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Utilizing Biomimicry to Design Sustainable Architecture

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abstract

Nature has an integral relationship with architecture and serves as a sustainable role model and inspiration for designers. The process of biomimicry in architecture has the potential to produce more sustainable design solutions and foster a connection between humans and nature. Existing biomimetic design projects have varying strengths and weaknesses as examples of the process. Utilizing guidelines and references from key leaders in biomimetic design consultancy (Biomimicry 3.8), selected case studies are assessed for their ability to demonstrate the benefits of this design strategy. Using these evaluations, the case studies are diagrammed and critiqued to determine how new projects could go further to improve the future of biomimicry.

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introduction

“A building exists in, and interacts with, the environment at various scales — from the cellular to the infrastructural — and the definition of that environment is important in framing its relationship and engagement with a design. Every design should anticipate not only its impact on the environment but also the changes in the environment that will subsequently impact it.”

- Simitch, A. and Warke, V., The Language of Architecture (2014)

Figure 01: Cover image of Laugier’s Essay on Architecture depicting the primitive hut (1753)

Architecture got its humble beginnings with primitive huts and caves in nature. Marc-Antoine Laugier, one of history’s first architectural theorists, uses the idea of the primitive hut as the prototype of all architecture. He believed that architecture was the mediator between nature and man. Nature and architecture have an interdependent relationship. As time goes on, architecture moves further from natural, primitive elements of building and utilizes more man-made technology. The current architecture and construction industries create a lot of waste that is damaging to nature. Nature, however, does not waste, and ecosystems work in a closed-loop cycle. If our man-made systems worked in similar ways, there would be little to no waste from construction. With this idea in mind, how can we design more like nature does, and therefore, more sustainably?

Utilizing biomimicry in architecture can have many benefits for design and the environment. Biomimicry is about learning from nature as a *model, mentor, and measure* (Benyus, 1997), and implementing natural principles in human processes. Biomimetic principles can elevate architectural design to be more sustainable and efficient. For this capstone, architectural case studies that utilize biomimetic principles have been researched and analyzed. The assessments of each project evaluate the strength and integrity of each project’s process and environmental impacts based on a list of established criteria. The following questions are overarching points of assessment for all projects:

1. How are designers utilizing biomimicry to create more sustainable design solutions?
2. What guidelines determine if a design is a high-integrity biomimetic project?
3. How can biomimicry be a part of the future of architecture?

project background

NATURE + ARCHITECTURE

Adrian Forty, in his book Words and Buildings, said that due to the many contradictions of environmentalism and varying historical interpretations, "nature continues to be an active – and disputed – category within architecture." (Forty, 2000) He discusses many views throughout history from architectural theorists on the role of nature within architecture, and the difficulties of assimilating manmade forms into natural cycles. Nature is a valuable mentor for designers, and a model for how to design more sustainably and utilize resources more efficiently. Architecture is all around us, and it is constantly sprawling, rising in height, or being destroyed to start anew. With new buildings popping up each day, the industry needs to learn how to produce architecture in more sustainable ways. Michael Pawlyn, a British architect known for his work in the field of biomimetic architecture and innovation, argues that "our use of resources can be characterized as linear, wasteful, and polluting, whereas in nature resources are maintained in closed-loop cycles" (Pawlyn, 2016).

BIO-INSPIRED DESIGN

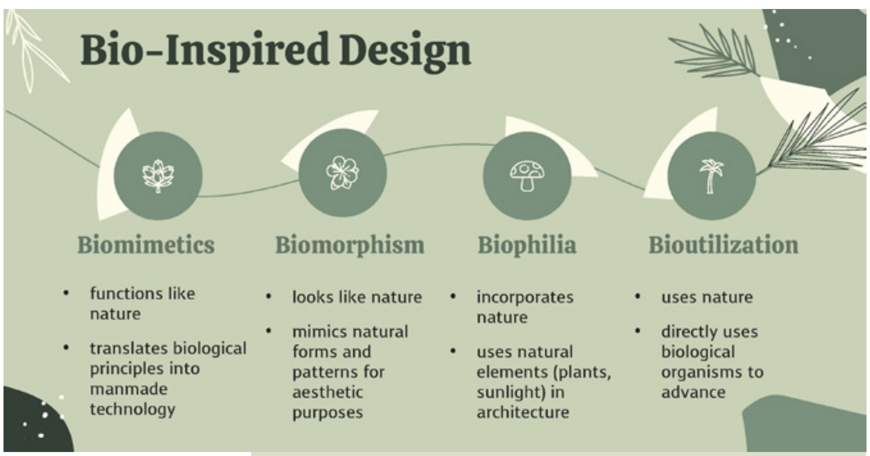

Figure 02: Definition diagram by author, 2022

The first thing to understand in this topic is bio-related design as a whole – encompassing biomimetics, biomorphism, biophilia, and bioutilization (Bernett, 2015) These bio principles of design have the common theme of being inspired by nature in some way, but they have different applications when it comes to design. While all four use nature as a foundation, sustainability is not a focus for all of them. Biomorphism is about mimicking natural forms for aesthetic purposes. Biophilia incorporates natural elements such as greenery or natural sunlight to heighten the human experience. Bioutilization takes biological organisms and implements them into technology to advance. Biomimetics mimics natural processes and techniques to solve human problems.

Biomimetics, also known as biomimicry, the focus of this review, appeared to be the most sustainable approach. Biomimetics is about translating biological principles into manmade technology and functioning like nature. It is inspired and informed by nature and delves into how we as humans and designers can learn to be more sustainable by following in nature's workflows. Biomimicry in design is about emulation of form, process, or ecosystems (Baumeister, 2013). It is not purely about the aesthetics of making a form look like nature. It's about how to make a manmade system that functions like nature. Biomimicry, as a topic, is not limited to sustainability-focused goals. It can be a guide for many other kinds of work performance as well, such as structural strength, adaptability, flexibility, environmental responsiveness, and many other forms. For this assessment, sustainability is a necessary condition for the project to be considered a high-integrity biomimetic example.

UNDERSTANDING BIOMIMICRY

To discuss biomimicry in architecture, it is first important to understand a foundation of biomimicry itself. Janine Benyus is a biologist, author, and innovation consultant. She popularized biomimicry in 1997 with her book "Biomimicry: Innovation Inspired by Nature". Her book is considered among many experts to be the "biomimicry bible". She also co-founded the world's first bio-inspired consultancy, Biomimicry 3.8, with Dr. Dayna Baumeister. Dr. Baumeister wrote the "Biomimicry Resource Handbook" in 2013. Biomimetic roots can be traced back further, especially in the scientific and engineering fields, but the terminology may have differed.

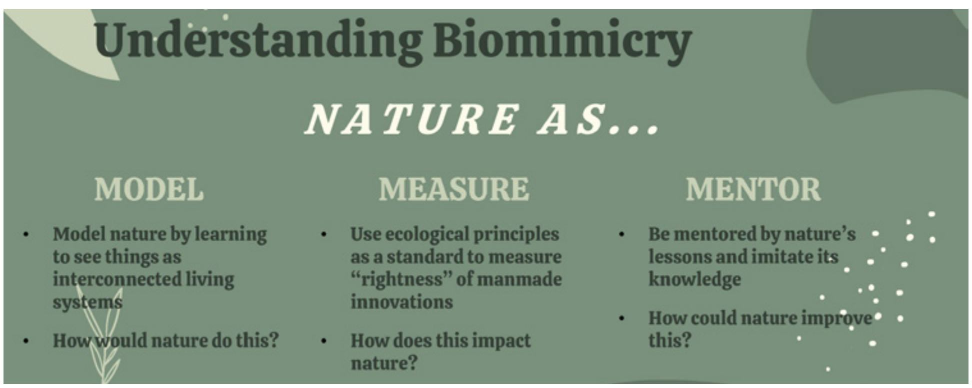

Figure 03: Biomimicry principles diagram by author, 2022 inspired by (Benyus, 1997)

The word biomimicry comes from the Greek word bios, meaning life, and mimesis, meaning imitation. Janine Benyus defines biomimicry as a science "that imitates or takes inspirations from [nature's] designs and processes to solve human problems, e.g., a solar cell inspired by a leaf" (Benyus, 1997). The goals of the practice are to see nature as a model, a mentor, and as a measure. Nature is the ultimate role model for humanity because nature has the answers on how to reuse waste, grow, and exist over billions of years. We should accept nature as a mentor on how to be better. Nature can also be used as a measure for ecological standards to which industries can be held accountable. Environmental impact is something to be considered in every realm of humanity. Benyus discusses biomimetics in relation to topics including farming, energy, manufacturing, healing, computing, business, and the future. She argues that biomimetics should be a factor in every industry.

The Biomimicry Resource Handbook offers a framework to explain how a sustainable approach to biomimicry could work. It gives examples and discusses how to grade a project on how well it is exemplifying the core ideals of biomimicry. A “good” biomimetic project should follow the three essential elements of biomimicry: emulate, ethos, and (re)connect. Emulating means to learn from and replicate nature’s forms, processes, and ecosystems in technology. Ethos refers to making sure the designs made are always life-friendly and are not creating negative environmental impacts. (Re) Connecting is about using design to celebrate connections between man and nature and finding value in nature.

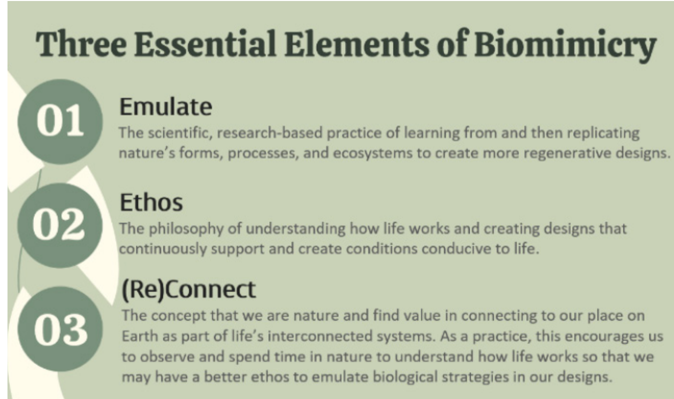

Figure 04: Elements diagram by author, 2022 inspired by (Benyus, 1997)

NATURE’S MANUFACTURING PROCESS

Benyus’ and Dr. Baumeister’s writings both discuss nature’s process for manufacturing: nature creates things through a “life-friendly manufacturing process” in water, at room temperature, without harsh chemicals or high pressures. Nature uses the world’s most common chemicals, like carbon, calcium, water, and phosphate to create some of the most complicated biological structures in the world. Then, these materials are reabsorbed or used for other purposes in nature, creating no unused waste. Nature has a hierarchy of structure, and it self-assembles and self-disassembles. Humans use every chemical available to create structures and materials, yet nature does it better with less.

One of the most famous examples of biomimicry is the invention of the now commonly known Velcro. In 1941, a Swiss engineer by the name of George de Mestral noticed many burrs attached to his clothes and his dog. Curious, Mestral examined the burrs and the fibers under a microscope. He realized that the burrs were made up of minuscule hooks, and they were adhering to the minuscule loops on his clothing fibers and his dog’s fur. Mestral considered the multitude of possibilities of mimicking this natural idea of hooks and loops connecting together as a manmade item. Thus, the idea for Velcro was born. Nature has many innovative strategies that can be utilized in man-made technology, and there are many more examples of existing biomimetically inspired inventions. The texture of shark skin inspired materials for swimsuits, allowing the wearer of the suit to travel through water faster. Benyus discusses how the inner shell of an abalone sea creature is “twice as tough as the highest-tech ceramics.” “Spider silk is five times stronger than steel.” “Mussel adhesive works underwater and sticks to anything”. Those are just a few examples of nature’s incredible abilities. Nature creates materials that are stronger than man’s while also creating less waste. Our architecture could be greatly improved if we took the opportunity to learn similar systems.

Figure 05: Architect Michael Pawlyn with 3D printed model (Pawlyn, 2021)

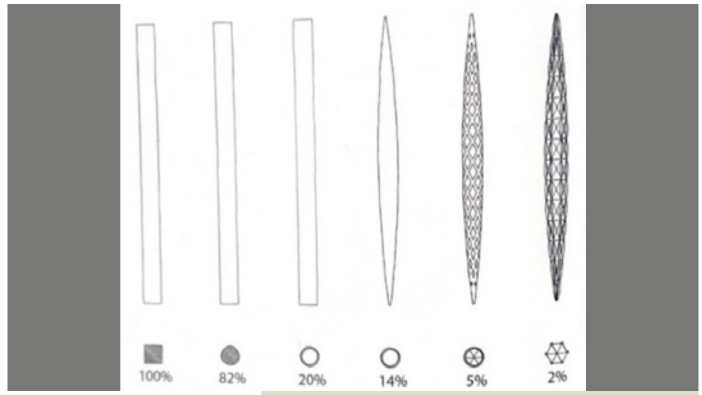

Figure 06: Structural materal efficiency (Pawlyn, 2019)

From the start of an architectural project to the end, there are lessons to be learned. In the early design process, a designer needs to consider the structural capabilities of their design. Architect Michael Pawlyn discusses how by utilizing nature’s hierarchical levels, structure can become more efficient in terms of the amount of material used to achieve an ideal structure. (see Figure 06.) Nature is able to use less material overall to achieve the same amount of structural stability. Nature suggests forms we may not naturally think of as designers. For example, the 30 St. Mary Axe, or Gherkin building, by Norman Foster is often associated with the Venus flower basket sponge. The building appears like the form and the structure of the sponge, “to do in air what the sponge does in water” (Foster, 2004). The lattice skeleton of the sponge and the round form allow it to disperse water currents around it and maintain its structural strength. This has been utilized in the skyscraper to deflect wind around the building and use it as an external pressure system to power natural ventilation within the building. The lattice structure on the exterior of the building supports it enough to allow for no interior columns disrupting the floor plan. Many other buildings use similar ideals that are inspired by nature, exemplifying the structural capabilities and innovations that are possible in architecture when we use biomimicry.

Through the practice of biomimicry, architectural design can become more sustainable, elevated, and efficient. Projects that follow the key elements of biomimicry have been reviewed and assessed for how they utilize biomimicry and what they could do to go further. Biomimicry in architecture can be used to innovate, reinvent, and overall, create a more sustainable and life-friendly environment to exist in.

approach + methods

PROJECT STATEMENT

Designers can use biomimicry as a tool to *learn from nature* and create more sustainable architecture. Existing biomimetic architectural projects have been investigated and analyzed to see how they are utilizing biomimicry to create innovative and sustainable architecture. "High-integrity" biomimetic projects will have utilized the foundational biomimetic ideas of using nature as model, measure, and mentor in their theoretical design process, along with following the core definition elements of emulate, ethos, and (re)connect. High-integrity projects would also use these principles with the goal of designing more sustainably in some way.

RESEARCH QUESTIONS

- How are designers utilizing biomimicry to create more sustainable design solutions?
- What guidelines determine if a design is a high-integrity biomimetic project?
- How can biomimicry be a part of the future of architecture?

APPROACH

A variety of design projects that use biomimicry have been reviewed. The projects have been analyzed individually and broken down into the strategy and mechanisms they use to achieve a function. A process discussed in the Biomimicry Resource Handbook has been used to look at each case study and walk through how it came to be the design it is based on its natural inspiration. This process is referred to as the Abstracting Design Principle (ADP) Process (Baumeister, 2013), but for the use of this research, the process is adapted and used to create simplified design principle diagrams. For each case study, the biological inspiration for the design has been broken down with the following analysis strategy:

1. Summarize the relevant biology of the biological principle/idea.
2. Highlight the key strategy/mechanisms of the paragraph.
3. Summarize the highlighted points in bullet point form.
4. Remove the biological terms and write a summary of the adaptive design principle left.

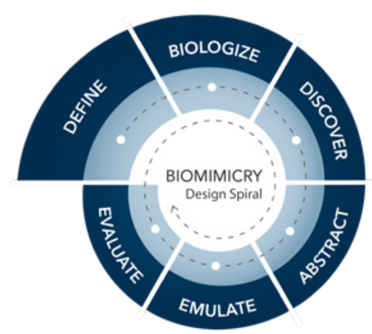

Figure 07: Biomimicry Institute's "Design Spiral", 2017

After the project's function is summarized, it has been diagrammed to show how the project works in comparison with its biological inspiration. Each project is then distilled into a simplified design principle, which is described and shown visually.

Next, each project has gone through a series of assessment questions to determine how well it embodies biomimetic principles. The questions are informed by Biomimicry 3.8's "Anatomy of a Case Study" that assists designers and researchers to determine how well a biomimetic case study is following the goal of creating designs that "create conditions conducive to life by emulating nature successfully". The overarching goal of biomimicry is to emulate nature's processes in a way that is helpful to mankind and nature.

ASSESSMENT PROCESS

Each project will have already "qualified" to be discussed by following the biomimetic principles and definition elements. (model, measure, mentor & emulate, ethos, reconnect)
If a project simply looks like the form of a natural element without giving any nod towards sustainability or a deeper design thinking, then it is just bioinspired. This analysis is centered on biomimetic practices specifically.

If the case study's research shows no evidence of achieving the category's goal that the question asks for, then it receives 0 points for that section. If the case study shows some evidence for acknowledging the question, but the evidence is not fully clear or abundant, then the project will receive a half point. If the project clearly shows evidence of achieving or exceeding the goals of the category, it will receive 1 point for that category. Each project received a score out of 5 points and a breakdown of which categories it achieved them in.

ASSESSMENT CATEGORIES

The assessment questions are separated into five categories. Each category has a key word heading, a list of descriptions of how the project may show that it succeeds in that category, and an overarching question that summarizes the goal of the category. In terms of grading the case studies in these categories, the projects are eligible to receive a maximum of 5 points across the 5 categories.

INTENT

Did innovators intentionally turn to nature during the initial early phases of the design process?

- Designers had a problem early in the design process and looked for solutions in nature as opposed to turning to nature retrospectively, in order to justify a design solution

(RE) CONNECT

Does the solution foster a (re) connection with nature?

- The project brings humans closer to and encourages caring about nature
- Creates an ethos of being involved by encouraging humans to feel a need to protect the environment
- The project is part of a regenerative system by lowering off-gassing, using local materials, or minimizing its carbon footprint

EMULATE

Is there a systemic reason for emulation beyond aesthetics?

- The project goes deeper than aesthetics - the biomimicry is embedded in the system and process of how the project exists
- The project is emulating form, process, ecosystem, etc. through its functions
- Project is functioning like nature

SUSTAINABILITY

Is there a sustainability win?

- The project has an effective use of "green" design that is measurable
- The project is potentially participating in a green rating systems (LEED, living building challenge)
- The solution can be used in different industries, product/service categories, countries

EXPAND

Does the solution have a potential to magnify its positive impact?

- The project either gives back to the community in a sustainable way (ex: providing power, fresh water, etc.) and/or leads by example by demonstrating an inspirational way to use biomimicry
- Through its ingenuity, success, or story, the solution can inspire others to learn from nature

SAMPLE SCORING MATRIX

INTENT	+1
(RE) CONNECT	+0.5
EMULATE	+1
SUSTAINABILITY	+1
EXPAND	+0
TOTAL SCORE:	3.5/5

LEGEND

CLEAR EVIDENCE (1 POINT)	+1
PARTIAL EVIDENCE (0.5 POINT)	+0.5
NO EVIDENCE (0 POINT)	+0

POST - ASSESSMENT

Each project has been graded according to each category and will have a scoring matrix modeled after the sample version to show where it gains points. The project has description detailing where it receives points in the categories and due to what evidence that was decided.

After each project has been assessed individually, they are then analyzed as a group to extract information about common themes and concepts across multiple varied design projects. The projects have been categorized in multiple ways to show what tactics are more common as opposed to less used ideas. The case studies have also been analyzed for how they could be strengthened or learn from each other going forward. Using the findings from the assessment process, the projects are analyzed for the potential that they hold as well as their current successes. Through considering the case studies with this lens of biomimetic principles, a road map is created for future projects.

case studies introduction

PROJECT SELECTION

Through researching the topic of biomimicry in architecture and design, a wide array of case studies were reviewed. These range from projects built in the 1800s that follow themes of biomimicry before it was a known design technique to more recent examples that follow biomimicry principles across a holistic scale. The case studies list was then narrowed down in order to more deeply analyze the more exemplary examples of biomimetic design.

Project Title	Designer	Year of Completion	Location
Ada	Jenny Sabin Studio	2019	Redmond, Washington
Aguahoja	Neri Oxman	2020	San Francisco MoMA
Beijing National Stadium	Herzog & de Meuron	2008	Beijing
Biomimetic Office Building	Exploration Architecture	2014	unbuilt/model
Birdsong Pavilion	Exploration Architecture	unknown	unbuilt/model
Casa Mila	Antoni Gaudi	1912	Barcelona, Spain
Council House 2	Mick Pearce	2006	Melbourne, Australia
Eastgate Center	Mick Pearce	1996	Harare, Zimbabwe
Eden Project	Michael Pawlyn/Nicholas Grimshaw	2001	Cornwall, UK
Eiffel Tower	Gustave Eiffel	1889	Paris, France
Elytra Filament Pavilion	Achim Menges	2016	University of Stuttgart
Esplanade Theater	DPA	2002	Singapore
Gherkin Building	Norman Foster	2004	London, England
Institut du Monde Arabe	Jean Nouvel	1987	Paris, France
Lumen	Jenny Sabin Studio	2017	formerly NYC, no longer on view
National Aquatics Center (Water Cube)	ARUP	2008	Beijing
Quadracci Pavilion	Santiaga Calatrava	2001	Milwaukee, WI
Sagrada Familia Basilica	Antoni Gaudi	1882 - present	Barcelona, Spain
Sahara Forest Project	Exploration Architecture	2012	Aqaba, Jordan
Serpentine Pavilion	Sergascano	2015	London, England (seasonally)
Waterloo International Terminal	Nicholas Grimshaw	1993	London, England

Figure 08: List of case studies

The Approach and Methods section discussed what qualifies as a case study a strong biomimetic example versus a weak one. This case studies section will begin by discussing a few of the weaker biomimetic examples. These projects are known in the realm of architecture, and frequently mislabeled as using biomimicry in their designs. They use natural elements on a more formal and surface level case, not in a deeper and intentional way that biomimetic design would use.

case studies analysis

BIOINSPIRED VS. BIOMIMETIC

For a project to truly follow the principles of biomimicry, it needs intentionality behind the design. Biomimicry is not a process that is done accidentally. It requires early iteration and involvement in the design process. It's not about making a building aesthetically "look like" nature. It's about emulating a process that happens in nature through the function of a building. The following projects are frequently referenced as having biomimetic qualities. While they may be inspired by nature, there is a difference between being bioinspired and biomimetic.

Figure 09: 30 St Mary Axe view, (Foster & Partners, 2004)

Figure 10: Venus's flower basket (Okeanos Explorer Program, 2012)

The 30 St Mary Axe building, known more commonly and colloquially as the Gherkin building, is frequently referenced as an example of biomimetic architecture. Many authors and designers claim its structure was inspired by that of the Venus's flower basket sponge. While it may look similar formally, the Gherkin's structure was scaled up in size greatly. The structures are not very similar functionally, only slightly similar from a formal standpoint. There is little evidence that the Gherkin building was purposefully designed to mimic the Venus's flower basket sponge. Biomimicry is something done early in the design process in order to solve a problem in a more efficient way like nature does. From the research done related to this project, it appears more as though the comparison between the two was made much later in the process, after the design idea had already been conceived.

In terms of sustainability, the building was designed to use passive cooling with its structure and double-skin facade. The open structure and rounded building shape was intended to deflect wind more easily and take in air to allow the building to "breathe" through the lattice structure. This strategy would allow the building to consume a much lower amount of power than a traditional building of the same size. However, this building is an example of how the maintenance requirements of a sustainable building do not always live up to the ideal expectations. In 2005, one of the operable windows broke, and this incident led to the building switching to primarily using traditional heating and cooling systems instead of the passive approach. The passive system did not function as efficiently and smoothly as it could have, so it is rarely used by many tenants now.

Figure 11: Sagrada Familia (Spain.Info, 2021)

Figure 12: Casa Mila (Nanani, 2023)

"Nothing is invented, for it's written in nature first."

\- Antoni Gaudi (1852 - 1926)

Antoni Gaudi was a Catalan architect and designer in the late 1800s and early 1900s. He is well known for his unique and organic architectural style. Gaudi was known for being inspired by nature's processes and forms and allowing his buildings to "grow" and "breathe" like nature would. His works are frequently interpreted as being biomimetic. Biomimicry is a more modern term that wasn't used during his time of work. He didn't necessarily have a goal of sustainable design, though the way he allowed buildings to breathe is related to passive cooling. His work came before the age of biomimicry in design, so it's not traditionally considered as intentional biomimetic design. That said, it is definitely bioinspired, and it begins to touch on the principles of biomimicry.

The National Aquatics Center, or "Water Cube" as it's known informally, was constructed for the 2008 Olympics in Beijing by PTW Architects, CCDI, CSCEC, and ARUP Engineering. While it does follow the form of water or soap bubbles in some ways, it is done in a more formal and aesthetic way than for functional use. This is a building used for aquatic activities, so the facade being made to symbolically look like water leans more towards being an aesthetic choice than a functional and purposefully biomimetic choice. That being said, the use of Ethylene tetrafluoroethylene (ETFE) for the "bubbles" does lend to a sustainability win. ETFE is a much lighter and thinner material than traditional glass. This allows for more light and heat transfer which assists in heating the interior of the building and the pools within. This strategy creates a 30% decrease in energy costs. While the facade is less biomimetic and more aesthetically bioinspired, the material efficiency does still encourage a sustainability gain.

Figure 13: National Aquatics Center, (Fong, 2009)

Figure 14: Beijing National Stadium (Museler, 2019)

Figure 15: Bird's nest (Natasha/ stock.adobe.com)

The Beijing National Stadium, or Bird's Nest, as it is colloquially called, was also designed for the 2008 Olympics, directly adjacent to the Water Cube. It was designed by the architecture firm of Herzog & de Meuron. This building is referenced as biomimetic due to its appearance being similar to a bird's nest. During its conception, it was actually inspired by the process of Chinese ceramics. It was intended to be "porous", a "public vessel", and appear somewhat randomized in structure. It was not intentionally designed to look or function as a bird's nest would. The comparison was made later in the design. The difference is clear also due to the shift of scale. Scaling the bird's nest "twigs" up to such large structural components with greatly porous gaps between them takes away the close-knit insulating function of a bird's nest. This scale shift undermines the ideal use and function of a nest and loses the biomimetic quality. Due to this, the building only formally looks similar to a bird's nest, but it does not emulate its processes in the same way.

SIMILARITIES

Overall, these projects tend to lean more towards the idea of bioinspired design than biomimicry. Some do still make strides in terms of sustainable design in the areas of material efficiency or passive heating and cooling. A key aspect of a high-integrity biomimetic project is that it has strong intentions to design with biomimicry. The project should begin using biomimicry early in the design process and use nature as a model in how it iterates and ideates. Some of these examples do that better than others, but none have strong intentionality in their design processes.

STRONG CASE STUDIES

In analyzing each of the 22 case studies that came up in the research, each one was researched for its design process and the designer's intent. The five case studies that were analyzed in more depth were determined to be "strong" examples of biomimicry according to the following categories of criteria:

INTENT

Did innovators intentionally turn to nature during the initial early phases of the design process?

(RE) CONNECT

Does the solution foster a (re) connection with nature?

EMULATE

Is there a systemic reason for emulation beyond aesthetics?

SUSTAINABILITY

Is there a sustainability win?

EXPAND

Does the solution have a potential to magnify its positive impact?

The projects are eligible to receive a maximum of 5 points across the 5 categories. These questions have been answered through research into each case study and their design processes; however, there could be differing sources or opinions on the process and the benefits. For the purpose of this thesis, projects that score a 0-2 on this scale are considered weak examples of biomimicry. Projects scoring a 3 on this scale are considered adequate examples of biomimicry. Projects scoring an 4-5 on this scale are considered strong examples of biomimicry.

INTENT TO DESIGN BIOMIMETICALLY

While all of these question criteria are important, question number one is particularly important. Designing with biomimicry in mind should come into play early in a design process for it to be truly high-integrity biomimetic design. Biomimicry is most successful when it is used to learn how to solve a problem. It should come into the process early on because designers can emulate nature to learn from the success that nature has found in the way it solves a problem. Biomimicry should be used as a strategy to create efficient architecture based on the way nature might solve a similar problem. Some designs are commonly misconceived as biomimetic architecture, as stated in the prior section. These are designs that were related to nature's processes and ideas retrospectively as opposed to early on. While they may still have some qualities that lend to biomimetic design or sustainability, they were not *intentionally* designed to follow nature's footsteps. This makes them weaker biomimetic examples, as they may not be truly *functioning* like nature, and are therefore not a helpful or informational emulation of nature's successes.

EASTGATE CENTER

DESIGNED BY
MICK PEARCE

Figure 16: Eastgate Center Exterior (Livin Spaces, 2018)

PROJECT BACKGROUND

The Eastgate Center is a shopping center and office building completed in 1996 by designer Mick Pearce in Harare, Zimbabwe. It was designed to forego traditional fuel-based heating and cooling systems and instead take a sustainable approach. It was intended to be like an ecosystem, not a “machine for living in”. Eastgate Center was designed to mimic the homes of termites. Termite mounds utilize a tall chimney structure that pushes hot air out of the mound, and smaller foraging holes lower down suck fresh cool air inside the mound. Once the fresh air has been heated by the thick mass of the mound, it travels up to be released out the top of the chimney. Mick Pearce saw the termite tactic as an inspiration for designing Eastgate Center. He used materials with heavy thermal mass - such as brick and concrete - to retain some heat gain within the building. The structure of the building allows fresh cool air in at the bottom and allows it to circulate up through the building and between floors. The air gets heated as it travels upward through the building and is then released out the top of the building in a chimney-like structure, similar to that of a termite mound.

This project was biomimetic by intent early on in the design process. In the realm of biomimetic architecture, it is known by many as a famous example. Mick Pearce successfully designed a building that followed nature's footsteps in a sustainable way, while also saving the client money on energy costs. The diagrams below from the designer assist in illustrating the heating and cooling process of a termite mound, and in turn, the Eastgate Center building.

Figure 17: Termite mound VS. building section (National Geographic, 2018)

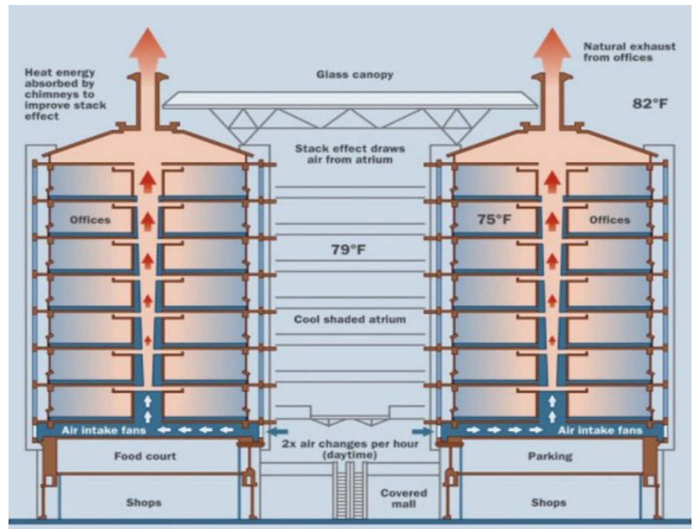

Figure 18: Heating and air flow sections (Pearce, 1996)

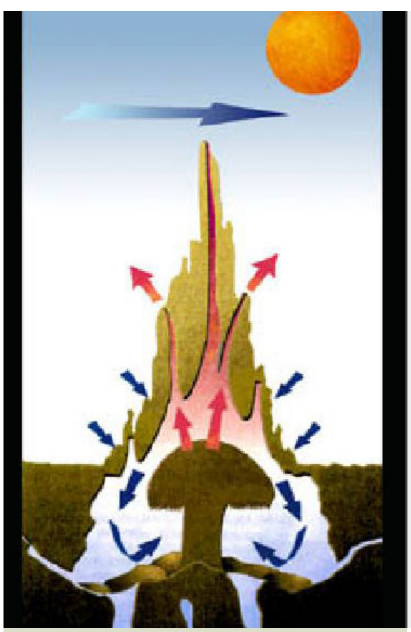

Figure 19: Termite mound section (Pearce, 1996)

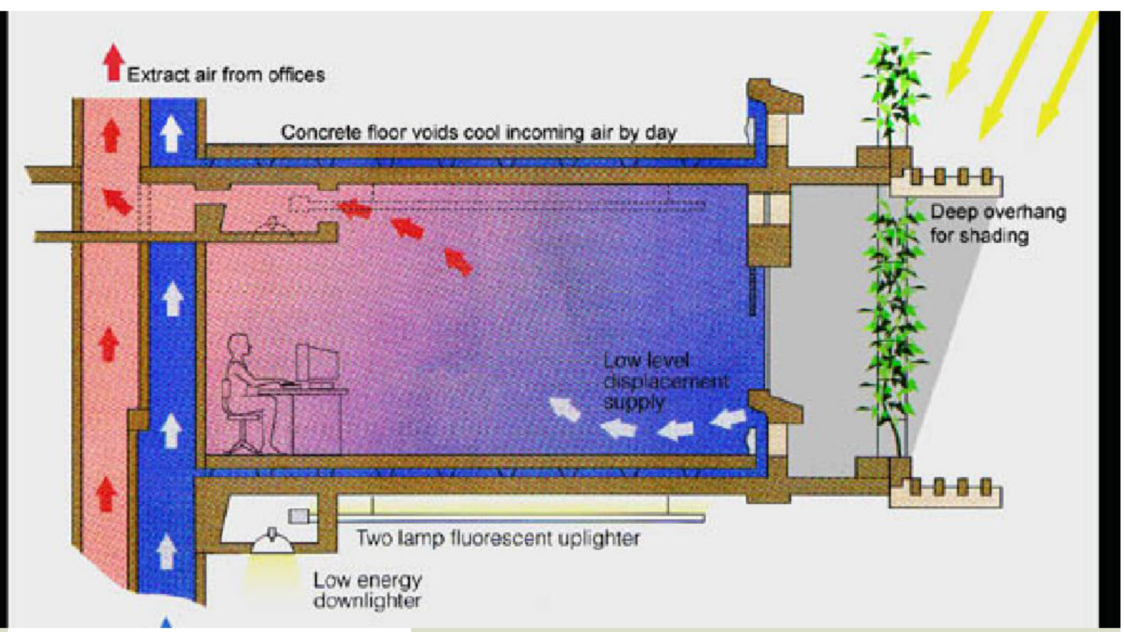

Figure 20: Heating/cooling process section (Pearce, 1996)

ANALYSIS

The Eastgate Center's airflow is shown adjacent to that of a termite mound in order to compare the projects in section. This illustrates the process that both use for passive ventilation and how the building is shaped to emulate the termite mound's structure.

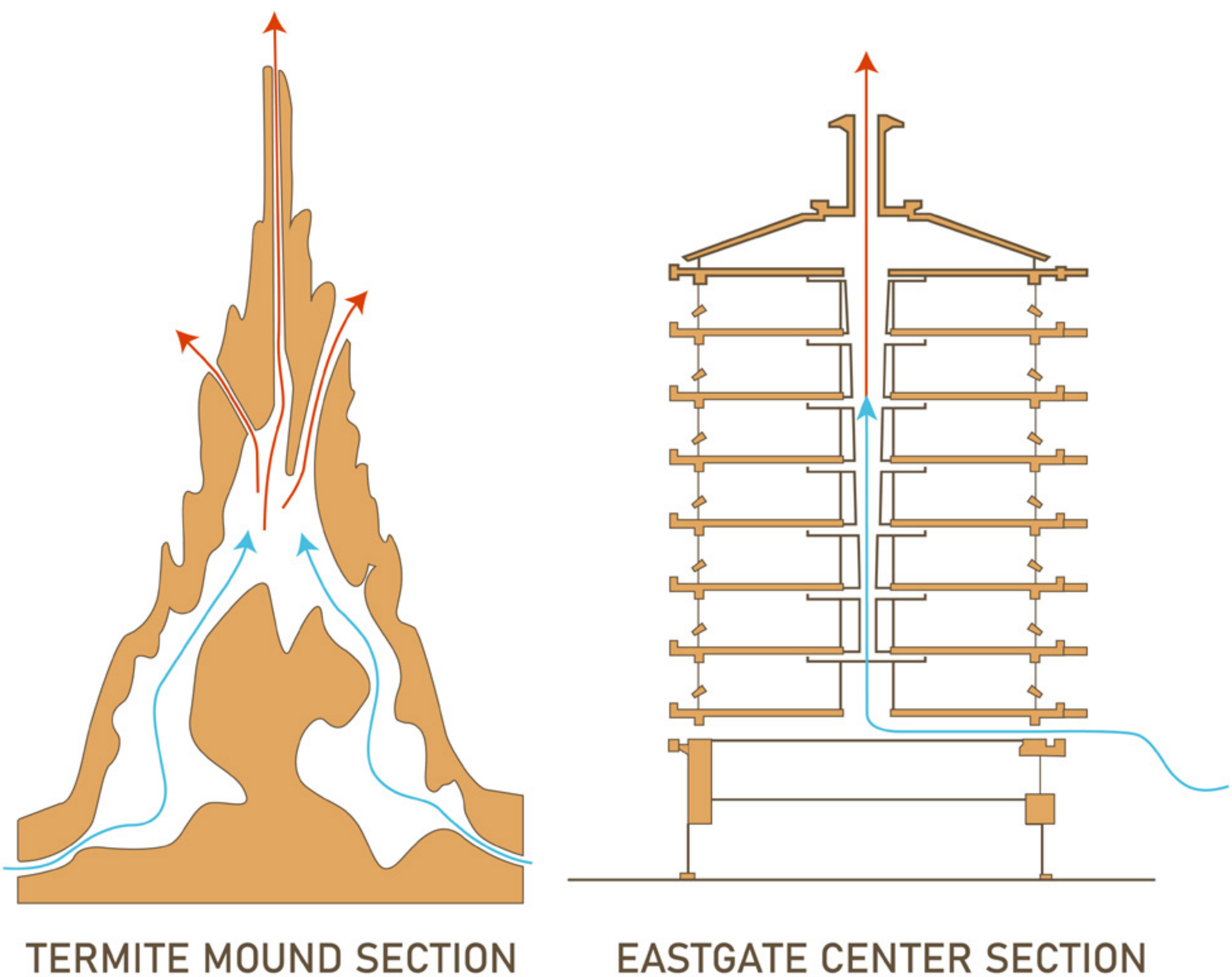

Figure 21: Termite mound and Eastgate Center comparison diagram by author inspired by (Pearce, 1996)

The Abstracting Design Principle (ADP) process was then used to break down the biological system of a termite mound that the Eastgate Center is emulating into a simplified description of the desired function.

PROCESS

1. Summarize the relevant biology of the biological principle/idea that the case study is emulating.
2. Highlight the key strategies within the summary.
3. Remove the biological terms and write a summary of the adaptive design principle left.

RESULT

Termite mounds have smaller foraging holes at the base that intake fresh cool air inside the mound. The cool air is heated by the thick mass of the walls which causes it to rise up due to the temperature difference between the upper and lower holes, and it is then released out the top of the mound's chimney as hot air. This is known as the "stack effect".

- cool air comes in / air is heated as it travels up / air is released

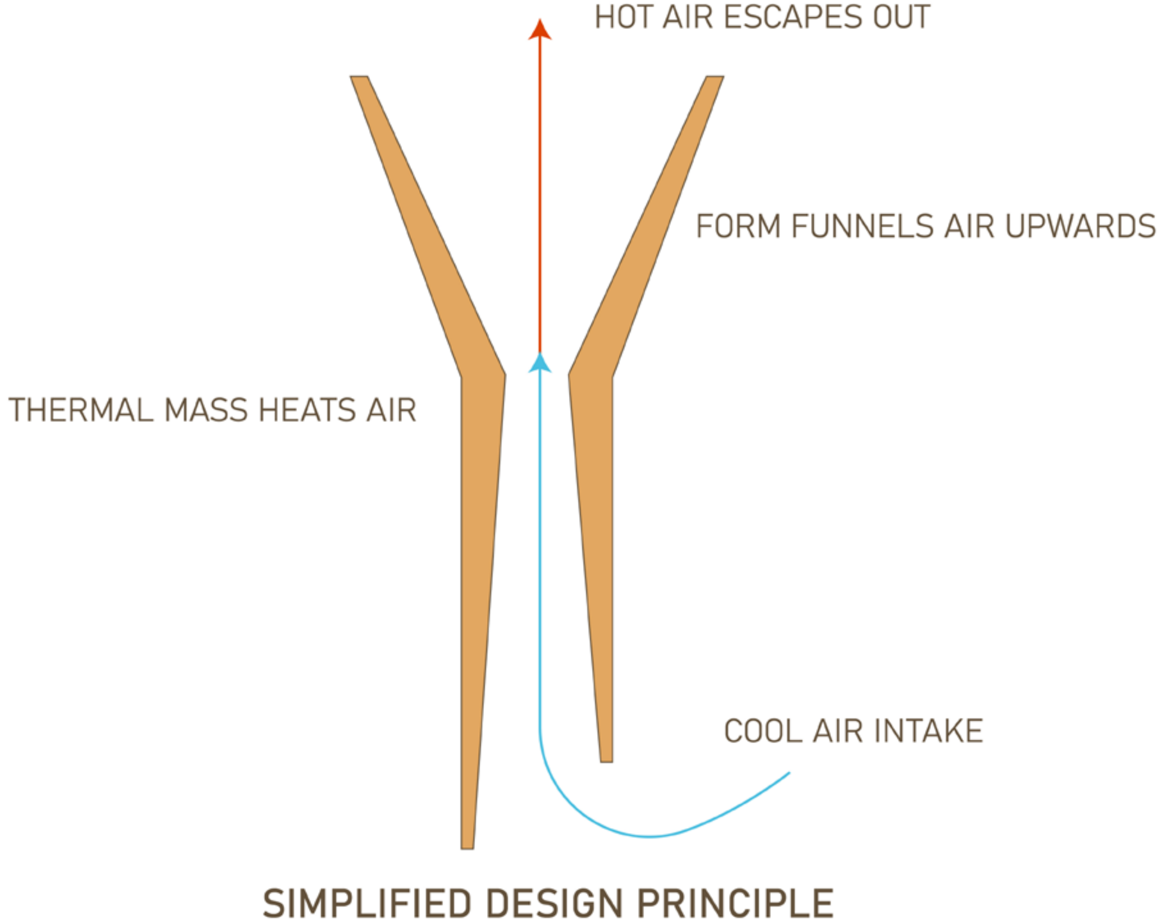

Figure 22: Author diagram of simplified design principle

SCORING MATRIX

INTENT	+1
(RE) CONNECT	+1
EMULATE	+1
SUSTAINABILITY	+1
EXPAND	+1
TOTAL SCORE:	5/5

LEGEND

CLEAR EVIDENCE (1 POINT)	+1
PARTIAL EVIDENCE (0.5 POINT)	+0.5
NO EVIDENCE (0 POINT)	+0

Did innovators intentionally turn to nature during the initial early phases of the design process?

Does the solution foster a (re) connection with nature?

Is there a systemic reason for emulation beyond aesthetics?

Is there a sustainability win?

Does the solution have a potential to magnify its positive impact?

This project scores a total of 5/5 points. It's proven itself to have intentionally followed an ecosystem in the way it operates, and in doing so follows a sustainable process of passive cooling. The designer used nature as inspiration early on in the process to problem solve. With its atrium between the two building towers and added greenery, it encourages an outdoor feel and thereby fosters the tenants' and visitors' connections with nature. Additionally, its construction participates in a regenerative system. Built with local Zimbabwean bricks, the use of local materials and integration of nature within the design shows that the building is not possible without the help of nature. This project comes from a place of respecting nature. The lesson from nature is formed in a way that is true to its original inspiration of the termite mound, and the lesson is clear in the section of the building.

Eastgate Center has magnified its positive impact by inspiring many articles about this strategy of passive cooling and encouraging other buildings to follow in its footsteps. The community benefits from it as it is a public building and the community is able to experience the high interior quality of the project. It expands the future of biomimicry as a teaching example academically and as an accessible design open to public interaction.

COUNCIL HOUSE 2

DESIGNED BY
MICK PEARCE

Figure 23: Council House 2 Exterior
(City of Melbourne, 2010)

PROJECT BACKGROUND

Council House 2 is a mixed-use building with retail on the bottom floor and offices on the upper floors. It was designed by Mick Pearce and completed in 2006 for the city of Melbourne, Australia. This project made environmental strides by being the first commercial office building in the country to meet the Green Building Council of Australia's six star green rating system. Council House 2 was commissioned in order to set an example for other developers and showcase the City of Melbourne's goals to achieve zero emissions for the municipality by 2020. It utilizes multiple sustainable materials in its construction, such as recycled concrete, recycled timber, and timber windows. It also uses wind turbines to extract air, solar hot water heating, and photovoltaic electricity. With the same designer as Eastgate Center, it is in many ways a refinement of the prior project. It uses similar strategies of passive heating and cooling, emulating a termite mound in the same way as Eastgate Center.

The inspiration from nature takes place both *literally* and *metaphorically* in this project. The project's structure is formed to follow the same functions as a termite mound, utilizing the passive ventilation process to create a 100% fresh air change for the building's tenants every half hour. In the literal sense, the project's exterior balconies include greenery as a feature to create an intentional relationship between the tenants and nature. The panels on the facade were also modeled after a tree's bark, to act as a second skin for the building's face. This project supports tenants with airflow and natural elements in a way that creates a holistic ecosystem and encourages a connection with nature.

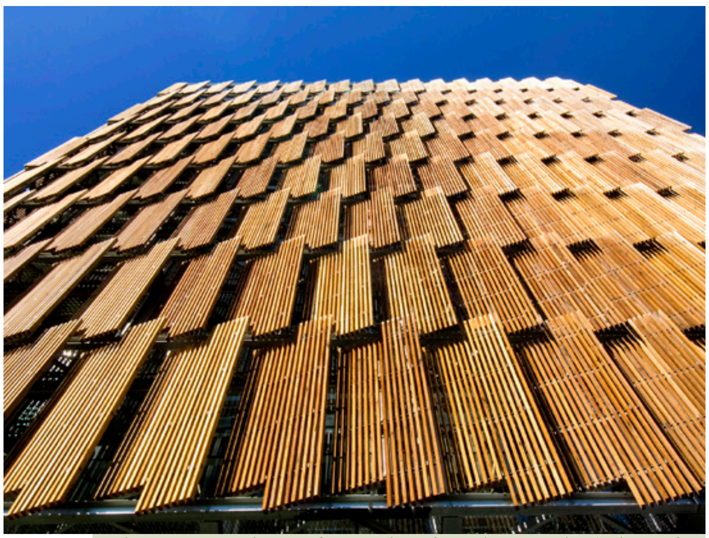

Figure 24: View of exterior facade panels (City of Melbourne, 2010)

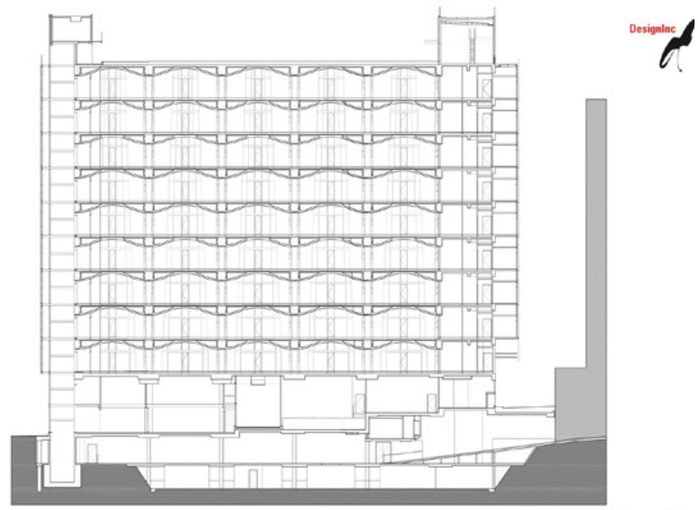

Figure 25: Building longitudinal section (Pearce, 2006)

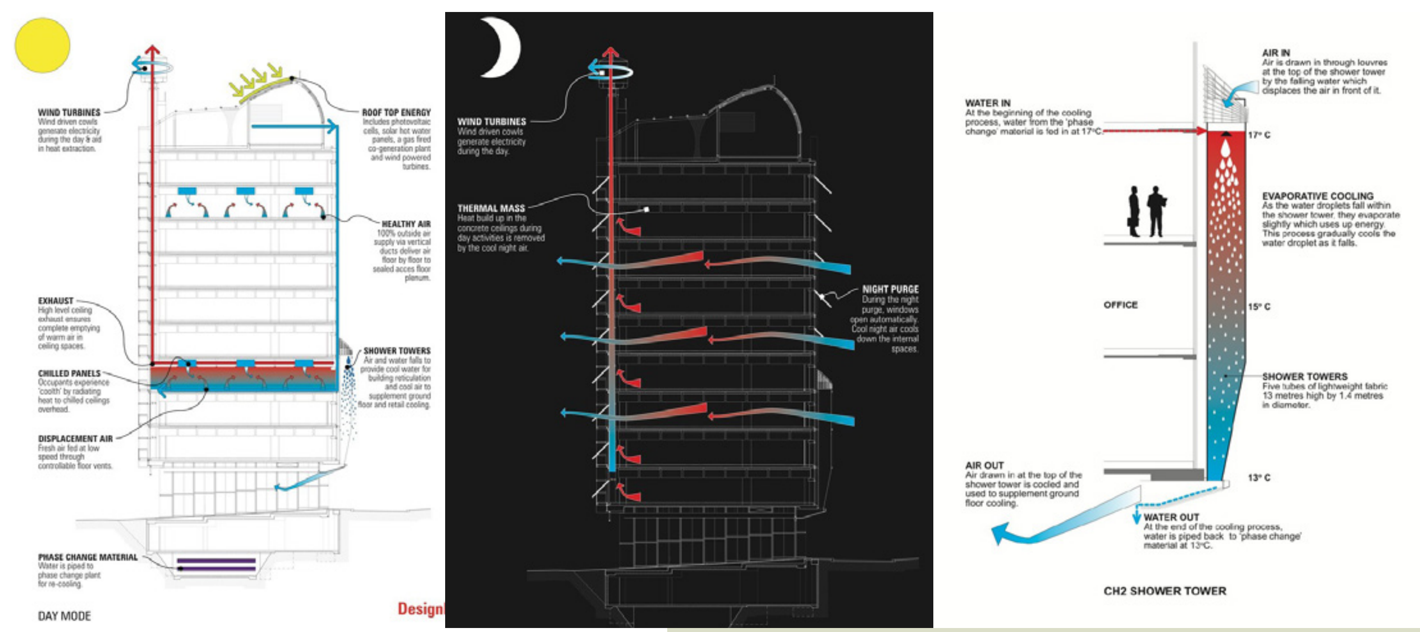

Figure 26: Heating/cooling sectional diagrams (Pearce, 2006)

ANALYSIS

In order to analyze this project, it's important to reference Eastgate Center as a precedent. The design team incorporated a heating and ventilating system that they found was successful in the prior design of Eastgate (Pearce, 2016) within Council House 2, but with some added sophistications. A comparison sketch of the termite mound airflow process adjacent to the Eastgate Center heating airflow process was shown earlier. Council House 2 uses the same process, but with some refinement. The two projects are shown adjacent to that of a termite mound below.

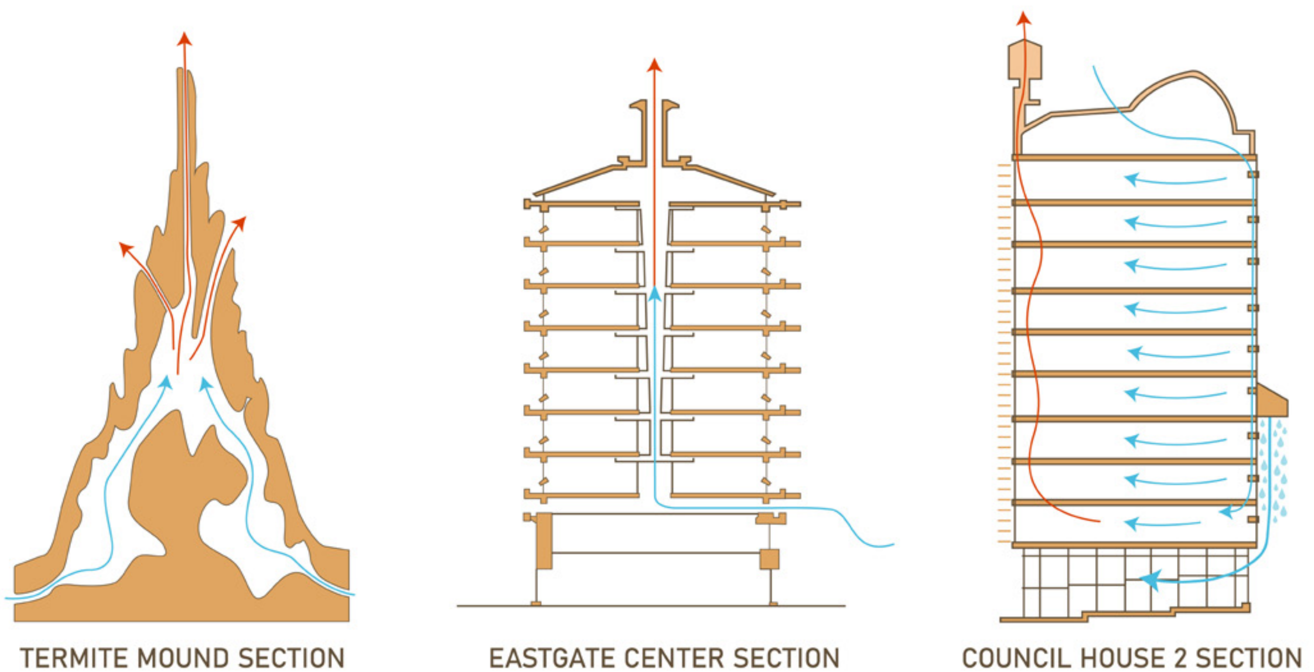

Figure 27: Comparison diagram of termite mound, Eastgate Center, and Council House 2 by author inspired by (Pearce, 1996)

The Abstracting Design Principles (ADP) process was used to break down the biological system of a termite mound into a simplified description of the desired function in the previous case study section. Council House 2 uses the same biological model, so the same breakdown is repeated.

PROCESS

1. Summarize the relevant biology of the biological principle/idea that the case study is emulating.
2. Highlight the key strategies within the summary.
3. Remove the biological terms and write a summary of the adaptive design principle left.

RESULT

Termite mounds have smaller foraging holes at the base that intake fresh cool air inside the mound. The cool air is heated by the thick mass of the walls which causes it to rise up due to the temperature difference between the upper and lower holes, and it is then released out the top of the mound's chimney as hot air. This is known as the "stack effect". Council House 2 also intakes water and moves it lower to cool it down and use it for underground cooling.

- cool air comes in / air is heated as it travels up / air is released
- water intake / cools as it falls / underground cooling

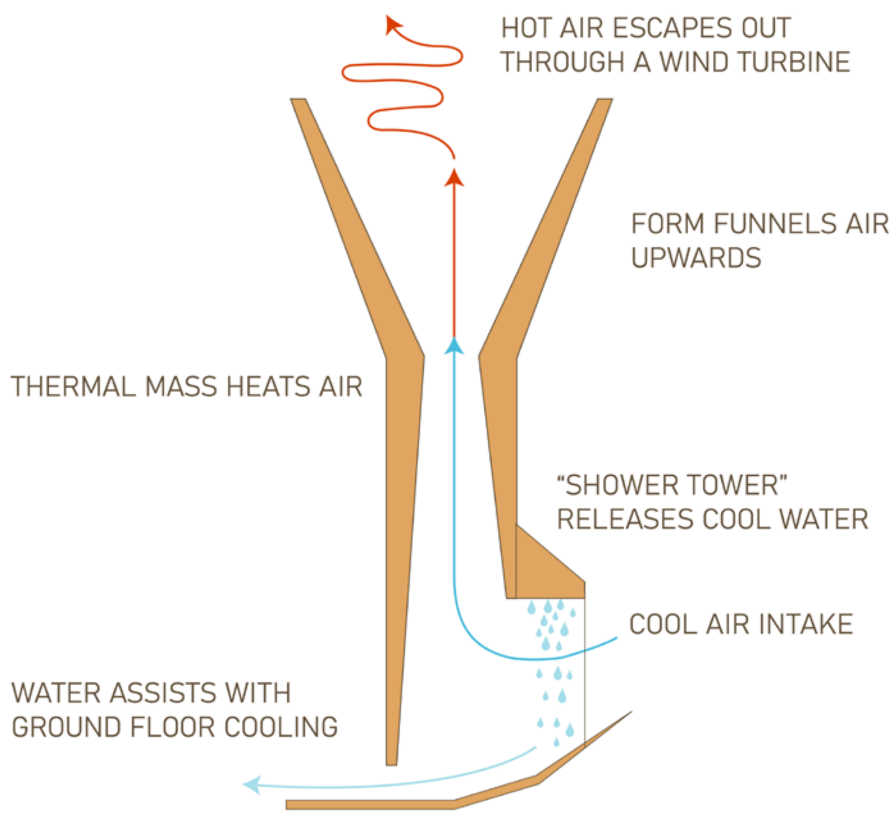

Figure 28: author diagram of simplified design principle

SCORING MATRIX

INTENT	+1
(RE) CONNECT	+1
EMULATE	+1
SUSTAINABILITY	+1
EXPAND	+1
TOTAL SCORE:	5/5

LEGEND

CLEAR EVIDENCE (1 POINT)	+1
PARTIAL EVIDENCE (0.5 POINT)	+0.5
NO EVIDENCE (0 POINT)	+0

Did innovators intentionally turn to nature during the initial early phases of the design process?

Does the solution foster a (re) connection with nature?

Is there a systemic reason for emulation beyond aesthetics?

Is there a sustainability win?

Does the solution have a potential to magnify its positive impact?

Council House 2 scores a 5/5 on the scale. It is designed by the same designer as Eastgate Center, and uses the same emulation strategy. This iteration makes the designer's intent to turn to nature early in the design process clear. In addition, this repetition means the project gains a point for authentically emulating nature. The project brings humans closer to nature in literal ways by bringing greenery within the building, but also creates a relationship between the project and nature by giving back to nature. Council House 2 includes an equivalent amount of plants to replace what was lost during development in order to oxygenate the air both inside and out. (Pearce, 2016)

The building's ability to achieve the top score of six stars in the Australia Green Star environmental accreditation shows its commitment to sustainable design through its use of wind turbines, solar heating, and other creative uses of natural resources. Council House 2 is in itself a strong example of encouraging a future for biomimetic design. It stands as a refined second iteration of using a termite mound as inspiration, and its multiple accolades show others the many strengths and benefits of designing with biomimicry.

EDEN PROJECT

DESIGNED BY MICHAEL PAWLYN
& NICHOLAS GRIMSHAW

Figure 29: Eden Project Aerial View
(Eden Project, 2023)

PROJECT BACKGROUND

The Eden Project was completed in 2001 by Grimshaw Architects. Before Michael Pawlyn developed Exploration Architecture - a firm known for encouraging biomimetic design and the designer of other case studies in this thesis - he was one of the central members of the Eden Project design team at Grimshaw Architects. The Eden Project was an idea conceived by Tim Smit and Jonathan Ball. The goal was to take the site of a China clay pit that had been in use for 160 years and exhausted to the point of no good soil or natural life, and build something that grew life. The quarried clay pit site required innovation to determine how to build a structure on top of an unstable ground. The design team turned to nature for solutions and considered the idea of bubbles. They studied the way bubbles adapt their form when they land on a surface and morph into each other. This idea spurred the form of the Eden Project, creating lightweight bubbles that could settle gently on the unsteady site.

The structure of each dome - or biome - is made up of a “hex-tri-hex” frame made of steel tubes. It is intended to be a lightweight, two-layered system created with relatively small and easy to transport pieces. The material between the framing is triple-layered Ethylene tetrafluoroethylene (ETFE). It is lighter in weight than glass and allows more light and heat to pass through. The National Aquatics Center in Beijing, referenced earlier, uses the same ETFE material. The material is environmentally efficient and saves transportation costs due to its lightweight nature. Due to the way it’s framed as well, it can be easily patched or replaced in pieces. The ETFE facade and hex-tri-hex framing together contribute to the efficient, lightweight structure that is able to form the “bubble” biomes of the building.

Figure 30: Interior dome view (Eden Project, 2023)

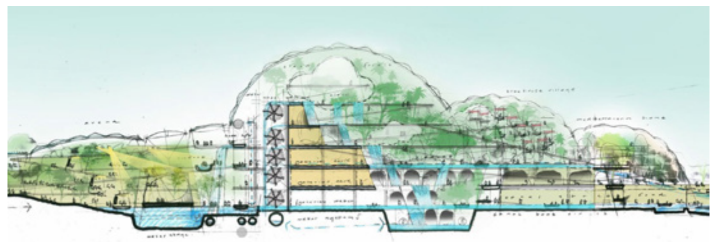

Figure 31: Section drawing of future Eden Project planned for China (Eden Project, 2023)

Figure 32: Hex-Tri-Hex structural close up (Eden Project, 2023)

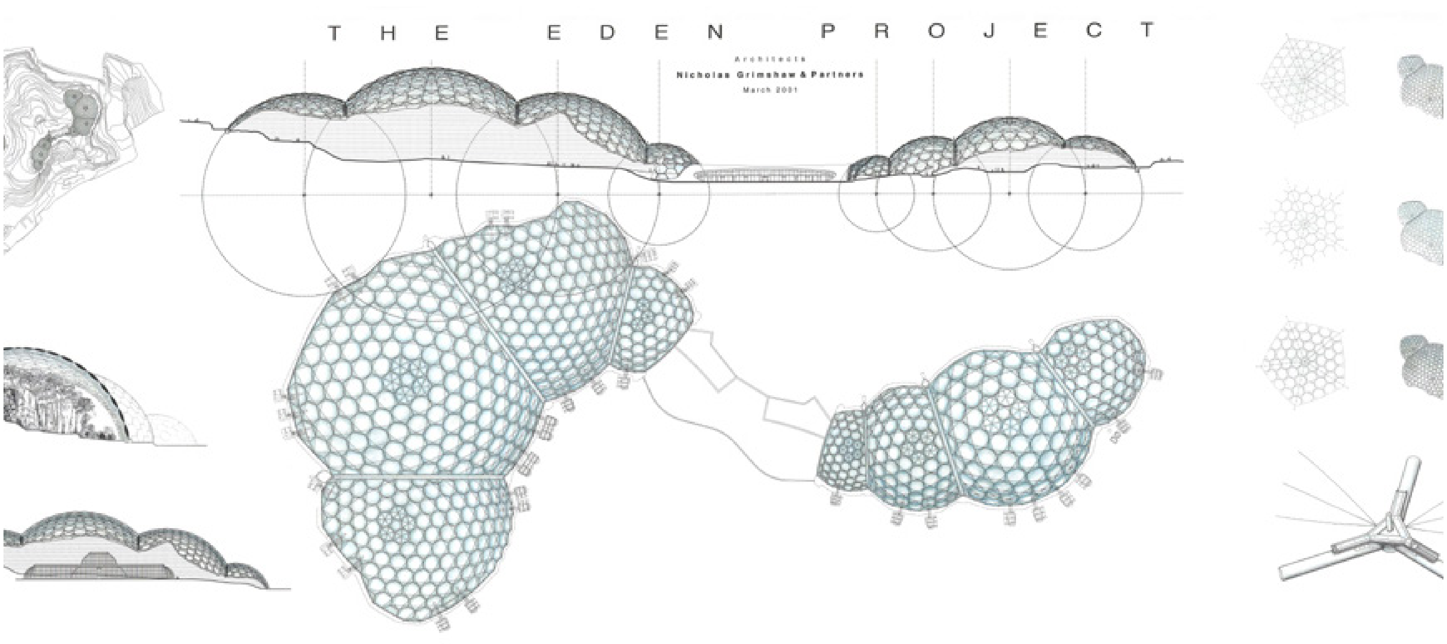

Figure 33: Diagrams and details (Grimshaw, 2001)

ANALYSIS

The Eden Project's process of floating onto an uneven site, settling and adapting to its surroundings, and growing life within is shown in a transformation sketch. This visual shows how the bubble form was used as strategy to adapt the structure's form to the surrounding landscape.

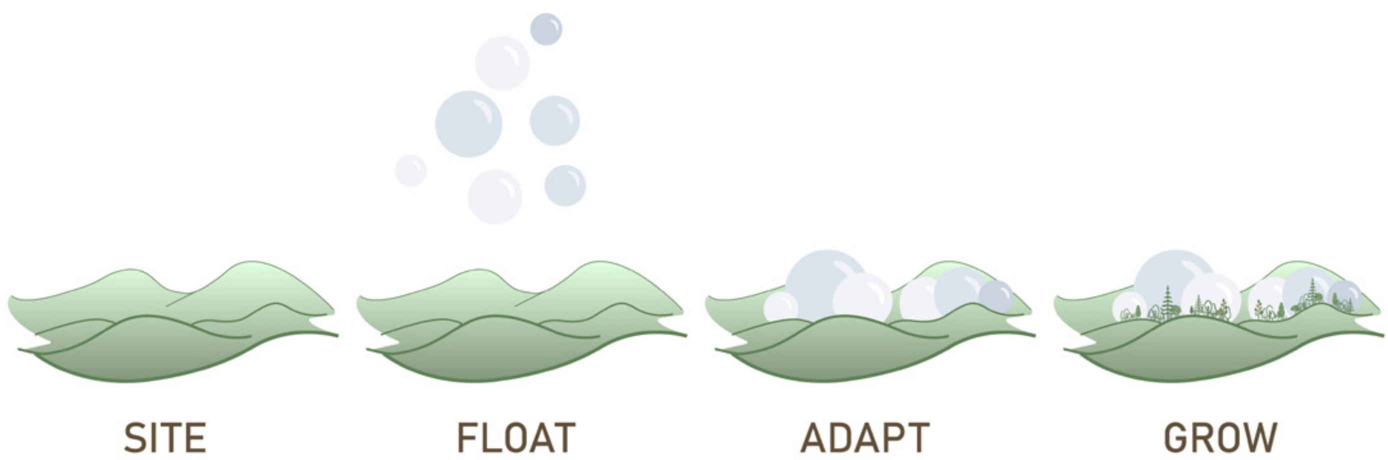

Figure 34: Transformation diagram by author

After diagramming the process of the project, the Abstracting Design Principles (ADP) process was used to break down the adaptation process of emulating a bubble into a simplified description and visual of the desired function.

PROCESS

1. Summarize the relevant biology of the biological principle/idea that the case study is emulating.
2. Highlight the key strategies within the summary.
3. Remove the biological terms and write a summary of the adaptive design principle left.

RESULT

Bubbles are very lightweight and float through the air. In the air, they are spherical, but when they land on something, they settle into the surface and adapt their form to a dome shape that begins at the top of the surface they've settled into.

- lightweight / settles into surface / adapts form

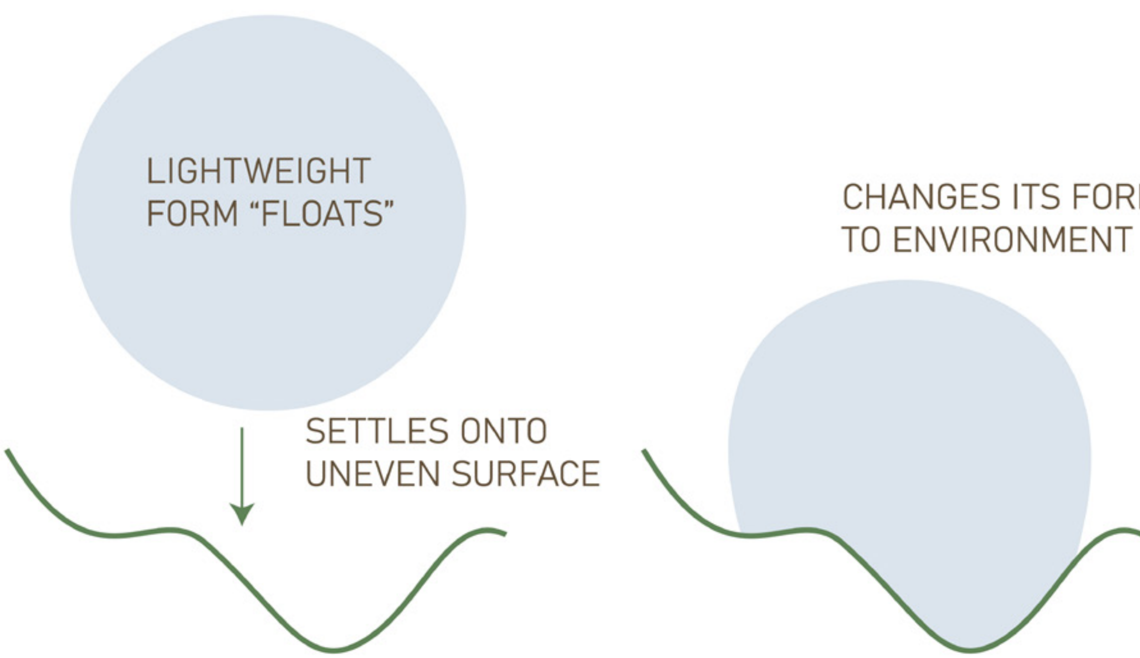

Figure 35: author diagram of simplified design principle

SCORING MATRIX

INTENT	+1	Did innovators intentionally turn to nature during the initial early phases of the design process?
(RE) CONNECT	+1	Does the solution foster a (re) connection with nature?
EMULATE	+0.5	Is there a systemic reason for emulation beyond aesthetics?
SUSTAINABILITY	+1	Is there a sustainability win?
EXPAND	+1	Does the solution have a potential to magnify its positive impact?
TOTAL SCORE:	**4.5/5**	

LEGEND

CLEAR EVIDENCE (1 POINT)	+1
PARTIAL EVIDENCE (0.5 POINT)	+0.5
NO EVIDENCE (0 POINT)	+0

This project scores a total of 4.5/5 points. The designers in this project ran into issues early on with having to build a structure upon a very uneven and unstable unused quarry site. There is evidence that they turned to nature for assistance and considered the structure of bubbles as a form capable of adapting to the uneven ground while also being lightweight enough to exist safely on the unstable site. It emulates the form and the quality of adaptation that bubbles possess. It loses half a point in the Emulate category because there is some argument from Biomimicry 3.8 resources that state that biomimicry is reserved for emulating living things, whereas emulating a bubble form does not constitute biomimicry. However, Eden Project still receives limited credit in that area due to the ecosystem it creates. While it may not be formally emulating a living organism, the overall process appears to contribute to a thriving ecosystem within the project.

The project uses multiple strategies to encourage humans to (re) connect with nature. The overarching concept of this project is nature-driven and invites humans inside to interact with the variety of plants. They participate in a regenerative system by "reducing energy use, making soil from recycled waste, buying locally, driving electric vehicles, and supporting responsible global trade" (Eden Project, 2023). They abide by a policy of practicing sustainability for their own projects, but also encouraging others to do so. They give back to nature by taking a "taking a place of utter dereliction and creat[ing] life in it" (Smit, 2023). The project develops biodiversity and growth in a place that was formerly decomposed and unusable. Eden Project also has several outreach programs to bring in community members that wish to learn more about their processes and expand their environmental practices further.

SAHARA FOREST PROJECT

DESIGNED BY EXPLORATION ARCHITECTURE

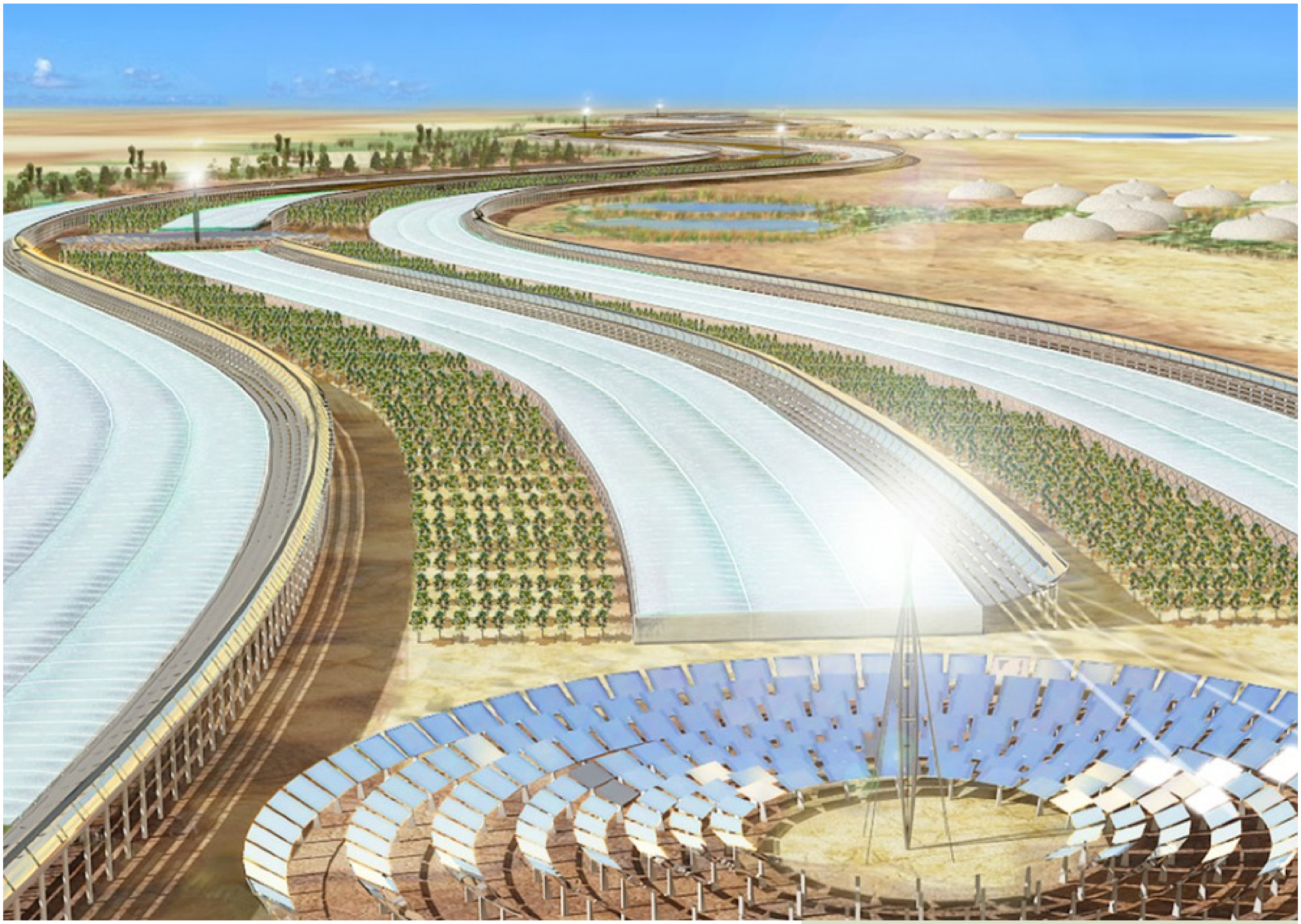

Figure 36: Sahara Forest Project Rendering (Exploration Architecture, 2012)

PROJECT BACKGROUND

The Sahara Forest Project is a project that aims to re-vegetate and provide fresh water, crops, and renewable energy to arid regions. It was created by Exploration Architecture, Seawater Greenhouse Ltd., Max Fordham Consulting Engineers, and the Bellona Foundation. The organization built a pilot project in Qatar originally in 2012 to test the idea, then after testing, the organization designed this project in Jordan which was completed in 2017. The project uses a saltwater infrastructure designed by Seawater Greenhouse Ltd. The technology combines solar power - whether it's photovoltaic or concentrated solar power - with salt-water cooled greenhouses. According to Max Fordham Consulting Engineers, one of the founding members, the project "aims to address five global problems: reduce greenhouse gas emissions, increase freshwater supply, support transition from fossil fuels, develop sustainable food production, and grow biomass."

One of the project's core technologies is seawater-cooled greenhouses. The creation of the seawater-cooled greenhouses were inspired by the Namibian fog-basking beetle. The Namibian beetle uses the shape and pattern of its shell to condense the humidity in the surrounding air within its exoskeleton. It collects these tiny drops of water formed from fog on its shell until they gather into larger droplets and roll down its wing to its mouth. The Sahara Forest Project in Jordan takes inspiration from this and uses a pumping system to bring seawater to the greenhouses. The seawater is then collected and used for multiple purposes within the greenhouse.

Figure 37: Namibian beetle close up image (Tyler, 2011)

Figure 38: Rendering (Exploration Architecture, 2012)

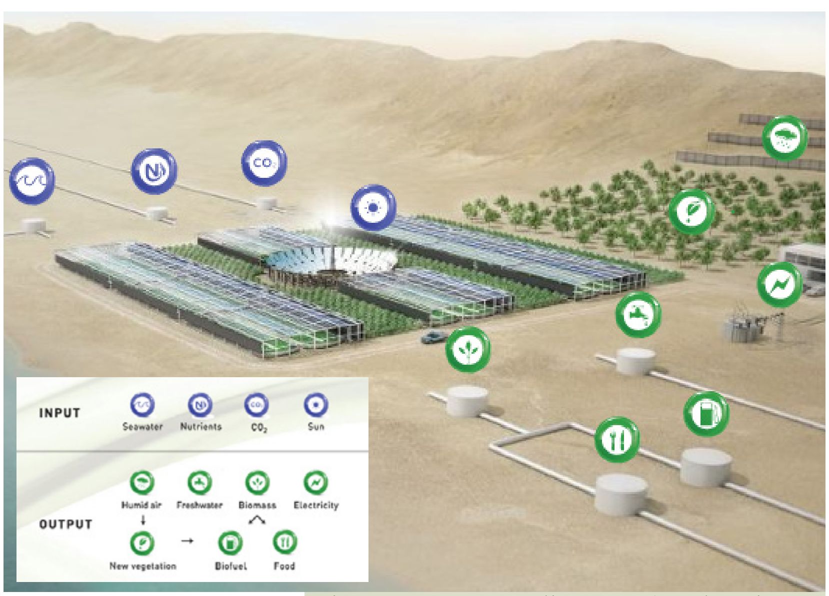

Figure 39: Process diagrams (Exploration Architecture, 2012)

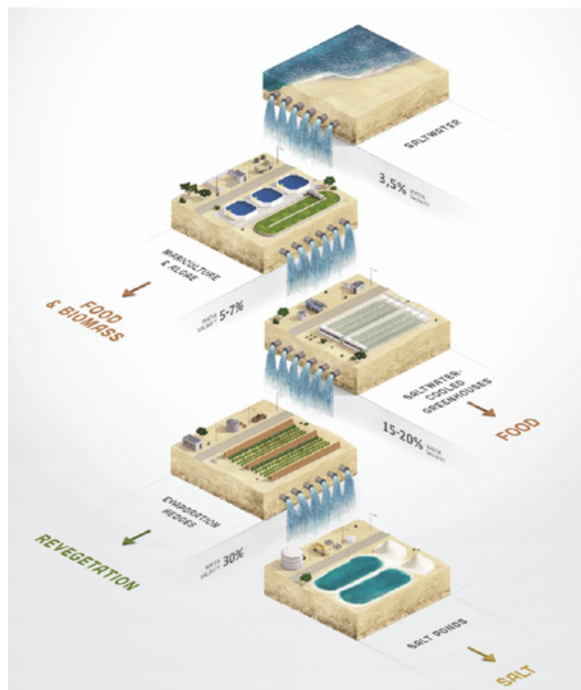

Figure 40: Process diagrams (Exploration Architecture, 2012)

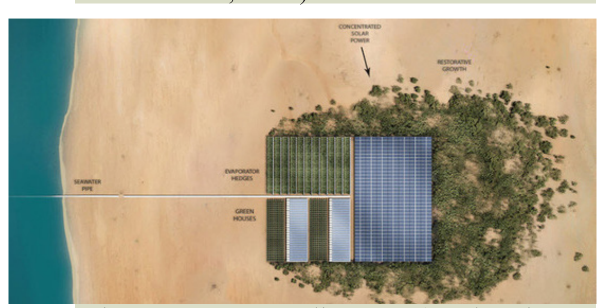

Figure 41: Process diagrams (Exploration Architecture, 2012)

ANALYSIS

A diagram of the section of the greenhouse and its surrounding landscape broken down into the functions the seawater holds in this project is shown below. The project uses an underground pumping system to collect seawater from the adjacent sea, which is then used in one of three ways:

1. It is humidified into the greenhouse.
2. It is pumped under the greenhouse and used to cool the temperature down.
3. It is purified and stored as a freshwater source.

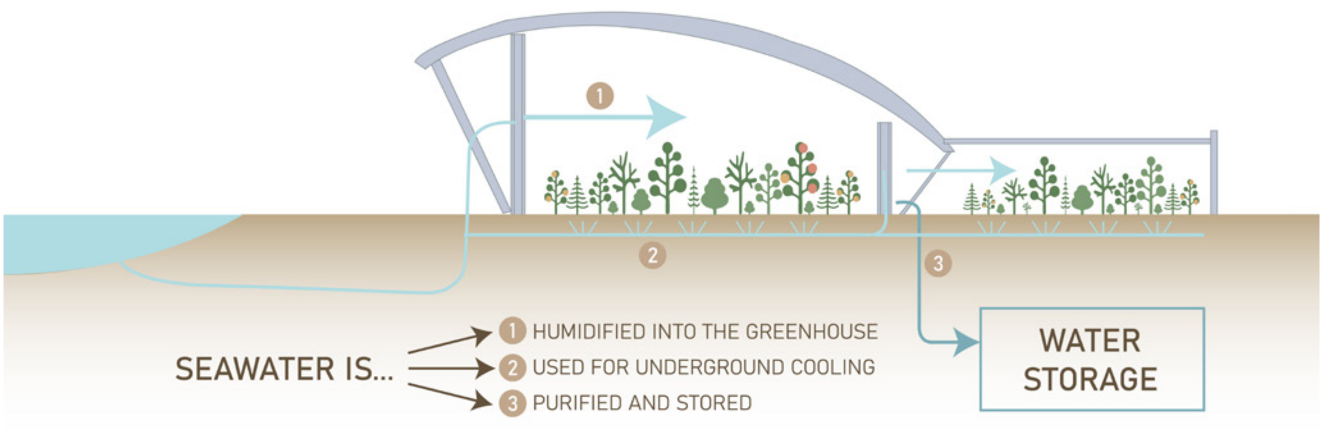

Figure 42: Sectional process diagram by author inspired by (Exploration Architecture, 2012) and (Seawater Greenhouse Ltd., 2012)

The Abstracting Design Principles (ADP) process was then used to break down the adaptation process into a more simplified description of the project's desired function.

EMULATION STRATEGY BREAKDOWN

1. Summarize the relevant biology of the biological principle/idea that the case study is emulating.
2. Highlight the key strategies within the summary.
3. Remove the biological terms and write a summary of the adaptive design principle left.

EXPLANATION

The Namibian beetle lives in a dry area with little water, so it uses the pattern of its shell to condense the humidity in the surrounding air within its exoskeleton. It collects these tiny drops of water formed from fog on its shell until they gather into larger droplets and roll down its wing to its mouth.

- dry area / condense air humidity / store water

SCORING MATRIX

INTENT	+1
(RE) CONNECT	+1
EMULATE	+1
SUSTAINABILITY	+1
EXPAND	+1
TOTAL SCORE:	**5/5**

LEGEND

CLEAR EVIDENCE (1 POINT)	+1
PARTIAL EVIDENCE (0.5 POINT)	+0.5
NO EVIDENCE (0 POINT)	+0

Did innovators intentionally turn to nature during the initial early phases of the design process?

Does the solution foster a (re) connection with nature?

Is there a systemic reason for emulation beyond aesthetics?

Is there a sustainability win?

Does the solution have a potential to magnify its positive impact?

This project scores a total of 5/5 points. Building a greenhouse that required a substantial water source in the Sahara Desert created immediate problems in the design process. With the goal of creating a thriving building of greenery and nature, the team turned to nature itself to solve the problem of a water source. The project uses a mechanism that was an "inspiration in the vital process of a type of beetle (the *Stenocara gracilipes*) that lives in the desert" (Biomimetic Sciences Institute, 2019).

The project receives a point for (re) connecting with nature as well, as one of its goals is to re-vegetate areas of uninhabited desert. It is a program run by humans to help heal nature. It has an emulation strategy that mimics the process of a biological model, not simply the form.

The project has sustainable goals of providing fresh water, food, and renewable energy in the form of biofuels in dry areas. The carbon negative project hopes to expand its program to other areas with similar strategies to give back to the community and expand the future of re-vegetating uninhabited deserts.

AGUAHOJA

DESIGNED BY NERI OXMAN
(MEDIATED MATTER)

Figure 43: Aguahoja Pavilion (Mediated Matter, 2018)

PROJECT BACKGROUND

Aguahoja is an experiment into the process of biomimicry in the form of biocomposites. The final pavilion, pictured above, is accompanied by a collection of material samples from the process of iteration to create the pavilion. It was an exploration from 2014 - 2020 into what these biocomposites are capable of, done by Neri Oxman and her research team Mediated Matter. The structure is digitally designed and 3D printed out of components found in natural things. The components used are cellulose, chitosan, pectin, and calcium carbonate which are found in trees, insect exoskeletons, apples, and bones. These four components are combined in varying percentages of each for different pieces, which yields a library of elements that vary in translucency, strength, texture, and environmental response. They vary in physical properties and adaptation, but they have their beginnings and endings in common. They are made up of the same four components, and they are all biodegradable in water.

These biocomposites utilize biomimicry in a metaphorical and literal sense. They are made up of natural components and follow *life-friendly* processes by breaking down in water. Additionally, they are formed in a way that symbolizes nature with their smooth skin-like forms. Due to each artifact's varied ratios of the four key components - they have different environmental responses. Some become yellower or fade due to humidity while others remain the same, some are brittle while others are flexible. Each one is created using the process of robotically manufacturing them in a way that makes them "grow" up gradually as they're created.

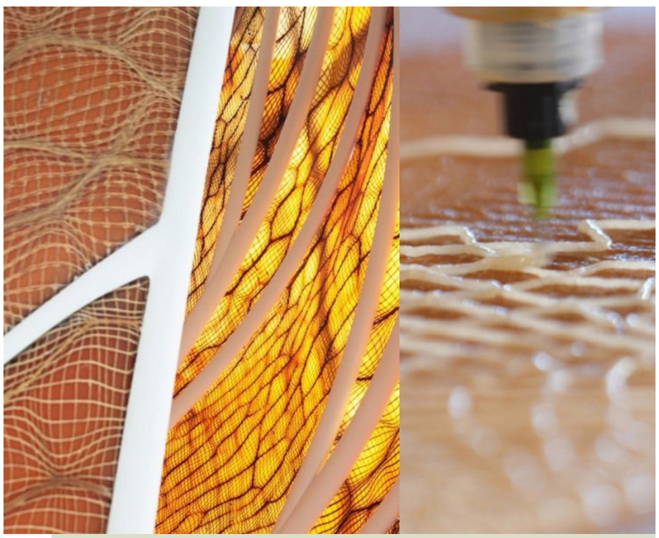

Figure 44: Material and extruder close up views (Mediated Matter, 2018)

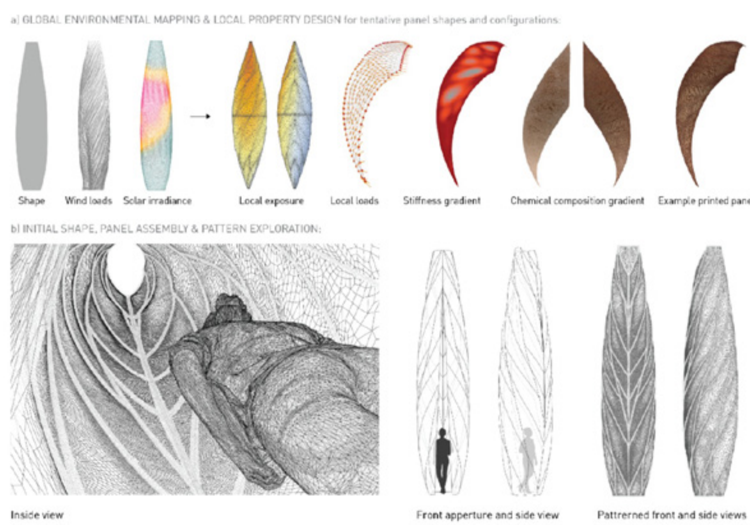

Figure 45: Assembly and elevations views (Mediated Matter, 2018)

Figure 46: Wall of material testing artifacts (Mediated Matter, 2018)

ANALYSIS

The diagram below illustrates the makeup of Aguahoja being three organic components found commonly in trees, beetles, and apples. These organic materials are combined in varying amounts and extruded from a 3D printer to create “skin-like” panels that vary in mesh density, thickness, transparency, color, and flexibility.

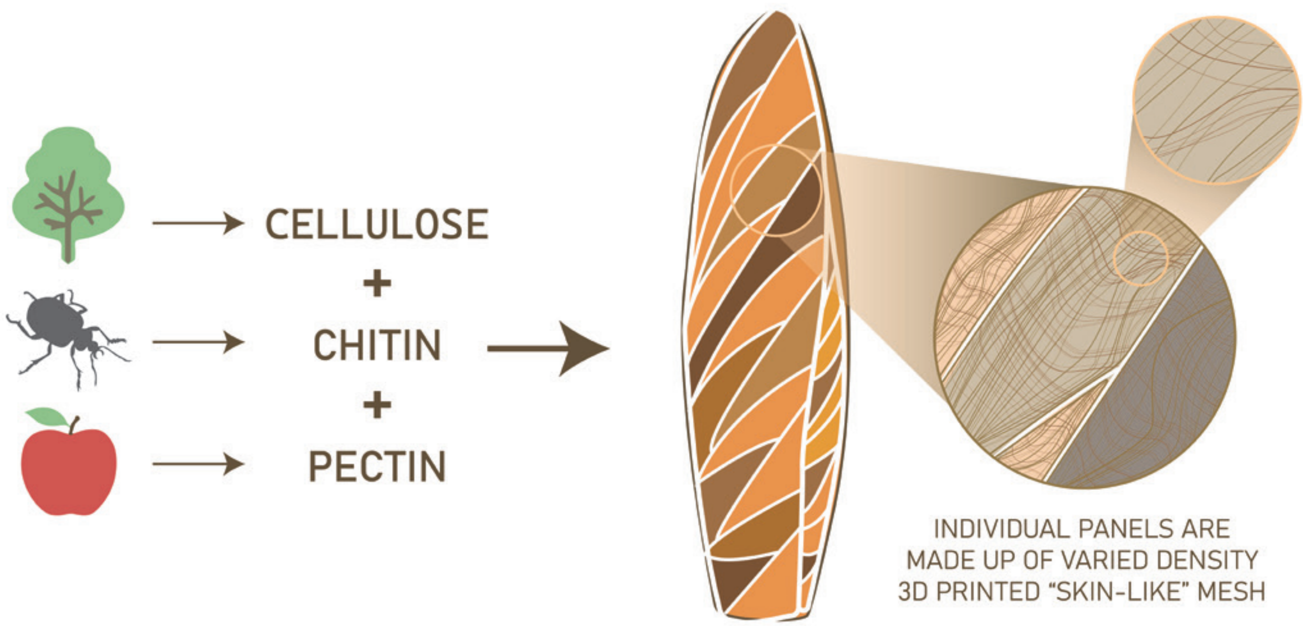

Figure 47: Process diagram by author inspired by (Mediated Matter, 2018)

The Abstracting Design Principles (ADP) process was then used to break down the adaptation process into a more simplified description of the project’s desired function, along with a visual of the project’s “life cycle” and how it emulates the life cycle of natural organisms.

PROCESS

1. Summarize the relevant biology of the biological principle/idea that the case study is emulating.
2. Highlight the key strategies within the summary.
3. Remove the biological terms and write a summary of the adaptive design principle left.

RESULT

Much like a plant in nature, Aguahoja is made of materials from Earth and has a varied woven structure of "skin" panels that gives an appearance of "growing" naturally. The panels are varied in their structure based on their material makeup and the amount of water added. The structure is born from organic materials and water and also decomposes with excessive water contact.

- "growing" naturally / born from organic materials / decomposes with excessive water

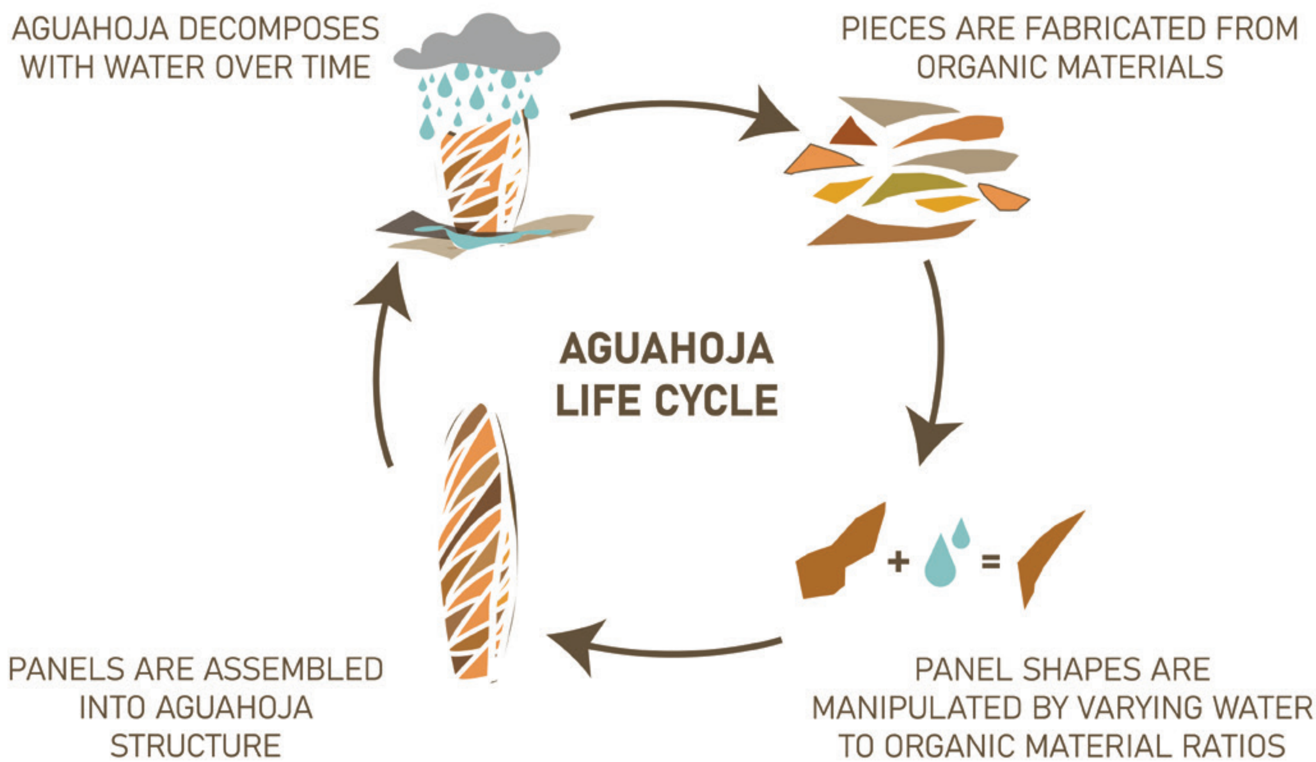

Figure 48: Life cycle diagram by author inspired by (Mediated Matter, 2018)

SCORING MATRIX	
INTENT	+1
(RE) CONNECT	+1
EMULATE	+1
SUSTAINABILITY	+1
EXPAND	+1
TOTAL SCORE:	5/5

LEGEND	
CLEAR EVIDENCE (1 POINT)	+1
PARTIAL EVIDENCE (0.5 POINT)	+0.5
NO EVIDENCE (0 POINT)	+0

Did innovators intentionally turn to nature during the initial early phases of the design process?

Does the solution foster a (re) connection with nature?

Is there a systemic reason for emulation beyond aesthetics?

Is there a sustainability win?

Does the solution have a potential to magnify its positive impact?

Aguahoja scores a 5/5 under the established criteria. It is a very intentional project as its entire process is rooted within nature. It uses a 3D printer to extrude organic materials and create a feeling of "growing" structure. The materials are biocomposites as they are created using natural ingredients. The entire structure can decompose with excessive water, so it "creates conditions conducive to life" with the use of life-friendly chemistry, modular and nested components, and use of readily available materials and energy which are aspirations for biomimetic design (Biomimicry 3.8, 2010).

The solution encourages a (re) connection with nature because it is created fully out of nature and mimics its processes. Since Aguahoja is a study into bio materiality, it is an example that is emulating nature holistically. It emulates nature at a micro scale with its form and structure, while also emulating process at an ecosystem level with the "life-cycle" it undergoes.

The project is sustainable due to its life-friendly process. It is born out of organic matter and water and it breaks down with water (Mediated Matter, 2018). It does not utilize harmful components. This project is revolutionary in how designers can consider building materials and building process. It magnifies its impact as a teaching moment to future designers that can learn how to create biopolymers and the benefits of using a life-friendly design process that is built with non-toxic and water based elements and has no harmful byproducts at the end of its life cycle.

comparison

SIMILAR THEMES AMONG CASE STUDIES

In analyzing these case studies, it was helpful to view them through multiple lenses. The case studies were studied individually in more detail, but the large group of them has also been studied from a zoomed-out view in order to compare similar themes. This approach illustrates how common ideas arise from categorizing them all at once with varying filters.

First, in the context of the established criteria for assessment, each case study was placed onto a four-field matrix to compare their biomimetic strength and their intentionality in achieving those goals.

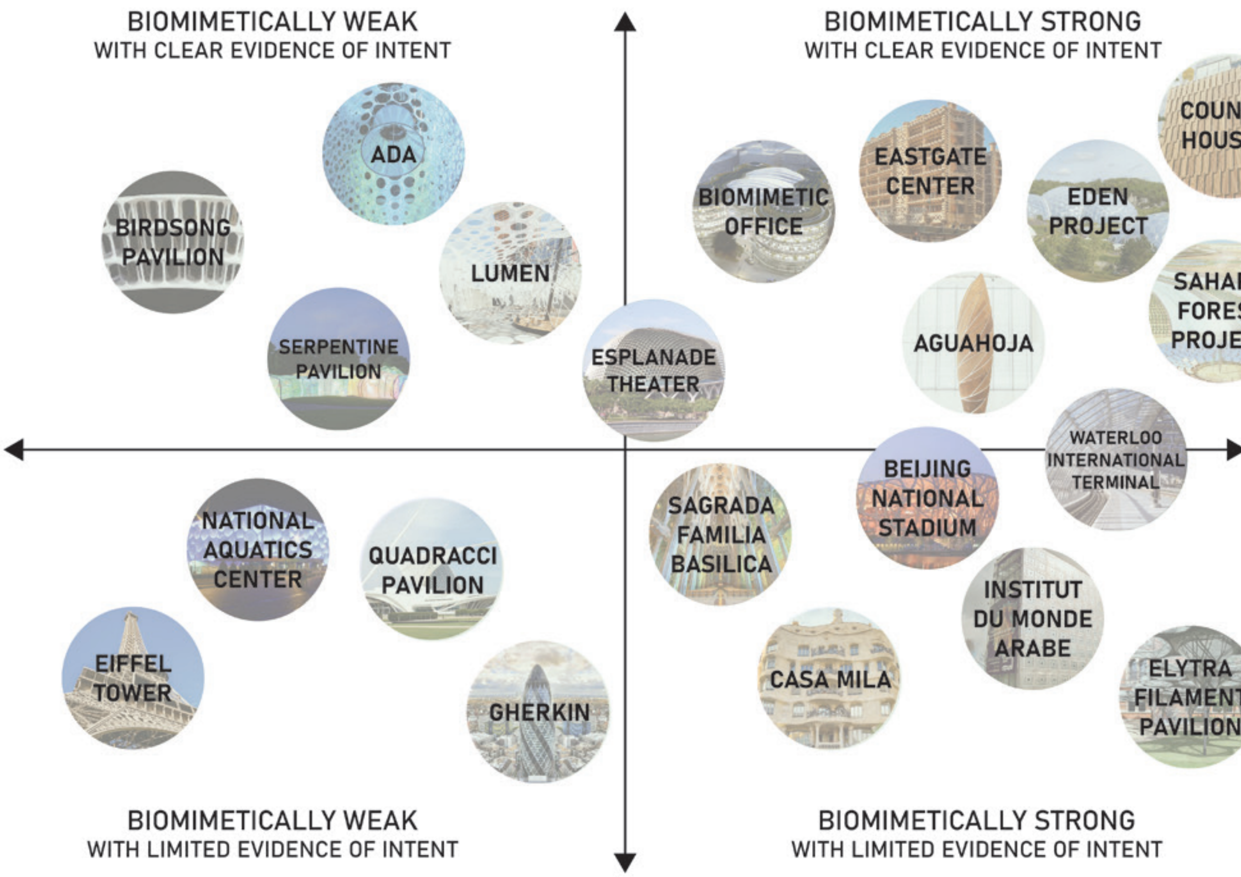

Figure 49: Four field matrix of case studies by author

This four-field matrix visualizes the assessment process to show how the projects rank in comparison to each other. The “strong” case studies analyzed in more depth fall in the top right quadrant, showing they are strong examples as well as intentional. This diagram helps to illustrate that some projects still successfully follow some biomimetic practice ideals without intentionally designing for it.

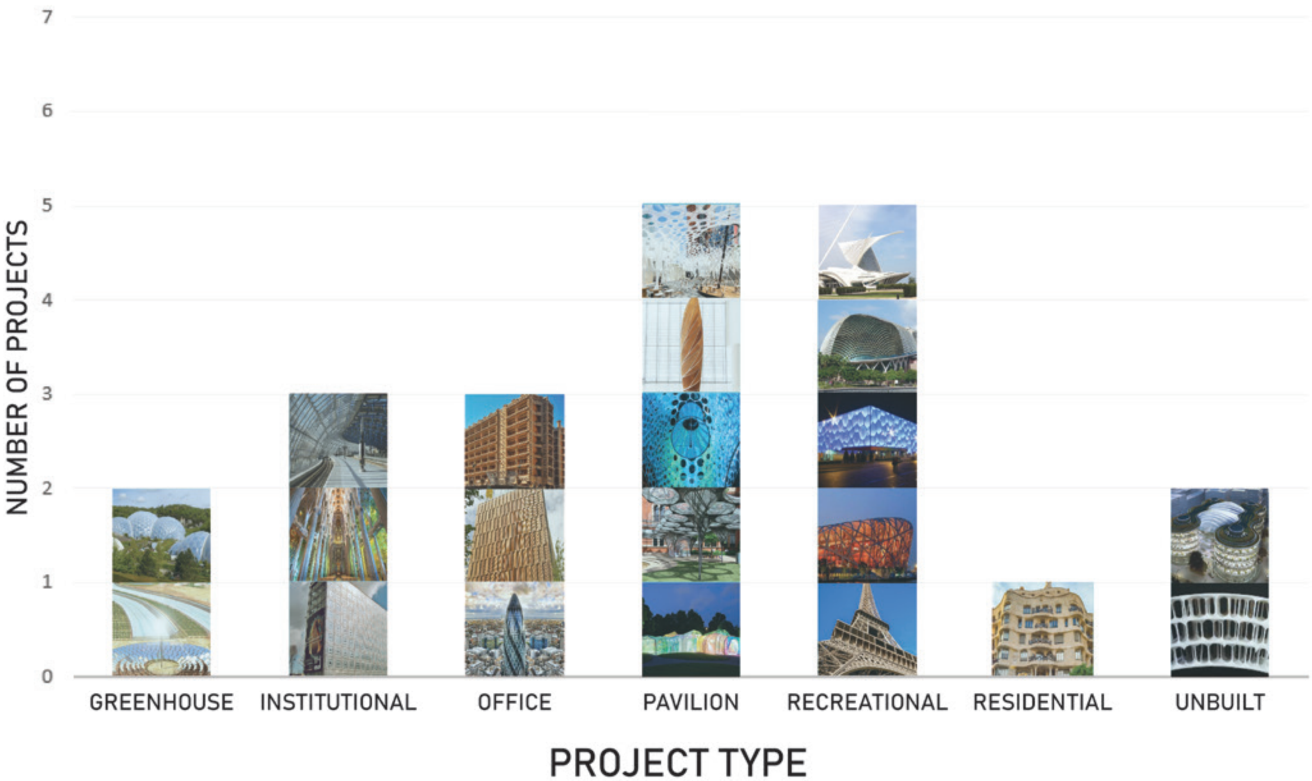

Figure 50: Project type bar graph inspired by graphics from (Blanco, Cruz, Lequette, Raskin, & Clergeau, 2021)

PROJECT TYPES

The graphic above outlines the project types featured in each case study. While some projects align clearly with specific categories, others, like the Eiffel Tower, are more difficult to classify. It is listed here as 'recreational' due to its status as a landmark and tourist appeal, yet it could potentially fit into the pavilion or institutional categories as well.

One thing this diagram illustrates is the abundance of biomimetic pavilions as opposed to full scale buildings. This could be attributed to the more experimental nature of biomimetic design. Pavilions are generally more of an artistic expression made at a smaller scale. These are less complicated projects to create and show an example of biomimetic design. In contrast, designing a holistically biomimetic building would require far more complexities, approvals, and expenses. This barrier explains why the number of pavilion type projects is abundant within the case studies, while the amount of large-scale biomimetic building projects is fewer and further between.

Another aspect to note about this graphic is the inclusion of a "greenhouse" category, of which there are two. Greenhouses are not necessarily considered a 'common' archetype of building, so it is notable that there are two within these studies. This could be attributed to the fact that designing a greenhouse tends to lend itself to an inherent 'green' or sustainable approach when dealing with natural systems of ecology.

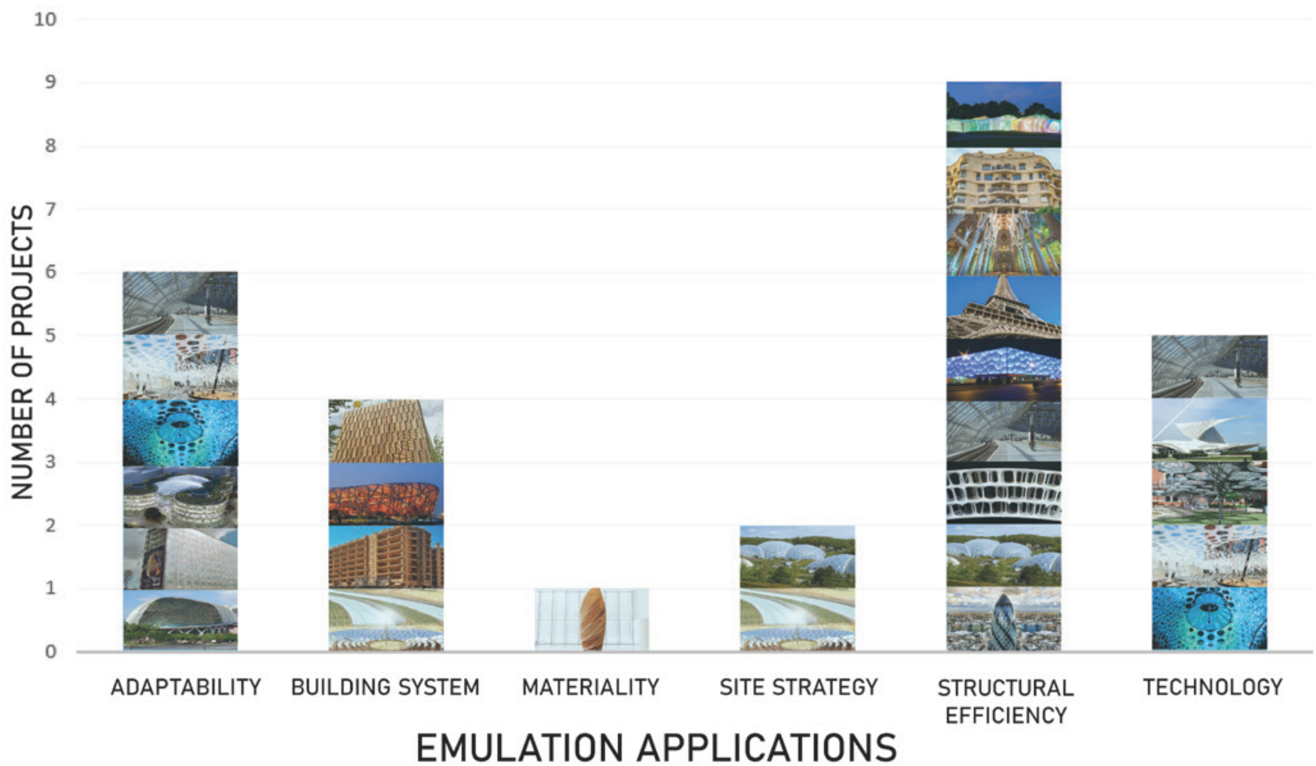

Figure 51: Emulation applications bar graph inspired by graphics from (Blanco, Cruz, Lequette, Raskin, & Clergeau, 2021)

EMULATION APPLICATIONS

This graphic demonstrates the type of emulation applications that each case study project uses to showcase their biological inspiration. There are many ways that a case study can emulate nature, with some projects falling into multiple categories.

'Adaptability' shows projects that emulate nature's responsive quality. These projects respond to the interaction of other forces, such as how a plant responds to sunlight (Institut du Monde Arabe) or wind (Waterloo International Terminal). 'Building system' aims to mimic an ecosystem's processes, utilizing natural resources and processing them in a way that nature would. 'Materiality' has to do with the components of the whole. Aguahoja integrates organic materials and uses life-friendly processes to manage them. 'Site strategy' projects use their functions in tandem with the site's characteristics. They respond to and interact with the site on which they have been built. Under the 'structural efficiency' category, nature's form or structure serves as inspiration, whether referencing an entire organism's form, as seen in 30 St Mary Axe (the Gherkin), or utilizing materials in a complex minimal way to create a structural "mesh" as observed in Serpentine Pavilion or the Birdsong Pavilion (Pawlyn, 2019). 'Technology' highlights projects employing robotic technology for optimized material and structural utilization.

The diagram reveals a dominant trend among these projects, emphasizing nature's structural efficiency as the most prominent emulation strategy within this selection of projects.

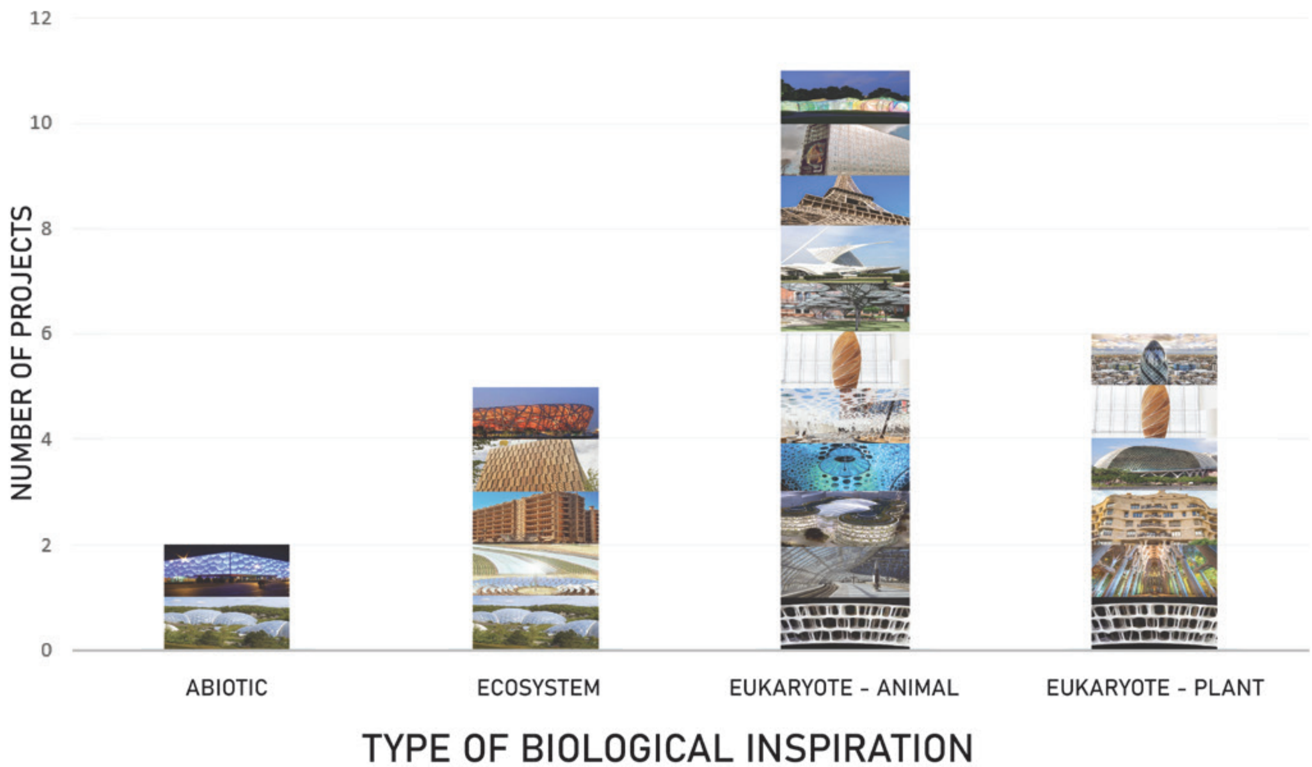

Figure 52: Biological inspiration type bar graph inspired by graphics from (Blanco, Cruz, Lequette, Raskin, & Clergeau, 2021)

BIOLOGICAL MODELS

The above representation illustrates the biological inspiration type each project uses. When considering these inspirations, "abiotic" references inspiration derived from non-living elements such as water or bubbles. The "ecosystem" category encapsulates projects aspiring to mimic at a holistic level, constructing complete systems and environments rather than focusing on a singular form or process. Finally, there are two "Eukaryote" categories, one for animals and one for plants. These two categories refer to mimicking living organisms but are separated to show more specific overarching options.

Among these categories, certain projects may draw from multiple organism types or processes, resulting in repetitions of images within the graphic to signify this duality. Despite some projects straddling multiple categories, the dominance of the "eukaryote - animal" category stands out among the others. This shows a common trend that many projects are modeled after animals.

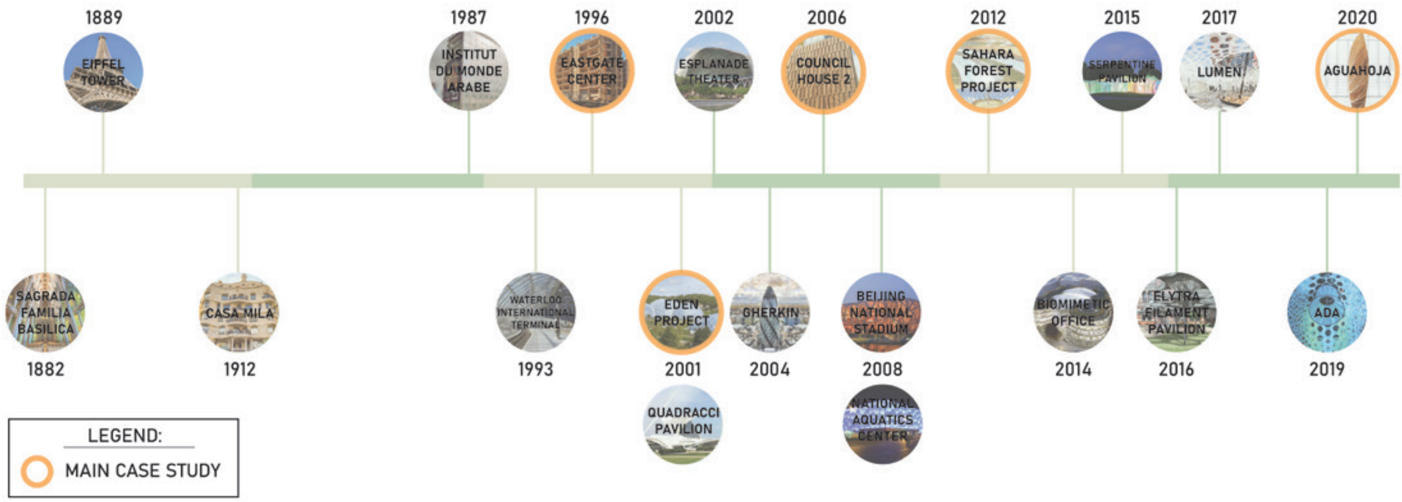

Figure 53: Timeline of projects

TIMELINE

The timeline shows where in time each of the selected case studies fall. Birdsong Pavilion, an unbuilt project, is not listed due to lack of evidence of when it was originally designed. This timeline shows two main clusters of projects. There are seven projects within the seven year period of 2001-2008. The other main cluster is the seven projects between the eight year period of 2012-2020. The outlying categories are two projects in the 1880s and a project in 1912, all before the term “biomimicry” was first documented in use in 1958 (Schmitt, 1958). There are then another three projects in the late 1980s and early 1990s.

The clusters of projects in 2001-2008 and 2012-2020 show an overall increase in utilizing biomimicry in design. When comparing the timeline against the other categorization graphics, some interesting trends appear. Within the 2001-2008 period of projects, the majority of those tend to fall in either the structural efficiency or building systems emulation applications category. This means that there was a trend towards seeing how designers can manipulate structure in advantageous ways. Projects in this time period were changing structure in ways to allow passive cooling opportunities or to maximize structural possibilities with materials.

Within the 2012-2020 time period, there are more projects that are innovating with the use of new material types or technologies. Considering this is the most recent time period of the timeline, it makes sense that it would tend towards innovative technology as a strategy. These projects are taking advantage of newer advances in other industries, such as robotics, nano science, and computational design, to expand on the possibilities of architecture.

looking to the future

THE FINDINGS + THE FUTURE

The established criteria for assessing the studied projects has highlighted the strong points of each case study along with the weak points where it could've gone further. This section builds on the information extracted from the case studies and speculates about the future possibilities in the design world.

PASSIVE COOLING + INDOOR AIR QUALITY

While it would be ideal for design to become more sustainable in all sectors across the board, some areas have higher stakes than others. A staggering statistic from the UN Environment Programme Global Alliance for Buildings and Construction in 2022 stated that buildings account for nearly 40% of carbon dioxide emissions. While practices are moving in the right direction towards decarbonization, the architecture sector needs to take more drastic actions to achieve their goals of net zero emissions.

In this landscape, the implementation of passive cooling emerges as a strong and impactful strategy to curb energy consumption and emissions. Eastgate Center and Council House 2 are both designed with this in mind. Council House 2, for instance, exemplifies a sophisticated system capable of completely refreshing the building's air every half-hour, ensuring a continuous supply of fresh air. This continuous air refreshing system is beneficial as well for the health of the building tenants by creating a positive indoor air quality. Such thoughtful design combined with highly efficient passive cooling strategies not only demonstrates the potential to regulate indoor environments on par with or surpassing traditional heating and cooling systems but does so with a significantly reduced environmental footprint.

MATERIAL EFFICIENCY + TECHNOLOGY

Michael Pawlyn's pioneering research delving into the structural efficiency of materials, coupled with case studies like Birdsong Pavilion and the Eden Project, illustrates the significance of employing materials with utmost efficiency.

In the construction industry, a concern lies in material waste and its environmental ramifications. These aforementioned case studies leverage technology and nature as sources of inspiration, creating innovative pathways that enable designers to achieve structures using fewer materials. This approach marks a promising future, one that could delve deeper. Advancements in computational innovations, artificial intelligence (AI), and increasingly sophisticated robotics offer a wide set of opportunities for digital iterations that lead to developing highly efficient prototypes. The technology we as designers are surrounded by opens new doors to design logical structures that create less waste and do more with less material. Multiple case studies mentioned, such as Ada, Lumen, and Elytra Filament, were made possible by the integration of robotics into the design process.

BIOMATERIALS

Another intriguing sector of evolving biomimetic design is biomaterials. Biomimetic materials are man-made materials that replicate the look or attributes of natural materials (Chesterman, Kohn, 2020). Additionally, the term “biomaterials” encompasses the utilization of natural elements to fabricate innovative materials that follow life-friendly processes, as seen in Aguahoja. Aguahoja’s methodology isn’t merely about mimicking nature; its material makeup is about bioutilization, crafting materials directly from organic sources while also replicating the mesh-like patterns found in natural structures, such as leaves.

These two approaches, whether replicating natural attributes or employing bioutilization techniques, fall under the umbrella of “biomaterials”, which have an ever-changing and exciting place in the future of design. Notably, inventions such as “Metavoxel,” a finalist for the 2022 Ray of Hope Prize, represent innovations in biomimetic design. Drawing inspiration from the deep-sea sponge, Venus’s flower-basket, Metavoxel is a prototype for a building material. It incorporates robotics and iterative material development, enabling mass production, customization, and reducing raw material consumption compared to traditional construction methods.

This prototype stands as just one among a vast array of examples showcasing the potential of biomaterials. With new technologies and opportunities arising every day, biomaterials assist in showing the promising future of more sustainable and efficient material options for construction.

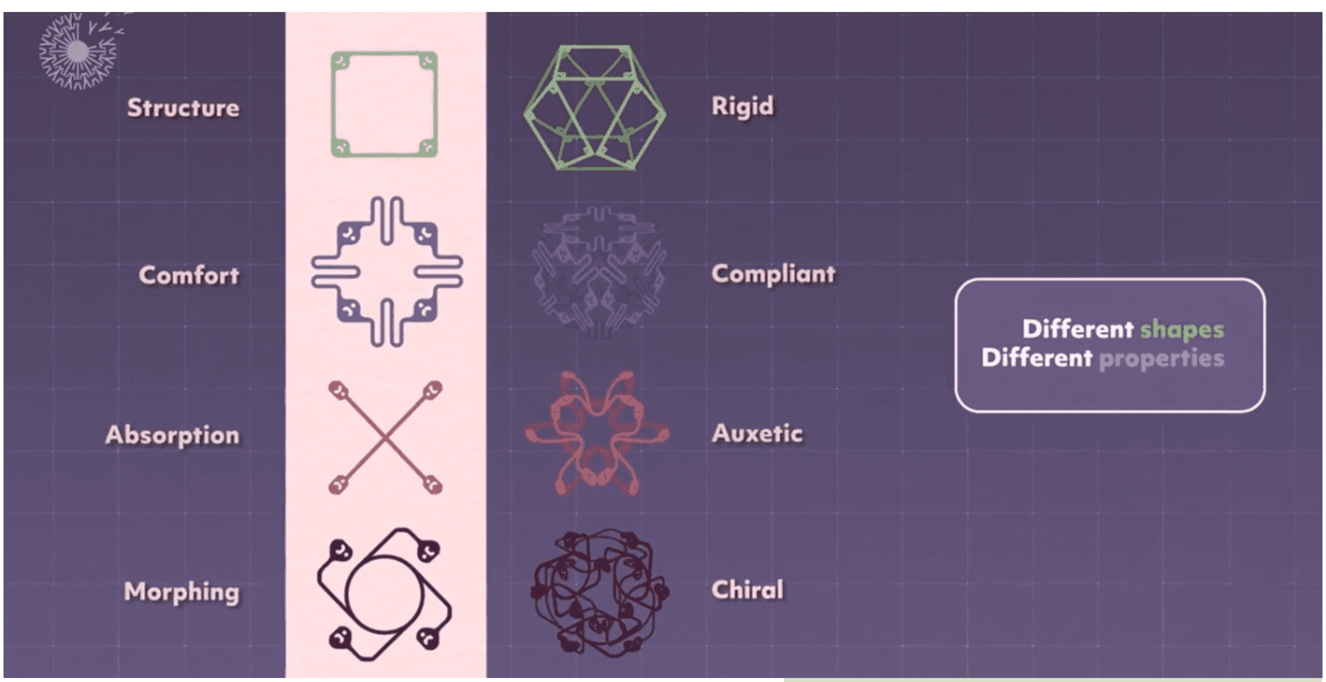

Figure 54: Metavoxel shape diagram, 2022

SCALE SHIFT

As recorded in the project types graphic previously, it is clear from the list of analyzed case studies that the number of pavilions is substantial in comparison to full-scale building projects. This illustrates an interesting idea about the importance of scale within this topic. Considering biomimicry in design is a fairly new concept, as the term was coined in 1958 (Schitt, 1958) by an engineer, but popularized in 1997 (Benyus, 1997), the practice overall is fairly experimental and innovative. It is difficult to develop a large budget, high stakes client project with an experimental and quite new practice.

Designing pavilions allows the maker more freedom to express the ideas of biomimicry without the same pressures of practicality and expense that a building would require. These pavilion examples are valuable and necessary to continue to learn how to design with nature as an inspiration. This idea is a takeaway because it shows a way for designers to get their foot in the door with biomimicry. Creating pavilions, or any type of smaller-scale design project, is a valuable teaching opportunity that is more accessible than designing a large-scale building.

BUILDING BLOCKS

Examining the work of Pawlyn with Exploration Architecture, who participates in both conceptual and realized projects, it’s evident that smaller-scale projects also hold educational value. For instance, conceptual unbuilt projects like the Birdsong Pavilion and Biomimetic Office Building may be smaller in scale, yet they offer crucial lessons and innovative ideas. These examples highlight that even at a smaller scale, the exploration of biomimicry in design holds many learning opportunities, paving the way for designers to delve deeper into this evolving field.

Figure 55: Birdsong Pavilion by Exploration Architecture, year unknown

Figure 56: Biomimetic Office Building by Exploration Architecture, 2014

conclusions

FINAL STATEMENTS

In our modern age of waste and pollution, it is crucial to search for solutions that lead to a more sustainable future. According to the analysis and assessments of the case studies, there are many positives to designing with biomimicry as a strategy. It brings humans closer to nature, both literally and metaphorically. Considering nature as model, measure, and mentor (Benyus, 1997) early on in the design process illustrates a designer's intent to connect the users with nature. Creating intentional design that considers the impact of nature both upon the design and vice versa is a necessity if we, as humans, want to change our current environmental conditions for the better.

The established criteria for assessing the chosen projects has highlighted the strong points of each case study along with the weak points where it could have shown more innovation. These five categories of criteria have been created from inspiration from many biomimetic research resources. Together, these ideals create a roadmap for what future strong biomimetic projects should strive for.

The ideal conditions for future strong biomimetic projects would be to:
1. Intentionally turn to nature as an inspiration for its success in closed-loop systems and problem-solving.
2. Design with a goal of (re) connecting humans to nature and creating a mutually beneficial relationship.
3. Emulate nature authentically for reasons beyond aesthetics in order to innovate with nature's processes.
4. Create projects with "conditions conducive to all life" or "life-friendly" processes in a way that promotes sustainability.
5. Magnify the positive impact of the project through teaching or giving back to its community.

In order to shift the future towards a healthier environment, all industries must work to change for the better. Architecture and design especially contribute extreme amounts to the problems of waste, energy consumption, and pollution. Biomimetic design takes inspiration from nature's closed-loop system with no waste and works to create design solutions that exist in a life-friendly way. This study of how various projects have used biomimicry in the past has made it apparent that it can be a very successful solution.

Biomimicry as a strategy offers a valuable framework for architects to rethink traditional design systems and find sustainable, efficient, innovative, and resilient solutions by emulating nature's time-tested strategies. Integrating biomimicry principles into architectural practice holds potential for creating buildings and cities that harmonize with the natural world while addressing serious environmental challenges.

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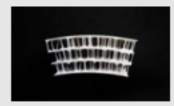
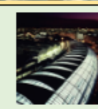
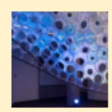
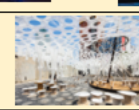
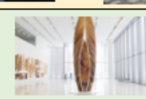
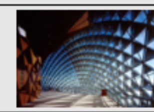
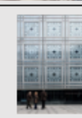
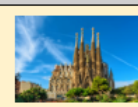
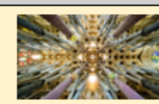
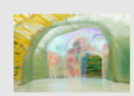
appendix A

MATRIX OF CASE STUDY INFORMATION

Project	Designer	Location	Images
Gherkin Building	Norman Foster	London, England	  
Eden Project	Michael Pawlyn/Nicholas Grimshaw	Cornwall, UK	 
Birdsong Pavilion	Exploration Architecture	unbuilt/model	
Biomimetic Office Building	Exploration Architecture	unbuilt/model	 
Waterloo International Terminal	Nicholas Grimshaw	London, England	 
Sahara Forest Project	Exploration Architecture	Aqaba, Jordan	 
Ada	Jenny Sabin Studio	Redmond, Washington	  
Lumen	Jenny Sabin Studio	formerly NYC, no longer on view	 
Aguahoja	Neri Oxman	San Francisco MoMA	
Elytra Filament Pavilion	Achim Menges	University of Stuttgart	
Eastgate Center	Mick Pearce	Harare, Zimbabwe	

Emulation Strategy	Strong vs. Weak (biomimetically)	Designer Contact	Link to more info
inspired by the structure of the Venus' flower basket sponge	8		https://steemit.com/architecture/@snaves/biomimetic-architecture-the-gherkin
form is inspired by bubbles, structure = geodesic dome, material is ETFE	9		https://ecobrooklyn.com/design/biomimicry-eden-project/
musical paviliion inspired by bird skull form	10	info@exploration-architecture.com	http://www.exploration-architecture.com/projects/birdsong-pavilion
first ever building to be comprehensively designed with biomimicry in mind	10	info@exploration-architecture.com	http://www.exploration-architecture.com/projects/biomimetic-office-building
mimics the form of pangolins' scales to respond to changes in air pressure from trains passing through	6		http://genselective.blogspot.com/2011/10/biomimicry-explored.html
seawater cooled greenhouse, desert revegetation	10	info@exploration-architecture.com	http://www.exploration-architecture.com/projects/sahara-forest-project
structure mimicking human body - material mimics the way living things react to sunligth	7		https://www.jennysabin.com/ada
structure mimicking human body - material mimics the way living things react to sunligth	7		https://www.jennysabin.com/lumen
made of a biopolymer - material that is derived from natural elements and can naturally "decay"	10		https://oxman.com/projects/aguahoja
form inspired by flying beetle shells - process done by robotics (using more form to use less material)	9		https://divisare.com/projects/319009-achim-menges-naaro-elytra-filament-pavilion
form/process inspired by termite mound	10		https://www.mickpearce.com/Eastgate.html

Project	Designer	Location	Images
Beijing National Stadium	Herzog & de Meuron	Beijing	
National Aquatics Center (Water Cube)	ARUP	Beijing	
Council House 2	Mick Pearce	Melbourne, Australia	 
Quadracci Pavilion	Santiaga Calatrava	Milwaukee, WI	
Esplanade Theater	DPA	Singapore	 
Institut du Monde Arabe	Jean Nouvel	Paris, France	 
Eiffel Tower	Gustave Eiffel	Paris, France	 
Sagrada Familia Basilica	Antoni Gaudi	Barcelona, Spain	 
Casa Mila	Antoni Gaudi	Barcelona, Spain	 
Serpentine Pavilion	Sergascano	London, England (seasonally)	 

Emulation Strategy	Strong vs. Weak (biomimetically)	Designer Contact	Link to more info
structural form/layering of materials is inspired by a bird's nest	10		https://www.arch2o.com/birds-nest-beijing-olympic-stadium-herzog-de-meuron/#!
structure allows for stable support while allowing in a lot of sunlight	9		https://www.arup.com/projects/chinese-national-aquatics-center
follows process of termite mound, intended to be a holistic system with its occupants as "participants" in the system	10		https://www.archdaily.com/395131/ch2-melbourne-city-council-house-2-designinc
forms follow bird's wings	5		https://inhabitat.com/amazing-calatrava-shade-pavilion-for-the-milwaukee-art-museum/
inspired by the protective skin system of a Durian fruit	9		https://dpa.com.sg/projects/esplanadetheatresonthebay/
adaptive facade dilutes light and heating	8		https://www.imarabe.org/en/architecture
inspired by the structure of femur and trabeculae bones	6		od/Biomimetics/Inspirtational%20designs/Eiffel%20Tower_files/Eiffel%20Tower.htm#:~:text=The%20French%20structural%20designer%2C%20Gustave,Eiffel%20tower%2C%20came%20from%20biom
interior columns branch up for more structure			
chrysalis inspired - allows in light and air			https://www.serpentinegalleries.org/whats-on/serpentine-pavilion-2015-designed-selgascano/

appendix B

MATRIX OF INITIAL ANALYSIS

Case Study Project	Designer	To what extent does the design or innovation ("solution" in short) create conditions conducive to life?	To what extent does the solution an innovation or design ("solution" in short) emulates nature?	Total Score	High Points	Low Points
Gherkin	Norman Foster	3	4	7	deflects wind, passive cooling means the bldg can consume as low as half the energy as a standard rectilinear skyscraper, also utilizes heating through the glazing	no longer really uses the passive cooling system since incident in 2005, so while the idea is nice, it's no longer really in practice
Eden Project	Michael Pawlyn	5	5	10	ETFE is stronger and lighter than glass (1% the weight of double glazing), so less steel is needed for strength, and less energy is needed for heating the building	
Birdsong Pavilion	Exploration Architecture	5	5	10	made from biologically-derived material	not built
The Biomimetic Office Building	Exploration Architecture	5	5	10	comprehensively designed with biomimicry, could be one of the lowest energy buildings in the world	not built
Sahara Forest Project	Exploration Architecture	5	5	10	seawater cooled greenhouse, desert revegetation	
Ada	Jenny Sabin Studio	4	3	7	utilizes AI for structure, uses materials that absorb and react to light like nature, great example of adaptive materials	
Lumen	Jenny Sabin Studio	4	3	7	creates a micro-climate, responds to heat, bodies, and sunlight	
Aguahoja	Neri Oxman	5	5	10	made of a biopolymer - material that is derived from natural elements and can naturally "decay"	
Elytra Filament Pavilion	Achim Menges	5	4	9	uses less material by using "more form" - uses AI/robotics to analyze the best ways to use less material	
Eastgate Center	Mick Pearce	5	5	10	uses 35% less energy than other local buildings	
Beijing National Stadium	Herzog & de Meuron	5	5	10	layers structure of bird's nest "twigs" for structure, then uses ETFE and concrete to insulate like a nests' layers	
National Aquatics Center (Water Cube)	ARUP	5	4	9	structure allows for stable support while allowing in a lot of sunlight, and the form of the bubbles makes the form self cleaning and assists in directing water capture	
Council House 2	DesignInc	5	5	10	follows process of termite mound, intended to be a holistic system with its occupants as "participants" in the system	
Quadracci Pavilion	Santiaga Calatrava	2	3	5	structure is intended to follow that of a bird's wings, "responds" to the lake	more commonly related to a sailboat than to nature
Esplanade Theater	DPA	4	3	7	provides impressive views while filtering light through a skin system	
Institut du Monde Arabe	Jean Nouvel	4	4	8	uses an "adaptive" facade system that is reactive to its environment and allows in varying amounts of light/heat	
Eiffel Tower	Gustave Eiffel	2	2	4	efficient in using less solid mass of material to create an off center structured frame	
Waterloo International Terminal	Nicholas Grimshaw	3	3	6	mimics the form of pangolin scales in order to respond to air pressure changes from trains passing	unclear if this was genuinely an initial inspiration to solve a problem or simply a formal comparison made after