BIOMIMICRY AS A STRATEGY TO ENHANCE ECOLOGICALLY REGENERATIVE DESIGN

YASEEN FATIMA SYED
19072112

MAY 2021

SCHOOL OF FUTURE ENVIRONMENTS
FACULTY OF DESIGN AND CREATIVE TECHONOLOGIES

A thesis submitted to Auckland University of Technology in partial fulfilment of the requirements for the degree of Master of Philosophy

ABSTRACT

Retrofitting and redesigning of cities has become more imperative as the pressures of climate change and rapid global urbanization continues to grow and this demands urgent responses. Unfortunately, the current design of buildings and whole cities leads to an overall degradation of natural resources and loss of biodiversity. As a result, it appears beneficial to observe and analyze how nature addresses similar issues while continuing to remain sustainable within itself.

Biomimicry is the term used to describe the imitation of these natural systems and strategies within human innovation to solve challenges. Understanding the systems of life within natural organisms and utilizing them in urban design and architecture, can be the starting point of the creation and evolution of sustainable cities that aim to become regenerative.

This thesis examines the three levels of biomimicry (*organism, behavioral and ecosystem*) and analyzes specific case studies within these to elucidate the best approach to produce sustainable and regenerative outcomes. Ecosystem based biomimicry has been shown to achieve this.

The thesis explores a complex field that correlates ecosystem functions, processes and services, and the potential design strategies required by designers in order to achieve self-sufficient architecture with ecologically improved performance. It has been concluded that the built environment must be expected to actively contribute towards building firmer ecological and social relationships as opposed to being idle contributors to Global warming and the degradation of the natural world.

Keywords: *biomimicry, systems thinking, ecosystems, regenerative built environment, regenerative design, regenerative development, humanism, sustainability, green architecture, efficiency.*

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ATTESTATION OF AUTHORSHIP

'I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgments), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.'

YASEEN SYED
MAY 2021

ACKNOWLEDGEMENTS

I owe my sincere gratitude to all those who have made this thesis possible and only because of them, my postgraduate experience has been one that I will forever cherish. My deepest gratitude goes to my supervisor, Charles Walker, without whom I could have never realised my potential in writing a Master's thesis. Whilst he gave me the freedom to explore on my own, Charles always guided me when my steps faltered. Through him, I have learnt how to question theories and how to express my ideas. His patience and support has helped me complete this thesis.

My adviser, Ricardo Sosa Medina, has always been there to listen and give advice. I am deeply grateful to him for our discussions that helped me sort out the critical thinking of my work. Architect Mick Pearce, for his insightful comments and constructive criticisms during my working experience with him. He is my inspiration and I am grateful and honoured to have had him as my first mentor in the world of Biomimicry. He encouraged me to think from different perspectives and has taught me a lot about appreciating the simple things in life.

My family and friends in New Zealand and Zimbabwe who have helped me stay positive and focused during these difficult times of *Covid19*. Their support has helped me complete my postgraduate research and I deeply appreciate them all. Most importantly, none of this would have been possible without the love and support of my mother, Nikhat Siddiqui. I would like to express my heart-felt gratitude to her. I find it extremely challenging to express my gratitude to her because it is endless. Not only is she an amazing mother but she is my best friend who has shared this entire journey with me. Therefore, it only feels right to dedicate this thesis to her.

Thank you.

CHAPTERS:

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

URBAN ECOSYSTEMS

Although they occupy barely 5% of land across the globe, cities disproportionately contribute to the degradation of the environment. This comes about as more and more people become urbanised, there is an intense amount of energy and water being used along with increased amounts of greenhouse gas emissions taking place, amongst others. Therefore, causing drastic climate change and an increase in the negative ecological impact, and loss of biodiversity (van Vliet et al.,2017). As these impacts are expected to increase and affect the built environment in the future, the hastening of redesigning and retrofitting of cities has become imperative, and has urged designers to search for less destructive and more natural solutions. The built environment is known as the main establishment for human interaction, economically, socially and culturally and is expected to adjust to the impacts of climate change (Reed, 2006).

The continuous urbanization and increased climatic change is not the only purpose of redesigning cities, but to also become accustomed to the impacts simultaneously. The imitation of nature, known as '*biomimicry*' is not a new concept and while the trend of returning to the natural world for inspiration for designing more holistic buildings has gained momentum, it is crucial for designers to understand how organisms within their natural systems (ecosystems) work to maintain a holistic atmosphere.

The challenge is to go beyond sustainability and resilience to adopt a regenerative approach to the design of buildings and cities. This means designing buildings to become more ecologically and socially responsible, rather than just minimizing the use of energy and water and other pollutants (Reed, 2006).

This thesis explores the notion of *biomimicry* at an *ecosystemic* level to address ways of conceptualising systems and solutions that offer sustainable, on-going and less destructive approaches to the designed environment. It involves '*systems thinking*' as a collective approach to problem analysis and solving, in which different elements at different levels are utilized and integrated in terms of their contribution to the whole and not just at specific individual levels (Meadows ,2008). This method is relevant to urban design and the built environment, where there has been an inclination towards labelling buildings as individual and isolated entities. Previous research on organisms and their behaviors within ecosystems sheds importance on the overall notion of *systems* being the more inclusive approach in which components and processes work towards regeneration.

THE PLACE OF ARCHITECTURE

Architecture is an interdisciplinary field that involves creating inhabitable places. Although several disciplines have made significant contributions to architecture, social science and ecological thinking are increasingly being recognized as key factors. As a result, architects are observing, learning and mimicking the natural world to produce naturally inspired designs for sustainable living. Too often, man-made methods generate designs using materials and resources that are derived in high energy intensive ways, some used incompetently eventually end up as waste. Nature creates materials within minimum resources, at ambient temperatures and does so in a way that enhances the environment rather than destroying it. As complexities related to climate change and biodiversity loss continue to increase by the day, this concept of turning to nature as an inspiration for innovative, sustainable building techniques as well as inspiration for aesthetic expression has resulted in buildings that are highly efficient, more durable and robust. Most importantly, these outcomes require less energy or fewer materials by communicating with nature using their mutual language to perform the imitated design concept. This method is termed as *Biomimicry*, the practice of imitating nature and its processes.

Architect Buckminster Fuller (1969) asked, "How to make the world work for a hundred percent of humanity, in the shortest possible time, through spontaneous cooperation, without ecological offense or the disadvantage of anyone?"

In his book, *Biomimicry in Architecture,* Michael Pawlyn (2011) responds that,

> To accomplish the mission statement made by Fuller, three major changes that we need to introduce are: achieving radical increase in resource efficiency, shifting from a fossil fuel economy to a solar economy and transforming from a linear, wasteful way of using resources to a completely closed-loop model in which all resources are stewarded in cycles and nothing is lost as waste… there is no better discipline than Biomimicry to help reveal many of the solutions that we need, than this systematic journey.(Fuller,1969, as cited in Pawlyn,2011, p.13)

The increased urbanization of more and more cities is a confirmation of the new direction of movement to adjust to current human needs. Unfortunately, this rapidly increasing urbanization results in almost a third of the global anthropogenic Green House Gas emissions (de la Rue du Can & Price, 2008). The built environment is expected to contribute actively within its capacity to provide shelter from a potentially hazardous future environment.

Biomimicry at ecosystem level is a progressive notion in the architectural vocabulary that not only accepts landscape as a site context but rather as a stimulant for architectural forms. Drawing parallels between biological organisms and components within the built environment can only go further if *systems thinking* is involved (Reed, 2006).

This thesis seeks to create a set of cohesive principles and strategies founded on a combination of qualitative methods; archival and inductive. This requires the investigation and analysis of principles and relationships within biological systems that that could form a grounding for an ecosystem based design theory. In which systems become the primary concept that ensures the use of resources within processes flows without any wastage, and conclude buildings as part of an ecosystem and not just monolithic entities. Therefore, enabling architects to design for a more regenerative future. The application of these principles and strategies would need to be well communicated within the design approach in order to gain maximum advantage.

CHAPTER OUTLINE

The thesis adopts a theoretical approach that intends to provide a better understanding of the relationship between nature and architecture and the role of *biomimicry* in facilitating this connection.

Chapters 1-4 address the definitions and literature review surrounding *biomimicry* and its introduction in architecture. Case studies are analyzed to differentiate between the three levels of biomimicry (*organism, behavioral, ecosystem*). This analysis concludes with the importance of ecosystem based design and its potential contribution towards regenerative design.

Chapters 5-7 discuss the systematic processes within an ecosystem and how the mimicry of these *systems* are useful in achieving regenerative design. A mapped study is then conducted to illustrate design strategies and principles that can be used to mimic ecosystems and create regenerative architecture.

Chapters 8-9 debate the criticism of biomimicry in relation to human achievements. As the chapters progress they discuss the economic value of biomimicry in architecture as a suitable investment in design.

Finally, the concluding Chapter 10 embraces biomimicry as a strategy to enhance ecologically regenerative design and recommends that the topic be further explored and developed for future scope.

CHAPTER 2
LITERATURE/PAST RESEARCH REVIEW

FOUNDATIONS OF BIOMIMICRY AND ARCHITECTURE

This literature review aims to give the reader an understanding of the existing literature and is divided into three parts. First, a general review of the existing theories of biomimicry, its levels and approaches. This is to provide a grounding and context for the introduction and progression of biomimicry in the architectural field. Secondly, the review seeks to provide greater detail and insight into the establishment of ecosystem based biomimicry and its benefits. Lastly, the final part discusses the importance of regenerative design and the urgency surrounding it.

The term *biomimetics* was first coined by American biophysicist and inventor Otto Schmitt in 1957, who, in his doctoral research, developed a physical device that mimicked the electrical action of a nerve. Revealing the first example of mimicry of biological means.

Furthermore, there are three new-age notable researchers in the field; Julian Vincent, Steven Vogel, and Janine Benyus. The backgrounds of these researchers differ, Julian Vincent being a professor of Biomimetics. One of the first few terms established in relation to man-made processes, materials, devices or systems that imitate nature to solve issues, usually in a more mechanical application (Vincent et al.2006). Steven Vogel is a professor of biology, and an American author as well. He wrote many books on biomechanics. And finally Janine Benyus, who is a published biological sciences author. Of these three researchers, Benyus is the most noteworthy in her attempt to promote biomimicry. In 1997, she coined the term *biomimicry* as "The conscious emulation of nature's genius" in her pioneering book, *Biomimicry: Innovation Inspired by Nature.* Moreover, Benyus went on to play a larger role in the development of a Biomimicry Institute. During her time at the institute, she developed information on identifying and understanding design translation and derived the two approaches to biomimicry, *biology to design*, and *design to biology*. After which she derived three different levels of mimicry, organism based, organism's behaviour based, and ecosystem based (Benyus, 1997).

Biomimicry is seen as the emulation of strategies observed in the living world as a foundation for design and building innovation, and has the ability to contribute to the establishment of a more sustainable architecture and urban environment (Pawlyn, 2011). ''The biomimetic concept is utilized in urban scale designs, as well as in many other smaller scale building components and materiality'' (as cited in Zari, 2020, p.3).

The introduction of biomimicry in the architectural world dates back to the 19th century, when architects sought inspiration from nature since the re-birth of science. Their aim was not just to imitate the forms of flora and fauna, but to discover methods of design parallel to the processes of evolution in nature. The Sagrada Família church by Antoni Gaudi begun in 1882, and is a renowned example of using nature's functional forms to solve a structural issue. Gaudi designed columns that resembled the branching canopies of trees to solve stagnant problems in supporting the vaults of the church (Chapin et al., 2000).

The degradation of ecosystems and rapid climate change, is an urgent issue for humans to address (Rastandeh et al.,2017). While many researchers have examined examples of biomimicry in the field of architecture to determine solutions for environmental degradation, the results have generalized all three levels (organism based, behavioral based and ecosystem based) as strong contenders (Vogel,1998). On the contrary, ecosystems remain the best known example of sustainable organization of life on this planet (Vincent et al., 2006). It is logical to therefore understand, how organisms and ecosystems work and what they ensure in the creation of a *regenerative habitat*. Comparative biomimetic case study analysis conducted by Zari (2010), recommends that ecosystem biomimicry, that is the imitation of how whole ecosystems function and the ways in which they work, can be considered the most effective type of biomimicry to combat climate change and biodiversity loss while aiming for *regenerative* systems. She concludes that this is because ecosystem biomimicry supports entire systems thinking and development, rather than just focusing on single elements (Zari, 2019).

While there is a lot of ambiguity surrounding the concept of what an *efficient* building is, it is important to understand the basis of this term. Many designers confuse the idea of *regenerative* design with that of *green architecture*. It must be clarified that there exists a distinct difference. *Green architecture* is a brand that is occupied with extracting efficiencies and savings (Mang & Reed, 2012a). Regenerative design is the practice of responsible architecture in which the natural world is engaged as a generator of architecture (Mang & Reed, 2012a).

To advance the practice and theory of regenerative design, Landscape professor John Tillman Lyle initiated a Center for Regenerative Design at the California State Polytechnic University of Pomona in 1994. He published one of the first comprehensive handbooks for regenerative design, *Regenerative Design for Sustainable Development.* Deeply apprehensive about environmental degradation and the depletion of resources, Lyle wrote about reversing the environmental damage caused by what he called “industrial land use practices” (Lyle,1994). In his view, the most fascinating and important aspect was the practice of nature’s continual cycling and recycling of materials and energy processes, which he urged be introduced into ‘industrial land use practices’ immediately. Lyle (1994) affirmed that the resulting systems would provide for “…continuous replacement, through (their) own functional processes, of the energy and materials used in their operation.” The goal of regenerative design is to create an architecture that focuses on conservation and performance by reducing the environmental impacts of a building by means of recycling and reuse (Mang & Reed, 2012a).

‘’This is because ecosystem biomimicry fits into a paradigm of whole systems thinking and change, rather than the design of single components. Ecosystem biomimicry remains the least explored aspect of biomimicry in built form’’ (as cited in Zari, 2020, p.3). In agreement with Vincent et al. (2006), one particular gap that has been identified is the lack of clearly defined principles of ecosystem based biomimicry, that architectural designers can employ in their attempt towards regenerative design. Hence, the focus of this research is directed towards the use of biomimicry of ecosystems and the framework of principles and design strategies required to translate the processes involved, into solutions that can produce ecologically regenerative designs that are suitable for human adaptation and living while maintaining environmental well-being.

HISTORICAL REVIEW

As mentioned earlier, the relationship with nature has been demonstrated throughout history. Many ancient civilizations, built monuments and temples for devotion to a higher order. All these civilizations had a strong connection with the natural world. Mathematical laws were incorporated, and the Golden Section (phi) formula was created to investigate the concept of plant and animal development. Eventually the formula became the primary proportion that aided in the designing of sacred buildings.

Benyus (1997) suggested looking to nature as a “model, measure and mentor”. To elaborate, the phrase “Nature as a model” is the imaginative principle of biomimicry, as it relays to us how it is that things are meant to be “brought forth” (Benyus,1997). “Nature as a measure” is the ethical principle of biomimicry, for it tells us that nature places principle ethical standards on what is possible for us to realize. Finally, “Nature as a mentor" is the philosophical principle of biomimicry, for it reaffirms that Nature is the conclusive source of wisdom, and is free from error. It not only shows us what we can extract from the natural world, but also what we can learn from the natural world be it in terms of design or in terms of systematic relationships. In conclusion, regeneration is the core objective of biomimicry.

While biomimicry in architecture is an upcoming concept today, some examples of early ideas of biomimicry were related to products and materials. These include:

- Spears-they were used and designed with the intention of mimicking the teeth of animals. (Organism based)
- Sneak and Pounce-this hunting technique was copied from the idea that large predators used when they would hunt their prey. (Behavioural based)

As time has progressed, various other examples can be seen in the world, some related to architecture some from other disciplines. A few common examples include:

- Hump back whale - a humpback whale inspired the wings of wind turbines.

Figure 1 (left)
Figure 2 (right)

Note. (left) Fin of humpback whale, (right) Turbine inspired by Humpback whale

- Fur and Burrs-inspired the concept of Velcro. In 1941, George de Mestral was confused by the burrs he found on his dog while playing outdoors. Keen to figure out how the burrs got stuck to his dog's fur he studied the burr under a microscope and realized the small hooks of the burr and loops of the fur allowed the burr to stick exceedingly well.

Figure 3 (left)
Figure 4(right)

Note. (left) Furs and Burrs, (right) Velcro inspired by furs and Burrs

- Gecko Feet-the small hairs under the feet of a gecko help it adhere to walls and scale across vertical and horizontal surfaces easily. This theory inspired the famous gecko tape today.

Figure 5 (left)
Figure 6(right)

Note. (left) Gecko feet, (right) Microscopic view of Gecko feet

- Birds-Inspired by Abbas ibn Firnas, a 9th century engineer and pioneer in aviation invention. Firnas experimented with flight and was the first human to fly with a pair of wings made from silk, wood and feathers. His flying diagrams based on machines were used to continue the investigation of flight in the late 20th century. Engineers continued to look at birds and mimicked their wings, shape and mode of flying. Humans were able to form airplane wings and bodies that looked almost like a bird.

Figure 7 (left)
Figure 8(right)

Note. (left) Wings of Plane, (right) Bird wings

- Shark Skin- The surface of shark skin as seen under an electron microscope, is made up of countless overlapping scales called dermal denticles. The denticles have grooves running down their length in alignment with water flow. These grooves disrupt the formation of parasites, or turbulent swirls of slower water, making the water pass by faster. This theory was translated for swimsuits. The rough shape also discourages parasitic growth such as algae and barnacles.

The resistance to bacteria has allowed the material to be used in hospitals for door handles and to cover surfaces to eliminate the spread of bacteria.

Figure 9

Note. Microscopic view of Shark skin

POPULAR TERMS OF BIOMIMICRY

Pawlyn (2011), has identified a number of ways in which biomimicry can be applied to architectural design. He discusses ideas for climate control, water and waste management and control, structural innovations, material development, and energy production, in his book, *Biomimicry in Architecture.*

In addition, Pawlyn also discusses other terms and types of biomimicry, which include *bio-morphism, bio-utilization, and biophilia*. He defined *bio-morphism* as being similar to biomimicry at organism level. As it is the direct mimicry of a natural form in design, i.e. Designing a building to resemble the shape of a flower.

Bio-utilization is the use of nature for additional beneficial purposes. This could include the use of trees to provide extra shading for windows instead of adding awnings or louvres.

Biophilia is the notion that there exists an instinctive relationship between humans and other living organisms. This would usually motivate the inspiration to use plants and other natural phenomena to create a holistic atmosphere.

Finally, biomimicry, in regards to architectural design is the imitating of natural forms, processes and systems that could be incorporated into design as sustainable solutions.

While the former two terms (bio-morphism and bio-utilization) are mainly involved in sculptural works, many designers make the connection between the two latter terms, biophilia and biomimicry. It is important to realize the fine line that distinguishes the two, therefore setting them completely apart from each other. While biomimicry is an innovative method to better building performance, Biophilia is focused on improving health and wellbeing of the user by use of evidence-based design. It encourages human experience with a building.

Garden's by the Bay: Singapore's strategy to convert *garden city* to a *city within a garden*, is a pioneering example of biophilia. There is iconic tree like structures, which are 25 meters to 50 meters in height amongst other features. They simply apply theories such as visual connections with nature, variability in airflow, and integration of natural systems, such as forest and ponds, as well as maintain the use of natural materials. Although these features do not necessarily, adhere to biomimetic principles, it somewhat heightens the human desire to connect with nature. These formulas allow human experience to take place, in that walking on the tree canopies allow for the visitor to feel as if he were walking on air. The materiality and patterns allow for the sense of touch and sight, which evokes different emotions within the user therefore creating a connection and a sense of place.

Figure 10

Garden’s by the bay

Note: Walkway at Garden’s by the bay by Grant Associates

The bridges allow for movement way above ground level that could allow for more interaction of breezes and winds that may create the illusion of *walking in the sky*.

Figure 11

Garden’s by the bay

Note: Waterfall at Garden’s by the bay by Grant Associates

Figure 11 demonstrates the idea of natural systems such as a waterfall, therefore invoking feelings of calmness that associate with water.

Figure 12

Garden's by the bay

Note: Walkways and trees at Garden's by the bay by Grant Associates

Figure 12 illustrates the form of trees and their branches, perhaps to inspire the idea of geometric pattern and natural symmetry along with various textured materials that bring the user closer to nature.

In essence, these two concepts draw upon nature in different ways. Biomimicry pinpoints the potential of life's *tested-and-true technologies* and is driven towards the idea of building betterment. Whereas, Biophilia recognizes the health benefits of human's biological connection with nature. In relation to each other, they illustrate the diversity of inspiration that can be derived from nature.

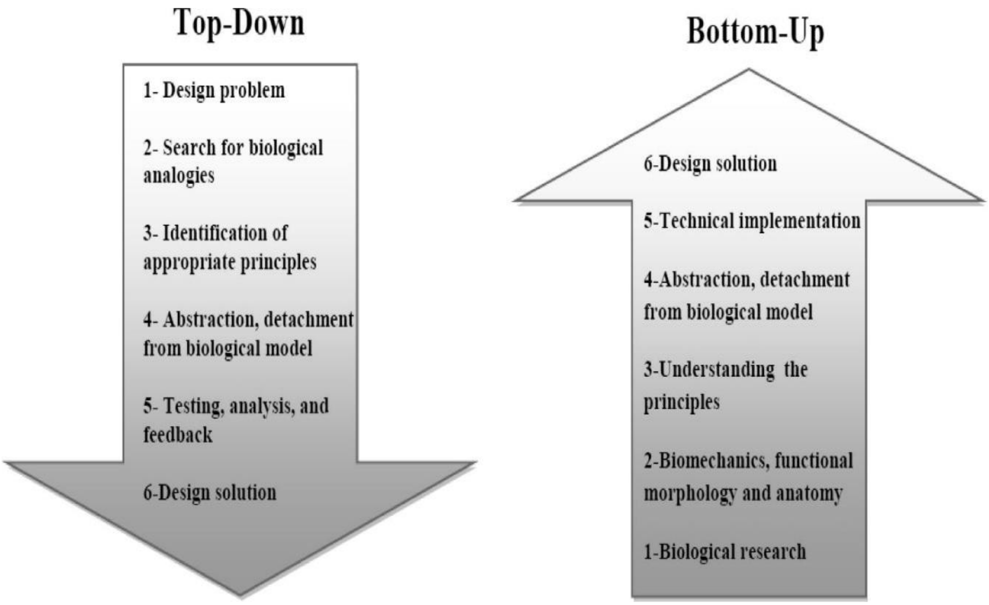
A SHIFT FROM PHYSICS TO BIOLOGY

As Physics has been the main driving factor of architectural technologies for more than a decade, it is challenging for designers to make the shift from *physics-based* designs to *biology-inspired* designs. The influence of physics introduced architectural technologies and other mediums through which most construction is performed. Biomimicry provides a suitable shift in thinking in that it would push people to realize that humans are not different from ecosystems and are in need of them for survival therefore changing the human ecosystem relationship (Mathews, 2011).

The theory of biomimicry integrates two factors: Biology and Design. Two approaches can be undertaken: *Design looking to Biology* and *Biology influencing design* (Zari ,2018). The first method is identified as defining a human need or designing issue, and looking to the ways other organisms or ecosystems solve this, termed here as Design looking to biology (*Top-Down approach*), and the second is applied when identifying a particular characteristic, behavior or function in an organism or ecosystem and translating that into human designs, referred to as Biology influencing design (*Bottom-Up approach*) (Biomimicry Guild, 2007).

Figure 13

Biomimicry top-down and bottom-up approaches



Note. Reprinted from by Biomimicry Guild, 2007.

<u>DESIGN LOOKING TO BIOLOGY</u>

The method where designers look to the living world for solutions requires designers to identify problems and biologists to then go onto match these to organisms that have solved similar issues.

This method of problem solving can be used as the fundamental approach to solving a given problem and the issue of how buildings relate to each other and the ecosystems they are part of.

Helms et al. (2008) introduced a framework of instructions for the *Design looking to biology* approach

Step 1: Define the problem-break down the problem into sub components.

Step 2: Reframe the problem – question how biology would overcome the problem

Step 3: Search for the Biological solution – use *trial and error* methods
Introduce different constraints and variables

- Broaden problem definition.
- Find the case study that provides evidence of survival under the most extreme conditions.
- Find alternative solutions within the same problem framework-how do certain organisms solve the same problem in different ways.
- Alternatively, find single solutions that solve multiple problems at the same time.

Step 4: Define biological solution – using functional decomposition to determine sub-functions

Step 5: Principle extraction – after analysing and understanding the solution, extract a principle or concept to abide by

Step 6: Principle application – translate principle into the new realm.

BIOLOGY INFLUENCING DESIGN

In this type of approach, the design process is heavily reliant on biological experts who can draw ideas from nature rather than on determined human design problems. A non-architectural example of this type of approach was that of the creation of a paint (lotus) that enables a building to be self-cleansing. This paint was derived from the concept of the lotus flower, which is known to emerge clean from swamps. Microscopic bumps, and ridges are formed on the surface thus minimizing area for dirt and water to accumulate and form mold and algae.

The breakdown of instructions introduced by Helms et al. (2008) for the *biology influencing design* approach involves:

Step 1: Identify a biological source-analyse its behavioural functions and solutions.

Step 2: Refine the biological solution – further analyse the biological solution and refine the options.

Step 3: Extract each part of the solution- after analysing and understanding the solution, extract a principle or concept to abide by

Step 4: Refine solution to non-biological needs – prepare the solution to be relevant in a non-biological context.

Step 5: Principle implementation – introduce the solution to the non-biological context with the inclusion of technological implementation.

Step 6: Principle application – translate principle into the new realm.

Whilst humans have been around since the oldest living forests and nature. It is safe to conclude that humans adapt to new environments easily and learn to use the natural resources available to them. However, as mentioned by Hawken (2007), similarities between human design solutions and strategies used by other species are not as common. This comes as a surprise as seeing that they exist in the same context and have the same range of available natural resources (Vincent et al., 2006).

However, an advantage of this approach is that while biology may influence human designs in ways that might be outside a systematic design problem, the results may have surprising outcomes such as innovations in technology and methods of design (Vincent et al., 2006). A downside of this approach is the time frame required. Biological research must be conducted and identified as relevant within the context first. After this, biologists and ecologists must be able to identify the potential of this research in the creation of original claims. Only after this can it be applied to design.

In both approaches, each step is dynamic as it can be constantly refined and have influence over other steps as a collective irregular process. The main distinction that will influence the outcome is the preliminary pathway (Harris, 2016).

Biomimicry is used in the field of design as a process of finding a solution. By using the process of biomimicry thoroughly, the resulting design outcome has potential to be enhanced in terms of improved efficiency and performance, more sustainable in terms of less resources used, wasted and released into the environment, and ground-breaking in terms of providing an exceptional solution with the opportunity for further research and discovery.

CHAPTER 3
BIOMIMICRY IN ARCHITECTURE

LEVELS IN BIOMIMICRY
Within the two approaches discussed in the previous chapter, (design looking to biology, and biology influencing design) three levels of biomimicry can be identified and mimicked to overcome a design problem (Biomimicry Guild,2007):

1. *Organism Level*-Mimicry of a specific organism.
   The organism level refers to a specific organism, i.e. a plant or animal. (This may include mimicking part or the whole organism)

2. *Behavioural Level*-Mimicry of how an organism behaves.
   The behaviour level refers to translating an aspect of how an organism behaves or relates to a broader context.

3. *Ecosystem Level*-Mimicry of an ecosystem.
   The eco system level refers to mimicking the whole Ecosystem and the common ideologies that allow them to function successfully (Zari, 2018).

According to Baumeister (2014), it is only when all three levels of biomimicry (Organism, Behavior and eco-system) have been taken into account will the design "behave like a well-adapted organism" and "create conditions conducive to life".

Deducing the concept of mimicry to three levels. There is a possibility to further investigate each of these levels. An additional five scopes to the mimicry exist. Mimicry can be initiated by means of what the design looks like (*form*), what it is constructed out of (*material*), what process was applied in realising it (*construction*), how it works (*process*) and finally what it is able to do (*function*). The differences between each kind of biomimicry are explained using a termite as inspiration in the Table below.

Table 1

A Framework for the Application of Biomimicry using the termite as an example

Level of Biomimicry	Example - A building that mimics termites:	
Organism level (Mimicry of a specific organism)	Form	The building looks like a termite.
	Material	The building is made from the same material as a termite; a material that mimics termite exoskeleton / skin for example.
	Construction	The building is made in the same way as a termite; it goes through various growth cycles for example.
	Process	The building works in the same way as an individual termite; it produces hydrogen efficiently through meta-genomics for example.
	Function	The building functions like a termite in a larger context; it recycles cellulose waste and creates soil for example.
Behaviour level (Mimicry of how an organism behaves or relates to its larger context)	Form	The building looks like it was made by a termite; a replica of a termite mound for example.
	Material	The building is made from the same materials that a termite builds with; using digested fine soil as the primary material for example.
	Construction	The building is made in the same way that a termite would build in; piling earth in certain places at certain times for example.
	Process	The building works in the same way as a termite mound would; by careful orientation, shape, materials selection and natural ventilation for example, or it mimics how termites work together.
	function	The building functions in the same way that it would if made by termites; internal conditions are regulated to be optimal and thermally stable for example. It may also function in the same way that a termite mound does in a larger context.
Ecosystem level (Mimicry of an ecosystem)	Form	The building looks like an ecosystem (a termite would live in).
	Material	The building is made from the same kind of materials that (a termite) ecosystem is made of; it uses naturally occurring common compounds, and water as the primary chemical medium for example.
	Construction	The building is assembled in the same way as a (termite) ecosystem; principles of succession and increasing complexity over time are used for example.
	Process	The building works in the same way as a (termite) ecosystem; it captures and converts energy from the sun, and stores water for example.
	function	The building is able to function in the same way that a (termite) ecosystem would and forms part of a complex system by utilizing the relationships between processes; it is able to participate in the hydrological, carbon, nitrogen cycles etc. in a similar way to an ecosystem for example.

Note. Reprinted from Biomimetic Approaches to Architectural Design for Increased Sustainability. Sustainable Building Conference by P. Zari, 2018.

The case studies discussed below, verify the approaches used (design to biology and biology to design), within the three different levels of mimicry (organism, behavioral, ecosystem) and how the buildings display these forms of mimicry at the additional five scopes (form, material, construction, process, function).

ORGANISM LEVEL

Living organisms have been evolving for over millions of years. Different types of organisms have adapted to constant changes in Earth's environment by refining their mechanisms of survival over several generations. Therefore, humans have a vast arena of examples to choose from to solve problems. Nature has already paved the way and has already addressed most of these problems, usually in energy and material effective ways.

In terms of mimicking, at organism level, it is the most straightforward level of biomimicry in that it could be the basic imitation of the pattern, shape or microstructure of a surface, such as a leaf or of a larger trait that can be seen by the naked eye, such as a kingfisher's beak.

However, as the mimicking of organisms tends to be that of a single or specific feature, rather than that of a whole system, the potential of the biomimicry aspect becomes a form of design technology that is an 'add-on' rather than being an integral part of it. Although this method may result in novel buildings with innovative technologies and materials, methods to increase regeneration are not necessarily explored.

CASE STUDY 1A- 30 ST MARY AXE (GHERKIN TOWER)

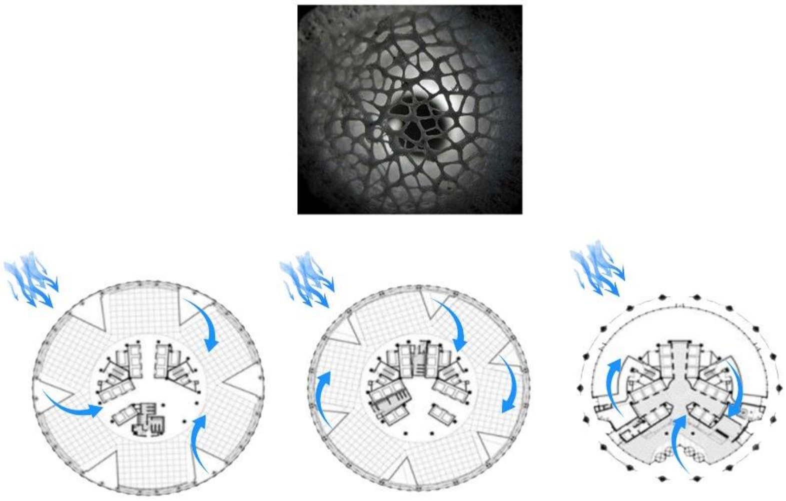
Foster and Partners may have completed 30 St. Mary Axe in 2004 in London, but its design just turned almost a billion years old. 30 St. Mary Axe offers an interesting example of biomimetic architecture at organism level with added elements from behavioral level. It uses the Biology influencing design approach (*bottom up approach*) in which a biological source is analyzed and translated into design.

The inspiration behind this building, is the Hexactinellid Euplectella aspergillum, also known as the Venus' Flower Basket (or sea sponge). The Venus Flower Basket collects nutrients from water by filtering water through spaces within its lattice. Flagella found on the inside walls of the Venus Flower Basket swirl the water upwards. It has a tubular curved body and is made up of triaxon spicules which make it stiff and aid in withstanding strong currents. The spicules are made from silicon, hence the organism appears glass-like and manages to trap natural sunlight, which gives it a more luminous glow. The Venus's Flower basket also features a lattice-like exoskeleton with a mesh like lattice that allows for it to effectively filter water and nutrients in and out of the openings of the lattice. The organism is also home to bioluminescent bacteria, thus allowing it to glow brightly in the gloom.

To emphasize sustainability, the building was designed to have natural ventilation. This was done by creating gaps between the floors, which would allow for circulation of air. The air between the extra layer of glass in the double skinned façade, not only makes the building double glazed but also enables the office space to be insulated via passive cooling and heating. The inclusion of this design feature for natural ventilation and insulation enables the building to consume half the power that a similar sized structure would use. The insulating effect keeps the building warm through passive solar energy during the winters, while the external pressure variations dispel the warmer air in the summers. Therefore, the building breathes in and out like a lung using the air flow within it, mimicking the flow of water and nutrients through the Venus' flower basket sponge.

Figure 14

Concept Diagrams to explain mimicry translation of Venus Flower basket to 30 St Mary Axe

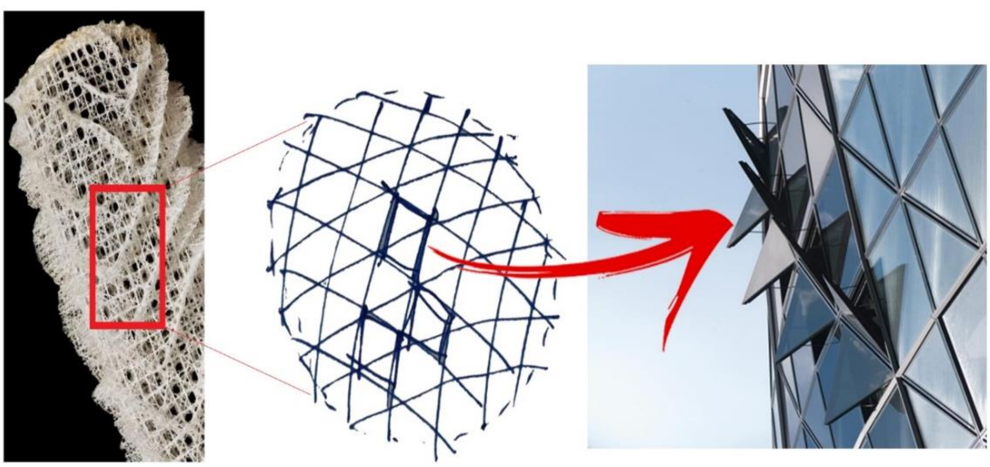


Note. Mesh pattern displayed within the plan
This allows for water to swish easily within the Venus flower basket
Similarly, the air flows easily within the building, by author Y. Syed ,2020.

While mimicking the behavioral techniques of the Venus' flower basket sponge. The building resembles the organism with its cone-like shape that stretches 180 meters tall, with a steel exoskeleton that dons stripes of navy colored, diamond-shaped pre-fabricated glass panels that wrap the building in a swirl of windows. Flexible Silica (silicon) is added onto the intersecting points of the lattice to reinforce the overall structure, allowing it to flex under stress, without compromising its structural integrity. The diagonal layout of the glass panels withstands the bending and torque stress on the exoskeleton.

Figure 15

Concept Diagrams to explain mimicry of Venus Flower basket to 30 St Mary Axe

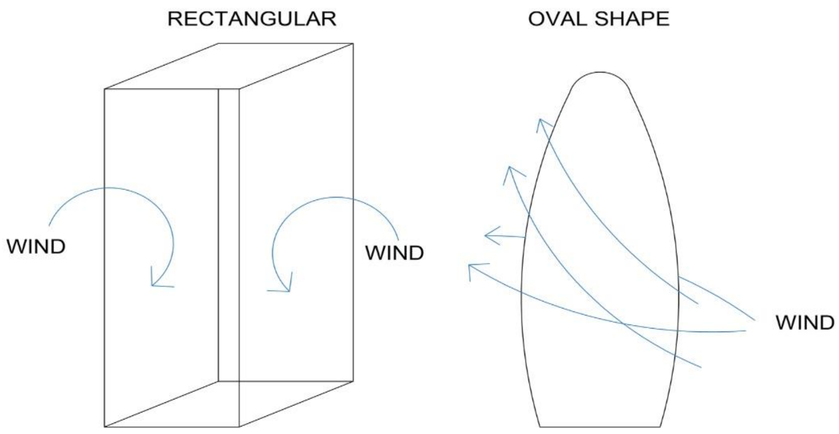


Note. The various openings on the façade mimic the lattice work of the Venus flower basket. The triangular panels that cover the building allow for airflow and sunlight penetration within the building, by author Y. Syed,2020.

The building's curved torso allows wind to easily pass around its shape unlike rectangular buildings which push the wind down towards pedestrians on the street on a windy day. In addition, the glass panels allow for sunlight penetration, illuminating the building. The openings at the lower levels harvest wind by sucking it in and swirling it upwards. The rotating floor slabs make for light wells that allow for additional natural daylight and ventilation on each level. These building features have reduced the air conditioning energy consumption by 50%.

Figure 16

Concept Diagrams to air flow around 30 St Mary Axe



Note. The wind swishes around the curved structure as opposed to rectangular buildings, by author Y. Syed,2020.

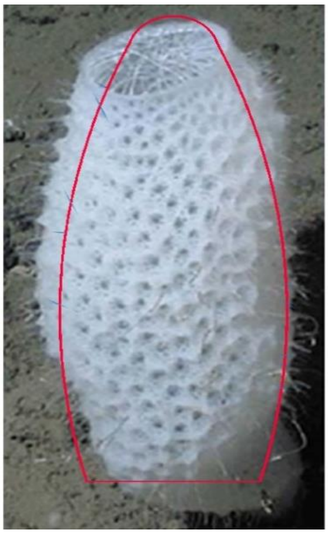
Other advantages include:

- Building wind-resistant structures
- Minimal wind blasting of pedestrians at street level.
- Fracture-resistant materials
- Provides architecture that aids ventilation
- Natural sunlight availability on each floor
- Easy self-assembly processed.

In conclusion, what the Venus Flower Basket does underwater, 30 St. Mary Axe mimics high in the air, and shows how nature models efficient design, even if it looks like a towering uncertainty.

Figure 17

Concept Diagrams to explain mimicry of Venus Flower basket to 30 St Mary Axe



Note. The overall silhouette of the building is superimposed onto the Venus' Flower basket to show the resemblance in composition, by author Y. Syed,2020.

Table 2

Biomimetic Relevancies

FORM	Resembles the Venus' flower basket. Tubular curved form.
MATERIAL	Made up of a silica-based cement, which is deposited on points of intersection in the lattice, similar to the exoskeleton of hexactinellid sea sponges made up of siliceous spicules. Glass finish to ensure transparency and sunlight penetration, making it luminous, just like the use of the triaxon spicules that are made from silicon, giving the Venus' flower basket a more luminous glow.
CONSTRUCTION	Constructed in a similar manner as the Venus flower basket, it consists of latticework scaffolding to ensure durability and flexibility against harsh winds. Curved form allows wind to swirl around the building and ensures it is not blasted downwards to pedestrians.
PROCESS	Passive solar energy during the winters keeps the building warm, while the external pressure variations dispel the warmer air in the summers. Therefore, the building 'breathes' in and out like a lung using the air flow within it, mimicking the flow of water and nutrients through the Venus' flower basket sponge.

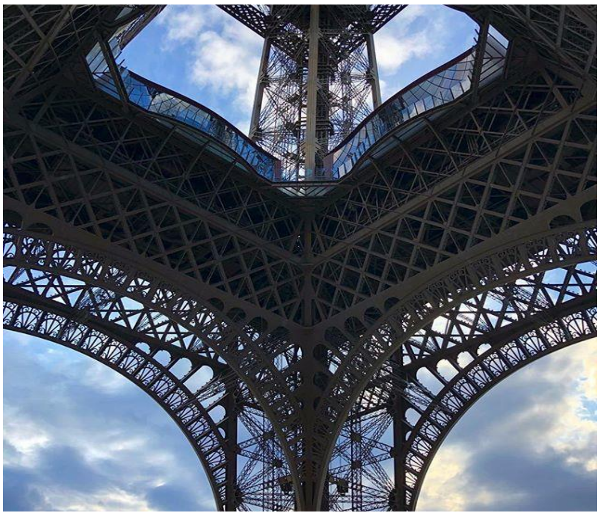
Note. Biomimetic relevancies, by author Y. Syed,2020.

<u>CASE STUDY 1B- EIFFEL TOWER</u>

Paris's most iconic landmark and the most recognizable masterpiece of the 19th century architecture - is a 324-meter-high iron lattice tower located near the Seine, on the Champ de Mars to the west of the city. The architect Gustave Eiffel (1832-1923) wanted a lightweight structure with maximum strength for his upcoming tower. Using the Design looking to Biology design approach (*top down approach*) in which a biological source is introduced to an identified design problem, he managed to overcome his design problem of durability. While researching on anatomy, the femur bone drew his attention. He noticed that the human thighbone (femur) was getting its strength from tiny tubes within it called osteons that are further composed of even tinier bundles inside called fibrils (Fratzl & Weinkamer,2007). Eiffel replicated this concept and introduced the idea of a hierarchy of trusses within trusses within trusses.

Figure 18

Internal trusses of the Eiffel Tower



Note. Image by D.Hammer ,2007.

Figure 19

Trusses within trusses, Femur bone made up of osteons, further dividing into fibrils.

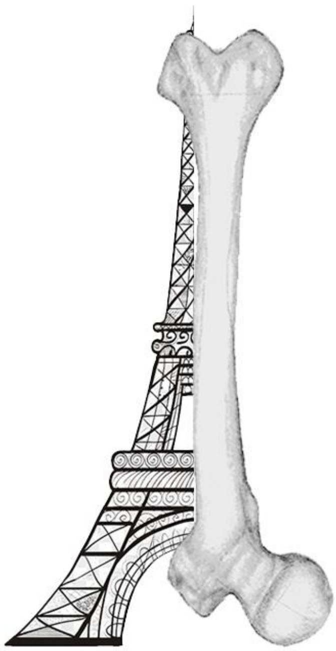
Note. Image by Philosophy Forum ,2006.

Eiffel realized that the femur is wide on top and grows narrower as it goes down the leg. He studied how the bone was reinforced and strengthened along lines of stress and realized that turning the bone upside could make for a much stronger base which could withstand the bending and shearing effects the tower would face due to the wind.

The open-lattice iron structure was made up of four massive arched legs, set on stone piers that were made to curve inwards until they joined into a single, tapered tower. In total 18,000 pieces were used to build the tower, joined by two and a half million thermally assembled rivets. Every piece was individually designed and manufactured for the project in Eiffel's factory in Paris.

Figure 20

Mirrored image of Femur bone and Eiffel Tower



Note. The image depicts the structural concept mimicked to create a strong base, by author Y. Syed,2020.

Table 3

Biomimetic Relevancies

FORM	Resembles the Female femur bone.
MATERIAL	Made up of tiny tubes within it called osteons that are further composed of even tinier bundles inside called fibrils.
CONSTRUCTION	Constructed in a similar manner as the femur bone, the tower consists of trusses within trusses to ensure durability and flexibility against harsh winds. Inverted femur bones, gives inspiration to the base of the tower, providing more durability at the base.

Note. Biomimetic relevancies, by author Y. Syed,2020.

<u>CASE STUDY 1C – ESPLANADE THEATRE</u>

The Esplanade Theatre and commercial district in Singapore, designed by DP Architects and Michael Wilford, hosts an elegant building skin, which influenced the look and function of the interiors. Inspired by the multi-layered Durian plant with its tough thorn-covered husk. The Durian plant uses its semi rigid pressurized skin to protect the seeds inside, as the building protects its visitors inside. The building exterior is part of an elaborate shading system that adjusts throughout the day to allow sunlight penetration while it protects the interiors from overheating.

The sunshades were inspired from spikes on the durian fruit. The shape allows for a sense of tranquillity and is typical in traditional Singaporean culture. The East and West facades are smothered with intense sun and therefore clamp longer sunshades. While the North and South facades were much smaller. The theatre is a steel structure.

Figure 21

Mirrored image of Esplanade Theatre and Durian plant

Note. Image by Parametric Architecture ,2014.

Environmentally the building has achieved the following:

- The dynamic sun shield allowed the building to be a landmark and contains a Singaporean personality from its biomimetic inspiration from the Durian Fruit, which is considered the *King of Fruit* in Asia.
- Comfortable environment for the users
- Allows natural light to enter whilst protecting the interior from over heating
- Lowered the usage of Air conditioning

The usage of biomimicry in an architectural sense allowed the following:

- Brought a sense of culture to the building
- Usage of geometry and patterns
- Usage of sun path to provide protection in needed area

Table 4

Biomimetic Relevancies

FORM	The building resembles the durian fruit
MATERIAL	The building mimics the skin of the fruit with sunshades that resemble the spikes on the durian fruit.

CONSTRUCTION	Constructed in a similar manner as the durian fruit grows. Careful placement of elements such as sun shading devices and textures, shapes, orientation creates the impression of a durian like structure.
PROCESS	Inspired by the durian fruit and its semi rigid pressurized skin to protect the seeds inside, the building uses a similar concept and protects its visitors inside. The building exterior is part of an elaborate shading system that adjusts throughout the day to allow sunlight penetration while it protects the interiors from overheating.

Note. Biomimetic relevancies, by author Y. Syed,2020.

BEHAVIOUR LEVEL

This is a deeper level of biomimicry application as it relates to the impersonation of the processes effective in the natural world. It involves the study and emulation of a series of operations or behaviors displayed in the natural world such as manufacturing, building, recycling and transportation. For instance, nature is known to manufacture structures at ambient temperatures and pressures using non-toxic solutions (mainly water) compared to the human method of bending, melting, casting and manipulating huge blocks or raw materials at exceptionally high temperatures and pressures. Biomimicry at behavioural level, is not necessarily mimicking the organism, but rather how it behaves or uses strategies for survival in relation to a larger context.

CASE STUDY 2A – EASTGATE BUILDING

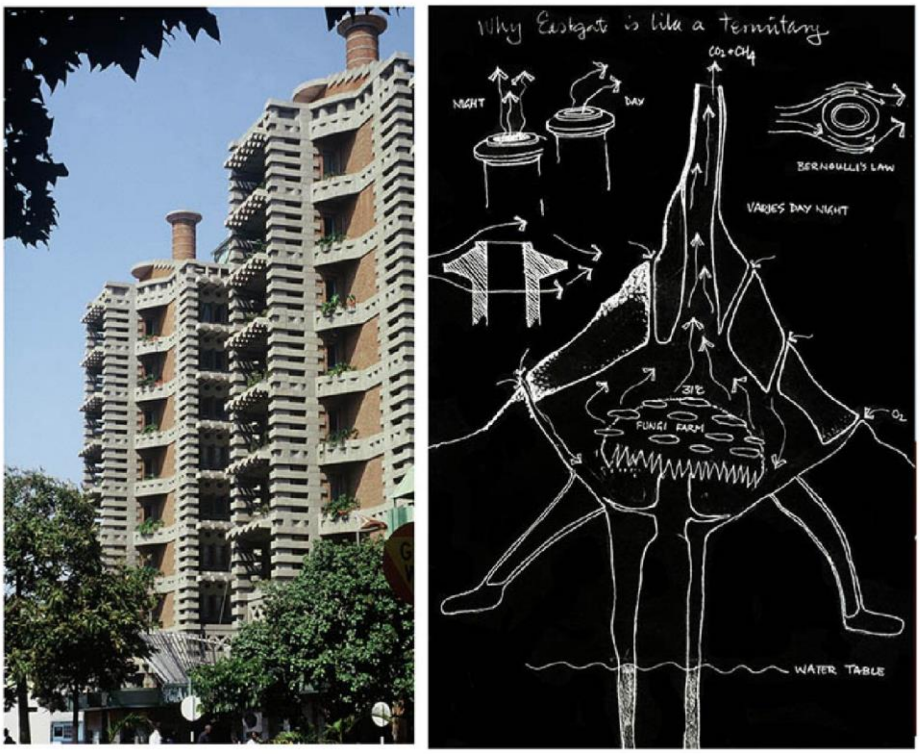
An example of this level of biomimicry is that of the East gate Building in Harare, Zimbabwe. The architect mimicked the behaviour that the termite would display while building the mound. Designed by renowned architect, Mick Pearce, this building is grounded on methods of passive ventilation and temperature regulation observed in termite mounds, in order to create a thermally stable interior environment. The use of the biology influencing design (*bottom up approach*) approach is applied, where the traits of an organism are being translated into the design process.

‘’East gate came about my understanding and ideas for a self-cooling building, when Arup approached me, in 1990 to design a building that is self-cooling, I got thinking about termites and their ability to design a habitat that is self-sufficient, that’s how East gate was born,’’ (Pearce, 2016).

Termites in Southern Africa are known to build mighty mounds in which they harvest a fungus, their main primary food source. This fungus needs to be kept at exactly 30.5 degrees Celsius. With the external temperatures ranging between 1.6 degrees Celsius at night to 40 degrees Celsius during the day, the termites manage to maintain their fungus by continuously opening and closing vents throughout the mound during the course of the day. Using a system designed for convectional currents, the air is sucked in at the lower parts of the mound, made up of muddy walls. After this the air is pushed upwards towards the peak of the mound. This process is a continuous one, in order to maintain regulated temperatures throughout the mound.

Figure 22

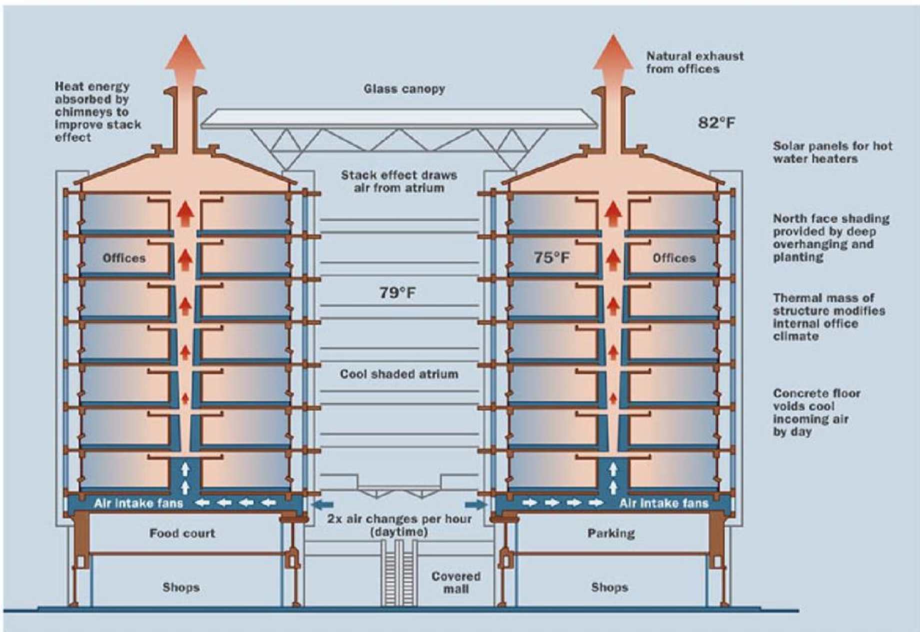
The masonry work and chimneys of East gate



Note. The image depicts the masonry work and the chimneys of East gate and how they compare to the tunnels within a mound, by Pearce Partnership,2012. Retrieved from : *http://www.mickpearce.com/biomimicry.html*

Figure 23

Sketch of a typical termite mound



Note. Figure 23 displays a section of East gate and shows the flow of air within the building, by Pearce Partnership,2012.
Retrieved from : *http://www.mickpearce.com/biomimicry.html*

Termites tend to cool themselves, or else they suffocate. Therefore, they use or rather create towers to trap and absorb wind inside their mounds. This is usually during September, October and November when the heat is extreme. Once the rains start, the towers melt down and the termites can then cool themselves, using the moisture from the clouds, wind and rain. The mounds are similar to *lungs*, as the structure inhales and exhales as temperatures rise and fall throughout the day, (Pearce, 2016).

Native Zimbabwean stonework and the self-cooling mounds of African termites inspired the East gate Building design. Temperatures stay controlled all year round with dramatically less energy consumption using architectural design methods inspired by nature. Zimbabwe has a moderate climate due to its altitude. With temperatures ranging from 7-27 Degrees Celsius, passive heating and cooling act as a probable substitute to mechanical methods. This mid-rise building designed by architect Mick Pearce in alliance with Arup engineers, has no conventional air-conditioning or heating. It uses less than 10 percent of the energy of a conventional building its size through passive cooling and heating techniques (Pawlyn, 2011).

The East gate building operates in a similar way to that of termite mounds in that outside air is drawn in through vertical ducts on the first floor. This air is either warmed or cooled by the building mass depending on which is hotter, the building concrete or the air. It is then pushed into the building's floors through the central spine of the two buildings before exiting via chimneys at the top. The building's complex system of vents and fans circulate air much like a termite mound does, with a resulting reduction in heating and cooling costs of 90 percent (Doan,2012).

Overall, the building had a few issues to tackle such as:

1. <u>Distribution of air</u>
   The air distribution systems were to distribute suitable quantities of external and recirculated air possessing desired qualities to a structure's internal spaces.
2. <u>Propel Air Flow</u>
   The air distribution systems must drive flow within a building using natural and forced means of ventilation
3. <u>Seasonal Response to Temperature</u>
   Design and materials that standardise internal temperature in reaction to external changes minimize energy consumption, pollution, and noise, while improving air quality and user comfort.

The lessons learnt from termites included:

1. <u>Evaporative cooling</u>
   Many animals use the physical properties of water to thermos regulate through the process of evaporation
2. <u>Natural Ventilation</u>
   Natural ventilation in some animal-built structures is achieved by design
3. <u>Tracheal Compression</u>
   Tracheal compression is a respiratory strategy used by insects such as beetles, crickets and ants equivalent to the inflation and deflation of vertebrae lungs.

Figure 24

Eastgate Building in Harare CBD

Note. Image by Arup
Retrieved from:*(https://albinorhinoblog.wordpress.com/2016/03/19/biomimetic-architecture/)*

Table 5

Biomimetic Relevancies

FORM	The building looks like it was made by a termite, it looks similar to a termite mound.
MATERIAL	Made up of sand and masonry blocks similar to a mound. Channels within the building expel hot air like that of a mound.
CONSTRUCTION	Constructed in a similar manner as termites would make their mounds. Gathering of earth in similar positions, creating towering forms, with channels in between.
PROCESS	Chimneys to dispel air and spaces between floor plates to allow the expulsion of hot air, and incoming of cool air, to maintain regulated temperatures within the structure. Mimics the tunnels and channels like that of a termite mound.
FUNCTION	The building functions in the same way that it would if it were constructed by termites, it may also function in the same way that a termite mound would in a larger context.

Note. Biomimetic relevancies, by author Y. Syed,2020.

CASE STUDY 2B – COUNCIL HOUSE 2

Designed by Architect Mick Pearce, Council House 2 (CH2) is designed revolving the analogy of a tree. The biomimetic approach was based off the *design to biology* theory. The entire building demonstrates volumes when it comes to the usage of biomimicry. In that the western façade is a replica of the epidermis layer of trees. This was done to monitor and control the external climate. The northern and southern facades were ideas inspired by the bronchi of a tree. These were designed as ventilation stacks that allowed for air ducts on the exterior. The stacks were angled and were made much larger at the top, allowing for control of natural light and encouragement of airflow. The eastern façade consists of the service core and toilets. This façade emulated the tree bark as it acts as a protective layer which filters lights and air in the wet areas behind it. Overall, the overlapping layers of the façade are constructed with perforated metal and polycarbonate in order to fix the louvres on.

Figure 25

Analogy of a tree like structure incorporated into CH2 Building

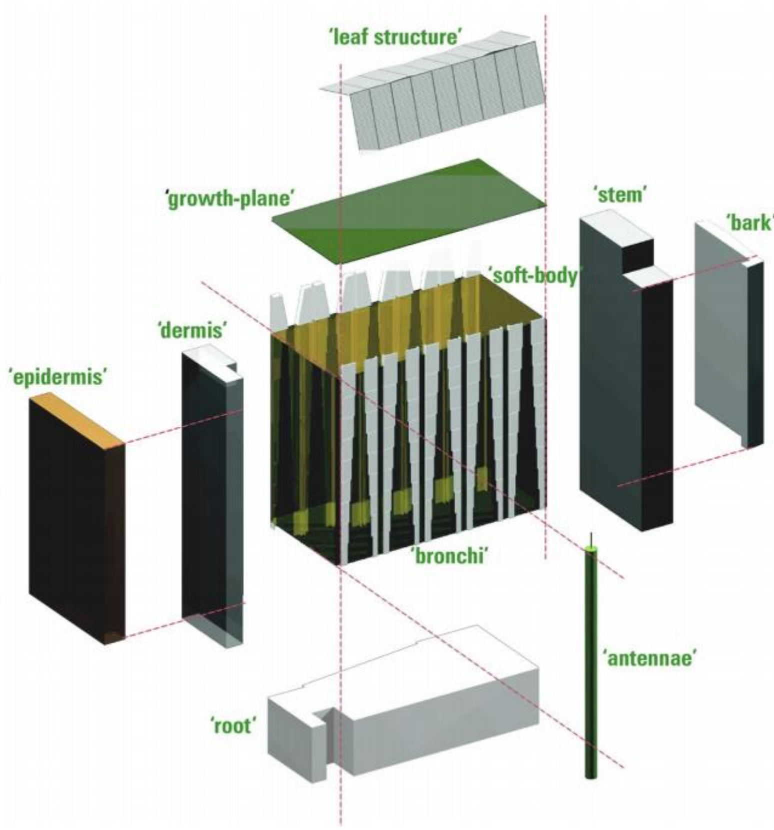
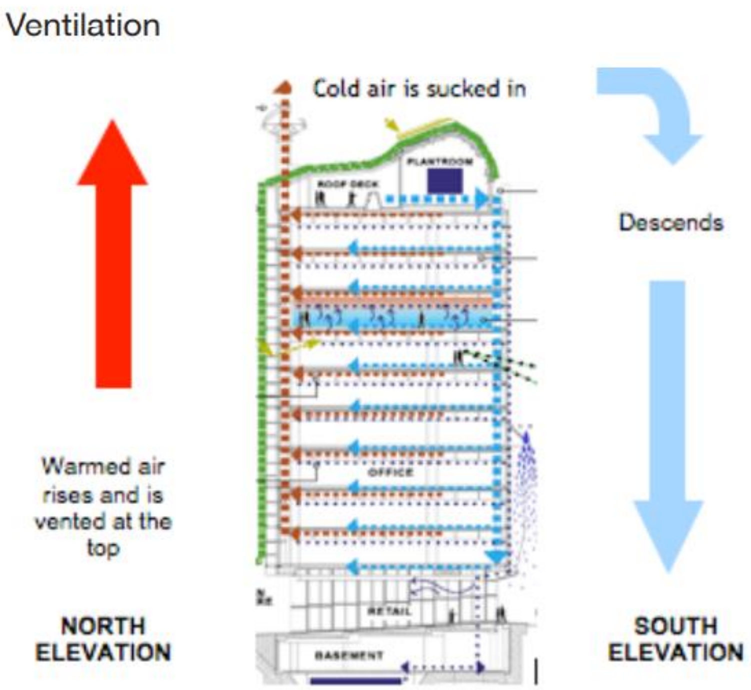


Figure 26

Building facades and cores

Figure 27

The passive heating and cooling system was inspired by termite mounds like that of the East gate building.

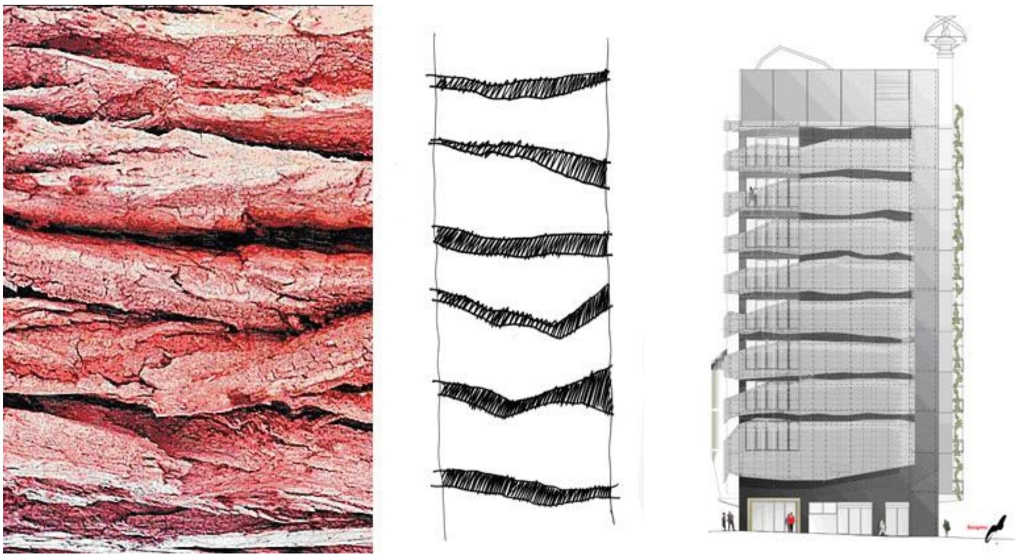


The 10-storey sustainable building was designed in such a way to set new standards for low energy and high occupant comfort, bringing together a range of innovative technologies not only for the benefit of those who work in it, but also to serve as a sounding board for the broader industry.

As mentioned by Mick Pearce, (2016) ''CH2 consumes 80% less energy and 70% less water than the average building its size, with these savings, the CH2 is estimated to pay for itself, within 5-6 years.''

Figure 28

The bark inspired eastern façade



Note. Image from Charrette, resulting in drawing and image by Design Inc.

Table 6

Biomimetic Relevancies

FORM	The building has elements that look are borrowed from the analogy of a tree.
MATERIAL	One façade emulates the bark of a tree that acts as a protective layer which filters lights and air in the wet areas behind it.
CONSTRUCTION	Constructed in a similar manner as a tree would grow. Careful placement of elements such as bark like textures, shapes, orientation creates the impression of a tree like structure.
PROCESS	Inspired by the bronchi of a tree. It was designed as ventilation stacks that allowed for air ducts on the exterior. The stacks were angled and were made much larger at the top, allowing for control of natural light and encouragement of airflow. Similar to how a tree would grow and branch out its leaves as canopies, to control light and air.
FUNCTION	The building functions in the same way that a tree would in a larger context.

Note. Biomimetic relevancies, by author Y. Syed,2020.

CASE STUDY 2C-WUHAN NEW ENERGY CENTRE

Utilizing the Biology influencing design approach (*bottom up approach*) in which a biological source is studied and translated into design elements, the Wuhan New Energy Center commonly known as the Energy Flower is designed to resemble the Calla Lily flower. With a 140-meter tower in the center the structure is surrounded by lower towers designed in the shape of flowers, which are covered in vegetation. The center tower expands upwards creating a bowl-like depression, whose surface is covered with large solar panels that are facing the sun, soaking up rays just as a real plant would. A vertical axis wind turbine buds up out of the center of the tower to produce wind energy. Rainwater is collected in the bowl-like depression below and a 120-meter solar chimney in the tower helps eject hot air from the building while pulling in cooler air below.

This building would make Wuhan the most sustainable city in China, as well as the most sustainable building in the world. It was designed by Soeters van Eldonk architects and Grontmij. Their main focus was to ensure the building was indeed a low energy building and not just a structure with bolted on renewables. While the building mimics the form of the Calla lily flower, it also imitates the behaviour of the flower, in terms of photosynthesis. The sustainable building is designed in such a way that it will be able to provide its own shade during the hot summers, while the solar panels arrayed on the roof will generate energy while heating and cooling the entire building. The collected rainwater will be used to supply water throughout the building. The building aims to apply the principle of natural ventilation. Therefore, this building concept, fits into the ideals of Biomimicry at Behavioral Level.

Figure 29

Mirrored Image of Calla Lily flower and Wuhan Energy Centre

Note. Shape and systems comparison ,by author Y.Syed,2020.

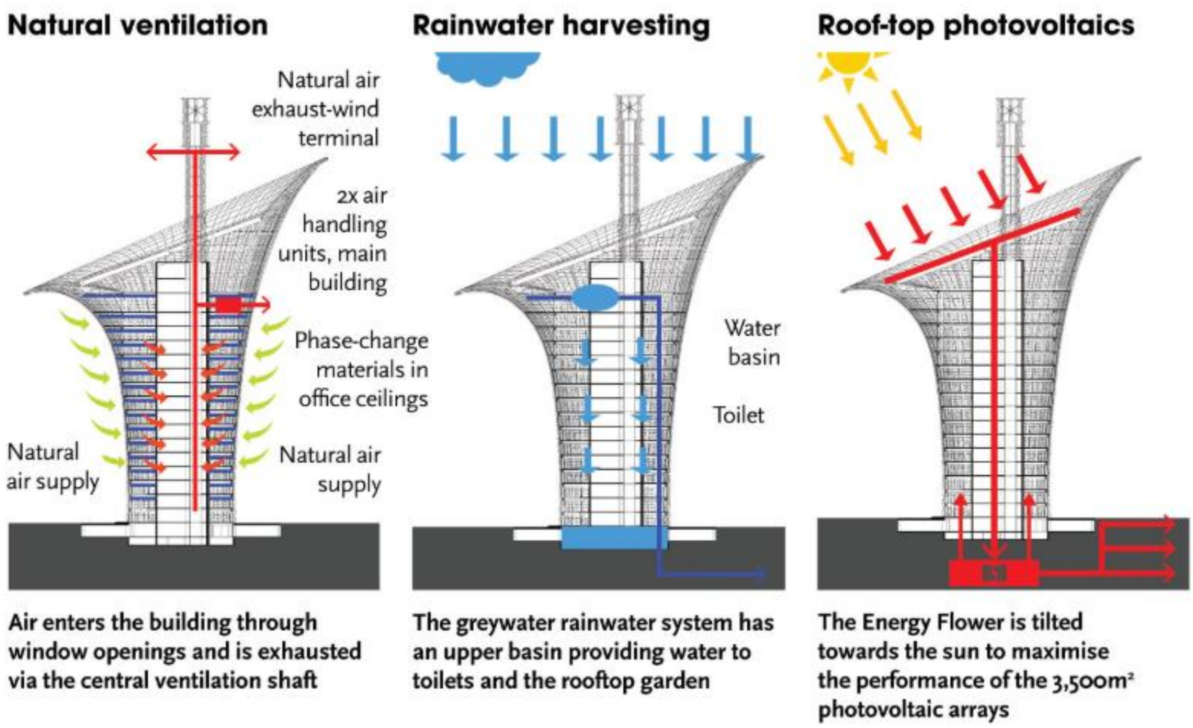
Figure 30

Wuhan New Energy Centre

Note. Wuhan New Energy Centre by aasarchitecture

Figure 31

Wuhan New Energy Centre Sectional Diagrams



Note. Reprinted from Wuhan New Energy Centre, by China in Bloom (CIB SE Journal) ,2015.

Table 7

Biomimetic Relevancies

FORM	Resembles Calla Lily flower.
CONSTRUCTION	Constructed in a similar manner as the Venus flower basket, it consists of lattice work scaffolding to ensure durability and flexibility against harsh winds. Curved form allows for wind to swirl around the building and not blast downwards to pedestrians.
PROCESS	140-meter tower in the center the structure is surrounded by lower towers designed in the shape of flowers, which are covered in vegetation. The center tower expands upwards creating a bowl-like depression, whose surface is covered with large solar panels that are facing the sun, soaking up rays just as a real plant would. A vertical axis wind turbine buds up out of the center of the tower to produce wind energy. Rainwater is collected in the bowl-like depression below and a 120-meter solar chimney in the tower helps eject hot air from the building while pulling in cooler air below. While the building mimics the form of the Calla lily flower, it also imitates the behaviour of the flower, in terms of photosynthesis
FUNCTION	The building functions like a plant, it produces for itself while contributing to the larger context.

Note. Biomimetic relevancies, by author Y. Syed,2020.

At behavioural level, all the case studies discuss above have shown common features, such as designing based on the idea of self-cooling and ventilating. Whether the inspiration is drawn from termites or from plants, the idea remains similar.

ECO SYSTEM LEVEL

This is the deepest and most holistic level of mimicry. It involves studying and emulating the behavior and performance of natural organisms in relation to their ecosystem. Natural organisms survive and sustain themselves due to their ability to thrive, function and perform in tandem with their natural ecosystem. A theory that almost everything can relate to is that nothing exists or operates in seclusion in the natural world, every organism is an integral part of a biome that is also part of a larger biosphere. Each cell has a part to play in this phenomenon called *life*.

Benyus (1997) and Vincent (2007) describe the mimicking of ecosystems as a vital part of biomimicry. It assures of a sustainable resolution to human trials as it enables human environments performing and doing what all well-adapted organisms have learned to do, which is creating conditions conducive to life and generations to come. However, in order to achieve this level of biomimicry and to attain sustainability it is recommended that the designer implement certain principles.

THEORETICAL PRINCIPLES OF ECOSYTEM BIOMIMICRY

The ecosystem principles discussed below are derived as a set of universal norms for the way most natural ecosystems function. They can be used as the foundation for further research to completely understand the diverse and imperative characteristics of each of the basic principles. Korhonen (2001) points out that mimicking at a basic level (organism-based) is insignificant in terms of increasing overall performance of the built environment. Opportunities exist for design to be positively integrated with global orders through a thorough understanding of ecology beyond this basic level.

The ecosystem principles listed can be applied to the design process in a more interesting way, by transforming them into a set of questions that can be asked at each stage of the design (Biomimicry Guild, 2007; Charest,2007).

Research conducted by Zari (2018) explains ecosystem principles as follows:

- Ecosystems are reliant on contemporary sunlight.
  -Contemporary sunlight is the main source of energy.
  -The sun path is a mechanism for spatial and time organization.

Solar radiation is the only source of energy directly or indirectly available to organisms. Majority of ecosystems exist by utilizing contemporary sunlight, which is converted by photosynthesis into biomass, which forms the basis of the food chain (Kibert et al., 2002). The sun acts as a system for measuring time, direction, orientation and spatial organization. An example of this would be, during certain seasons in the year, certain species are seen migrating while others begin the process of pollination and flowering.

Using this principle in the built environment could result in a significant change. The sun would be the source of energy that can be stored and organized according to climate change. This could result in a significant reduction of environmental impacts while maintaining significantly positive physical and psychological health impacts. (Kellert,2016).

- Ecosystems optimize the whole system rather than its components alone.
  -Matter is cycled and energy is transformed effectively.
  -Materials and energy are used for multiple functions.
  -Forms tend to be determined by functions.

Ecosystems use energy and materials in a way that optimize and contribute towards the whole system rather than individual components (Kelly,1994). In an example of both materials and energy effectiveness, organisms in these ecosystems tend to use materials for more than one function (Benyus, 1998). This allows for less wasted energy and surplus energy that can be used for other functions such as reproduction, overall health and growth.

In relation to the built environment, the mimicry of this aspect would ensure effective material cycles and well managed flow of energy that could challenge conventional building attitudes and minimize wastage of natural resources that are already in shortage.

- Ecosystems are dependent and are in harmony with their local conditions.
  -Materials tend to be obtained and used locally.
  -Local abundances become opportunities.

While species exist within ecosystems, they tend to be in relationships with other organisms in close proximity (Allenby & Cooper, 2007). Organisms use the resources within their immediate reach and are well adapted to the specific climatic conditions that they are exposed to. The ecosystem as a whole is well adapted to its local conditions and remains in harmony with the other organisms around it due to the extensive relationships created between them.

Incorporating this theory in the built environment would require a thorough understanding of the particular environment. Buildings can be seen working in tandem with their environment (site) and with other buildings. This is seen as creating opportunities and relationships within the place by obtaining local materials and variables.

- Ecosystems are diverse in terms of components, relationships and information.
  -Diversity is correlated to resilience.
  -Relationships are complex and therefore operate in various hierarchies.
  -Ecosystems are made up of interdependent, cooperative and competitive relationships.
  -Emergent effects tend to occur.
  -Complex systems are self-organised and well distributed.

A diverse system is often described in biomimicry as a stable one, capable of adapting to change. In that through this kind of stable networking, should one element or organism fail, it does not disrupt the entire system. Ecosystems are organized based on hierarchy (Kibert et al., 2002). They are governed by different principles and at different scales. This cooperation between individuals and species is important in the creation of ecosystem relationships and dynamics.

Translating this into the built environment would ensure relationships between buildings and other variables are given as much consideration and importance during the designing of the individual building itself.

- Ecosystems create conditions favourable to sustainable life.
  -Production and functioning are environmentally gentle.
  -Ecosystems enhance the biosphere as they function.

As ecosystems advance from development stages to more complex stages with time, due to the activities of the organisms within them, the system tends to becomes more flexible with the idea of change. Making it capable of supporting more organisms with longer and more complex life cycles (Odum, 1969; Faludi ,2005).

Introducing this idea to buildings would allow for architects to develop buildings that could be part of a cycle that could keep regenerating itself whilst moving forward, rather than reaching a stage of redundancy.

- <u>Ecosystems adapt and evolve at different levels and at different time frames.</u>
  -Constant instability achieves a balance of non-equilibrium.
  -Limitations are seen as creative mechanisms.
  -Ecosystems have the ability to self-heal and replenish.

Adaptation and evolution allows organisms and ecosystems to persist through the constantly changing, cyclic environments they exist in.

The impact of this principle in the architectural world could result in phenomenal changes and contributions that can challenge the idea of the 'lifespan of a building'. This could mean incorporating additive techniques that could inspire adaptive functions and perhaps even techniques that could help in the expiration of particular aspects that are no longer needed as the building evolves. Mechanisms that promote building evolution and self-maintenance could be incorporated as well.

Although the principles are inspired from nature's ecosystems it should be noted that they are applicable towards building designs for future innovations. The main aim of regenerative design is to develop designs that can be progressive as time continues.

<u>CASE STUDY 3A –THE EDEN PROJECT</u>
The built environment is the most abundant ground for Biomimicry. Based off the blueprints of plants, Architect Jolyon Brewis of Grimshaw Architects, wanted to showcase various plants of the world and human dependency on them. He took to the concept of biomimicry when he based the design of the building off spirals of pine cones, sunflowers and pineapples. The design was developed using Fibonacci's sequence (0, 1, 1, 2, 3, 5, 8, 13, 21, 34 ...) where every number is the sum of the previous two.

With the main goal behind the Eden Project was to create an environment to educate people about the living world. This project illustrates how biomimicry and architecture can achieve sustainability. By implementing local and holistic approaches. Using locally sourced materials and reconnecting with history and ecology. It can provide an outline for the successful integration of nature with architectural and engineering projects, moving us towards achieving a more sustainable future. Keeping that in mind, The Eden Project is designed based on the principles of biomimicry at Ecosystem level. Making it a lavish initiative and home to the world's largest indoor rainforest.

The client wanted a building that was made responsibly, with locally sourced materials that would increase energy efficiency while reducing the building's environmental impact wherever possible. To begin with, the site selected was a China clay quarry that was uneven and was in need of being quarried. This being the sole challenge of building a large greenhouse on an irregular land that shows constant change. While the principal concept of design came from plants, the form of bubbles provided a prototype for the form of the structures. Seeing that bubbles adapt to the surface they land on, the architects sought this as the solution to ever-changing ground levels. Studying carbon molecules and the concept of phyllotaxis (Mathematical basis for plant growth, derived by the Fibonacci sequence) the structures of the project were formed.

The Eden project consists of three biomes. The roofs of the biomes are made from hexagonal shapes. They are made from a material called Ethylene Tetrafluoroethylene (ETFE) that is lightweight in comparison to glass and still manages to remain stable. The use of these ETFE panels required less steel work and allowed for more sunlight penetration into the biomes. The hexagonal cushions trap air between two layered panels, thus acting as a thermal blanket, which results in a building that requires less electricity to heat. In addition, ETFE resists corrosion and maintains itself, it is easily recyclable, and hence at the end of its useful life it will provide technical nutrients for a new product. The result is a highly efficient and sustainable structure that weighs less than the air contained within it.

Figure 32

Hexagonal external panels of roof

Note. Image by Tal,E.J. 2012. Retrieved from*:*
https://en.wikipedia.org/wiki/Eden_Project#/media/File:EdenProjectRoof.jpg

The three biomes are designed to represent three distinct climates found across the globe.

1. The Humid Biome
2. The Warm Temperate Biome
3. The Roofless Biome

The Humid Tropics Biome, a multi-domed greenhouse, recreates the natural environment of a tropical rainforest. The warm, humid enclosure is home to hundreds of trees and other plants from rainforests in South America, Africa, Asia and Australia such as banana, coffee, rubber and giant bamboo plantations. The temperature is maintained at a tropical level with ambient moisture levels (Pawlyn, 2011).

The Warm Temperate Biome has the same multi-domed structure as The Humid Tropics Biome. However, it houses varied plant life such as olives and grapes that grow in temperate rainforests in Southern Africa, the Mediterranean and California. Similar to tropical rainforests, temperate rainforests receive a high volume of rain every year, thus making them an ideal environment for varied plant life. But since they are farther away from the equator than tropical rainforests, they do experience distinct seasons (Pawlyn, 2011).

The third and final Biome in the Eden Project is the Roofless Biome, an open area with varied plant life from the local Cornwall area, as well as similar climates in Chile, the Himalayas, Asia and Australia. Each biome, grows plants and vegetation that is used as supply to locals. One of the main goals for the Eden Project was to become less dependent on external sources, including water wastage. Water is harvested to keep the plants watered and almost two thirds of the water needs are provided from the water collected on site. Underground drainage systems collect the water coming on to the site, which is used for irrigation and toilet utilities. The rainwater that falls onto the Biomes is used to irrigate the plants inside, as well as top up the rainforest waterfall and maintain the high levels of humidity inside.

Figure 33

Eden Project biomes, located on uneven land.

Note. Eden Project aerial view, by William,T ,2018.

Retrieved from: *(http://www.edenproject.com/sites/default/files/ep-t1/HERO-Eden_by_Tamsyn_William_0.jpg)*

Table 8

Biomimetic Relevancies

FORM	The building looks like an ecosystem in which plants are grown and matured. While mimicking the form of bubbles, it manages to house its inhabitants while remaining adaptable in terms of shape and form.
MATERIAL	Made up of hexagonal and pentagon shapes, as inspired by carbon molecules and bubbles. The material used is ETFE, which is lightweight and transparent to ensure sunlight.
CONSTRUCTION	Constructed in a similar manner to carbon molecules and plants using the Fibonacci sequence. Each ETFE panel is different and unique as the distinctive patterns of nature (spirals of pine cones, sunflowers and pineapples).
PROCESS	Captures and converts energy from the sun and stores water.
FUNCTION	The building functions in the same way that is similar to the environment, in that it utilizes relationships between processes, it takes part in solar and hydrological cycles, and performs in a larger context.

Note. Biomimetic relevancies, by author Y. Syed,2020.

CASE STUDY 3B –Sahara Forest Project Qatar, Tunisia and Jordan

In the dry, desert regions of Namibia, mainly in coastal areas where morning fog is ample and rainfall is uncommon, fog harvesting is a vital source of water. A native species is known to survive by collecting water from the fog courtesy of its distinctive back structure. The Namibian Fog-Basking desert beetle has an array of hydrophilic bumps across its waxy hydrophobic surface that collect and route droplets of water straight into the beetle's mouth. Allowing it to quench its thirst. This technique has been applauded and has become a world-wide phenomenon.

Figure 34

Stenocara gracilipes beetle directing water down its back towards its mouth

Note. Stenocara gracilipes beetle of Namibia by Inmaterria.

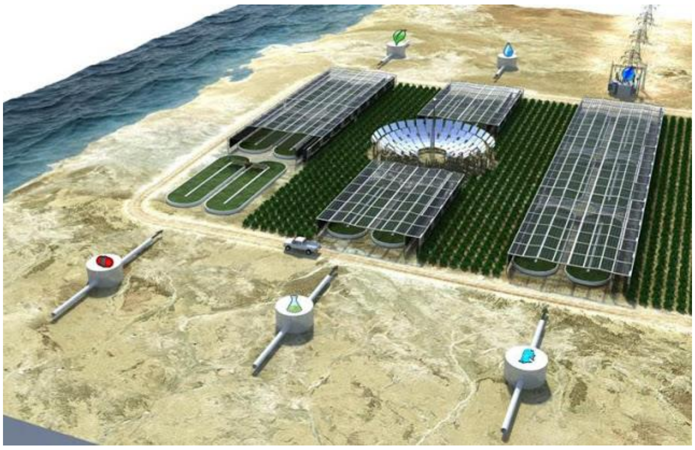
The Sahara Forest Project was a greenhouse project that drew inspiration from the Namibian fog-basking beetle, that aims to combat extreme climate change in an arid environment (Pawlyn, 2011). The architectural design team endeavoured to come up with an eco-system design that was not just sustainable but also regenerative. Three essential mechanisms headed the design of the greenhouse, the most important one being the creation of a saltwater cooled greenhouse, followed by concentrated solar power (CSP) and finally technologies to aid in desert vegetation growth.

Charlie Paton, one of the designers of the project, created systems that would provide evaporative cooling and humidification in the greenhouses using salt water. The inclusion of saltwater cooled greenhouses would present appropriate conditions for year-round cultivation. The systems would take the evaporated air and condense it to fresh water ensuring heat throughout the night within the greenhouse. This method would produce more than enough water for the interior plants. The excess water would be discharged out for the surrounding plants to grow. The evaporation process would produce salt that would be crystallized at different stages. Each stage would consist of an extraction of various elements. Usually, calcium carbonate and sodium chloride would be extracted first from the saltwater. These elements were both compressed into building blocks. The remainder of the elements that were extracted were utilized in other processes to minimize on waste (Pawlyn, 2011).

Solar power was another sustainable feature to be introduced. It involved using solar tracking mirrors to concentrate heat from the sun which would in turn produce steam to run the turbines, thus producing zero carbon electricity. This was rendered twice as effective as photovoltaics. The aim of the Sahara Forest Project was to restore the growth of forests and to adopt methods that would lead to the reverse of desertification.

Figure 35

Sahara Forest Project Qatar, Tunisia and Jordan



The architectural contribution of this sustainable attempt has been widely celebrated and appreciated in the Middle East and Africa, where barren deserts occupy almost 60 percent of the land. Essentially the contribution made by this system helps to grow more vegetation and produce water that can be used by the nation eventually, should the project be replicated and expanded around the desert. The contribution made by biomimicry at this level, not only makes a difference in the architectural sector but also plays a role in the economical aspect of the county by combating the idea of export and import and eventually builds the country in a way that it can become a self-sufficient system.

Table 9

Biomimetic Relevancies

FORM	The building looks like an ecosystem that a (beetle) would live in.
MATERIAL	Uses water as the primary chemical medium.
CONSTRUCTION	The systems are designed to mimic the behaviour of a beetle, and how it survives within its ecosystem. Principles of succession and increasing complexity are expected over time.
PROCESS	The structure works in the same way as a (beetle) ecosystem works. It collects, converts and stores water and captures, converts and stores energy from the sun.
FUNCTION	The building functions in the same way as a (beetle) environment. It utilizes relationships between processes; it takes part in solar and hydrological cycles, and performs in a larger context.

Note. Biomimetic relevancies, by author Y. Syed, 2020.

CHAPTER 4

PRINCIPLES OF BIOMIMICRY AT ECOSYSTEM LEVEL IN DESIGN

As discussed previously the principles of biomimicry are derived in regards to an ecosystem level. From there stems another set of specific principles that provide a basis for further study in designing within the limitations of architecture, available technology and knowledge.

These principles are as follows:

- Adaptation
- Material as a system
- Evolution
- Emergence
- Form and behaviour

Adaptation:
Adaptation being the evolutionary process that ensures a species is at ease and is well suited within its current habitat. It also refers to the process of endurance, in which an organism begins to naturally accept its current situation and environment (Hensel et al., 2010).

Material as a system:
Material system does not only place importance on the material elements of a building alone, but rather describes a system in which, material, form, structure and space are co-related. The production and assembly of these systems along with their interaction with environmental influences (Hensel et al., 2010).

Evolution:
Like the natural world, architecture is a form of imitated life, subject to dynamic principles of replication and selection. With constant change and progression, the idea behind evolutionary architecture is to achieve a balanced interdependent relationship that is similar to the relationships seen in the natural environment (Frazer ,1995).

Emergence:
This process emphasizes on the existence of a complexity that generates new systems, capable of displaying new properties of interaction (Frazer ,1995).

Form and behavior:
The consequences of relating these principles to architectural design could range from a redefinition of when a building is considered finished. Designing it to be more dynamic over time, as well as being able to respond to new conditions and possibly to become self-sustainable (Frazer ,1995).

From the case studies discussed above, it seems that in this level of biomimicry, there is creation of a *regenerative environment*. An environment that is self-sufficient. A cluster of buildings that can be likened to a *Rube Goldberg* machine. In which, the action of one triggers the initiation of another, eventually resulting in achieving a stated goal or merely just continuing within the cycle. Thus, allowing the concept of continuity to be introduced.

CHAPTER 5
REGENERATIVE DESIGN

WHICH LEVEL OF BIOMIMICRY IS MORE PROMISING AND WHY?

Biomimicry at each of the above-discussed levels has its own advantages and disadvantages. While the first two levels mimic at a *basic* level, it is only fair to conclude that biomimicry at ecosystem level has a more promising outcome as it eventually takes into consideration continuity and longevity. Ecosystem biomimicry falls into the paradigm of whole systems thinking and changing, rather than the designing of individual components. Even though ecosystem biomimicry remains the least explored type in the built environment, the examples discussed above show more logical solutions for global issues and future development. This level allows for the development of a building throughout time and it aims to create a sense of place for the building within the realms of people, nature and the overall environment. It goes beyond sustainability and has the potential to become regenerative.

As designers, when we begin the process of design, we always tend to fast-forward our thinking to the final product, sometimes not bearing in mind the lifecycle of the building after it is built. Does it complete a span of ten years and then get demolished, after which do we repeat the cycle and build another? Alternatively, does it continue to stand and contribute to the environment and ecosystem around it? The solution may be found in the mimicry of ecosystems. Ecosystems follow an order and demonstrate systematic references as to how the built environment can function like a complex living system that is able to adapt and adjust to change, rather than just remaining as unrelated building objects within a context (Zari, 2018).

DESIGNING BUILDINGS FOR THE FUTURE
Designers tend to design buildings with lifespans that far exceed the speed of change of the technology used to service them. While considering the technology that is currently available, the progression of this technology and the results it may produce must be taken into consideration for future use in the building. There is need to keep an eye on new advancements in technology. Sometimes we encounter a new technology that may not be suitable at that given time. This could be due to the cost or the client's opinion of risk. The overall idea is to ensure that cities and buildings become regenerative. Regenerative in this context means designing with an aim to produce measurable ecological and social health outcomes rather than design, which aims to simply minimize energy or water use, or the emission of pollutants (Reed, 2006).

Although there are currently several approaches to sustainable design in architecture, very few have proven effective at a massive scale. Biomimicry readily offers a relatively new solution to the issue of sustainability. It requests the combination of multiple disciplines working together to produce buildings and systems that are not only more valuable to its users but also give back to nature. If implemented well, imitating these natural processes could prove worthy in the field of architecture and in the economic world.

REGENERATIVE BUILDINGS AND ITS IMPORTANCE

An ecological opinion by experts understands that the relationships between systems is necessary in order to support them to regenerate. Mang and Reed (2012a) stress this key concept by mentioning that regenerative thinking helps in redefining the built environment —from the generic building-centric definition to one that consists of relationships between infrastructure and natural systems, as well as the culture, economy and politics of communities. The terms *green*, *sustainable* and *regenerative* are widely used along the same lines of literature, however they do have qualitatively different values. While green design and sustainability aim to reduce damage to the remaining natural world and human health, by using resources more efficiently. Regenerative design is an advocate for a much more holistic integration between humans and nature. Setting goals around the need to revive human and natural communities into a co-existing cluster, where humans exist in a symbiotic relationship with the living lands they inhabit (Mang & Reed, 2012a). Where the focus is shifted from single elements to systems, the transformation of transactions to relationships, and from design as art to design as thinking, from habits of destruction to awareness of the need for resilience.

DEFINING GOALS FOR REGENERATIVE DESIGN

The core element for regenerative design is not just the performance of a single building, but rather of its living context. The exclusive socio-ecological system in which the building is just one of several interdependent and interactive components and dynamics. Therefore, regenerative goals are created and achieved based on the contribution of the built environment to the regenerative capacity of a larger context. This includes determining its capacity as a source of increasingly healthy life for all its primary members as well as for the larger systems that it is dependent on.

The following terms are drawn from the work of Regenesis and Lyle (1994).

Evolution-designing beyond improving current systems performance to embedding continuous improvement through time and variables.

Human and Nature Relationships-recognizing the caring side of humans and their contribution to the place and its capacity to continue to thrive.

Growing Capacity vs. Producing Things- set specific goals that address aspects of operations, organization and aspiration

Operational capacity goals: focuses on growing the potential of resource based-energy, materials and support systems, that enable the evolution of life in a place.

Organizational capacity goals: focuses on how to utilize the built environment and the design process to enhance the distinctive character of a place as something to be cherished.

Aspirational goals: aligning human and natural creativity, to create opportunities for all participants to make significant and meaningful contributions to their place.

CHAPTER 6
ECOSYSTEM BIOMIMICRY FOR REGENERATIVE DESIGN

DEVELOPMENT OF ECOSYSTEM CONCEPT AND ECOLOGICAL DESIGN

The Use and Abuse of Vegetational Concepts written by Arthur Tansley in 1935, made way for an entirely new concept of ecology. He suggested the word 'ecosystem' as a label for the interactive system of living organisms and their non-living counterparts within a habitat. Tansley and a few other biologists were the first to verbalize a systems view of life in that era. He came up with the philosophy of how life was strategically organized and maintained an order within a specific context. He concluded that living organism and their physical environment were a connected entity, and that they could not be removed from their special environment, in which they formed a physical system (Tansley, 1935).

For Tansley and other apprehensive ecologists the ecosystem presented a valuable framework for investigating the effect of human activities on natural systems and resources. After a few years, the concept was further explored and redefined. Taking into account the social (*human actions*) and built ideologies (*infrastructures*), it became a framework for sustainable urban planning and progression.

In the later years of the 1950s and 1960s, Eugene and Howard Odum set the foundation for the progression of ecology into modern design and they used the ideology of ecosystems as the main ordering structure of the environment. They issued *The Fundamentals of Ecology*, in 1953, as the first handbook of ecology. Their work stood out, garnered attention from many disciplines, and highlighted the importance of relationships between natural ecological systems. Howard Odum went onto further develop a set of key theoretical concepts and theories alongside some methodologies to understand the flow of energy within any scale of system. He focused on water bodies in his main research and went on to initiating the extensive use of wetlands as water quality improvement in ecosystems.

ECOSYSTEM LEVEL BIOMIMICRY AS A METHOD FOR REGENERATIVE BUILT ENVIRONMENTS

Most literature in relation to regenerative design, suggests that understanding and analyzing organisms and the ecosystems in which they are based is vital for the process of developing a regenerative design method (du Plessis, 2012). A part of this stems from the fact that ecosystems have not been altered by human influence, and yet they manage to remain efficient and have a well maintained organization of life. Ecosystems are generally more resilient and are able to survive frequent changes that may be brought about by abrupt fluctuations within the norm. While combating these occasional fluctuations they are able to continue to support the survival of their organisms (Gunderson & Holling, 2002).

The idea behind the introduction of biomimicry into the design world is not only to see the living world as a plethora of ideas, and exploitation of resources, but to mainly note the systems of organization that can be applied to buildings and human context. Mimicking these ecosystems can suggest insights into how the built environment could function more like a complex living system within the natural world and how buildings can inter connect with nature, become self-sufficient and contribute towards the greater picture of the future.

In the early 1960's, cybernetic Gordon Pask claimed that architects are system designers who must show an interest in the organizational system of buildings. In his understanding, Pask (1969) mentioned that architects would resolve problems using architectural rules. Even though they designed systems, they did not position themselves as system designers. Architect John Frazer expressed interest in Pask's adaptive systems theory and how it may be applied to architectural design processes to improve forms and functions (Haque , 2007). Pask's concept consisted of creating architectural systems that would design a building. This began from relationships to components and followed the bottom-up design approach. It focuses on behaviors, which would co-evolve with its environment as well as its own components, creating an orderly system using biomimetic principles within a holistic design approach.

ECOSYSTEM PROCESSES (HOW THE ECOSYSTEM OPERATES)

Generic architectural design is often limited within the constraints of building boundaries, site requirements, budgets and project completion times. Ecosystems on the other hand, are dependent on factors such as climate, biodiversity and resources as catalysts to initiate their entire system.

Ecosystem processes are generally very considerate of the resources that are being used and ensure almost no waste. They stand by the ideology that the waste of one component is considered as an opportunity for another component. There is use of shared energy, and reduction, if not total elimination, in duplication of effort to ensure the system works comfortably producing efficient results without having to use additional materials and resources unnecessarily.

These processes have become popularized as industrial ecology today, where the waste of one component is considered the *treasure* of another. Denmark has been ahead of the line in promoting the idea of industrial ecology. Ever since the 1970's quite a few industries in Denmark have supplied or sold by products and wastes to other industries. Asnaes, the leading coal-fired power plant in Denmark, sold processed steam to Statoil (an oil refinery) and Novo Nordisk (a pharmaceutical plant). Some of Asnaes' remaining heat was supplied to the town's heating scheme, thus reducing the total of domestic oil burning systems in use (Ehrenfeld & Gertler, 2008). Furthermore, the left-over heat was also used to heat the water of Asnaes' commercial fish farm. The local farmers would then use the sludge from the fish farm as fertilizer. By treating some of its waste, Novo Nordisk sold high nutrient liquid sludge to farmers. Statoil delivered cool and purified wastewater to Asnaes, which helped in reduction of Asnaes' freshwater extraction. Apart from this, Statoil removed sulphur from its surplus gas and sold all of its cleaned surplus gas to Asnaes and Gyproc (a plasterboard factory). The removed sulfur was sold to Kemira (a sulfuric acid producer). By desulfurizing its smoke, Asnaes sold the resulting calcium sulfate to Gyproc as an alternative to mined gypsum, which was being imported earlier (Ehrenfeld & Gertler, 2008).

ECOSYSTEM FUNCTIONS (WHAT THE ECOSYSTEM DOES)

Understanding the functions of an ecosystem and translating them into buildings and urban settings may make them more biomimetic but not necessarily as good as generic designs in terms of ecological performance. This is due to the fact that mimicry of functions often happens at an extremely metaphorical level, as what works for nature might be slightly different in terms of requirements for the built environment. However, this is where the built environment needs to learn to adapt, to what is *necessary* over what is *luxury*. Application of the functions of ecosystems in upcoming designs could result in more dynamic buildings and cycles, which are more fruitful in the end.

ECOSYSTEM SERVICES (THE OUTCOMES)

This framework of strategies integrates the functions and processes of the ecosystem with the experiences and expectations of the user. Potschin and Hines-Young (2011) explain that, the functions of ecosystems directly or indirectly have an impact in determining the benefits for its users (humans and other living organism).

According to the Millennium Ecosystem Assessment (2005) and Potschin et al. (2011) The processes (how they operate) and functions (what they do) of these ecosystem lead to services (the outcomes).

These services can be categorized into four main outcomes:

1) Provision-the production of food and materials locally
2) Regulation-the regulation of climate and other natural processes
3) Supporting-the use of the sun as the primary source of energy
4) Cultural-recreation and leisure.

Using design strategies to achieve these services can become the drive behind improved ecological performance of buildings.

In architecture, these services are often disguised in the form of natural spaces of relief such as green pockets, parks, green spaces, wetland, lakes and many more. Initially these features may be seen as aesthetic expression but they have underlying benefits such as invoking human well-being, recreation, cooling effects as well as cultural expression.

The processes, functions and services are seen as a balanced equation and are slowly being translated into urban settings today. Examples of these include air purification, water flow regulation and carbon sequestration amongst others (Gomez-Baggethun & Barton, 2013). The aim is to create buildings and urban settings that can reach beyond sustainability. To create buildings that become self-reliant and regenerative within a system. A building or urban system that can produce renewable energy at ambient temperatures and pressures, produce food, materials, clean air and water and many more without compromising and challenging climate and biodiversity.

Apart from attaining healthy and less destructive methods in production of necessities, it goes without saying that one of the most important realizations of this process, is the creation of a holistic environment in which humans can learn to co-exist with other organisms by realizing their importance and contribution in facilitating this new improved system.

According to O'Connell and Hargreaves (2004), Innovative ecologically regenerative advancements could act as *filters* (devices that purify air and water), *creators* (of food and materials) and *producers* (of energy) for the remaining built environment that continues to degrade ecosystems. If architects were to include these regenerative pointers within their designs and were to accomplish the slightest aspects of ecosystem functions, there is potential for some causes of climate change and biodiversity loss ascribed to the built environment to be eased. At the same time, the built environment could become more adaptable to climate change, while simultaneously generating favourable biodiversity outcomes.

CHAPTER 7

FRAMEWORK OF DESIGN STRATEGIES AND PRINCIPLES

A FRAMEWORK OF DESIGN STRATEGIES AND PRINCIPLES TO ACHIEVE REGENERATIVE DESIGN

Benyus (1997), recommends that designers should always consider optimisation and effectiveness as the focal aims of a building design, “Nature always doubles up on functions, think of a feather –waterproof, air foil, self-cleaning, insulating, beauty for sexual reproduction. What can we expect from our buildings?” (as cited in Peters, 2011, p.46).

Benyus (1997) terms ecological design as “place-based”, paying attention to a site’s exclusive ecology and particular land type, “Every building has to pull its ecological weight. Maybe we have a CO2 storage metric to meet and we ask, can the building sequester carbon in concrete based on the functions of coral?” (as cited in Peters, 2011, p.46).

From all the theories and information gathered within this field, it should be noted that the primary goal of introducing regenerative design is to:

- Reduce loss in biodiversity
- To adapt to climate change

Therefore, many of the strategies and principles of design should relate to these two themes as the main goals when designing at ecosystem level. As discussed in the previous chapter, the equation for determining a framework of strategies could be calculated using the following formula,

Process + Function=Service

(How it works + what it does= outcome for humans and other living organisms)

The following ideologies were mapped out to understand the relationships between the theories and processes discussed above:

Process + Function=Service
How it works + what it does = outcome for humans and other living organisms

Process (*how the ecosystem operates*)

1. Evolve to survive:

The constant addition and incorporation of information to ensure steady performance. To be able to include theories and strategies that are encouraging in a process or cycle.

Function (*what the ecosystem does*)

- Replication of strategies that Work-Repeat successful approaches
- Integrate the unexpected-introducing blunders and mishaps in ways that can lead to new forms and functions.
- Reshuffle information-exchange and modify information to create alternative options

Process (*how the ecosystem operates*)

2. To treat waste as an opportunity:

To conservatively take advantage of resources and opportunities around us. Materials and energy need not to be wasted. To use a particular material and to harness a particular form of energy that is available without having to compromise the entire system. To ensure that one component's waste becomes another component's fuel.

Function (*what the ecosystem does*)
As designers, we can initiate the use of materials and energies by:

- Creating multi-functional design-meet multiple needs and expectations with one sturdy resolution.
- The use of alternative solutions and low energy processes, minimizing the use of energy by bargaining on the required temperature and pressure.
- Recycling of all materials-to be able to re-use and not waste materials.
- The creation of a 'loop' in which the unwanted materials of a process can be diverted into another process that may require these 'unwanted' materials.
- Fit form to function, in that select for shape or pattern based on need.

Process (*how the ecosystem operates*)

3. Adapt to changing conditions:

To be responsive towards ever changing contexts

Function (*what the ecosystem does*)

- Maintenance through self-renewal by adding materials and energy that will challenge the system and allow it to heal simultaneously.
- Creation of a sense of resilience through addition of variations-by ensuring the smooth continuation if the cycle or system even when a variation is introduced at any given point
- Incorporation of diversity-inclusion of processes, forms and systems that meet a functional need.

Process (*how the ecosystem operates*)

4. Integrate development alongside growth:

To invest in opportunities that ensure that there is development in the process whilst growth continues

Function (*what the ecosystem does*)

- Assemble units one at a time to ensure build-up of components
- Create conditions to allow components to interact and move towards an enriched system

Process (*how the ecosystem operates*)

5. Be familiar with local advantages and to be responsive towards them:

Fit into the local surrounding

Function (*what the ecosystem does*)

- Create relationships-find value in circumstances that build up both sides.
- Use readily available material and energy-build using accessible materials while gathering help from freely available energy thus materials will last longer as they are familiar with the climate already.
- Use phenomena that have shown success in repeating themselves.
- Learn from feedback-use modifications to ensure appropriate cyclic reactions.

Process (*how the ecosystem operates*)

6. Use of processes that do not cause further harm:

Use chemistry that supports life

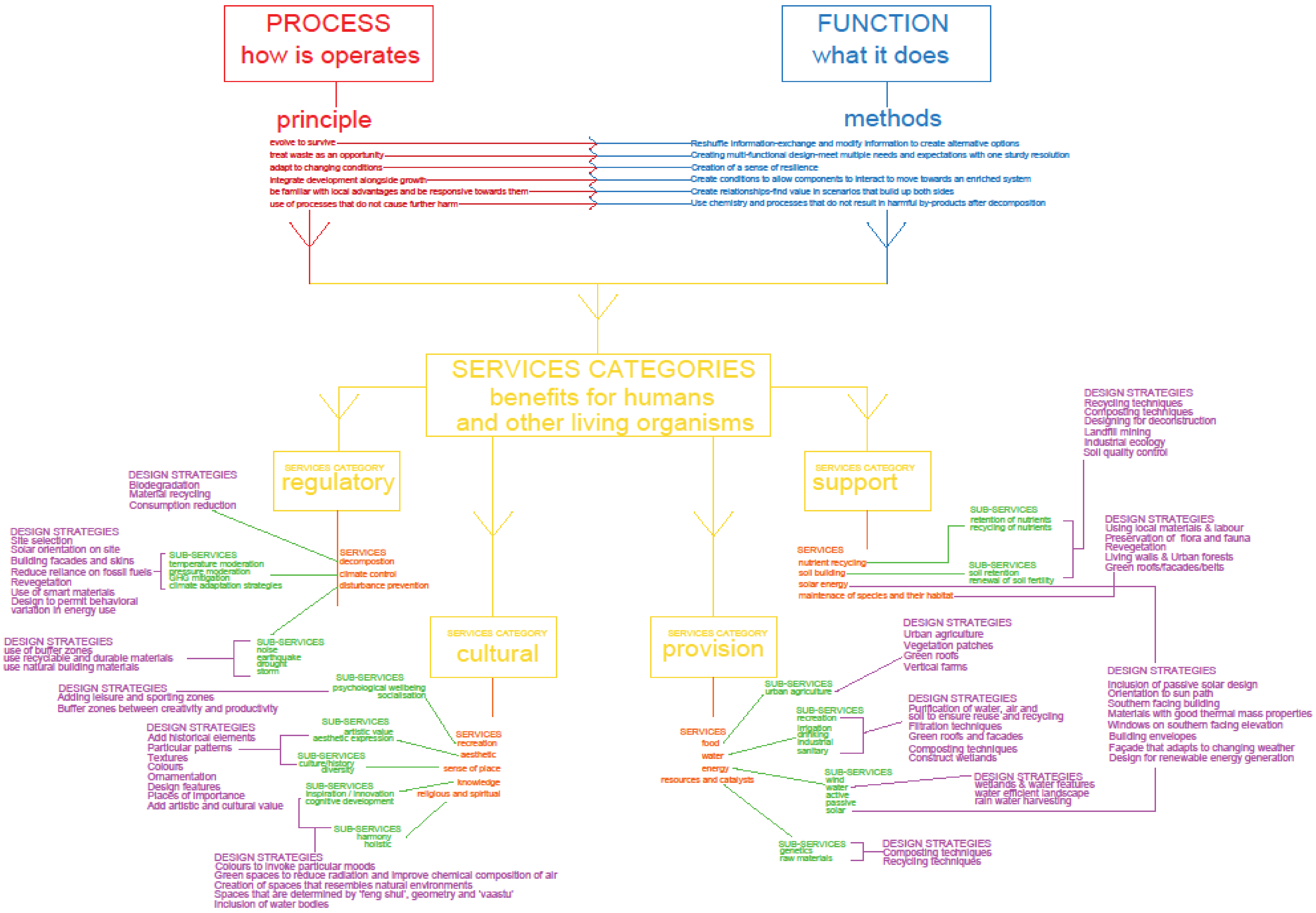
Function (*what the ecosystem does*)

- Only use what is necessary in the most logical way to avoid any sort of waste and damage to the environment.
- Use chemistry and processes that do not result in harmful by-products after decomposition.
- Use of water as a solvent.

Using the ESA (Ecosystem services analysis) system derived by Zari and Hecht (2020) and the principles derived above from various theories within the field, a map is generated to analyse and to create a comprehensive tool kit for designers to apply within their design schemes to achieve regenerative ecosystems. Using the four categories of service types applicable to the built environment (Regulation services, provision services, supporting services and cultural services) as primary outcomes, we can further expand them into ecosystem service categories and sub categories that we wish to achieve within different building designs and urban settings.

Figure 36 (below)

Ecosystem Based Biomimicry, design strategies mapping.



Note. Ecosystem Based Biomimicry, design strategies mapping, in relation to services, functions and processes required, by author Y. Syed,2020.

DESIGN STRATEGIES TO ACHIEVE SERVICES AND / SUBSERVICES

1. CULTURE:
   (Aesthetic, recreation and well-being, sense of place, cultural diversity, sense of knowledge, spiritual and religious space)

a) Aesthetic: According to Manzini (1994), aesthetics represents the way a historical period and the values it contains take shape, it becomes a way of expressing a synthetic and therefore understandable form.

Design strategies:
In this effort to create conversation with nature, many architects try to focus the center of action with the addition of landscape. The building becomes an extension of the natural landscape thus using landscape design techniques to arrange the spatial configuration of architecture.
The factors that establish the relationship between a building and its site depend on a number of reasons, such as, topography, space and geometry. In addition, it actively depends on its ecological, climatological and function processes.
Greenery enlivens the space with its color, serves as a contrast to the built, artificial, grey mass, within a noisy and polluted environment, and arouses aesthetic pleasure.
Inclusion of water bodies invoke particular experiences of calmness and increase moisture and coolness.
Add artistic value and inspiration.

b) Recreation and psychological well-being

The idea of comfort and well-being as the definition of sustainability have become quite the global theme. Society is aware of the benefits that come about from human interaction with the natural environment. These reactions are sensory stimulating and help to promote our wellness in physical, psychological and health terms.

Design strategies:
Adding leisure, sporting spaces for outdoor activity, and socialising spaces as buffer zones between creativity and productivity.
Addition of open spaces with arrangements of greenery that resemble natural environments.

c) Sense of Place and cultural diversity

Design strategies:
Introduction of historical and cultural aspects by introducing
Particular patterns
Textures
Colours
Ornamentation
Design features
Places of importance

d) Sense of Knowledge

Design strategies:
Green spaces and more holistic spaces to encourage mental well-being thus inspiring learning, and focus based activities.
Use of certain colours and textures to create a sense of place and atmosphere.

e) Spiritual and Religious space

Design strategies:
Colours to invoke particular moods.
Inclusion of Zen corners to allow for detoxification of human minds.
Green spaces to reduce radiation and improve chemical composition of air.
Creation of open spaces with arrangement of greenery that resembles natural environments.
Ornamentation.
Spaces of religious importance that are determined by *feng shui*, geometry and *vaastu*.

2. SUPPORTING SERVICES:
(Habitat provision, use of solar energy, species maintenance, nutrient cycling, soil building)

a) Optimising the use of solar light will enhance the form of the building's mass, the relationship between the building and its surroundings, the type and size of openings, the inclination of walls, and the creation of light wells, courtyards, galleries, atria, conservatories, cornices, overhangs or shading devices.

Design strategies:
Energy use in buildings can be reduced intensely by working with easy to apply design principles. This comprises of:

- Inclusion of passive solar design.
- Proper orientation to the path of the sun - orientating buildings so they are southern facing.
- Using materials with good thermal mass properties - Using wooden and stone materials, as they are good absorbers of heat.
- Designing buildings that encourage a natural flow of heat in the winter and good ventilation in the summer.
- Covering of southern facing windows with transparent materials (glass) to encourage solar gain.

All of these design features add nearly nothing to the normal cost of a building, but can make a notable difference in the impact on the environment.
Using active solar technologies as they involve the use of mechanical and electrical equipment to move solar heated fluids from solar collectors to the building's interior, where it is released as needed.

b) Species maintenance

Design strategies:
Using locally attuned materials and labour to avoid pollution and extra gas emissions

c) Retention of nutrients for cycling

Design strategies:
Recycling techniques
Composting techniques
Designing for deconstruction
Landfill mining
Industrial ecology

d) Renewal of soil fertility

Design strategies:
Soil quality control
Soil retention

e) Habitat provision

Design strategies:
Revegetation
Preservation of existing flora and fauna
Urban sanctuaries for wildlife
Living walls
Urban forests
Green roofs
Green facades
Green belts

3. <u>REGULATION SERVICES:</u>
(Disturbance prevention, decomposition, purification, climate regulation)

a) Disturbance Prevention

Design strategies:
Omitting sound pollution by introducing buffer zones of greenery and other elements to take into consideration include air-tight construction, the use of high levels of insulation, high-performance doors and windows, and the use of durable, recyclable and preferably natural building materials in construction.

b) Climate regulation

Design strategies:
Including building facades and skins can help in significant reduction of heat
Site selection
Solar orientation and control (passive solar designs)
Design to reduce reliance on fossil fuels
Revegetation
Design to permit behavioral variation in energy use
How the building works with wind, airflow and the effects of materials?

Materials
NASA defines ''smart materials'' as materials that ''remember'' configurations and can conform to them when exposed to a specific stimulus. Smart materials included into the design and construction of a building can accomplish the same thermoregulating function that skin performs for the body. The primary goal behind use of these smart materials is to ensure sensory recognition of the environment and processing of this sensory information and then acting on the environment.

According to Nessim (2015), materials should exhibit the following characteristics in order for them to be categorized as smart materials that are idea for regenerative design principles.

- Immediateness-they should respond in real time
- Multifunctional-they should respond to more than one environmental state
- Selectivity-their response should be exclusive to the event
- Directness-their response is local to the *activating* event

c) Decomposition

Design strategies:
Biodegradation
Material recycling

Consumption reduction

d) Purification

Design strategies:
Purification of water, air and soil to ensure reuse and recycling
Filtration techniques
Green roofs and facades
Composting techniques
Construct wetlands

4. PROVISION SERVICES:
(Provision of fuel and energy, fresh water, raw materials and food)

a) Provision of fuel and energy

Design strategies:
Building envelopes: Due to its calculated position on a building that acts as a medium between the inside and the outside.
Designing a building envelope to control the heat in buildings, without the use of electricity or mechanical elements, to decrease energy consumption.
By designing a building envelope, particularly a façade, to recover heat and generate electricity.
By designing the façade to adapt to changing weather conditions.
Introduce active and passive solar energy using specific materials and by following the sun path.
Designing for renewable energy generation.

b) Provision of fresh water

Design strategies:
Drinking
Irrigation
Sanitation
Recreation
Other industrial processes
Wetlands
Rain water harvesting and storage
Porous paving surfaces
Water efficient landscaping

c) Provision of food

Design strategies:
Urban agriculture
Vegetation patches
Green roofs
Vertical farms

d) Provision of raw materials

Design strategies:
Recycling techniques
Composting techniques

Table 10

Design strategies and Services

SERVICES	DESIGN STRATEGIES
CULTURAL SERVICES (aesthetic, recreation, sense of place, cultural diversity, sense of knowledge, spiritual, religious space)	▪ Introduction of historical and cultural aspects ▪ Particular patterns, texture, colour, ornamentation ▪ Holistic spaces to encourage mental well-being ▪ Green spaces-reduce radiation and improve chemical composition of air ▪ Open spaces that resembles natural environments
SUPPORTING SERVICES (habitat provision, solar energy, species maintenance, nutrient cycling, soil building)	• Inclusion of passive solar design • Proper orientation of buildings to the path of the sun • Using materials with good thermal mass properties • Encourage a natural flow of heat in and ventilation • Covering of southern façade with transparent materials • Using locally attuned materials • Recycling techniques • Composting techniques • Industrial ecology • Soil retention • Revegetation • Preservation of existing flora and fauna • Living walls/Urban forests/Green roofs
REGULATORY SERVICES (disturbance prevention, decomposition, purification, climate regulation)	• Including building facades and skins • Site selection • Solar orientation • Design to reduce reliance on fossil fuels • Revegetation • Design to permit behavioural variation in energy use • Multifunctional- respond to more than one environmental state • Material recycling • Purification of water, air and soil to ensure reuse • Filtration techniques • Composting techniques • Construct wetlands

PROVISION SERVICES (provision of fuel and energy, fresh water, raw materials, food)	• Drinking • Irrigation • Sanitation • Recreation • Other industrial processes • Rain water harvesting and storage • Porous paving surfaces • Water efficient landscaping • Urban agriculture • Vegetation patches/ Green roofs/Vertical Farms • Recycling techniques • Composting techniques

Note. *Design strategies and Services, by author Y.Syed, 2020.*

In their paper, *Biomimicry for Regenerative Built Environments: Mapping Design Strategies for Producing Ecosystem Services*, Zari and Hecht (2020), further investigate how these services influences the environment and whether they can physically be mimicked and maintained. They summarize their results in Table 10 and conclude that although not all of the services can be easily mimicked, the four categories of services are a necessity.

Table 11

Ecosystem Services Analysis

Ecosystem service	Ranking criteria			Examples of existing design methods that could be potentially be used	Positive environmental implications
	Applicability to the built environment	Ecological significance	Negative environmental impact caused by the built environment		
Supporting services					
1. Habitat provision (including: provision of genetic information; biological; fixation of solar energy; and species maintenance)	Medium	High	High at a local scale	Revegetation; preservation of existing flora and fauna; urban wildlife sanctuaries; living walls; urban forests; green roofs and facades; wildlife corridors; green belts	Increased biodiversity; reduction of the urban heat island effect; sequestration of carbon; increased air, water and soil quality; remediation of some forms of water, air and soil pollution; possible protection from wind or wave surges; more adaptable ecosystems as the climate changes; reduction of storm water peak flows
2. Nutrient cycling (including: decomposition; soil building; and the provision of raw materials)	Medium	High	High at a regional/ global scale	Recycling and reuse techniques; cradle-to-cradle design; composting techniques; design for deconstruction; landfill mining; industrial ecology	Reduction of waste; reduced need for mining/ growing/production/transportation of materials and energy leading to reduction in greenhouse gas (GHG) emissions, waste and ecosystem disturbance; decreased use of energy; increased health of ecosystems and humans
Regulation services					
3. Purification	High	High	High at a local/ regional scale	Living machines; phyto-remediation and bio-remediation; filtration techniques; green roofs and facades; urban forests; constructed wetlands; composting techniques	Increased health of living organisms; increased terrestrial and marine productivity; reduction of air and water pollution; eutrophication reduction; remediation of polluted sites; reduced ozone damaging gas and GHG emissions
4. Climate regulation	High	High	High at a global scale	Storage of carbon in building structure; revegetation; design to enable behaviour change in energy use; renewable energy generation; passive solar design; non-high thermal mass infrastructure and landscaping; design to reduce reliance on fossil fuels	Mitigation of the causes of climate change; more adaptable communities; mitigation of the urban heat island effect; improved health of living organisms
Provisioning services					
5. Provision of fuel/energy for human consumption	High	Medium	High at a global scale	Design for renewable energy generation; cogeneration methods; design to enable behaviour change to reduce energy use; industrial/construction ecology	Reduced transport and energy generation-related GHG emissions; more self-reliant and therefore robust urban environments; reduction of air, water and soil pollution; reduction of mining and drilling impacts
6. Provision of fresh water	High	High	High at a regional scale	Rain water harvesting and storage; grey/black water recycling; design incorporating water saving equipment; porous paving surfaces; water efficient landscaping	Reduction of water pollution; increased health of riparian systems; reduction of the urban heat island effect; increased quality of water; increased health of living organisms

Note. *Ecosystem Services Analysis by P. Zari ,2012.*

Table 11 explains these different levels of work within a system of hierarchy, in which work at the lower levels focus on existence (that which is already established), increasing performance and efficiency. Work done at higher levels is concerned with potential (what could be but is not yet established), introducing potential for new life and creativity while advancing the whole system. The framework below was inspired by the works of Charles Krone, in the 1960s and 1970s and can be utilized to determine the strategies applied to the building concept.

Level of Work POTENTIAL

↓

Core principle regenerate / improve

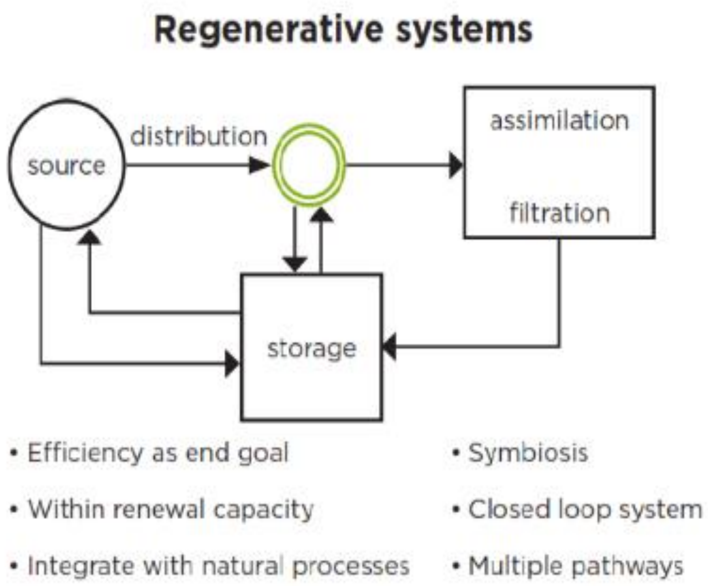
Level of Work EXISTENCE

Core principle maintain / operate

The aim, of this framework is to utilize it as a measure that allows designers to consider the integration and evolution of all work. It can be used as an instrument to detect which design strategies can be integrated and affiliated with regenerative goals.

Figure 37

Lyle's Regenerative Systems



Note. Retrieved from *(http://akihan.hubpages.com/hub/Regenerative-Architecture)*

According to Lyle (1994), he reasons that the perception of regeneration is compulsory for sustainability and argues that "in order to be sustainable, the supply systems for energy and materials must be continually self-renewing, or regenerative, in their operation. That is, sustainability requires on-going regeneration" (p.10).

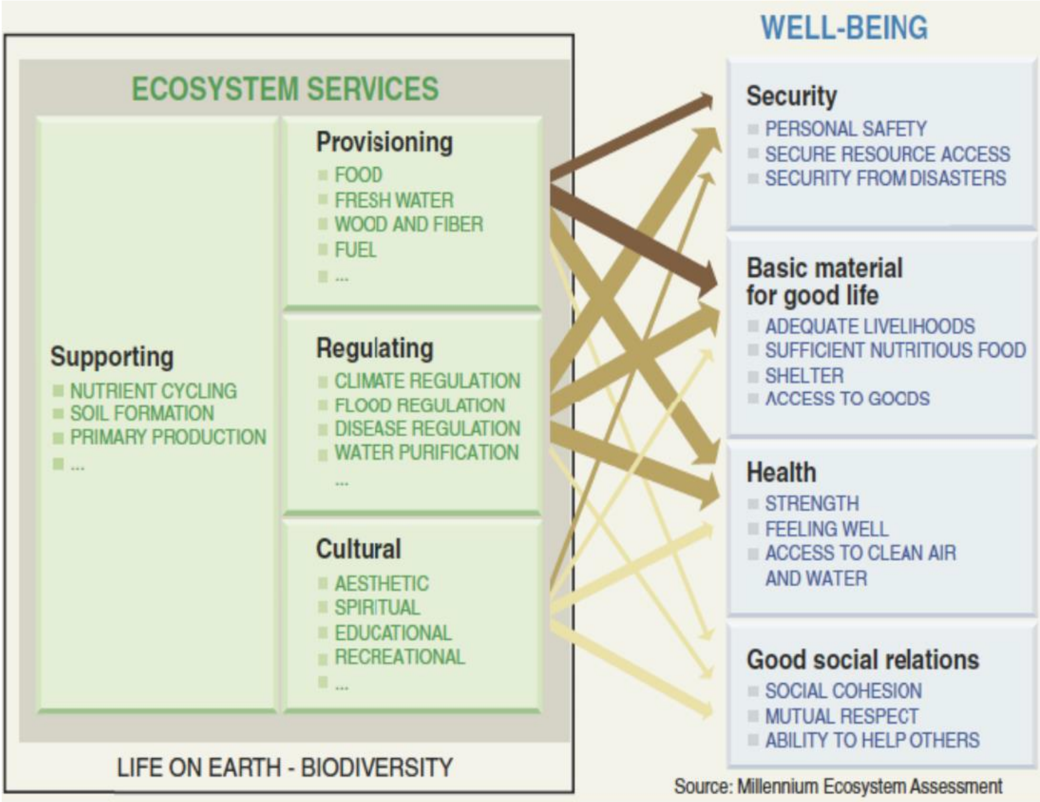
<u>ECOLOGICAL WELL-BEING AND HUMAN WELL-BEING</u>

In 1971, ecologist Howard Odum confirmed that the ecosystem was the main fundamental ordering structure of nature. He took note of relationships between ecological systems and humans and suggested that human ecosystems would be "…places in which human beings and nature might be brought together again for shared benefits" (as cited in Mang and Reed, 2012b, p.6). Lyle (1994) highlighted that "The relationship between humanity and nature is likely to be the ecosystem…Since all ecosystems include human influence and most include human presence, we might as well think of human ecosystems as the ordering systems of life on earth" (p.11).

And therefore The Millennium Assessment Programme (Figure 38) describes ecosystem services as the benefits people obtain from ecosystems, and recognized the four categories of service: *provisioning*, *regulating* and *cultural* services and their relationships with humans and the *supporting* services required to maintain these four categories of services (Hes & Du Plessis, 2015).

Figure 38

Ecosystem Services



Note. Ecosystem Services by the Millennium Ecosystem Assessment, (2005)

Zari (2012) explains that understanding ecosystem services is a logical technique to help achieve goals for regenerative design advancements. She further explains that this understanding could be a potential starting point to kick start design strategies. Instead of focusing on human defined goals, it is recommended to aim for more biological system services in order to appreciate how life can continue in set locations and climates.

<u>COLLABORATING WITH PLACE — HUMANS AND THE ECOSYSTEM</u>

In an ecological example, sustainability seeks to create a shift in how humans carry out their role on the planet. Landscaper, Joshua Ramo (2009) urged people to amend their role as architects of a system that can be controlled to gardeners of a living, evolving ecosystem. He pointed out the construction of everything from nations to bridges in this revolutionary age, and stated that architects' tools of imagination were deadly. Ramo wished to convince humans to see themselves as partners in co-evolution with the living system in which they exist. Hence, creating a progressive harmonization of human and natural systems. Collaborating with place also requires understanding place as a living whole. Regenerative development begins with a whole systems evaluation that covers a vast arena of patterns consisting of multiple scales of systems and a number of different features. To create the connection and consideration that creates a partnership, an understanding of *who* a place is, its distinctive soul and ways of operation is needed in addition to how it works. All living systems, be it a human, a plant or a place, has a continuous distinctive core from which stems its organizational capabilities and intricate arrays of relationships that produce its actions, growth and development.

CHAPTER 8
ANALYSIS

BIOMIMICRY TO INCREASE SUSTAINABILITY

To achieve sustainability, Pawlyn (2011) argues that "biomimicry-design inspired by the way functional challenges have been solved in biology is one of the best sources of solutions that will allow us to create a positive future and make the shift from the industrial age to the ecological age of humankind" (p.10).

Biomimicry is often described as a tool to increase the sustainability of human designed products, materials and the built environment (Berkebile & McLennan, 2004; Baumeister, 2014). It should be known that a lot of biomimetic technologies or materials are not naturally more sustainable than conventional equivalents and may not have been initially designed with such goals in mind (Reap et al., 2005).

As discussed, most examples of biomimicry are based on organism level. While biomimicry at the organism level may be encouraging for its potential to produce innovative architectural designs, there is a stronger hope for buildings to become a part of something more (Aldersey-Williams, 2003; Feuerstein, 2002). Perhaps, as part of a larger system, that is able to mimic natural processes and can function like an ecosystem in its conception, use and eventual end of life, the potential to contribute to a built environment that goes beyond sustainability and starts to become regenerative on its own (Van der Ryn, 2005; Reed, 2006).

This does not in any way inhibit the concept of organism-based mimicry, however the contribution to sustainability is unfortunately highly unlikely, similar to a non-biomimetic building. An example of this is New Zealand town Tirau's iconic dog and sheep building (form biomimicry at the organism level). It imitates the suggested animals and just about creates for visual pleasure.

We can establish that a building that is able to mimic natural mannerisms and can function within an ecosystem in its creation has greater potential to be part of a regenerative built environment. While the organism based building could be termed biomimetic, but the potential for amplified sustainability would most definitely be quite low. It is recommended that if ecosystem based biomimicry is to be considered as a way to increase sustainability of an architectural project or design, the mimicking of general ecosystem principles should be amalgamated into the design at the initial stage and these principles should be used as an evaluative tool guide throughout the design process as described by the Biomimicry Guild (2007) (Hastrich, 2006; Zari, 2018).

BIOMIMICRY AS AN ECONOMIC SOLUTION

The incorporation of sustainable practices into construction processes and activities have become imperative for accomplishing the greening plan of the construction industry. There has been a spread of several sustainable construction practices with biomimicry standing out among them.

As an innovative approach that studies and matches nature's forms, processes, and strategies to offer sustainable solutions to human challenges, biomimicry is beginning to gain momentum in its application across various fields. Lack of awareness, lack of professional knowledge, and lack of training and education have been identified as the top three barriers that mitigate biomimicry adoption and implementation.

LIMITATIONS OF BIOMIMCRY

Limitations surrounding the different levels of biomimicry do exist, in that there is the concept of mimicking the organism's shape or material, which does not really contribute much to the aspect of sustainability. Apart from having impressive designs and aesthetics, the idea does not provide a strong argument in promoting biomimicry for change. There is the idea of mimicking behavioural patterns that could be suitable for natural organisms and particular flora and fauna but perhaps they do not seem to be suitable for humans. Nature operates at certain temperatures and pressures but some of these variables can be insensitive towards human needs.

Research done by Kelly (1994) and Vogel (1998), identify three leading complications during the imitation process:

- Evolution is a synonym for improvement, and therefore every generation should have an advantage from the previous, when transitioning. Knowing that the results you end up are better than the original strategy is enough determination to work harder. Thus, there is constant pressure to produce better results. Sometimes this is just not possible, which leads to failure of development. Nature inevitably will end scope for design if it does not see improvement at every given stage.
- Natural products need continuous maintenance. Although biodegradable products benefit from this, it is a simple reminder to not mimic so obediently. There must be some sort of originality involved.
- Organisms evolve from their natural state. Although some genetic engineering professionals have attempted to do so, the consequences have not been pleasant and have proven to be a bad idea. Some ideas may not be suitable for humankind.

ARE ECONOMIC CONSIDERATIONS A PART OF THE STRENGTH OR WEAKNESS OF BIOMIMETIC STUDY?

In response to threats of depleted resources, increased effects of global warming, and overall increased awareness of human impact on the natural environment, biomimicry has become a topic of speculation. In order to understand the impact of Biomimicry on economy, the SWOT (Strength, weakness, opportunity, threat) analysis method is used. SWOT being one of the earliest and commonly used organizing frameworks in supervision related studies. In this case, strengths and weaknesses are to measure the existing internal environment, while opportunities and threats are for external environment.

Due to the economy, all the modern methods of building are based on fossil fuels. Whilst the easiest way to build is with machines, it unfortunately consumes huge amounts of energy and resources, making it extremely wasteful. There is need to move away from fossil fuel and towards an age where there is more balance. An age where there is more egalitarianism (Pearce, 2016).

In regards to economic approach in terms of biomimicry, there is almost no doubt that these nature-inspired concepts will be effective in cost reduction and energy consumption of buildings. As asserted by the architect of East gate, Mick Pearce (2016), East gate proved to use less than 10% of energy that a normal building its size would consume, and therefore, spared the stakeholders 3.5million alone as there was no air conditioning required to be installed in the building.

SWOT ANALYSIS

STRENGTHS

Some key aspects that enforce the use of biomimicry include:

- Using required energy only.
- Creating an appropriate form according to its function.
- Providing recycling of everything.
- Benefitting from local materials and elements.
- Avoiding any sort of redundancies.

The buildings encouraged by biomimicry design have gained recognition due to their rare but natural shapes. Studies showed that biomimicry approaches help to reduce infrastructure maintenance costs and help in reducing liability to environmental fines and taxes. Kellert (2016) acknowledged more advantages in the importance of biomimicry in the built environment as this practise aims to improve the human condition through better understanding and connection with the natural world.

According to results, harnessing freely available energy, using readily available materials and recycling all materials are ranked as the most beneficial strengths of biomimicry. Biomimicry combined with kinetic architecture allows architects to construct dynamic modular pieces, which enables different benefits for buildings such as:

Drawing inspiration from sunflowers or pineapples – house systems harnessing solar energy more accurately tracking the sun with solar sensors

Drawing inspiration from desert animals - moving shadings in order to control sunlight.

WEAKNESS

Some factors limiting the notion of biomimicry include:

- The technological availability to mimic nature.
- The applicability of a component or system to the existing building.
- Financial cost.
- The ability of the building to become adaptable and support the system.
- The ability of the system or element to reach its maximum potential.
- The effect and complexity of the site context and climate on the element or system.

A vital factor of biomimicry is that the concept wires the idea of collaboration. Having said that, combining different professions including new design and technology is challenging. Based on an interview conducted by Turkish students in 2012, Kenny et al. (2013) discovered biomimicry as an alternative and sustainable design approach to traditional water infrastructure systems. They summarized the main obstacles to innovations, identifying that regulatory and economic grounds are some of the major limitations to integrating alternative design approaches in the water sector of developed countries.

While on the topic of collaboration, the concept of mimicry requires some ethical considerations. In that, while the argument is to resort to natural processes, the idea that these processes will be suitable for humans is not guaranteed. For instance, the idea of using behavioral biomimicry to inspire certain temperatures and pressures may be suitable for certain species however, the same temperature or cooling methods can be detrimental for humans.

Lurie-Luke (2014) found out that biomimicry has a huge impact in the material development industry. Newly developed materials have features, which are reacting to external stimuli and surface topography. The main challenges faced during the design process were, specific production requirements according to specific material. Along with this issue, the installation and maintenance of these materials is highly concerning for the stakeholders as the construction project aims to finish within a desired budget and time frame, which is most likely to vary as natural mimicry can have different results each time within various periods.

According to his study, Grigorian (2016) identified that biomimicry is evaluated and resulted with the fact, that it needs time and exposure before gaining consensus as a mainstream method of advancing structural design strategies.

The lack of experienced labor, in regards to modelling of dynamic systems makes for another weakness that slows down the production. In addition, imitating nature is not an easy task. The production of similar systems is only possible with appropriate software and engineering design. Another downside includes that of clashing opinions. There is a need for people with a wide range of knowledge to work together. It is rare for extremely different professionals to be working hand in hand. They all come from different backgrounds with different technical languages and different approaches.

In the design industry, one of the main challenges faced by architects and designers is that many a times, investors and developers do not buy into the idea of a building inspired by natural processes immediately. They assume the architect is looking for a platform to display his experiments, and in doing so the investor assumes, they will not get a building of value. It is difficult to convince an investor to use natural methods of cooling as they usually misunderstand the concept of it all, as risky and time consuming. “Until they actually saw the advantage of self-cooling systems in East-gate, and the numbers and figures reduced significantly, they didn’t expect a self-cooling building to produce the results it has produced today” says Mick Pearce (2016).

<u>OPPORTUNITY</u>

Possible opportunities include:

- Creation of more natural materials that are less destructive to the environment.
- Careful use of materials to reduce waste.
- Creation of a healthier environment.
- Creation of building elements and systems that are more adaptable.
- Improved efficiency and performance in areas of application.

Kenny et al. (2013) specified that opportunities surrounding infrastructure development are increasing at an alarming rate in that governments and communities are continuously demanding the integration of efficient solutions for innovative architectural designs, which will go on to trigger future incentives. Sustainable development has become a popular slogan across many fields and has accelerated the search and development of technology and other resources. These developments are an added advantage to spread the idea of biomimicry. New technologies and design approaches have the ability to become much cheaper than traditional approaches whilst providing advanced quality. Advanced technology is in high demand and is able to produce new materials or methods to mimic nature and produce newer ways to leave sufficient resources for upcoming generations. Sustainability has become the flag bearer of the future and has created opportunities for younger talent and advanced knowledge to work together.

<u>THREATS</u>

The idea of construction projects and their completion within a short period of time can create an issue for new design inventions. Stakeholders want to see results within a short timeframe using whichever technology possible. Pressure to complete tasks within the allocated time force the return to traditional technologies over new innovative improvements. The most difficult task is to secure finance for these newly developed technologies, as the outcomes are uncertain. In addition, newly developed materials can have system failures or any other issues, which ultimately leads to further risks for the stakeholder.

Market conditions are a major threat for the construction industry as financial fluctuations are frequently occurring. Kenny et al. (2013) claimed that regulations are one of the primary obstructions to innovation. Grigorian (2016) disclosed that new concepts such as biomimicry need more time to develop in accordance to the market's needs. Testing standards for these dynamic systems are challenging as they are manufactured distinctively.

In conclusion, imitating nature has been a dominant solution for eons. The demand for sustainability has garnered more attraction as the world faces the issue of global warming. This has directed architects and designers to bring in the laws of nature into their designs. These newly emerging concepts have the potential to positively shape the future of construction industry.

Table 12

SWOT Analysis

STRENGTHS	OPPORTUNITY
• Effective use of energy. • Climate adaptation ability. • Enhancing comfort. • Higher value and quality.	• Improving efficiency. • Sustainability focused policy. • Technological developments. • An increase in environmentally responsible buildings. • Creating natural materials that are less harmful to the environment. • Use materials more capably to reduce usage and wastage.
WEAKNESS	THREAT
• Higher initial or maintenance costs. • Lack of systems expertise (Professionals). • The need for coordination of different professionals. • Special manufacture requirements. • The ability of the system or element to reach its maximum effectiveness is uncertain. • The applicability of the element or system to the existing building is uncertain. • The contribution made may not be suitable for humans as opposed to nature and other species.	• Unfamiliar systems. • System failures. • Materials do not comply with the regular standards. • Cost is high.

Note. SWOT analysis, by author Y. Syed,2020

CHAPTER 9
CRITICISM

<u>NATURE VS HUMANITY</u>
Nature is a creation of God, and has its own intricacies that Man can undoubtedly never replicate accurately. As revolutionary as biomimicry may sound, it is important to know when to draw the line in regards to imitation. Humans have different capabilities, requirements and respond differently from nature and vice versa. Therefore, some aspects simply cannot be mimicked unless they can be turned into human advantage.

Science writer Joe Kaplinksky (2006), mentions that while architects are being pressurized to draw inspiration from nature and being told to control the 'generative geometry' of their building forms to reduce further destruction, it seems as though human needs are being considered primary. In his opinion, there is a down side to this growing rage of turning to biology. It has become an 'idolization of nature' that seeks to reduce humanity and human achievement.

According to Kaplinksky (2006), the key themes of this environmentally conscious way of thinking asserts that:

- Human necessities place constraints on the natural world
- Nature consists of mysteries beyond human comprehension
- Humans should be humble and place diminished confidence in our abilities.

These themes contradict the human 'Enlightenment Principles' that have given rise to many discoveries and achievements in the technological, scientific and engineering field. Human achievement and progression is seen as insignificant in comparison to natural phenomena. There is acknowledgement of the positives of nature but it is important to realize that as humans, our capabilities and requirements for survival are different.

The first notion of nature placing significant constraints on our lives stems from the fact that we are in the running against natural resources and their limits. If we were to completely mimic nature, it would seem as though the problem of resource depletion and climatic change could be completely avoided. If the quality of sustainability is calculated on the measurement of untouched nature, then this would mean putting an end to building completely.

Kaplinksky's, (2006) second idea presents nature as a mystery beyond our comprehension. Janine Benyus discussed her admiration for nature and its unique characteristics such as flight, the ability to remain afloat, and the ability to breathe under water and many more (Pawlyn, 2011). Kaplinksy (2006) argues that nature's attributes do not make human capabilities any less outstanding. He credits humans with having observed and creating means of flying and equipment for under water breathing, by using knowledge, technology and science. Achieving these feats are much more worthy of praise (Kaplinksky, 2006).

Finally, his third theory of the 'idolization of nature' and the diminished confidence placed in human abilities. One of the most vital differences to note is that human artefacts are manufactured, whilst living things are grown. Living things are self-sufficient organisms and human artefacts are man-made structures that rely on external support. The ideology of manufacturing creates ground for innovation and new possibilities. Kaplinksy (2006) mentions that had everything been self-sufficient and self-maintaining in the built environment, factory innovation, labour and constitutions such as the economy would be non-existent (Kaplinksky, 2006).

To soften his criticism, Kaplinksy (2006) commends the creation of regenerative ecosystems and acknowledges its worth. He also takes into consideration that it is a complex system that is in its development stage. However, he re-iterates that it should be not be considered a turning point within the built environment as it weakens the notion of architecture and the concept of simple and sophisticated buildings (Kaplinksky, 2006). From all his ideas and thoughts, Kaplinksy (2006) urges that the relativity of a good idea cannot be determined based on its relation and contribution to nature alone, but rather on its ability to adapt to human needs and concerns.

It is understood that while we have much to learn from the natural world, we must not underestimate the progress and achievements made by humans. It is through this sequence of progression that there has been a transformative impact on the world where an independent civilization has been created. This independence has allowed humans to appreciate nature as an aesthetic and as science (Kaplinksy, 2006).

TECHNOLOGY GAP

As we aim to integrate biology into our designs and future cities, it cannot be ignored that technology will always bridge the gap between human innovation and biological inspiration. For example, while the natural world produces heat, other catalysts do so naturally. Humans were not created with the ability to do so. Therefore, to achieve a truly biologically sustainable building, technology is an effective catalyst. However, the question remains, if *no technology* is used as the criteria of a biological or sustainable building, how can we achieve this, as man is not programmed in the same manner as organisms and nature as discussed above. If we introduce technology to aid in achieving these biologically sustainable buildings, does it remain sustainable as the technologies that are being developed are not completely organic and biological?

Having said that, biomimetic technologies accept the connection between nature and technology, as it is concerned with the precision of nature. However, it also acknowledges that the preservation of nature comes from the disconnect between nature and technology. Therefore, if biomimetic technology is considered as an additional catalyst that is not natural, the metaphorical importance of this technology is vague. What is it exactly that is not natural in biomimetic technology?

Another point of concern is that while the technology being developed is serving its purpose in the building, the repercussions of it are also an issue. As Newton’s third law states, “for every action, there is an equal and opposite reaction”. As we work progressively to attain regeneration, are we creating further obstacles? Are we becoming less sustainable in our effort to attain regeneration?

EFFICIENCY AND SUSTAINABILITY

Apart from the above concerns, it is worth questioning that while we chase the concept of sustainability, are we as humans becoming less sustainable. We tend to be driven towards the concept of embracing nature, but at the cost of the few natural resources that we have left.

There is a fine line between being sustainable and efficient in that, are we planning to minimize and eliminate pollution, rather than achieving clean air and water. Are we minimizing waste rather than eliminating it completely by inventing cycles that would monitor the correct usage of resources? Do we aim to minimize energy use rather than use energy from non-damaging renewable sources?

In my opinion, the difference between sustainability and efficiency is that of longevity and relevancy. Which concept provides a stronger threshold in terms of regenerative design?

BENEFITS

While we encounter a few obstacles with biomimicry it also worth indulging a few advantages of the concept. Apart from creating aesthetically pleasing designs and more organic forms, biomimicry also enables:

- Designing a building that is conceived because of its current environmental specific requirements.
- Producing more advanced sustainable design.
- Linking design and environmental issues towards a more sustainable solution.
- Biomimicry can enhance ways of thinking and designing that bring about buildings that are more responsive.
- Biomimetic technology can help overcome environmental issues such as global warming, the greenhouse effect and the Ozone hole.

CHAPTER 10

CONCLUSION

The swiftly spreading out of the built environment urges for more creative ways to address the increasing sensitivity of the environment and rapidly changing climate. Biomimicry is seen as a potential solution that allows for humans and nature to coexist. Giving humans an opportunity to enroll back into a state of equilibrium and regeneration. Many parallels exist between nature and architecture. Some of which have been studied and analyzed for many years, and some which are now coming into light and showing their relevancy as we seek to repair the strained relationship between the built environment and the natural world.

While most orthodox approaches to sustainability aim to reduce energy and resource consumption, biomimicry is different as it provides a platform for natural systems to demonstrate the possibility of regenerative design. Not only is nature a form of readily available inspiration around us, but it has also survived and evolved within the same conditions available to humans, using only the material and resources available on the planet. Thus, we ought to grasp onto the notion of potential design for future development by employing the wisdom of our predecessors.

Along with social problems, the built environment accounts for a majority of the world's global environmental issues with enormous proportions of waste, material, energy use and greenhouse gas emissions (Doughty & Hammond, 2004; Mazria, 2003). The need for an effective ecological sustainable design method is becoming more urgent and necessary. Of course, the aim of this is not to downplay the needs of society. However, with several approaches to sustainable design in architecture, very few have proven effective. Together with the built environment, it is necessary to demonstrate the relationship between humans and ecosystems. While we do exist in the same environment, it is essential that we realize that we are not simply mimicking an ecosystem, but rather, we are a part of it. We must realize the role we are expected to play and should only use what is within our means responsibly.

Biomimicry at ecosystem level offers a sensibly new resolution to our issues of sustainability. Complex design issues require system level thinking to identify solutions that are holistic and not narrow in their responses. *Systems thinking* within the biomimetic field aims to recognize and implement design methods that have been established within ecosystems. Biomimicry brings this to life through building systems to accomplish several purposes with one simple, yet multi-functional design.

It is time to make ground from biological and ecological methods to create structures to technological demand. Thus, reducing if not completely removing the stigma attached to the built environment in relation to Global Warming.

FUTURE SCOPE

Nature on its own has learned how to achieve efficient multifunctional solutions. This should inspire designers to further develop solutions based off natural biomimetic systems. Systems that embody resilience. By adapting to change to fit within its context. Incorporation of biodiversity and exemplifying flexibility through deviation and redundancy. Systems that are resistant to uncertainties, as well as the unforeseen.

The integration of two or more seemingly distinct concepts found in nature into an exclusive combination with excellent functions is an interesting direction to venture into. Even though the biomimetic field has been around for quite some time and has just recently come into light, more research is required to comprehend the principles of regenerative design and ecosystem biomimicry to implement it as a need for society and ecology, there is a possibility of it growing into an enormously promising field in the near future. Thus, paving the way for an ecological era, as humans have already gotten most of the solutions that we require in achieving this goal. The design of cities to work like *Rube Goldberg* machines is seen as extremely intriguing as we would realise that every component has a part to play in the entirety of it all.

A growing interest has been reported particularly in Australia and New Zealand, which includes a national policy that urges the adoption of regenerative design by the government. According to Architectural Designers New Zealand, (2019), Jerome Partington of Jasmax New Zealand and the Chair of Living Future Aotearoa, New Zealand has championed energy efficient and ecologically responsible architecture. He initiated the transformational change in the architecture and construction sector of New Zealand and aims to accomplish high performance projects that are not only intergenerational but also have social and ecological value.

The intention of this research is to help provide a platform for more and more architects and other design professionals to engage in systems thinking within ecosystem based biomimicry as a measure to maintain relationships and bonds within a complete cycle whilst producing futuristic architectural designs that are a part of a broader holistic spectrum. As building designs are becoming more progressive, the overall intention of biomimicry at ecosystem level is to produce an ecosystem in which human attributes and needs along with natural attributes and needs coexist and improve the environment.

LIMITATIONS OF THE RESEARCH

Even though the field of architecture has consistently been the most intrigued by biomimicry and has demonstrated some remarkable buildings. Unfortunately, one of the greatest limitations of this research topic is that Biomimicry in relation to regenerative design is still an evolving discussion and is therefore still in the developmental phase. While mimicry at the other two levels (organism and behavioral level) have been common in practice, there are only a very small number of building projects throughout the world that have managed to truly integrate a fraction of biomimicry and natural laws at ecosystem level. Having said that, even though the integration of nature has been included at a small scale, these projects have produced positive results and seem to be promising towards the futuristic idea of exploring the entire notion of regenerative architecture. The key is to accurately translate the language of nature within design realms.

Whilst the amount of research and awareness is not fully developed, and most design strategies are somewhat generic there is a positive attitude moving contemporary sustainable design towards regenerative biomimetic development in New Zealand. There is complete faith in the discipline of architecture to transform the world into a more sustainable utopian abode.

References

Aldersey-Williams, H. (2003) Zoomorphic - New Animal Architecture, London, Laurence King Publishing.

Allenby, B. R., & Cooper, W.E. (2007). Understanding industrial ecology from a biological systems perspective.

Architectural Designers New Zealand. (2019) Retrieved from https://www.adnz.org.nz/events/details/3806/8/0/

Asian building and construction, 2001. Esplanade theatres on the bay. Singapore: DP Architects

Baumeister,D .,(2014).Biomimicry Resource handbook-A seedbank of best practice.

Benyus, J.M., (1997). Biomimicry: Innovation Inspired by Nature. Perennial (Harper Collins).

Berkebile,B. & McLennan,J. (2004).The Living Building. Biomimicry in Architecture, Integrating Technology with Nature.Bioinspire18.

Biomimicry Guild (2007) Innovation Inspired by Nature Work Book, Biomimicry Guild, April.

Chaplin, F. S., Zavaleta, E. S., Eviner, V. T., Naylor, R. L., Vitousek, P. M., Reynolds, H. L., . . . Diaz, S. (2000). Consequences of changing biodiversity. Nature, 405(6783), 234-242.

Charest, S. (2007). Ecosystem Principle Research.

de la Rue du Can, S., & Price, L. (2008). Sectoral trends in global energy use and greenhouse gas emissions. Energy Policy, 36(4), 1386.

Doan, A. (2012). BIOMIMETIC ARCHITECTURE: Green Building in Zimbabwe Modelled After Termite Mounds. Inhabitat - Sustainable Design Innovation, Eco Architecture, Green Building.
https://doi.org/inhabitat.com/building-modelled-on-termites-eastgate-centre-in-zimbabwe/

Doughty, M.& Hammond. (2004). Sustainability and the Built Environment at and Beyond the City Scale. Building and Environment,39,1223-1233.

du Plessis, C. (2012). From the Autonomous House to Regenerative Design and Beyond: An Evolutionary Narrative

Ehrenfeld, J. & Gertler, N. (2008).Industrial Ecology in Practice: The Evolution of Independence at Kalumdbord. Volume 1, Issue 1.
https://doi.org/10.1162/jiec.1997.1.1.67

Faludi, J. (2005). Biomimicry for green design. World Changing.

Feuerstein, G. (2002). Biomorphic Architecture-Human and Animal Forms in Architectural Designs. Stuttgart, Edition Axel Menges.

Frazer, J. (1995). An evolutionary Architecture. London: E.G. Bond Ltd.

Fratzl, P. & Weinkaner, R. (2007). Nature's Hierarchical Materials. Germany

Fuller, B. (1969). An Operating Manual for Spaceship Earth. Illinois: Southern Illinois University Press.

Gomez-Baggethun and Barton, (2013). Classifying and valuing ecosystem services for urban planning.
https://doi.org/10.1016/j.ecolecon.2012.08.019

Grigorian, M. (2016). ''Biomimicry and theory of structures-design methodology transfer from trees to moment frames'', Journal of Bionic Engineering, vol. 11(4), pp.638-648, 2014.

Gunderson, L. H., & Holling, C. S. (2002). Panarcy. Understanding Transformations in Human and Natural Systems. Washington D.C.: Island Press.

Haque, U. (2007). The Architectural Relevance of Gor-don Pask. *Architectural Design. 77 (4)*, 54-61.

Harris, D. (2016). How can biomimicry be used to enhance the design of an architectural column?
https://doi.org/10.13140/RG.2.1.3101.4008.

Hastrich, C. (2006) The Biomimicry Design Spiral, Biomimicry Inspired Newsletter, 4.1,5-6.

Hawken,P. (2007). Blessed Unrest,New York,Viking Press.

Helms, M., Vattam, S., Goel, A.K., Yen, J., & Weissburg, M., (2008). 'Problem-driven and solution-based design: twin processes of biologically inspired design', Association for Computer Aided Design in Architecture, retrieved 7 September 2019

Hensel, M., Menges, A., & Weinstock, M. (2010). Emergent Technologies and Design. Towards a Biological paradigm for Architecture. New York: Routledge.

Hes, D. and Du Plessis, C. (2015). Designing for Hope: Pathways to Regenerative Sustainability, New York: Routledge.

Kaplinsky, J. (2006). Biomimicry versus humanism. Architectural Design, 76(1), 66-71.

Kellert, S. (2016) ''Biophilia and biomimicry: evolutionary adaptation of human versus nonhuman
nature'', Intelligent Buildings International, vol. 8(2), pp. 51-56.
doi:https://doi.org/10.1080/17508975.2014.902802, 2016.

Kelly, K. (1994). Out of control-the new biology of machines. London: Fourth Estate.

Kenny J, Desha C, Kumar A, et al. (2013) Using biomimicry to inform urban infrastructure design that addresses 21st century needs. In: First international conference on urban sustainability and resilience: UCL London (London).

Kibert, C.J., Sendzimir,J & Guy,G.B. (2002) Construction Ecology, New York, Spon Press.

Korhonen, J. (2001). Four ecosystem principles for an industrial ecosystem. Journal of Cleaner Production, 9, 253-259.

Lurie-Luke, E. (2014). ‘‘Product and Technology Innovation: What can Biomimicry Inspire?’’,
Biotechnology Advances, vol. 32, pp., 1494-1505.

Lyle, J.T. (1994). Regenerative Design for Sustainable Development. New York, NY: John Wiley and Sons.

Mang, P. and Reed, B. (2012a). Designing from Place: A Regenerative Framework and Methodology. Building Research & Information, 40(1): 23–38.
https://doi.org/10.1080/09613218.2012.621341

Mang, P. and Reed, B. (2012b). Regenerative Development and Design. Encyclopaedia of Sustainability Science & Technology, 2112, Chapter 303, Springer.

Manzini, E. (1994). Design, Environment and Social Quality: From "Existenzminimum" to "Quality Maximum". Design Issues, 10(1), 37-43. https://doi.org/10.2307/1511653

Mathews, F. (2011). On desiring nature. Indian Journal of Ecocriticism, 3, 1-9.

Mazria,E.(2003) It’s the Architecture,Stupid!Solar Today,May/June.

Meadows, D. (2008). Thinking in Systems, Chelsea Green, White River Jet., VT.

Nessim, M. (2015). Biomimetic architecture as a new approach for energy efficient buildings through smart building materials. Journal of Green Building 1, 10 (4), 73–86.
https://doi.org/10.3992/jgb.10.4.73

O’Connell M.J. & Hargreaves, R (2004). ‘Carbon constraints in the building and construction industry: challenges and opportunities’, BRANZ Issues Paper No. 2, BRANZ, Judgeford, New Zealand

Odum, E. P. (1969). The strategy of ecosystem development. Science, 164, 262-270.

Odum, H.T. (1969). Environment, Society and Power, Wiley Interscience.

Pask, G. (1969). The Architectural Relevance of Cyber-netics. *Architectural Design. 39 (7)*, 494-496.

Pawlyn, M. (2011). Biomimicry in Architecture, RIBA Publishing, London

Pearce, M. (2016, December 7), Biomimicry Solutions
http://www.mickpearce.com/biomimicry.html

Peters, T. (2011). Nature as a Measure. The Biomimicry Guild.
https://doi.org/10.1002/ad.1318

Potschin, M. and R. Haines-Young (2011). Ecosystem Services: Exploring a geographical perspective. Progress in Physical Geography 35(5): 575-594
Ramo,J .(2009), The Age of the Unthinkable: Why the New World Disorder Constantly Surprises Us And What We Can Do About It.Little Brown and Company, New York.

Rastandeh, A., Brown, D. K., & Zari, M.P. (2017). Biodiversity conservation in urban environments: a review on the importance of spatial patterning of landscapes. Paper presented at the Ecocity World Summitt, Melbourne, Australia.

Reap,J . , Baumeister,D. & Bras,B. (2005).Biomimicry and Sustainable Engineering.

ASME international Mechanical Engineering Conference and Exposition. Orlando, Florida, United States of America.

Reed, B. (2006). Shifting our Mental Model - “Sustainability” to Regeneration. Rethinking Sustainable Construction 2006: Next Generation Green Buildings. Sarasota, Florida.

Tansley, A.G. 1935: The use and abuse of vegetational concepts and terms. Ecology 16, 284 307. Progress in Physical Geography - PROG PHYS GEOG. 31. 517-522. https://doi.org/10.1177/0309133307083297.

Van der Ryn, S. (2005). Design for life: the architecture of Sim Van der Ryn. Salt Lake City: Gibbs

van Vliet, J., Eitelberg, D. A., & Verburg, P. H. (2017). A global analysis of land takes in cropland areas and production displacement from urbanization. *Global Environmental Change, 43*, 107-115. doi:https://doi.org/10.1016/j.gloenvcha.2017.02.001

Vincent, J. (2007). Systematic technology transfers from biology to engineering. Philosophical Transactions of the Royal Society, 360, 159-173.

Vincent, J. F. V., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., & Pahl, A.-K. (2006). Biomimetics - its practice and theory, Journal of the Royal Society Interface: The Royal Society.

Vogel, S. (1998). Cat's paws and catapults. New York: Norton and Company.
Xiong, J., & Bauer, C. E. (2002). Complex evolution of photosynthesis. Annual Review of Plant Biology, vol. 53, pp. 503 - 521.

Zari, M.P. (2007). Biomimetic Approaches to Architecture. Toronto Sustainable Building Conference 07. Toronto, Canada.

Zari, M.P. (2010). Regenerative Design for the Future. BUILD. 115. 68-69.

Zari, M.P. (2012). Ecosystem Services Analysis for the Design of Regenerative Built Environments. Building Research & Information. 40(1): 54–64.

Zari, M.P. (2012a). Ecosystem Services Analysis for the Design of Regenerative Built Environments. Building Research & Information. 40(1): 54–64.

Zari, M.P. (2018). Biomimetic Approaches to Architectural Design for Increased Sustainability. Sustainable Building Conference.

Zari, M.P. (2019). Ecosystem services impacts as part of building materials selection criteria. Materials Today. 3-4. 10.1016/j.mtsust.2019.100010.

Zari, M.P. and Hecht, K. (2020). Biomimicry for regenerative built environments: mapping design strategies for producing ecosystem services. Biomimetics. 5. 18. doi:https://doi.org/10.3390/biomimetics5020018.

Glossary

Biomimicry: Also known as Biomimetic design, an evolving design discipline that looks to nature for sustainable design solutions.

Ecology: The scientific study of the living situations of organisms and their interactive behavior with each other and with the surroundings.

Ecosystem: The framework of living organism and their non-living counterparts. A system of processes required to continue a life cycle.

Ecosystem concept: A framework of principles for redesigning urban settings, buildings, and other systems of energy, water, nutrients, and waste using adaptation to and incorporation of nature's processes. It has been developed to be used to shape an approach in architecture.

Ecological sustainability: Sustainability based on ecological principles focusing on the essential functions and processes of living organism and systems, while maintaining their biodiversity without compromising in the long term.

Green Architecture: the notion of architecture that promotes energy efficiency, recyclable building materials and positioning of a building with attention to its effects on the environment.

Regenerate:
• To revitalize; to bring or come into improved existence; to convey new and more dynamic life
• To form or construct especially in an enhanced state; to renovate to a better, higher or more worthy state; revitalized or renewed
• To reform emotionally or ethically, to invest with a new and higher spiritual nature
• To improve a place or system, especially by making it more energetic or fruitful

Regenerative Design: An organization of technologies and strategies based on an understanding of the detailed workings of an ecosystem that helps in generating designs that restore socio-ecological protocol (such as producing refreshed capacity for liveliness, sustainability and progression) rather than diminishing their primary life support systems and means.

Sustainability: The ability to escape exhaustion of natural resources while preserving ecological balance.

Systems Thinking: The theory of adopting a systematic approach that can be seen as a 'way of life' in other organisms. Systems thinking is used to implement biomimetics in architecture to create a building that is within a system and not just monolithic in its contribution.