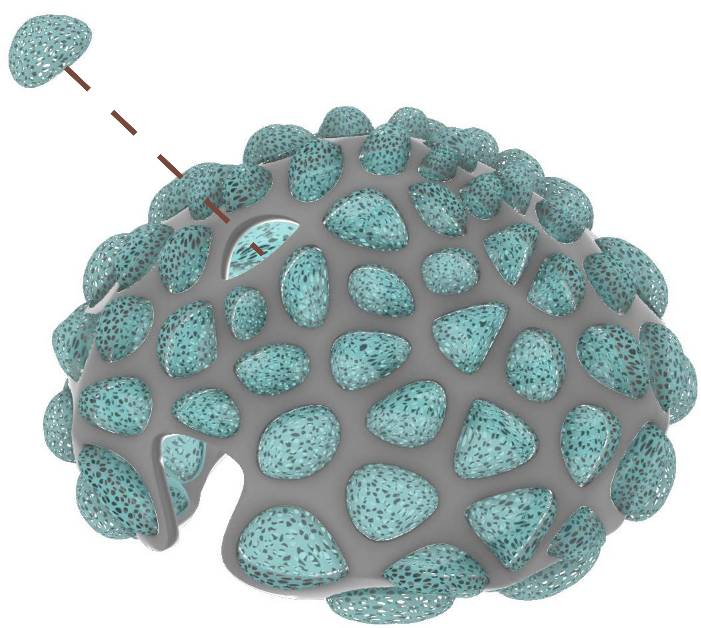
The Hydration Room



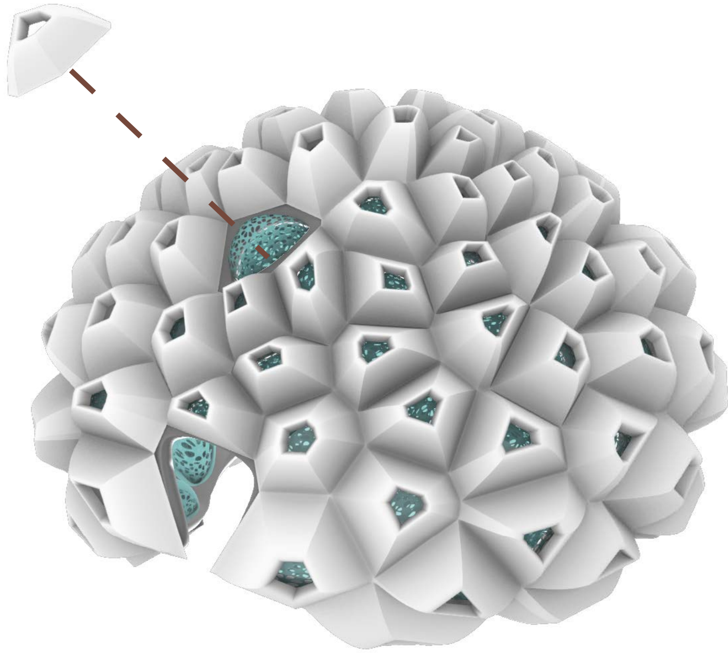
The biological model reference and design features of the Hydration Room



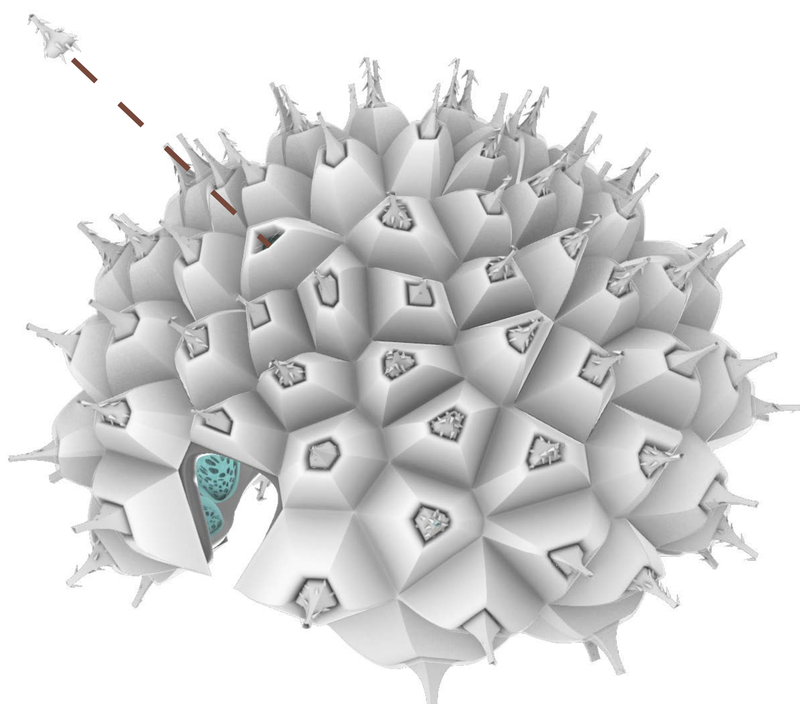
Structure. The helical pattern of the structure speeds up water transporation.



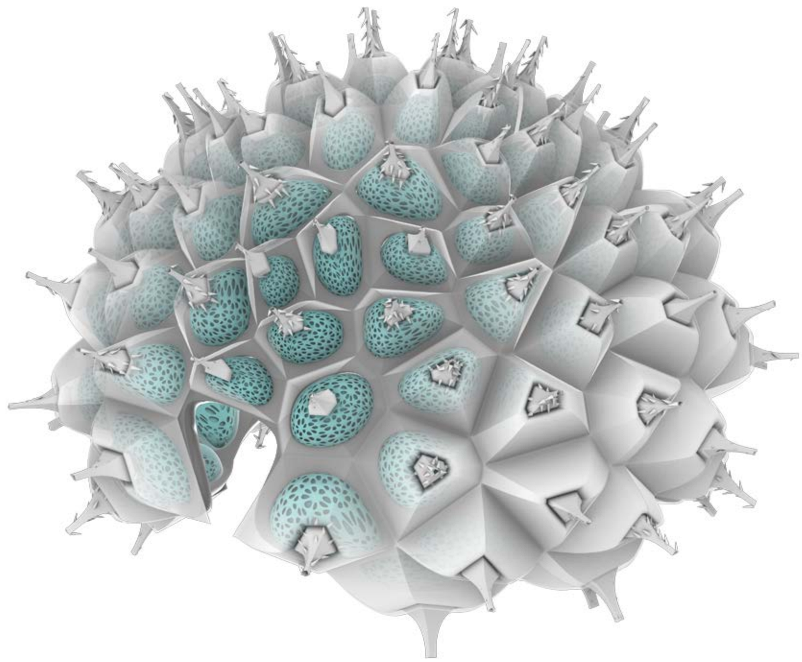
Thermal mass



Extruded self-shading unit



Water catching unit (spine)

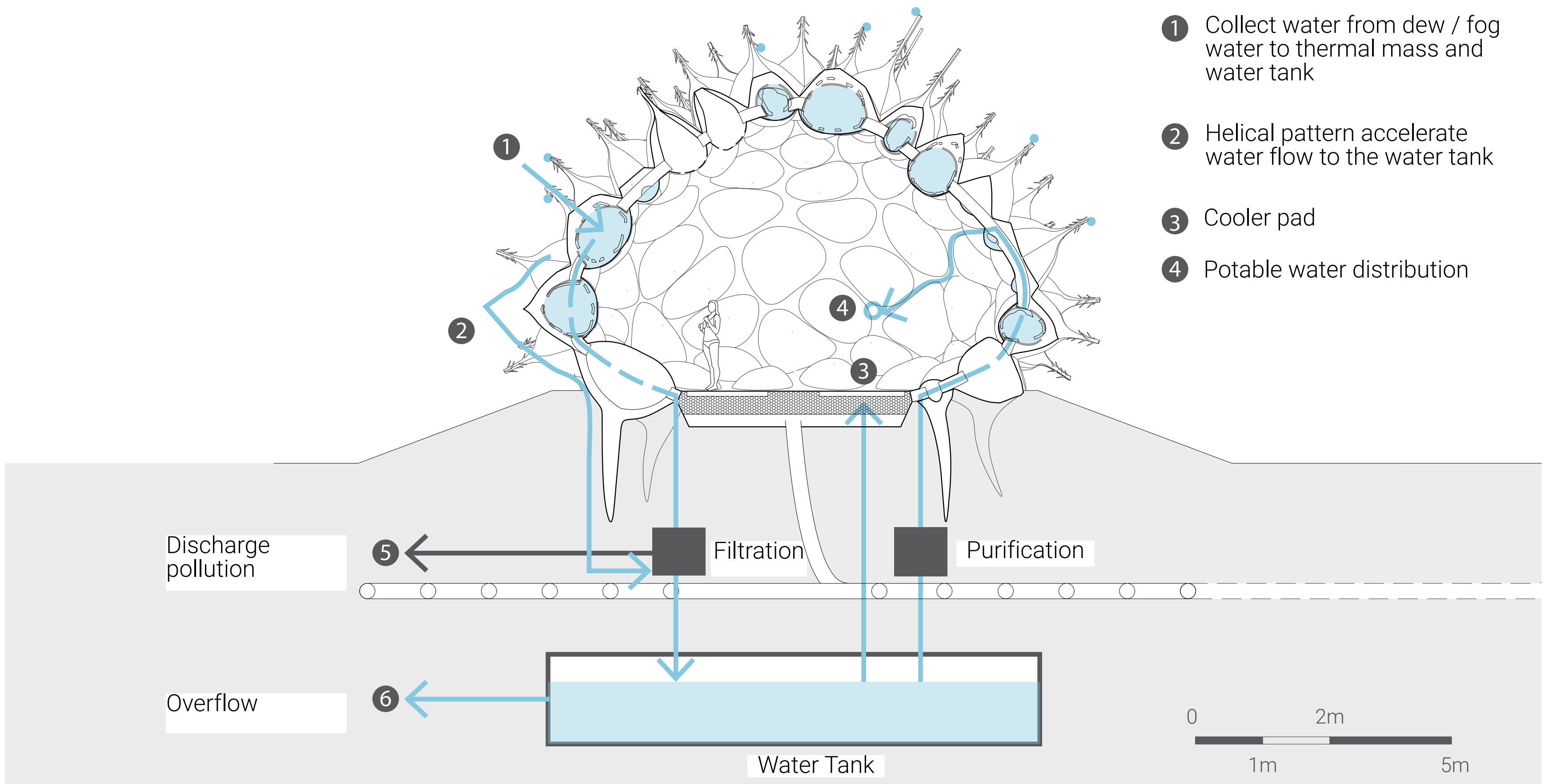


Waterproof membrane at the most out layer to prevent water lose.

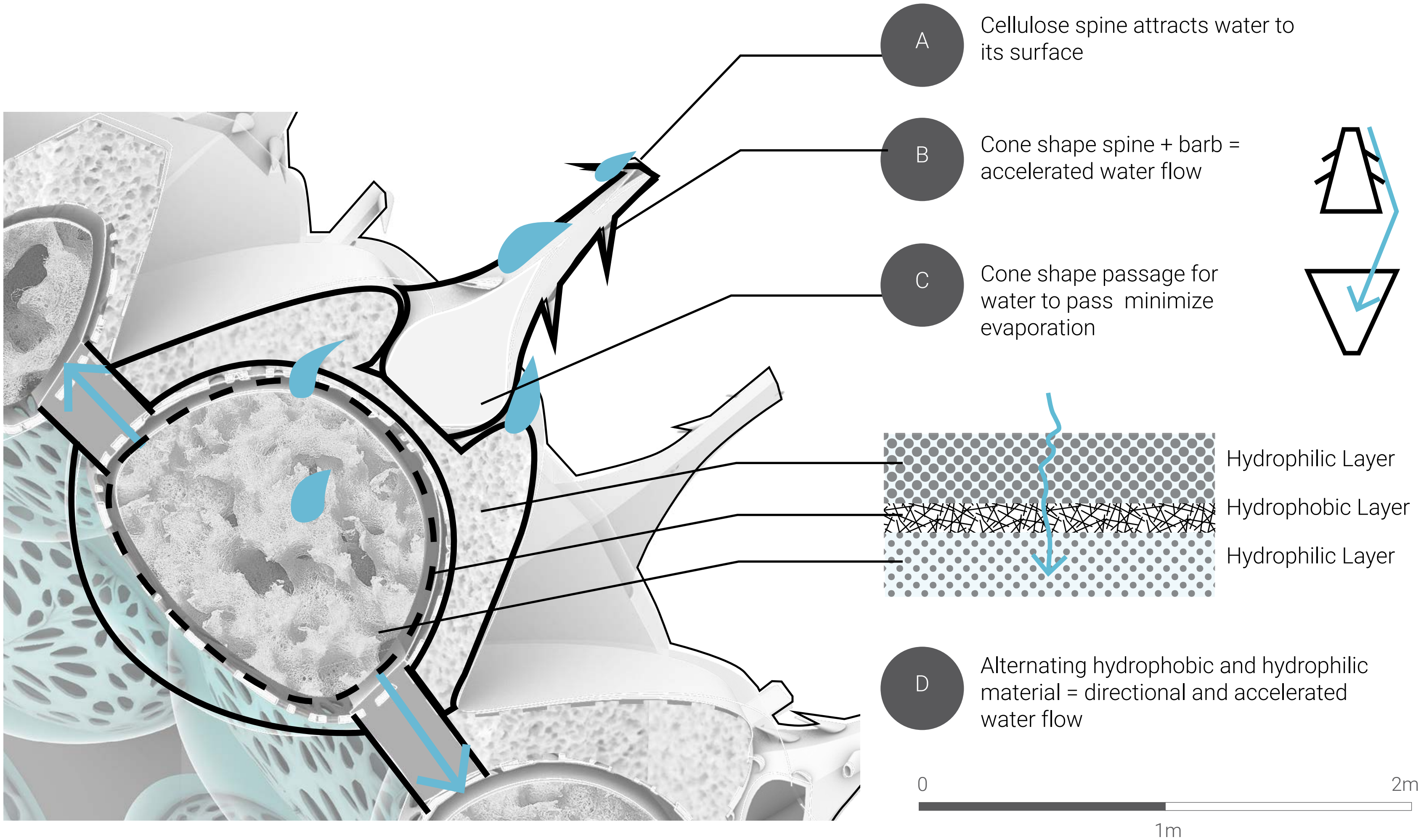
Water Collection System

The water collection system is designed to collect water before it evaporates, emphasizing the speed of water flow. Like cacti, the system collects water in two ways, from the ground and the spine. The helical pattern of the self-shading units accelerates water flow to the ground, stored in the water tank after filtration or purification, then pumped up to either the cooler pad or the drinking water faucets when needed. The water is collected through the spine from dew and fog by its geometry and material properties. This process can be divided into four steps:

- The Cellulose-made spine attracts water to its surface.
- The Conical shape and the barb direct the water inside and accelerate water flow.
- The conical passage minimize water evaporation.
- Once the water enters the module, the alternating hydrophilic and hydrophobic material accelerates water flow. This specific material layering creates a capillary force to drive water to the interior.



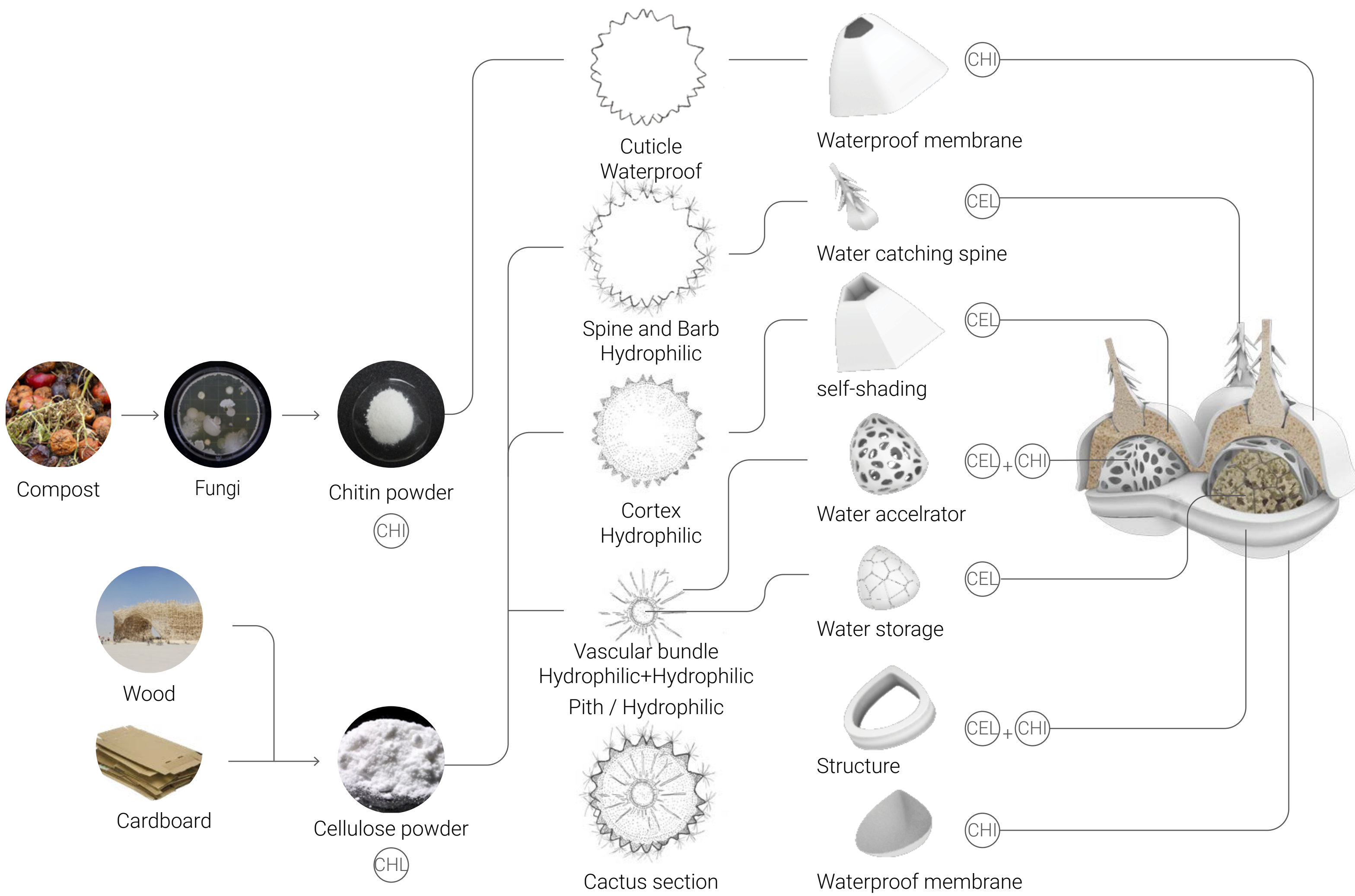
The water collection system



The module for water collection

Material Characteristics

Cellulose and chitin are used to emulate the material characteristics mentioned above for water capture, acceleration, and storage by alternating cellulose and chitin to achieve the functions. Here, you can see different layers of the module correspond to the composition of a cactus. The waterproof layer is made of chitin to prevent water loss, the water-capturing spine, spongy self-shading unit, and spongy thermal mass are made of hydrophilic cellulose, with a water flow accelerating layer in the middle made of chitin. The structure is made of chitin and cellulose, and interior waterproof layer is also made of chitin.



Material characteristics

HVAC

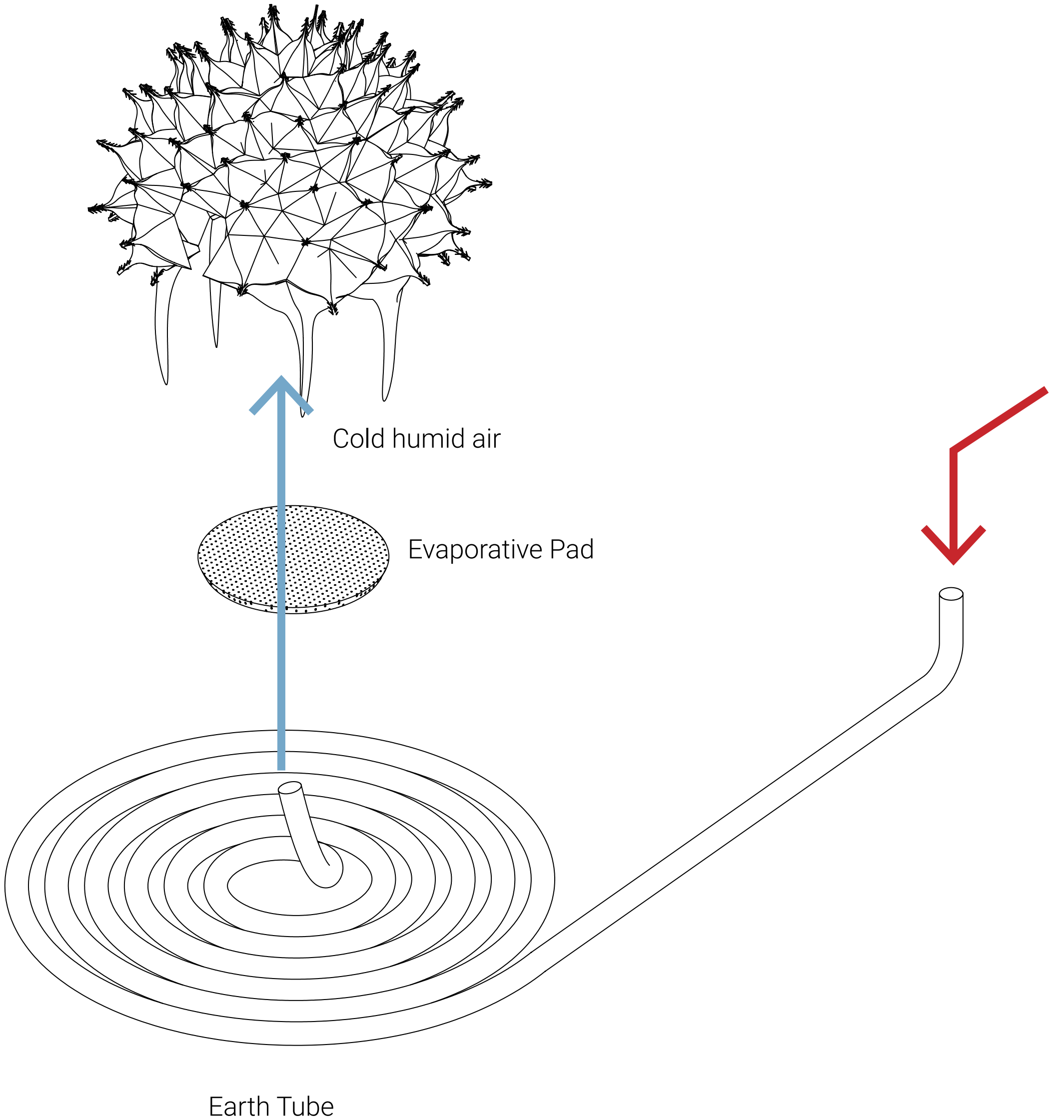
Thermal Mass

Black Rock Desert is hot in the day and cold at night, therefore the cellulose thermal mass needs to absorb water to maintain the temperature of the interior.

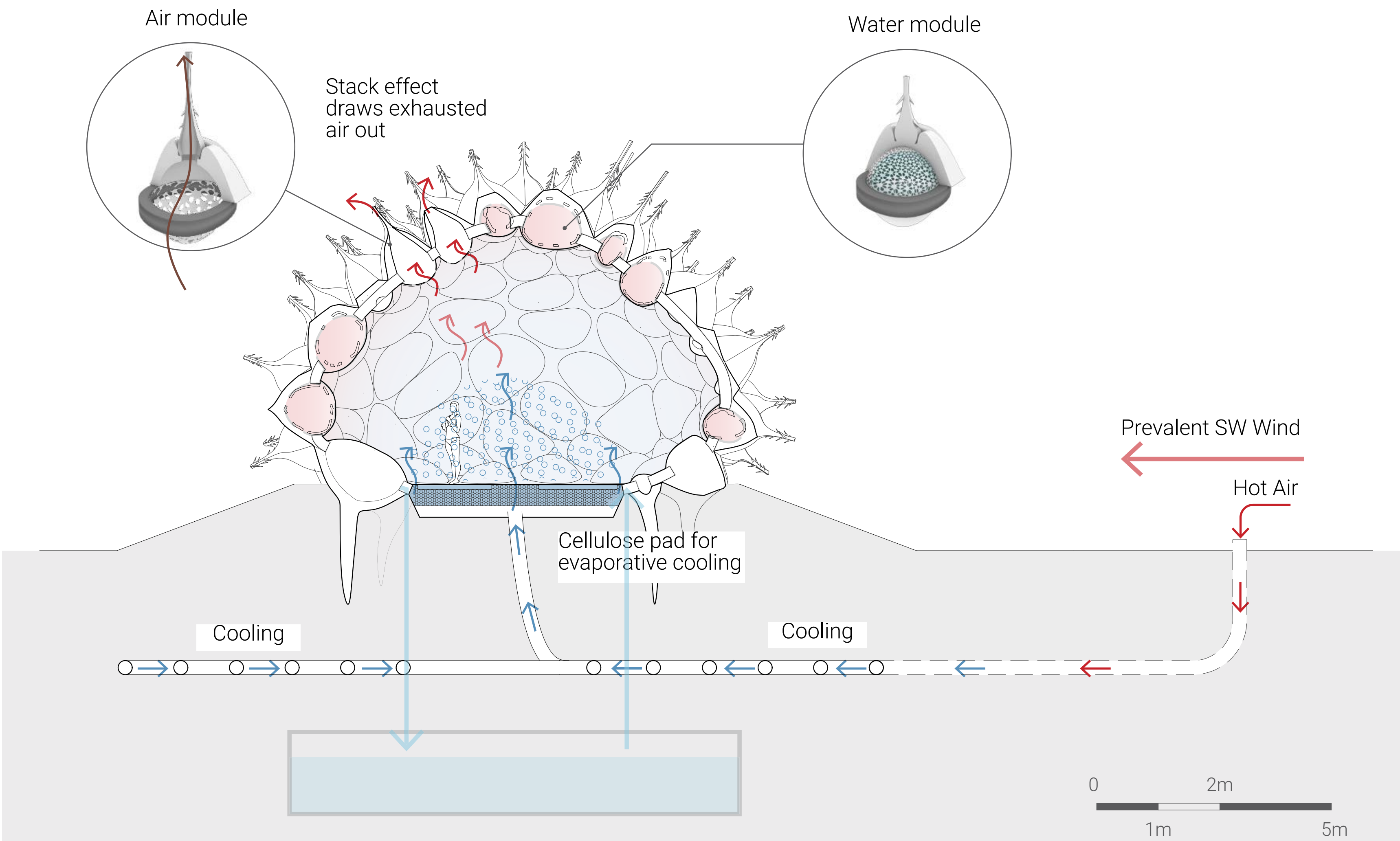
Ventilation

The wind-driven ventilation demonstrated from prairie dog nests is replicated for natural ventilation. The pavilion is placed at a higher elevation and one end of the tube is placed in the direction of prevailing wind, the elevated terrain creates a pressure difference which draws the air into the tube and come out from the other end. Heat transfer is integrated to the tube: with the temperature underground being lower than above ground, the tube is placed 2m below the surface with at least 100 meters of tube length, to allow heat transfer from hot to cold. As the cold air passes through the cooler pad which contains water, it humidifies the interior. The exhausted air then drawn out from the air module which acts as a solar chimney. The air module has a hollow spine and with no thermal mass for air outlet.

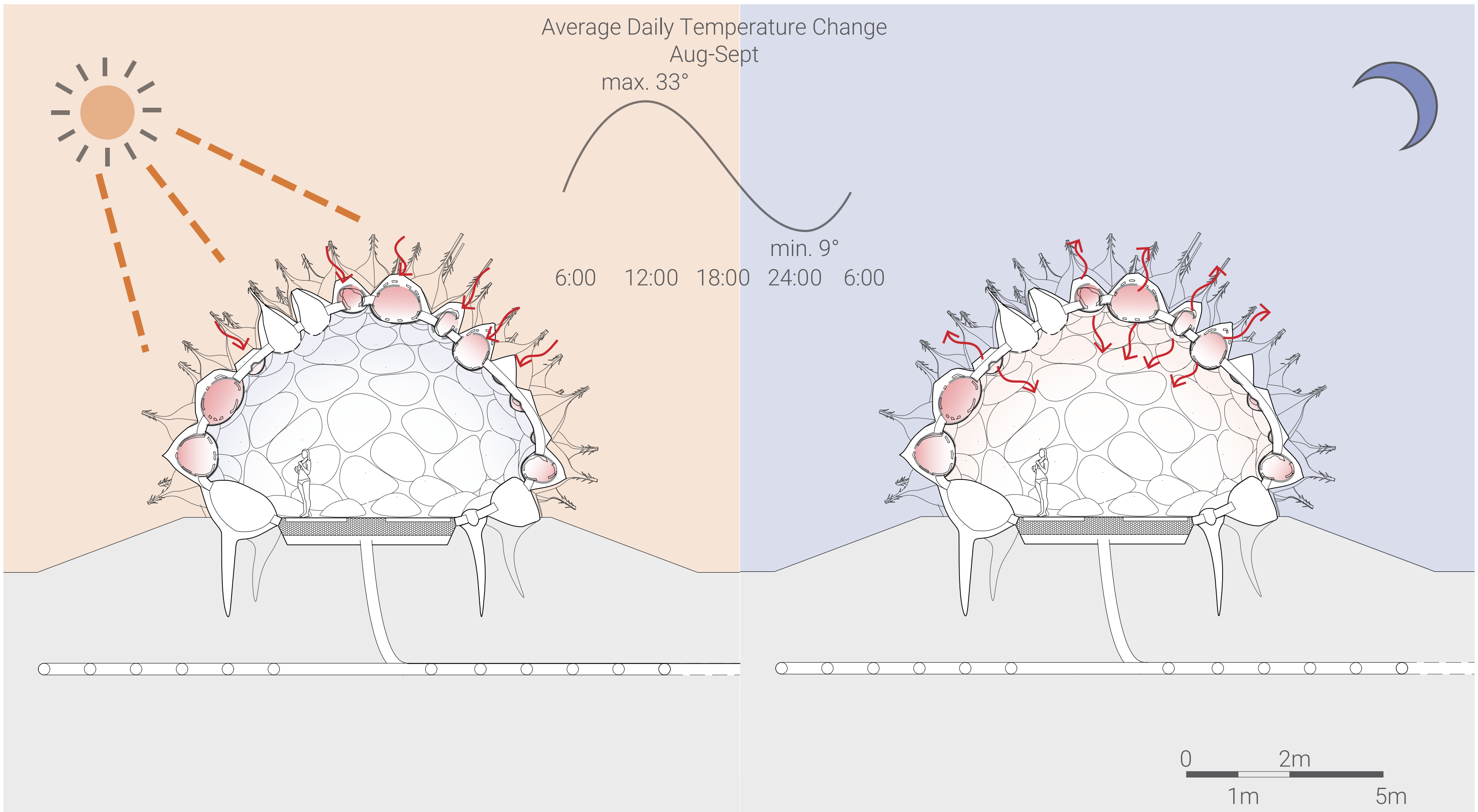
The Hydration Room then is a self-sustaining paradise for the Burners who want to stay away from the dry hot desert or for those who want a cool drink and natural air-conditioning.



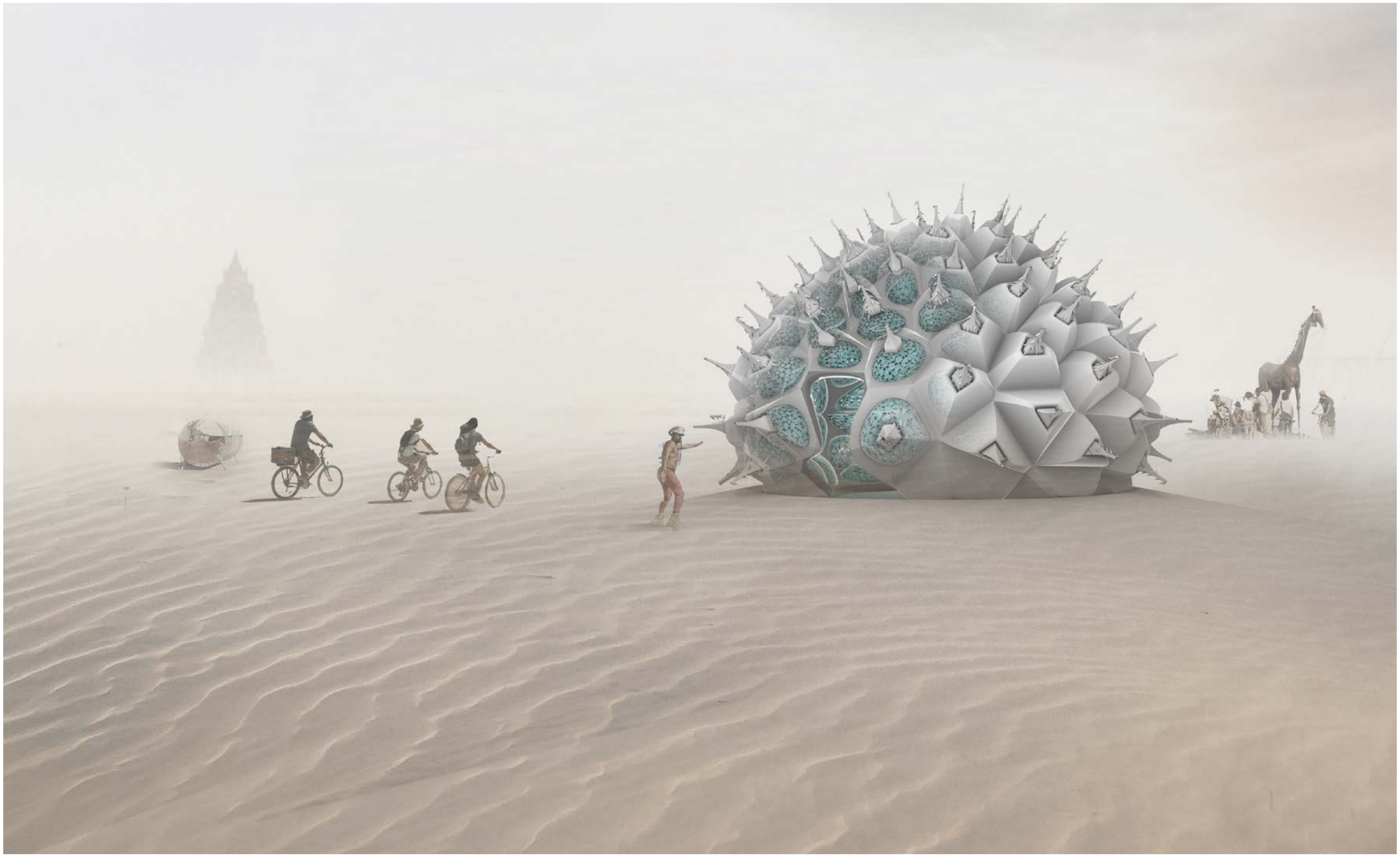
The ventilation and humidifier



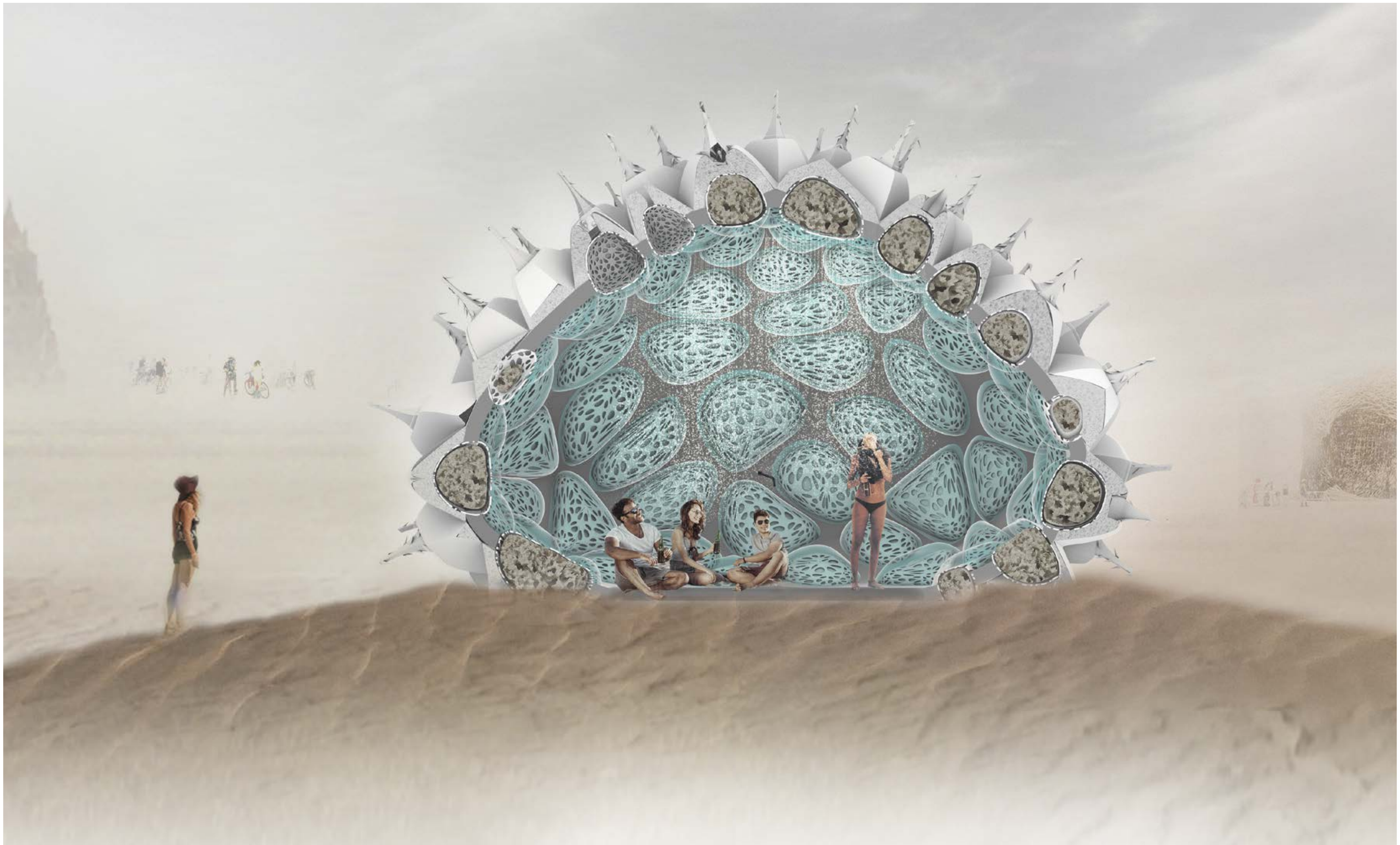
Wind-driven ventilation and evaporative cooling



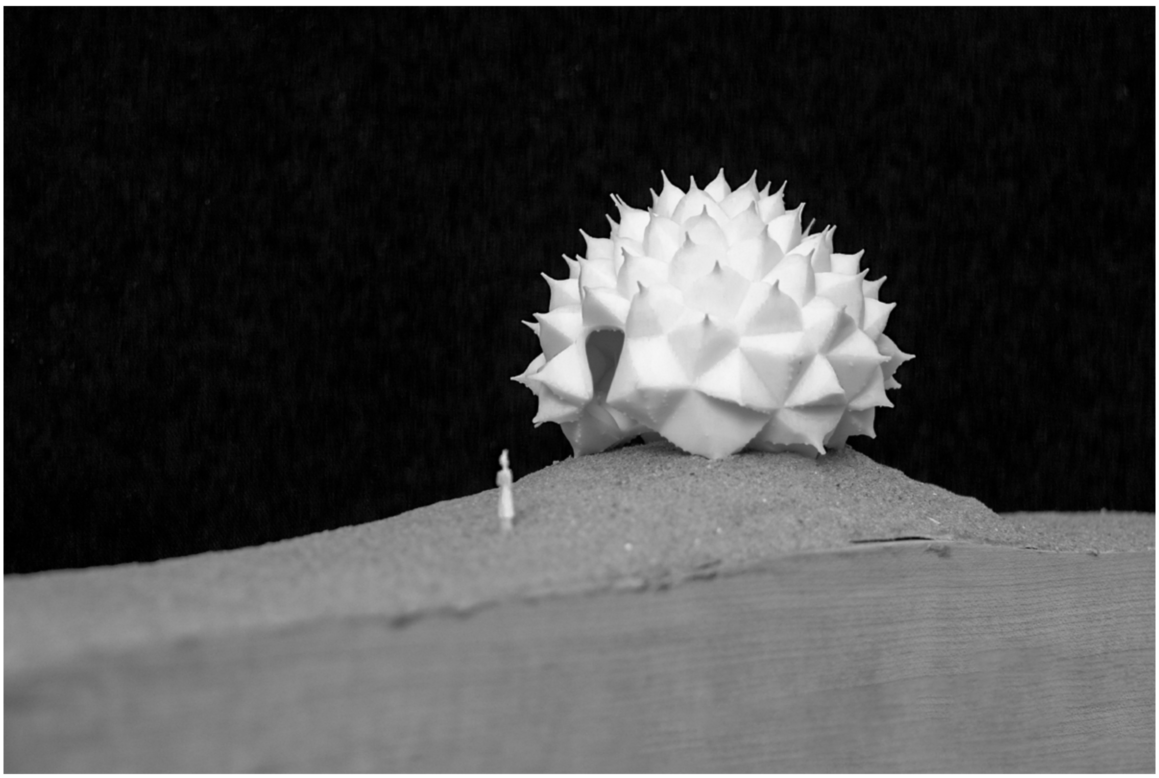
Thermal mass to reduce temperature fluctuation



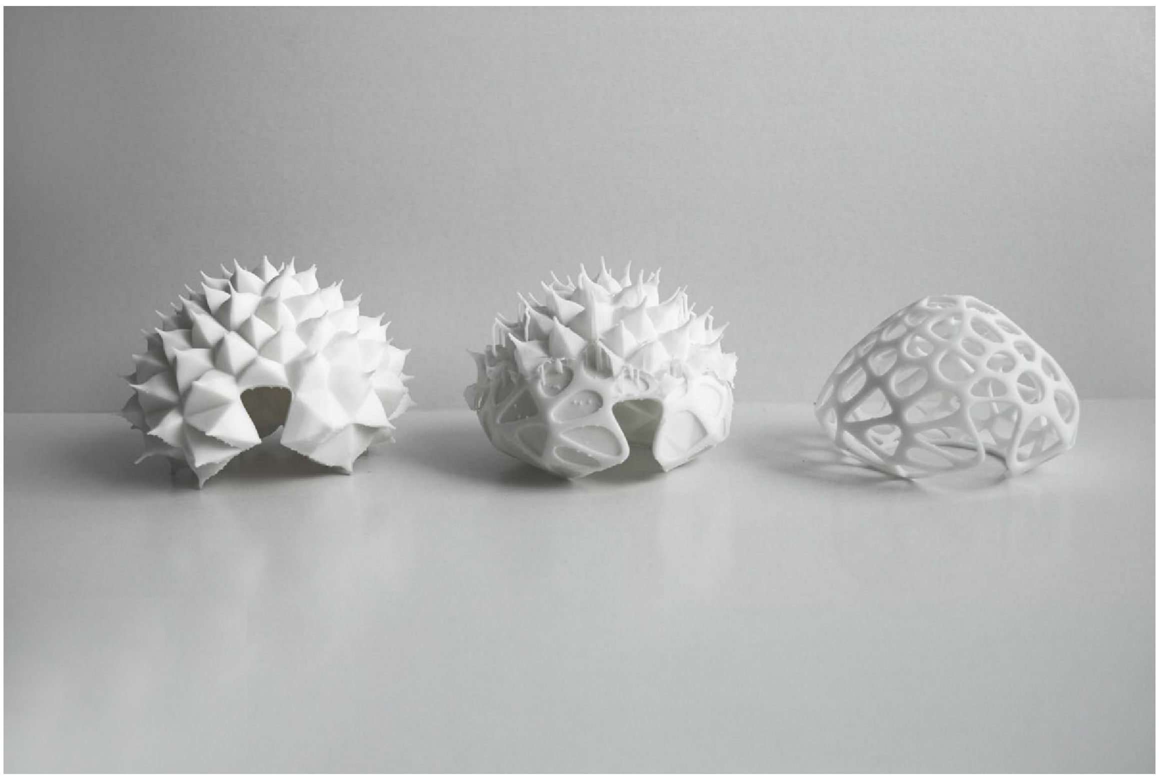
Render of The Hydration Room - exterior view



Render of The Hydration Room - interior view



Model photo - the Hydration Room



Model photo - layers of the Hydration Room

Model photo - the module of the Hydration Room

Model photo

Chapter 6: Conclusion

This thesis began by understanding the philosophy and approaches of biomimicry, and the most current technology in material and 3D printing. The study of biological models and the ecosystem in the Black Rock Desert was translated to the resulting architecture. This thesis intended to establish a comprehensive strategy for architecture and its surroundings, rather than a single solution.

Architecture has long been designed to serve humans only - the forms, the function, the process, and the spaces follow the solely human needs. However, this way of designing architecture has brought immense pollution to Earth. To create a regenerative environment, designers should consider reducing the disturbance to the environment.

The established design process demonstrated that biomimicry can be a tool to develop design strategies for a sustainable and regenerative built environment from the organism, behavior, and ecosystem approaches. A self-sustained network and “living” architecture is realized, in form, structure, material layering, HVAC, and life cycles for Burning Man. By analyzing the finite and renewable resources of the ecosystem of Black Rock Desert Playa, the morphological and physiological mechanism of cacti for thermal regulation, and termite and prairie dog behavior for HVAC.

The Hydration Room emulated the functions and processes of cacti to collect water, resist wind, and regulate the temperature through its geometry and material layering, which reflect the physiology and morphology dimension of the organism approach. The geometrical emulation is realized in the water catching layer, the extruded self-shading unit, the helical pattern, and the round shape. The emulation of the material property is in alternating hydrophilic (cellulose) and hydrophobic (chitin) material, which functions autonomously to transport water.

The passive ventilation system of the Hydration Room emulated the ventilation of termite mounds and prairie dog burrows, a realization of behavior approach. It is believed that maximizing the morphological and physiological mechanisms along with passive HVAC, enhance the energy performance of architecture.

The use of wind and sunlight from the Black Rock Desert and the waste recycle from Burning Man reflects the dimension of the ecosystem approach. The wind and sunlight power the HVAC of the Hydration Room for ventilation and the geothermal of the sand for heat exchange. The building materials were the recycled organic and non-organic waste of Burning Man.

Today’s technology in material and construction enhance the effect of a regenerative living environment by using cellulose and chitin as building material for a life cycle that simulates a nutrient cycle in nature, as well as adapting the schedule of the ecosystem. By using 3D printing to build functionally graded material which acts as the tissues or cells grown from a cactus. The procedure to implement biomimicry in mainstream architecture is evolving, from copying the figures in ancient times to making architecture like a living matter with today’s technology.

The architecture developed in this thesis is not to be considered the only way to implement biomimicry or to achieve sustainability in the architectural realm. However, the design method that has been established may be applied and adapted to any architectural project that seeks to protect the environment. The transferable processes include:

1. Gaining an understanding of the locally available or potentially locally renewable matter for building material.
2. Keep up to date with technologies that promote and enhance sustainability for building operation, construction, and life cycle, such as 3D printing for multi-function material with biomaterials.
3. Take advantage of the abundant natural energy sources such as the sun, wind, water, or heat to operate the architecture, and maximize the value of every resource, even waste.
4. Study the morphology and physiology features of local biological examples to develop forms, structure, material layering, and HVAC system.

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