BIOMIMICRY AS DESIGN LENS FOR LANDSCAPE ARCHITECTURE

by

SIGURD CARL SANDZÉN IV

(Under the Direction of Brian LaHaie)

ABSTRACT

In 1996, Janine Benyus developed the term “biomimicry” to describe design solutions prevalent in biological environments. The past two decades has seen biomimicry applications in multiple disciplines, including engineering, architecture, and material sciences. This design tool has yet to be comprehensively applied to projects developed within the landscape architecture profession. This thesis examined biomimicry’s potential to landscape architecture as a tool for innovation in design. A checklist analysis was developed for this thesis using biomimicry guidelines defined by Janine Benyus, creator of the term. Architectural case studies were used to determine the successful application of the checklist, while landscape architecture case studies determined biomimicry applications present in contemporary design approaches. Case study checklists were evaluated to determine correlations between criteria, and general guidelines for the application of biomimicry in landscape architecture were abstracted from the findings.

INDEX WORDS: landscape architecture, biomimicry, biomimetics, architecture, ecological design, closed-loop systems, material reuse, collaborative design

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DEDICATION

"The Secret of Happiness lies in looking at all the wonders of the world and never forgetting the two drops of oil in the spoon."

-Paulo Coehlo, *The Alchemist*

For my mother and father.

And for my brother.

I would not be here without you.

ACKNOWLEDGEMENTS

"Nobody tells this to people who are beginners, I wish someone told me. All of us who do creative work, we get into it because we have good taste. But there is this gap. For the first couple years you make stuff, it's just not that good. It's trying to be good, it has potential, but it's not. But your taste, the thing that got you into the game, is still killer. And your taste is why your work disappoints you. A lot of people never get past this phase, they quit. Most people I know who do interesting, creative work went through years of this. We know our work doesn't have this special thing that we want it to have. We all go through this. And if you are just starting out or you are still in this phase, you've got to know its normal and the most important thing you can do is do a lot of work. Put yourself on a deadline so that every week you will finish one story. It is only by going through a volume of work that you will close that gap, and your work will be as good as your ambitions. And I took longer to figure out how to do this than anyone I've ever met. It's going to take a while. It's normal to take a while. You've just got to fight your way through."

-Ira Glass

To Brian, Donna, Em, 250 Dubose, the Class of 2015, the CCDP, and everyone who had a part in getting me this far: thank you.

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CHAPTER 1

BIOMIMICRY: A DESIGN LENS FOR LANDSCAPE ARCHITECTURE

"Biomimicry" is an explorative tool for problem-solving, which integrates design and ecological disciplines. Janine Benyus, author of *Biomimicry: Innovation Inspired by Nature* and creator of the term "Biomimicry", describes the universal application of the biomimicry process as "an era based not on what we can extract from nature, but on what we can learn from her" (Benyus 1997). This exploration creates products which utilize natural form, function, and process. Although landscape architecture has developed each of these design practices independently, the profession rarely utilizes them collectively. As Jonathon Porritt of *Form for the Future* states, "It's not the lack of biophysical plenty that will constrain the future of humankind, but rather the lack of vision and creativity on our part" (Benyus 1997). This thesis introduces the concept of biomimicry and explores its potential as a design tool to generate new ideas in the landscape architecture profession.

Biological systems evolve over time, influenced by environmental opportunities and constraints to generate physical forms that are both innovative and resilient. Beginning in the 1970s, a rapid increase in the exploration of natural systems as a means of contemporary design solution occurred. Universities and businesses are currently utilizing these systems to create products which perform closer to nature's modeling.

This modeling is derived from natural form, function, and processes which are implemented into design solutions.

In 2008, the Biomimicry Guild discovered new solutions for water collection through the Namib Desert Beetle (Malik et al. 2014). The German house paint company, Ispo, using biomimicry principles, developed a self-cleaning paint based on the lotus flower's micro-rough surface (Figure 1) (Heck, Rogers, and Carroll 2014). Car

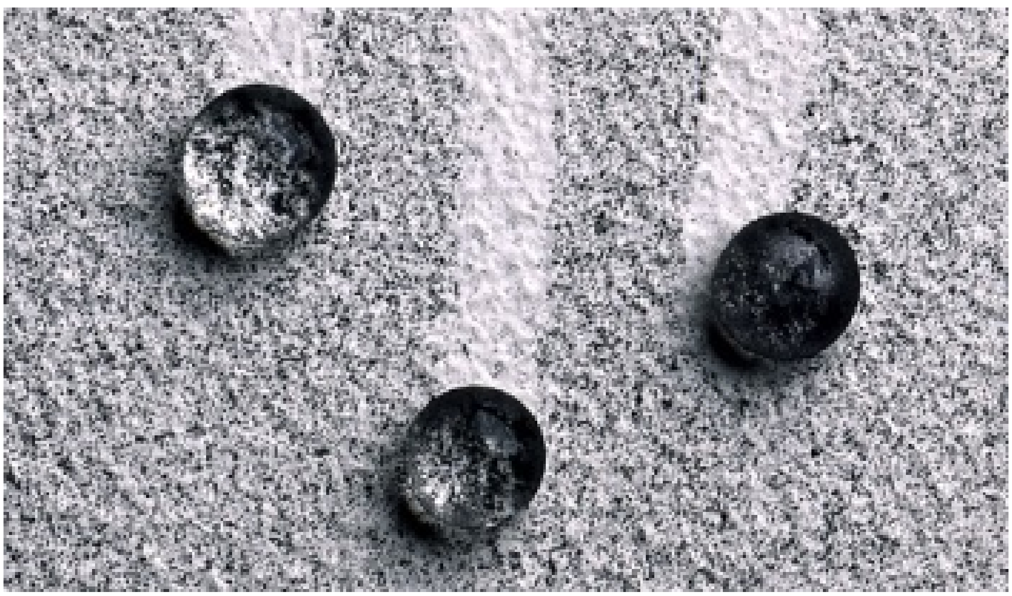

Figure 1. Water Droplets Running Off Ispo Paint Surface (Professional Trade Publications 2012)

manufacturer Mercedes-Benz developed a new concept car based on the shape of the boxfish (*Ostraciidae spp.*), to reduce drag (Figure 2) (Bartol et al. 2008). The way in which design professions use nature as inspiration has also evolved, developing into an explorative design process rather than individual products. Utilizing biomimicry in design processes provides a linkage between innovation and conservation, which uses examples of natural forms, functions, and processes to relate to the surrounding environment.

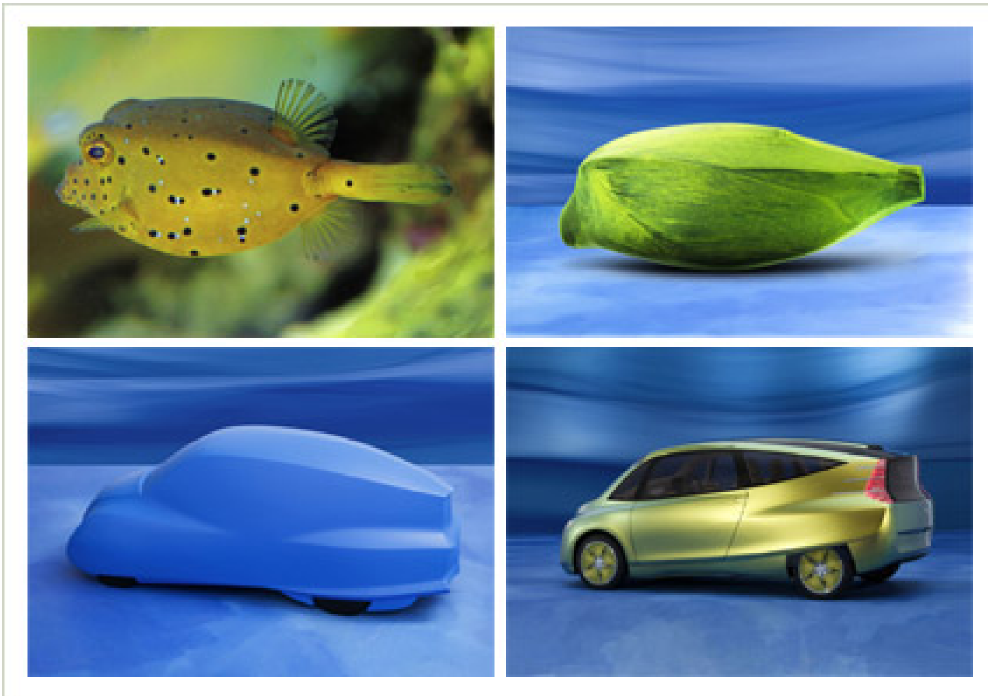

Figure 2. Mercedes-Benz Concept Car (DaimlerChrysler)

"How can biomimicry be used as a design tool to generate new ideas in landscape architecture?"

Throughout the thesis, sub questions will be addressed:

- *How have elements of biomimicry been represented historically?*
- *How is biomimicry practiced presently?*
- *Can contemporary uses of biomimicry provide insight to its potential in landscape architecture?*
- *To what extent can the guiding principles from the Biomimicry Resource Handbook be applied to landscape architecture?*

This thesis will use principles developed by Janine Benyus in her work, *Biomimicry Resource Handbook*, to generate a checklist for landscape architecture utilizing the criteria in which biomimicry is taught through her educational resources. The following six objectives from Benyus' work will address biomimicry as a tool, subcategorizing individual processes and components.

1. **Evolve to Survive**

   Progressive: The favoring of beneficial design traits are selected over detrimental practices

2. **Adapt to Changing Conditions**

   Entrepreneurial: Design changing to fit evolving demands of natural and built environments

3. **Be Locally Attuned and Responsive**

   Native: Recognizing and responding effectively to local needs and conditions

4. **Integrate Development with Growth**

   Holistic: Investing in "smart growth" to increase likelihood of prolonged success

5. **Be Resource Efficient**

   Smart: Perform and function effectively while minimizing waste

6. **Use Life-Friendly Chemistry**

   Clean: Use processes to eliminate toxic byproducts

This checklist was used as an evaluative tool to examine innovative case studies in Chapters Three and Four, in order to provide a rubric to compare the selected project designs and analyze the checklist's applicability in landscape architecture.

Application and Relevance to the Profession

The integration of design and ecology has been important to the development of contemporary landscape architecture. The pioneers of this discipline often perceived innovative form as a secondary by-product to their primary goal of landscape function. This is evident in the works of landscape architect Ian McHarg and his "ecological inventory" method (Cote, Dale, and Tansey 2007). His work has influenced the way in which landscape architecture is practiced. However, his data-driven inventory has been criticized by contemporary landscape architects in a similar manner. Nina-Marie Lister, landscape ecologist and principal of PLANDFORM, discussed the current practice of ecological design in her essay, *Industrial Ecology as Ecological Design: Opportunities for Re(dis)covery*. Her primary concern was that an unbalanced weight of scientific application and analysis had been applied to landscape architecture solutions. Lister acknowledges this need for refocusing intuitive design into contemporary practice, stating that "there is a growing collective voice calling for reconciliation of falsely polarized, competing aspects of art and science, culture and nature" (Cote, Dale, and Tansey 2007). The field of biomimicry has the ability to address this need within design practices without sacrificing the importance of form or function. The aesthetics of natural systems are derived from their performances; with biomimicry, man-made systems do not have to be determined by physical characteristics, but how they collaborate with the systems around them.

In her essay, Lister debates the growing concern of function predominating the design process in contemporary practices of landscape architecture, ecology, and environmental planning. Her argument focuses on ecological and industrial design as a tool for more than a direct modeling of nature, stating:

> In essence, nature is an analogue for design, and through such inspired design, a metaphor for human learning. What this implies is room for a more creative design practice allowing for synthesis with human culture, aesthetics, and ingenuity" (Cote, Dale, and Tansey 2007).

Methodology

Research methods for this study were adapted from Elen Deming and Simon Swaffield's *Landscape Architecture Research: Inquiry, Strategy, Design (Deming and Swaffield 2011)*. A historical overview of biomimicry and its uses was written using secondary descriptions from academic publications. The grading rubric for successful implementation of biomimicry was adapted from secondary descriptions, allowing further analysis of each case study. The examination of each project applies the descriptive case study method for comparisons of each individual design implementation. These case studies and their rubrics are further analyzed to create design guidelines for biomimicry practice in landscape architecture.

Chapter Summaries

Chapter Two examines the historical context of biomimicry as it applies to design. The Chapter focuses on examples where natural forms have historically been utilized in design solutions and the scope of which those natural forms were studied. The chapter also identifies contemporary practitioners of biomimicry from varying fields of design, their identified philosophies, and their design processes.

Chapter Three examines biomimicry case studies. The evaluation of each case study is determined by a rubric based on Janine Benyus' "Life's Principles" in her *Biomimicry Resource Handbook (Baumeister et al. 2014)*. Each case study focuses on unique biomimicry projects implemented to achieve specific goals in relation to the site's context. Few contemporary examples of biomimicry as a design methodology exist in landscape architecture; therefore the case studies in Chapter Three address projects in the architectural field, which has recently employed this process in design. This analysis provides insight for the application of biomimicry within landscape architecture in Chapter Four. The rubric itself will be analyzed and addressed at the end of each case study to determine its applicability in the landscape architecture profession.

Chapter Four applies the analytical case study method used in Chapter Three for an implemented landscape architecture design. Comparisons between projects and their individual rubrics are analyzed to determine strengths and weaknesses of each. The information collected is synthesized into a proposal of guidelines for landscape architecture's application of biomimicry as a design tool.

Chapter Five examines the possible scope of which biomimicry can be utilized by landscape architecture as a design process. The chapter reexamines the research process, case studies, and analytical tools to suggest future research possibilities and questions remaining after this investigation.

CHAPTER 2

HISTORICAL CONTEXT OF BIOMIMICRY'S PHILOSOPHY AND APPLICATIONS

The use of natural processes to inspire innovative form is not a new practice. Specific applications of biomimicry are the primary reason the practice has gained traction in the 21st century. The evolution of these applications towards design thinking has been a transitional process; practitioners are now looking to nature for mutually beneficial relationships between natural and designed environments. The historic utilization of nature's functions and forms has developed a new method of systems design. This approach has set the standard for the present use of design through biomimicry.

Function: Application History

The application of biomimicry predates the contemporary resurgence in this field by at least a decade. Artists, scientists, and designers have looked to the natural world for inspiration often, although primarily for innovations in function. In 1904, the winged seeds of *Alsomitra macrocarpa* were used as design inspiration for air gliding by Ignaz and Igo Etrich (Vincent et al. 2006). Réne-Antoine Réamur examined wasps' use of wood pulp in 1917 to suggest a new paper production method (Pawlyn 2011). In 1955, a pet inspired one of the most popular technological innovations from natural function; the hooked seeds of a burdock plant latched on to a dog's coat. This led to invention of George de Mestral's Velcro (Vincent et al. 2006).

Function + Form: JFV Vincent

During the mid-20th century, the application of biomimicry solidified as a specific tool for academic and professional applications. Dr. Otto Schmitt, the founder of biomedical engineering, was a major part of this application. In 1957, his doctoral research focused on creating a product that mimicked the electrical actions of a nerve. Through his research process, he came to understand and define the practice of biomimetics (Vincent et al. 2006). Schmitt's research broke new ground within the field of biophysics, a practice which had not previously viewed the natural world as a source for applicable design. Schmitt stated:

> Biophysics is not so much a subject matter as it is a point of view. It is an approach to problems of biological science utilizing the theory and technology of the physical sciences. Conversely, biophysics is also a biologist's approach to problems of physical science and engineering, although this aspect has largely been neglected (Harkness 2002).

In 1965, the field of engineering began to echo Schmitt's proposal. Dr. Julian FV Vincent spent much of his academic career exploring biological ideas for engineering purposes. As a Senior Research Associate at the University of Oxford's Zoology Department, Vincent developed and chaired the Centre for Biomimetics at the University. He published over 300 papers, articles, and books exploring applications of the subject, most notably his collaborative essay, *Biomimicry: its practice and theory* (Vincent et al. 2006). Vincent wrote extensively on biological properties that can be adapted for design and implementation in multiple fields. He proposed an integration of technological and biological fields, echoing Schmitt's research, in his paper *Biomimetics in Architectural Design*:

> The twinning of biology and technology requires care and sympathy, since the two -ologies are so very different. Biology is descriptive, open-ended and full of surprises. Technology is numerical, close-ended and (ideally) never surprising. The common ground is that both are explorations of how to solve problems (Vincent 2014).

Schmitt's paper provided linkages between ecological and architectural practices, using case studies to provide possible solutions available for form and function in design, primarily at the material level. Vincent's case studies examined in his essay included his study on the structural integrity of the cuttlefish and its porous, lightweight properties. His proposal suggested a solution for cost-effective material selection in building construction. One example in his essay, currently in production, examined traits of the Bombardier Beetle's exothermic, hydrocarbon emissions as a method for extinguishing fires (Vincent 2014).

Vincent's understanding of biomimetics and its implications through multiple fields of design began to shape the way in which the term biomimicry would later be popularized. While this approach has been successful in utilizing nature for design innovation, it still relies on the model of "nature as tool" for designers to use and interpret. Biomimicry can be seen as an adaptation of nature instead of integration with nature.

Function + Form + Process: Janine Benyus

The application of biomimicry continued to grow in the 1990s, but the primary contributions to the field continued to link form and function without focus on process. This model furthered the view of man-nature hierarchy, with biomimicry used as tool to further technological advancements through the abstraction of nature's resources.

In 1998, Biological Scientist Janine Benyus popularized the definition of biomimicry as it is currently used today. Benyus' previous academic research on wildlife systems focused on cooperative relationships and self-regulating feedback cycles in nature. Her publication, *Biomimicry: Innovation Inspired by Nature*, noted the disconnect between natural processes and her academic field, stating that she "practiced a human-centered approach to management, assuming that nature's way of managing had nothing of value to teach us" (Benyus 1997). Benyus' approach of biomimicry focused on systems linkages between design and the natural world.

In response to the systems applications Benyus discovered in her research, she, and contemporaries, began to expand the scope of educational resources for biomimicry. In 2005, Benyus and Bryony Schwan co-founded The Biomimicry Institute, a website that offers lesson plans, classroom exercises, and educator training courses through the Institute's Education Network (Institute 2014). The award-winning website *AskNature* was developed in 2007 by Benyus, Schwan, and Chris Allen, which cataloged the multi-professional practices of biomimicry into a resource database (Institute 2008-2015). The culmination of their previous projects resulted in the *Biomimicry 3.8* website in 2010, which acts as both a for-profit consulting company and not-for-profit educational tool (Biomimicry Group 2014). This expansion of biomimicry practice has taken root in multiple educational fields; the first biomimicry degree program will be available to incoming students at Arizona State University during the 2015 Fall Semester (Arts). Holistically, these resources intended to educate a wider scope of practitioners in the field of biomimicry and its enhanced potential for design.

Present Approaches

Today, Benyus' and Vincent's work continues to explore possibilities of biomimicry applications in the design professions. The foundation of their literature has brought biomimicry to the foreground in many professional fields, including industrial design, architecture, packaging science, and engineering. Michael Pawlyn and his group, Exploration Architecture, have been using the explorative design process to develop closed-loop and resource-efficient systems on a global scale (Figure 3) (Pawlyn 2011). Neri Oxman, a Ph.D. candidate in design and computation at the Massachusetts Institute of Technology, said of her biomimicry design process: "I'm trying to 'invent' or define a new field in design, to generate forms, which are smart in the way that they relate to their environment" (Figure 4) (Press 2008). The field of biomimicry is expanding and evolving in a similar manner to the practice itself. Each example of successful design implementation is specific in its application, while the broader context of its philosophy binds them together.

Figure 3. Close-Loop System Concept Model by Exploration Architecture (Pawlyn 2011)

Figure 4. Oxman, Neri. *Beast*. 2008. (Press 2008)

CHAPTER 3

BIOMIMICRY ANALYSIS THROUGH ARCHITECTURE

The field of biomimicry has expanded dramatically over the past decade and has been utilized by multiple disciplines to overcome a variety of academic and professional challenges. Landscape architecture is one profession where there are limited explicitly-defined biomimicry projects. The selection criteria of the following case studies aim to link specific projects from design fields which apply biomimicry principles to possible applications in landscape architecture. A simple, three-point criteria was developed in order to identify potentially relevant case studies:

1. **Date of Execution:** Biomimicry design implemented in the past two decades (1995-2015)
2. **User Location:** Biomimicry design utilized by different contemporary designers in a variety of locations
3. **Identity:** Biomimicry Design that has been identified as such, by critics or designer of said project

The criteria with which these case studies were analyzed were partially developed through Janine Benyus' *Biomimicry Resource Handbook (Baumeister et al. 2014).* The chapter "Principles of Life" offers specific design standards for Benyus' definition of true biomimicry-inspired design. Her list is separated into 6 categories, each with three or more subcategories further defining the criteria's application to biomimicry in design. These six principles are defined as followed.

1. **Evolve to Survive** *(Progressive)*

   Continually incorporate and embody information to ensure enduring performance

   - *Replicate Strategies that Work*

     Repeat Successful Approaches
   - *Integrate the Unexpected*

     Incorporate mistakes in ways that can lead to new forms and functions
   - *Reshuffle Information*

     Exchange and alter information to create new options
2. **Adapt to Changing Conditions** *(Entrepreneurial)*

   Appropriately respond to dynamic contexts

   - *Incorporate Diversity*

     Include multiple forms, processes, or systems to meet a functional need
   - *Maintain Integrity through Self-Renewal*

     Persist by constantly adding energy and matter to heal and improve the system
   - *Embody Resilience through Variation, Redundancy, and Decentralization*

     Maintain function following disturbance by incorporating a variety of duplicate forms, processes, or systems that are not located exclusively together
3. **Be Locally Attuned and Responsive** *(Native)*

   Fit into and integrate within the surrounding environment

   - *Leverage Cyclic Processes*

     Take advantage of phenomena that repeat themselves
   - *Use Readily Available Materials and Energy*

     Build with abundant, accessible materials while harnessing freely available energy

- *Use Feedback Loops*

  Engage in cyclic information flows to modify a reaction appropriately
- *Cultivate Cooperative Relationships*

  Find value through win-win interactions

4. **Integrate Development with Growth** *(Holistic)*

   Invest optimally in strategies that promote both development and growth

   - *Self-Organize*

     Create conditions to allow components to interact in concert to move toward an enriched system
   - *Build from the Bottom-Up*

     Assemble components one unit at a time
   - *Combine Modular and Nested Components*

     Fit multiple units within each other progressively from simple to complex

5. **Be Resource Efficient: Material and Energy** *(Smart)*

   Skillfully and conservatively take advantage of resources and opportunities

   - *Use Low Energy Processes*

     Minimize energy consumption by reducing requisite temperatures, pressures, and/or time for reactions
   - *Use Multi-Functional Design*

     Meet multiple needs with one elegant solution
   - *Recycle All Materials*

     Keep all materials in a closed feedback loop
   - *Fit Form to Function*

     Select for shape or pattern based on need

6. **Use Life-Friendly Chemistry** *(Clean)*

   Use chemistry that supports life processes

   - *Break Down Products into Benign Constituents*

     Use chemistry in which decomposition results in no harmful by-products
   - *Build Selectively with a Small Subset of Elements*

Assemble relatively few elements in elegant ways

- o *Do chemistry in water*

  Use water as solvent

This criterion was organized through a checklist that analyzed each of the case studies, developed by the thesis author (Figure 5). The subsections of each category were evaluated on a four-point scale to qualitatively and quantitatively determine a site's degree of success through biomimicry applications.

- **None (0):** Category contained no biomimicry principles; did not provide linkages of biomimicry principles in other categories
- **Minimal (1):** Category contained minimal biomimicry principles, but vague or incorrectly applied; provided partial or inaccurate linkages of biomimicry in other categories
- **Partial (2):** Category contained biomimicry principles, but either not wholly evident or concretely applied; provided possible linkages of biomimicry in other categories
- **Extensive (3):** Category contained evident biomimicry principles thoroughly; provided linkages of biomimicry principles for other categories

These considerations were also applied to the design critique in Chapter Four and in overall recommendations in Chapter Five.

Criteria Analysis

Case Study Template | *Scope of Conditions Met*

	Minimal (1)	Partial (2)	Extensive (3)
Evolve to Survive			
Replicate Strategies that Work			
Integrate the Unexpected			
Reshuffle Information			
Adapt to Changing Conditions			
Incorporate Diversity			
Maintain Integrity through Self-Renewal			
Embody Resiliency through Variation, Redundancy, and Decentralization			
Be Locally Attuned and Responsive			
Leverage Cyclic Processes			
Use Readily Available Materials and Energy			
Use Feedback Loops			
Cultivate Cooperative Relationships			
Integrate Development with Growth			
Self-Organize			
Build from the Bottom-Up			
Combine Modular and Nested Components			
Be Resource Efficient (Material and Energy)			
Use Low-Energy Processes			
Use Multi-Functional Design			
Recycle All Materials			
Fit Form to Function			
Use Life-Friendly Chemistry			
Break Down Products into Benign Constituents			
Build Selectively with a small Subset of Elements			
Do Chemistry in Water			
Weighted Average			

Figure 5. Biomimicry Analysis Checklist (Table by Author)

Case Study One: Eden Project

Designer: Grimshaw Architects
Location: Cornwall, United Kingdom
Date: 2000

Overview

In 2000, the UK Registered Charity Eden Trust sought to develop the Eden Project. Their primary objectives for the site were to focus on tourism, charity, and education surrounding horticulture, science, and architecture. Eden Trust enlisted Grimshaw Architects to develop a plan for the site's development, which was located within a 160-year-old china clay quarry. Grimshaw's proposal looked to biomimicry for the site's layout, using the concept of soap bubbles (Figure 6) to fit buildings within the existing topography (Pawlyn 2011). Project Eden was constructed in two phases, the Biomes (2000) and the Core (2007).

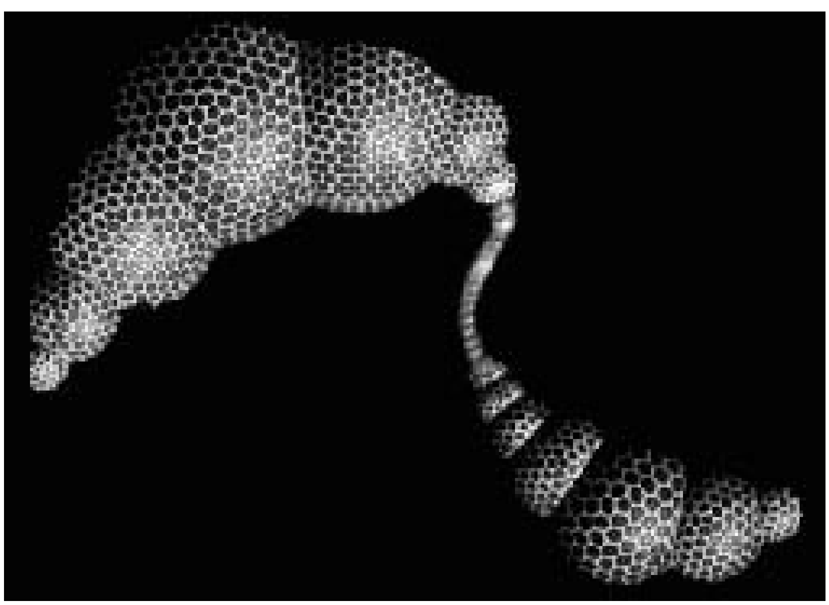

Figure 6. Soap Bubble Model Concept (Pawlyn 2011)

Grimshaw interpreted the clay quarry's existing topography as a wall for structural support of the biomes (Figure 7). The biomes consist of two main geodesic domes that function as research facilities for Mediterranean and Rain Forest climates. Six smaller domes form a "necklace" along the quarry's north face, connecting the two main biomes (Figure 8). Together, the Biomes form the largest conservatory in the world (Project). The Core addition shares the site's north edge, located southeast of the Biomes. The Core was developed as a central educational center, and, as stated by the Eden Project, "was inspired by natural form, crafted from natural materials and is an exemplar of sustainability in its approach, design and actual construction" (Elworthy). Grimshaw Architects actively pursued biomimicry principles for the Eden Project, focusing on material selection, water harvesting, and solar energy for design and construction solutions.

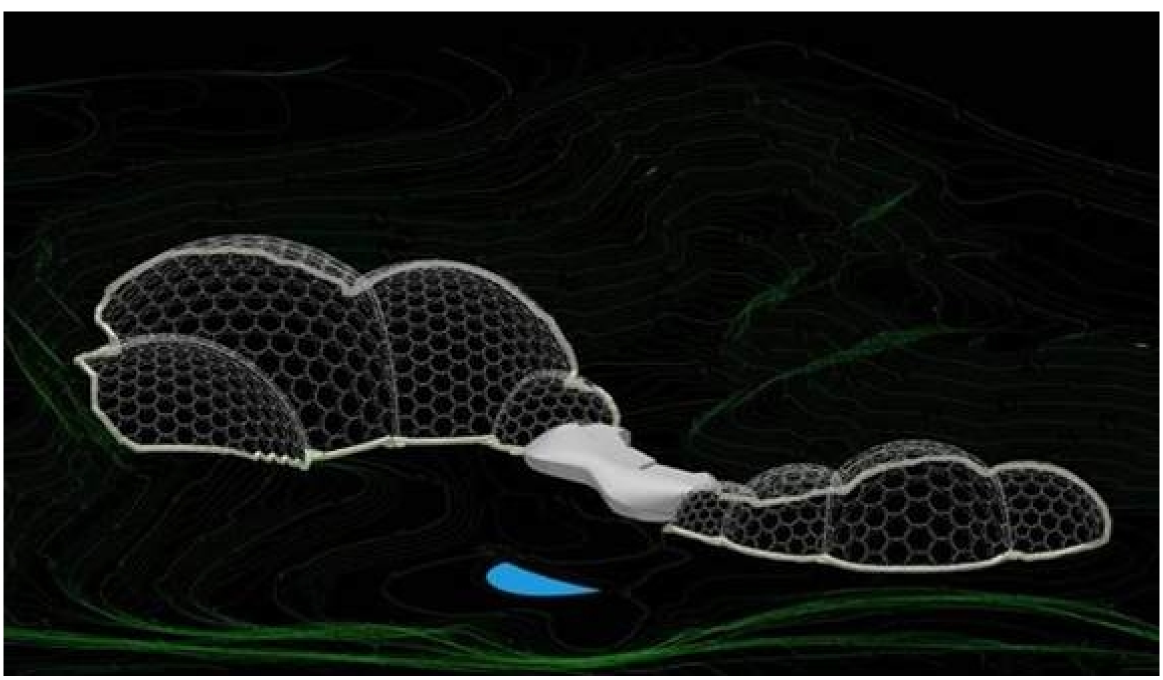

Figure 7. Room Partitions Informed by Quarry Topography (Pawlyn 2011)

Figure 8. Linked Biome Corridor (Architects)

Material selections for both Core and Biomes were important for their individual functions. The Biomes were formed from a hex-tri-hex geometry, resembling a honeycomb pattern, with three layers of ethylene tetrafluoroethylene (ETFE) plastic sheets fit between steel beams (Figure 9). The space between each ETFE layer is inflated with air, creating rigidity between the steel beams. ETFE plastics were selected due to their recyclability and self-cleaning properties. Due to these material selections, after construction it was found that the Biomes were lighter than the air contained within them (Pawlyn 2011).

Figure 9. Hex-Tri-Hex Geometric Form of Biomes (Architecture)

The Core's design was inspired by tree forms around the existing site, with a central "trunk" and canopy roof to shade and collect sunlight (Figure 10). The materials used intended to increase energy efficiency while reducing the building's environmental impact wherever possible. The Core's walls are insulated with Warmcel, a product made with recycled newspapers. Heineken bottles were recycled for floor tiles, while the wood flooring was reclaimed lumber. Heating is produced from underground tubes that warm air before it enters the building. Outsourced materials were considered in the selection process: wooden support beams were Forest Stewardship Council-certified and constructed using glue-laminated layers whose offcuts were used as fuel. The concrete used recycled aggregate for 90% of the concrete composition, and was sourced from local China Clay industry waste.

Figure 10. Trunk and Canopy Roof of the Core (Architects)

One of the main goals for the Eden Project was to become less dependent on external resources, including water usage. An underground drainage system was constructed to collect all water running to the site, while rainwater that hits the Biomes is collected at the ground level. This water is used to irrigate plants and maintain humidity in the Biomes. The recycled water is then used to maintain the Rainforest Biome's waterfall pressure and as toilet water for the site's utilities. Over half of the Eden Project's water needs are harvested on site.

Light conditions for the site were utilized to generate passive heating and solar energy. Sunlight can directly infiltrate the Biomes' ETFE sheets to heat the Mediterranean and Rainforest climates to proper temperatures. The sun's heat is trapped between the triple-layered sheets, which acts as a thermal blanket for the

Biomes. Energy is produced from photovoltaic panels on the Core's roof to provide hot water and energy storage for the Eden Project's backup generators.

Checklist Analysis

1. **Evolve to Survive**
   Extensive: Replicate Strategies that Work
   Integrate the Unexpected
   Reshuffle Information

The design process for the site successfully utilized the natural form of the clay mine as structural support for architecture, developing biomes that physically interacted with the site's topography. The ETFE sheets and steel beams of the Biomes interact with themselves to provide rigidity for the flexible foundation.

2. **Adapt to Changing Conditions**
   Partial: Maintain Integrity through Self-Renewal
   Extensive: Incorporate Diversity
   Embody Resiliency through Variation, Redundancy, and Decentralization

Biome self-cleansing ETFE sheets are minimally maintained, while steel beams and the Core's sheet metal roofing require external maintenance. The ETFE sheets are modular within the hex-tri-hex steel beams and can be removed entirely.

3. **Be Locally Attuned and Responsive**
   Partial: Leverage Cyclic Processes
   Use Readily Available Materials and Energy
   Use Feedback Loops

Extensive: Cultivate Cooperative Relationships

Automated systems regulate the temperature, humidity and water indexing within the Core and Biomes, but are programmed for fixed responses that can't evolve over time. Readily available materials were used as amendments for the concrete aggregate and wooden beams, but outsourcing for steel and plastics was needed.

4. **Integrate Development with Growth**
   Partial: Self-Organize
   Extensive: Build from the Bottom-Up
   Combine Modular and Nested Components

The complex structure of the biomes is resultant of simple materials, the ETFE plastic and steel beams, working collaboratively as a multifunctional system. The Eden Project's two development phases built the biomes and Core separately, which gave opportunity for development to adapt to previous built conditions.

5. **Be Resource Efficient**
   Partial: Recycle All Materials
   Extensive: Use Low-Energy Processes
   Use Multi-Functional Design
   Fit Form to Function

Recyclable materials were used primarily in the Core's construction, utilizing wood and glass to maximize goals for ecological sustainability. While the steel beams for the biomes were not recycled, ETFE plastics were selected for their post-use value as fully recyclable materials. All construction projects in the Eden Project considered natural conditions of the clay mine: biomes used the mine's walls for structural support, while the Core was constructed at the most gentle topography changes where light could be efficiently used for its photovoltaic cells.

6. **Use Life-Friendly Chemistry**
   Minimal: Do Chemistry in Water

   Partial: Break Down Products into Benign Constituents

   Extensive: Build Selectively with a small Subset of Elements

There was no evidence that the Eden Project utilized water as solvent in the design's realization. Steel and concrete were used in construction, but the material decomposition of the site will result in minimal harmful byproducts to the environment. The unique solution of fitting each structure to the site's initial conditions, and the materials selected for its construction, allowed Grimshaw to use relatively few elements to maximize visual and educational experiences within the site.

Conclusion

From the checklist evaluation, the Eden Project provided successful applications of biomimicry to their design (Figure 11). The project's weighted average scored a 2.55, with 60% of the criteria meeting extensive requirements in the scope of conditions and 95% of the checklist's criteria meeting at least partial requirements. None of the criteria conditions failed to meet minimal requirements.

Grimshaw Architects focused on material selections through biomimicry, resulting in decentralized materials (ETFE plastics, steel beams) that performed multiple functions in relationship to the comprehensive design. Examples where Eden Project was not impactful in the scope of conditions included material reuse and recycling and on-site cyclic processes.

In comparison with other case studies, the Eden Project was the most successful in utilizing existing topography for the design. The project met the client’s needs by linking visually-impactful public space within the site’s main functions.

Criteria Analysis

Eden Project — *Scope of Conditions Met*

	Minimal (1)	Partial (2)	Extensive (3)
Evolve to Survive			
Replicate Strategies that Work			■
Integrate the Unexpected			■
Reshuffle Information			■
Adapt to Changing Conditions			
Incorporate Diversity			■
Maintain Integrity through Self-Renewal		■	
Embody Resiliency through Variation, Redundancy, and Decentralization			■
Be Locally Attuned and Responsive			
Leverage Cyclic Processes		■	
Use Readily Available Materials and Energy		■	
Use Feedback Loops		■	
Cultivate Cooperative Relationships			■
Integrate Development with Growth			
Self-Organize		■	
Build from the Bottom-Up			■
Combine Modular and Nested Components			■
Be Resource Efficient (Material and Energy)			
Use Low-Energy Processes			■
Use Multi-Functional Design			■
Recycle All Materials		■	
Fit Form to Function			■
Use Life-Friendly Chemistry			
Break Down Products into Benign Constituents		■	
Build Selectively with a small Subset of Elements			■
Do Chemistry in Water	■		
Weighted Average			**2.55**

Figure 11. Biomimicry Analysis Checklist: Eden Project (Table by Author)

Case Study Two: Burke Brise Soleil

Designer: Santiago Calatrava
Location: Milwaukee, Wisconsin
Date: 1994

Overview

The Milwaukee Art Museum was first developed as a War Memorial by noted architect Eero Saarinen in 1957. In 1994, the Trustees of the Milwaukee Art Museum held a design competition for "a grand new entrance, a point of orientation for visitors, and a redefinition of the museum's identity through the creation of a strong image" (Tzonis 2007). Spanish modernist Santiago Calatrava won the competition for the museum's expansion, combining his interests in architecture, art, and engineering with conceptual design focused on biomimicry. It was completed in 2001 as Calatrava's first completed building in the United States (Tzonis 2007).

The expansion of the Milwaukee Art Museum housed multiple functions, including a 16,000 square foot temporary exhibition space, a 300-seat lecture hall, a 100-seat restaurant, and a gift shop. The main feature of Calatrava's design focused the Quadracci Pavilion, a 90 foot high glass and steel reception hall shaded by a moveable sunscreen (Figure 12) (Tzonis 2007). The shade structure's individual name was baptized the Burke Brise Soleil (French translation for "sun breaker", an architectural feature which reduces heat gain by deflecting sunlight) (Figure 13)(Britannica). While Calatrava does not usually specify biomorphic inspiration in his architectural designs, the Burke Brise Soleil is notably inspired from avian forms, even classifying each individual structure as "wings" (Tzonis 2007).

Figure 12. Quadracci Pavilion and Burke Brise Soleil (Museum Vers. 1.0 (2013))

Figure 13. Burke Brise Soleil, Extended (Henderson 2013)

The Burke Brise Soleil was designed to orient the Milwaukee Museum of Art on axis with the city's downtown corridor, with its projected wings to act as a visual attraction. The symmetrically-winged shade structure responds to light and wind conditions. A computerized system moves each wing throughout the day to provide shade for the Quadracci Pavilion (Figure 14). The system automatically overrides daily movements if wind speeds exceed 23 miles per hour (Tzonis 2007).

Figure 14. Wing Time-lapse, Burke Brise Soleil (Tzonis 2007)

Material selection for the Soleil reinforces Calatrava's modernist aesthetic. Each wing is 217 feet wide and designed with 36 individual steel "fins", ranging between 26 to 105 feet long (Tzonis 2007). The wings, collectively weighing 100 tons, reposition themselves through 22 hydraulic cylinders located within the Quadracci Pavilion. Overall, the project's material use included 22,000 cubic yards (or 81 million pounds) of concrete, 2,100 tons of steel, an acre of marble flooring from Carrera, Italy, and six miles of PVC tubing. 915 separate glass panes were installed, with fewer than 6% of these being "standard-orientation" windows; the rest of these panes were custom tilted, curved, or both. 235 panes for the Quaddracci Pavilion were imported from Spain (Museum Vers. 1.0 (2013)).

Checklist Analysis

1. **Evolve to Survive**

   Extensive: Replicate Strategies that Work

   Integrate the Unexpected

   Reshuffle Information

Calatrava's concept reimagined traditional, small-scale deployable structures (awnings, umbrellas) into a large-scale architectural art installation. The Burke Brise Soleil is a visually dominant design feature that responds to environmental changes.

2. **Adapt to Changing Conditions**

   None: Maintain Integrity through Self-Renewal

   Partial: Incorporate Diversity

   Extensive: Embody Resiliency through Variation, Redundancy, and Decentralization

Materials selected in the design (marble, steel, and glass) need continual external maintenance to mechanically and visually function. These limit the scope of diversity in their ability to perform multiple functions. However, the individual moving parts of the Soleil's wings respond to each other in adapting to wind and solar site conditions.

3. Be Locally Attuned and Responsive

None: Use Readily Available Materials and Energy

Cultivate Cooperative Relationships

Partial: Leverage Cyclic Processes

Use Feedback Loops

Custom-built glass, concrete, PVC pipes, and globally-sourced marble showcase the limited potential for success in this category. The cyclic processes and feedback loops are partially applicable in the Soleil's mechanized response systems.

4. Integrate Development with Growth

Minimal: Self-Organize

Partial: Build from the Bottom-Up

Combine Modular and Nested Components

The Soleil is partially developed "bottom-up" and within nested components through the fin design of its wings. Each fin is nested within larger component wings, although movement of individual wings is limited to and dependent on wing positions.

5. Be Resource Efficient

None: Use Low-Energy Processes

Recycle All Materials

Partial: Use Multi-Functional Design

Fit Form to Function

There was no indication within the design process that there was any concentration on material recycling or development of alternative energy sources. The design of the Soleil functions as an example of performative architecture and pedestrian attraction while fitting into the existing site conditions design by Eero Saarinen in 1957.

6. **Use Life-Friendly Chemistry**

   None: Break Down Products into Benign Constituents

   Do Chemistry in Water

   Build Selectively with a small Subset of Elements

Construction process used intensive energy processes throughout, exemplified by glass, marble, and concrete production and installation. These materials used focused on aesthetic, rather than performative, values to enhance the project's design.

Conclusion

While Calatrava's project met 55% of the criteria's extensive or partial conditions, it was not a successful application of biomimicry design (Figure 15). Burke Brise Soleil's weighted average of 1.8 resulted in 40% of the criteria failing to meet minimal biomimicry conditions. The lack of low-energy processes and material selections were main reasons for the limited role of biomimicry.

Burke Brise Soleil was most successful in its design for visual impact and public space. The biomimicry functions of the site were minimal in comparison with the Eden Project. Biomimicry applications played an integral part of creating a unique experience of place, though its role was limited to a predominantly aesthetic presence in relationship to overall construction.

Criteria Analysis

Burke Brise Soleil *Scope of Conditions Met*

	Minimal (1)	Partial (2)	Extensive (3)
Evolve to Survive			
Replicate Strategies that Work			■
Integrate the Unexpected			■
Reshuffle Information			■
Adapt to Changing Conditions			
Incorporate Diversity		■	
Maintain Integrity through Self-Renewal			
Embody Resiliency through Variation, Redundancy, and Decentralization			■
Be Locally Attuned and Responsive			
Leverage Cyclic Processes		■	
Use Readily Available Materials and Energy			
Use Feedback Loops		■	
Cultivate Cooperative Relationships			
Integrate Development with Growth			
Self-Organize	■		
Build from the Bottom-Up		■	
Combine Modular and Nested Components		■	
Be Resource Efficient (Material and Energy)			
Use Low-Energy Processes			
Use Multi-Functional Design		■	
Recycle All Materials			
Fit Form to Function		■	
Use Life-Friendly Chemistry			
Break Down Products into Benign Constituents			
Build Selectively with a small Subset of Elements			
Do Chemistry in Water			
Weighted Average			**1.8**

Figure 15. Biomimicry Analysis Checklist: Burke Brise Soleil (Table by Author)

Case Study Three: CH_2 Building

Designer: Mick Pearce Architects
Location: Melbourne, Australia
Date: 2006

Overview

In 2006, the city of Melbourne commissioned the design of Council House 2 (CH_2), a sustainable office building. The conceptual design involved the collaboration of multiple professions, including architects, engineers, artists, environmental experts, future occupants, the Commonwealth Scientific and Industrial Research Organization (CSIRO), and the Sustainable Energy Authority of Victoria (Webb 2005). CH_2's Principal Design Architect, Mick Pearce, had previously developed architectural standards for biomimicry as the lead architect for the Eastgate Centre in Harare, Zimbabwe. In 1996, Pearce used the model of termite mounds to develop passive cooling techniques that allowed the Eastgate Centre to use less than 10% of the energy of a traditional building its size(Brittany 2012). The design of CH_2 included similar applications of biomimicry process, shown through the building's response to Melbourne's climactic conditions as a primary challenge and opportunity for innovative design.

Melbourne's climate is noted for its drastic daily and seasonal condition changes. The building was designed to address these conditions, responding to the climate's main transitional modes: summer, winter, day, and night. The interior and exterior construction of the building was programmed to respond to external conditions to regulate its internal temperature while addressing the building's water and energy use.

Temperature control throughout the building responds through natural light, material selection, and passive heating and cooling systems. Window design reduced the need for artificial lighting and allowed for passive heating. Upper and lower blinds installed on the northern façade allow natural lighting conditions with protection from glare during the summer. The external western timber shutters move in response to daily and seasonal sun positions, opening to catch morning sun and closing in the afternoon (Figure 16). The windows on each floor are located at the highest point of the concrete ceilings for passive warmth, and are widest at street level for maximum lighting conditions (Antony Wood 2014).

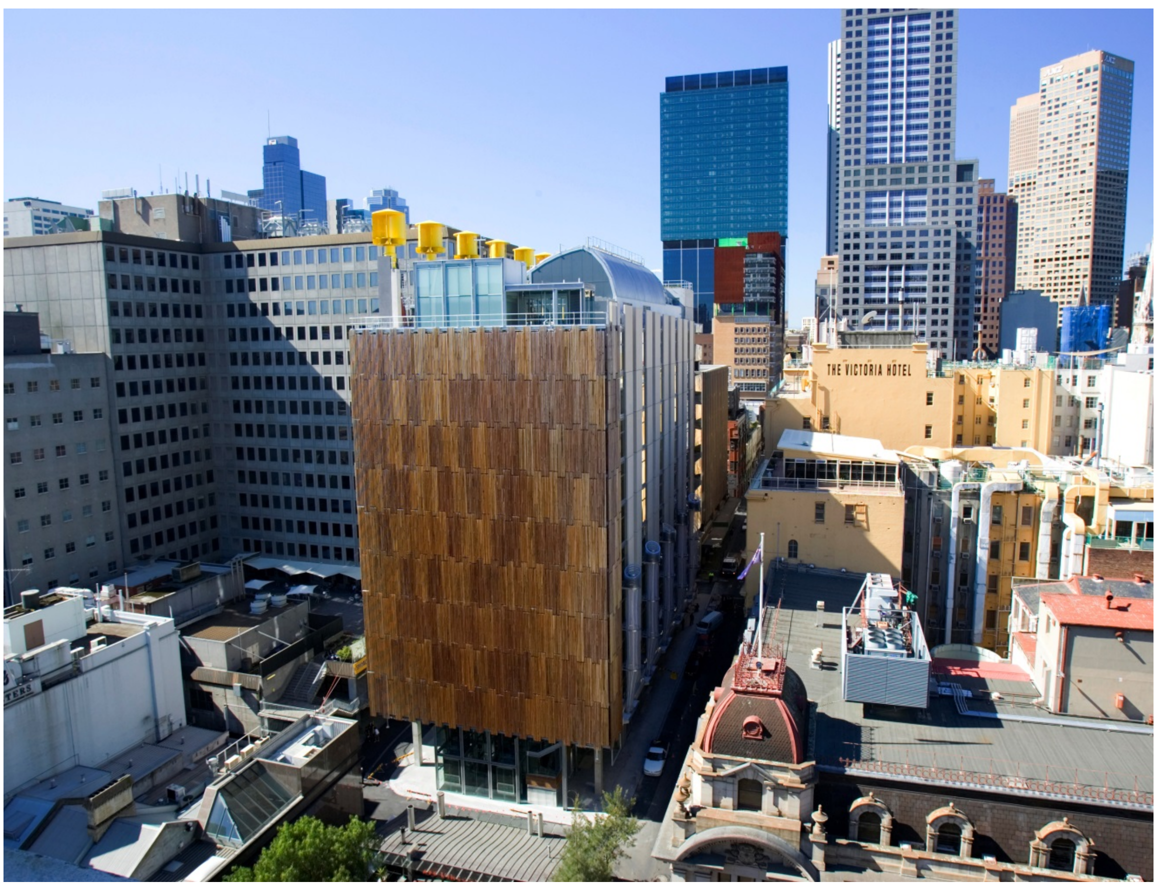

Figure 16. CH_2 Building Western and Northern Façade (Snape)

Material selection for the building's construction was designed to interact with light conditions for temperature regulations. Radiant cooling techniques were implemented to passively cool the building while eliminating the use of chilled ventilation air. Pre-cast, vaulted concrete ceilings increased the surface area of the ceiling, which increased its thermal mass, a material's ability to store heat. The heat stored by the concrete ceilings is released during the evenings through a "night purge": windows automatically open at night when the external temperature falls below the temperature of the internal concrete ceilings, removing the previous day's heat through cross ventilation. This purge occurs independently in response to each floor's internal temperature (Webb 2005).

Water harvesting, recycling, and usage were addressed in the temperature regulation of the building. The total roof area captures rainwater while the building's Blackwater Treatment Plant cleans blackwater, greywater, and sewerage (sewer water) (Figure 17). This water is then used to provide temperature control through its chilled ceiling panels along the vaulted concrete ceilings. Captured rainwater is distributed to the roof landscape and vertical plantings on the building's northern façade (Antony Wood 2014).

Figure 17. Water Capture System along CH_2 Roof (Antony Wood 2014)

The building generates its own energy to function properly, while all emissions associated with CH_2 have been offset. Gas micro-turbines located along the roof are used to generate electricity and provide less reliance on city power grids. Solar panels adjacent to the turbines provide 60% of the building's hot water supply for passive heating and domestic use. The panels also generate energy required for the movement of the western façade's timber shutters. The energy offset includes recyclable materials used; the design recycled approximately 87% of the materials on site. This included the timber shutters, recycled from over 200 demolished houses in the surrounding area (Figure 18) (Melbourne).

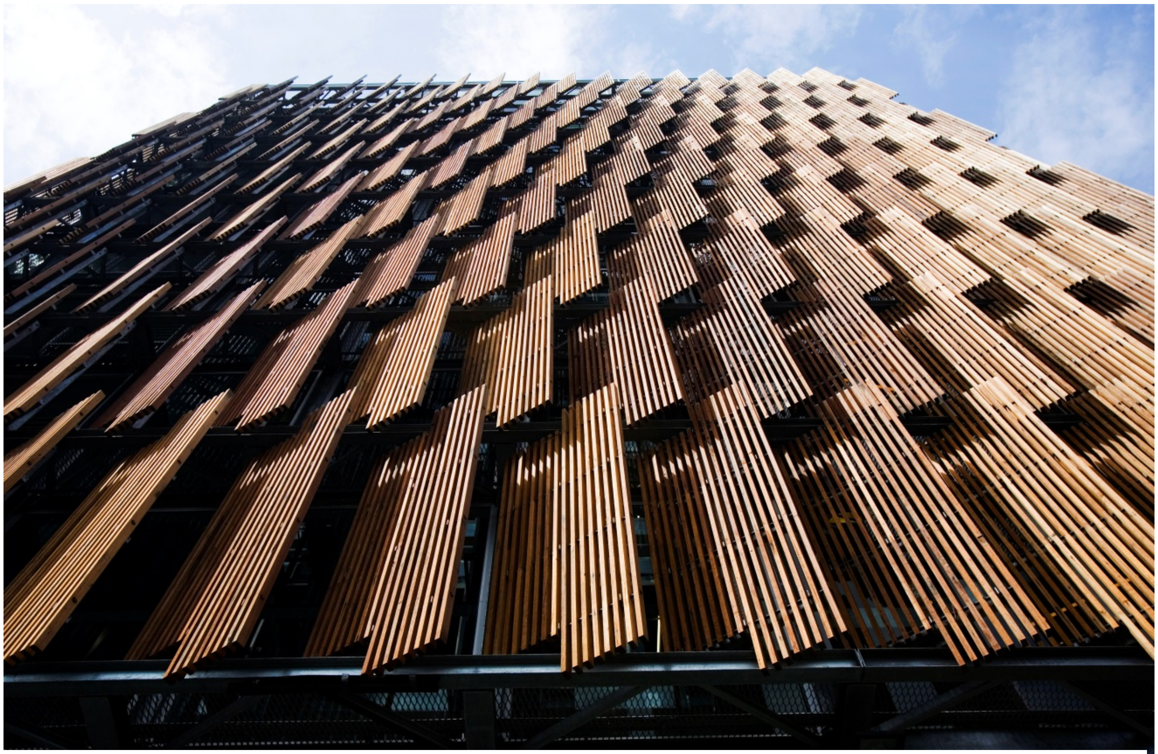

Figure 18. Western facade timber shutters (Snape)

Checklist Analysis

1. Evolve to Survive

Extensive: Replicate Strategies that Work

Integrate the Unexpected

Reshuffle Information

The CH_2 Building uses Mick Pearce's passive cooling techniques developed from the Eastgate Centre to design an integrated system that addresses the building's lighting, temperature, water usage, and energy storage. The concept developed from collaborative processes resulted in direct biomimicry applications to the building's façade; designing the structure's "epidermis" on the western façade to moderate external climates on the north and south.

2. Adapt to Changing Conditions

Extensive: Incorporate Diversity

Maintain Integrity through Self-Renewal

Embody Resiliency through Variation, Redundancy, and Decentralization

The building uses its vaulted concrete ceilings, western timber structures, window systems, water harvesting and recycling systems, and energy production in conjunction to respond to the local environmental conditions passively and ecologically. The energy used to meet the building's needs is low-cost, regenerative, and work in collaboration with other processes.

3. Be Locally Attuned and Responsive

Partial: Use Readily Available Materials and Energy

Extensive: Leverage Cyclic Processes

Use Feedback Loops

Cultivate Cooperative Relationships

Materials used in the project were central to its design concept. Concrete ceilings provide passive cooling while glass windows were framed by timber on northern, southern, and eastern façades for low-embodied energy design. Concrete and glass are material selections that cost a large amount of embodied energy to both manufacture and install; alternative selections might have proven to minimize this energy use impact.

The building responds to seasonal and daily modes through controlled climactic conditions. The timber shutters on the western façade respond to seasonality by adjusting their movement speeds to provide appropriate lighting and passive heating. The building's "night purge" is dependent on both external and internal climactic conditions, and responds to each floor individually.

4. **Integrate Development with Growth**

   Extensive: Self-Organize

   Build from the Bottom-Up

   Combine Modular and Nested Components

Each element of the building's design was organized to respond to comprehensive challenges in terms of environmental control and water and energy efficiency. The elements are nested within each other in terms of functionality; blackwater generated by the building is treated on-site and reused for temperature cooling, heating, and irrigation.

5. **Be Resource Efficient**

   Partial: Recycle All Materials

   Extensive: Use Low-Energy Processes

   Use Multi-Functional Design

   Fit Form to Function

While material recycling is used extensively in the project, it is not holistically applied, as seen through pre-cast concrete foundation and ceilings. Temperature control and energy production utilize passive processes efficiently and in conjunction with independent building processes, resulting in a zero-carbon footprint. Material forms define their specific functions, as exemplified in the vaulted concrete ceilings ability to increase internal light conditions and provide thermal mass.

6. **Use Life-Friendly Chemistry**

Extensive: Break Down Products into Benign Constituents
Build Selectively with a small Subset of Elements
Do Chemistry in Water

Structurally, the building relies on a small subset of materials to maximize its efficiency. Its performative functions focus on a smaller subset, addressing external light, wind, temperature, and water conditions to improve the structure's internal functions.

Conclusion

CH_2 began project development intending to implement biomimicry principles. The project's goal to blend the building's interior climate with exterior environmental conditions was successful in its biomimicry applications. The CH_2 Building received a weighted score of 2.85, with 100% of the criteria meeting extensive or partial condition requirements (Figure 19).

Focus on building response to environmental conditions and overall recycling strategies were most determinate in the design's score. Multi-functional uses for water, temperature, and light created unique conditions for interaction within separate components of the building. Inability to recycle all materials was a limiting role in the design.

Collective collaboration within multiple professions was more evident in CH2 than any other case study. Building functionality showcased multiple interactions with the design's individual elements on a more comprehensive level than the Eden Project. However, the distinctive experience of the design was limited to exclusive views inward, preventing impactful relationship possibilities for public interaction.

Criteria Analysis

CH_2 Building — *Scope of Conditions Met*

	Minimal (1)	Partial (2)	Extensive (3)
Evolve to Survive			
Replicate Strategies that Work			■
Integrate the Unexpected			■
Reshuffle Information			■
Adapt to Changing Conditions			
Incorporate Diversity			■
Maintain Integrity through Self-Renewal			■
Embody Resiliency through Variation, Redundancy, and Decentralization			■
Be Locally Attuned and Responsive			
Leverage Cyclic Processes			■
Use Readily Available Materials and Energy		■	
Use Feedback Loops			■
Cultivate Cooperative Relationships			■
Integrate Development with Growth			
Self-Organize			■
Build from the Bottom-Up			■
Combine Modular and Nested Components			■
Be Resource Efficient (Material and Energy)			
Use Low-Energy Processes			■
Use Multi-Functional Design			■
Recycle All Materials		■	
Fit Form to Function			■
Use Life-Friendly Chemistry			
Break Down Products into Benign Constituents		■	
Build Selectively with a small Subset of Elements			■
Do Chemistry in Water			■
Weighted Average			**2.85**

Figure 19. Biomimicry Analysis Checklist: CH_2 Building (Table by Author)

Applications for Landscape Architecture

Biomimicry process as applied to design in the built environment can easily be interpreted and analyzed using Janine Benyus' concepts from her *Biomimicry: Resource Handbook*. Landscape architecture, a field which borrows knowledge from multiple fields; architecture, ecology, engineering, etc. presents unique challenges and opportunities for the application of biomimicry's components.

CHAPTER 4

BIOMIMICRY ANALYSIS THROUGH LANDSCAPE ARCHITECTURE

The application of biomimicry is inherently both a collaborative and multidisciplinary process. As noted in Chapter Three, the CH_2 building relied extensively on collaboration from individuals in differing disciplines to create innovative design solutions. This resulted in a project that delivered innovative systems that responded and evolved in accordance with environmental conditions. Landscape architecture is a profession which embraces knowledge from multiple disciplines. The practice of biomimicry is a universal tool that encourages collaborative thinking. Landscape architects are often in the unique position of primary facilitator among multiple design disciplines, as exemplified in this chapter.

The analysis of biomimicry as a design tool for landscape architecture was done through two case studies. These projects were chosen by the same criteria outlined in Chapter Three: Date of Execution, Location, and Identity. However, these projects did not necessarily have to be identified as using biomimicry principles. This was done to examine if biomimicry principles have already been implemented in landscape architecture and haven't defined themselves as such. The case studies in Chapter Four used the same checklist analysis method used in Chapter Three.

Case Study One: Sidwell Friends School

Designer: Andropogon Associates
Location: Washington, DC
Date: 2007

Overview

Sidwell Friends Middle School was founded on the Quaker philosophy to educate and guide students towards a better social and environmental awareness (Gelfand and Freed 2010). When the school looked to expand its 50-year-old, 33,000 square foot building, the school administrators hired the landscape architecture firm Andropogon Associates to develop a design strategy that met their philosophy (Architects 2013). Completed in 2007, the Sidwell Friends Middle School development became the world's first Platinum LEED-New Construction K-12 school building. The 39,000 square foot classroom expansion focused on efficient and educational responses to water usage on site, including a close-looped wastewater system and water storage facilities to treat 100% of wastewater and stormwater on site (Kweon 2012).

The 9,000 square foot courtyard of Sidwell Friends Middle School contains a biology pond, rain garden, and terraced constructed wetland. Each of these elements work together to treat specific water conditions, and gathers water from the natural slope of the site. Wastewater is collected from the building's toilets and faucets and deposited into settling tanks for on-site, close-looped treatment. The tanks collect solid waste while water is released underground to the constructed terraced wetland. Over 3,000 gallons of wastewater per day are treated in the wetlands, circulating through the system 3-5 days before reuse. Water is then treated through on-site trickling filters, recirculating sand filters, and a UV disinfection unit before being stored for use in greywater storage tanks. This closed-looped system is self-contained within the courtyard to prevent contamination of the stormwater treatment systems (Figure 20). From 2011 to 2012, this system prevented over 317,000 gallons of wastewater from entering the District of Columbia's sewer system. The wastewater cleaning process is diagramed throughout the courtyard to educate its students and visitors (Kweon 2012).

Rainwater and stormwater are captured by the School's educational green roof and the courtyard's biology pond and rain garden (Figure 21). The green roof filters and

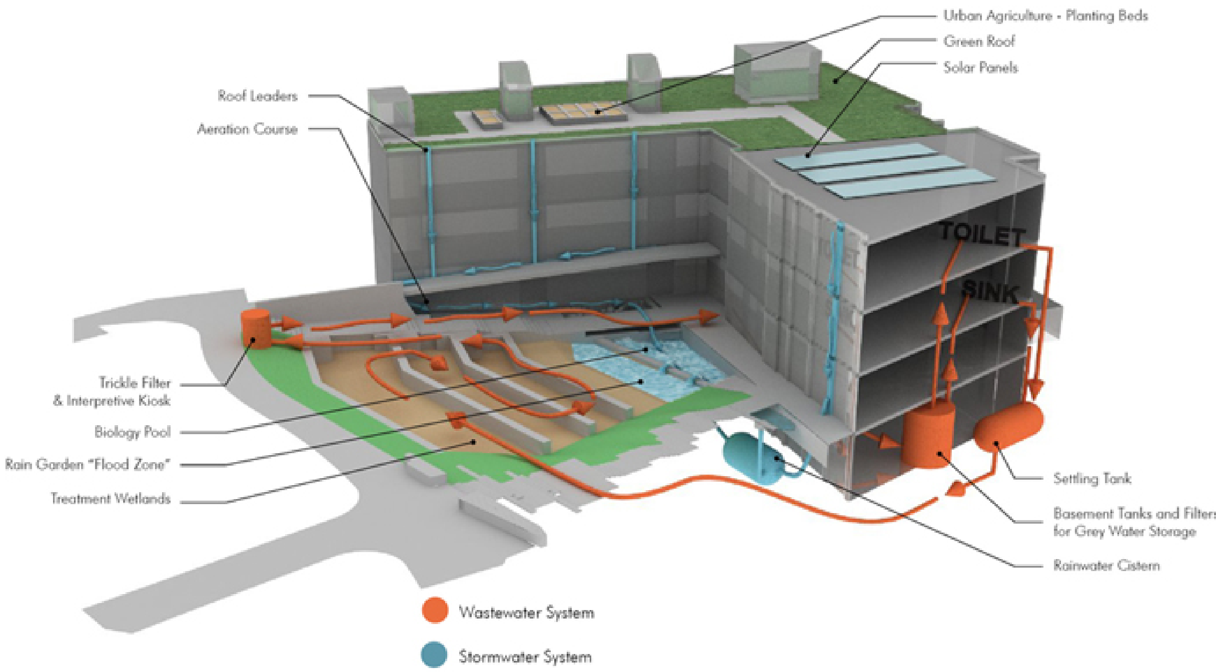

Figure 20. Closed-Loop Wastewater and Stormwater Treatment Systems (Associates)

stores rainwater in underground cisterns for summer use in the biology pond. 68% of a 1-year-storm's rainfall on the site (or 9,820 gallons) is captured by the green roof addition. Overflow and water from paved surfaces are directed to the biology pond and rain garden through vegetated swales (Kweon 2012).

Figure 21. Rain Garden and Biology Pond (Associates)

Careful plant selection was incorporated into the design to mitigate water usage. Over 80 species native to the Chesapeake Bay region were installed in place of turf, reducing water need. The plant species were selected for specific usages in the biology pond, rain garden, and terraced wetland. Each area needed to respond to specific water conditions for filtration and treatment through natural biological processes. The use of native species on this project has earned recognition from the National Wildlife Federation as a wildlife habitat (Architects 2013).

Specific material selections for the Sidwell Friends Middle School façade were made to reflect their moral and environmental awareness values. The building and landscape utilized a range of reclaimed materials from local resources. 78 tons of stone installed for the wetland walls and stairs was sourced from abandoned quarries and railway bridges (Figure 22). 8,000 board feet of flooring and decking for the building extension were made from pilings salvaged from Baltimore Harbor, while the unique façade cladding was created from 100-year-old wine barrels (Figure 23). Usage of locally-sourced, reclaimed materials prevented over 100 tons of resources from entering landfills (Kweon 2012).

Figure 22. Recycled Stone Used for Terraced Wetland (Associates)

Figure 23. Recycled wine barrel cladding (Associates)

Checklist Analysis

1. **Evolve to Survive**

Extensive: Replicate Strategies that Work

Integrate the Unexpected

Reshuffle Information

Sidwell Friends Middle School adapted previous passive water treatment techniques into its rain garden and constructed terraced wetland systems. The design incorporated both wastewater and stormwater cleaning strategies within its courtyard space to act as treatment facility and educational tool.

2. **Adapt to Changing Conditions**

Partial: Maintain Integrity through Self-Renewal

Extensive: Incorporate Diversity

Embody Resiliency through Variation, Redundancy, and Decentralization

Self-renewal is exemplified in the native plant selections for the courtyard and green roof. The plants adapt and maintain integrity of constructed treatment systems through natural succession. Material selection for the building construction showed little indication of self-renewal applications. The diversity of plants, treatment systems, and reuse strategies allow for multiple educational and visual experiences throughout a 9,000 square foot space. The variation and decentralization of treatment systems has completely recycled all wastewater and stormwater on site, while reducing dependency on public sewer and water utility systems.

3. **Be Locally Attuned and Responsive**

Partial: Use Readily Available Materials and Energy

Extensive: Leverage Cyclic Processes

Use Feedback Loops

Cultivate Cooperative Relationships

Contemporary materials were used for the structural construction of the building. However, the materials used for flooring, façade cladding, and courtyard hardscapes significantly reduced dependency on energy-reliant materials for their implementation. The close-loop system for wastewater treatment recirculates all wastewater back to facility uses, primarily toilets. Rainwater harvested from green roofs is stored and used depending on seasonal and physical conditions of the biology pond.

4. Integrate Development with Growth

Partial: Build from the Bottom-Up

Extensive: Self-Organize

Combine Modular and Nested Components

Each individual component in the water treatment system acts in concert toward a cohesive design. The rain garden, biology pond, and wetland are individual components which are integrated in a complex system of water treatment. Each part of the design was implemented collaboratively, with exception to the wastewater treatment system to prevent stormwater contamination.

5. Be Resource Efficient

Partial: Recycle All Materials

Extensive: Use Low-Energy Processes

Use Multi-Functional Design

Fit Form to Function

While multiple materials were successfully installed to maximize material recycling, the construction of the Middle School's educational expansion relied on uncycled concrete, brick, mortar, and steel. New materials were also used in the wastewater filters and UV units. The overall design minimized energy consumption through smart water design, reducing dependency on public utilities for water treatment while reducing the school's water consumption by 93%. Courtyard design fit form to function, developing the wetland, rain garden, and biology pond to fit the natural, sloping topography of the site.

6. **Use Life-Friendly Chemistry**

Partial: Break Down Products into Benign Constituents
Build Selectively with a small Subset of Elements
Do Chemistry in Water

The singular instance found where decomposition resulted in no harmful byproducts was plant selection for water treatment sites. Plant decomposition increased biological interaction between plant species and the soil, which increased the productivity of the site's water treatment capabilities. The recycled materials used were selected from a small subset of elements. However, the structural elements for the school, combined with wastewater filtration components, revealed a more complex selection of materials. Chemistry in water was used effectively, but not as a solvent. The entire design was dependent on the multifunctional aspects of water decontamination and reuse.

Conclusion

Sidwell Friends Middle School's ecological application to redevelopment and expansion met 100% of biomimicry criteria with extensive or partial requirements. The project's weighted average score was 2.65 (Figure 24).

The utilization of cyclic processes in combination with experience of place yielded a similar score result to the Eden project, which performed similar design solutions. The relationship between vegetative and built elements of design proved to be most applicable to the biomimicry criteria. Their successful performance as individual elements and collective whole was comparative to the relationships throughout the CH_2 building design.

The facilities for Sidwell Friends Middle School provided multiple educational tools for students and visitors alike. This was exemplified through educational experiences throughout the courtyard and green roof development. Educational tools pertaining to site consideration and development were found restrictive within the building expansion, which limited the holistic blending of landscape and built environment.

Criteria Analysis

Sidwell Friends Middle School — *Scope of Conditions Met*

	Minimal (1)	Partial (2)	Extensive (3)
Evolve to Survive			
Replicate Strategies that Work			■
Integrate the Unexpected			■
Reshuffle Information			■
Adapt to Changing Conditions			
Incorporate Diversity			■
Maintain Integrity through Self-Renewal		■	
Embody Resiliency through Variation, Redundancy, and Decentralization			■
Be Locally Attuned and Responsive			
Leverage Cyclic Processes			■
Use Readily Available Materials and Energy		■	
Use Feedback Loops			■
Cultivate Cooperative Relationships			■
Integrate Development with Growth			
Self-Organize			■
Build from the Bottom-Up		■	
Combine Modular and Nested Components			■
Be Resource Efficient (Material and Energy)			
Use Low-Energy Processes			■
Use Multi-Functional Design			■
Recycle All Materials		■	
Fit Form to Function			■
Use Life-Friendly Chemistry			
Break Down Products into Benign Constituents		■	
Build Selectively with a small Subset of Elements		■	
Do Chemistry in Water		■	
Weighted Average			**2.65**

Figure 24. Biomimicry Analysis Checklist: Sidwell Friends Middle School (Table by Author)

Case Study Two: Allegheny Riverfront Park

Designer: Michael Van Valkenburgh & Associates (MVVA)
Location: Pittsburgh, PA
Date: 1994

Overview

The city of Pittsburgh invested in major transportation infrastructure along its waterways during the 20th century. This development cut the rest of the city off from the recreational and ecological experiences of its rivers. In 1994, the Pittsburgh Central Trust began to investigate the possible restoration of linear sites along the confluence of the Allegheny and Monongahela Rivers. Michael Van Valkenburgh & Associates (MVVA) was selected to address the design challenges of the proposal. MVVA used Frederick Law Olmstead's original 1911 concept as a template, proposing two linear strips of land along the river to reconnect the city with important resources (Figure 25) (Trust). The sites' challenges included a 25 foot sectional grade change from the river to the city, two major highway lanes which bisect the park's center, and significant seasonal flooding of the park's lower level (Amidon 2005).

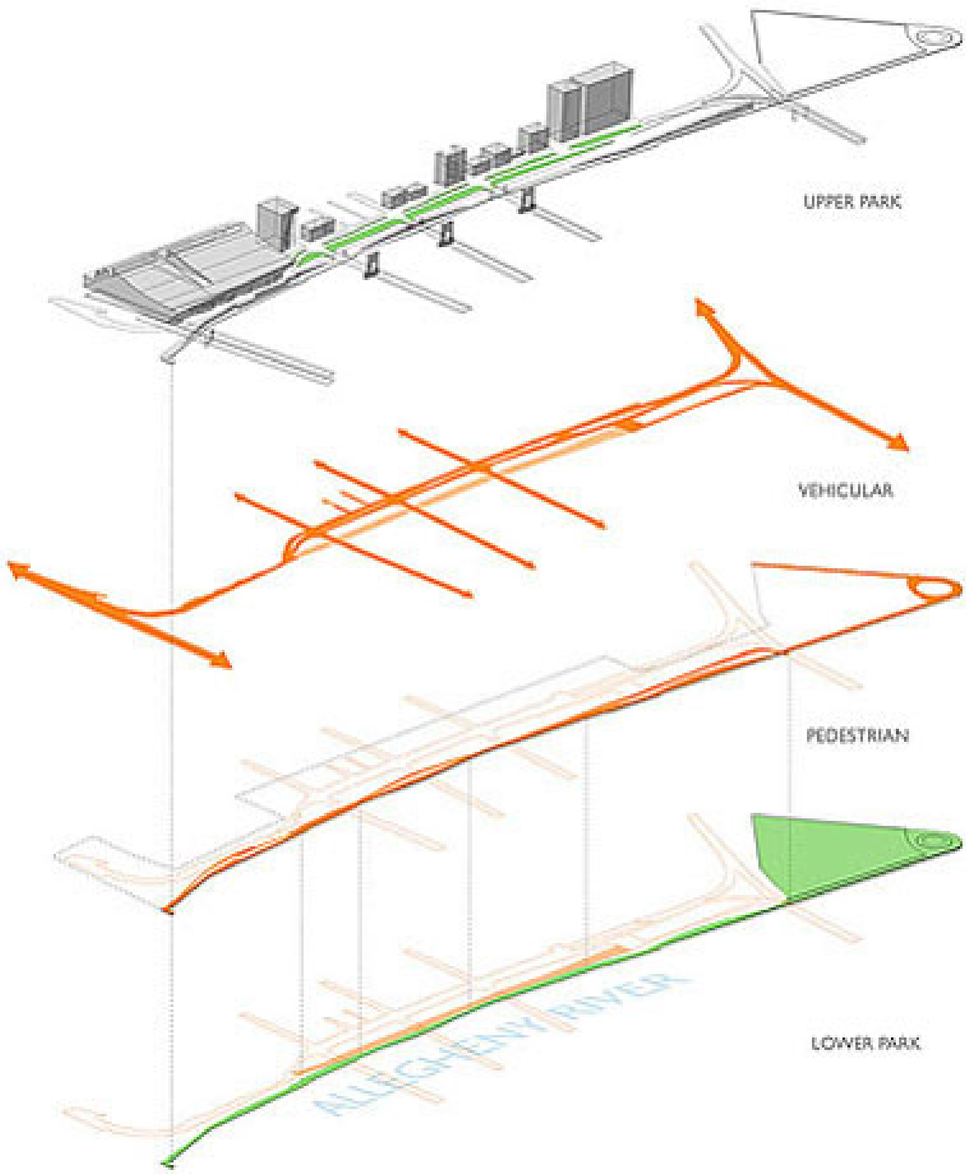

Figure 25. Allegheny Riverfront Circulation and Connection Diagram (Inc.)

The two levels of Allegheny Riverfront Park were connected by two, 350-foot long ramps to address the significant grade change. The upper level functioned as a promenade which visually and physically connects to the city, while the lower level operates with a natural aesthetic, restoring ecological function back to the waterfront

(Figure 26). The ramps linking the two levels together provide ADA-accessible connection while acting as an effective sound barrier for the highway (Hatfield.).

Figure 26. Upper and Lower Levels of Allegheny Riverfront Park (Inc.)

A key decision early in the design process was MVVA's acceptance of the site's conditions, developing with the highway's constraints instead of against them. This resulted in the lower tier's 14-foot pedestrian pathway dramatically weaving between highway and river, in contrast to the upper level's broad, semiformal promenade. The lower tier's cantilevered design allows for curvilinear form, bringing pedestrians out over the waterway (Figure 27) (Hatfield.).

The lower level of the park is subject to the natural conditions of the river, including seasonal floods which raise the Allegheny River between 5-10 feet each spring. MVVA selected plant material based on the river's seasonal water level variance (Hatfield.). River birch and silver maple selections exemplified vegetation which survived in similar "inundation zones", and rejuvenating after being broken or crushed. Boulders were installed along the walkway to limit soil erosion (Trust).

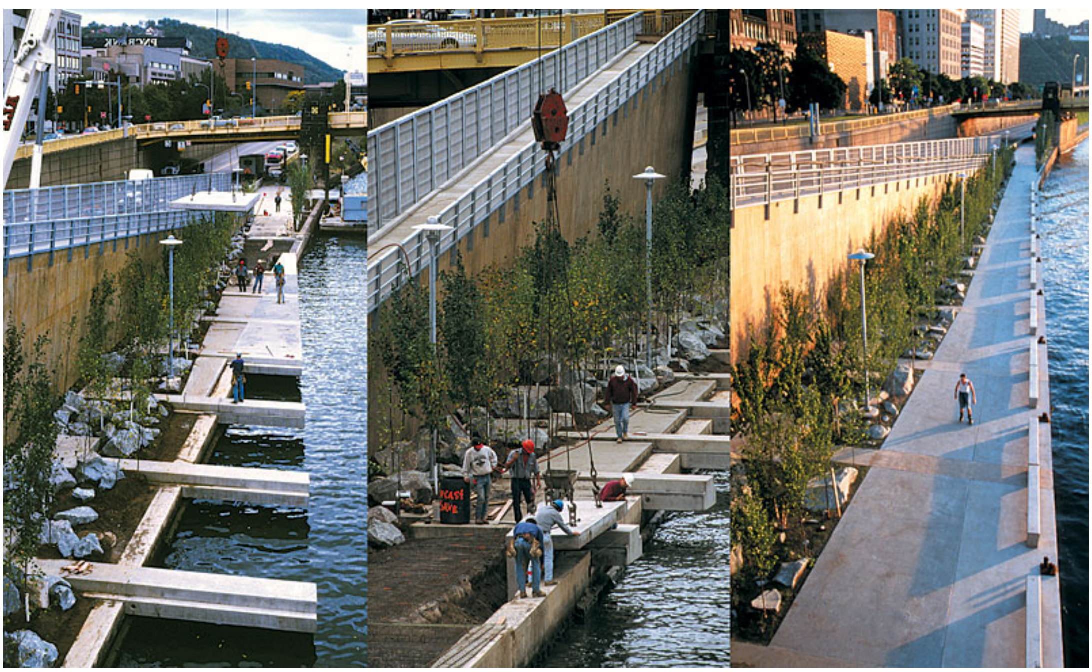

Figure 27. Cantilevered pedestrian walkway (Inc.)

Checklist Analysis

1. **Evolve to Survive**

   Extensive: Replicate Strategies that Work

Integrate the Unexpected

Reshuffle Information

MVVA replicated initial strategies proposed by Olmstead's vision of Pittsburgh's waterfront while uniquely linking the city to riparian public space. The site utilizes its context by implementing design strategies that provide pedestrian access through, around, and under existing infrastructure.

2. **Adapt to Changing Conditions**

   Minimal: Maintain Integrity through Self-Renewal

   Partial: Incorporate Diversity

   Embody Resiliency through Variation, Redundancy, and Decentralization

Evidence of self-renewable properties exists in plant selection for the lower level. The diversity of canopy and vegetative walls act as individual elements while also addressing sound quality along site. Ramps connecting both levels provide sound barriers and safety walls for seasonal flooding.

3. **Be Locally Attuned and Responsive**

   None: Cultivate Cooperative Relationships

   Minimal: Use Readily Available Materials and Energy

   Use Feedback Loops

   Partial: Leverage Cyclic Processes

No examples of the site's utilization of energy processes were found. Materials used during construction were heavily reliant on solid concrete, which forms the volume of the ramps and walkways. Materials locally used included the upper level's promenade paving of bluestone, locally mined from Pennsylvania quarries. Reuse of on-site, industrial coal slag improved soil composition for stabilization and drainage. The entirety of the site was planned for the cyclic process of seasonal riparian inundation.

4. Integrate Development with Growth

None: Self-Organize

Build from the Bottom-Up

Combine Modular and Nested Components

There were no examples found of the park's self-organization to foster new growth. The site's composition, while creating dynamic space, yielded no modular or nested components which acted in collaboration with one another.

5. Be Resource Efficient

None: Use Low-Energy Processes

Minimal: Recycle All Materials

Extensive: Use Multi-Functional Design

Fit Form to Function

Solid-fill concrete applied as a major element to the site's construction showed no utilization of low-energy processes. Sole material reuse strategy found was on-site industrial coal slag, recycled to develop a river soil composition for installed vegetation. The designed product exemplified multifunctional use to the site as an experiential pedestrian corridor which buffered traffic sound, recreated ecological processes along the river, and responded to flooding conditions. Fitting of form to function was also extensively considered, as the site responded to its natural and constructed contexts.

6. **Use Life-Friendly Chemistry**

   None: Break Down Products into Benign Constituents

   Do Chemistry in Water

   Minimal: Build Selectively with a small Subset of Elements

Allegheny River Park's construction showed no evidence of material usage that responded to ecological conditions over time. There were no examples found in design or construction that utilized water as solvent. While concrete played a major component in the park's development, very few additional elements were used outside plant material and bluestone paving.

Conclusion

MVVA's Riverfront Park did meet extensive or partial requirements to 40% of the criteria, but failed to meet minimal requirements for 35%. The project's weighted average score was 1.3, the lowest of case studies focused on in this thesis (Figure 28).

The project was limited in biomimicry applications due to the large amounts of concrete used, constricting the site's modularity due to natural flooding conditions. Minimal recycling processes were considered during construction, which led to high-energy materials selected for the majority of the design. In relation to feedback loops, none were found evident in the natural evolution of site.

Allegheny Riverfront Park did focus, successfully, on designed performance in relationship to seasonal flooding. Comparatively, the ecological function of the site performed a role more impactful than the mainly aesthetic Burke Brise Soleil. While scoring lowest on biomimicry applications, the unique design solution received multiple awards, including the 2002 EDRA/Places Place-Making Award, a 2002 ASLA Design Honor Award, and a 1997 Progressive Architecture Awards Citation (MVVA).

Criteria Analysis

Allegheny Riverfront Park — *Scope of Conditions Met*

	Minimal (1)	Partial (2)	Extensive (3)
Evolve to Survive			
Replicate Strategies that Work			■
Integrate the Unexpected			■
Reshuffle Information			■
Adapt to Changing Conditions			
Incorporate Diversity		■	
Maintain Integrity through Self-Renewal	■		
Embody Resiliency through Variation, Redundancy, and Decentralization		■	
Be Locally Attuned and Responsive			
Leverage Cyclic Processes		■	
Use Readily Available Materials and Energy	■		
Use Feedback Loops	■		
Cultivate Cooperative Relationships			
Integrate Development with Growth			
Self-Organize			
Build from the Bottom-Up			
Combine Modular and Nested Components			
Be Resource Efficient (Material and Energy)			
Use Low-Energy Processes			
Use Multi-Functional Design			■
Recycle All Materials	■		
Fit Form to Function			■
Use Life-Friendly Chemistry			
Break Down Products into Benign Constituents			
Build Selectively with a small Subset of Elements	■		
Do Chemistry in Water			
Weighted Average			**1.3**

Figure 28. Biomimicry Analysis Checklist: Allegheny Riverfront Park (Table by Author)

CHAPTER 5

CONCLUSION: BIOMIMICRY AS DESIGN LENS FOR LANDSCAPE ARCHITECTURE

Biomimicry as Contextual Approach

The analysis of biomimicry applications through case studies revealed each successful design involved a heavily context-dependent design process. The highest scoring case studies utilized comprehensive design strategies to solve challenges unique to each site. This application of biomimicry principles showed varying degrees of success between projects, including designs where biomimicry was not identified. This indicates that that the success of biomimicry in design is not dependent upon its deliberate implementation. Biomimicry has the ability to enhance context-based design strategies in landscape architecture by understanding local, natural processes in relation to site.

Biomimicry as Design Guideline

The highest-scoring designs observed in the case studies committed to a collaborative process between experienced professionals from individual fields. The CH_s building began the development stages of design with workshops engaged in sharing information between experts within separate disciplines. Biomimicry itself is a process that involves multiple variables interacting both independently and collaboratively, and cannot succeed without this unified, holistic approach. Applied design disciplines, including landscape architecture, are unique fields where relationships between multiple professions are central to innovation. Utilizing biomimicry as a design guideline in landscape architecture brings landscape architecture to the forefront of this collaborative process, allowing the profession to orchestrate multiple disciplines with its specific knowledge of each.

Comparative case study analysis revealed criteria groups which shared similar requirements. Successful biomimicry-applied projects showed a 100% correlation between criteria groups within the original biomimicry checklist. Each criterion which showed this correlation were analyzed and grouped into general guidelines for future applications of biomimicry within the landscape architecture profession. These similarities found throughout biomimicry analysis in the built environment were abstracted to form a better understanding of contemporary applications of biomimicry to design.

1. **Innovate Specifically**
   - *Criteria Met:*
     - Replicate Strategies that Work
     - Integrate the Unexpected
     - Reshuffle Information
     - Fit Form to Function

This guideline is the most similar to current successful landscape architecture practices. The biomimicry design lens enhances innovative design strategies by examining natural systems which act in accordance with an environment's context. This allows for site-specific design responses to scale, allowing for unique individual applications to each project. This distinctiveness extends beyond design process, as contextual design incorporates the local identity of site, physically, culturally, socially, and aesthetically. Creation of place-making experiences is supported by strategies which have been implemented historically while focusing on challenges presented on an individual basis. Biomimicry holds an opportunity to design in harmony with nature and its complex systems, rather than against environmental practices which have seen resounding successes over an evolutionary timeline.

2. Decentralize and Unify

- *Criteria Met:*
  - Incorporate Diversity
  - Embody Resiliency through Variation, Redundancy, or Decentralization
  - Combine Modular and Nested Components
  - Use Multi-Functional Design

Decentralized elements have the ability to implement multi-functional design, individually and collectively with other components. Landscape architecture can apply biomimicry principles to develop diverse functions for small elements which work together in a designed landscape. In linking with direct biomimicry principles, this allows for responsive evolution to challenges and growth beyond a project's completed implementation. Smaller, modular elements within design decrease maintenance time and costs due to interchangeability. As in biological systems, this allows for increased performance of site components through their modular and varied characteristics. Uniquely individual elements employed throughout a site can enhance user experience and change to fit evolving site demands.

3. **Close the Loop**

- *Criteria Met:*
  - Leverage Cyclic Processes
  - Self-Organize
  - Use Feedback Loops

Design that evolves is design that lasts. Replicating strategies employed by natural evolution to the built environment can generate solutions impactful for present and future use. Landscape architecture can use this strategy to move away from public resource dependency and towards self-sufficient and sustainable practices. Feedback loops play the role of catalyzing a site's evolution, which allows for post-implementation strategies to increase project resiliency. Energy and food production methods within built systems are prime examples of these strategies implemented in densely urban environments.

4. **Empower Locality**

- *Criteria Met:*
  - Use Readily Available Materials and Energy
  - Recycle All Materials

Materials that are locally sourced and recycled are common in natural systems. Design strategies which minimize the unnecessary expense of energy are extensively applied in nature. Innovative use of local and available resources cuts energy required and costs necessary to realize design. "Material" extends beyond individual design features: it considers social, cultural, and historic resources within a built environment.

It brings regional identity and enhances place-making, affecting economic, cultural, and social environments surrounding a site at the very beginning stages of design.

Future Research

Time and scope for this thesis investigation limited potential scopes of biomimicry that could be further analyzed. This thesis was conducted through the perspective of biomimicry as application to landscape architecture, with design being the primary focus. Other perspectives might include how an economic analysis might relate to the success of biomimicry strategies and applications. Material selections were noted in relationship to source location and environmental impact. What is the current scope of biomimicry applications to performance and form with materials in the built environment? Collaborative measures between professions were a primary focus for project development and conceptualization in the successful biomimicry applications studied. What procedures have been taken to ensure productive collaboration on large-scale projects, and which were most effective in yielding desired results? Finally, the sites analyzed through this thesis were all comparatively similar in scale. How might biomimicry be useful in community, city, or regional design scales?

Conclusion

Evolution is the ultimate iterative selection process. For over 3.8 billion years, biological systems have been designed to maximize their efficient performance in materials, form, structure, and process (Biomimicry Group 2014). They link between sustainability, resiliency, and form resulting in highly responsive design solutions that are aesthetically appealing, effective, and educational. They work as a collaborative, collective process, utilizing knowledge from multiple fields to evolve and survive in specific environments. Their unique and reactive forms perform at multiple scales with other organisms. The implementation of biomimicry itself allows its users a greater education of the immensely unique natural systems with which these structures were designed. These are the important strategies which Biomimicry design can emulate within the built environment.

Biomimicry as design inspiration for landscape architecture has already taken place. It can be seen in ecological design strategies, such as replicating and recreating natural wetland systems in retention ponds. It is prevalent in selecting native plant material to improve soil complexity in vacant urban lots. The importance of biomimicry as a design strategy for landscape architecture lies in its process. The collaboration of multiple fields to develop functional, aesthetically-impactful spaces defines biomimicry as much as it does landscape architecture. Biomimicry applications can expand landscape architecture's role in design to enhance form, function, and processes of design as a primary facilitator in collaborative, sustainable design processes. The importance of biomimicry's role in facilitating innovative design lies in its application. In Michael Palwyn's introductory chapter for *Biomimicry in Architecture*, he states:

> Just as with any design discipline, [biomimicry] will not automatically produce good architecture, and we should be wary of trying to become purely scientific about design. Architecture should always have an emotional dimension – it should touch the spirit, it should be uplifting and it should celebrate the age in which it was created. (Pawlyn 2011)

The potential for Biomimicry as an innovative tool for landscape architectural practice is great. Like all forms of design process, it must be implemented to strategically reach its greatest potential. Utilizing biomimicry principles as a guideline, and not structured doctrine, creates the fluidity needed for successful design application.

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