HIERARCHY OF BIOMIMICRY TECHNIQUES FOR THE BUILT ENVIRONMENT

By

LAURA FINTON

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN BUILDING CONSTRUCTION

UNIVERSITY OF FLORIDA

2010

To Grandma Poo

ACKNOWLEDGMENTS

First and foremost, I would like to thank my parents for their endless love and support throughout my educational career and my life in general. My mom is the most caring and selfless person I have ever met. Whenever I need something, or she just thinks I might, she stops everything to help me. My dad has always provided me with great advice and a kind voice of reason. There are no words to describe how blessed I feel everyday knowing they are by my side.

I would like to thank Dr. Kibert, Dr. Ries, and Dr. Sullivan for sharing their knowledge and providing fundamental guidance for my thesis. It is due to passionate teachers like them and Dr. Lucas that make learning an engaging experience. And a special thanks to Dottie for being all-knowing and always helpful. They helped make the process of completing my thesis enjoyable.

I would like to thank my sister, Kathryn, for making everything fun and for telling me what a good writer I am. Her creativity, positive energy and listening skills are inspiring; I sometimes even catch myself thinking I want to be more like her. I also owe an enormous amount of gratitude to Sergio for always believing in me and for being such a beautiful person. He has helped me in so many ways over the past few years I don’t even know where to begin. His confidence in me is shocking at times and I can only hope to live up to it. I would also like to thank Stella for keeping me so happy with her concerning looks, fluffiness, and general presence. To the rest of my family, and friends old and new, I thank you.

TABLE OF CONTENTS

LIST OF TABLES

Abstract Of Dissertation Presented To The Graduate School
Of The University Of Florida In Partial Fulfillment Of The
Requirements For The Degree Of Master Of Science In Building Construction

HIERARCHY OF BIOMIMICRY TECHNIQUES FOR THE BUILT ENVIRONMENT

By

Laura Finton

December 2010

Chair: Charles J. Kibert
Cochair: Robert Ries
Major: Building Construction

Biomimicry, taken from the Greek words of life and imitation, is a science that seeks inspiration from nature’s designs and processes to solve human problems. Biomimicry is used throughout the design, construction, and engineering industries as a starting point to generate sustainable ideas for the built environment. However, not every technique that gains inspiration from nature is equivalent in their level of adherence to biomimicry, and thus, to sustainable solutions. Identification and implementation of a systematic way to rank techniques based on the level of biomimicry achieved in sustainable construction would clarity what technique is best for the built environment, the natural environment, and human health.

Several factors identify and define what makes biomimetic systems sustainable systems. Gathered from a variety of established ecologically friendly construction methods and principles, and from the definition of biomimicry itself, seven *Biomimicry Factors* are brought together to facilitate in the creation of a hierarchy of techniques for the built environment. This hierarchy determines a ranking of five chosen systems used in the built environment that gain sustainable benefits because of the use of biomimicry techniques within their framework. Application of an Analytic Hierarchy Process is used

for ranking the biomimetic construction techniques and the factors are weighted to strengthen the reliability of such a working model. The *Biomimicry Factors* are given weights according to their importance for creating a healthy and environmentally supportive system. This model can be adopted, under a variety of preferences, for determining the most suitable and sustainable option from different construction techniques inspired by nature.

CHAPTER 1
INTRODUCTION

> The system of nature, of which man is a part, tends to be self-balancing, self-adjusting, self-cleansing.
>
> --E.F. Schumacher, *Small is Beautiful*

Biomimicry, a term derived from the Greek words of life and imitation, is a science that seeks solutions to human problems by mimicking nature's designs and processes. As it relates to the environmentally unfriendly built environment, biomimicry draws on methods and techniques found in natural systems to suggest sustainable solutions. In its application, the focus is on what we can learn from nature, as opposed to recent focuses that have been on what we can extract from it.

Nature has learned through evolutionary processes efficient ways to accomplish a variety of tasks, many of which are applicable to society's needs. The use of ecological means adds new value to our sustainable alternatives and offers new possibilities as well. Many complex and efficient systems have risen from several billion years of evolution. This accumulation of knowledge, if applied to the design of human ecosystems, could provide excellent ways to merge it with nature.

Problem Statement

Researchers and environmentalists have been developing new ways of creating a more sustainable built environment in recent years. Much attention has been paid to structured certification programs such as the United States Green Building Council's Leadership in Energy and Environmental Design (USGBC's LEED) and Green Globes. Depending on credits selected, certification programs may require a reduction in the demand for unrenewable resources and frown upon the use of harmful chemicals, among others. These kinds of constraints are undoubtedly a step in the right direction.

However, they leave little room for flexibility or input from project participants and do not strive to add to the knowledge base of natural design approaches. Regionally specific construction techniques and remediation of pitfalls in materials application are just a few things that biomimicry can add to the table.

The popularity and knowledge of using nature as a design tool has grown. Recognizable companies using this concept include Autodesk- with their sponsorship of asknature.com, large architecture firms such as HOK, and the consultancy group Biomimicry Guild- who offered their assistance with this thesis. With more industries realizing its potential and profitability, the sustainable message must not be forgotten. Sustainable problems associated with construction are all very much interconnected, it is important to let people know how to solve their problems sustainably instead of just throwing attractive technologies at them. Janine Benyus, cofounder of Biomimicry Guild, suggested that the process of solving sustainable problems is very important, and thus, identifying a system for the process is equally as important (Stroud 2009).

Making decisions for choosing the best type of construction method can be a daunting task considering all the possible options, not to mention factoring health and nature friendliness into the equation. A way to assess and rank the sustainable construction options based on what is fundamental for the owner, project participates, and future occupants would help to meet their basic objectives while satisfying what is required to keep our environments healthy. A comprehensive and systematic method to complete the task of ranking different levels of biomimicry achieved in sustainable construction has not been developed. Identifying what makes biomimicry sustainable is crucial, so that these solutions can be readily integrated into our options for construction.

Hypothesis

Many methodologies, such as industrial ecology, cradle to cradle, and factor 4, are helping us realize and approach our sustainable goal. Review and understanding of these principles, along with what defines natural systems, is crucial to the development of a solution. A setback with achieving sustainability through biomimicry is the undefined aspects of biomimetic construction as it relates to the benefits for our health and environments.

Upon hearing the term biomimicry, one might automatically presume it is sustainable, a healthier alternative than a conventional technique, or less harmful for the natural environment. Just by copying a natural technique does not necessarily make the construction technique any more natural. Take Velcro for example, it is inspired by burrs (seeds) of burdock plants, but uses synthetic materials for manufacturing and ultimately ends up in a landfill.

It is established that biomimetic techniques are beneficial in more ways than one. However, the level which these techniques support the environment, human health, and even the builder, designer, or owner, is comparatively unaccounted for. A solution to this problem may lie in identifying common ideas of the above principles, along with many others used in the industry, to better understand the reaches of such construction methods. Thus, the hypothesis of this thesis is a reproducible method for identifying the levels of biomimicry achieved in sustainable construction would clarify what technique is best for the built environment, the natural environment, and human health.

Objective

The main objective of this thesis is to identify and implement a systematic way of ranking biomimicry for sustainable construction. Reaching this objective will clarify the misconceptions that arise with the perceived benefits associated with biomimicry, assist the decision process by creating a dependable decision-making tool, and account for the variables that affect what makes a “best” construction technique. The approach for reaching this objective and subsequent goals is outlined below and presented in greater detail throughout this thesis.

Approach

Assessments of leading principles and methods are presented in Chapter 2, to establish key elements and common threads to help define sustainable construction. The course of this review will ultimately suggest a set of factors which comprise important qualities for ecological design. These factors are brought together in Chapter 3 to clarify what is attributable to a biomimetic technique. Definition of these factors facilitates the analysis of five biomimetic case studies. The case studies are rated for how well they adhere to biomimetic and sustainable construction by using the factors as categories for rating. The case studies are presented in Chapter 5 along with their ratings and the reasons these specific cases were chosen to complete a hierarchy for the purpose of this thesis.

This information is then applied in an Analytic Hierarchy Process (AHP) to determine the level of biomimicry achieved in each case study. The AHP process is described further in the Methodology Chapter including descriptions of the scales used for ranking and the preferences applied to create a hierarchy. Preferences relating to the factors are needed for final weighing of the options. Two sets of preferences were acquired allowing for comparison of the final results in the Conclusions chapter. One set is reached through processes described throughout this thesis and the other was obtained by surveying the Biomimicry Guild.

CHAPTER 2
ASSESSMENT OF SUSTAINABLE PRINCIPLES AND METHODS

Purpose

Along with the theories that shape biomimicry, other established principles and methods are needed to develop a comprehensive understanding of how our built environment can function in harmony with the natural environment. An analysis of current sustainable construction ideologies is needed to produce guidelines that will be used in a consistent method for ranking levels of biomimicry in construction techniques. Assessments of the main concepts behind successfully implemented principles and methods are presented below.

The result of this assessment is to synthesize defining factors of what is most valued for biomimetic sustainable construction. The resulting factors are identified and discussed in detail in the next chapter. An extensive look at what benefits they offer the natural environment and the design, construction, and engineering industries is reviewed as well.

Biomimicry

The idea of biomimicry, or using nature as a mentor, has been in existence since the beginning of man. Not until recently has this proven method of solving problems coined this term. The underlying approach, however, has appeared repeatedly throughout the years. An early known example includes the studying of birds by Leonardo da Vinci and the Wright brothers to gain insight on how to create a “flying machine”. In 1960, Dr. Jack Steele called the fundamentally same principle bionics, which was originally defined as “the analysis of the ways in which living systems actually work and having discovered nature's tricks, embodying them in hardware" (Lodato 2001).

Biomimicry has caught the attention of a growing audience since a biologist by the name of Janine Benyus came onto the sustainable scene with her book, *Biomimicry: Innovation Inspired by Nature.* Her background in forestry, coupled with strengths in botany, soils, water, wildlife, and tree growth, led her to become fascinated in the relationships and adaptations of organisms. In *Biomimicry* (1997), she discusses that "Despite the fact we face the same physical challenges that all living beings face--the struggle for food, water, space, and shelter in a finite habitat—we were trying to meet those challenges through human cleverness alone". Suggesting that many aspects of our natural world remain unknown and separate from our lives, we should work to uncover these techniques, teach them, and use them in our own lives.

Benyus vividly depicts a world in which nature is used as a model, a measure, and a mentor for the design of human systems. In her book, she outlines steps to a biomimetic future:

1. Quieting: Immerse ourselves in nature.
2. Listening: Interview the flora and fauna of our own planet.
3. Echoing: Encourage biologists and engineers to collaborate, using nature as model and measure.
4. Stewarding: Preserve life's diversity and genius.

Within step 3, Benyus lists ten questions that will be answered yes if our new solutions promote life. They stem from, "Will it fit in?", "Will it last?", and "Is there a precedent for this in nature?".

Benyus discusses winning strategies developed through natural selection that are used by all complex, mature ecosystems. She calls these strategies the ten commandments of the redwood clan:

- Use waste as a resource
- Diversify and cooperate to fully use the habitat
- Gather and use energy efficiently
- Optimize rather than maximize
- Use materials sparingly
- Don’t foul their nests
- Don’t draw down resources
- Remain in balance with the biosphere
- Run on information
- Shop locally

By emulating these strategies in our economy, since it is a complex system as well, we could create conditions conducive to life. Applying these biomimicry lessons in construction related industries could perhaps allow for us to correct our unhealthy practices and to continue expanding our built environment without affecting the future of the natural environment.

Biophilic Design

Edward O. Wilson, Pulitzer Prize winner and biologist at Harvard University, was one of the first originators of the biophilia concept. His work draws on the studies of comfort and physiological responses, human evolutionary biology, and environmental psychology (Browning 2000). It is most commonly described as “our biologically based affinity for natural setting (Kellert, Heerwagen & Mador 2008). Biophilic design promotes sustainable design while suggesting a more creative outlook. As Kellert et al (2008) suggests, biophilic design is not only about conserving energy, but producing human energy as well. This area of design narrows in on what can be done to be sustainable and increase human productivity and creativity of the buildings occupants.

Six specific elements that designers and developers can incorporate to achieve biophilic design in the built environment are defined by Kellert et al (2008) as:

1. Environmental features
2. Natural shapes and forms
3. Natural patterns and processes
4. Lights and space
5. Place-based relationships
6. Evolved human-nature relationships

These elements stem from the two basic dimensions of biophilic design. The first being organic or naturalistic, defined as shapes and forms in the built environment that directly, indirectly, or symbolically reflect the inherent human affinity for nature. The second dimension being place-based or vernacular dimension, defined as buildings and landscapes that connect to the culture and ecology of a locality or geographic area.

Cradle to Cradle

McDonough and Braungart (2002) coined the concept *cradle to cradle*, which suggests these five steps for products and systems to move towards eco-effectiveness:

- Step 1: Get "free of" known culprits. Move away from using substances that are known to be bioaccumulative, such as PVC, cadmium, lead, and mercury.

- Step 2: Follow informed personal preferences. Make informed decisions and choose the option that is least harmful to human and environmental health.

- Step 3: Creating a "passive positive" list. This includes the X list of substances that are most problematic, the gray list of substances that are not quite so urgently in need of phasing out, and the P list of substances that are healthy and safe for use.

- Step 4: Activate the positive list. Redesign products from beginning to end with eco-effective principles in mind by using substances on the P list.

- Step 5: Reinvent. Designing products with the idea of them generating positive effects for other systems for further use.

Following nature's model of eco-effectiveness means separating the materials we use in our society into biological substances, which can be decomposed by the natural ecosystem, and technical substances, which can be deconstructed and reused by the manufacturer or in other products.

The last step to eco-effectiveness suggests creating systems that help one another towards the common goal of sustainability instead of just creating systems that are less harmful for the environment. Natural systems produce waste that actually improves the environment. If systems in the built environment worked in this fashion, then one's waste will become another's fuel.

Natural Capital

Natural capitalism is the stock of goods and services made possible by natural ecosystems and natural processes such as the cycling of nutrients and water, regulation of atmosphere and climate, pollination and the maintenance of biodiversity, control of pests and diseases, and the assimilation and detoxification of society's wastes (Lovins 2001). These services, provided to us at free of cost, allow our global economy to prosper. The value that their services provide is unmatched by any man made contribution. The notion of natural capitalism that natural systems are unequaled by human inventions, is shared by the driving force behind biomimicry.

Hawken, A. Lovins, & L. H. Lovins (1999) outlines the four principles of natural capitalism as follows:

- The first principle of natural capitalism is to solve the environmental dilemmas in the world today by increasing resource efficiency.
- The second principle actually stems from biomimicry, driving industrial innovation with the design lessons of nature to eliminate the concept of waste.
- The third principle is closing material loops by shifting the focus of the economy from the processing of materials to resource productivity.
- The last principle is investing in natural capital to reverse the destruction of the earth's natural systems.

Industrial Ecology

Industrial ecology is defined by Graedel and Allenby (2003) as

> Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain sustainability, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete products, and to ultimate disposal. Factors to be optimized include resources, energy, and capital. (p. 18)

The application of industrial ecology largely focuses on making the material and energy flows sustainable. It proposes modeling our systems after natural ones for the purpose of achieving a closed loop system that reduces waste while adding inputs.

As it relates to industrial ecology, Kay (2002) depicts four principles for design of production-consumption systems:

- Interfacing**:** The interface between societal and natural ecosystems reflects the limited ability of natural ecosystems to provide energy and absorb waste before their survival potential is significantly altered and the fact that the survival potential of natural ecosystems must be maintained. This is referred to as the problem of interfacing.

- Bionics: The behavior and structure of large-scale societal systems should be as similar as possible to those exhibited by natural ecosystems. This is referred to, after Papanek, as the principle of bionics. (In the industrial ecology literature it is often referred to as mimicry.)

- Appropriate biotechnology: Whenever feasible, the function of a component of a societal system should be carried out by subsystem of the natural biosphere. This is referred to as using appropriate biotechnology.

- Non-renewable resources: Non-renewable resources are used only as capital expenditures to bring renewable resources on line.

Kay’s interpretation of bionics for industrial ecology is profound in recognizing the benefits in extracting the “learning” aspect from nature, which is “embedded in the structure and behavior of natural systems”. He goes on to express how careless it would be to disregard the teachings of several billion years of evolution.

Natural Step

Karl Henrik Robert, a Swedish oncologist who developed *The Natural Step*, recognized the detrimental effects of materials on human health and set out to form a framework for considering these effects (Kibert 2008). A panel of leading international scientists then collaborated and established the root causes of society being unsustainable. They named this set of principles of sustainability The Four System Conditions. According to the natural step, four basic conditions need to be met in order to maintain the essential natural resources, structures, and functions that sustain human society and human action is the primary cause of the rapid change we see in nature today (Natural Step n.d.). In a sustainable society, nature is not subject to systematically increasing:

- Concentration of substances extracted from the earth’s crust
- Concentrations of substances produced by society
- Degradation by physical means
- And, in that society, people are not subject to conditions that systemically undermine their capacity to meet their needs

Kibert (2008) summarizes the message of the natural step as “reduce resource extraction, increase reuse and recycling, and minimize emissions that affect both ecosystems and human systems”. Using biomimicry techniques and designing systems for our built environment that mimic natural systems, will concurrently set our society up for following the Natural Step principles, and thus, reach a sustainable future.

Factor 4 and Factor 10

First developed by Weizsacker, A. Lovens & L. Lovins (1997), the book, *Factor Four: Doubling Wealth, Halving Resource Use*, suggests that for humanity to live sustainable today, we must rapidly reduce resource consumption to one-quarter of its current levels. The abilities exist in today's industry to accomplish such reductions in resource consumption by simply requiring public policy prioritization and implementation (Kibert 2008). Another concept which could have even more promising, long term effects on the built environment is Factor 10, which suggests a tenfold reduction in resource consumption.

Lean Construction

Lean Construction is a production management based approach to provide methods and tools for sustainable construction (Huovila & Koskela 1998). It provides the means to communicate revolutionary, sustainable ideals in manufacturing design, supply, and assembly. The ultimate goals are an extension from a lean production system, which is to maximize value and minimize waste, by applying them throughout the project delivery process. A give and pull usually exists within the industry between time, cost, and quality; but lean construction sets out to challenge this belief.

Lapinski, Horman, and Riley (2006) identify the value and waste on a LEED certified project in their report, *Lean Processes for Sustainable Project Delivery*. The purpose of their study was to provide a clear breakdown of the activities that contribute to sustainable objectives during project delivery. This study gave insights about how to successfully deliver sustainable facilities through adopting project delivery methods that are not laden with process waste.

Lean construction principles have been proven to reduce waste and improve process performance in many highly complex development and production environments. Lean construction is a continuous and adaptive method for improving what we build and how we build it (MSU 2006). A sustainable built environment will not develop overnight nor will it prosper with using the same management principles that have been employed in the past. New and more efficient ways of managing eco-friendly projects needs to be developed and that is where lean construction comes into play.

One principle of lean that shares common elements with biomimicry and thus, the natural environment is, “Whole system optimization through collaboration and systematic learning” (Abdelhamid 2007). This calls for all project participants and project systems to ultimately work together in order to attain the benefits that come from a high level of connectedness. Another aspect of lean construction that biomimetic construction techniques employ as well is that it places emphasizes on material processes (Huovila & Koskela 1998).

CHAPTER 3
FACTORS FOR DEFINING A BIOMIMETIC SYSTEM

The starting point to create a method for ranking biomimetic construction is assessment of the ecological aspects found within the principles and methods discussed in Chapter 2. From these templates, overlapping aspects and fundamental concepts driving sustainability can be identified, extracted, and synthesized. Many of these aspects are applicable to help define biomimicry as well, but some of the leading forces behind this concept suggest the importance of additional factors specific to its definition. Regrouping of recognized successful factors borrowed from the wide range of methods evaluated, allows for better understanding of what is most defining of biomimetic construction. The factors synthesized from the previous assessments are:

- Energy for Construction
- Energy for Operation and Maintenance
- Chemical Makeup
- Interdependence
- Deconstruction
- Function
- Physical Properties

These seven factors are of critical importance for rating the five case studies based on their adherence to biomimetic construction.

The factors are separated into three categories for the purpose of assigning preferences to each one based off of what benefits they offer our built environment. Although each is crucial to the development of a hierarchy, some factors show greater potential for allowing techniques to attain a higher level of biomimicry. In conclusion for this chapter, each category will be expanded to include the associated intensity of preference and the reasoning behind it. But first, identified below is the principle or method for sustainable construction each factor was derived from. Followed by a comprehensive analysis of what each factor exemplifies and guidelines the techniques should adhere to in order to be rated higher for that factor.

Synthesis for Sustainable Biomimetic Factors

The need for renewable energy sources is a dominant familiarity found throughout all reaches of society. Encompassing almost every aspect of our lives, ways in which we can use and harvest energy without affecting the ability to do so in the future is touched on in almost every method. The ultimate goal is similar and largely independent of the proposed tactic. From stringent quantitative analysis as suggested by Factor 4 and Factor 10, to simply reducing wastes by implementing Lean Construction, reducing environmental degradation by lessoning our use of nonrenewable energy led to the importance of including Energy for Construction and Energy for Operation and Maintenance factors.

The category of factors that allows for our systems to be seamlessly integrated into processes developed by natural systems is called Natural Harmony factors. As set forth in Cradle to Cradle, it is imperative to move away from using materials that are known to be bio accumulative and to separate substances that can be decomposed or deconstructed for further use. The Chemical Makeup and Deconstruction factors are shaped from aspects such as this as well as from the principles of the Natural Step. The Interdependence factor is influenced by Cradle to Cradle as well. In the last step to eco-effectiveness, it expresses that systems should help on another towards the common goal of sustainability. Lean Construction adds to this factor by emphasizing whole system optimization through collaboration and a high level of connectedness. By adhering to these factors, natural harmony will be restored through improving systems together and using what they create as potential for future systems.

Taken from the science of Biomimicry and Biophilic Design, adopting the factors of Physical Properties and Function allow for human invention to behave in similar manners as the natural system. Since the inspiration is nature and nature produces little inefficiencies, implementing these attributes for construction methods that share a similar purpose help them become efficient as well. Industrial Ecology defines four principles, one of which is the principle of bionics, or making the behavior and structure of our systems as similar as possible to those exhibited by natural systems. This shows the attributes associated with mimicking nature, such as physical properties and function, are important in other sustainable principles as well. These factors are called character specific, in the sense they adhere to exclusive qualities pertaining to the natural system being imitated.

Sustainable Energy Factors

Energy for Construction

Energy for Construction measures the amount and source of energy required from raw material extraction to the end of the construction process. The following outlines what this definition encompasses and how biomimetic techniques are evaluated for this factor. Methods for decreasing energy use and considering alternative sources throughout the construction process are also described.

There are countless numbers of energy intensive activities often used for the construction of our built environment. The activities relating to construction are comprised of raw material extraction, transportation, manufacturing, assembly, and final installation or construction. Some materials, more than others, require significant energy expenditures for their extraction. The embodied energy of transportation is often times easily reduced. Local material extraction decreases transportation required to deliver those materials to manufacturing. Also, routes that use the least fuel are preferred along with choosing the most efficient mode of transportation in terms of emissions. A construction technique that employs the mentioned methods, among others, will help reduce the energy required for construction and score higher for this factor.

Manufacturing and assembly of materials are processes that cover a broad range of activities and thus, widely differ on energy expenditures from case to case. Different processes may use methods that have a small amount of related emissions to large emission rates, such as with the production of concrete. The materials used in the construction of the biomimetic techniques play a large role in the energy needed for their construction. Material choices that have less embodied energy associated to their production will help them score a higher rating.

The actual construction or assembly process of the techniques depends on a variety of means used to carry out the procedures. Heavy equipment, transportation to the site, and land clearing are among the components which make this stage energy intensive. Nature uses what is easily accessible and efficient for its creations. Construction associated activities for the biomimetic technique that use a renewable source of energy or shows a reduction of energy used as compared to a conventional method will allow for it to attain a higher rating for this factor.

Energy for Operation and Maintenance

Energy for Operation and Maintenance is defined as the amount and source of energy required for operation and maintenance of the system. This factor is independent from the factor of Energy for Construction since the operation and maintenance of a biomimetic technique is often unrelated to the energy use and source needed for its construction. The activities pertaining to both of the factors related to energy have a large impact on our environment and should therefore, for the purpose of this thesis, be considered separately.

Construction of our built environment currently uses numerous energy intensive activities that degrade the health of both our society and the natural environment. But the act of constructing and the processes involved to achieve it are not necessarily even half of the battle. Once a building or even a source of renewable energy is constructed, differing amounts of energy may need to be poured into it throughout its life for operation and maintenance. True biomimetic systems and those found in nature solely rely on sources such as the sun, wind, and other systems to help maintain their function. The biomimetic case studies evaluated will be given higher ratings for this factor if they implement renewable sources for operation and maintenance or implement methods for reducing their dependence on nonrenewable energy.

Natural Harmony Factors

Chemical Makeup

The factor of Chemical Makeup is defined by how closely the chemicals used in the systems composition match the chemical make up in the natural system or if they are not harmful to humans and the natural environment. The materials that comprise biomimetic construction should not contain synthetic chemicals such as the toxins the construction industry has for so long been destructively using. The following describes why chemical usage in construction is unhealthy for both our society and the natural environment and how suitable alternatives can be accomplished through biomimicry.

Not too long ago, everything we used was manufactured directly from nature. Slowly but surely we have learned how to alter these natural materials into something very unnatural. By means of heat, ungodly strength, and a variety of different treatments, human intervention with the purest and friendliest of materials have created a monster- synthetic chemicals. At the root of this evil lie the original problems.

The resent obstacles we have encountered as a growing species have led to unnatural creations, such as chemicals, to help find a resolution to the problems. The chemical industry felt a surge in the 1940's and this increasing influx resulted in the use of synthetic chemical products throughout the commercial industry, domestic sectors, and the natural environment as well. These developments have allowed us to jump over bigger and better hurdles, but they are causing problems of their own. Even though these techniques are still being heavily employed today and have been a favorite in the past, we cannot keep up this toxic behavior and their popularity is decreasing due to education.

Wide-ranging environmental problems and health concerns are the resulting effects of our heavy use of synthetic chemicals. Our global economy is based a great deal upon the use of synthetics whose ecological impact and negative health effects are not yet clearly understood or fully realized. Such a toxic economy cannot limit its reaches to that which does not have ramifications to our ecology. The earths systems are regulated by the climate and our atmosphere in ways we can only attempt to understand, disrupting these natural systems with synthetic chemicals is bound to do unthinkable damage with long term use.

The onset of chemical usage for manufacturing has created problems, problems in which we can declare null and void by simplifying our materials and their processes. The technologies, the designers, and the models exist to redesign our society within natural limits, but we must also be willing to make a global effort to rethink our lives. The possible environmental impacts and the detrimental stresses faced by humans from the use of unnatural processes and chemicals calls for a new outlook when designing and building using certain materials. Natural substitutes can be found and currently exist in nature for replacing toxic building materials, industrial materials, and systems.

Nature identifies problems and solves them in chemical-free ways that we can only envy. Complex materials in a rainbow of functions have been crafted long before we conjured up synthetic chemicals. Attributes associated with the built environment such as strength, flexibility, and durability, along with many others, are already in chemical free existence, waiting to be discovered and utilized. Uncovering natural methods of construction, in terms of its chemical make-up, help define a biomimetic solution.

A biomimetic construction technique that uses little to no harmful chemicals during its manufacturing process and utilizes nature friendly materials in its production, shows a closer relationship with a true biomimicry inspired technique. Thus, a technique that integrates these properties will be rated higher according to the chemical factor. The creation of a construction technique which had been generated due to the influence of a natural method, but does not adhere to the use of limited synthetic chemicals, will be scored lower in this category.

Interdependence

Interdependence exists when a system has a reciprocating relationship with an outside system or plays a role in the support or facilitation of another's survival. Varying degrees of beneficial relationships are found throughout nature and biomimetic construction can exhibit similar relationships as well. The details illustrated below describe how interdependence functions to support the natural world and how it can be applied for the built environment's advantage.

Natural systems work together and readily depend on each other to function efficiently and effectively; much the same way that humans depend on each other and natural systems as well, for survival and happiness. If one system diverts from the natural plan that mother earth has so carefully devised and begins to unfairly outweigh another system, both systems could be on a path to destruction. This is the case with what our culture has done by building unsustainably. Nature has a refined balance and stabilization that is ingrained to her. This equilibrium is effective and achieved by obeying natural laws governing interaction such as interdependence of systems.

In the beginning of the 20th century, John Muir observed, “When we try to pick out anything by itself, we find it hitched to everything else in the Universe.” This quote touches on the fact that there is a place for every living organism in the universe and their errands are essential for the growth and livelihood of everything that is in it. This interconnectivity is vital in the natural world. When the cooperation and give and pull of systems allow them to work together effectively, a place opens up for all new systems and products of life to develop and become simultaneously stronger, as well as individually more secure. There are niches for species to hold within our biosphere that keeps everything running smoothly. This coexistence is imperative and the lesson needs to be more readily implemented in our built environment, with more symbiotic cooperation and less competition with nature.

However, the human species has been developing increasingly more niches for competition that is driving us into turmoil. Partnerships must be implemented more regularly into our society and with our built environment in particular, if we are to have continued success and developments for generations to come. In 1993, the

International Union of Architects and the American Institute of Architects wrote in their Declaration of Interdependence for a Sustainable Future, “Sustainability, in the context of this interdependence, requires partnership, equity, and balance among all parties”. If there is any doubt in this theory, look at nature and its biological interactions. Millions of symbiotic relationships exist in which associations occur from an organism living inside or on another. The relationship is not only beneficial for both, but also essential for the survival of the organism.

Picture the human body as an ecosystem, not unlike the earth. In actuality, it has a lot in common. If something goes astray, for instance, bacteria multiplying rapidly or a limited supply of oxygen entering the system, the stability that is preferred for efficiency and overall health is thrown off balance. As the body tries to counteract these disruptive occurrences it activates or inactivates other systems. Without the help of good bacteria or the ability of your heart to slow down, preserving your body in a healthy and happy state would be impossible. Every network functions in this way; there is a balance that must be preserved. We as humans cannot put ourselves and what we create, including the built environment, above this truth.

Many question whether the ecosystem would improve without the presence of humans. But could it possibly even survive without the Black Spruce or blue-green algae? It should be a goal then, to make our systems in our built environment depend on each other like the systems of our ecosystem. If collaboration and cooperation has worked so effectively for mother earth all these years, then we can make it work in our aspirations as well. In the way the construction industry has been battling against nature, it is as if our ecosystem has been doing us harm over the past few centuries. It is time now to organize partnerships and for the two to work with each other. Systems operating on mutually exclusive terms will not guarantee a win for any player in the game of life. Interdependence hitches the universe together and keeps everything at equilibrium. Competition between companies improves quality, but competing with mother earth reveals no winners.

In order to have interdependence, the construction industry has to look for ways to share what is created or what is not needed. With these unselfish actions, waste can become another system's fuel. The next needy system in line can prosper; and in turn, fill a much-needed niche in our man-made ecosystem. That way we grow stronger as a whole, become more efficient in the long run, and help solve this problem that our unsustainable environment has created.

Some professionals in the construction industry and many building owners simply focus on the fact that the interdependence of networks and systems complicates a building's operation and affects its performance (Hart 2008). But naturally occurring networks in the most efficient of organisms, including humans, are complicated and do not function alone. That is what makes these systems so beautiful and inspiring in their development.

By creating a system within the built environment that cherishes this natural feat of interdependence and helps balance all things, living or not, will facilitate the sustainable movement. A biomimetic technique that pursues a symbiotic relationship with outside systems will earn a higher rating for the interdependence factor than a self-contained technique. A greater number beneficial alliances that exist between systems will also positively affect the score in this category.

Deconstruction

Deconstruction specifies how the system can be disassembled and reused when taken out of commission. Nature exhibits the ultimate deconstruction and closed loop material processes through reuse and decomposition. If biomimetic construction techniques incorporate some of the key elements of deconstruction described below, our built environment would likely become much more integrated and compatible with mother earth.

Deconstruction is a key element for helping preserve natural resources and saving energy for future construction processes. How we deconstruct and reuse materials in the built environment can be thought of as the artificial way to decompose. Mimicking decomposition, as in natural systems, allows for the built environment to turn full circle and become a key functional force for pumping new life back into the industry. One of nature's basic concepts is to minimize the amount of energy consumed over time. Deconstructing allows for resources to be "harvested" locally, instead of at the original source such as in mines and forests, which are many times located far away and results in an energy laden process. Nature makes the most out of what is available to her in the most efficient way possible.

The opportunists in nature, such as weeds, concentrate on growth and throughput (Benyus 1997). In other words, how fast raw materials can be turned into products. This is a suitable method of living for the opportunistic species in *nature* since there is plentiful and renewable supply of the raw materials they need, such as soil and nutrients, and other species are then able to feed off them. The response to this method of survival is decay and repair which is an endless cycle that keeps the natural community stable. However, for the opportunistic species that we have made ourselves become, there is no such built-in cycle. It is up to us to resemble the natural process of decomposition in our built environment and help close the loops.

Nothing in nature is wasted. Instead, these communities are self-contained. They do not look towards environments outside of its own reaches to help sustain itself. By circulating everything that is needed within its habitat, biological communities run smoothly and precious resources are not lost.

Devising plans for the deconstruction of systems in the design phase, before the system is even constructed, will help our built environment become self-renewing. Biomimetic systems that have deconstruction in mind are equipping us to help live more sustainably. Differing types and amounts of deconstruction take place within all kinds of systems; with higher rates of recyclability and reuse being more profitable and desired. Separating the built environment from the linear model which comprises the extraction of raw materials and dumping of used materials in landfills, will allow less waste to be lost from a system which can operate so well on recycled, reused, and refurbished materials.

Good design of a biomimicry inspired system incorporates deconstruction in its framework and lays the foundation for new systems to come. If we can think of the waste that is produced from the construction industry as a potential commodity, instead of an unusable product, then the concept of waste will disappear and thought will be given into how we can reuse building materials, instead of just dumping reusable building materials. The alternative to the biomimetic approach of decomposition via deconstruction would look increasingly towards spending copious amounts of energy getting rid of future materials, which does not make sense any way you look at it and is entirely unsustainable. Incorporating and realizing a deconstructable or decomposable future for the inspired system will allow it to attain a higher score for this factor as compared to a system whose future lies in a landfill.

Character Specific Factors

Function

The factor of Function identifies how close the relationship is between the biomimetic system's function in the built environment and the observed function of the natural system. Adopting the way a natural system operates within our biosphere to supply a similar role for a purpose in construction, supports healthier alternatives than the ways some current construction techniques are cleverly forced to function. The following describes what benefits arise from mimicking the way nature functions.

When a developing design or a current technique used in the built environment is able to become sustainable by adapting similar qualities from a natural technique that has addressed similar conditions, the resulting biomimetic system will serve a similar function of that which is observed. According to American architect Louis Sullivan, "Form ever follows function". If we are to design by this principle, the shape of our buildings and systems should be dictated and formed around their intended function or purpose.

Evolution has allowed for the form of its organisms to be the most perfect at what they are intended to do. With biomimicry, we are copying nature's form in our construction techniques in hopes of it resulting in a similar function, but as it relates to the built environment instead. A construction technique can also reap the benefits or be the result of the adaptation of a natural systems form that has an unlike function or purpose. Although the resulting technique is inspired by biomimicry, it takes on a whole new interpretation of the original purpose and reason that the natural strategy was intended for.

Designs in nature are often times versatile. Solutions for the built environment can be developed from specific features of a natural design to help solve an entirely different problem than the original model is solving. Like modeling a car after a box fish. Its shape is suitable for transporting passengers and somewhat efficient in wind tunnel tests, but the purpose of this fishes shape is more for defense purposes. If similar design techniques are employed, but a different purpose other than the one originally observed is obtained, then it is used for other reasons than mother earth intended.

The effectiveness of our copied form might not be the best if serving a different function than the inspiration because it is not what nature intended it for. The further away the systems adopted form is from providing a function that it was originally intended to, the closer another form probably is at offering up better and more efficient solutions. A different function we need to obtain may be what other forms are already accomplishing. Thus, more research and investigation should be done to seek out other natural methods for providing the services needed.

Nature, through evolution, recreates what works best and what has proven to be the most efficient. The form that functions the best wins out; and ones that do not work simply die out. However, in the beginning of this trial and error type of operation, many forms are tested. This is possible because of the natural variations in organisms, since no two creations are entirely identical. With the understanding that the better functioning organism is carrying the better form, the likelihood of its successful shape being formed again is increased and the weaker forms dwindle and eventually fade away.

The mutations that are created in nature have to define their own function in hopes of it being key to their survival. Their functions are forced to develop because of the form it is given. So as evolution is concerned, function follows form. A giraffe does not have a long neck because it eats leaves; just as humans did not develop thumbs so they could hold things better. The things in nature that function the best in turn get better results and are able to outlive the others. Their form becomes optimum for duplication and nature grows resilient. In this manner, whatever functions the best for survival lasts the longest and grows the strongest.

In regards to designing for human scale, form tends to follow function. A system inspired by biomimicry will copy the form in hopes that it generates the desired function. That is why in this category, to design against the original function using the same form, creates a system that is less like the natural model. If we are to duplicate their form but for a different function, we are acquiring the ability to build in such a way crediting natures knowledge, but we are altering the original function from its intended purpose. Granted, any idea borrowed from nature and implemented into the built environment is not going to hold on to the same exact functions as they first appeared. The same principles can still remain intact, however, which will allow the creation to be closely related to life and therefore, a higher degree of biomimicry.

There are many things our culture needs to find solutions to that nature has not had to deal with nor will it ever be presented with. Finding a sustainable solution through biomimicry gets us one step closer to achieving a balance between our built environment and the natural environment, no matter what the original objective might have been. This is why viewing function as a factor of ranking biomimetic systems has a lesser importance than some of the other factors. Systems that are created in similar fashions as the original, yet serve the built environment in a dissimilar way as the original serves the natural environment, obtain a lower association with biomimicry inspired techniques and consequently, a lower score associated with this factor.

Physical Properties

The Physical Properties factor measures how closely the design of the system resembles the physical properties and design of the natural system. The physical attributes of biomimetic construction techniques are crucial to providing adherence to biomimicry, similar to the previously mentioned factor of Function. Outlined below explains why mimicking physical forms found in nature for construction purposes can be useful and what criteria is used for measuring this factor.

Inspiration for ideas to help towards the sustainability of the built environment can originate from natural systems and borrow a wide, or limited, range of aspects. One of the most visible ones, especially to the naked eye, is the associated physical attributes. These design decisions that were first created by mother earth are primarily copied, where their applied form allows for an unconventional, man-made system to function efficiently.

In order to earn a higher score for this factor, the principle design strategies of the original form are minimally manipulated in the form of the system to be used in the built environment. The materials used, however, do not necessarily have to be identical to the natural model. For replicating a design solution inspired by biomimicry, imitation of relevant proportions relating to the structure and different properties of the natural design are important.

Preferences on Factors

Although each being crucial to the development of a hierarchy, some factors above others show greater potential for attainment of a higher level of biomimetic construction. In the following, each factor category will be expanded to include the associated intensity of preference and the reasoning behind it.

Higher preferences are assigned to the factors of Energy for Construction and Energy for Operation and Maintenance. Renewable energy sources and energy sources that are less harmful to the environment are main focuses and a common thread in all theories regarding creating a built environment that more sustainable through biomimicry or other methods. That is why a high importance is given to these two energy related factors.

An intermediate set of preferences are assigned to the factors of Interdependence, Deconstruction, and Chemical Makeup. These factors are crucial for the built environment to pursue and adhere to in order sustain our lives at a healthy, functional level for our generation and for future generations. These factors are also important for maintaining our natural environment at its current level and for restoring damage that has already been done. A mixture of these factors is mentioned at differing levels of importance throughout the construction industry for helping the built environment reach a sustainable level.

Lower associated preferences are given to the factors of Function and Physical Properties as compared to the other factors. These factors are specifically looking at adherence of the biomimetic system used in the built environment to the aspects of the inspiring, natural system. It is important when ranking the systems on how closely they resemble biomimicry to consider such individual and specific factors such as function and physical properties. However, these factors do not guarantee on their own that the system will help the built environment become more sustainable, which is why they are given lower weights than some of the other factors.

CHAPTER 4
METHODOLOGY

A method for ranking the levels of biomimicry that are reached for construction techniques inspired by natural processes remains undefined. A solution to this problem lends itself to be systematized in such a way as to utilize the factors that define such sustainable, biomimetic systems to create a hierarchy of the techniques. A logical method for achieving the results of a hierarchical list of different biomimicry techniques is by applying the Analytic Hierarchy Process (AHP). A description of how the problem at hand is organized and structured to carry out this process is provided below, along with a description of AHP. Application of AHP requires a spectrum of techniques for ranking, factors with comparative weights to evaluate the techniques, and ratings for each factor as they apply to the specific technique.

Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a structured method for managing possible outcomes of specific, complex problems (The Quality 2010). This method of decision making provides options to the decision maker for attaining the best outcome based on their particular needs. The AHP does not provide a “correct” answer. The results are a function of the decision maker’s personal preferences and their understanding of the problem. In this manner, two different parties can be confronted with the same problem and arrive at different conclusions. This method of evaluation is ideal in situations where opinions are valued and the options can be justified through the development of many pertinent factors. The steps involved for applying AHP are:

- Develop the problem into a decision goal, established the techniques to achieve it, and determine the important factors for evaluating the techniques.

- Establish preferences among the factors of the hierarchy by making a series of judgments based on pairwise comparisons of the factors.
- Synthesize these judgments to arrive at weights for the hierarchy.
- Complete the hierarchy by weighing each technique against the factors.
- Final decision can be made by choosing the highest scoring technique (Saaty 1999).

Application

The problem is decomposed into a set of sub-problems. These sub-problems help define the important aspects that relate to the decision at hand, which is determining the levels of biomimetic construction. Five different levels will be determined for the five different construction techniques presented in the case studies.

In this thesis, sub-problems are referred to as biomimicry factors and the preferences for them have been mentioned in the previous chapter. These preferences are converted into weights by comparing one factor against another, two at a time. Each of the five techniques is given seven separate ratings, one rating representing each factor. Ratings reflect the degree in which the related technique adheres to the definition of the factor. They will be assigned with the development of the techniques covered in the next chapter. Below are the scales that explain the qualitative value that the different numerical ratings (1-5) will have.

Rating Scales

Energy for Construction

The amount and source of energy required from raw material extraction to the end of the construction process:

1) Very large amount of energy needed and energy attained from an unrenewable source.

2) Large amount of energy needed and/or small amount attained from a renewable source.

3) Moderate amount of energy needed and/or partial amount attained from a renewable source.

4) Small amount of energy needed and/or large amount attained from a renewable source.

5) No energy needed or all energy attained from a renewable source.

Energy for Operation and Maintenance

The amount and source of energy required for operation and maintenance of the system:

1) Very large amount of energy needed and/or energy attained from an unrenewable source.

2) Large amount of energy needed and/or small amount attained from a renewable source.

3) Moderate amount of energy needed and/or partial amount attained from a renewable source.

4) Small amount of energy needed and/or large amount attained from a renewable source.

5) No energy needed or all energy attained from a renewable source.

Chemical Makeup

How closely the chemicals used in the systems composition match the chemical make up in the natural system or if they are not harmful to humans and the natural environment:

1) Chemical composition does not match that of the natural system and/or is very harmful to humans and the natural environment.

2) Chemical composition shares few similarities to that of the natural system and/or is harmful to humans and the natural environment.

3) Chemical composition shares similarities to that of the natural system and/or is potentially harmful to humans and the natural environment.

4) Chemical composition is very similar to that of the natural system and/or is slightly harmful to humans and the natural environment.

5) Chemical composition is identical to that of the natural system and/or is not harmful to humans and the natural environment.

Interdependence

If the system has a reciprocating relationship with an outside system or plays a role in the support or facilitation of another's survival:

1) No reciprocating relationship or support of another's survival.

2) Slight reciprocating relationship or support of another's survival.

3) Moderate reciprocating relationship or support of another's survival.

4) Strong reciprocating relationship or support of another's survival.

5) Very strong reciprocating relationship or support of another's survival.

Deconstruction

How the system can be disassembled and reused when taken out of commission.

1) No use of system when taken out of commission.

2) Minimal reuse of system when taken out of commission.

3) Partial reuse of system when taken out of commission.

4) Extensive reuse of system when taken out of commission.

5) Full reuse of system when taken out of commission

Function

How close the relationship is between the biomimetic system's function in the built environment and the observed function of the natural system.

1) The functions share no relationship.

2) The functions share a weak relationship.

3) The functions share moderate relationship.

4) The functions share a strong relationship.

5) The functions share a very strong relationship.

Physical Properties

How closely the design of the system resembles the physical properties and design of the natural system:

1) No resemblance of physical properties.

2) Low resemblance of physical properties.

3) Moderate resemblance of physical properties.

4) Strong resemblance of physical properties.

5) Very strong resemblance of physical properties.

Summary

The factors and the descriptions of their associated ratings listed above will be used in the following chapter to assess the case studies relation to sustainability and biomimicry. In general, a technique scoring a rating of 1 for any factor means no adherence to its definition for the built environment. Likewise, a score of 5 means a very high adherence to the factors definition. The higher the rating, the more the technique is sustainable or related to the natural source of inspiration.

CHAPTER 4
EVALUATION OF BIOMIMICRY TECHNIQUES

A brief case study is presented for each biomimicry technique used to complete the hierarchy. These techniques were chosen for their proven effectiveness in the built environment and their wide variety of applications within the construction, architecture, and engineering industries. The information contained in the case studies is primarily focused on analyzing the data related to the seven biomimicry factors.

If the biomimicry technique makes up only one component of a system to be evaluated, the entire system is evaluated through the energy factors and natural harmony factors. This is because the biomimicry technique alone does not offer a complete proposal for an application in the built environment. Character specific factors are used to evaluate the biomimicry technique as a separate component from the whole, since this is the area where inspiration has come from the natural environment.

A brief synopsis is stated for each factor followed by a detailed review of the case study relating to that factor. After review of each system’s specific components that are related to the seven factors, ratings are established as to how well they met each factor’s criteria. Ratings for each factor are based solely on the assessment of the case study’s approach to sustainability and how well it adheres to the fundamentals of the natural system it is mimicking. For better understanding of the numerical ratings, the scales used are described in the Methodology Chapter. These ratings are not a leading indicator of how the case studies compare against each other. Analysis and comparison of the ratings for the case studies will be discussed further in the Results chapter along with their application in AHP.

Eastgate Centre

Inspiration- Termite Mound. The Eastgate Centre is a shopping center and office building located in Harare, Zimbabwe. Mick Pearce, the architect, design the building with a passive cooling system mimicked after termite mounds. These mounds use vents and passages to keep the interior at the relatively same temperature day and night. The same design techniques are used in Eastgate, which helps it use only 10 percent of the energy needed by a similar conventionally cooled building.

Energy for Construction. Eastgate's passive cooling system implemented several techniques to diminish the amount of embodied and transport energy needed for construction.

Renewable materials, local and regional materials, and modular construction techniques were utilized during the construction process (Gissen 2002). These techniques help reduce the demand for energy intensive materials and decreases the energy required for transportation of materials to the construction site. No renewable form of energy was used.

Rating: 2

Energy for Operation and Maintenance. Eastgate uses renewable energy which allows for a dramatic decrease in the amount of energy needed to operate the building, but it uses mechanical systems as well.

Most of the cooling stems from a passive system of ducts and chimneys with vertical and horizontal components; mechanical fans are necessary part-time to supply air into the offices (Thomas 2002). Cold air is drawn in at night which chills the slabs under the office floors to help cool the interior during the day (Gissen 2002). Eastgate

Centre uses less than 10 percent of the energy required to operate a building of the same size (Knight 2009).

Rating: 4

Chemical Makeup*.* The chemicals in the materials used for Eastgate share a few similarities to those of the natural system, but others are harmful to humans and the environment.

The main components of Eastgate are brick, stone, steel, glass, and precast concrete (Baird 2001). Concrete is the main contributor which makes this system unhealthy for the natural environment mainly because of the carbon dioxide produced during the manufacturing process. Once concrete is made, however, it provides for excellent indoor air quality with no off-gassing or toxicity. Some of the materials used, such as local aggregate, stone, and timber, share similar properties of the termite mound, which is comprised of sand and bark as well.

Rating: 3

Interdependence. Several relationships exist within the cooling system and with outside systems.

The passive cooling system or the mechanical fans in Eastgate are not efficient enough to keep Eastgate between 21 and 25 degrees Celsius year around when working alone; they have to work in conjunction to achieve stability. The fans distribute air into ducts via the double-floor slab to supply grills at low levels in the offices. The air is then extracted at high level, via exhaust ports, and continues to rise out of the building through chimneys. The underside of the concrete slabs provides a means of air turbulence as the air moves across the surface (Baird 2001). This turbulence increases the amount of heat transfer to the slabs, and thus, the offices above. The properties these systems exhibit work together to support and facilitate the heating and cooling process; which in turn, allows for the occupants to have a healthy, productive, and comfortable environment.

Rating: 3

Deconstruction. A portion of the materials used in Eastgate’s construction can be disassembled and reused when the building is taken out of commission.

Concrete, glass, and brick are readily deconstructed and demolished at the end of a buildings life and a percentage of these materials can then be reused for similar construction applications. The metal work within the mechanical systems can be collected and recycled as well.

Rating: 3

Function. The function of the passive cooling system employed by Eastgate provides the basic function of the system developed in termite mounds.

The function of the networks of tunnels in the termite mounds is to keep the temperature at 30 to 31 degrees Celsius (Thomas 2002). This function of the tunnels is mimicked by Eastgate to control the range of interior temperatures as well. Termites use the earth to function as a form of thermal mass for temperature regulation and Eastgate implements the use of concrete slabs to function as a thermal mass technique as well.

Rating: 4

Physical Properties. The passive design of Eastgate follows several principal design methods of the natural system, but does not directly resemble it physically.

The center of the mound is open with many chambers and passages connecting to it (Thomas 2002). Eastgate has a central atrium which pulls in air and allows it to infiltrate the rest of the building through “passages” such as ducts and double slab concrete flooring. Ridges on the outside of the mound enable the air to be cooled before it flows in the mound; this physical property inspired the designers of Eastgate to cast ridges into the slabs to allow the same heat exchange to take place. Eastgate also mimics the main airspace used to discharge the warm, stale air from the mound, in the form of several chimneys.

The design of the passive system was heavily influenced by the physical properties of termite mounds. However, in order for the passive system to work, a limited mechanical system needed to be employed as well. If it were not for the dependence on fans, Eastgate would have scored a higher rating for the design of its system mimicking the cooling system of the mound.

Rating: 2

Living Machine

Inspiration- Wetland. Dr. John Todd, President of Ocean Arks International, developed a wastewater treatment system modeled after ecological approaches to treating water (EPA 2002). The Living Machine is a waste water treatment system that makes use of natural elements in its processes and is capable of cleaning water to tertiary standards. Diverse ecosystems of microorganisms called biofilms and wetland vegetation are used to help cleanse gray and black water from residential, commercial, industrial, and agricultural applications (Kirksey 2009). Conventional wastewater treatment processes use large amounts of energy and chemicals to allow the reuse of water back into our systems. Natural wetland ecosystems, on the other hand, are decentralized and provide the same basic functions as the traditional system with less negative impacts on human activity and environmental health.

Energy for Construction. A Living Machine is constructed on site and uses local materials and labor, which helps reduce the energy required for construction.

Each treatment process design is different depending on the volume and content of the water and local climate in which it is constructed. These variable factors can affect the amount of energy that is required for construction since the process requires a greenhouse when applied in more temperate climates (EPA 2002) and the size and number of tanks that support the vegetation and organisms are varied. Typical tanks that process the water are made from plastic which accounts for a portion of the energy expended during construction. However, the energy required for construction of a Living Machine system, even with a greenhouse, plastic tanks, and mechanical equipment, is much less than what is needed to make a traditional activated sludge system. Construction time is relatively small which helps reduces the energy used due to the close proximity of materials and the relatively small footprint of the system.

Rating: 3

Energy for Operation and Maintenance. The Living Machine requires a variety of low energy maintenance tasks and uses electric, solar, and wind energy to operate.

The activities needed to operate and maintain the Living Machine includes cleaning of the inlet/outlet structure, cleaning the screen and tank, removing and disposing of sludge, maintaining and repairing machinery, management of vegetation, routine harvesting to promote plant growth, and removal of accumulated plant litter (Kirksey 2009). Many of these activities are carried out though simple labor techniques and require little energy. Savings are also attained from reducing the amount of water that has to be transferred over long distances because these systems are located on site.

A study conducted by Austin and Nivala (2009) compared a tidal flow wetland system (TF), like the Living Machine system, to a conventional, mechanical activated-sludge treatment system (MLT). They calculated the energy demand as a function of the pump power and run times that support the design flood and drain cycles of the TF system. This system used low-head, high volume pumps that were responsible for moving the wastewater from cell to cell. The process resulted in a daily power consumption of 211 kilowatts (kW) and the MLT system consumed 884 kW. The energy requirement of the TF system equals to about 25 percent of the energy required to operate a MLT system.

Rating: 3

Chemical Makeup. The living machine incorporates many of the same organic materials and natural chemicals found in wetlands.

Many chemicals, such as methanol, are not needed because biosolids and nitrified water from processing are recycled back into the system for further denitrification. This process also helps to dispose of these biosolids that would most likely require supplemental chemicals for stabilization and treatment to reduce pathogens. The living machine treats wastewater without requiring caustic chemicals or chemicals that are harmful to the environment and without large amounts of biowaste as part of the treatment process (Living Machine 2010).

Gravel aggregate, natural vegetation, and microorganisms treat the water throughout the beginning and middle stages. These processes mimic natural ecosystems techniques for treatment, but a final disinfection stage in treatment can involve chlorine to kill any pathogens that are left in the water. This is only an optional stage and is not pursued with every water treatment system.

Rating: 5

Interdependence. The Living Machine helps to integrate natural and human systems for a mutually supporting water treatment process.

This wastewater treatment strategy simultaneously supports the environment, human economic needs, and human health (Kirksey 2009). The biomimetic system facilitates the other named systems in part because of its self-regulating processes; it functions through interdependent relationships of nutrient exchanges between its components. The living machine works so well due to the diverse subsystems and their ability to work together to form the reciprocating relationships found in nature.

Rating: 5

Deconstruction. Parts of the Living Machine can be seamlessly integrated back into nature or recycled.

The living elements, such as organisms and plants, used in the water treatment system can be returned to their natural ecosystems when the system is no longer needed. These elements are what provide the treatment processes and when compared to the safety of discarding the cleaning agents in alternative treatment systems, it is undeniably better. The plastic tanks and aggregate involved in the system are possible to be recycled, but the mechanical components may not be as easily reused. What can be done with the pipes, water pumps, and control systems when no longer needed is something to be considered on a case by case basis. The cellular design of a Living Machine allows the system to be improved upon depending on need and advances in technology (Todd & Josephson 1996). The system does not need to be taken out of commission in order to grow, which is a problem faced by many conventional systems over time and the reason many are deconstructed.

Rating: 3

Function. The living machine provides the same basic processes to naturally treat wastewater as wetlands.

The functions that the Living Machine provides include the use of plants and animals to help the processes of sedimentation, filtration, clarification, adsorption, nitrification and denitrification, volatilization, and anaerobic and aerobic decomposition (EPA 2002). These basic functions are found in wetlands, but the Living Machine speeds up the natural processes. Some systems utilize a tidal process by alternately flooding and draining the basins of the system, a function that mimics the tidal cycles that occur in nature (Living Machine 2010). Both wetlands and the Living Machine filter contaminated water through similar processes to attain a quality of water that is fit to be recycled back into the natural environment or built environment for reuse. Wetlands, however, provide a habitat and dictate a way of life for the numerous species that live and depend on it. The role of a living machine in the built environment could develop a much more integrated function as appreciated by the inspiring ecosystem.

Rating: 4

Physical Properties. There is a moderate resemblance of the living machine's design to the natural ecosystem's design.

The physical attributes of the water treatment system that mimics the design of wetlands involves the biotic design aspects of using natural materials such as aggregate, living organisms, and plants. The properties that do not resemble the natural design is the condition that these elements are contained in multiple, separate tanks and the use mechanical pumps and piping as the physical means in which to exchange water. Additionally, plastic mesh is used to assist with trapping and settling solids and to provide a means in which bacteria can colonize (EPA 2002).

Rating: 3

PureBond Adhesive

Inspiration- Mussel. Kaichang Li, an assistant professor in Oregon State University's College of Forestry, noticed how mussels gripped to rocks so well even under water. Figuring out that mussels secrete proteins known as byssal threads that are strong yet flexible, he and his colleagues began searching for a protein that would mimic similar properties. They stumbled upon soy protein that gave excellent results when used in the adhesion of hardwood plywood panels. The manufacturer, Columbia Forest Products, now uses this urea formaldehyde-free adhesive in a variety of their products.

Energy for Construction. The use of PureBond is applied to wood products which require energy intensive extraction processes, but the adhesive itself is from a renewable resource.

Many of the hardwood plywood products from Columbia use recycled content, regional materials, and certified wood. This helps cut down on the energy spent on transportation and processing of raw materials. However, plywood goes through many processes including sawing and heating, which uses a large amount of nonrenewable energy.

Rating: 2

Energy for Operation and Maintenance. Very little maintenance is required for the upkeep of PureBond wood products.

PureBond is highly water resistant, which helps reduce damage to wood and less need for maintenance or replacement. Only slight touch-ups may be needed when the finish of the wood is damaged or soiled.

Rating: 5

Chemical Makeup. PureBond makes use of a similar protein to that of mussels and contains very little unhealthy chemicals.

Pectin is found in both the soy protein used in PureBond and the mussel protein (Piland 2005). The key protein mussels secrete that give it strength and water resistance was actually graphed to a soy protein. According to Columbia's product information, small amounts of acetone is used as a solvent, less than half a percent of the product by weight, but most is immediately volatilized. Little to no volatile organic compounds are emitted from the adhesive and all the oil is extracted from the soybean flour, so nothing that could be harmful is present. Wood naturally contains a various amount of compounds that may be volatilized under certain conditions, but nothing is introduced during the manufacturing process.

Rating: 4

Interdependence. The adhesive can work in conjunction with a variety of materials to support healthy alternative products.

The applications for a urea formaldehyde-free adhesive, such as PureBond, are countless. This adhesive facilitates the production of other systems with similar qualities of the plywood such as strength and water resistance, along with no negative health effects on humans and the natural environment. The plywood product itself does not have a reciprocating relationship with an outside system, but PureBond supports the creation of healthier alternatives for the built environment.

Rating: 3

Deconstruction. Extensive reuse of wood products utilizing this adhesive is available.

All components in Columbia's products are completely natural. The adhesive, PureBond is based from food quality soy flour and is the wood used is even certified by the Forest Stewardship Council (FSC). The FSC regulates and monitors many aspects of appropriate use of forests including pesticide use. Wood products utilizing the PureBond adhesive are safe to recycle, reuse, and even decompose when the product is no longer needed in its original form.

Rating: 5

Function. There is a strong relationship between the function of byssal threads and the protein used in PureBond.

Soy proteins are modified to perform similar functions to byssal threads. Both of these proteins provide exceptional water resistance and strong adhesion properties. Mussels attach themselves underwater and take countless thrashing from waves and are still able to hold on tight. PureBond allows for Columbia's hardwood plywood products to approach Type 1, or waterproof, performance (Columbia 2006) while still maintaining strength. The function of the natural protein also allows for extreme flexibility, essential to its underwater habitat. PureBond does not make use of this function as does the byssal threads.

Rating: 3

Physical Properties. PureBond does not match the physical properties of the mussel's natural adhesion methods.

The physical properties of byssus do not resemble the properties of the adhesive. The chemical structure is partially resembled, but in application, the mussels produce thread like tentacles for attachment purposes and the glue does not. There numerous, physically apparent threads that extends out from the mussel to connect it to an object. The adhesive, on the other hand, penetrates and is absorbed by the wood.

Rating: 1

Wind Turbine

Inspiration- Whale Fin. By studying the flippers on humpback whales, Dr. Frank E. Fish discovered some features of their structure which helps whales move more efficiently through water. This observation has led to the creation of wind turbine blades that mimic whale flippers. The design aspect which aids whales to be more successful in their movements is the use of tubercles, or bumps, found on the edge of their fin. Tubercle Technology, a term coined by the company WhalePower, is advancement in fluid dynamics with many applications. This technology has proven to be more efficient and also quieter when applied to wind turbines (Society 2008).

Energy for Construction. Turbines require an extensive amount of energy throughout manufacturing, transportation, and installation.

The components that make up a turbine consist of the blades, tower, nacelle, generator, and a concrete base. These components are often times manufactured and built in separate factories, which require energy intensive machinery and processes that are not usually generated by sustainable means. After the manufacturing process, other energy intensive activities include, transportation to the area in which they are to be installed, extensive land clearing around the area of installation, cranes being brought to the site to lift and place components, and connection of the turbine to the grid.

Rating: 2

Energy for Operation and Maintenance. Turbines require a backup form of energy and their maintenance is often unpredictable, but they produce renewable energy which helps counteract the negative energy requirement.

Plants that produce other forms of energy need to be available to supply electricity when the wind is not adequate for producing power. The American Wind Energy Association (2009) indicates that for a 100 megawatt wind plant, only about two megawatts of conventional capacity is needed. Although the amount of energy required for supplying electricity when the wind in not blowing is small, the source may not be renewable. Another negative aspect of turbines is the transportation needed to perform necessary maintenance activities since they are often located in remote areas or even off shore. Positive aspects are that wind power does not incur the waste disposal issues associated with conventional energy generation, turbines consume far less water than other power alternatives, and fewer lubricant problems will arise because of tubercles allowing for a longer operating life (Canter 2008).

Whalepower turbine systems are identical to conventional turbines expect for the tubercles on the blades which makes them more efficient. The energy payback time (EPT), which is how long a system has to operate to generate the amount of electricity required for its manufacture and construction, for a typical turbine is only 3 to 8 months (Santillan, Heaston, Woodward & Joshi 2010). The American Wind Energy Association reports that turbines have one of the shortest EPTs of any energy technology. So although turbines have a large energy requirement for manufacturing and construction, they more than make up for it due to their efficient energy production during operation.

Rating: 4

Chemical Makeup. The chemicals used in the construction of turbines can be harmful to humans and the environment, but while the turbine is in use, there is minimal to no off gassing.

Materials used in the construction of turbines include, cast iron, steel, copper, aluminum, fiberglass, concrete, and epoxy (Santillan et al. 2010). A life-cycle assessment carried out by Jungbluth et al (2004) showed carbon dioxide, nitrous oxide, sulfur oxide, and particulate emissions resulting from various process stages of the wind turbine life cycle, but most were found during the materials manufacturing stage. This study concluded that the absolute values of greenhouse gases emitted were between 11 to 13 grams per kilowatt hour (g/kWh). This is a sizable reduction of chemicals emitted into our atmosphere compared to other forms of energy production, such as coal, which can produce carbon dioxide levels up to 1050 g/kWh. These materials and their processes contain hazardous chemicals, but during the operation period, on shore turbines pose little threat to emitting chemicals. Offshore wind power plants, however, discharge zinc from the cables during operation (The American 2009).

Rating: 2

Interdependence. Turbines support the built environment's energy needs and exhibit a reciprocating relationship with other sources of energy.

Turbines are an excellent source of renewable energy, but need a backup system when the wind conditions are not favorable for producing energy. Turbines rely on these other forms of energy to generate power and allow turbines to be a more dependable source of energy at the same time, which leads to greater implementation. Wind power allows for the decreasing need of environmentally unfriendly energy sources and helps nonrenewable sources run less often. The amount of energy needed from the backup sources is little which is ideal because these forms of energy are not usually sustainable. Turbines enable countless human activities and vital processes in the built environment to be possible while maintaining healthy standards.

Rating: 5

Deconstruction. Some deconstruction options for turbine components are available after they are taken out of commission, but most options are very energy intensive.

According to a life cycle assessment of a wind turbine, dismantling a turbine once it is out of service, accounts for three to 14 percent of the total emissions (Wind Energy n.d.). The activities involved in deconstruction include transportation from the erection area to the landfill, recycling some of the components, and recovering other material.

Several options are available for disposal of turbine blades, one of which is being disposed of in a landfill. Incineration and recycling are the other options which have both positive and negative effects on health and the built environment. Old turbine blades can be burned to generate energy and the remaining scrap can be used in cement application, but this process emits hazardous by-products (Ellyard 2000). Mechanical recycling reduces the size of the scraps from turbines, pounds the resin out of the fibers, and separates the fiber from the smaller filler and polymer material. The smaller material can be used for other filler applications and the fiber is being researched for reinforcement and particle board purposes (Pickering 2006).

Rating: 2

Function. The function of the tubercles on the blades of the turbine share a strong relationship to the function they provide for a whale fin.

In the case of the humpback whale, the tubercles on the front edge of the flippers help generate lift without the occurrence of stall, enhance maneuverability, and enable the animal to be more agile (Society 2008). This concept, when applied to turbine blades, enhances their efficiency when moving through the air just as it achieves benefits for whales as they move through water. A performance improvement of nearly 40 percent is gained as compared to a turbine without tubercles because the operating angle of the blades is able to increase (Canter 2008). The Whalepower turbines are also less likely to stall.

Rating: 4

Physical Properties. The physical design of the turbine blade mimics the natural physical properties of tubercles found on whale fins.

Whales exhibit a bumpy feature on the structure of their flipper known as tubercles. Tubercles appear on the leading edge of their flippers and create vortices which help them move through the water. This physical property has inspired the same design for turbine blades because of the efficiencies it produces for whales, even though it defies traditional engineering theories. Bumps are constructed on the leading edge of the blades similar to the shape and proportion of the whale tubercles,

Rating: 5

Lotusan Paint

Inspiration- Lotus Leaf. Sto Corp. is the manufacturer of Lotusan Paint. This paint was inspired by the surface of the lotus leaf for its superior ability to stay clean in muddy conditions. This self-cleaning ability is possible due to the surface properties of the leaf. The same properties were duplicated for a new coating application that allows a surface painted with Lotusan paint to stay clean as well. When it rains, the water collects dirt particles as it rolls down the surface because its bumpy texture does not allow for dirt to stick.

Energy for Construction. Sto Corp is taking measures to reduce the amount of energy required to produce their products, but their efforts are not far reaching.

According to Sto Corp. (n.d.), since 2008 they have reduced electricity use and waste water, recycle in their manufacturing processes, and implemented a program for airborne particulate capture and exposure reduction.

According to the LEED Compliance Information Sheet (n.d.) for Lotusan paint, 25 percent of the raw material volume by weight is extracted locally to their manufacturing plants. This reduces the amount of energy and fuel required for the transportation of raw materials. However, the manufacturing of the paint is an open loop process so there is no recycled content in the paint (LEED Compliance n.d.). Recycling leftover paint would help reduced the energy needed for raw material extraction, transportation, and manufacturing of new paint.

Rating: 3

Energy for Operation and Maintenance. Lotusan paint is self-sustaining and requires no energy for operation and maintenance since it relies on the natural elements for cleaning.

According to Sto Corp., it has a 10 year weatherproofing warranty, so additional measures might be necessary to sustain the integrity of the product later in life. As with other paints, touch ups and recoating may be required. In arid regions or during dry seasons, supplemental maintenance methods such as cleaning the substrate with water is needed to keep substrate free of stains.

Rating: 4

Chemical Makeup. StoCoat Lotusan Low VOC exterior paint is a water based acrylic coating and does not contain an identical chemical makeup as the original source of inspiration.

According to the manufacture's Material Safety Data Sheet (2001), the hazardous ingredients contained are titanium dioxide, triethoxy silane, polymethylethoxysilane, and cristobalite. It is not considered a carcinogen by the state of California nor poses a health hazard according to the International Agency for Research on Cancer's and the National Tocxicology Program's criteria for determining that a particular chemical is a human carcinogen (Material Safety 2001). The Volatile Organic Compound (VOC) concentration of the product is 83 g/L (LEED Compliance n.d.) which complies with the low VOC content limit of 100 g/L (Green Seal 2008) required by LEED Indoor Air Quality credit 4.2: Low Emitting Materials- Paints and Coatings.

Rating: 3

Interdependence. This biomimetic product exhibits some interdependence properties.

Through experimental data, it has been recognized in reference to the lotus leaf, and thus, paint mimicking the physical properties of the lotus leaf, that the "interdependence between surface roughness, reduced particle adhesion and water repellency is the keystone in the self-cleaning mechanism of many biological surfaces" (Barthlott & Neinhuis 1997). The different properties expressed by the paint work interdependently to achieve the desired effect of the naturally occurring system. However, as far as facilitating an outside system, the paint does little expect to help the surface of the building breathe as compared to other coatings. This high water vapor permeability reduces the growth of mold, mildew, and algae. The natural cleanliness of the paint translates to a positive relationship with the environment since it will reduce the need for chemical cleaning, reduce depletion of water, and require no added energy expenditure.

Rating: 2

Deconstruction. Recycling of the empty paint cans and lids can be done depending on the local regulations. No attempts are made to reuse or recycle leftover, unused StoCoat Lotusan paint by the company.

Hazardous decomposition products according to the fact sheet are carbon oxides and hydrocarbons (Material Safety 2001).

Rating: 1

Function. The function that Lotusan paint is it mimicking from the lotus leaf are identical.

The exterior properties of the lotus plant provide the function of keep the leaves clean of dirt in the natural environment, since this is a plant that lives in muddy conditions. Paint with Lotus-Effect® technology provides the function of keeping the exterior of the substrate clean as well.

Rating: 5

Physical Properties. The surface of Lotusan paint resembles the surface of the lotus leaf.

Both the paint and the lotus leaf have microstructures that generate the phenomenon of super-hydrophobicity, which is when water droplets on surfaces exhibit contact angles above 140 degrees (Spaeth & Berthlott 2008). When the cells of the leaf and applied paint are magnified 7,000 times, their molecular structure looks almost identical to each other (Goodman 2009).

Rating: 5

CHAPTER 5
RESULTS AND CONCLUSIONS

After independent analysis of the factors, a pairwise comparison was performed, two factors at a time, to convert the categorical preferences to more specific numerical values for applying AHP. Assigning the comparative values was achieved by following the descriptive scale in Table 5-1. After familiarization with the scale and by using Table 5-2, one factor was chosen from column *i* and compared against another factor from row *j*, until all factors had been compared against each other. For example, comparison of Energy for Construction in column *i* to Function in row *j*, obtains a weight of 5 because it is considered *absolutely more important*. The reverse comparison of Function in column *i* to Energy for Construction in row *j*, would then obtain the reciprocal of 5, which is 1/5. Table 5-2 shows the values attained based off of the conveyed preferences in this thesis and Table 5-3 shows the values attained based off the Biomimicry Guild's preferences.

The weights obtained from the respective preferences on factors are shown in Table 5-4 and 5-5. Weights are tabulated by dividing a preference value in a cell by the total sum of the column. Using the previous example, 5/ (3+1+4+5+1+4) =0.217.

Table 5-1. Pairwise comparison values

Value	Description
1	Factor in column *i* and factor in row *j* are of equal importance.
2	Factor in column *i* is slightly more important than the factor in row *j*.
3	Factor in column *i* is strongly more important than the factor in row *j*.
4	Factor in column *i* is very strongly more important than the factor in row *j*.
5	Factor in column *i* is absolutely more important the factor in row *j*.

Table 5-2. Preferences on factors

i \ *j*	Chemical Makeup	Physical Properties	Deconstruction	Energy for O and M	Function	Interdependence	Energy for Construction
Chemical Makeup	1	4	2	1/3	3	1/2	1/3
Physical Properties	1/4	1	1/4	1/5	1	1/4	1/5
Deconstruction	1/2	4	1	1/2	4	4	1/2
Energy for O and M	3	5	2	1	5	4	1
Function	1/3	1	1/4	1/5	1	1/4	1/5
Interdependence	2	4	1/4	1/4	4	1	1/4
Energy for Construction	3	5	2	1	5	4	1

Table 5-3. Biomimicry Guild's preferences on factors

i \ *j*	Chemical Makeup	Physical Properties	Deconstruction	Energy for O and M	Function	Interdependence	Energy for Construction
Chemical Makeup	1	3	2	1	1/2	1/2	1
Physical Properties	1/3	1	1/2	1/3	1/4	1/4	1/3
Deconstruction	1/2	2	1	1/2	1/3	1/3	1/2
Energy for O and M	1	3	2	1	1/2	1/2	1
Function	2	4	3	2	1	1	2
Interdependence	2	4	3	2	1	1	2
Energy for Construction	1	3	2	1	1/2	1/2	1

Table 5-4. Weights on factors

i \ j	Chemical Makeup	Physical Properties	Deconstruction	Energy for O and M	Function	Interdependence	Energy for Construction	Average
Chemical Makeup	0.099	0.167	0.258	0.096	0.130	0.036	0.096	0.126
Physical Properties	0.025	0.042	0.032	0.057	0.043	0.018	0.057	0.039
Deconstruction	0.050	0.167	0.129	0.144	0.174	0.286	0.144	0.156
Energy for O and M	0.298	0.208	0.258	0.287	0.217	0.286	0.287	0.263
Function	0.033	0.042	0.032	0.057	0.043	0.018	0.057	0.040
Interdependence	0.198	0.167	0.032	0.072	0.174	0.071	0.072	0.112
Energy for Construction	0.298	0.208	0.258	0.287	0.217	0.286	0.287	0.263

Table 5-5. Biomimicry Guild’s weights on factors

i \ j	Chemical Makeup	Physical Properties	Deconstruction	Energy for O and M	Function	Interdependence	Energy for Construction	Average
Chemical Makeup	0.128	0.150	0.148	0.128	0.122	0.122	0.128	0.132
Physical Properties	0.043	0.050	0.037	0.043	0.061	0.061	0.043	0.048
Deconstruction	0.064	0.100	0.074	0.064	0.082	0.082	0.064	0.076
Energy for O and M	0.128	0.150	0.148	0.128	0.122	0.122	0.128	0.132
Function	0.255	0.200	0.222	0.255	0.245	0.245	0.255	0.240
Interdependence	0.255	0.200	0.222	0.255	0.245	0.245	0.255	0.240
Energy for Construction	0.128	0.150	0.148	0.128	0.122	0.122	0.128	0.132

Table 5-6 through Table 5-12 shows the comparisons of each factor’s ratings pertaining to the case studies. The resulting weights are shown in the *relative scores* area on Table 5-13. The relative score is developed by dividing a number in a cell from the factor’s scores tables shown below by the entire column it appears in. The weight of a factor is then multiplied by the relative score of the same factor and the sum of these products establishes the final score for one case study. This process is shown for both sets of weights in Table 5-13 and Table 5-14. The final scores are shown in Table 5-15 and Table 5-16.

Table 5-6. Chemical scores

	Eastgate Centre	Living Machine	PureBond	WhalePower	Lotusan Paint
Eastgate Centre	1	3/5	3/4	3/2	1
Living Machine	5/3	1	5/4	5/2	5/3
PureBond	4/3	4/5	1	4/2	4/3
WhalePower	2/3	2/5	2/4	1	2/3
Lotusan Paint	1	3/5	3/4	3/2	1

Table 5-7. Physical scores

	Eastgate Centre	Living Machine	PureBond	WhalePower	Lotusan Paint
Eastgate Centre	1	2/3	2/1	2/5	2/5
Living Machine	3/2	1	3/1	3/5	3/5
PureBond	1/2	1/3	1	1/5	1/5
WhalePower	5/2	5/3	5/1	1	5/5
Lotusan Paint	5/2	5/3	5/1	5/5	1

Table 5-8. Deconstruction scores

	Eastgate Centre	Living Machine	PureBond	WhalePower	Lotusan Paint
Eastgate Centre	1	3/3	3/5	3/2	3/1
Living Machine	3/3	1	3/5	3/2	3/1
PureBond	5/3	5/3	1	5/2	5/1
WhalePower	2/3	2/3	2/5	1	2/1
Lotusan Paint	1/3	1/3	1/5	1/2	1

Table 5-9. Operation and maintenance scores

	Eastgate Centre	Living Machine	PureBond	WhalePower	Lotusan Paint
Eastgate Centre	1	4/3	4/5	4/4	4/5
Living Machine	3/4	1	3/5	3/4	3/5
PureBond	5/4	5/3	1	5/4	5/5
WhalePower	4/4	4/3	4/5	1	4/5
Lotusan Paint	5/4	5/3	5/5	5/4	1

Table 5-10. Function scores

	Eastgate Centre	Living Machine	PureBond	WhalePower	Lotusan Paint
Eastgate Centre	1	4/4	4/3	4/4	4/5
Living Machine	4/4	1	4/3	4/4	4/5
PureBond	3/4	3/4	1	3/4	3/5
WhalePower	4/4	4/4	4/3	1	4/5
Lotusan Paint	5/4	5/4	5/3	5/4	1

Table 5-11. Interdependence scores

	Eastgate Centre	Living Machine	PureBond	WhalePower	Lotusan Paint
Eastgate Centre	1	3/5	3/2	3/5	3/2
Living Machine	5/3	1	5/2	5/5	5/2
PureBond	2/3	2/5	1	2/5	2/2
WhalePower	5/3	5/5	5/2	1	5/2
Lotusan Paint	2/3	2/5	2/2	2/5	1

Table 5-12. Energy for construction scores

	Eastgate Centre	Living Machine	PureBond	WhalePower	Lotusan Paint
Eastgate Centre	1	2/3	2/2	2/2	2/3
Living Machine	3/2	1	3/2	3/2	3/3
PureBond	2/2	2/3	1	2/2	2/3
WhalePower	2/2	2/3	2/2	1	2/3
Lotusan Paint	3/2	3/3	3/2	3/2	1

Table 5-13. Relative scores and average weights of techniques

		Chemical Makeup	Physical Properties	Deconstruction	Energy for O and M	Function	Interdependence	Energy for Construction
	Average Weights	0.126	0.039	0.156	0.263	0.040	0.112	0.264
Eastgate Centre	Relative Score	0.176	0.125	0.214	0.190	0.200	0.176	0.167
	Average Weight x Relative Score	0.022	0.005	0.033	0.050	0.008	0.020	0.044
Living Machine	Relative Score	0.294	0.188	0.214	0.143	0.200	0.294	0.250
	Average Weight x Relative Score	0.037	0.007	0.033	0.038	0.008	0.033	0.066
Pure Bond	Relative Score	0.235	0.063	0.357	0.238	0.150	0.118	0.167
	Average Weight x Relative Score	0.030	0.002	0.056	0.063	0.006	0.013	0.044
Whale Power	Relative Score	0.118	0.313	0.143	0.190	0.200	0.294	0.167
	Average Weight x Relative Score	0.015	0.012	0.022	0.050	0.008	0.033	0.044
Lotusan Paint	Relative Score	0.176	0.313	0.071	0.238	0.250	0.118	0.250
	Average Weight x Relative Score	0.022	0.012	0.011	0.063	0.010	0.013	0.066

Table 5-14. Relative scores and average weights of techniques from Biomimicry Guild

		Chemical Makeup	Physical Properties	Deconstruction	Energy for O and M	Function	Interdependence	Energy for Construction
	Average Weights	0.132	0.048	0.076	0.132	0.240	0.240	0.132
Eastgate	Relative Score	0.176	0.125	0.214	0.190	0.200	0.176	0.167
	Average Weight x Relative Score	0.023	0.006	0.016	0.025	0.048	0.042	0.022
Living Machine	Relative Score	0.294	0.188	0.214	0.143	0.200	0.294	0.250
	Average Weight x Relative Score	0.039	0.009	0.016	0.019	0.048	0.071	0.033
Pure Bond	Relative Score	0.235	0.063	0.357	0.238	0.150	0.118	0.167
	Average Weight x Relative Score	0.031	0.003	0.027	0.031	0.036	0.028	0.022
Whale Power	Relative Score	0.118	0.313	0.143	0.190	0.200	0.294	0.167
	Average Weight x Relative Score	0.016	0.015	0.011	0.025	0.048	0.071	0.022
Lotusan Paint	Relative Score	0.176	0.313	0.071	0.238	0.250	0.118	0.250
	Average Weight x Relative Score	0.023	0.015	0.005	0.031	0.060	0.028	0.033

Table 5-15. Biomimicry technique's final scores

Technique	Eastgate Centre	Living Machine	PureBond	WhalePower	Lotusan Paint
Final Score	0.182	0.222	0.214	0.184	0.197
Level	5	1	2	4	3

Table 5-16. Biomimicry technique’s final scores as weighted by Biomimicry Guild

Technique	Eastgate Centre	Living Machine	PureBond	WhalePower	Lotusan Paint
Final Score	0.182	0.220	0.210	0.180	0.200
Level	4	1	2	5	3

Results

The tables throughout this chapter present the numerical data obtained through two applications of Analytic Hierarchy Processes and explanations provide guides on how the data was tabulated. The reasoning behind conducting this process was to determine the levels of biomimicry achieved by five techniques for the built environment. The two different processes applied, resulted in the same techniques achieving the highest, second highest and third highest level. The results of both AHPs conclude that the Living Machine, a wastewater treatment system that mimics natural wetlands, achieves the highest level of sustainable biomimetic construction. The second highest technique, PureBond, is an adhesive inspired from mussel's byssus used by Columbia Forest Products in manufacturing of hardwood plywood. The third highest is Lotusan paint, a coating developed by Sto that gained inspiration from the lotus' self-cleaning abilities.

The preferences presented in this thesis determined dissimilar levels of biomimicry achieved for Eastgate Centre and WhalePower than did the Biomimicry Guild's preferences. In one process, Eastgate Center, a mixed use building implementing a passive cooling system learned from termite mounds, achieved the fourth highest level and WhalePower, turbine blades that mimic the bumps found on whale fins, achieved the lowest level of biomimicry. However, the raw scores for Eastgate were the same in both AHPs.

Conclusions

From the results obtained by both applications of AHP, it is fair to conclude that for the purpose of this thesis, the construction technique that exemplifies the highest level of adherence to biomimicry is the Living Machine.

Returning to the hypothesis of this thesis, identification of the levels of biomimicry achieved help to understand what technique is most beneficial to implement in the built environment for our society and the natural environment as well. By evaluating the highest scoring technique, identification of the sustainable aspects associated with its implementation lead to clarifying what is most beneficial for and by the decision maker. The resulting technique can be confidently constructed to contribute to the growth of sustainability through using natural, healthy methods. Because not all biomimetic techniques are created equal in their support for maintaining the natural qualities of our environment, assessment of their level of adherence is important for correctly choosing the best option.

Even though the benefits perceived are based on preferences relating to aspects of the decision method. Two different preferences used in this thesis obtained very similar results. This indicates that personal preferences, if systematically derived, will allow for the attainment of a decision that best suits a variety of needs.

AHP can be conducted to evaluate dissimilar construction methods, as carried out in this thesis, or it can be applied to comprehend the varying levels of biomimicry achieved for like techniques. The latter of the two will most likely result in a better comparative analysis and could possibly show the degree in which biomimicry benefits the decision maker as compared to a conventional technique. Another variation in this process that could better suit the decision maker and the problem would be to create different factors than the ones identified in this thesis. Assessing the options based on factors that relate to each technique specifically and that have personal value to the decision maker could allow for a better idea of the benefits each technique has to offer.

The information attained to assess each biomimetic case study was researched thoroughly. However, identical information such as product data sheets or life cycle costing could not be obtained for each case study. This could lead to inconsistent information and slightly skewed ratings. Rating options for the built environment will produce more accurate results when identical information is attainable for all options. As long as the methods for applying AHP are consistent and the process is carried out systematically, as outlined in this thesis, the resulting levels of biomimicry will provide a dependable decision making hierarchy.

APPENDIX
PREFERENCE FORM SENT TO BIOMIMICRY GUILD

INSTRUCTIONS:

STEP 1: Please scan over the definitions of the factors on the next page.

STEP 2: Please review the scale below to complete the next steps.

STEP 3: In the **Comparison Chart** below, weigh each factor's importance for **sustainable biomimetic construction** against each other (comparing two factors at a time) using the **scale of 1 to 5.**

Example 1: If you believe **Chemical Makeup** (in column *i*) is *"strongly more important"* than **Physical Properties** (in row ***j***) for sustainable biomimetic construction, you will fill in a **3** in the corresponding cell (shown in the **Green** cell on the Comparison Chart). Then, when comparing **Physical Properties** (in column *i*) to **Chemical Makeup** (in row ***j***) you would fill in the reciprocal of 3, which is **1/3**, in the corresponding cell (shown in the **Blue** cell on the Comparison Chart).

Example 2: If you believe **Deconstruction** and **Chemical Makeup** are equally important factors (refer to scale) for a sustainable biomimetic construction technique, you will fill in a **1** for both cells (see Yellow and Orange cells below)**.**

STEP 4: Continue to compare each factor in **Column *i*** to each factor in **Row *j*** following the examples above.

** Please replace the filled out **example** values (colored cells) with your own values.*

Scale

1- Factor in column ***i*** and factor in row ***j*** are of equal importance.
2- Factor in column ***i*** is slightly more important than the factor in row ***j***.
3- Factor in column ***i*** is strongly more important than the factor in row ***j***.
4- Factor in column ***i*** is very strongly more important than the factor in row ***j***.
5- Factor in column ***i*** is absolutely more important the factor in row ***j***.

Comparison Chart

j / *i*	Chemical Makeup	Physical Properties	Deconstruction	Energy for O and M	Function	Interdependence	Energy for Construction
Chemical Makeup		3	1				
Physical Properties	1/3						
Deconstruction	1						
Energy for O and M							
Function							
Interdependence							
Energy for Construction							

Definitions

Energy for Construction
The amount and source of energy required from raw material extraction to the end of the construction process.

Energy for Operation and Maintenance (O and M)
The amount and source of energy required for operation and maintenance of the system.

Chemical Makeup
How closely the chemicals used in the systems composition match the chemical make up in the natural system, or if they are not harmful to humans and the natural environment.

Interdependence
If a system has a reciprocating relationship with an outside system or plays a role in the support or facilitation of another's survival.

Deconstruction
How the system can be disassembled and reused when taken out of commission.

Function
How close the relationship is between the biomimetic system's function in the built environment and the observed function of the natural system.

Physical Properties
How closely the design of the system resembles the physical properties and design of the natural system.

LIST OF REFERENCES

Abdelhamid (2007). “Lean Construction Principles.” Graduate class offering at Michigan State University, http://www.slideshare.net/tabdelhamid/lean-construction-introduction (September 2010).

Baird, G. (2001). *The architectural expression of environmental control systems,* Spon Press, New York.

Barthlott, W., and Neinhuis, C. (1997). “Purity of the sacred lotus, or escape from contamination in biological surfaces.” *Planta,* 202(1), 1-8.

Benyus, J. M. (1997). *Biomimicry: Innovation inspired by nature*, William Morrow and Company, Inc., New York, NY.

Browning, W. D. (2000). “Biomimicry, biophilia, and building community.” In D. E. Brown, M. Fox, M, M. R. Pelletier (Eds.), *Sustainable architecture white papers,* 55-60, Earth Pledge, NY.

Canter, N. (2008). “Humpback whales inspire new wind turbine technology.” *Tribology & Lubrication Technology*, 10-11.

Columbia Forest Products. (2006). “PureBond.” http://www.columbiaforestproducts.com/Content/Documents/PureBond_Brochure.pdf (September 2010).

Ellyard, D. (2000). “Putting it together- the science and technology of composite materials.” http://www.science.org.au/nova/059/059key.htm (August 2010).

EPA United States Environmental Protection Agency. (2002). “Wastewater technology fact sheet: The living machine.” http://water.epa.gov/scitech/wastetech/upload/2002_12_13_mtb_living_machine.pdf (July 2010).

Gissen, D. (2003). *Big and green: Toward sustainable architecture in the 21st century*, Princeton Architectural Press, New York.

Goodman, T. (2009). “Inspired by the lotus leaf: Lotusan paint.” http://inventorspot.com/articles/inspired_lotus_leaf_lotusan_paint_23083 (September 2010).

Graedel, T. E., & Allenby, B. R. (2003). *Industrial ecology*, Prentice Hall, Englewood Cliffs, NJ.

Green Seal. (2008). “GS-11 Green Seal environmental standard for paints and coatings.” http://www.greenseal.org/certification/standards/paints_and_coatings.pdf (August 2010).

Hart, S. (2008). “The case for commissioning.” *GreenSource,* http://www.buildinggreen.com.lp.hscl.ufl.edu/auth/article.cfm/2008/1/1/The-Case-For-Commissioning (October 2010).

Hawken, P., Lovins, A., & Lovins, L. H. (1999). *Natural capitalism: Creating the next industrial revolution*, Little, Brown and Co., Boston, MA.

Huovila, P. & Koskela, L. (1998). “Proceedings from IGLC ‘98: Contribution of the Principles of Lean Construction to Meet the Challenges of Sustainable Development,*”* Guaruja, Brazil, http://www.ce.berkeley.edu/~tommelein/IGLC-6/HuovilaAndKoskela.pdf (July 2010).

Kay, J. J. (2002). “On complexity theory, exergy, and industrial ecology.” In C.J. Kibert, J. Sendzimir, and G.B. Guy (Eds.), *Construction Ecology,* Spon Press, New York.

Kellert, S. R., Heerwagen, J. H., Mador, M. L. (2008). *Biophilic design,* John Wiley & Sons, Inc., Hoboken, NJ.

Kibert, C. J. (2008). *Sustainable construction: Green building design and delivery,* 2nd Ed., John Wiley & Sons, Inc, Hoboken, NJ.

Kirksey, W. (2009). “Creating a sustainable water infrastructure for the 21st century.” http://www.livingmachines.com/images/uploads/resources/Final_LM_White_Paper.pdf (September 2010).

Knight, D. J. (2009). “Inspired by nature.” *Conservationist*, 63(6), 30-33.

Lapinski, A. R., Horman M.J., Riley D. R. (2006). “Lean processes for sustainable project delivery.” *Journal of Construction Engineering and Management*, 132(10), 1083-1091.

Living Machine. (2010). “Living Machine.” Worrell Water, http://www.livingmachines.com (September 2010).

Lodato, F. (2001). *Bionics: Nature as a tool for product development*, Cambridge.

Lovins, L. H. (2001) “Natural capitalism: Path to sustainability?” *Corporate Environmental Strategy*, 8(2), 99-108.

McDonough, W. & Braungart, M. (2002). *Cradle to cradle: Remaking the way we make things*, North Point Press, New York.

MSU Michigan State University. (2006). “Lean Construction- A promising future for MSU.” https://www.msu.edu/~tariq/C2P2AI_LeanConstruction_WhitePaper.pdf (July 2010).

Natural Step. “The Four System Conditions.” http://www.naturalstep.org/~natural/the-system-conditions (August 2010).

Pickering, S. J. (2006). "Recycling technologies for thermoset composite materials-current status." *Composites Part A: Applied Science and Manufacturing,* 37(8), 1206-1215.

Piland, J.D. (2005). "New adhesive flexes its 'mussels'." *Wood & Wood Products,* 110(9), 77-78.

Saaty, T.L. (1999). *Decision making for leaders: The analytic hierarchy process for decisions in a complex world*, RWS Publications, Pittsburgh, Pennsylvania.

Santillan, J., Heaston, M. S., Woodward, D. S., Joshi, M. M. (2010). "Environmental impacts associated with manufacturing of solar and wind power alternative energy systems." *Remediation Journal*, 20(2), 107-113.

Society for Experimental Biology (2008). "Whales and dolphins influence new wind turbine design." ScienceDaily, http://www.sciencedaily.com /releases/2008/07/080707222315.htm (September 2010).

Spaeth, M., & Barthlott, W. (2008). "Lotus-Effect: Biomimetic super-hydrophobic surfaces and their application." *Advances in Science and Technology*, 60, 38-46.

Sto Corp. (2001). "Material Safety Data Sheet." 80217 Stocoat Lotusan Low VOC, http://www.stocorp.com/dmdocuments/80217MSDS.pdf (August 2010).

Sto Corp. (n.d.). "LEED compliance information sheet." http://www.stocorp.com/dmdocuments/216LEED.pdf (August 2010).

Stroud, S. (2009). "Evolution meets creation in biomimicry." http://www.designophy.com/article/design-article-1000000076-evolution-meets-creation-in-biomimicry.htm (August 2010).

The American Wind Energy Association. (2009). "Wind Web Tutorial." American Wind Energy Association, http://www.awea.org/faq/wwt_statistics.html (September 2010).

The Quality Portal. (2010). "Analytical Hierarchy process: Overview." http://thequalityportal.com/q_ahp.htm (June 2010).

Thomas, D. (2002). *Architecture and the urban environment: A vision for the new age*, Architectural Press, Boston, MA.

Todd, J., Josephson, B. (1996). "The design of living technologies for water treatment." *Ecological Engineering*, 6, 109-136.

BIOGRAPHICAL SKETCH

Laura Finton graduated from the University of Florida in May 2008 with a Bachelor of Design in architecture. During her undergraduate coursework and internships, she recognized the importance of integrating natural qualities from the environment into her designs for the built environment. Motivated to learn how to turn her conceptual designs into reality, she obtained an internship with a general contractor upon graduation.

Laura returned to the University of Florida to further her education through the M. E. Rinker School of Building Construction. With the knowledge of the importance for a more sustainable built environment, she concentrated her graduate studies in areas such as biomimicry, renewable energy sources, life cycle analysis, value engineering, and passive design. In 2009, she earned her Leadership in Energy and Environmental Design Accredited Professional (LEED AP) credential from the United States Green Building Council.

Laura obtained a Master of Science in building construction with a concentration in sustainable construction in December 2010. In the near future, she plans on earning her professional architecture degree and her general contractor’s license. She hopes to expand on her education in sustainable design and construction and work towards improving the health of our built environment and natural environment in years to come.