Bio-Form Mimicry in Architectural Design (The Influence of Biomimicry on Building Behaviour)

Thesis · January 2021

DOI: 10.13140/RG.2.2.14934.98882

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Bio-Form Mimicry in Architectural Design

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A Thesis submitted in partial fulfillment of the requirements for
The Degree of Master of Science in Architectural Engineering

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2021

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DECLARATION

I declare that, Hala Sayed Mahmoud Aamer, this thesis entitled "Bio-Form Mimimcry in Architectural Design" is the result of my own research except as cited in the references. It is being submitted to the degree of Master of Science in the Faculty of Engineering at Shoubra, Benha University. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ACKNOWLEDGEMENTS

First and foremost, I thank ALLAH, the glorious and compassionate, for helping me to achieve my goal and complete this work. I would like to express my gratitude to everyone who has been by my side throughout the development of this thesis.

I would like too to express my sincere gratitude to Prof. Dr. **Mohamed Khairy Amin**, Professor of Architecture, Architecture Department, Faculty of Engineering At Shoubra, Benha University, for the continuous support of my master study and research, His patience, motivation, enthusiasm, and professional knowledge, guidance helped me and encouraged me to complete this work.

Besides, I would like to express my gratitude to Prof. Dr. **Ahmed Farid Hamza**, Professor of Architecture, Architecture Department, Faculty of Engineering at Shoubra, Benha University, for his supervision, support and for the useful comments and remarks that had strengthened this work and to Associate Prof. Dr. **Islam Ghonimi**, Associate Professor of Architecture, Architecture Department, Faculty of Engineering at Shoubra, Benha University, for his guide, support, and encouragement throughout this work.

I would like to thank the rest of the Thesis Committee Prof. Dr. **Khaled Mohamed Dewidar**, Professor of Architecture, Architectural Engineering Department, Faculty of Engineering, Ain Shams University and Prof. Dr. **Eman Hanim Ahmed** Professor of Architecture, Architectural Engineering Department, Faculty of Engineering at Shoubra, Benha University, for taking time out of their busy schedule to lend their expertise and a wealth of experience to my thesis defence.

Last but not least I would like to thank my father **Sayed Aamer** for the endless encouragement, support. Special thanks to my lovely small family, my husband **Mohamed salah** and my dear daughters **Perihan and Kenzy** for their support, understanding, patience and constant presence in my life**.** Also, thanks to my whole family my mother, my sisters **Heba** and **Hadeer**. Finally, thanks to all my friends who have supported me during this work.

Hala S. Aamer

I. ABSTRACT

This research is considered to be a step to exceed the theoretical stage of the integrated interdisciplinary approach between biology, technology, and architecture to the applied and practical stage. This thesis investigates biomimicry in architecture for the purpose of functionality rather than morphology, to achieve biomimetic building systems that provide improved building behaviour efficiency. Conventionally, the biomimetic approach in architecture has been limited to simple imitation. This had an adverse impact on its functional performance, and lead to failure to fulfil sustainability as the main target.

In fact, some architects have delivered remarkable projects with the help of the digital revolution. Many examples of successful bio-morphic architecture that used nature as a source of form can be seen. Projects were achieved by generating and controlling three-dimensional form; however, that successes do not necessarily mean they successfully transferred the performance of living systems to the building behaviour. They benefited from the simulation of biological behaviour to create a more complex form, but that is not enough to improve the building behaviour efficiency, despite the deep understanding of biology. The priority of biomimicry in architectural design is to transfer some extraordinary adaptations that have evolved in natural organisms into systems of building behaviour.

This academic thesis mainly aims at creating a biomimetic design framework for building behaviour, which can be adopted by architects to design and develop biomimetic systems. Accordingly, this purpose was achieved by creating a multi-phased biomimetic design framework, as a result of combining the conventional biomimetic design framework with technological aspects. The biomimetic approach could be transferred from the theoretical framework to the practical framework by highlighting the technological tools and methods used to apply biomimicry.

In order to verify the proposed design framework, an experimental phase was conducted with the guidance of several mechatronic professionals and biologists. The practical application is a prototype for a responsive facade unit, starting with the abstracted life principles of a selected biological role model, and then transferring them into a digital model, and finally the stage of digital fabrication in order to evaluate the application of such approach to building behaviour. In fact, such practical experimentation helped in setting a clearer and more defined design framework from the conceptual stage to the implementation stage. The main finding concluded from this diverse and wide-ranged study was that the proposed framework is not meant to be strictly followed, but to be flexibly adopted as a guiding schema.

Keywords: *Biomimicry, Biomimetic design, life principles, biological role model, building behaviour, self-responsive, generative design, parametric design, algorithms.*

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II. GLOSSARY OF TERMS AND ABBREVIATIONS

GLOSSARY OF TERMS	
Term	**Definition**
Algorithm	A process or set of rules to be followed in calculations or other problem-solving operations, especially by a computer. (OED)
Biomimicry	The conscious emulation of life's genius. Learning from and then emulation biological forms, processes, and ecosystems to create more sustainable designs. (Benyus J.M. 1997)
Biomorphic	Biomorphic describes anything resembling or suggesting the forms of living organisms. (Biomimicry Institute, 2017)
Biophilic / Biophilia	biophilia is a term popularized by E.O. Wilson to describe the extent to which humans need connection with nature and other forms of life. The biophilic design emphasizes using natural materials, forms, living things, air, sun, and water in the design. (Biomimicry Institute, 2017)
Digital Fabrication	- Digital fabrication uses design-to-fabrication workflows to enable a faster construction process, minimise resources, and use material-specific design solutions. (Wintour, P., 2018) - Digital fabrication is a design and manufacturing workflow where digital data directly drives manufacturing equipment to form various part geometries. This data most often comes from CAD (computer-aided design), which is then transferred to CAM (computer-aided manufacturing) software. (Wikipedia, accessed 2020)
Encode	Convert (information or instruction) into a particular form. (OED)
Form-Finding	Finding an (optimal) shape of a [form-active structure] that is in (or approximates) a state of static equilibrium. (Bessini, J., 2017)
Fitness	In order for a genetic algorithm to simulate evolution, selection criteria need to be established to stipulate which agents are to breed. This criterion is termed 'fitness' and as a result, how one defines fitness is critical to how a genetic algorithm works. (De Landa, M., 2002)
Generative Design	Generative design is a form-finding process which starts with design goals (fitness) and then explores innumerable possible permutations of a solution to find the best option. It can work on geometry. (Wintour, P., 2018)
Iteration	It is the repetition of a process in order to generate a (possibly unbounded) sequence of outcomes. (Wikipedia, accessed 2020)
Kinetic Response	Kinetic Response described as a reaction caused by the motion. (Sharaidin, K., 2014)
Morphogenetic	Refer to 'the logic of form generation and pattern-making in an organism through processes of growth and differentiation'. (Leach, N., 2009)
Plug-in	In computing, a plug-in (or plugin, add-in, addin, add-on, or addon) is a software component that adds a specific feature to an existing computer program. (Christensson, P., 2006)
Tools	
Rhino 3D	Rhinoceros (typically abbreviated Rhino, or Rhino3D) is a commercial 3D computer graphics and computer-aided design (CAD) application software (Food4Rhino, 2020)

Grasshopper	It is a visual programming language and environment that runs within the Rhinoceros 3D computer-aided design (CAD) application. (Food4Rhino, 2020)
Wallacei	It is an evolutionary multi-objective optimization engine that allows users to run evolutionary simulations in Grasshopper 3D. (Food4Rhino, 2020)
Heteroptera	It is a plug-in for grasshopper comprised of a variety of tools in different categories. (Food4Rhino, 2020)
Culebra	It is a 2D & 3D Multi-Object Behaviour library written in C# (Wrapper around Culebra Java library) focused on hybrid system interactions with custom Visualization, Data, and performance features. It contains a collection of objects and behaviours for creating dynamic multi-agent interactions. For more information see the Culebra Java Library. (Food4Rhino, 2020)
SolidWorks	It is a solid modeling computer-aided design and computer-aided engineering computer program, used to develop mechatronic systems from beginning to the end. (Capitol Technology University, 2020)
ABBREVIATIONS	
CAD	Computer-aided design (CAD) is the use of computers
CAB	Computer-Aided Biomimetics tools
CAM	Computer-aided manufacturing (CAM) also known as Computer-aided Modeling or Computer-aided Machining is the use of software to control machine tools
E2BMO	Engineering-to-BioMimetic Ontology
TRIZ	Teorija Reshenija Izobretateliskih Zadatch, which translates to Theory of Solving Problems Inventively
E2B	Engineering-to-Biology Thesaurus
BMO	BioMimetic Ontology

V. INTRODUCTION

'From my designer's perspective, I ask: Why can't I design a building like a tree?
A building that makes oxygen, fixes nitrogen, sequesters carbon, distils water,
builds soil, accrues solar energy as fuel, makes complex sugars and food,
creates microclimates, changes colours with the seasons and self-replicates.
This is using nature as a model and a mentor, not as an inconvenience.
It's a delightful prospect…' (McDonough and Braungart, 1998)

A. Topic Overview

Motivated by global climate change, including global warming and greenhouse gas emissions, architects and designers undertook a duty to look for more efficient, sustainable building systems. Throughout history, nature has been a source of inspiration for various motivations/purposes. Motivated by these global challenges, the needs emerged for mimicking nature with the aim of sustainability. Nature provided a source of solutions for smart ways that developed all fields with innumerable talented strategies.

In fact, most attempts towards mimicking nature involved drawing inspiration from the external form while neglecting the internal behaviour of living organisms. This conventional approach in architecture results in the simple imitation architecturally limited in the external envelope of the building as a separated outer shell, rather than the integration with the internal systems which could increase the building behaviour efficiency.

Previous characterization of biomimicry in architecture researches has been limited to studying specific aspects related to the bio-morphogenetic forms and patterns applied to the façade design. Achim Menges stated the biomimetic design processes in morphogenetic architectural design (Achim Menges, 2012). Likewise, Lidia Badarnah asserts that forms in nature follow environment, and affirms the application of biomimetic approaches to building envelope for environmental adaptation (Badarnah, L., 2017). Additionally, there are valuable studies regarding applying biomimicry to design building envelopes (Webb, M. & Green, R., 2015; Fecheyr, D. & Bhiwapurkar, P., 2017; G. Schieber, 2018; Morteza, S. 2019)

Therefore, biomimetic is not the simple imitation of Nature, neither in material and function nor in creative aspect; however, it is the comprehension of natural life principles to help in understanding the philosophy underlying the forms. James and Hoff proved that the failure of building envelope design to fulfill its targets will trigger more internal problems and issues. This will result in the adverse impact on maintenance planning, operation and costs that might ruin the aesthetic aspect and value of the building in the future (Salim N., 2014).

The need for further studies regarding the utilization of biomimicry in architectural design, by focusing on functions and performance of the living organisms is emphasized by many researches. The biologist Janine Benyus presented three dimensions for Biomimicry (Janine, 1997). Two approaches discussed by Biomimicry Guild, and three levels of biomimicry that may be applied to a design problem are typically given as form, process and ecosystem (Biomimicry Guild, 2007). Likewise, the biologist Julien Vincent explained the difference between Biomorphology and Biomimicry living systems behaviour (Vinecnt, 2014). Additionally, Vincent and Ruben Kruiper published “Computer-Aided Biomimetics" (CAB) tools to support the integration of relevant biological knowledge into biomimetic problem-solving processes (Vincent &Kruiper, 2018).

Moreover, in 2007, Pedersen Zari explored a set of ecosystem principles. Zari discussed Biomimetic for sustainability (Zari P., 2008), consistently confirmed that the goals of mimicking nature must change from sustainable to regenerative development (Pedersen Zari, M., 2018). Likewise, some tools for regenerative design processes were created that are useful for setting up the holistic thinking necessary in this approach (Kibert, 2016; Svec et al., 2012; Plaut et al., 2016). Additionally, Michael Pawlyn referred to various works in the field of biomimetic architecture and innovation (Pawlyn, 2011; 2016).

Petra Gruber authored a series of books and academic researches in the field of Biomimetics in architecture. In Petra's book “Biomimetics in Architecture - Architecture of Life and Buildings” the abstract concept of life onto the built environment was described. Strategic search for life's criteria in architecture delivers a new view of architectural achievements (Gruber, P., 2011; 2019).

Recently, modern technological development in the biological domain helped to conclude the behaviour of living organisms and to understand the motives underlying that biological formation through a deep analysis of its composition. Consequently, rich biological information is available on the performance of the living organisms that can be simulated in the architectural domain. In order to be able to transfer that performance to the building behaviour, it was necessary to resort to technological tools in the architectural domain that are more advanced than those previously used.

Despite this vast variety in the studies on biomimetic architecture, attention has been paid to the theoretical approach for biomimicry in architecture, while hardly following a methodical design framework. Previous studies lack adequate knowledge of the technological tools used to transfer the biological performance of living organisms to the building behaviour. Thus, such shortcoming is addressed through establishing a design framework, which enables architects and designers to follow design biomimetic building behaviour systems at a technical level.

This thesis represents one of the steps that shed light on the practical framework of biomimicry in architecture and focused on the technical aspect currently used in transferring biomimicry approach to the architectural domain with the aim of transferring behaviour not just forms.

B. Research Problem

Despite the vast variety in the studies on biomimetic architecture approach, attention has been paid to the specific aspects related to the bio-morphogenetic forms and patterns applied to facade design, while neglecting the internal behaviour of living organisms underlying those forms. Likewise, the literature review in Egypt highlighted the shortcomings of the previous characterization of biomimetic architecture approach within researches. Previous studies lack adequate knowledge of the technological tools used to transfer that biological performance of living organisms to the building behaviour, producing a simple imitation as a result of the knowledge gap to apply this approach at the technical level.

Likewise, previous researches in the study of the building behaviour from the ecological aspect indicated that despite relying on the building design of its envelope in a manner that claims to be environmentally friendly Figure 1, the buildings have failed to maintain the principles of sustainability. That problem arose from the simple imitation of nature, where the designer drew inspiration from the external patterns in nature to design external building's envelope, neglecting the internal behaviour of living organisms. This simple imitation led to energy consumption within the building to solve the resulting internal problems in building behaviour.

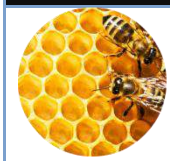
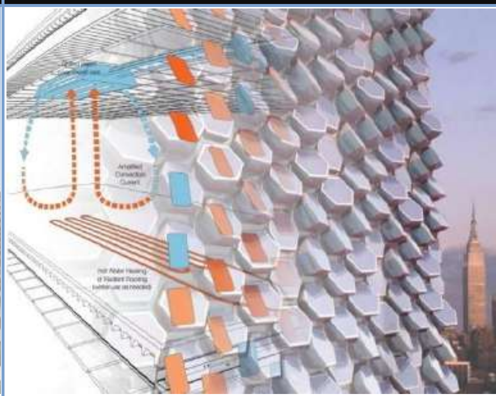
Biomimicry for Form-Finding	Biomimicry for Sustainability
 	
- Mimicking Honeycomb (Static Form) - Using technologies for Form-finding - This design looks like nature does not work as nature	- Mimicking Honeycomb (Kinetic system) - This sustainable design can face climate change and (Works Like Nature).

Figure (1): Comparison between Biomimicry for form vs. Biomimicry for sustainability
Source: Author

The Research problem can be summarized in the following points:

- Most papers have imitated morphological aspects of natural organisms by using algorithms from nature. Search for the form is still the most important issue.
- The focus of recent literature is on the building envelope/façade to improve energy efficiency while neglecting their internal integration.

- Previous studies lack adequate knowledge of the technological tools used to transfer the biological performance of living organisms to the building behaviour.
- No clear methodology is available for the biomimetic approach to support architects and designers at the technical level.

C. Research Aims & Objectives

Based on the previous problem, this thesis helps in closing the technical gap in biomimetic architecture approach, through integrating the biomimetic approach and the technological tools. Hence, the major aim is to establish a methodological framework which is based on the potential strategies in nature as design drivers of building behaviour systems, highlighting the recent technological tools used to transfer those strategies into the architectural domain.

The second aim is to check the applicability of this design framework through implementing a simplified prototype of responsive facade unit. Worth mentioning that the purpose of the application/outcome of this prototype is not the design of the responsive unit; rather than being the processes in which the design and the fabrication go through.

In order to fulfil the aforementioned targets, the following objectives will be sought:

1- Clarify the possibilities that can be offered by Biomimetic architecture to develop bio-inspired building behaviour systems that can help to reach sustainability.

2- Explore the advanced architectural interpretation of life criteria.

3- Identify the main principles of Biomimetic Design Approach and review significant case studies.

4- Achieve a clear methodology for Biomimetic Approach looking for functions, behaviour and ecosystems of living systems to produce biomimetic building elements which could enhance building behaviour efficiency.

5- Propose a methodological framework to support architects and designers in the biomimetic approach at the technical level.

6- Design and implement a prototype of a responsive facade unit to validate the proposed biomimetic design framework.

7- Reach criteria for measuring the success rate of the bio-inspired design, to ensure the mimicking of the biological role models in building behaviour.

D. Research Methodology

In order to fulfill the purpose aforementioned, analytical and experimental methodology will be adopted through five stages. First: a literature review of the history of biomimetic architecture will be reviewed; second, explore biomimetic design approaches, levels of biomimicry and nature's life principles; third, using comparative analysis, various crossovers from nature were explored resulting in a methodological framework for the biomimetic design approach for building behaviour, which is looking for functions, behaviour, and ecosystems within the living systems and implements same into the building elements to reach the architectural targets. Forth, the application of the proposed methodology to verify the results is an example of the utilization of the Biomimetic Design Framework Methodology for Building Behaviour. It also helps to acquire a hands-on experience for the digital model and fabrication of physical models through all the steps, starting from defining the building behaviour target till the implementation stage, for inevitable further explanation and to clarify the methodology. Through the prototyping and physical testing, an outcome will be demonstrated by using accessible kinetic facade components with the integration of sensing devices and parametric design tools: fifth, using measuring criteria to identify the rate of utilization of biomimicry for the selected projects.

E. Research Structure

The thesis structure is divided into three main parts; first, the theoretical study; second: the experimental study and application; third, the analytical study, as follows:

PART I: Theoretical Study

Chapter One: Historical Background and Literature Review

The first chapter is considered as an introduction to this thesis. Hence, it begins with an overview on the global challenge, by showing the important issues which currently face the world, then presented the reason which motivated architects to deal with biology to obtain solutions for global issues. Afterwards, it focuses on the definitions of biomimicry and terminology through collecting an intensive literature review, as an essential historical background of biomimetic architecture providing a trial to investigate the overlaps between architecture and nature. Finally, the chapter discusses the importance of mimicking nature at behaviour level by reconnecting to nature. The main points of chapter one can be summarized as follows:

- Motivations for biomimetics approach
- Definitions of Biomimetic origins
- Historical background for using Biomimicry in different fields
- Background of Biomimetic Architecture

Chapter Two: Biomimicry as a Sustainable Design Methodology

The second chapter presents a brief overview of biomimetic approaches and the importance of mimicking nature at behaviour level for a sustainable design. This chapter adopted the solution-based approach, which is concerned with turning the potential strategies in nature into architectural elements. Subsequently, nature is reconnected by identifying the selected life principles in biological organisms that could be transferred to the architectural domain. Finally, an in-depth analysis was carried out to a set of well-proven experiments using the two-phased analytical methodology for the biological role model, to abstract its potential strategies into architectural elements. The main points of chapter two can be summarized as follows:

- Biomimetic design approaches
- Levels of biomimicry in architecture
- Reconnecting to nature (Life criteria)
- The selected life principles to be transferred to the architectural domain
- Biological Domain Methodology for solution-based approach
- Mapping Biological Role Models performance

Chapter Three: The Influence of Biomimicry on Building Behaviour

The third chapter focuses on the investigations of role models and their performance, creating the hypothesis of translating more life criteria into building behaviour elements. Additionally, linking the life criteria to the building behaviour targets has been achieved through a clear methodology of the problem-based approach for building behaviour. Afterwards, the architectural interpretation of the selected life principles was applied to the building behaviour elements, in order to achieve the specific architectural targets through analytical study. Finally, the chapter discusses the benefits of the biomimetic approach in building behaviour through well-proven successful case studies for achieving its targets. The main points of chapter three can be summarized as follows:

- Identifying the building behaviour targets and elements.
- Life criteria interpretation in building behaviour.
- Case studies of transferring the life principles to building behaviour element in order to reach their targets.
- Reaching a clear methodology of the problem- based approach in order to link the biological domain to the architectural domain.

PART II: The Experimental Study and Application

Chapter Four: Transfer Nature to Architecture

The fourth chapter discovers the technological tools and methods. This chapter is an attempt to understand how biological solutions transfer to the architectural domain in the form of a digital model or an architectural element rather than being a text. Three main experimental trajectories will be explored that matched the objectives of the chapter; first, defining the Computer-Aided Biomimetics tools (CAB); second, exploring the computational design tools used to transfer the biological domain information at the architectural level; third, applications on the behaviour-based algorithms. Finally, the Biomimetic Design Framework for Building Behaviour will be formalized. The framework will be made by analyzing the selected case studies, supported by applications on the behaviour-based algorithms which are derived from that transformation using the methodology proposed by the researcher. The proposed methodological framework technically supports architects and designers in the biomimetic approach. The main points of chapter four can be summarized as follows:

- Decoding Nature and scripting tools.
- Proposed methodological framework technically supporting architects and designers in the biomimetic approach.
- Computational design tools and fabrication methods.
- Design experiments on the application of the computational tools.

Chapter Five: Application of the Biomimetic Design Framework to Building Behaviour

The fifth chapter represents the application of the proposed methodology, aiming to reach a hands-on experience for digital model and the fabrication of physical model through all the steps, starting from defining the building behaviour target till the implementation stage, for the inevitable explanation and to clarify the methodology. Furthermore, design and implement a prototype of a responsive facade unit and a digital and physical prototype is introduced to validate the proposed biomimetic design framework

PART III: Analytical Study

Chapter Six: Measuring the Influence of Biomimicry on the building behaviour

Finally, the evaluation criteria for measuring the extent of benefit from the imitation into three main dimensions: the biological domain, the architectural domain, and the transferring domain then it branched into eight dimensions deducted from the study elements, in order to conclude common characteristics of the successful projects which can be used as standards for future projects.

Chapter Seven: Results and Recommendations

The seventh chapter represents the general results of the aforementioned research structure reached by the researcher, and the recommendations proposed by the researcher for the architectural approach adopted in the study to support future studies. Additionally, the references on which the study was based were presented.

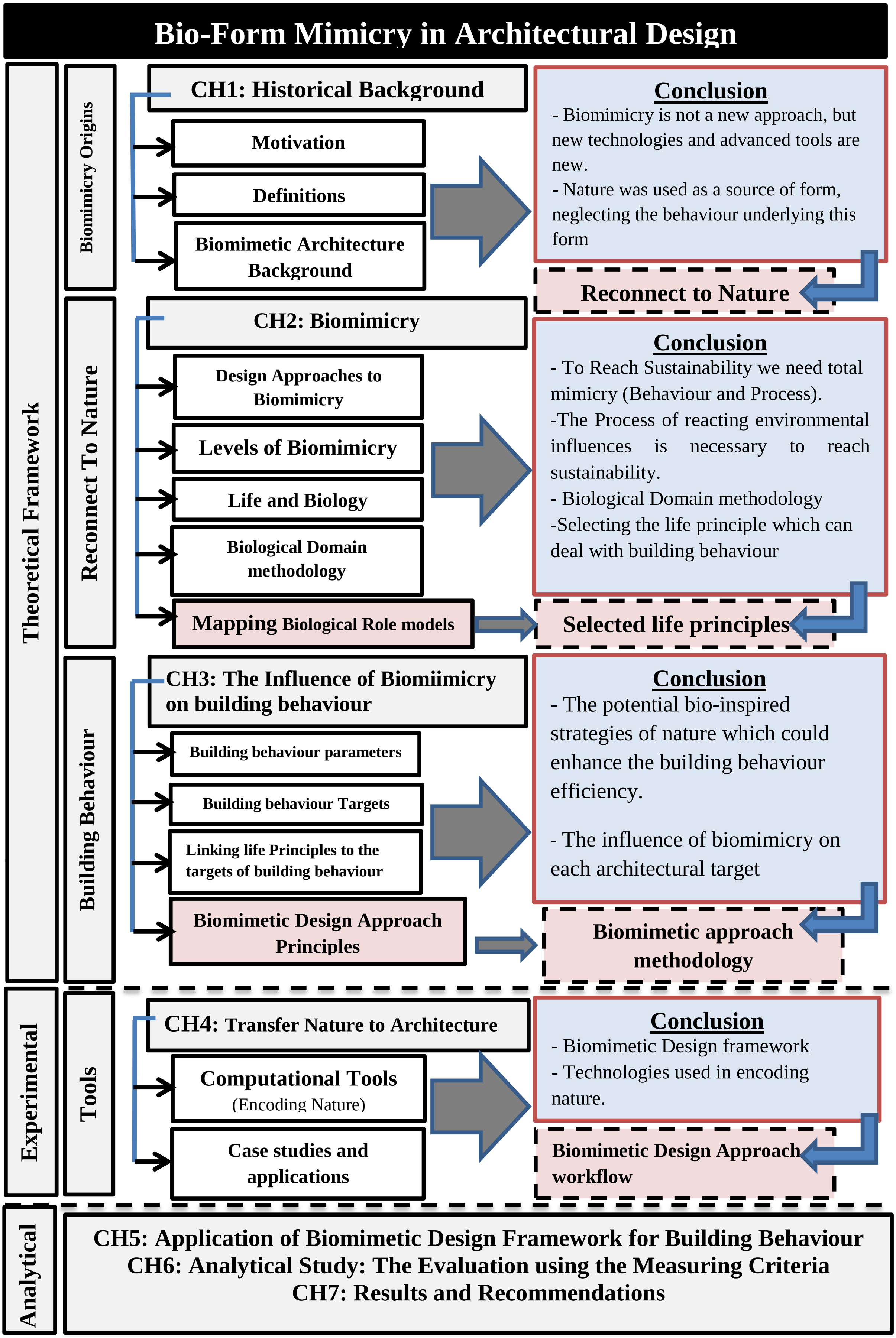


Figure (2): Methodology Chart

CHAPTER 1: Historical Background & Literature Review

Introduction

Motivated by global climate change, including global warming and greenhouse gas emissions, architects and designers undertook a duty to look for more efficient, sustainable building systems. Biomimicry is often described as a tool for increasing sustainability, where self-sustaining ecosystems can be created through learning from natural processes which can face these global challenges.[1]

Climate change is one of the most perplexing issues confronting today's world. It involves many aspects such as science, finance, society, governmental issues, and moral and ethical inquiries. Most probably the adverse impact of climate change will continue for hundreds of years to come. If we investigate carbon dioxide as an example, it causes ozone depletion and requires a long time for the planet to get rid of. In other words, even if substances harming the ozone ceased to be used/emitted, its dangerous effects will still continue to be seen, probably for generations to come. Figure (1-1) shows the effects of expected scenarios of climate change.[2]

Figure (1-1) The Potential Future Effects of Global Climate Change
Source: https://climate.nasa.gov/effects/, accessed Sep, 2019

According to United Nations Climate Change Secretariat report published in 2019, as appeared in Figure (1-2), repercussions observed or foreseen in climate variables were predominantly regarding temperature, precipitation, or sea-level ascent. Additionally, more explicit indicators can be seen, for example, ocean fermentation level, the status of glaciers, the occurrence of extraordinary climate and the connection between public, territorial and worldwide climate conditions. The report provided data referring to climate conditions applied as a database for estimating impacts. Additionally, the report announced, specifically, situations of temperature increment in the medium term (2050) and long haul (2100), quantitative and subjective assessments of precipitation change, including territorial varieties, and long-term projections of sea-level ascent.[3]

1 Hussein, A., “Biomimicry - Architecture learnt from the nature”, Sheffield, United Kingdom, 2015
2 https://climate.nasa.gov/solutions/adaptation-mitigation/, accessed Sep, 2019
3 United Nations Climate Change Secretariat Report, 2019

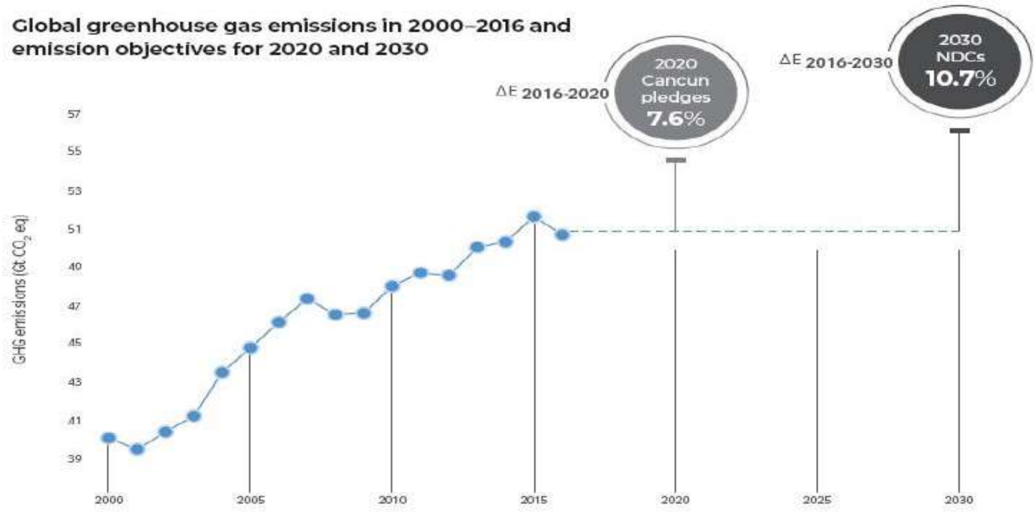


Figure (1-2) Global GHG Emissions
Source: UNFCCC 2019 Report

Based on the previous report, sustainable buildings became a priority, being the most required characteristic in building design. From a conventional perspective, sustainable approach guarantees satisfaction to future generations, where rather than consuming non-renewable resources, sustainable buildings produce more vitality, freshwater that surpluses the needs. This goal is not yet achieved in maintainable, LEED, and green-guaranteed extends today. A lot of efforts are still needed to be done to address the effects of climate change, pollution, and over-consumption of resources. To the contrary, resources are continued to be subject to our degradation.[4]

Designing a project or building based on the surrounding environment is a vital key to its success. As a settled framework, the project is the first level of the system, while the surrounding environment/ neighbourhood is the second level of the system, and finally the city, watershed, or whatsoever equivalent element being the third level of the system. Therefore, the collaboration between the project and the adjacent systems should be considered. For example, Brattleboro Food Co-op lost a valuable chance to develop its surrounding farming area as a result of focusing only on obtaining the LEED certification.[5]

Biomimicry is a Learning process and a deep understanding of natural organism's performance, the idea of the connection between human and earth systems. Biomimicry represents a profound understanding of the processes performed by natural organisms. Such understanding is based on learning such processes in details, resulting in a design that connects human to earth systems. According to Figure (1-3), ecological techniques can be seen in four levels: conventional, Leeds, Biomimicry, and regenerative. As a practical methodology, Biomimicry is inspired by nature where it mimics biological processes existing therein. Figure (1-3) shows the levels of ecological techniques for sustainability, starting the conventional level, through LEED and Biomimicry till the regenerative level, which turns the

4 Kessler, Helen J., "Sustainability from Building to Community: on Regenerative Design", Article, Facilities net, 2017
5 Kessler, Helen J., 2017, Op. cit

maintainable into a regenerative outlook. In order to maintain sustainability, the study will adopt the Biomimetic approach as a novel step to provide a generative design capable of providing sustainability and overcoming climate changes. Biomimicry is a nature-based methodology that practically uses its forms and performances as a model for designers. The biomimetic design depicts measures that reestablish, restore, or rejuvenate their wellsprings of vitality and materials, making practical frameworks that incorporate the necessities of society with the uprightness of nature.[6]

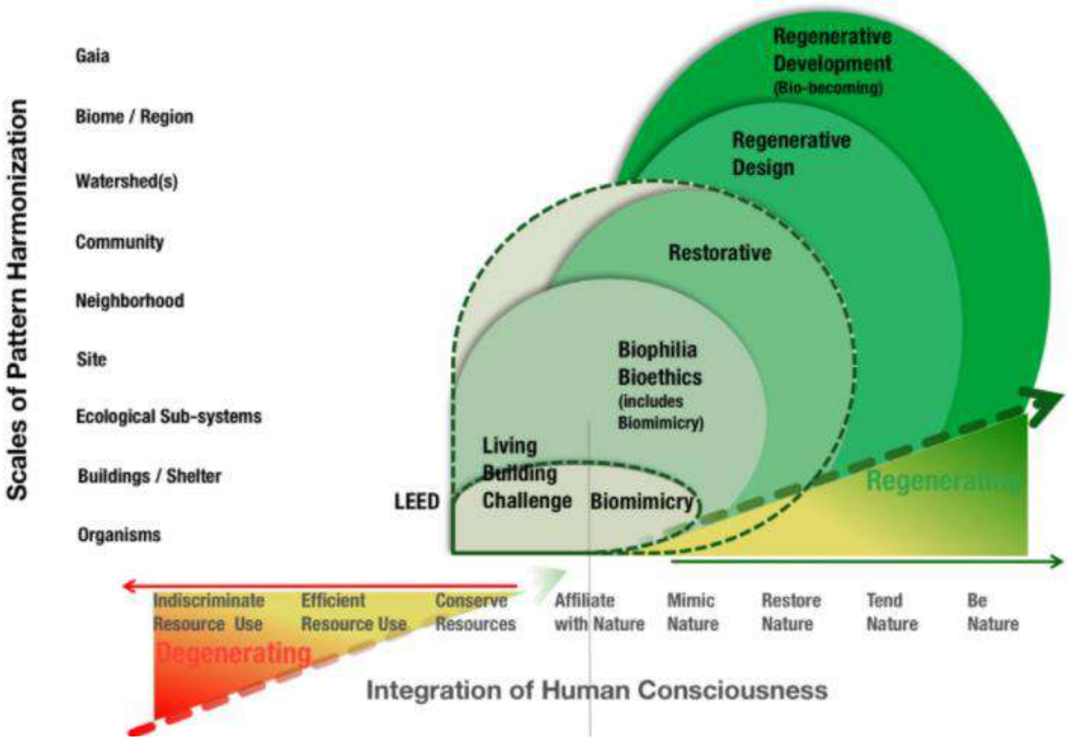


Figure (1-3) Levels of Ecological Strategies for Sustainability (shifting from sustainable to regenerative)
Source: Re-genesis Group, accessed Jan, 2020

Systems of the building, structures, fabricating cycles, horticulture, and human activity will work more efficiently by mimicking biological performance and utilizing nature as a model and guide. Nature's strategies and techniques are considerably more successful and unquestionably more maintainable than technical designing approximations. The standards directing biomimetic are derived from an environmental comprehension of how life functions, and give a theoretical beginning stage to move into all the more entire and biomimetic approach; Figure (1-3).[7]

Accordingly, this chapter will focus on the natural strategies for overall global issues prevailing. The study will also investigate how Biomimicry is forming sustainable design and headway in an array of fields like energy, architecture, transportation, horticulture, medication and communication. As a result of continuous application of Biomimicry approach, biomimetic methodologies will definitely witness a change that will encompass

6 Raymond. J. Cole, "Rating Systems for Sustainability", Article, Springer Science Business Media, New York, 2013
7 https://www.dezeen.com/2019/10/07/michael-pawlyn-architects-declare-interview-regenerative-architecture/, accessed Jan, 2020

components and building systems, which will, in turn, fulfill building objectives and enhance its efficiency. This chapter will present a historical background and a literature review for the origins of Biomimicry. After that, a timeline of biomimetic innovations starting from da Vinci flight till 2019 innovations will be included, along with the historical background of utilizing Biomimicry in architectural design.

1.1 Historical Origins of Biomimicry

According to Werner Nachtigall, the German term "Bionik" initially originates from the English word "bionics", which was introduced by the US Air Force Major J.E. Steele at "Bionics Symposium: Living models – The Way to New Innovation" conference in 1960, evidently as a coinage of the words "biology" and "technics" or "electronics". In German, the expression "Bionik" was coined of both the first and last syllables of the words Biologie [biology] and Technik [technology].[8]

1.1.1 Biomimicry Definitions

Based on Benyus's definitions, Biomimicry implies the imitation of life. The word was coined from the Greek roots "*bios*" (life) and "*mimikos*" (impersonation). In 2002, Janine Benyus described "Biomimicry" as the investigation of nature most successful strategies and then, the imitation of these functions and process to tackle human issues. The concept of Biomimicry is that, during its 3.8 billion years of innovative work, nature has developed proficient systems and processes that acted as internal solutions for a lot of waste management problems, asset effectiveness and the executives' issues which hugely bother today's world. [9]

The term "Biomimetics" was coined by Otto Schmitt in the 1950s. The coinage represented the exchange of concepts and analogues between biology and technology. It has generated significant and successful innovations; however, it is still in its infancy phase and still needs an ideal opportunity to turn out to be completely incorporated into all fields. In the year 2006, the biologist Julien Vincent defined Biomimicry as the reflection of good design from nature".[10]

In 2007, the Biomimicry Guild explained that there are two types of Biomimicry in the design process. The first is defining a human need or design issue and looking for the solutions by which other biological role models or ecosystems solved this issue. The second is identifying a particular characteristic, behaviour or function in a biological role model or ecosystem and making an interpretation of that into the human design.[11]

8 Nachtigall, W., “Bionik, Grundlagen und BeispielefürIngenieure und Naturwissenschaftler”, 2002
9 Benyus, J., “Biomimicry: Innovation inspired by nature”,USA: Perennial, 2002.
10 Vincent, J., “Biomimetics: Its Practice and Theory”, J. R. Soc. Interface 2006
11 Guild, B.,” Innovation inspired by nature work”, book. Biomimicry Guild., 2007

Petra Gruber is an architect and a pioneer in the biomimetic approach. Petra defined biomimetic architecture, also known as Architekturbionik, as “a developing field of nature into behavioural analogies, strategies, functions and methodologies or data delivered from living biological role models". Furthermore, Petra has always been encouraging designers and architects to search in biology for a solution to their problems by mimicking living organisms. According to Petra, seeking in biology for a specific biological role model to be mimicked is the approach by which Biomimicry can be achieved. Nature is a huge organization rich in strategies and performances, where any problem facing humans can be solved through ever-existing inspiration from nature, by selecting a specific organism that solved a similar problem.[12]

Additionally, in Michel Pawlyn's book published in 2011, Biomimicry was defined as “mimicking the functional basis of biological forms, processes and systems to produce sustainable solutions". The Biomimicry Institute defined Biomimicry as being “An approach to innovation that seeks sustainable solutions to human challenges by emulating nature’s time-tested patterns and strategies”.[13]

In 2010, the architect Maibritt Zari referred to Guild's methodology and discovered that there are three levels applied to design problem which are ordinarily as form, process and eco-system. Maibritt refined the biomimetic architecture from the above-discussed approaches defined by Biomimicry Guild and selected the first approach which adopts human needs and requirements. It's called the problem-based approach. [14]

1.1.1.1 The Terms Bionics, Biomimetics and Biomimicry

The term "Biomimetics" is the study of biological forms, processes, functions, and interactions to the surrounding to solve analogous human problems. Table (1-1) shows the utilization of each of the terms used in the improvement of biomimetic technologies. The proposed definition underlines the significance of function. Mimicking a biological performance is the approach to the biomimetic innovation; it is not just one of the classifications or levels or viewpoints to consider. Additionally, the outcome of human innovation within the context of mimicking the natural function is morphology made of either organic material or a biological aesthetic. Hypotheses of living systems recognize the significance of function as follows: it is what that makes biology not the same as other characteristic sciences.[15]

12 Gruber, P., “Biomimetics – Materials, Structures and Processes, Biological and Medical Physics”, Biomedical Engineering, New York, 2011

13 https://biomimicry.org/what-is-biomimicry/, accessed Sep, 2019

14 Maibritt, P. Z., “Biomimetic Approaches to Architectural Design for Increased Sustainability”, Zealand Sustainable Building Conference, New Zealand, 2010

15 Bellomo, N., “Modeling Complex Living Systems: A Kinetic Theory and Stochastic Game Approach”. Birkhauser: Boston, 2008

Term	Definition	Revised definition	Scope
Biomimetics	Modelled on or resembling a natural biological material, process, etc.; (of a synthetic method) that mimics biochemical processes" OED 1960	The study of biological functions, the forms, processes, and interactions to solve analogous human problems	Wide: Engineering, Medicine, Information Technology, Economics Systems science **(for innovations)**
Bionics	"The science of systems which have some function copied from nature, or which represent characteristics of natural systems or their analogues" [16]	Biomimetic approach to augment or replace a particular biological function with electronic or electromechanical components	Limited: Engineering Medicine Cybernetics **(for Mechanics)**
Biomimicry	"New science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems" [17]	Biomimetics to develop sustainable innovations; sustainable Biomimetics	Limited: Research and development with a goal of sustainable development **(for sustainability)**

Table (1-1): Terms, definitions and related fields
Source: S. Jacobs, Int. J, 2014

1.1.1.2 The Term "Biomimicry": It's a coinage of two terms as follows:

1- **Biology**: the science of life.
2- **Technology:** the deductive fabrication of products, devices and processes by using the materials and functions of nature, taking into account the laws of nature.

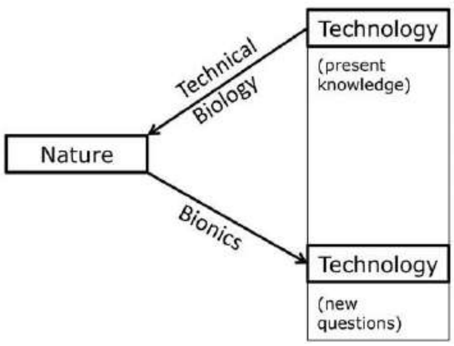


Figure (1-4) Diagram explaining the relationship between (bionics), technical biology, and technology
Source: Gruber P. 2011

Technical Biology analyses and depicts developments and processes of nature, considering the examinations and engaging techniques for material science and technology.

However, Bionics is the seeking in a thicket of nature's constructions and processes for inspiration in order to achieve an independent mechanical creation. Both disciplines complement each other in the function of continuing scientific-technical progress and development.

16 Nachtigall,W., "VorbildNatur. Bionik – Design fürfunktionelles Gestalten", Springer: Berlin, 1997
17 Benyus, J.M., "Biomimicry: Innovation Inspired by Nature", Harper: New York, 1997

The relationship between natures (biology), technology, and architecture have been subject to an ancient debate with many historical twists and turns; Figure (1-4). Nevertheless, those previous decades have brought remarkably quick paradigm shifts. There is no clear methodology for this relationship. The scope of this thesis is trying to reach a clear methodology for linking biology, technology and architecture.[18]

Biomimicry features an innovative, constructive approach to designs; or a process of innovation inspired by nature. Janine Benyus is considered a pioneer in Biomimicry approach. In Janine's book titled "Biomimicry: Innovation Inspired by Nature" published in 1997, Janine suggested shifting human's perspective from learning about nature to learning from nature, as a method to solve our problems across various fields. She set Biomimicry dimensions that could be followed to reach an innovation or a design mimicking nature.

1.1.2 Biomimicry Dimensions [19]

In "*Biomimicry*" book, Janine Benyus presented the idea that we could be better off by mimicking how problems are solved by nature. Benyus mentioned that the overall approach is based on three dimensions as discussed below: (a) Nine Principles of Biomimicry; (b) Nature as a model, measure and mentor; and, (c) The Design Spiral methodology that leads to Biomimicry-inspired practice.

1.1.2.1 Principles of Biomimicry[20]

A- Nature runs on sunlight

Examples of "natural sources" of energy include wind; however, all sources of energy within nature are dependent on the sun. Nature realizes how to generate energy efficiently, such as leaves direct towards the sun, and can efficiently receive 95% of the energy needed through the photosynthesis process (plants utilize the sun to transform light into sugar, the normal food that the plant lives on - and afterwards human eat the plant). Additionally, the photosynthetic process utilizes water and releases the oxygen which is required by all organisms to survive. However, nature does this by utilizing daylight instead of fossil fuels.

B- Nature uses only the energy it needs

Nature relies on the benefits rather than the whole natural capital at its disposal. It doesn't over-use its resources, which means it doesn't unnecessarily consume and deplete

18 Razin, A., "Biomimicry Architecture, from the Inspiration by Nature to the Innovation", Architecture and Engineering, Russia, 2018
19 Benyus, J. M., "Biomimicry: Innovation inspired by nature" (3rd Ed.). NY: Williams and Morrow & Co. 2002
20 Sue L.T. Mcgregor ,"Transdisciplinarity and Biomimicry",Article, Transdisciplinary Journal of Engineering & Science, Mount Saint Vincent University, Canada, 2013

its resources. To make the best use of the limited environment, every organism finds a special method, using just what it needs to survive and sustain.

C- Nature fits form to function

Nature fabricates a structure that works effectively and elegantly as it built everything within the bounds of accessible resources. Furthermore, the shape of the organism is decided based on what it is expected to do. Moreover, nature's structures are organic. Rather than being linear (squares and blocks), larger than usual and focusing on the form only, their size are only as big as needed to achieve its function. Additionally, nature adopts enhancement rather than maximization. The biological role models in nature co-evolve, adapting to the surrounding changes of others as they fit form to function.

D- Nature recycles everything

In nature, everything is recyclable; as everything has a usage. Waste ought to be a useful resource, as it will be reused again for another reason. This means that nature needs this waste; as it needs to sustain itself as waste is considered as food or sustenance. In fact, nature doesn't produce waste, and it doesn't foul its own nest since it needs to live in it. Therefore, nature operates its system in closed frameworks; each co-existing element consumes the waste of another as its lifeline.

E- Nature rewards cooperation

Nature depends on associations between integrated relationships since nature realizes the importance of cooperation and the adverse effects of individuality. Indeed, at times tasks cannot be performed individually. Besides, nature permits predation and rivalry to exist through participation. So, the characteristics of biological systems operate on symbiotic, complex organization of mutually beneficial relationships. Therefore, cooperating is fulfilling and necessary.

F- Nature banks on diversity

Nature depends on an assorted variety of conceivable outcomes to select the best solution, instead of a one-size-fits-all, homogeneous methodology. Also, nature likewise predicates on randomness, for more than a single reason. Irregularity makes randomness open opportunities for an assorted variety, where the randomness of entropy (the breakdown of request) allows adaptability. The bank of diversity is a result created by a wide variety of plant and animal strategies, by utilizing the whole habitat, not only pieces or parts of the system. Furthermore, a system must be as diverse as its environment to stay viable. These systems respect regional, cultural and material uniqueness of its place. Besides, these systems are adaptable, taking into account changes in the requirements of individuals and communities and allowing for emergent diversity.

G- Nature demands local expertise

Similarly, as nature, in general, requires a rich bio-diversity for the sake of adjustment and development, local ecosystems need a wealthy range of overlapped resources and the existence of many local species to create a vibrant natural community. Accordingly, locals are familiar with the limitations within which they are living and are familiar with other species who share the same domain and who have developed their adaptive skills. If a certain resource doesn't exist, it is not used, as nature doesn't have to import from outside. The natural eco-systems are attached to the local region; consequently, sustainability requires dependence on local expertise and indigenous awareness.

H- Nature curbs excesses from within

Nature imposed its own restrains, where it first confirms the availability of resources before building. Nature suffers no ego, as it maintains balance with the biosphere; the part of earth and environment in which living organisms exist, and which is equipped for supporting life.

I- Nature taps the power of limits

Nature uses its limitation as a power to avoid deviations. Species prosper within the limits existing within its environment. They do not search elsewhere for resources, and they sparingly utilize existing materials. Nature relies on its constant internal feedback systems for data on the most proficient method for achieving maintaining balance. While nature makes the best utilization of the existing resources and acts within its limits as a source of intensity, it is also constantly aware of maintaining life-friendly temperature, working within its limits, and using energy efficiently to save it to the future; otherwise, nature would have vanished. So that learning out how to live using limited resources is the main motive for inventions, as limits create power. This concept is the opposite of seeing boundaries as the boldness to overcome the limitations due to scarcity, and continue our development as nature teaches us to thrive within limits.

1.1.2.2 Nature as a Model, Measure and Mentor

The previously mentioned principles are the main nine principles of Biomimicry which Janine presented. Janine defined the idea of using nature as model, measure and mentor as the second dimension of Biomimicry. She defined Biomimicry as a new way to view and value nature. Besides, Benyus assumed that if people want to consciously emulate nature’s intelligence, they need to look at nature differently, as people must look at nature as a model, a measure, and a mentor. Therefore, counseling the genius of life brings nature's wisdom to influence today's pressing, chaotic and sinister problems.

a. **Nature as Model** – Biomimicry is a science that studies the models of nature and simulates or inspires their designs and functions to solve human problems.
b. **Nature as Measure –** Biomimicry uses an environmental criterion to judge the rightness of our innovations. Nature has learned after 3.8 billion years of evolution what works what is appropriate and what lasts.
c. **Nature as Mentor** – Biomimicry is a holistic way to display and appreciate nature as it presents a paradigm shift based on abstraction from nature and lessons learnt rather than mere observation of nature as shown in Figure (1-5).[21]

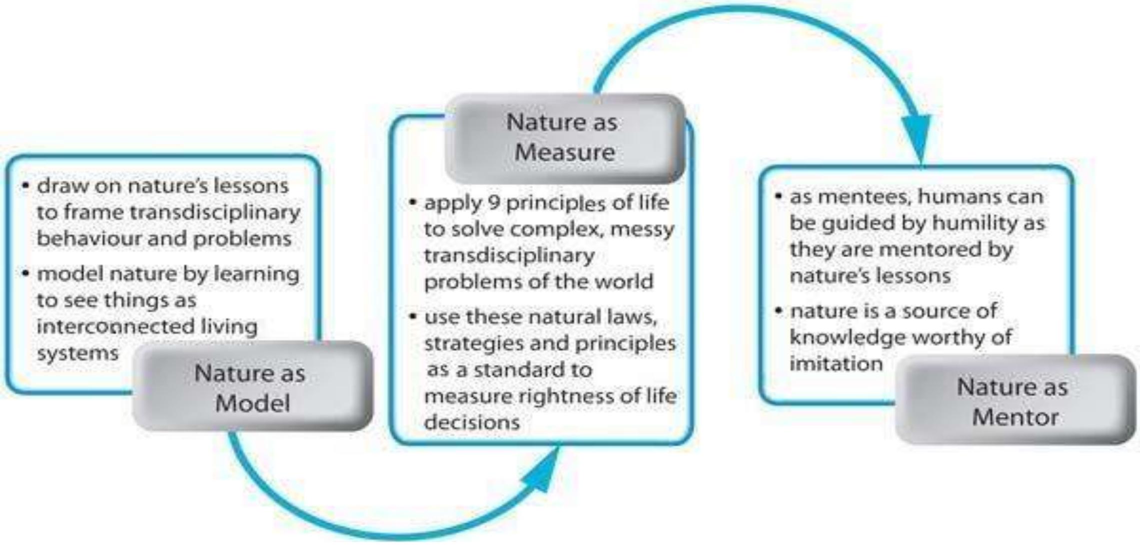


Figure (1-5) Nature as Model, Measure and Mentor
Source: Sue L.T. McGregor, 2013

1.1.2.3 Biomimicry Design Spiral

This is the third dimension characterized by Janine, as it is one of the most powerful aspects of the Biomimicry design. The Biomimicry design spiral moves outward direction, exactly as spirals in nature expand outwards. The spiral cycle starts from the core, where each 'lap' around the spiral is little and quick. Taking various quick laps towards the beginning of a design process permits the designer to rapidly investigate potential alternatives and opportunities, unlock hidden suppositions, produce and filter through numerous uncontrollably inventive concepts, and see what starts to develop before focusing on a specific solution pathway. This approach limits the time expected to accomplish radically sustainable innovation.

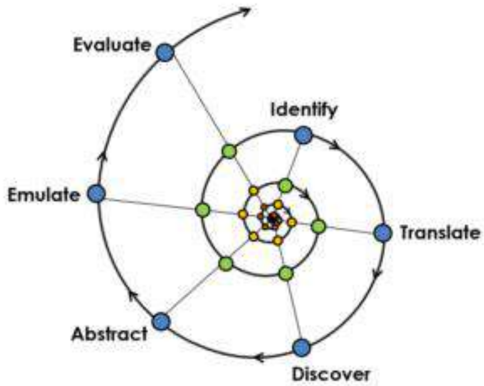


Figure (1-6) Biomimicry Design Spiral Diagram
Source: https://asknature.org/, accessed Jan, 2020

21 Benyus J.,"Biomimicry Innovation Inspired by Nature", San Francisco, 1997

The spiral is a voluble process, where any part of the project can be investigated, and attention can be paid to what's most important to the designer and his project at any given time. This design spiral provides a methodology for Biomimicry that depends on the target aimed. The design spiral works as follows: it starts with the Identification step, which uses Biomimicry for design. For the purpose of seeking to create something totally novel, Discover step can be the beginning. In the case of aiming to expand the portfolio of innovative and sustainable design techniques and solutions, the Abstract step can be the beginning. Furthermore, for reaching the goal of getting out of trouble and spark creativity, the Emulate step can be the beginning. Finally, for enhancing the sustainability of an existing design, the Evaluate step can be the beginning. These steps are shown in the Biomimicry design spiral diagram; Figure (1-6).[22]

The Biomimicry Design Spiral is a step-by-step methodology for transforming nature's processes into an inventive and sustainable design solution. It was developed by Carl Hastrich in 2005. Hastrich is an industrial designer who was one of the pioneers who set the basis for Biomimicry as it is seen today. Hastrich adopted a standard design process which included the remarkable advances required for Biomimicry, and afterwards, imitation for one of nature's unavoidable examples is done. Hastrich transformed the process into a spiral; Figure (1-6). The Biomimicry Design Spiral is utilized when the issue highlighted is totally understood. As follows the steps to utilize this strategy:

- **Identify** step: where the objective is to identify the functions that your design needs to perform – what you want your design to be able to do.
- **Translate** those strategies into words or text that makes sense in the biological domain.
- **Discover** strategies used by nature to perform those functions.
- **Abstract** step: you “reverse engineer” the discovered strategies in an abstracted way, and describe the ability of how they work in terms that make sense to your design occupation.
- **Emulate** step is using professional skills to create a design solution based on mimicking one or more of the functions and process that have been discovered and abstracted.
- **Evaluate** step: this step is used in two dimensions; where the first is evaluate your design solution against your original design; while the second is to evaluate your design against nature’s unifying strategies (or “Life’s Principles”) and nature’s rules for sustainability. [23]

22 DeLuca, D, “The power of the Biomimicry Design Spiral”, The Biomimicry Institute, 2016
23 DeLuca, D., 2016, Op. cit.

The Biomimicry Dimensions inferred according to Janine's classification stated that if designers want to consciously mimic the intelligence of nature, they must imitate the principles of Biomimicry, and look at nature as a model, measure, and mentor. They should also use the spiral of biomimetic design to solve their design problems while bringing the wisdom of nature as shown in Figure (1-7).

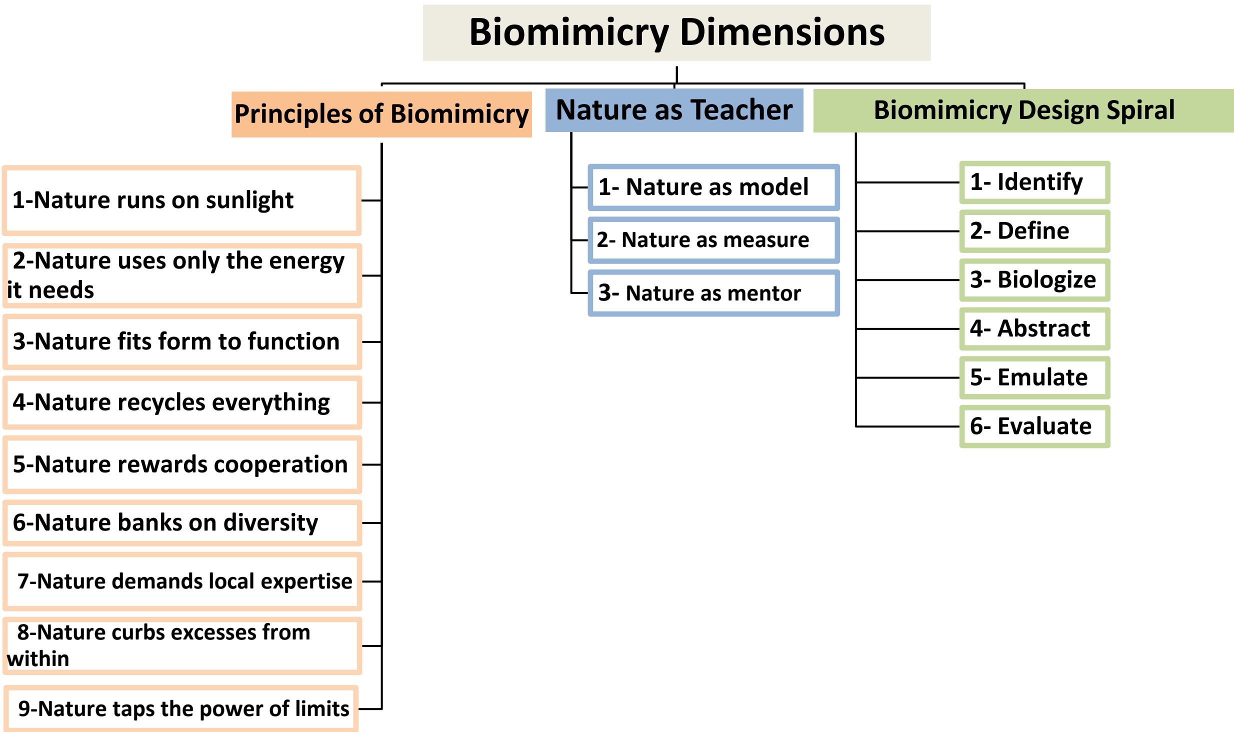


Figure (1-7) Janine's Biomimcry Dimensions
Source: Author

1.2 The Importance of using Biomimicry in Architecture

In order to define the importance of using Biomimicry in architecture, first, motivations that led to the introduction of the biological domain in architecture shall be discovered, the benefits from using Biomimicry in architecture shall be discussed, and then the pioneer organizations and companies that adopt Biomimicry thinking in their products nowadays will be reviewed.

1.2.1 The Motivations underlying Biomimicry

Nowadays, humans are exploring and investigating the living world and biological phenomena by using technological advancements. The realization of Biomimetics and the emergence of Biomimetics as a field of research increase the human ability to understand and imitate nature. As mentioned by Maibritt Zari, "Mimicking organisms or ecosystems is an expanding field of research in both academic and design discourse". Zari sorted the motivations underlying Biomimicry as three main motives as follows:[24]

24 Pedersen Zari, M. "Ecosystem services analysis for the design of regenerative built environments", Building Research and Information (BRI), 2012

- **Biomimicry for Innovation**

  Biomimicry can be considered as a source of innovation in creating new materials and technologies. Most biomimetic studies relate to this reason and do not necessarily aim to improve the environmental performance of human technology. In fact, it is about new approaches to technical problems and increased performance efficiency. This investigation type is particularly related to robotic computing and materials technologies that do not focus on sustainability issues.

- **Biomimicry for sustainability**

  Increased interest can be observed in the potential of Biomimicry as a way to create materials, products and products based on engineering solutions. Biomimicry is the enhancement of the environmental performance of human technologies and the improvement of the built environment. Besides, the mimicking of a living organism in the design itself is a mean to achieve greater sustainability.

- **Biomimicry for human well-being**

  The third motivation to explore biomimetic originates from analyzing whether the design dependent on the comprehension of the living world can contribute to increasing human psychological well-being, due to its inherent connection with the concept of Biophilia.

1.2.2 Benefits of using Biomimicry in Architecture

Recent examples of overcoming adversity can be observed regarding how Biomimicry can be applied to the building design. While buildings act as a protective barrier from nature's boundaries, but this doesn't imply that they don't have anything to obtain from the biological world. Indeed, nature regularly constructs structures with function and solutions that human-fabricated structures could conveniently imitate. Therefore, researches engaged within biomimetic exploration, science, and applications have undergone great developments and are now affecting the next generation of building elements and systems as well as the whole building systems.

For instance, photovoltaic systems, which harvest solar energy, are the first step of mimicking the manner in which a leaf harvests energy. Researches are on their way to create PV cells that closely resemble nature. These water-gel-based cells are basically fake leaves that couple plant chlorophyll with carbon materials, and finally providing a more adaptable and cost-effective solar cell. Therefore, the photovoltaic system gathers energy from the sun, which was enlivened by the way in which leaves capture daylight as a feature of photosynthesis; Figure (1-8).[25]

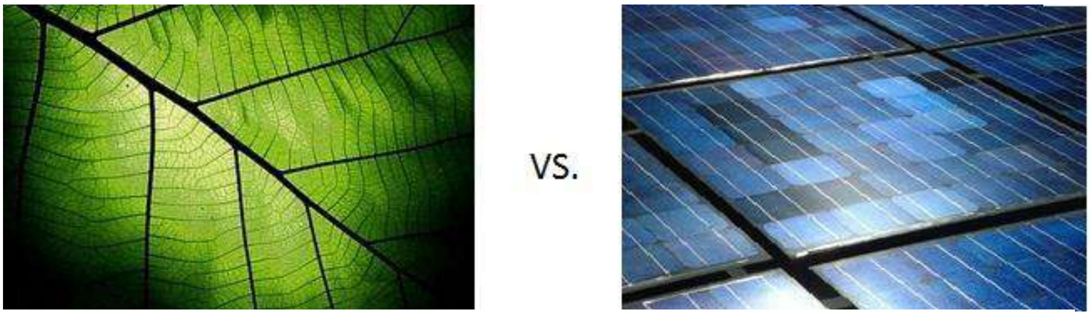


Figure (1-8) Plant photosynthesis vs. photovoltaic cells
Source: https://roboplant.wordpress.com, accessed Jan, 2020

Researches carried out on spider web decorative patterns- technically known as stabilimenta- found that the center decorations act as a warning signal to birds. Birds are able to perceive the reflection of ultraviolet light on silk and change their path to avoid nets. Contingent upon the source of light, spiders makes intensive designs to provide a broader area for reflection. According to this decorative center of spider webs, studies indicate that it reduces damage from flying birds; Figure (1-9). Spiders' act to protect its network from predators has recently inspired the development of window glass that prevents birds from hitting; Figure (1-10).

Figure (1-9) Spiders decorate their webs
Source: https://www.thoughtco.com, accessed Jan, 2020

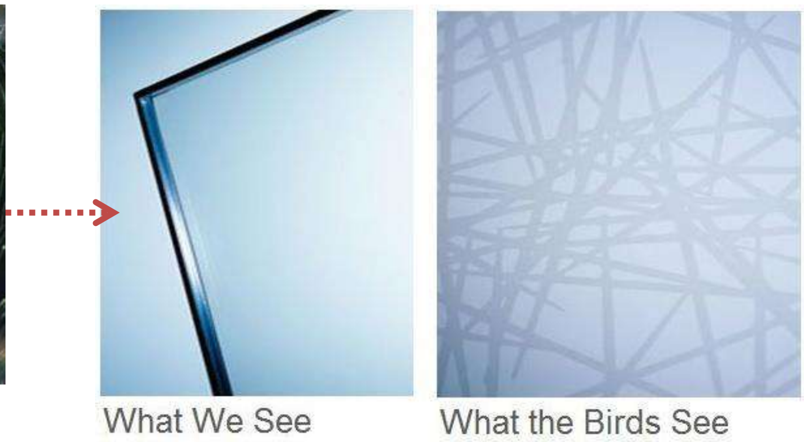


Figure (1-10) Bird-friendly glass looks like spider web to birds
Source: https://asknature.org/idea/ornilux, accessed Jan, 2020

These benefits have been realized across various fields and industries, and the success of that biomimetic process is measured by most industries that adopt biomimetic thinking. According to the Fermanian Institute of Business and Economics's recent report, Figure (1-11) shows increased activity in this field.US GDP is estimated to reach about $425 billion by the year 2030 based on measuring the success of biomimetic innovations. Depending on

25 https://www.wbdg.org/resources/biomimicry-designing-model-nature, accessed Jan, 2020

expectations set by the report, biomimicry will affect various fields, particularly building construction, material science, chemical manufacturing, power generation, which will provide significant growth and profit opportunities for and investors and developers alike.[26] From this report, the extent of benefiting from the biomimicry on industries in various fields was clarified; and thus, the focus of the study will be how to benefit from that, especially in the architectural design and building behaviour.

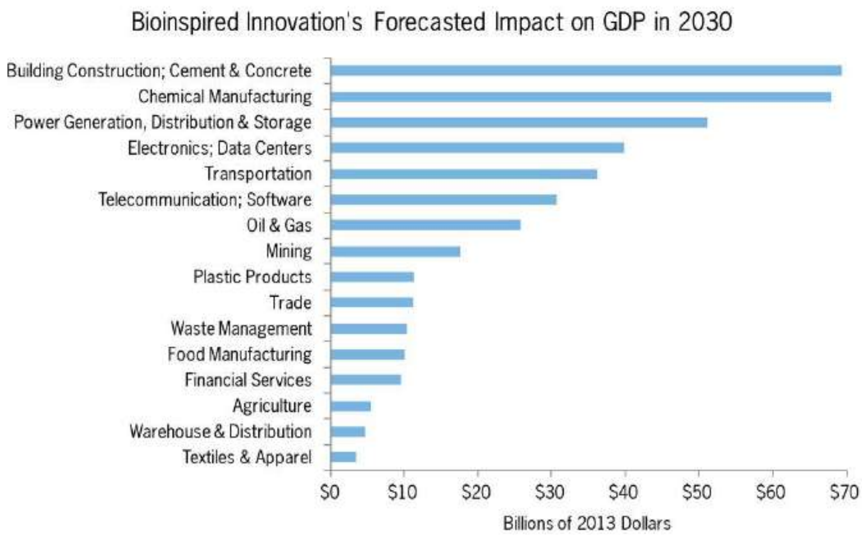


Figure (1-11) Increasing activity in the field that bio-inspired innovation
Source: https://biomimicry.org/nature-business/, accessed Jan, 2020

1.2.3. Organizations and Companies based on Biomimicry

Forward-thinking companies looking for new sources of innovations while producing pioneering and sustainable products and processes can find enticing opportunity in Biomimicry. However, probably those companies will realize that Biomimicry will face the same obstacles facing other methods of study and design, especially when teams are keen to maintain the sustainability and renewable aspects of life in their innovations. Given the impacts of climate change and the world's growing population, now is the time for organizations of all kinds across various fields to adopt nature as a source of invention.[27]

Biomimicry provides a methodology and framework for a sustainable solution, as Biomimicry asks how it can accomplish the various functions that humans need, such as making fibers stronger than steel at lower temperatures as spiders do, from carbohydrates. As mentioned by David Suzuki, toxin-free cells or solar cells that mimic the way leaves convert sunlight into energy, which were created by studying the Biomimetic strategies will provide smarter innovation. Biomimicry has influenced product development in companies that adopted biomimetic thinking, and placed these companies in an outstanding position such as PAX Scientific, InterFace, Whale Power and REGEN energy.[28]

26 The Biomimicry Institute, "Nature and Business: Developing a Sustainable Society Together", AskNature, accessed Feb, 2020

27 https://biomimicry.org/nature-business/, accessed Feb, 2020

28 Verbeek, K. "Biomimicry and Industrial Design", https://bioinspired.sinet.ca/content/biomimicry-and-industrial-design-karen-verbeek, accessed Feb, 2020

The success achieved by these organisations shows the importance of Biomimicry as a study. Hence, the framework of the study of this chapter began with a historical overview of the use of Biomimicry in various fields, and then the study will be allocated to Biomimicry in architecture throughout history.

1.3 Nature as a Mentor throughout History

From a historical standpoint, as mentioned before, the term Biomimetics was introduced by Otto Schmidt, who was responsible for developing the field of biophysics and establishing the field of biomedical engineering. Otto's work precedes the work of D'Arcy Thompson, the eminent biologist, mathematician and author of "On Growth and Form" published 1917. His book provides a descriptive index of natural forms and mathematical functions. Since its publication, the book has served as a treasure of inspiration for biologists, artists, architects and mathematicians. Furthermore, the next part will be a historical overview of mimicking nature in various fields. Inventions based on that mimicry will also be reviewed.[29]

- **Leonardo Da Vinci: 1452-1519**

Leonardo da Vinci was a naturalist, artist, and invertor. Da Vinci applied biomimicry to the investigation of birds in the desire for empowering human to fly. Studying his drawings included in his notebook is essential even today. Da Vinci was fascinated by flying, and drew several diagrams of schematic flights as shown in Figure (1-12).[30]

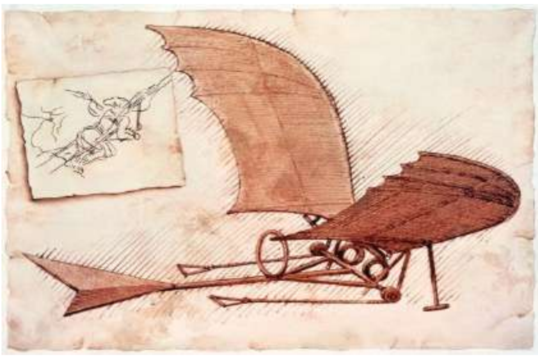


Figure (1-12) Da Vinci Flight Sketch
Source: https://www.britannica.com, accessed Jan, 2020

- **Sir George Cayley: 1773-1857**

The English nobleman and aviation explorer Sir George Cayley was interested in streamlined shapes. Sir George used to perform an autopsy on the corpses of dolphins and woodpeckers, in order to analyze their forms. In 1816, he designed a balloon with low air resistance, and in 1829; Figure (1-13), he created a kind of parachute by mimicking the fruit Tragopogon pratensis, after investigating its flying ability to sail in a very stable balanced way.

Figure (1-13) Sir George Cayley's Man Carrying Glider
Source: http://www.flyingmachines.org, accessed Jan, 2020

29 Pelce, P.," New Visions on Form and Growth", Oxford, 2000
30 https://ehistory.osu.edu/exhibitions/biomimicry-a-history, accessed Jan, 2020

- **Post Industrial Revolution**

Over the years, biomimetic approaches for technology and innovation have received increasing attention, as an alternative to the techniques that destroyed eco-systems that resulted from the industrial age. Nature is seen here as an inspiring source of knowledge. Scientists have conceptualized nature into their work on Biomimicry. This part undergoes important stages which represented the development of Biomimicry in the post-industrial revolution era in the twentieth century as follows:

- **1903:** In the USA, Wilbur and Orville Wright made their first successful motorized flight, in Kitty Hawk, North Carolina. Their achievement sparked the rapid development of motorized flight. The biplane is displayed at the Pima Air and Space Museum in Tucson, Arizona.
- **1912**: The Italian Senator and photo-chemist Giacomo Ciamician wrote a paper presenting a world without chimneys, where mankind found the secret of photosynthesis and could manage the world without charcoal.
- **1950s**: The term "Biomimetics" was coined by the American biophysicist and inventor Otto Schmitt.
- **1997**: Jenine Benyus, published her groundbreaking book, "Biomimicry: Innovation Inspired by Nature", where she coined the term "Biomimicry" and instilled the interest of this topic into engineers and designers worldwide. In addition, Janine started her own consulting organization, called Biomimicry 3.8. The mission of the organization was is to teach the world to innovate, learn, and be inspired by nature. She continues to struggle for a future that listens to nature rather than exploits it.[31]

- **Velcro: 1948**

While Georges de Mistral was on a hunting trip in the Swiss Alps with his dog, he noticed that burs in the woods were stuck with his clothes and dog's fur. While it was a nuisance, he saw it as an opportunity. After examining the burs, noticed that its surface consists of many tiny hooks. They stick to objects by attaching those hooks to surfaces like fabric and animal fur. Through mimicking, Velcro was invented by making a surface covered with tiny hooks and engaging it with a surface covered with tiny loops, producing the useful product known today; Figure (1-14).[32]

Figure (1-14) Velcro product result from mimicking burs
Source: https://ehistory.osu.edu/exhibitions/biomimicry-a-history, accessed Jan, 2020

31 https://foreignpolicy.com/2014/12/01/biomimetics-a-short-history, accessed, Jan2020
32 https://ehistory.osu.edu/exhibitions/biomimicry-a-history, accessed Jan, 2020

- **Bullet Train: 1990s learning from kingfishers how to break through boundaries**

In the late 1990s, Japan applied biomimicry in trains as a form. The chief engineer was able to tackle an issue arising from bullet trains through one of his hobbies: bird watching. The train released a booming noise after exiting the tunnel, as a result of compressed air that forms at the front of the train when it zooms through the tunnel.

Figure (1-15) Bullet train inspired by Kingfishers
Source: https://ehistory.osu.edu/exhibitions/biomimicry-a-history, accessed Jan, 2020

The engineers attempted to find the solution by looking in nature. Kingfisher, which successfully cuts into the water with little drag, was chosen as a role model. By looking to its beak, Figure (1-15), its shape was observed to take the form of the wedge, where it starts at a point and increases slowly in its diameter until it reaches the skull; Figure (1-16). This form could push the water out of the way, rather than ahead of the bird. That's exactly what the engineers wanted in their train by pushing the air off the road and not before the train, resulting in the train slicing the wind which will fix the booming sound.[33]

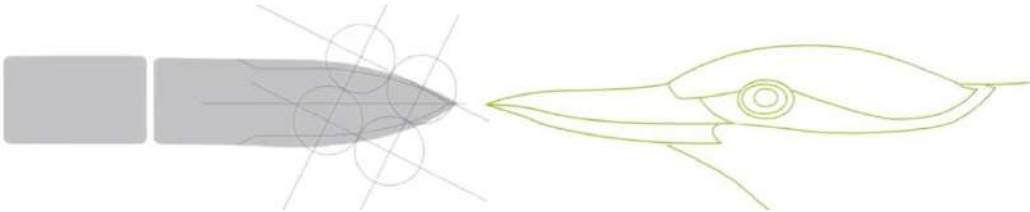


Figure (1-16) kingfisher Beak Mimicry
Source: https://gmisummit.com/gmis-2019/, accessed Jan, 2020

- **Wind Turbines: Learning from schools of fish how to create efficient wind power**

The wind turbines in the horizontal axis cause turbulence when placed close to each other, which reduces the efficiency of wind turbines (conventional turbines). Through studying the method of how swarms to fish swim in harmony, the defect in wind turbine was solved. The rotation axis can be made in the vertical position, and turbines could be positioned close to each other without disrupting the other engines, resulting in an increase in the efficiency by up to 10 times the shape of the horizontal axis as shown in Figure (1-17).[34]

Figure (1-17) Wind turbines inspired by fish swarm
Source: https://asknature.org/, accessed Jan, 2020

33 https://www.treehugger.com/how-the-kingfisher-inspired-the-shape-of-a-high-speed-train-4864551, accessed Jan, 2020
34 Op. cit

- **Gecko Feet**

By studying the reason why footpads of geckos are able to crawl across vertical surfaces, their feet were found to be are covered with hundreds of microscopic setae. These setae allow geckos to stick to the surface and unstick from the surface easily. This research resulted in an adhesive substance that is used to more efficiently stick things to walls and surfaces; Figure (1-18).

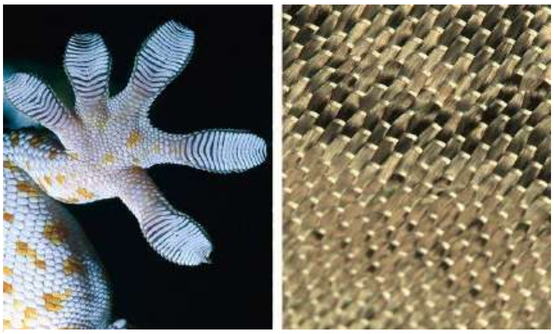


Figure (1-18) the foot pads of geckos
Source: https://ehistory.osu.edu, accessed Jan, 2020

- **Sharkskin**

Upon studying sharkskin, it was found to be antibacterial. An in-depth study of skin's configurations, Figure (1-19) found that it consists of strategically placed "bumps" that works at the microscopic level to push the bacteria away. Thus, this feature was utilized in mimicking a microscopic tissue that repels bacteria in the same way. This material, called Sharklet, was very useful especially in hospitals, and it has been used for covering surfaces and door handles to eliminate the spread of bacteria as it contained 94% fewer bacteria compared with a smooth surface.[35]

Figure (1-19) Sharkskin details
Source: https://ehistory.osu.edu, accessed Jan, 2020

- **Harvesting Desert Fog**

The Namibian beetle collects fog by raising its back in the air while the fog flows. The Bumps on its shell picks up water droplets and then those droplets flow on it's back towards its mouth. By mimicking the beetle's fog-collecting technique, a fog-collecting structure that could be placed in the tent and the building surfaces to hold water, named "Dew Bank Bottle" was designed by Pak Kitae; Figure (1-20).[36]

Figure (1-20) Fog-collecting inspired from Beetle
Source: https://www.bloomberg.com/, accessed Jan, 2020

35 David J. Staley, Ohio State University Associate Professor of History, is interviewed by history major Wyatt Schreiner (Ohio State Univ. Class of 2018) about biomimicry. https://ehistory.osu.edu/exhibitions/biomimicry-a-history, accessed Jan, 2020
36 https://www.bloomberg.com/news/photo-essays/2015-02-23/14-smart-inventions-inspired-by-nature-biomimicry, accessed Jan, 2020

- **Nature's Water Filter**

The 2003 Nobel Prize was granted to Peter Agri of Johns Hopkins, who in 1990 revelated a membrane protein that permits water to go through cell dividers. The revelation of Aquaporin tackled an antiquated issue in Bio-chemistry. Danish organization Aquaporin use this idea to build up another seawater desalination strategy for energy efficiency; Figure (1-21).[37]

Figure (1-21) Water filtration by protein membrane
Source: https://www.bloomberg.com/news/, accessed Jan, 2020.

- **Fin to the Wind**

Looking to the ability of humpback whales to swim gracefully, it was found that their swimming prowess is due to the presence of a row of warty ridges on the front edge of their fins, called tubercles. After that, those bumps were mimicked, as Frank Fish, a biology professor at West Chester University in Pennsylvania, found that by adding rows of these similar bumps to the turbine blades, that could reduce drag and noise, increase the speed to change the direction of the wind and increase the energy harnessed by 20%; Figure (1-22).[38]

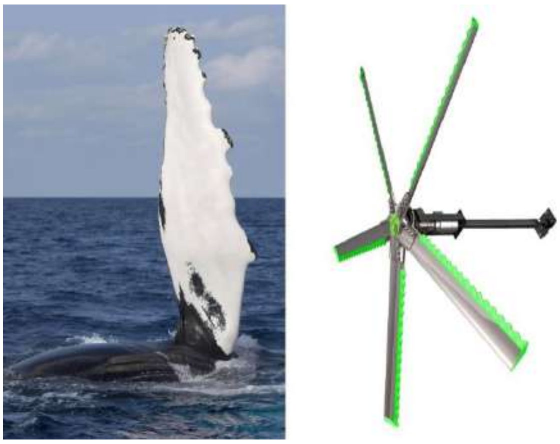


Figure (1-22) The Humpback whale fan
Source: https://www.bloomberg.com/, accessed Jan, 2020

- **Firefly Light bulbs**

According to the research published by scientists from Belgium, France, and Canada, when insects of the genus Photuris light fires in their bellies, the radiance is extended by their sharp, serrated scales. Based on this investigation, a similar structure was built on a light-emitting diode (LED), which could increase its brightness by 55 percent; Figure (1-23).

Figure (1-23) Firefly light bulbs
Source: https://www.bloomberg.com/, accessed Jan, 2020

37 Op. cit
38 Op. cit

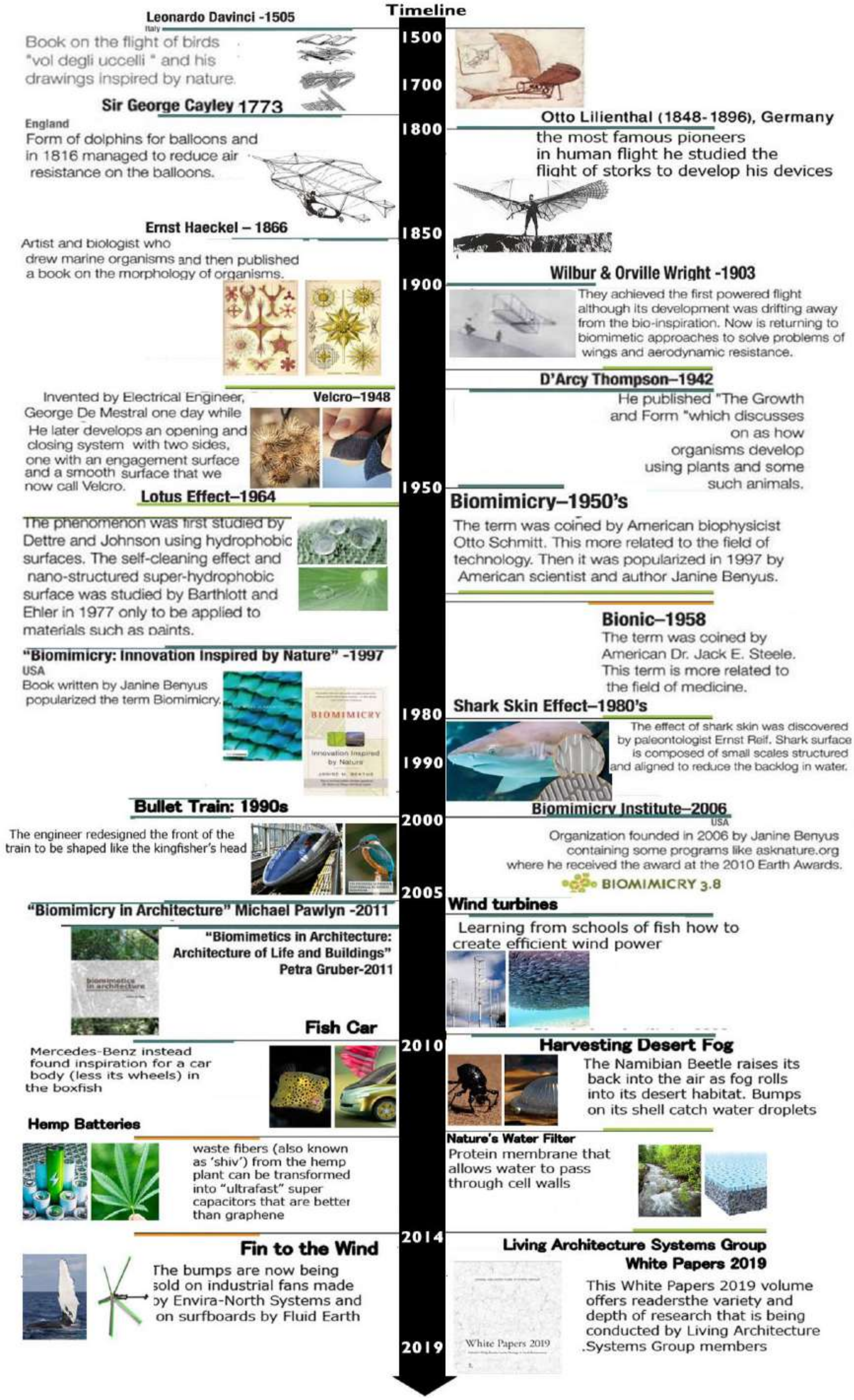


Figure (1-24) Biomimicry Timeline
Source: Edlyn García La Torre 2013, developed by Author

1.4 Biomimetic Architecture Background

Biomimicry affected various fields, especially the field of architecture, where nature was the main source of inspiration. Biomimicry was first used in architecture when early human learned by observing animals and how can they interact with the surrounding. [39] The ancient Egyptians, Romans, and Greeks integrated motifs inspired by nature into their design. For example, trees were used as an inspiration for columns, Late Antique and Byzantine arabesque tendrils are inspired by the acanthus plant.[40] Architecture started using biomimetic approach since prehistoric times. Due to the human needs to go out from the caves for hunting and gathering in summer times, they need to create shelters to protect from climatic conditions and other potential dangers.

Since the only available source that they could use or obtain ideas from was nature, they created their primary shelter by observing birds building nests and animals building a hut for the purpose of protection. They learnt how to create their first natural tent using tree branches and leaves by mimicking birds' nests; Figure (1-25), this was considered as the first trial of mimicking nature.

Figure (1-25) Shelters inspired from Bird's nest
Source: http://www.birdingtheislands.com/trip-reports
: https://www.crystalinks.com/, accessed Jan, 2020

1.4.1 Pre-Industrial Revolution Rock-Cut Architecture

- **Egyptian civilization: (3000 to 600) BCE**

In the Luxor Temple, 1400 BC, the resemblance was noticed between graceful columns of papyrus-cluster built with sandstone column and the papyrus umbels in its bud. During this period, many other Egyptian columns are mimicked from nature, such as stone columns carved to imitate tree trunks, bundled reeds, plant stems and capitals with motifs of lily, lotus, palm or papyrus. In the 27th century BC, the ancient Egyptian architect Imhotep is credited with carving the columns to imitate the assembly of reeds; Figure (1-26).[41]

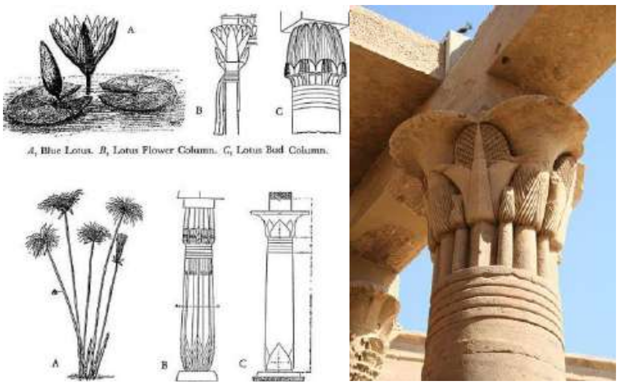


Figure (1-26) Philae Temple columns inspired from plants
Source: https://es.wikipedia.org/wiki/Capitel_egipcio
: https://archian.wordpress.com, accessed Jan, 2020

39 Arash Vahedi, "Nature as a Source of Inspiration of Architectural Conceptual Design", M.Sc., Eastern Mediterranean University, 2009

40 Alois Riegl, "The Arabesque" from Problems of style: foundations for a history of ornament, translated by Evelyn Kain, Princeton, NJ: Princeton University, 1992

41 Shaw, I, " The Oxford History of Ancient Egypt", Oxford University, Oxford, 2000

- **Indian Rock-Cut Architecture: (200BC to 500AD)**

Caves were used as a shelter since the monolithic era. So, it is quite logical that Buddhist temples and shrines in India were carved into caves mimicking the mountainsides; Figure (1-27). These temples finally doubled as trade posts on the Silk Road. Additionally, in India, examples were seen of the column's structures and their vegetal capitals that mainly mimicked floral and tree forms. For example, the floral and vegetal motifs in the rock-cut columns and capitals of the Ajanta Caves are inspired by religiously sacred plants and flowers like lotus and embolic.[42]

Figure (1-27) Kailasa Temple
Source: http://perimga.pw/pre-industrial-architecture.html, accessed Jan, 2020

- **The Greek and Roman**

During this period, the emphasis was placed on designing intricate and complicated forms of trees and Acanthus to enrich architectural motifs. Designing and crafting the intricate, detailed and complex shapes of plants and flowers on stones were extremely difficult and time-consuming. Only a few of the selected master craftsmen and craftsmen were skilled at designing and crafting those floral and geometric features; Figure (1-28).[43]

In later periods, trees and plants were the major element for imitation as aesthetic and decorative motifs, especially in the Baroque and Rococo periods. These were the times when intricate and richly decorated floral motifs by using stone, masonry, and stucco were popular. The distinct use of floral and plant motifs with more geometric intricacy, thus the designs appear widely in the Islamic structures of the pre-medieval periods.[44]

Figure (1-28) Corinthian column in Pantheon, and floral decorations in the column capitals of Maison Carrée
Source: MdRian, 2014

42 MdRian, I., Sassone, M.," Tree-inspired dendriforms and fractal-like branching structures in architecture: A brief historical overview". Frontiers of Architectural Research, 2014
43 Pollio, V., "The ten books on architecture", Book, New York, 2004
44 MdRian, 2014Op.cit

- **Medieval Period: Masonry vaults from 12th century AD to 16th century AD**

The Gothic typical style is primarily characterized by being surrounded by vaults made of stained glass supported by columns. These supports are a bundle of thin columns which turn into ribs on the upper side and form an intricate ribs network to hold the vaults; Figure (1-29). This gothic bundle column may be inspired by ancient Egyptian columns used in their vernacular homes to make intense supports which were in turn inspired by a bundle of papyrus plants.

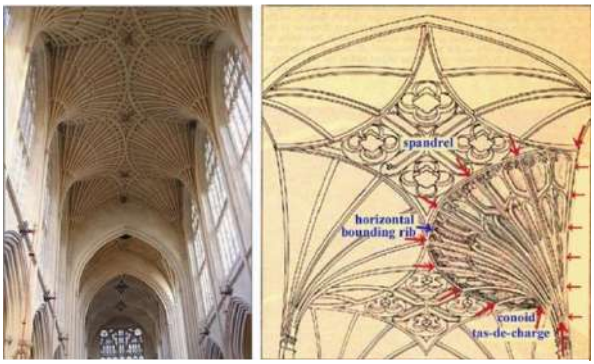


Figure (1-29) Masonry Vaults
Source: MdRian, 2014

1.4.2 Post-Industrial Revolution from the 16th Century AD

The Eiffel Tower built in 1889 after the industrial revolution was indirectly inspired by the famous German palaeontologist Hermann von Mayer work. Von was studying the structure of bones, especially the human femur, which can withstand a vertical load of one ton before fracture. In 1866, the Swiss engineer Karl Coleman visited von Mayer, who was busy inventing a new type of lever for weighty loads. He instantly noticed that the trabecular structure of the femur followed lines of force. The Eiffel tower was inspired by this skeleton. It represented a new type of as the using a minimum of material and structural efficiency; Figure (1-30).[45]

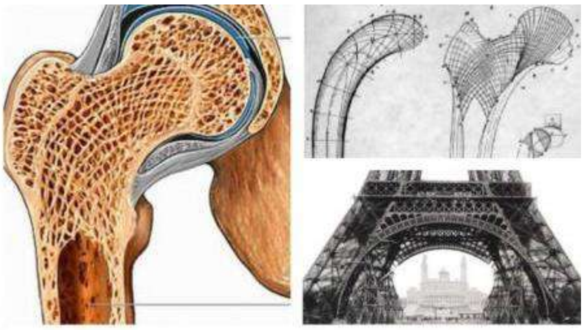


Figure (1-30) Eiffel Tower inspired by Femur
Source: Bagh-e Nazar, 2019

- **Biomorphic, Zoomorphic and Anthropomorphic: From the 16thcentury AD**

Zoomorphism appeared in the 16th century. It was a direct mimicking of nature, whereas it takes animal morphology as the masterpiece for architectural projects. The animal was represented in three-dimensional imitations of entire or parts of animals. In addition, it was represented in two-dimensional mappings that turned into houses by mimicking skeletons and animals; Figure (1-31).


Figure (1-31) Oriental Milwaukee Art Museum
Source: https://calatrava.com, accessed Jan, 2020

45 Bagh-e Nazar," Inspiration from Nature in the Training of Structural Design in Architecture", Article, The Scientific Journal of Nazar research center, 2019

1.4.3 Modern Architecture: (Geometry of Nature) From 18th Century AD

Nature's geometry has been a subject of discovery since the beginning of scientific research era. The laws of symmetry and proportion found in nature were already investigated and described in ancient Greece. The beauty that human perceives in nature clarified at various levels, notably, the mathematics governs the patterns which are responsible for the physical formation. Mathematics seeks to discover and abstract the patterns existing in nature. These visual patterns find explanations in chaos theory, fractals, logarithmic spirals, topology and other mathematical patterns. These patterns were discovered in modern architecture since the 18th century in the following order:[46]

a. The Golden Section
b. Spirals in Architecture
c. Chaos Theory and Architecture
d. Construction lightness
e. Curved Surfaces with Girders (Seashell)
f. Folded Structures
g. Ernst Haeckel's Tables of Marine
h. Hexagonal Design Inspired by Nature
i. Cable Structures Inspired by The Spider Web

a. The Golden Section

Throughout history, the golden ratio has been used in many engineering constructions, where this unique ratio can be found in the human body, typography, solar systems, DNA, schematic diagram, and architecture. It can be clearly realized in both ancient and modern structures. The Greeks were aware of the delightful aesthetic effects of the golden ratio. The appearance of the golden ratio in many architectural structures provided a sense of balance and balance. The geometric shape of the golden ratio is basically pleasing to the eye. For example, consider the ancient Greek Parthenon, located on the Acropolis of Athens, Greece; it's famous by the symbol for the golden ratio; Figure (1-32).[47]

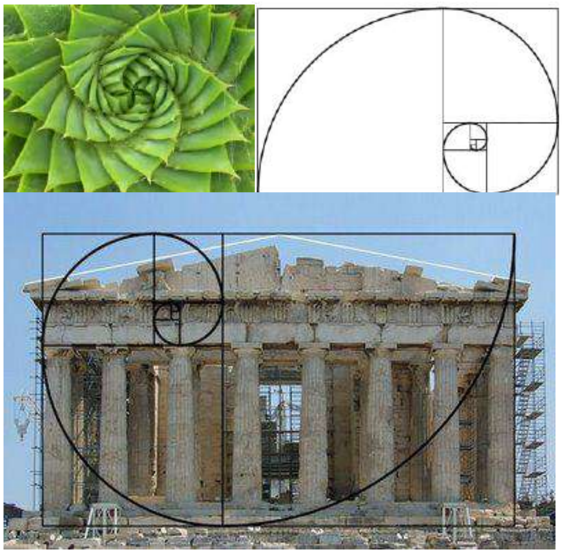


Figure (1-32) Golden Section
Source: https://www.cubettech.com, accessed Jan, 2020

46 Stewart, I., "What Shape is a Snowflake? Magical Numbers in Nature", Weidenfeld & Nicolson, London, 2001
47 http://jwilson.coe.uga.edu, accessed Jan, 2020

- **Le Corbusier (1887-1965)**

Since the 18th century, Le Corbusier developed the "Modular" technique. It's a measurement system based on the relationship between the golden section and the proportions of the human body, with an average size of 1.83 m and 1.75 m. Le Corbusier used this system in his business, particularly in housing units. This system is still valid nowadays as an attempt to create a human scale in architecture; Figure (1-33).[48]

Figure (1-33) United Habitation
Source: https://www.architravel.com, accessed Jan, 2020

b. Spirals in Architecture

Nature has adopted the spiral shape as a highly effective design for growth, strength and viability. No wonder man has used the spiral in art and integrated the elegant and graceful spiral shape as a major element in architectural design; Figure (1-34).[49]

Figure (1-34) Vatican Museum
Source: https://paterakoristudios.com/, accessed Jan, 2020

- **Frank Lloyd Wright (1869-1959)**

Wright represented organic architecture and postulated a building's view as a living being. Some of the designs are reminiscent of the skeletons of marine creatures or spider webs. At the New York Guggenheim Museum, Wright applied the IUD to the main circulation space of an exhibition hall. That was a controversial concept until today, but the resulting space is impressive; Figure (1-35).[50]

Figure (1-35) Guggenheim Museum
Source: https://www.guggenheim.org/, accessed Jan, 2020

48 Gruber, P.,“ Biomimetics in Architecture”, Springer-Verlag Wien, 2011.
49 https://paterakoristudios.com/spirals-in-architecture, accessed Jan, 2020.
50 Gruber, P., 2011Op.cit.

c. Chaos Theory and Architecture

Formal styles are also common in architecture today. Formalism is no longer limited to simple geometric shapes. New computational methods and construction techniques made controlling complex geometric shapes possible. Discoveries in physics led to the realization of more dimensional space and the use of chaos theory and fractal geometry.

The architecture of Eisaku Ushida and Kathryn Findlay is based on the contemporary theory of chaos and fractals. The helix as a fractal shape produces similar fractal shapes, however, they are subdivided. This geometric feature is also being exploited in construction. The "Truss wall house" by Uchida and Findlay has been included to represent the many projects that can be featured here. Despite the obvious intuitive spatial qualities, the architect's statement proposes mathematical modeling of the design; Figure (1-36).

Figure (1-36) Truss Wall House
Source: http://www.archilab.org, accessed Jan, 2020

d. Construction Lightness

The principle of lightweight construction requires reducing materials and exerting efforts in construction through the structure and design. This structure and design are determined according to the laws of physics by the flow of forces. The architects admire the integration of form, function, and creation process in biological structures and try to follow as shown in Figure (1-37).

Figure (1-37) Sydney Opera House Section
Source: http://theconversation.com, accessed Jan, 2020

Danish architect Jorn Utzon won the competition for a new Sydney Opera House in 1957. Figure (1-38), it is a design reminiscent of the arranging of mussel shells. Engineer Ove Arup and Peter Rice participated in the project. Although the opera was not completed according to Utzon's original design, the project can be seen as a victory by overcoming practical, political and bureaucratic difficulties.

Figure (1-38) Sydney Opera House
Source: http://theconversation.com, accessed Jan, 2020

e. Curved Surfaces with Girders (Seashell)

Seashells have successfully played a role in protecting its inner content for hundreds of millions of years. Scientists and chemists are trying to mimic seashell's structure, and it can be expected to be used as a stronger building design or as a substitute for bones. In case the seashell cracked, the seashell polymer forms a structure that strengthens and grows. In Valencia, Spain, the seaside city is beautifully built around the sea using concrete shell structures by mimicking seashells. HP dual bending machine was used to reduce the bending moment, and create a shell structure with a thin curved surface that only produces compressive forces within the plane; Figure (1-39).

Figure (1-39) Oceanographic Valencia
Source: http://www.valencia-cityguide.com, accessed Jan 2020

- **Arc and Vaults**

Antoni Gaudi, Frei Otto, and Heinz Eisler utilized strings to develop a form in experimental models. In the 1960s, many examples of organic architecture used free-form shapes with curves and shells; Figure (1-40). They closely observed the natural shapes and boldly created advanced skeletal systems. Gaudi designed equilibrated structures standing like a tree, needing no inner brace or outer brace, with smooth, hyperbolic, parabolic, and oblique arches (spiral cones). Intelligently anticipated complex structural forces were made via suspended string models with weights.[51]

Figure (1-40) Antoni Gaudi Architecture
Source: https://www.archdaily.com, accessed Jan, 2020

51 Panchuk,N.,"An Exploration into Biomimicry and its Application in Digital &Parametric" [Architectural Design] Waterloo, Ontario, Canada, 2006

f. Folded Structures

Folded structures were first introduced in the early twentieth century. Folded structures were associated with the development of the reinforced concrete. The basic idea of creating this type of buildings was to strive for a maximum building height with greater rigidity and achieve a lightweight structural element. This means that folded structures are among the most cost-effective constructions such as Sardar Vallabhbhai Patel Stadium as shown in Figure (1-41).[52]

Figure (1-41) Sardar Vallabhbhai Patel Stadium
Source: https://en.wikipedia.org, accessed Jan, 2020

One of the most important folded form buildings is the Chapel at the Air Force Academy in Colorado Springs, USA. The primary construction of this facility consists of triangular metal panels that form a folded structure. The structure consists of 100 tetrahedral elements fabricated in the workshop and assembled on site. At the time the building was constructed, the expert community objected; however, it later turned into an example of modern architecture in the USA; Figure (1-42).

Figure (1-42) Air Force Academy Chapel
Source: https://www.airforcetimes.com, accessed Jan, 2020

- **Ernst Haeckel's Tables of Marine**

Ernst Haeckel was ranked among the world's most famous biologists in his time; he was an artist and a scientist. Ernest published a book entitled "Kunstformen der Natur on protozoa and marine creatures and was widely popular. Magnificent change in size was made possible through enhanced microscopes. Heckel produced countless diagrams during his many journeys and expeditions, which were later processed into highly aesthetic engravings; Figure (1-43).[53]

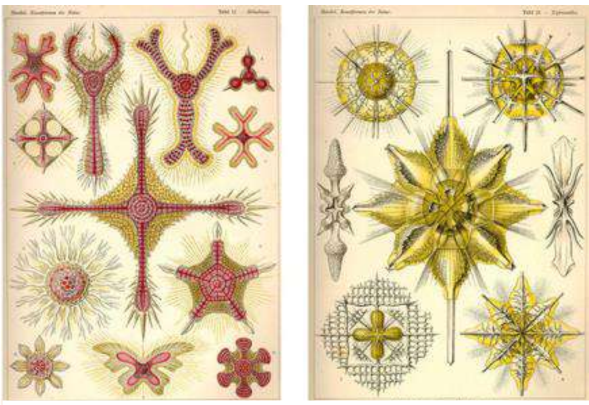


Figure (1-43) Ernst Haeckel's Tables of Marine
Source: Michela 2014

52 Šekularac,N.,"Folded Structure In Modern Architecture", University of Belgrade, Serbia, 2012
53 Rossi,M., "The Fuller's heritage: organic models and artificial microcosm", Politecnico di Milano, Italy, 2003

g. Hexagonal Design inspired by Nature

Honeycombs have a set of hexagonal cross-sections with accurate thicknesses and equal 120° angles between them. The hexagonal cells are diagonal to prevent the sticky honey from escaping, and the comb is completely aligned with the direction of the Earth's magnetic field. Hexagonal cells constitute the lowest total wall area compared to triangular or square sections. Those hex patterns can be found in nature, in giraffe skin, and turtleback; Figure (1-44).[54]

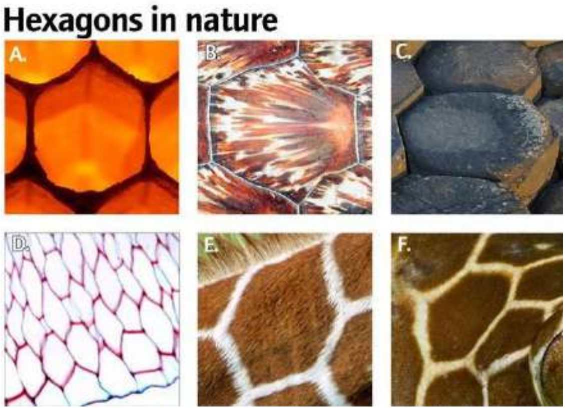


Figure (1-44) Hexagons in Nature
Source: https://www.pinterest.com/, accessed Jan, 2020

For instance, the new Bursa stadium is inspired by the hexagonal cells; Figure (1-45). The surface tension of soap film bubbles pulls the liquid surface to be the smallest possible area. A typical bubble mixture has polyhedron cells with various shapes and a slightly different curve. This bubble pattern was used as an inspiration for the structural system also in the design of the 2008 Olympic swimming pool in Beijing; Figure (1-46).

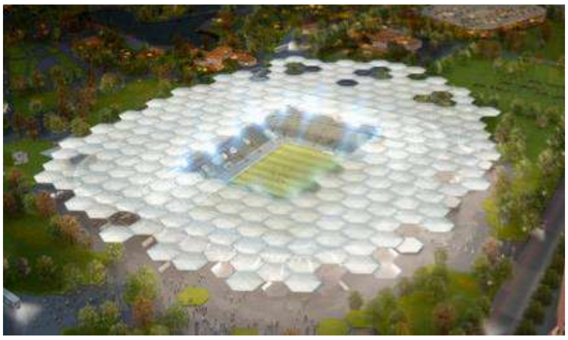


Figure (1-45) New Bursa Stadium
Source: https://www.archdaily.com, accessed Jan, 2020

Figure (1-46) Olympic swimming pool in Beijing
Source: https://www.archdaily.com, accessed Jan, 2020

h. Cable structures inspired by the spider web

The spider appears to be able to alter its natural behaviour in order to build an ideal web structure according to the environmental conditions. Spider web is one of the results of

54 Ball,P.,"Patterns in Nature: Why the Natural World Looks the Way It Does", The University of Chicago Press, 2016

complex animal structure. The spider construction rule provides a useful tool for exploring the behavioural strategies of a typical web construction method.

Spider webs have an identical structure to a radial cable network, although spiderwebs have no rigidity. This network is applied to the cable structure system for large area and lightweight roof. Jenny Sabin Studio's Lumen consists of the upper and lower cables which are then connected by bracing cables to resist the upper and lower loads of the roof; Figure (1-47). The cable roof system consists of an external compression ring, a center shaft, and continuous radial gear cables. The compressive forces acting on the outer circular ring are in balance with the tensile forces of the inner radial cables.[55]

Figure (1-47) Jenny Sabin Studio's "Lumen"
Source: https://www.archdaily.com, accessed Fab, 2020

1.4.4 Contemporary Architecture Inspired by Nature

In recent times, bio-inspired buildings are designed with dynamic and complex structures, unlike traditional box-like buildings. They are self-sustainable buildings that are able to produce electricity using wind and sunlight. It is an eco-building designed as a zero-energy building. It is famous for its innovative modern designs such as Diamond Tower, DNA Tower, Crescent Tower Oxygen Eco-Tower, Tower, Cobra Tower and Aqua Tower as shown in Figure (1-48).

Figure (1-48) Cobra Tower and Aqua Tower
Source: https://www.archdaily.com, accessed Feb, 2020

The dialogue between architecture and nature will continue to develop along with the deeper understanding of the globe, and the way its systems will be adopted in various scales and applications. From the purely aesthetic Art Nouveau motifs of Binet's Monumental Gate to LILYPAD the floating Ecopolis model designed for future climate changes as shown in Figure (1-49).

Figure (1-49) LILYPAD Ecopolis
Source: http://vincent.callebaut.org, accessed Jan, 2020

55 Jin K., Park,K.,"The Design Characteristics of Nature-inspired Buildings", Sungkyul University, Anyang, South Korea, 2018

1.5 Nature as a Source of Form- Finding

Upon the historical background of biomimetic architecture, nature was used as a source for form-finding only, ignoring the behaviour of its living systems. Modern shapes were extracted through a methodology Figure (1-50) using digital design technology that focuses on digital design processes. Computational design is a morphogenetic process that uses structured algorithms as non-linear systems for unique, endless and non-reproducible results.[56]

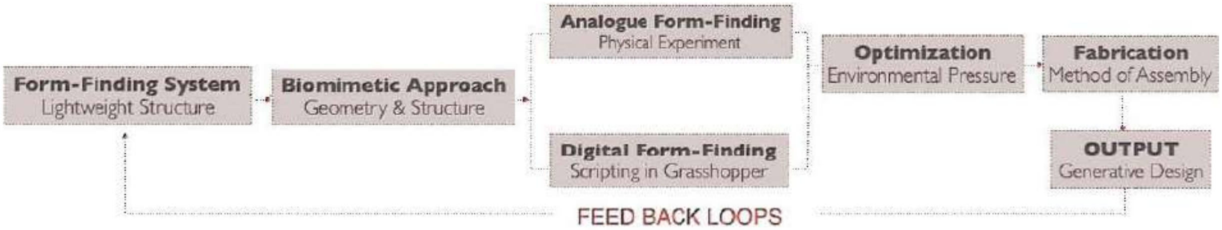


Figure (1-50) Digital Design Methodology
Source: Pezeshk .S. 2019

The strategies of instruction are an evolutionary process inspired by natural elements. In this paradigm Figure (1-51), the form is generated step-by-step through a defined algorithm which contains a series of mathematical rules, supported by the underlying logic rather than geometric rules. This is the methodology for form-finding concerning the natural forms while neglecting the behaviour generation. This thesis will adopt a clear methodology for enhancing building behaviour.[57]

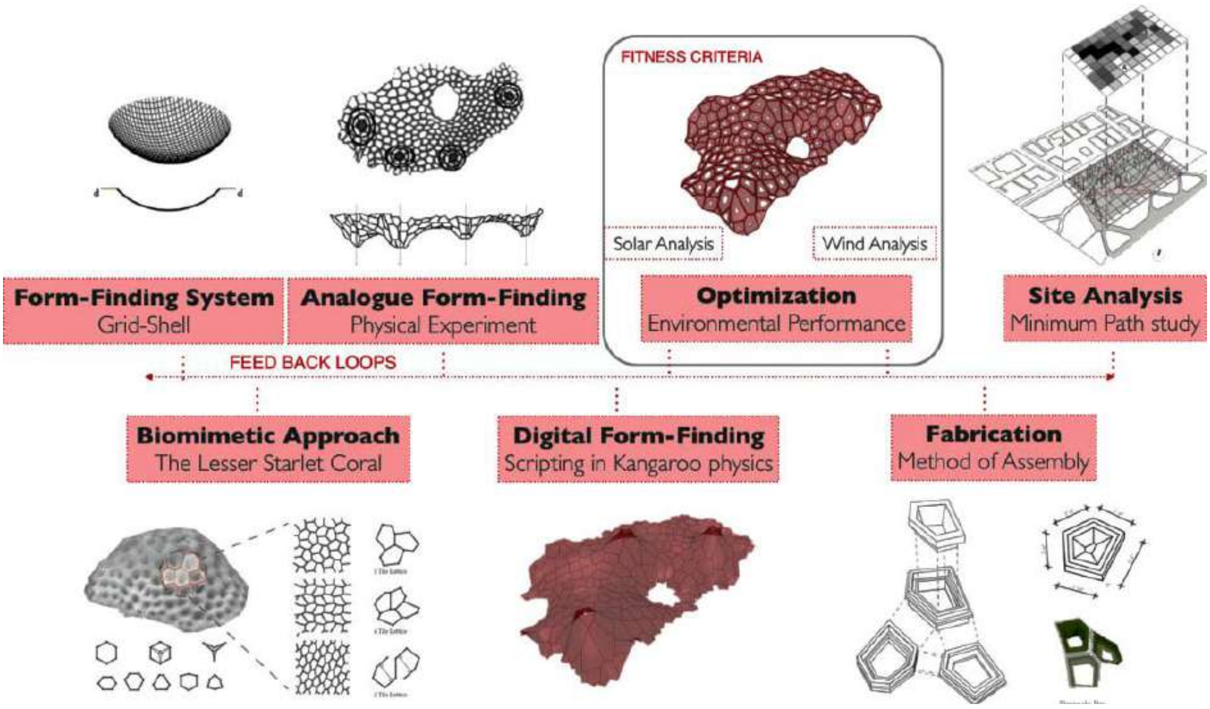


Figure (1-51) Form-Fining by Algorithmic Design Process
Source: Pezeshk, S. 2019

56 Pezeshk, S.," Generative Pedagogy: Lost in Transition", Conference Paper, Generative Art Conference, 2019
57 Pezeshk, S, 2019 Op.cit.

Chapter Summary

This chapter attempted to define the motivations behind using Biomimicry in architecture. It also investigated the various definitions of Biomimicry and its origins and the benefits of dealing with Biomimicry based on the available research and literature. The chapter presented significant bio-inspired innovations timeline in various fields, starting from Da Vinci flight till the contemporary innovations. After that, biomimetic architecture was highlighted. The historical timeline of utilizing the Biomimicry in architecture throughout history was presented; Table (1-2).

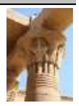
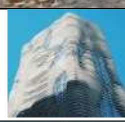
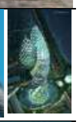
Classification	Period	Location	Example	Description	Image
Pre Industrial Revolution **Rock-Cut Architecture**	1400 BC	Egypt	**Ancient Egyptian Architecture:** Luxor temple columns	During this period, other Egyptian columns that have the common features like plant stems can be found. Indian Buddhist temples and shrines were carved into caves and mountains, decorated floral ornamentations in the Baroque and Rococo periods and Medieval period: masonry vaults	
	200BC to 500AD	India	**Indian Rock-Cut:** Kailasa Temple		
	Baroque and Rococo 500 BC to 400 AC	Greece and Europe	**Greek and Roman:** Corinthian column in Pantheon		 
	Medieval period 1200 AD to 1600 AD	Northern Europe	**Early Gothic:** Fan vault in the Thomas de Cambridge		 
Post Industrial Revolution	16th Century AD	France	Eiffel Tower	Biomorphic and Zoomorphism takes animal morphology as the role model for architecture projects	
	From 16th Century AD	United States	**Biomorphic:** Oriental Milwaukee Art Museum		
Modern Architecture	1869-1959	World wide	**Spirals in Architecture** Guggenheim Museum New york	**The geometry of Nature:** • Golden Section • Spirals in Architecture • Chaos Theory and Architecture • Construction lightness • Curved Surfaces with Girders (Seashell) • Folded Structures • Ernst Haeckel's Tables of Marine • Hexagonal design inspired by nature • Cable structures inspired by the spider web	
	19th Century AD	World wide	**Construction Lightness:** opera house in Sydney		
	20th Century AD	World wide	**Hexagonal** Olympic swimming pool in Beijing		
	21th Century AD	World wide	**Cable structures** Jenny Sabin Studio's Lumen		
Contemporary Architecture	21th Century AD	World wide	**Eco-friendly** Cobra Tower Aqua Tower	Recently, natural inspiration buildings are designed with dynamic and complicated structures, unlike conventional box-like buildings.	 
	21th Century AD	World wide	**Futuristic** LILYPAD Ecopolis		

Table (1-2): Biomimetic Architecture Time line
Source: Author

This chapter explained that, through the historical background, nature was used as a source for shapes and geometry, while neglecting the functions and processes underlying the form, which led to the emergence of projects that looks like nature but do not function like nature. The focus of the thesis study is to formalize a clear methodology for transferring the functions and process of the living system to architecture.

The chapter clarified that according to the Innovation Timeline, Biomimicry has already solved many problems in several fields by mimicking the performance of the organisms. Those strategies can be useful in architecture, where Biomimicry can produce advanced architectural elements such as structure, sensors renewable systems in building behaviour, etc. Moreover, it is imperative to reconnect to nature to identify the potential natural strategies that can be transferred into architectural elements to enhance the efficiency of building behaviour which will be described in details in the following chapters.

The second chapter will deal with reconnecting to nature and obtaining lessons from life principles. Then the following step will be searching for possibilities of transferring those principles to architecture to enhance building behaviour, maintain sustainability, and acquire solutions that could help to overcome the global challenge.

CHAPTER 2: Biomimicry as a Sustainable Design Methodology

Introduction

Based on the historical background mentioned in the previous chapter, Biomimicry is not a new approach in the field of architecture. Although nature has been used as a source of inspiration; however, it was used only as a design/form, without looking at the behaviour of living systems, which is not sufficient to reach sustainability targets. Therefore, this chapter will encourage reconnecting to nature and setting life principles, which could be utilized in building behaviour. Along with the Industrial Revolution, new technologies and advanced tools for observation were developed, especially electron microscopy. Accordingly, the scanning tunneling microscope enabled the analysis of nature at the atomic level, and then at the Nanoscale level, which will help to conclude the behaviour and functions of the organism through deep analysis.

New discoveries have been made regarding this scale alteration through which living things are observed, such as the first profiling of DNA in the 1980s. Thus, new insights arose digging deep into the behaviour of organisms, which could help to explore the method living systems in nature encode, store, reproduce, transmit, and express. All these developments gave rise to the "Biology Revolution".[1]

Nature processes are system-based. According to the biologist Vincent, these systems transfer from biology into engineering at several levels. Based on this categorization, without mimicking entire systems within designs, the use of Biomimicry in architecture will still be limited to being either a form-finding process that called partial mimicry rather than being total mimicry. In nature, form, function and structure are interrelated and indistinguishable. The transfer of morphology and form rarely goes beyond imitation of a few features of a particular organism, which hardly match the function of the imitated natural systems; Figure (2-1).

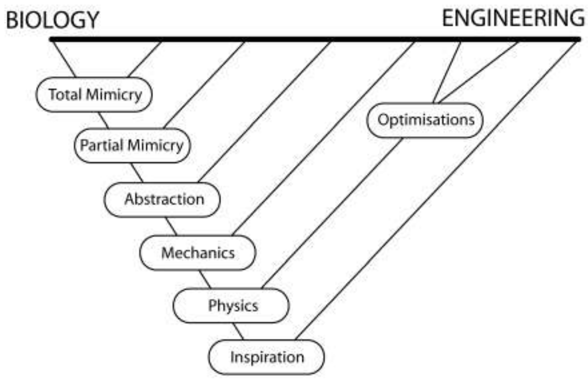


Figure (2-1) Levels at which ideas, functions, or concepts might be moved from biology to engineering
Source: Vincent, J., 2008

Recently, the biomimetic approach offered many potential theories and innovations in the field of architecture, as mentioned in the previous chapter. In fact, these innovations have changed our view of other natural living systems as role models; thus, the use of the Biomimicry approach enables the application of significant sustainable development in various fields. In this chapter, strategies provided by biological role models will be discussed.

1 Panneerchelvam & Norazmi, “The modern process of DNA profiling” was developed by Alec Jeffreys, 2003

Those strategies can enhance building behaviour and encourage focusing on the performance of the biological role models platform. This can, in turn, facilitate the design of Biomimicry to reach the total mimicry aimed at sustainability.

Nature transfer was limited to mechanical and structural systems. This partial mimicry was due to the lack of technological tools back then. However, it was successful in solving certain mechanical and structural problems. Due to technological development, biological characteristics became clearer based on the deep analysis carried out on living organisms. Comparisons were also conducted between the characteristics of biological systems and mechanical systems made by man to mimic these systems. The old mechanical explanations of nature are insufficient to explain the complexity of nature.

The main key differences on modes of architectural manifestation of nature (Artificial versus Natural Modes): self-sameness vs. self-similarity, repetition vs. replication, difference vs. differentiation, diversity vs. uniformity, dynamic vs. static and Euclidian vs. non-Euclidian.[2]

The main key differences on modes of architectural manifestation of nature (Artificial versus Natural Modes): Linearity vs. Nonlinearity, Hierarchy vs. Non-hierarchy, controlled vs. self-organized, surface vs. deep organization, fixed vs. adaptive and evolving, Maximize vs. Optimized.[3] Table (1-2): comparisons revealed significant differences, which indicate the importance of shifting to the biomimetic approach to mimic those systems and obtain the ultimate benefit of the total mimicry.[4]

Human-made Systems (Mechanical)	Biological Systems
– Simple	– Complex
– Linear flows of resources	– Closed-loop flows of resources
– Disconnected and mono-functional	– Densely interconnected and symbolic
– Resistant to change	– Adapted to change
– Wasteful	– Zero waste
– Long-term toxins frequently used	– No long-term toxins used
– Often centralized-mono cultural	– Distributed and diverse
– Fossil fuel dependent	– Run on current solar income
– Engineered to maximize one goal	– Optimized as a whole system
– Extractive	– Regenerative
– Use global resources	– Use local resources

Table (2-1): A Comparison of mechanical human-made systems and bio-systems
Source: Mohammed, M., 2014

2 Ghonimi, I., "Architecture Manifestation of Nature scientific paradigm shift," Journal of Al -Azhar University Engineering Sector, 2011
3 Ghonimi, I., "The role of nature form versus life principles in Achieving sustainability of bio-mimic architecture", Article, Journal of Engineering Sciences, Assiut University Faculty of Engineering, 2015
4 Mohammed, M., "Biomimicry Levels as an approach to Architectural Sustainability", Faculty of Engineering - Port Said University, 2014

According to the comparison between the mechanical and biological systems, certain aspects of nature, undetectable to the human eye, have been discovered by science and technology. Those discoveries encouraged new approaches to transfer this knowledge to architecture. Terminologies attributed to those approaches include: *Bionics, Biotechnics, Biotechnique, Biognosis, Biomorphism, Biophilia, Bioinspiration, Biomimesis, Biomimetics and Biomimicry*. All of these conceptual terms are derived from the same concept: transfer of biological characteristics as a whole, and mimicking the whole system.[5]

2.1 Biomimetic Design Approaches (Solution-based, Problem-based)

Various Biomimetic approaches can be found. Two approaches have been recognized for Biomimicry utilization application. Both approaches have different starting points and diverse characteristics in their design processes, with various terminologies in biomimetic as the following:

- Challenge to biology and Biology to design (Baumeister, 2014)
- Top-down and Bottom-up (Speck & Speck, 2008)
- Biomimetics by analogy and Biomimetics by induction (Gebeshuber& Drack, 2008)
- Problem based and solution-based (Helms, Vattam, & Goel, 2009)
- Technology pull and biology push (ISO/TC266, 2015)

- **Solution-Based and Problem-Based Approaches**

a. **Solution-Based Approach:** identifies a particular characteristic, behaviour, or function within an organism or ecosystem then looks for the design problem that could be addressed.

b. **Problem-Based Approach:** is concerned with the design problem and then examines the methods in which organisms or ecosystems overcome the problem; Figure (2-2).[6]

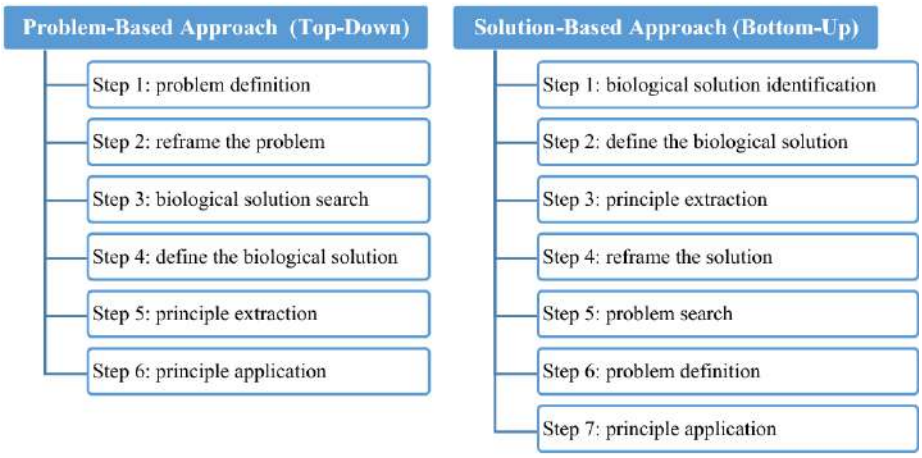


Figure (2-2) Solution Based Approach and Problem Based
Source: Karam M., 2017

5 Oztoprak, Z., "A Biomimetic Perspective Retro fitting of Building Envelopes", Doctoral Thesis, Middle East Technical University, 2018
6 Chayaamor-Heil, N., "Biomimicry in Architecture: State, methods and tools", 2018

Both problem-based approach presented by Massey and Wallace and the approach based on inspiration from nature shares the same serial steps from problem to solution. However, the main difference between both approaches lies in the biological extension required to be added to the latter, in support to architects and engineers. Juilan Vincent provided an overview of the simplified methodology. In the top the classical problem solving presented by Massey and Wallace and in the bottom general biomimetics with a biological domain added to the general problem-solving; Figure (2-3).[7]

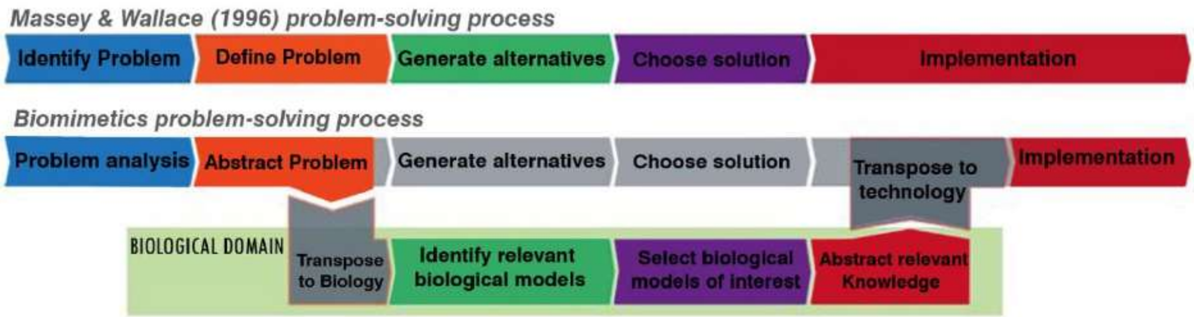


Figure (2-3) Classical Problem-Solving (top) and Vincent overview of simplified biomimetics (bottom)
Source: JulianVincent, Biomimetics 2018

Finally, the last type of methodological solutions is the biological abstract approach. Processes within this approach are based on an abstraction of biological knowledge and turning it into general sense strategies for solving problems and avoiding problems related to the utilization of raw biological data. The more advanced abstraction process was formalized by Vincent and was initially inspired by TRIZ. To access these strategies, a TRIZ tool is currently under development in the form of ontology by Vincent. According to Fayemi, all these processes can be described with the help of the same eight main steps, in the form of a feedback loop rather than sequential steps. As a result, Fayemi proposed a unified Technology pull biomimetic feedback loop process; Figure (2-4).[8]

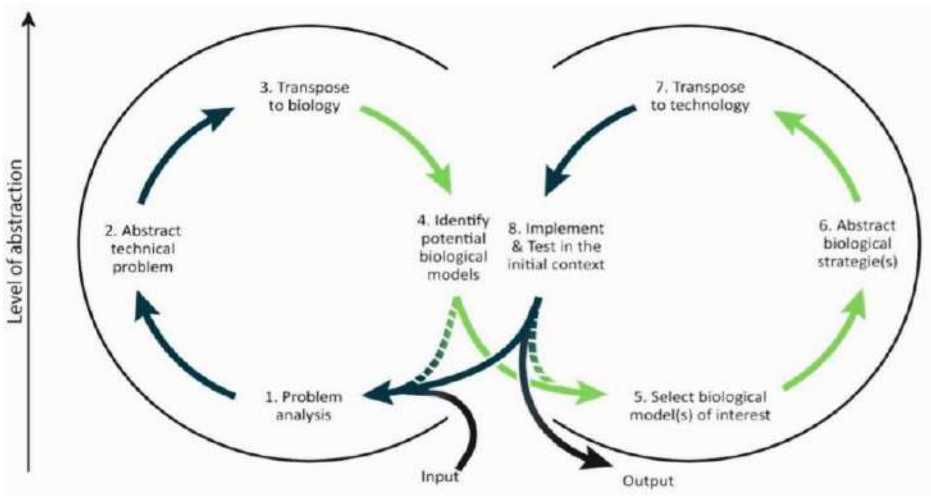


Figure (2-4). The Unified Technology-Pull Biomimetic Process
Source: Graeff, Eliot, 2019

7 Vincent, J.," Towards a Design Process for Computer-Aided Biomimetics", Article, Biomimetics J, 2018
8 Graeff, E.; Maranzana, N.; Aoussat, A., " Engineers' and Biologists' Roles during Biomimetic Design Processes, Towards a Methodological Symbiosis", International Conference on Engineering Design, ICED19, 2019

The processes of the classical methodology for biological abstract approach and the unified technology-pull biomimetic feedback loop could be summarized into three main sections:

1- The search for the biological role model criteria.
2- The abstraction of the results.
3- Implementation in design and technology.

In the biomimetic approach, both biologists and architects have a specific role. Biologists' role is to provide the database of biological knowledge, while architects' role is to provide the knowledge of architectural design in parallel. To provide an example, the biomimetic case is formalized, Figure (2-5), by collecting the knowledge from architectural strategies and biological strategies in the form of a network to solve the extreme cold problem by the integration of the two domains. This integration provides multi-criteria choice assistance and decision-making tool that could be used in each project.[9]

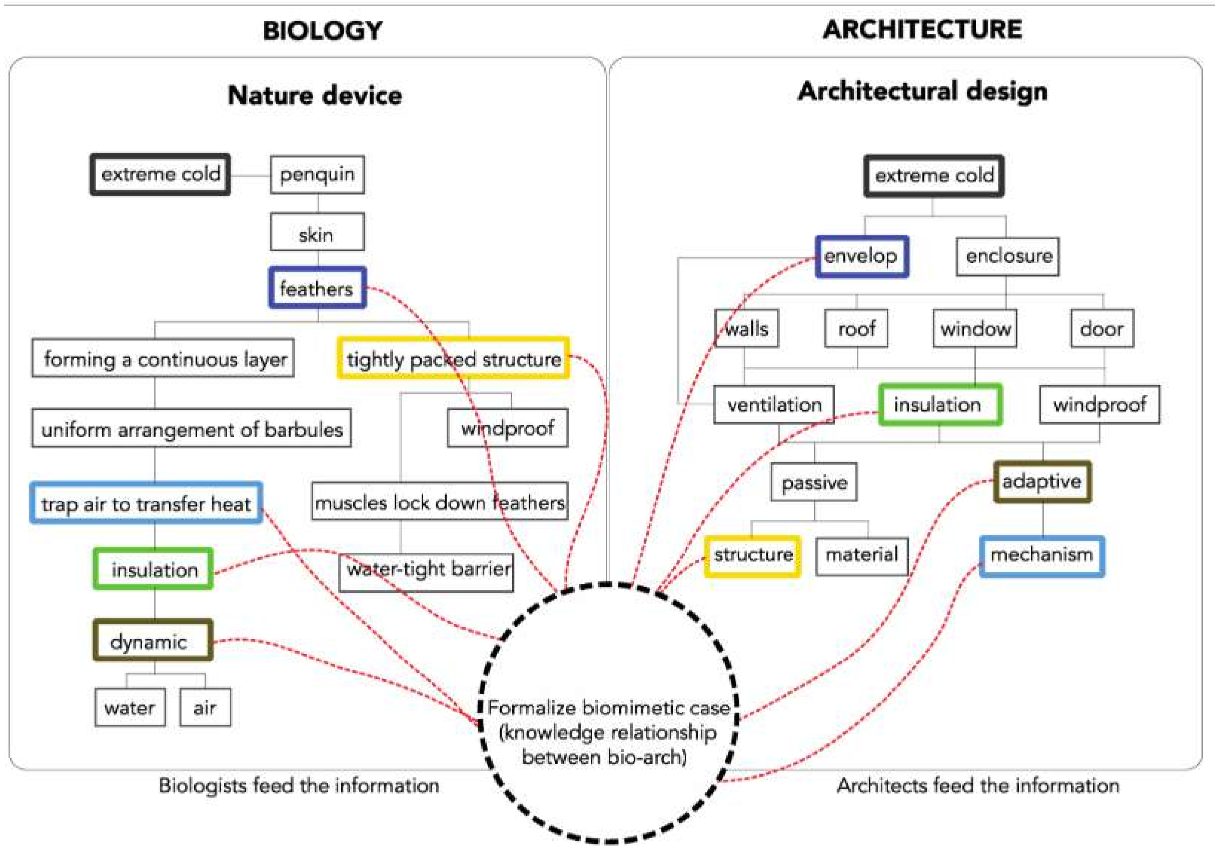


Figure (2-5) An Ontology that would bring together knowledge from architecture and those from biology
Source: Chayaamor Heil, N., 2018

9 Op. cit.

2.2 Levels of Biomimicry in Architecture

There are three levels of Biomimicry: First, the Organism level refers to a specific organism such as a plant or animal and may involve mimicking part or whole of the organism. Second, the behaviour level that refers to mimicking organism behaviour, and may include interpreting an aspect of how an organism behaves or relates to a larger context. Third, the ecosystem level which is the mimicking of whole ecosystems and the common principles that allows them to function successfully. Table (2-2) shows the comparison of the three biomimicry levels in the case of mimicking termite in a building, by comparing the resulting form, materials used, construction, the processes within the building and the function that the building performs for each level.[10]

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 utilising 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.

Table (2-2) Biomimicry Levels
Source: Shiva, K.2015, (adapted from Zari P, 2012)

10 Razin, A., "Biomimicry Architecture: From the Inspiration by Nature to the Innovation of the Saharan Architecture", Russia, Architecture and Engineering, 2018

The study will focus on the behaviour level of Biomimicry, which represents the profound understanding of biological strategies, process, functions and systems. Besides, this level focus on the most probable solution routes, compound multiple analogies and the co-evolution of problems and solutions which could deal with the building systems to enhance building behaviour.

2.3 Behaviour Level: Mimicking the adaptation performed by organisms within their environment

A significant number of the living systems share the same environmental challenges facing humans; however, these organisms could solve their problems using limited energy and the resources available, and then continue to develop the solutions even when facing further challenging environmental conditions. Designers must know whether a given behaviour of an organism is appropriate to be imitated by humans, and any appropriate part of its behaviour will increase the sustainability of the construction. That is known as the behaviour level of biomimicry.

Several designers attempts have emerged to achieve mimicking nature in its behaviour between failure and success depending on the degree of benefit from behaviour simulation and the result of that simulation, there are examples, searching for form was the most important aspect and others go beyond the biomorphic using deeply nature simulation and getting the solution for architectural form by mimicking nature in behaviour level. The following examples are attempts to mimic biological performance in nature to architecture.

- **Harbin Opera House inspired by white snow structure**

The Harbin Opera House is an example of mimicking the snow-white structure for a soothing aesthetic. The architect tightens the building's integration with nature, by making the building looks like an extension of the surrounding snowy terrain. The whole building is following the natural rhythm by acting like a wavy snow-capped mountain. For providing a form that looks like ice and snow, the Whitestone and white concrete were used. The skylight above of the auditorium provides natural daylight during the day, resulting in energy saving and special lighting effects; Figure (2-6).[11]

Figure (2-6) Harbin Opera House inspired by white snow structure
Source: https://www.archdaily.com, accessed Jan, 2020

11 https://www.dezeen.com/2015/12/16/mad-sinuous-harbin-opera-house-completes-north-east-china/, accessed Feb, 2020

- **Praxis of Flow inspired by simulating self-organizing biological systems**

Arthur Azoulay and Melody Rees designed this project based on simulating the self-organizing biological systems behaviour, resulting in a morphological study that assumes an expanded field of motion and rotational forces where the selective decision-making is utilized in sculpting innate and intentional spatial relationships and formal qualities; Figure (2-7).[12]

Figure (2-7) Praxis of flow
Source: http://www.evolo.us, accessed Jan, 2020

- **Bundle House inspired by mimicking the natural flow of organic structures**

Bundle House has created as part of Hernan Diaz Alonso’s spring 2012 XLAB studio at SCI-Arc an exercise in morphology and generative artificial landscaping. The previously flat site is transformed into the topography of different curvatures and reciprocal spatial influences. The formal language is one of Biomimetics, translating the natural flow of organic structures behaviour into the language of articulated, habitable space; Figure (2-8).[13]

Figure (2-8) Bundle House
Source: http://www.evolo.us, accessed Jan, 2020

- **Skyscraper in Manhattan inspired by hybrid responses of mangrove plant**

Skyscraper in Manhattan is an example for mimicking the behaviour of the mangrove plant and its collective the mangal. The building has been provided with the ability to adapt, transform, mutate and adjust like the biological role model based on the site's urban and social character in Manhattan. This skyscraper also mimics the social associative principles as well as structural capacities and hybrid responses to environmental and contextual conditions which found in the mangrove plant; Figure (2-9).[14]

Figure (2-9) Skyscraper in Manhattan
Source: http://www.warrenellis.com/mangal-city, accessed Feb, 2020

12 http://www.evolo.us/architecture-designed-to-simulate-self-organizing-biological-systems, accessed Jan, 2020
13 http://www.evolo.us/bundle-house-generating-and-controlling-three-dimensional-form, accessed Jan, 2020
14 http://www.warrenellis.com/mangal-city, accessed Feb, 2020

- **The Eastgate Centre in Harare and The Council House2 office building inspired by Termite Mounds**

The same biological role model was mimicked in the two projects; the Eastgate Centre in Harare and the Council House 2 office building. Both projects are considered as an attempt for mimicking termites' behaviour, the way that they build their mounds.

At Eastgate Center does not require any conventional heating or cooling by mimicking the behaviour of termites as they keep their mounds at a constant temperature by sealing and opening holes with the outer mound's shell, to permit air to ventilate and balance the temperature inside. Eastgate uses ducts and fans instead of termites to work in the same method as mounds. Therefore, it consumes 10% of the energy wasted in a traditional building of the same size; Figure (2-10).[15]

Figure (2-10) Eastgate Centre
Source: National geographic, accessed Jan, 2020
https://www.youtube.com/watch?v=620omdSZzBs

The CH2 is designed to be a highly energy-efficient, sustainable building with all of its systems mimicking the passive ventilation techniques and the observed temperature regulation in termite mounds. In order to create this indoor thermal constant, water is extracted and cleaned from the sewers beneath it, mimicking the same termite method for using near groundwater as an evaporative cooling mechanism; Figure (2-11).[16]

Figure (2-11) CH2 office building
Source: https://asknature.org, accessed Feb, 2020

- **Abu Dhabi Performing Arts Centre based on growth phenomena**

The concept of the Zaha Hadid Performing Arts Center, conceived as a sculptural form, naturally emerges from a linear intersection of pedestrian paths within the cultural district, gradually developing into a living organism that grows a network of successive branches that form a structure like fruit on a vine resulting of mimicking human behaviour in the cultural district; Figure (2-12).

Figure (2-12) Abu Dhabi Performing Arts Centre
Source: https://www.zaha-hadid.com/architecture/, accessed Feb, 2020

15 https://ehistory.osu.edu/exhibitions/biomimicry-a-history, accessed Jan, 2020
16 Mohammed, M., “Biomimicry Levels as an approach to Architectural Sustainability”, Faculty of Engineering - Port Said University, 2014

- **China's Unveils Crystalline Sports Centre based on Emergent Phenomena**

The Crystalline Sports Centre is based on mimicking the behaviour of crystal patterning found in nature at different scales for capturing the daylighting. The design features large membrane bubble windows with views out to the Park and the city. This patterning of the windows spreads out onto the metal panel facades of the building, erupting as zones of solar panels on the roof; Figure (2-13).

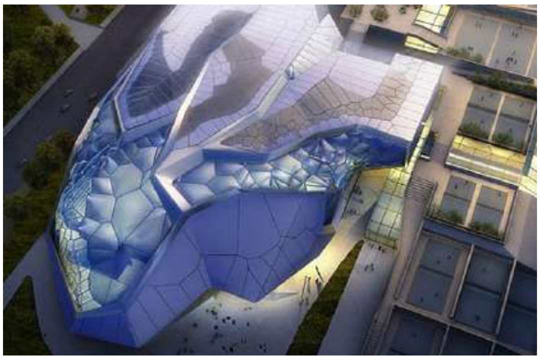


Figure (2-13) China's Unveils Crystalline Sports Centre
Source: http://www.rolandsnooks.com/yeosu-pavilion, accessed Feb, 2020

The previous are all successful examples of bio-morphic architecture by generating and controlling three-dimensional form. However, this success does not imply the successful transfer of living systems performance to building behaviour. The mimicry on the behaviour levels in these examples resulted in several outcomes. Certain projects benefited from the simulation of biological behaviour as a more complex form based on the deep understanding of biology. This is not enough to reach sustainability. Janine Benyus mentioned that "Looking to nature for inspiration isn't just about curvy nature it's about function, Curviness is not enough". Architecture is not required to look like nature but to work like nature. The other type of projects benefited from the same simulation at the behaviour level, by transferring processes and functions to the building behaviour, thus the building was able to enhance the building behaviour and face climate changes.

In order to verify whether or not a given building was successful in mimicking the living organisms' performance and transferring them to the building behaviour, the study will set criteria for measuring the success of these projects, and the extent of their benefit from the simulation of nature at the behaviour level. These criteria will, in turn, help future designs benefit from the transfer of nature life standards, processes and functions to building behaviour to enhance building efficiency and achieve sustainability. In brief, to solve our problems as nature does, biomimetic design needs to consider the whole system, processes, and behaviour existing within nature as a source of a sustainable solution rather than the mere forms.

The goal of this chapter is to investigate the solution-based approach and to search for a link between biological role models and building behaviour. Besides, the chapter also aims to identify the natural strategies in the biological domain that can be simulated in the architectural domain that, in turn, enhance the building behaviour. Therefore, the general life principles in living organisms will be identified, and then the principles that can be achieved in buildings will be selected. Then, attempts will be made to formalize a methodology to simulate the selected biological role model using selected life principles, in order to achieve its performance which can then be transferred to the architectural domain. So, reconnection to nature is necessary by studying biology and life principles, then mapping selected performances of biological role models which can be turned into building behaviour.

2.4 Natural Strategies for Sustainability

All living systems on Earth have encountered the same basic conditions, through the process of evolution. For the purpose of maintaining sustainability, nature has developed a set of "principles" that allow organisms to survive. Successful living organisms are characterized by resilience, optimization, adaptation, systems-based, and life-supporting. The Seven Pillars of Life are the essential principles of life described by Daniel E. Koshland in 2002 in order to create a universal definition of life. One stated goal of this universal definition is to aid in understanding and identifying artificial and extraterrestrial life. The seven pillars are Program, Improvisation, Compartmentalization, Energy, Regeneration, Adaptability, and Seclusion. These can be abbreviated as PICERAS.[17]

The general principles of natural design are used as guidelines for developmental progression. While it is difficult to effectively categorize the entire collection of natural designs into discrete units, recurring principles, as described below, can be observed which form a coherent strategy for investigation.

2.4.1 Life Principles [18]

Technology in the biological domain has allowed scientists to discover the organizational structures of living organisms on multiple layers of the hierarchy, down to the layers of matter at the Nanoscale. This resulted in deep exploration of the dynamics of life, growth, metabolism and life phenomena existing in living organisms. Besides, understanding adaptive behaviour involves change over time. Life principles common among living organisms were observed to be interlinked, meaning that the dependence on solar energy for food and nutrients is what allows the establishment and maintenance of organized structures. Growth becomes possible through metabolism and the transfer of energy and matter into new organic tissue. Sensing and interaction are also necessary for adaptive behaviour similar to the occurrence of growth. Furthermore, the classical life principles could be considered as the fundamental principles of existence, they were identified as follows: complexity, propagation, use of energy, sensing and reacting, metabolism, adaptation, intelligence and self-healing.

2.4.1.1 Complexity

Complexity can be observed at all levels in biology. The complexity of a system generally arises from the interactions of its interconnected elements rather than the properties of those elements themselves. Complexity science is the study of this emerging behaviour of

17 Daniel E. Koshland Jr, "The Seven Pillars of Life", Science 295, 2002
18 Gruber, P., "New approaches and Application of Biology's Life Criteria on Architecture", Biomimetics in Architecture book, 2011

a system. It attempts to understand the way that the complex behaviour of an entire system emerges from its interacting parts. In general, complex behaviour cannot be derived from the behaviour of the entire system components. Furthermore, biomimicry is to imitate the complex behaviour of the entire system.[19]

All characteristics of life evolve from the complex organization of the organism itself, as the existence of life in the organism depends on the level of complexity in which dynamic processes such as differentiation and change of structure and form occur. Often the system takes the form of natural patterns, so it could be defined as the degree of integration and differentiation of the system. High complexity is associated with high degrees of integration and differentiation, and vice-versa Differences linked to the levels of complexity also vary in the characteristics of systems and the method by which they behave. The levels of complexity in nature are classified into several ascending levels, from macromolecule level to biosphere level; Figure (2-14).[20]

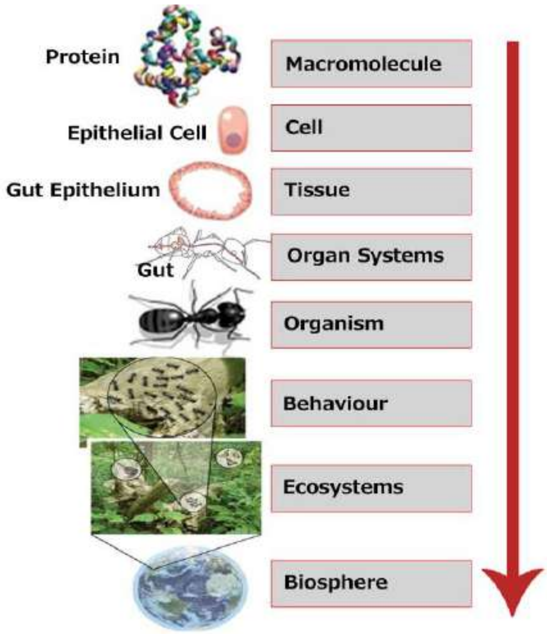


Figure (2-14) The levels of complexity
Source: https://www.nature.com, accessed Feb, 2020

2.4.1.2 Propagation

Organisms are able to reproduce by transmitting genetic information. The axiom of biogenesis specifies that life can only emerge from life. Cell division is a form of reproduction in single-celled organisms that is responsible for generating identical copies of those organisms and this is called mitosis. This strategy of reproduction and propagation allows the genetic recombination that leads to diversity in the genome, as the genetic code is the base of information transfer over generations which is the basis of evolution. The standard Feedforward Backprogation NeuralNetwork generally consists of an input layer, several hidden layers, and an output layer; Figure (2-15).[21]

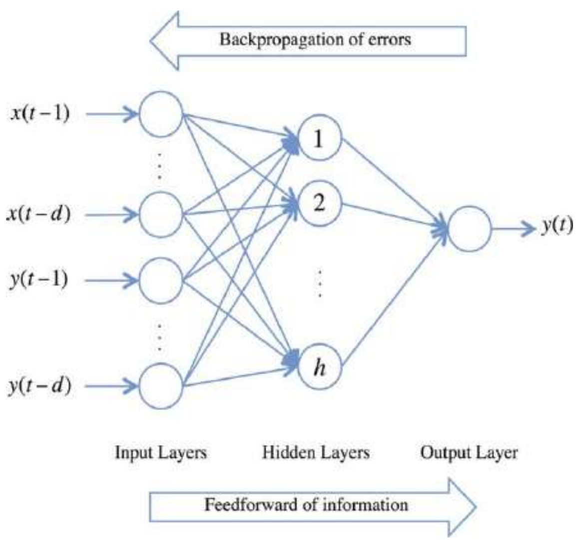


Figure (2-15) A Feed Forward Back Propagation Neural Network
Source: Jeffrey W., 2020

19 www.complexyexplorer.org, accessed Feb, 2020
20 Ingrid Lobo,"Biological complexity and integrative levels of organization", Ph.D. Nature Education ,2008
21 Jeffrey W. Brown, Taheri, A., "Signal Propagation via Open-Loop Intrathalamic Architectures", Article, Eneuro J, Jan, 2020

2.4.1.3 Growth

Growth is a progressive increase in physical size and occupation of space with an incorporated process of self-organisation. One of the classic signs of living systems is "Biogenetic Laws". In biology, growth depends on cell division for changing the cell size. On a larger scale, different growth strategies could be identified in organisms, such as tip growth, rim growth, budding, extrusion, or emergent. Figure (2-16), budding in plants. [22] Architecturally, growth means adding elements or spreading to increase the space.[23]

Figure (2-16) Budding in Plants
Source: Gruber P., 2018

2.4.1.4 Use of Energy

Living organisms use the available energy to perform different types of activities. They absorb energy and convert it into other forms, where they use solar energy or nutrients in a low-energy process. The energy in nature is defined as the systematic analysis of all major sources of energy and all the transformations that have shaped the development of the biosphere and civilization. Therefore, innovative and suitable ways of living must be devised while increasing our demand for energy to provide other sources for it; Figure (2-17).

Figure (2-17) Renewable Energy Infrastructure
Source: https://engineering.jhu.edu, accessed Feb, 2020

2.4.1.5 Sensing and Reacting

Sensing and reacting terms describe the ability of the living systems to deal with internal or external stimuli in order to survive without losing their integrity. Responding systems return to their initial state after experiencing perturbation. In architecture, for example, it refers to the internal and external adaptive systems in the building; Figure (2-18).

Figure (2-18) Mimosa leaf, closing when touched
Source: https://www.youtube.com, accessed Feb, 2020

22 Vincent, J., “Aspects of life”, book, 2016
23 Vincent, J., 2016, Op.cit.

2.4.1.6 Metabolism

Metabolism is the totality of all chemical processes in an organism. The internal environment of a living organism is kept stable within certain limits through its regulatory mechanisms, despite differences in the environment, this process is called Homoeostasis. Homoeostasis is characterized by complex and intertwined control cycles. Complex body molecules are synthesized under energy consumption from chemically simpler precursors. On the other hand, complex nutrients are chemically broken down into simpler substances under energy production; Figure (2-19). Most life on Earth gets their energy from the sun. Plants use photosynthesis to capture sunlight, and herbivores eat those plants for energy, carnivores eat herbivores, and decomposers digest plant and animal matter, etc. [24]

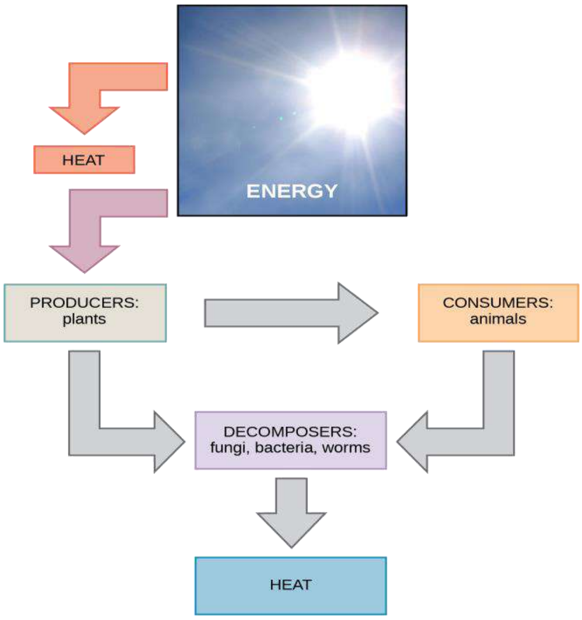


Figure (2-19) Metabolism and Energy
Source: https://commons.wikimedia.org, accessed Feb, 2020

2.4.1.7 Adaptation

The survival of living organisms depends on their capability to adapt or resist external events through appropriate behaviour or change of internal chemistry using internal control systems. This includes many adaptation strategies such as camouflage, imitation, strength in fighting, speed in escaping, ability to feed on “indigestible” materials, high rate of reproduction, safety in numbers as swarms, chemical defence, surviving in sub-zero temperatures by developing an anti-freeze, dehydration, controlled freezing, modified diet, etc. Adaptation processes are usually very specific, where lifestyle and organism-environment can be concluded from its adaptation, desert adaptation for example; Figure (2-20).[25]

Figure (2-20) Desert Adaptation for plants and animals
Source: https://www.pinterest.com, accessed Feb, 2020

24 Vincent,J.,2016, Op.cit.
25 Gruber, P., 2011 Op.cit

2.4.1.8 Intelligence

Intelligence is the capability to acquire and apply knowledge and skills to solve new problems. It is assessed by calculating the speed of response to any external change. This speed results from the amount of information stored in the system and its significance, whether it is neurological, chemical or cosmetic, which affects the analysis of that change. Intelligence includes all living organisms and artificial intelligence includes man-made structures. That term appears frequently in recent times in the field of machine learning and artificial intelligence that mimics the human brain as it is a complex set of networks; Figure (2-21).[26]

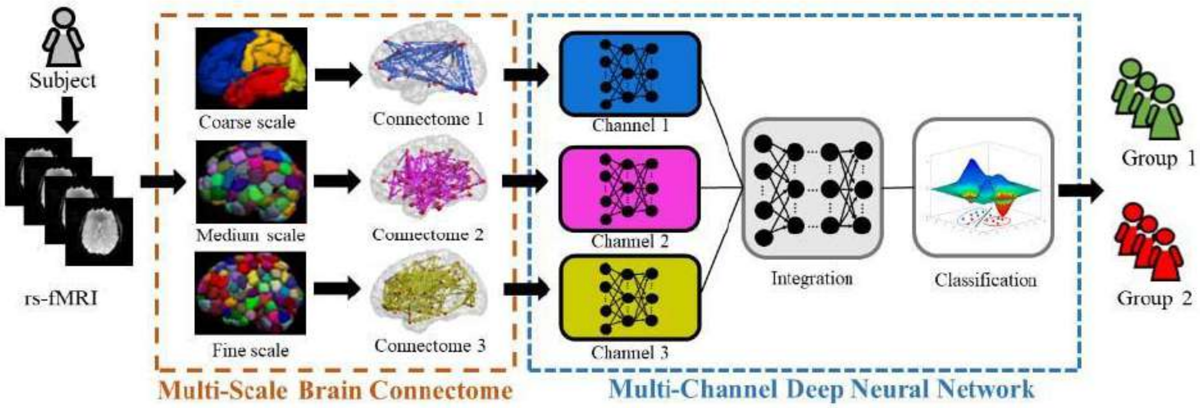


Figure (2-21) Schematic diagram of the proposed multichannel deep neural network
Source: RSNA (Radiological Society of North America), 2019

2.4.1.9 Self-Repair and Healing

Different groups of organisms have independently developed many different approaches to dealing with wounds. This process is found in all hierarchical levels of organisms, from the macromolecule level to the entire organism level of complexity and can be considered a prerequisite for life. In technical materials and structures, self-repair remains a major challenge. There are only a few successful examples of man-made materials or structures. It is divided into an initial rapid self-sealing mechanism and a later mechanism for long-term self-healing and self-cleaning, for example, the lotus plant is a high water repellant, as clean leaves mean more photosynthesis; Figure (2-22).

Figure (2-22) Desert Adaptation
Source: http://www.biomimicrybe.org, accessed Feb, 2020

26 https://www.rsna.org/en, RSNA, (Radiological Society of North America), accessed Feb, 2020

2.4.2 Potential strategies offered by Biological role models (Solution-Based Approach)

Biomimetic architecture is an emerging contemporary design practice that explores a new methodology to interconnect scientific evidence in the biological domain with creative design in the architectural domain, through the information flow between biology and technology; Figure (2-23).

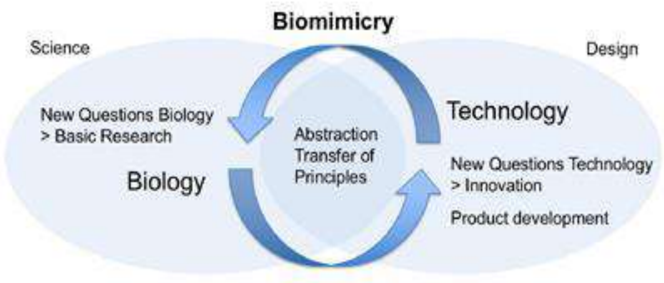


Figure (2-23) Information flow between Biology and technology
Source: Gruber, P., 2019

The role of Biomimicry in architecture is to clarify the abstracted life principles to be transferred to technology. Static patterns in natural role models like shell structure, morphological patterns, and self-organization were investigated and applied to architecture; however, dynamic transfer was not implemented. Moreover, the other dynamic principles of life must be transferred to architecture.[27]

There are a large number of biological role models that can be mimicked in architectural design, thus, to facilitate the possibility of dealing with them, the most promising selected life principles- that are architecturally achievable and could deal with building behaviour- have been identified. Those selected life principles manifest in three topics that were considered important issues in Biomimetics and building behaviour. Those were sensing, reacting to all environmental factors, complexity, and adaptability type. Those topics were chosen based on their necessity to identify the level of complexity in which each organism operates. This facilitates mimicking its behaviour and adaptation strategies such as structure change, texture type, chemical response or kinetic response which will be helpful in building behaviour; Figure (2-24).

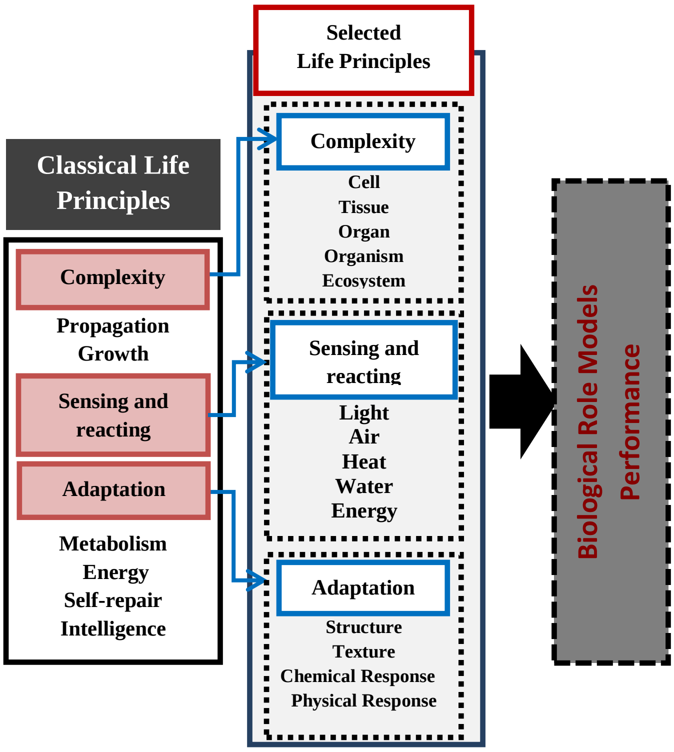


Figure (2-24) Selected Life Principles to explore the performance of biological role model
Source: Author

27 Gruber, P., "Patterns, Growth and Energy Lessons from Biology for Architectural Design", Cardiff University, 2018

The performance of organisms is investigated to identify their multi-functional mechanisms, functional strategies and measured variables like (Gain/loose, change of material properties/structure/temperature, maintain, exchange, filter, etc.), change may present as an opening ratio, a reflectance value for light in microns, the relative humidity level in % RH or an increase/decrease of temperature in °C. These reactions show the method and extent by which the biological role model performs and adapts the environmental factors and the level of complexity. Therefore, the main duty of these principles is to clarify the performance of the biological role model, and the potential of their translation into systems enhancing building behaviour.[28]

2.4.3 Biological Domain Simulation Methodology (Solution-Based Approach)

The biological domain is considered the first step in Biomimetic design for sustainable building behaviour. It provides architects with all the sufficient information that helps to achieve the required goal and to convey the life principles to buildings. This can be done by mimicking organism's performance that provides solutions to the problems that we face, whether at the global level, like climate change, or at the level of the building by achieving strategies that help it to adapt to the environment.

Biological Domain will be divided into two phases adapted from Vincent overview[29]; Figure (2-25). The first phase is the experimental phase based on the biological database or literature researches. It includes studying the biological strategies that show the methods and extent by which the biological role model performs. The second phase is the abstraction of relevant knowledge resulting from the biological simulation, in order to reach the abstracted information that could be transferred to the architectural domain into the prototyping phase. This is the phase of biomimetic application and prototypes of the selected biological models.

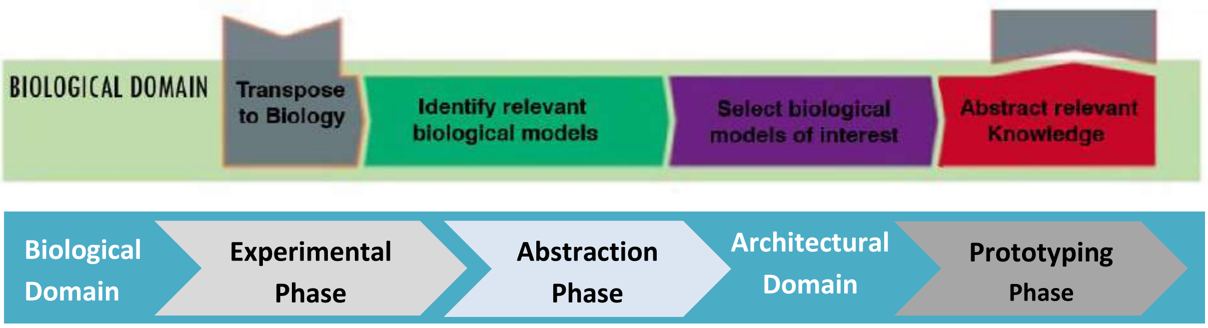


Figure (2-25) Biological Domain according to Vincent overview (Top)
Source: JulianVincent, Biomimetics 2018
Adapted Biological Domain methodology (Bottom)
Source: Author

28 Aysu KURU, "Multi-functional biomimetic adaptive façades: Developing a framework", Conference Paper, 2018
29 Vincent, J.," Towards a Design Process for Computer-Aided Biomimetics", Article, Biomimetics J, 2018

2.4.3.1 Biological Domain Phases

- **Experimental phase**

  In this phase, the strategies examined are classified into major categories representing selected life principles. Those categories are: sensing and reacting to environmental factors, complexity levels, and adaptability type. More than one strategy can be concluded from a single organism, where most organisms employ multi-strategy role models to achieve their goals.

- **Abstraction phase**

  In the first, the main strategies are arranged into groups during the experimental stage. In the second stage, the strategies are derived from the main performance of the biological role model which is responsible for achieving those strategies and goals.

2.4.3.2 Architectural Domain Phase

- **Prototyping phase**

  Upon formalizing the simplified version of a biological role model strategies through biological domain phases, these strategies are transferred to the architectural domain into the prototype phase by testing the capabilities of those potential strategies and developing prototypes whether physical or digital models, using architectural software.

2.5 Biological Role Model Case Studies

The main purpose of the methodology suggested by the researcher is formalizing an abstract form of the biological information and principles to be transferred to the architectural domain. This will be done by analyzing the case studies based on the aforementioned two-phased methodology. To verify the methodology, the study will conduct an in-depth analysis of three exemplary biological role models. Possibility of transferring the processes observed in the models to the architectural domain will be investigated. Each of the case studies represents a promising strategy for building behaviour.

2.5.1 Case Study 1: Moon Flower *Ipomoea Alba*

The selected biological role model in this case study is Ipomoea Alba flower, known by “Moonflower”. This plant opens only in the evening and remains open throughout the night until it closes at dawn. Ipomoea is spirally wrapped during the bud state which provides a strong and effective packaging configuration; Figure (2-26).[30]

Figure (2-26) Ipomoea Alba (open and closed state)
Source: https://davesgarden.com/,accessed Feb, 2020

2.5.1.1 Biological Domain

- **Experimental phase**

On a cellular level, the actuating elements responsible for the flower movement were identified and found to be and located in the petal bands. The structural changes, which are responsible for flower opening during maturation and flower closing during senescence, were found to be controlled and driven by a specific group of inner epidermal cells on both edges of the mid-petaline bands; Figure (2-27).[31]

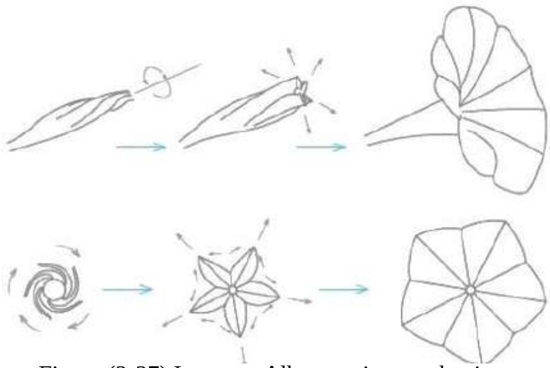


Figure (2-27) Ipomoea Alba opening mechanism
Source: Schleicher, S, 2016

- **Abstraction phase**

This plant acting on the tissue level of complexity, as this tissue is controlled and driven by a specific group of inner epidermal cells on both edges of the mid-petaline bands. It reacts to light and heat among environmental factors using physical response type of adaptability. This performance could be defined as a shape change and growth; Figure (2-28).

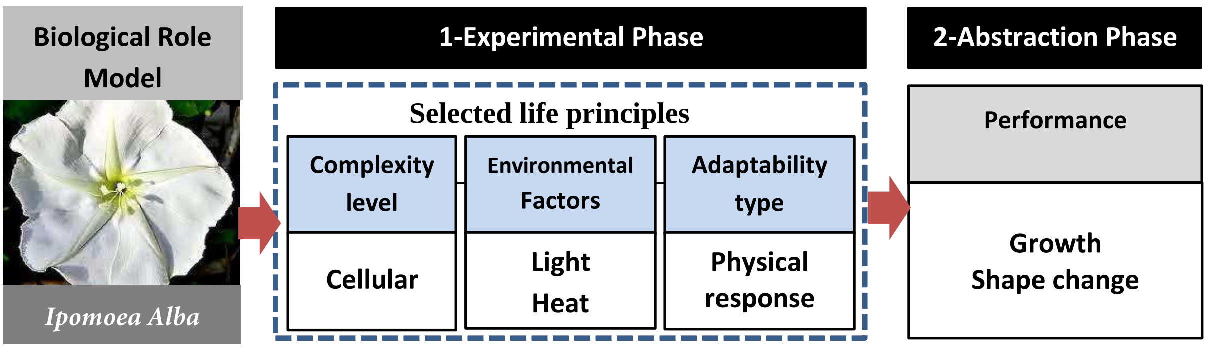


Figure (2-28) Ipomoea Alba abstracted principles
Source: Author

30 Schleicher, S.," Bio-inspired Compliant Mechanisms for Architectural Design”,Ph.D. thesis, Munich, 2016
31 Schleicher, S., 2016 Op.cit

2.5.1.2 Architectural Domain

- **Prototyping phase**

In order to test the previous abstracted principles of the opening mechanism in Ipomoea, one of its key structural elements was abstracted and rebuilt digitally. As a first step, a geometric model was generated to represent the flower bud in its closed state and its opening mechanism. This parametric model was generated based on one longitudinal and three circumferential circles located at the top, bottom, and lower third of the middle axis; Figure (2-29).[32]

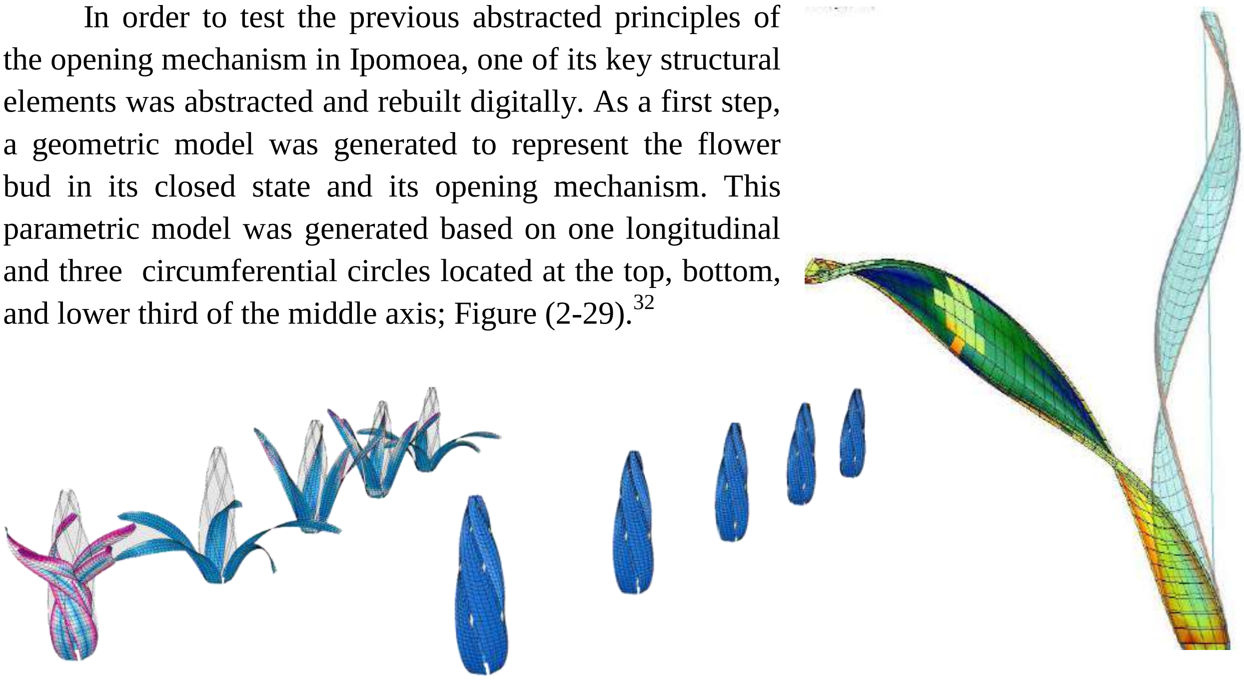


Figure (2-29) Digital model for Ipomoea Alba mechanism
Source: Schleicher, S, 2016

This digital model is a base for a mathematical model with which it was possible to numerically mimic the blooming of the flower. It also presented the kinetic behaviour for the same biological role model, which demonstrates that new concepts for flexible kinetic structures could be derived from highly specialized plant mechanisms. It also shows diversity by which the natural systems approach can solve problems related to kinetic mechanisms from the solutions of the engineering approach; Figure (2-30).

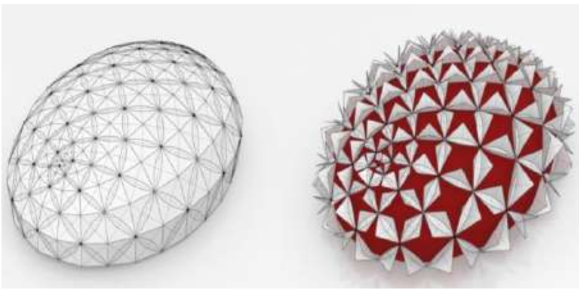


Figure (2-30) Flexible component inspired by Ipomoea
Source: Schleicher, S, 2016

2.5.2 Case Study 2: Bird of Paradise Flower *Strelitzia Reginae*

The biological role model chosen in this case study is called Strelitzia. Due to its exotic appearance, it's considered a very popular plant grown worldwide. It is also known as Bird-Of-Paradise flower; Figure (2-31). This plant does

Figure (2-31) Strelitzia Reginae budding mechanism
Source: https://onszaden.com, accessed Feb, 2020

32 Schleicher, S., 2016 Op.cit

not depend on hydraulic operation, but it is driven by the application of external load to a specific point. Strelitzia initiated by this subtle change and then fascinates by the performance of an independent and reversible deformation motion; Figure (2-32).[33]

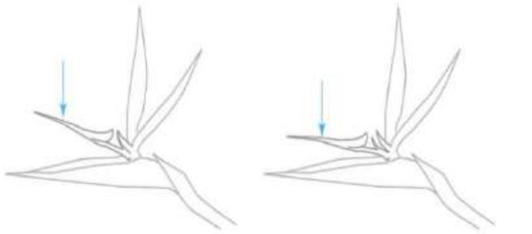


Figure (2-32) Strelitzia reginae reaction to the external
Source: https://onszaden.com, accessed Feb, 2020

2.5.2.1 Biological Domain

- **Experimental phase**

A closer look at the cross-section of the perch showed its symmetric monocular accumulation. There are three loosely connected side ribs on each side, the top of which features a thick petal wing that covers the cavity of the perch's sheath. By gradually cutting off all the unrelated parts, the exact location of the compatible mechanism was revealed. Its basic organs have been traced back to a distinct mechanical interaction between its superior lateral rib and its adjacent wing; Figure (2-33).[34]

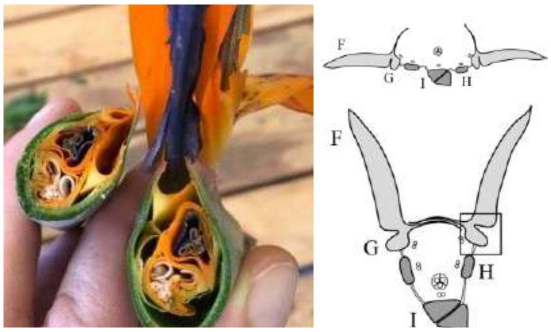


Figure (2-33) Strelitzia reginae Cross Section
Source: https://onszaden.com, accessed Feb, 2020

- **Abstraction phase**

This plant acting on organ level of complexity, as there are three loosely connected lateral ribs. This flower has a mechanical interaction between the highest lateral rib and its adjacent wing. The bird as external force actuates the flower by its weight to open the flower bud to pollinate and this passive actuation of flower aperture reacting to the heat of environmental factors using the physical response of adaptability type. The performance can be defined as a shape change mechanism along with the simulated mechanism; Figure (2-34).

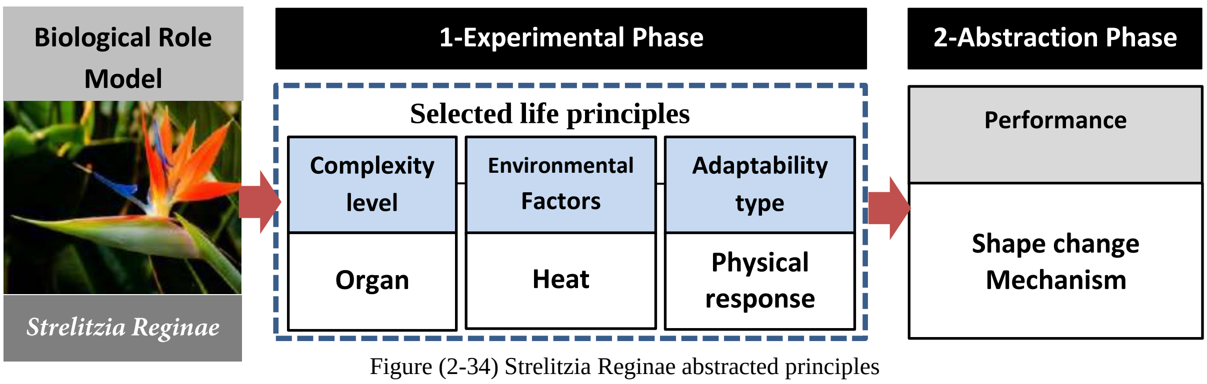


Figure (2-34) Strelitzia Reginae abstracted principles
Source: Author

33 Schleicher, S.," Bio-inspired Compliant Mechanisms for Architectural Design", PhD thesis, Munich, 2016
34 Rivas, E.,Adrover, "Deployable Structures (Small architecture series", Book, Laurence King Publishing, 2015

2.5.2.2 Architectural Domain

- **Prototyping phase**

In order to test the previous abstracted principles of the kinetic mechanism in Strelitzia, the digital model is exported to create a kinetic model of this mechanism; Figure (2-35). Here, the bundle of curves is turned into a series of cantilevering rods that are anchored only on one end. material with specific properties should be used to make the rods.[35]

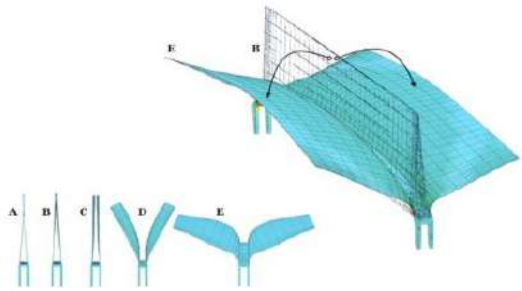


Figure (2-35) Digital model for Strelitzia Reginae
Source: https://asknature.org/, accessed Feb, 2020

The underlying mechanical effect that is responsible for the distinct deformation of the perch is called "lateral-torsional buckling" and is occurring between the flap-like lamina and the adjacent lateral rib, so it is obvious that an external loading of the structure at a specific point is the trigger of this plant movement. These two elements interact with each other in a way that can best be demonstrated with a physical model; Figure (2-36).

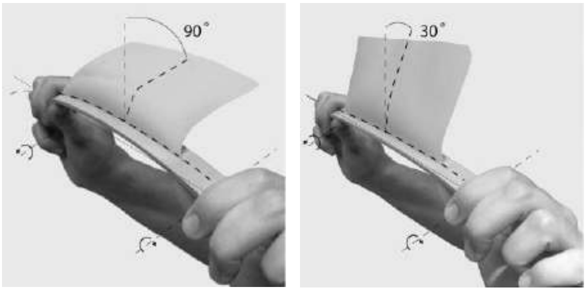


Figure (2-36) Physical model for Strelitzia Reginae
Source: Schleicher, S, 2016

The use of non-articulated mechanical systems reduces the amount of maintenance normally associated with responsive facade systems. It can be created using 3D printing, and it can be produced with the same material. Flectofin is a non-articulated louver system that is able to shift the fin at 90 ° by inducing bending stress in the spine due to a displacement of the support or a temperature change in the lamina; Figure (2-37).[36]

Figure (2-37) Flectofin hingeless louver system
Source: ttps://asknature.org, accessed Feb, 2020

35 Schleicher, S., 2016 Op.cit
36 https://asknature.org/idea/flectofin-hingeless-louver-system/, Accessed Feb, 2020

2.5.3 Case Study 3: Solar sea slug *Elysiacrispata*

The chosen role model for this case study is called Elysia. A unique characteristic of Elysia crispata is its ability to take functional chloroplasts (plastids) from its green algal food source and store them, in a process called kleptoplasty. The slugs can be found “basking” in clear and shallow waters, absorbing the sun’s energy to drive photosynthesis. This allows E. crispata and some of its relatives to go weeks or even months without food, making them the only known solar-powered animals; Figure (2-38).[37]

Figure (2-38) Solar Sea slug
Source: http://solarslug.info, accessed Mar, 2020

2.5.3.1 Biological Domain

- **Experimental phase**

Close up view of E. crispata showing individual chloroplasts (tiny green spots) sequestered in its tissues. The limited dispersion ability and broad trophic range of E. crispata make it an excellent living model for studying local adaptation in food use. E. crispata also possesses a transparent body with a variety of colours, as the rhinophores protruding from the back can range from blue to red to green. Besides, the slug’s colour is known to fade or intensify with the sequestration of chloroplasts within its tissues.[38]

The interface between the skin and external world the skin of Elysia crispata is translucent. Therefore, visible colours come from internal tissues and organs or any material that might be incorporated into the skin. The inter-relationship between the skin and internal systems factors that determine the colour of Elysia crispata is tightly linked to the system it uses to harness energy. In case that E. crispata goes an extended period of time without food, few chloroplasts are present and its colour becomes very pale; Figure (2-39).[39]

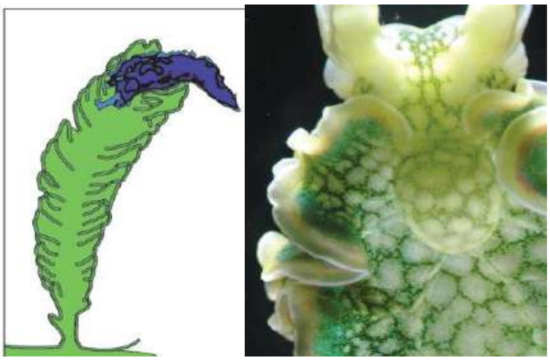


Figure (2-39) Interface between the Skin & External World
Source: Ilaria Mazzoleni, 2013

37 Ilaria Mazzoleni, “Architecture Follows Nature—Biomimetic Principles for Innovative Design”, Book, Taylor& Francis Group, 2013
38 Op. cit
39 Op. cit

- **Abstraction phase**

Elysiacrispata acts on tissue level of complexity. This tissue controls the colour of Elysia which is tightly linked to the system it uses to harness the energy. It absorbs the sun's energy to drive photosynthesis. This type of adaptability is called the chemical response. The performance could be defined as a colour change mechanism along with the simulated mechanism; Figure (2-40).

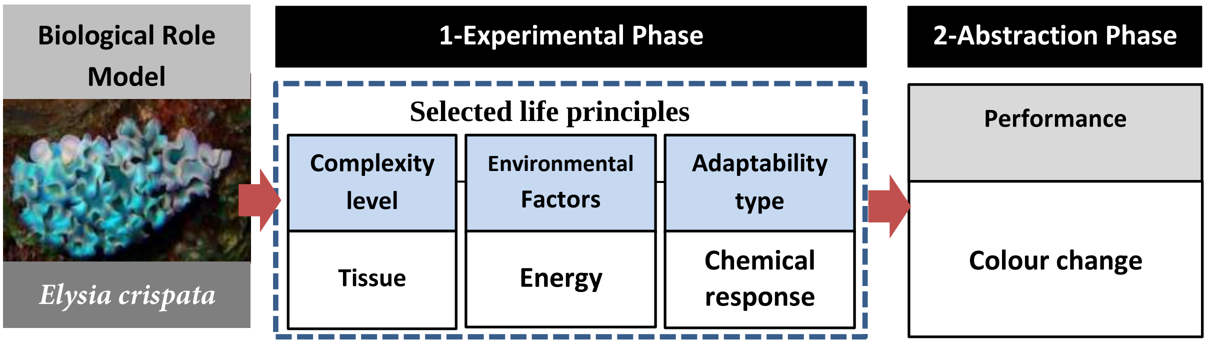


Figure (2-40) Elysia crispata abstracted principles
Source: Author

2.5.3.2 Architectural Domain

- **Prototyping phase**

A Proto-Architectural Project based on the eastern coast of Haiti, the building intends to fulfill the need for a dependable energy source during the time of reconstruction after the 2010 earthquake. The envelope system, inspired by the processes that generate colour in E. crispata, is a photo-bioreactor made of layered plastic modules and tubes filled with algae.

Using locally abundant resources such as ocean water, sun, and micro-organisms, the building produces biofuel, enabling it to change colours, ranging from red to blue to green, as the algae mature. The growth and harvest of the algae provide a dynamic beautification of the structure that communicates its level of energy production; Figure (2-41).

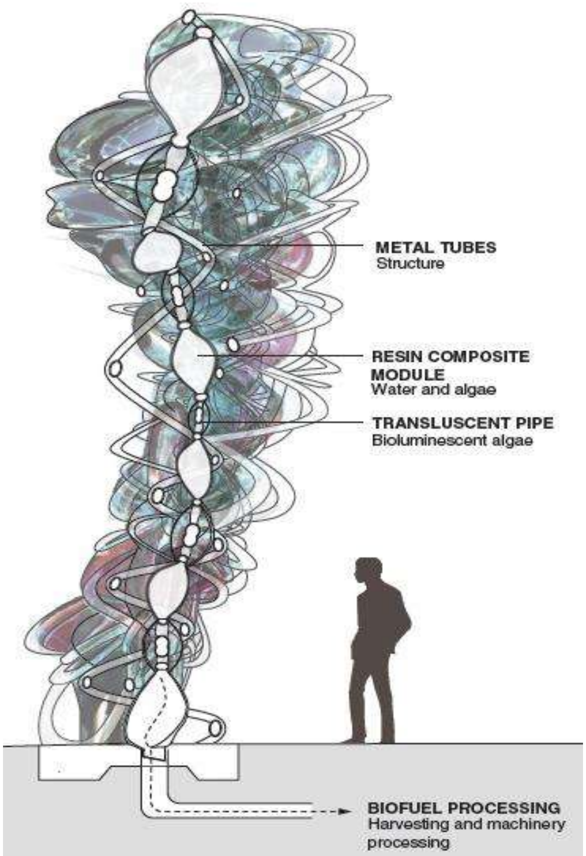


Figure (2-41) The building's hollow tubular structure
Source: Ilaria Mazzoleni, 2013

Algae are living organisms that use the sun, energy, and CO2 to photosynthesize. Mimicking the translucent effect of the E. crispata skin, the building's hollow tubular structure of the envelope contains bioluminescent algae, creating a light source during the night. The multiple layers of sacs enclosing microalgae and the tubular structure containing bioluminescent algae create an array of ever-changing colouration inside and outside the structure; Figure (2-42).

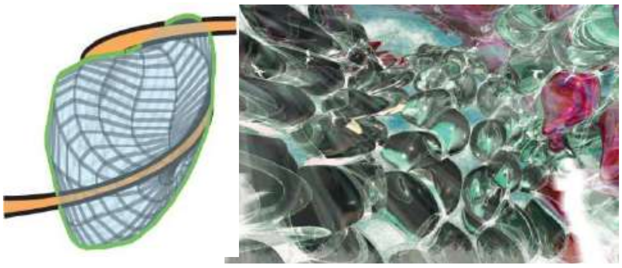


Figure (2-42) Envelope system inspired by E.crispata
Source: Ilaria Mazzoleni, 2013

2.5.4 Case Studies Discussion

Based on the analysis of the case studies, natural strategies could be architecturally mimicked, which in turn solve problems that have not yet been solved, and this is called the solution-based approach. The case studies spanned diverse strategies of the biological domain. The first and the second case study adopted the dynamic strategies of kinetic mechanisms, which produced a kinetic model without hinges. The third case adopted energy production strategy and dependence of food on solar energy, which produced a dependable energy source of the zero-energy system. Additionally, each biological model had an exceptional strategy that could combine multiple performances to achieve its goals. Based on the case studies, several strategies were observed among the biological models, despite using the same performances. Here arises the importance of the methodology suggested by the researcher, as it clarifies the performance to be transferred to the architectural domain based on selected life principles, rather than focusing on the performance and ignoring the strategies.

2.6 Biological role models Performance Database

In Petra Gruber, Barbra Imhof, and Vincent j. project titled "Growing as Building", a growing database was created of the most common performance of biological role models by simulating 37 role models, which provided the foundation of the Biornametics research. These are important elements of the "scientific input" and are categorized into three main themes that are considered relevant issues in Biomimetics and architecture: shape change and growth, Nano-surfaces, adaptation and reorganization. The role model information was processed into datasheets and working tools, such as cards in order to perform the second phase. This database helps to illustrate the classification and mapping of the biological role models and to identify the most common performance of role models. Besides, this growing database will help in facilitating the abstraction phase. These biological performances could be defined as: change colour, growth, and shape change, variety of shapes, hierarchies, self-healing, and communication.

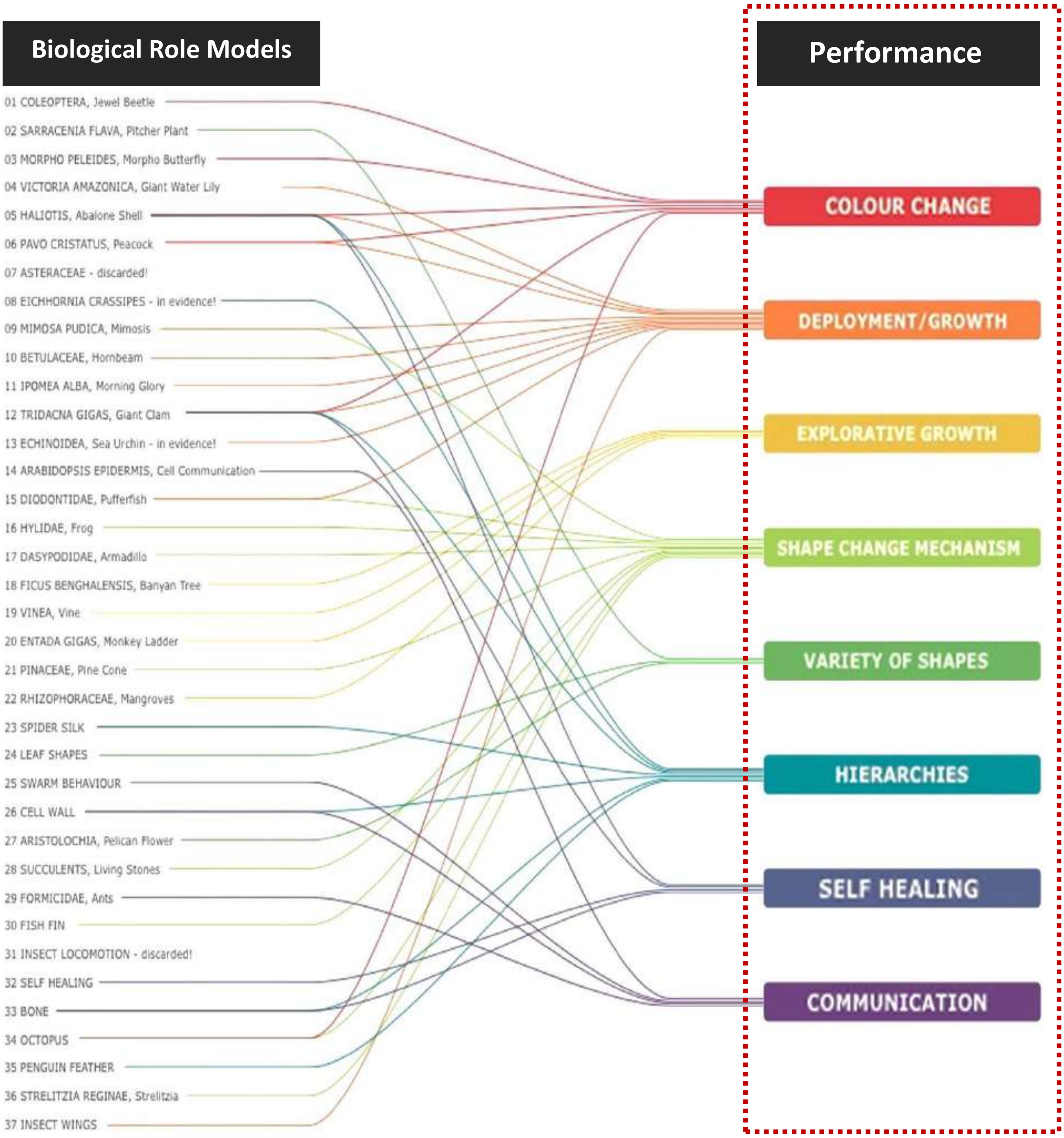


Figure (2-43) The growing database provided ‘Growing as Building’ Project
Source: Petra Gruber, 2018

Based on the database provided by the “Growing as Building” project, the same organism can manifest several performances at the same time to achieve the goal of survival. In addition, common performances were observed in most organisms, such as growth, shape change, change of colour mechanism. These performances were found to be the most prevalent upon analyzing 37 samples of biological role models. Most prevailing performances followed by hierarchy and communication, then, the performances that had the least prevalent among the analyzed living organisms are self-healing, explorative growth, and variety of shapes. Therefore, those performances will be the most important in order to be transferred to the architectural domain.

Chapter Summary

Based on the major problem mentioned in the previous chapter, nature was used as a source of form and ignoring its functions and process, the goal of this chapter is to search for natural strategies produced by biological domain for building systems which could enhance building behaviour. Furthermore, this chapter will adopt reconnecting to nature by defining the life principles in biology and nature which could be transferred to the architectural domain. The selection of life principles is based on the potential of the principles to deal with building behaviour such as: complexity level that is concerned with the level in which the biological role model behaves, reacting to the environment that is to define the environmental factors with which the organism deals, and the adaptability type which determines how the biological role model can adapt to the climate issues and survive.

Dealing with nature in the biomimetic architecture approach could be summarized in two approaches. The first approach is to observe natural strategies as solutions from nature to solve building behaviour problems, which is called Solution-Based approach. The second approach is to identify the architectural targets as a problem then search in biology for solutions, this approach is called Problem-Based approach. By following the Biomimetic approach workflow proposed by the researcher, the first step is to select one of these approaches; Figure (2-44). The second step is to reconnect to nature and select the life principle to deal with building behaviour, and then the third step is to simulate the biological role model using the selected life principles and the organism's performance. The outcomes of using this approach will definitely fulfill the architectural targets of building behaviour.

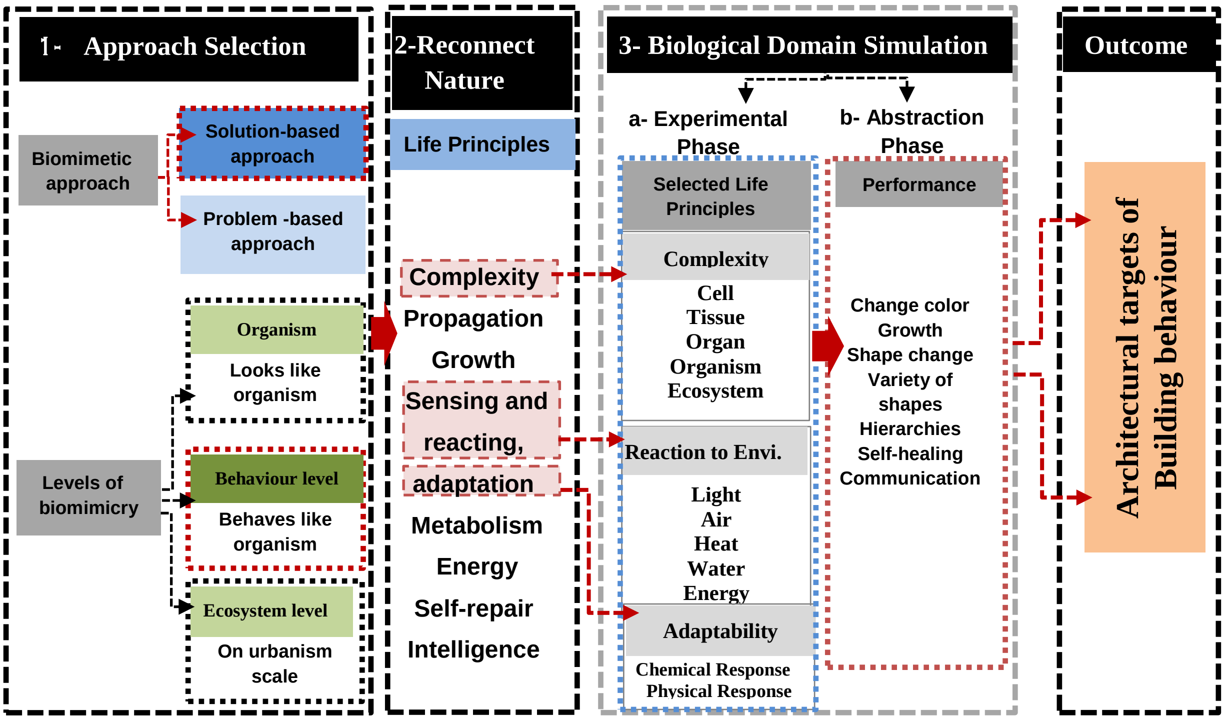


Figure (2-44) Biomimetic Architecture Approach Workflow
Source: Author

Based on the in-depth analysis of three exemplary biological role models and illustration of the possible transfer process of their principles, the following was concluded:

1- Living organisms operate at a level of complexity much deeper than that simulated by external shapes and skin's pattern, as some organisms operate at the tissue level and others on the micro-level, etc. This was the reason for performing projects that look like nature but not work like nature.

2- Living organisms manifest multi-function performance at the same time. Consequently, they produce many levels of adaptation, and therefore, it became necessary to use a holistic view and deal with the organism as a whole system.

3- Finally, when simulating an organism, it is necessary to know some information, i.e.: at which level of complexity it performs and deals with which environmental factors, and the performance of each type of adaptation that can be mimicked and transferred to architecture.

Next chapter will deal with the second approach "Problem-based approach" by defining the building behaviour targets as problems and search for the potential strategies that nature presents.

CHAPTER 3: The Influence of Biomimicry on Building Behaviour

Introduction

Biomimicry suggests innovative and eco-friendly approaches that can provide appropriate and flexible solutions, as mentioned in the previous chapter. These solutions could maximize the efficiency of building behaviour and provide a wide range of natural strategies for the main factors of building behaviour. For instance, learning from plants how they make use of air pollution and convert carbon dioxide into oxygen. The previous chapter presented the particular characteristics of the biological role models such as the selected life principles and the growing database of their performance. These characteristics will assist architects to identify the biomimetic strategies' information in an abstracted form to be transferred to the architectural domain.

The biomimetic approach has discovered the similarity of building behaviour needs and biological role models performance. Biomimicry is proposed to create buildings which are resilient to climate change, embedded in wider ecological systems, energy-efficient and waste-free. It is currently driving a paradigm shift in architecture and material science by drawing inspiration from nature's life principles.

This chapter will adopt the problem-based approach of the biomimetic approaches which concerns the targets of building behaviour as problems, then seeking in biology for solutions. Furthermore, this chapter specifically discusses the embodiment of biomimetic strategies into building behaviour elements and studying the influence of using a biomimetic approach on enhancing building behaviour efficiency. Thus, the goal of this chapter is searching for potential strategies which could enhance self-sustainability, widen ecological building elements, and boost building behaviour efficiency.

3.1 Building Behaviour: The Building as a System

The term "Behaviour" could be defined as the level of service provided by building material, component, or system, in relation to an intended or expected quality. For instance, the structural behaviour of a building may be judged in terms of its resistance to dead, live, soil, wind, hydrostatic, and seismic loads as prescribed by applicable codes. Within the established thresholds for these loads, the structure would be required to behave adequately according to expectations in terms of strength; durability, deflections, and vibrations.[1]

The concept of respect the building as a whole system stems from modern systems theory and the application of building science principles to building behaviour and performance. As innovation became increasingly a means of achieving new forms of architectural expression by mimicking nature. While, in twentieth-century analysis and

1 Ted J. Kesik, "Building Science Concepts", Ph.D., the University of Toronto, Canada, 2019

review of the building failures, indicated that biomorphic approaches of the design were inadequate, and this was due to the simple imitation of nature or limited analysis at the level of building component. In both cases -whether in nature or in the building- the behaviour of the entire system was not considered.

Therefore, the behaviour of the entire system is an important approach to building science. In order to apply the building systems approach in the design and assessment of buildings, it is first necessary to establish a framework of behaviour requirements. This section depicts a hierarchy of performance requirements derived from building science principles framework based on the pioneering work of the late Neil Hutcheon.[2] These requirements consist of four main factors sorted according to the importance of each element as the minimum requirements for health, and safety represented the first priority, then environmental control that influences the quality of indoor environment, Sustainability, and aesthetics considerations respectively; Figure (3-1).

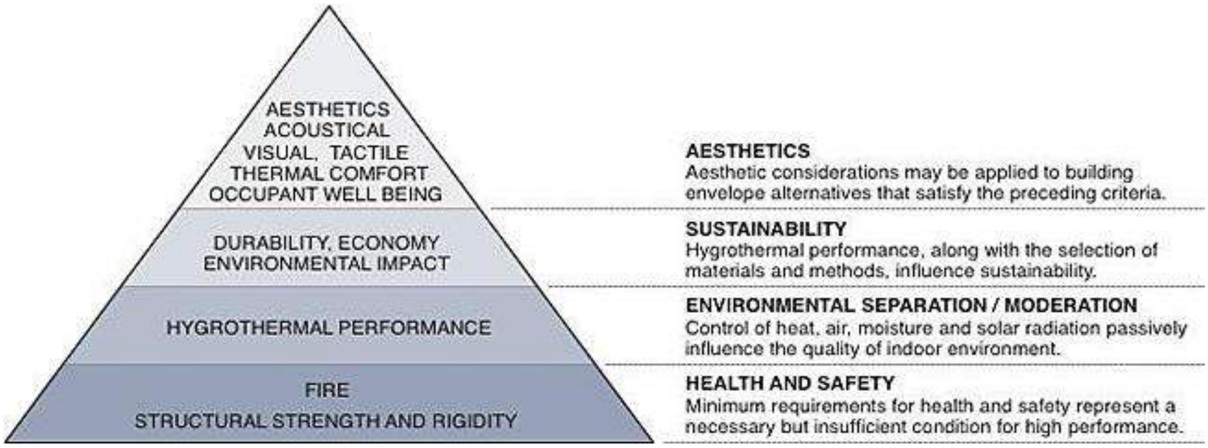


Figure (3-1) Building science hierarchy of behaviour requirements
Source: Ted J. Kesik, 2019

3.1.1 Building Behaviour Elements

The building behaviour approach requires designers to consider the interactions between the primary elements consciously. Harmonation of these elements is the key to the well-performing building. According to the highly specialized nature of contemporary building science, it is recognized that materials, components, equipment, and systems must be properly integrated to achieve a high-performance building. At the same time, it must be appreciated that most behaviour problems involve the building enclosure, which represents the primary passive environmental control system. These primary elements could be identified as; first, the external elements which consist of the building enclosure system and structure which are considered as the primary external defense of environmental conditions. Second, the internal components consist of building systems (electrical/mechanical systems), interior elements, and materials that interact with physical phenomena.

2 Kesik, T. and David De Rose, “ Development of a Wall Performance Classification System”, Toronto ON: CIB World Building Congress, 2004

Building behaviour (performance) is a highly complex, resultant phenomenon. It involves numerous simultaneous and sequential physical phenomena, and the response of the building as a system will vary depending on the nature and arrangement of the constituent elements.[3] Based on the schema depicted in Figure (3-2), complex behaviour may be described, phenomena depicted, the direct response of the building enclosure to the temperature, air pressure, and humidity difference between the indoor and outdoor environments results in heat loss and air leakage. The indirect response influences thermal comfort and indoor air quality if the enclosure provides low effective thermal resistance. These indirect reactions are considered as the architectural targets for building behaviour.[4]

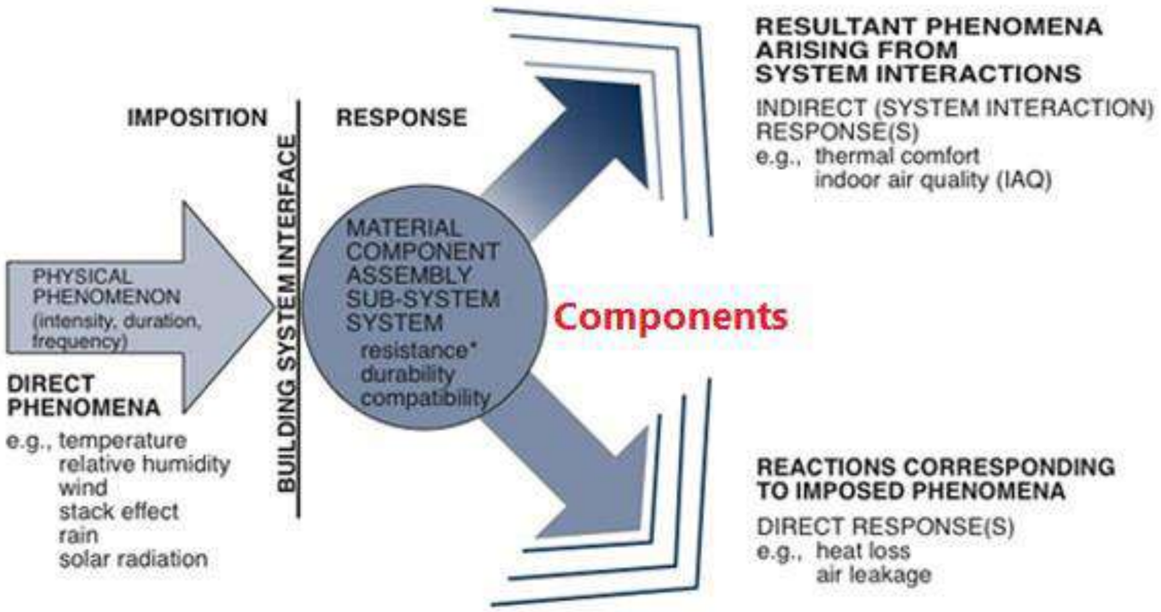


Figure (3-2) Relationship between Physics, Materials, Components, and Systems
Source: Adapted from Ted J. Kesik, 2019

Each of the above elements varies in importance, depending on the type of building and its intended use and its location. Building science specialization is often needed to deal with particular aspects of these features of systems such as energy modeling, flood-proofing, durability, indoor air quality, blast resistance, etc. But in all cases, the most important factor is the interconnectedness of all these systems within the building and dealing with a fundamental perspective of how these features of the systems interact in the building as a system model.[5]

3 Hutcheon, N. & Handegord, G., “Building Science for a Cold Climate”, Canada, 1983
4 Ted J. Kesik, 2019, Op.cit.
5 Timothy F. H. Allen, “Hierarchy theory: a vision, vocabulary, and epistemology", New York: Columbia University Press, 1996

3.1.2 Building Behaviour Architectural Targets

Contemporary building science supports the societal objective of sustainable architecture by balancing the physical elements of the building and the functional requirements, ideally without compromising architectural aesthetics and high performance. These parameters are intended to provide designers with an explicit means of accounting for compliance with the functional requirements of buildings.[6]

Building system integration involves the building structure, its enclosure (envelope), the interior elements, and the building services i.e., mechanical, electrical, etc. Figure (3-3). Optimizing performance goes beyond compatibility between the structure, enclosure, interior, and services. It involves the assessment of economic, social, and environmental parameters so that performance targets are attained affordably within the skill capacity of the industry.[7]

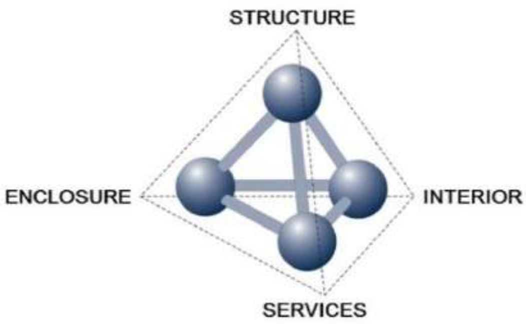


Figure (3-3) Building System Integration
Source: Ted J. Kesik. 2019

The previous section could summarize that building behaviour consists of two primary parameters. The first is the building behaviour elements; they are the physical components of the building. The second is the building behaviour targets, these functional requirements of building behaviour elements:

a- Building behaviour elements:

1. External Components: Envelope - Structure
2. Internal Components: - Building systems (i.e., mechanical, electrical, etc.)
   - Interior elements
   - Materials

b- Building behaviour architectural targets:

1. Efficient structure
2. Efficient Materials
3. Indoor Environmental Quality
   (Thermal comfort-Visual comfort- Indoor air quality)
4. Energy efficiency
5. Water efficiency

6 Ted J. Kesik, 2019 Op.cit.
7 Ted J. Kesik, 2019 Op.cit.

These building behaviour parameters help to identify problems that exist in the building. By identifying targets as problems the next step will be seeking solutions in biology and get the potential strategies to implement in building behaviour.

3.2 Biomimetic Approach in Building Behaviour

Within the scope of building behaviour approach, biomimicry offers a wide variety of solutions derived from biological role models by embodying technologies proved to have survived previous problems with a greater economy of means. Architects have achieved some truly remarkable bio-morphic projects by the digital revolution. However, for the purpose of achieving the sustainable building, the main target will be transferring some of the extraordinary adaptations that have evolved in natural organisms to the building behaviour to achieve its targets. The study will adopt the problem-based approach by defining the architectural targets of building behaviour as problems and searching in nature for the potential strategies which could help to achieve these targets.

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Based on the mapped diagram; Figure (3-4), it is a combination of the study elements which consists of the two major sectors. The first sector is the biological domain and its factors which concerns by providing the required information that was deduced from the previous chapter. The second sector is the architectural domain parameters that are considered the targets of this study. The next section is searching for a link between these sectors by a proposed methodology of problem-based approach.

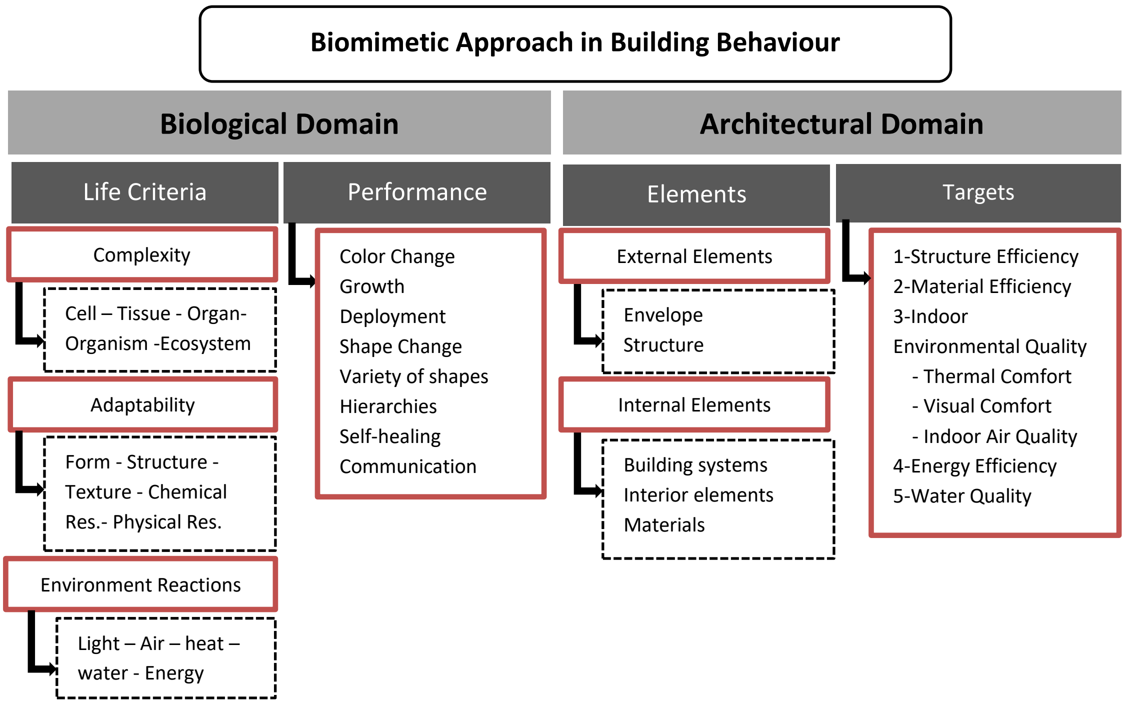


Figure (3-4) Study mapping diagram of the biological domain factors and building behaviour factors
Source: Author

3.3 Potential Strategies offered by Biomimicry to Implement in Building Behaviour

In order to achieve the goal of this chapter and verify the benefit of using biomimicry in building behaviour, the researcher proposed a transfer methodology of the selected life principles through the problem-based approach to achieve the building behaviour's targets. This chapter will adopt using the problem-based approach methodology, by identifying the architectural targets of building behaviour as problems then search the biological systems for solutions. Biological Domain will divide into two phases. First, the experimental phase that the selected biological role model is simulated according to the selected life principles. Second, the abstraction phase that specific performance of the biological role model is selected, then implemented in the architectural domain in prototype phase as an architectural element such as Envelope, Structure, Building systems, Interior elements, Materials) to achieve the specific target; Figure (3-5).

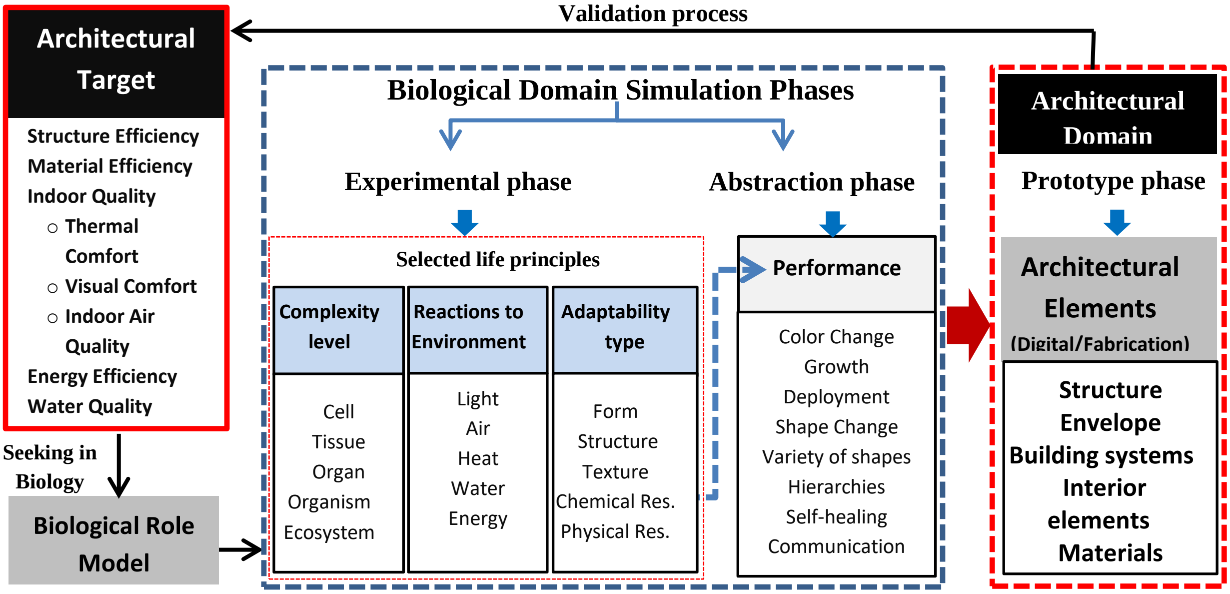


Figure (3-5) Problem-based Approach Methodology
Source: Author

With a view to proving the influence of biomimicry on the building behaviour, this effect will be studied on each of the architectural targets of the building behaviour. After that, a successful case study will be presented for each target. The case studies will be analyzed using the proposed methodology of the problem-based approach by the researcher in order to identify strategies that can increase the efficiency of each of those targets, represented in:

1- Structure Efficiency
2-Material Efficiency
3-Indoor Quality
4- Energy Efficiency
5-Water Quality

3.3.1 Structure Efficiency

The efficient structure target could be achieved by seeking in nature for solutions using the referred problem-based approach or solution-based approach as mentioned in the preview chapter. The result of using biomimicry in structure optimization will be three major ways; customized/freeform design, simulation-driven design, and lattice design as shown in Figure (3-6). These major ways may be used in combination with one another. For Instance, lattices may be incorporated in a freeform design process or in a simulation- design process.[8]

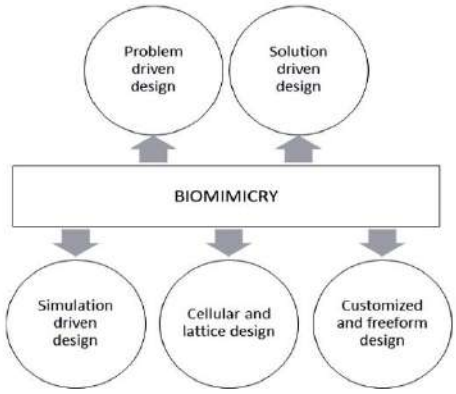


Figure (3-6) Biomimetic design approaches for Structure optimization
Source: Anton Du Plessis, 2019

Nature has optimized complex structures to fulfill specific functions within the constraints imposed by the organism itself or the external environment. Learning from these biological structures may enhance our use of efficient structures in the building in a sustainable manner.[9] These natural structures classified according to the type of element that they are made of (beam or surface) and whether they occur internally or externally to the shape, as shown in Figure (3-7). The biomimetic approach can play a key role, in helping structure-function optimization based on observations of cellular structure in nature.

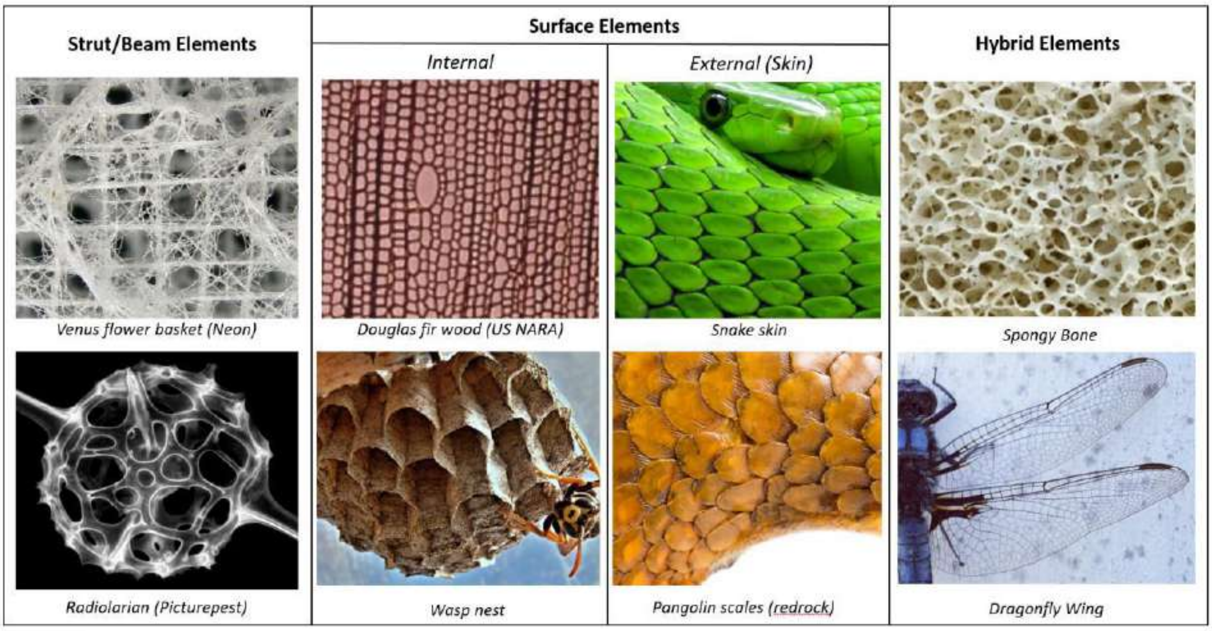


Figure (3-7) Natural structure classification
Source: Anton Du Plessis, 2019

8 Anton Du Plessis, Chris Broeckhoven, "Beautiful and Functional: A Review of Biomimetic Design in Additive Manufacturing", Article, Elsevier, 2019
9 Anton Du Plessis, 2019 Op.cit.

One of the most important characteristics in the natural structure is the hierarchy. With increasing levels of hierarchy, the structure becomes more efficient in terms of the amount of material used to achieve a given objective Figure (3-8).[10] In biology, the structure benefits from bonds at every level from atoms to molecules to cells to organisms and upwards, hierarchical structures also deliver benefits in stiffness and fracture control and this is achieved through interfaces between, and within, each level of the hierarchy.[11]

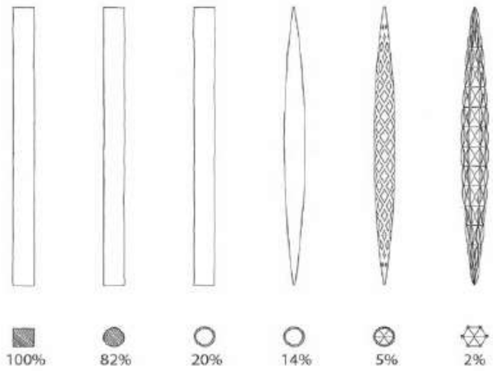


Figure (3-8) Hierarchical structuring results Material Reduction and light weight
Source: Michael Pawlyn, 2016

The Eiffel Tower Figure (3-9) manifests three levels of hierarchy, but the majority of human engineering uses only one level. Selected examples from a variety of structural parts that illustrate the power of simulation in mimicking nature for product design that outperform conventional designs and are manufacturable and lightweight. The first example is the Hardmarque automotive piston. The end result is reported to be 25% lighter and equally strong compared to the original aluminium part. The second example of Renishaw is reported 40% of weight savings Figure (3-10).[12]

Figure (3-9) Hierarchical structuring The Effiel Tower, accessed April, 2020
Source: Michael Pawlyn, 2016

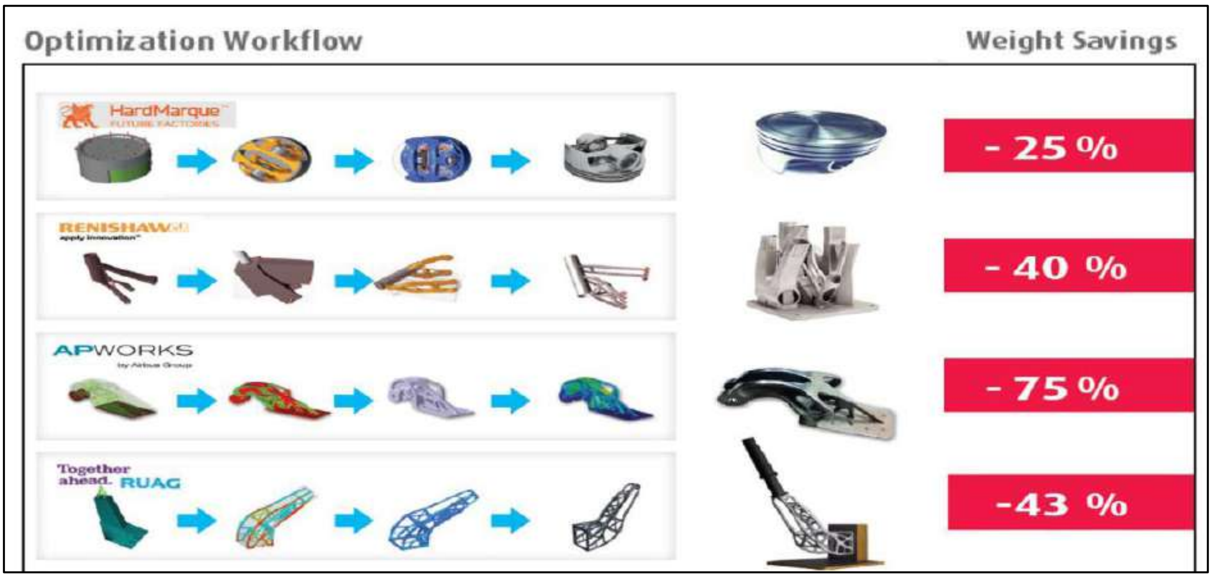


Figure (3-10) Examples of simulation-driven biomimetic design with weight savings
Source: Anton Du, 2019

10 Michael Pawlyn, 2016, Op.cit.
11 McKeag, T., "Little things multiply up: Hierarchical structures", Zygote Quarterly, Vol. 9, 2014
12 Anton Du Plessis, 2019, Op.cit.

The first step is searching for the role model which can help to reach the architectural target. In this case, the target is structure efficiency. Diatoms Figure (3-11), studied at the Alfred Wegener Institute in Germany, show morphological characteristics in their bio-silicate structures. These characteristics result in astoundingly stable, yet lightweight structures that exhibit most significantly a material-saving construction even in the details.[13]

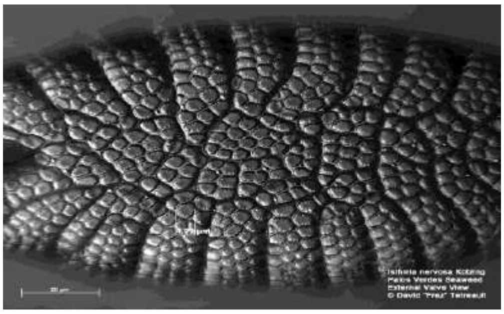


Figure (3-11) Isthmia nervosa Micro Alga
Source: https://www.flickr.com, accessed, April 2020

a- Biological Domain

- **Experimental Phase**

Close up view of Isthmia Nervosa it identified the actuating elements that are responsible for the production of accumulated silicate in the skeletons of diatoms at the cost of food ingestion; therefore, better material efficiency is an evolutionary advantage for the life-forms; Figure (3-12).[14]

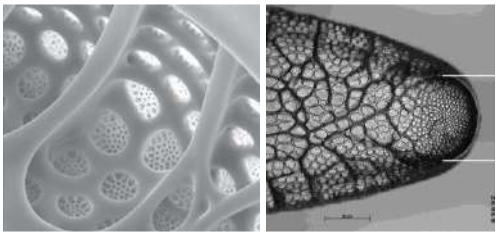


Figure (3-12) Isthmia nervosa, a detailed capture of the structural membering.
Source: Werner Nachtigall, 2015

- **Abstraction Phase**

This Biological role model is acting on the cellular level of complexity. Upon investigating the formation of structure, the following was shown: this type of adaptability of the Isthmia taxonomy is the characteristic rib structures. To fulfill the architectural target of efficient structure the constructional criteria consists of performative characteristics occur in the combination of the highest protection from the environmental factors. The performance could be concluded as hierarchies along with the simulated form morphology; Figure (3-13).

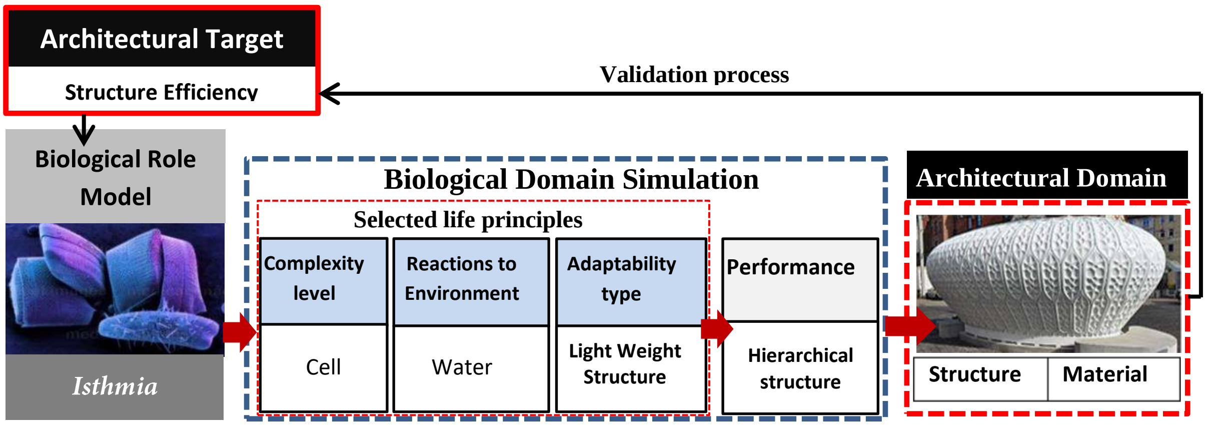


Figure (3-13) Isthmia nervosa abstracted principles
Source: Author

13 Werner Nachtigall,"Biomimetics for Architecture & Design", Springer, Germany, 2015
14 Werner Nachtigall, 2015, Op.cit.

b- Architectural Domain

- **Prototyping Phase**

In order to test the previously abstracted principles of Isthmia; Figure (3-14), one of its key structural elements Isthmia with rib and pore structures, was abstracted and rebuilt digitally as a first step then fabrication step. A parametric model was generated to represent the structural morphogenetic design based on the steps of morphogenetic design break down into the following echelons; the first is the development steps of the hierarchical facade and envelope structure. The second is a constructional morphogenetic design by material and fabrication optimization; Figure (3-15).[15]

Figure (3-14) COCOON_FS digital model
Source: http://www.evolo.us/, accessed April, 2020

Figure (3-15) Digital model for Concoon-Fs pavilion components
Source: Archdaily.com, accessed April, 2020

Fabrication phase based on the previous step material and fabrication optimization as COCOON_FS pavilion suite envisioned both natural lightweight construction as well as highly efficient technical design solutions. The self-supporting COCOON_FS shell consists of FRP (Fiber Reinforced Polymers) that simultaneously form the skin and the supporting structure. Compared to biological solutions in ǀervosa algae, COCOON_FS uses the behaviour of lightweight of efficient structure design; Figure (3-16).

Figure (3-16) COCOON_FS fabrication components
Source: http://www.evolo.us/, accessed April, 2020

The “Cocoon-fs” pavilion is the result of the international research project “PlanltonTech” which aims to develop prototypes with applications in architecture and design based on “Biomimesis”, in this case, focused on the study of marine microorganisms; Figure (3-17).[16]

Figure (3-17) COCOON_FS Pavilion as built
Source: http://www.evolo.us/, accessed April, 2020

15 Op.cit
16 http://www.evolo.us/new-construction-materials-based-on-biomimetic-principles-pohl-architekten/, accessed April, 2020

3.3.2 Material Efficiency

Structure and materials are indistinguishable in nature, which is a radically different way of thinking to grasp in an architectural context. Nature organises structure and materials together through a hierarchic system. So an efficient structure is supposed to provide lightweight efficient material inspired by nature. Neri Oxman introduced a new design approach called “material ecology” that aims to establish a deeper, more scientific and precise relationship between the design object and an environment.

Natural organisms sense and respond to environmental stimuli. In buildings, smart materials emulate the intelligent response processes in nature. For example; shape-changing materials in plants have inspired synthetic materials recently used in sun-harvesting solar panels and reactive textiles. The possible application of “smart materials” in architecture can be seen either in sensors or actuators or as no-tech/low-tech hydromorphic materials used in building structure, building mechanical elements, building envelope, building core and building coating.[17]

Bio-Inspired materials mainly produced by imitating structural, functional, and behavioural aspects of natural organisms each individual approach of bio-inspired material yields innovative sustainable outcomes; Figure (3-18), those Bio-Inspired materials can fall into four major categories:

(1) Using natural materials in the manufacturing process for better recycling as well as mimicking.
(2) Structural properties such as a material with thermal behaviour or load-bearing.
(3) Functions such as a material with intelligent response or waterproofing.
(4) Biological processes of natural organisms; growing and reproductive material.[18]

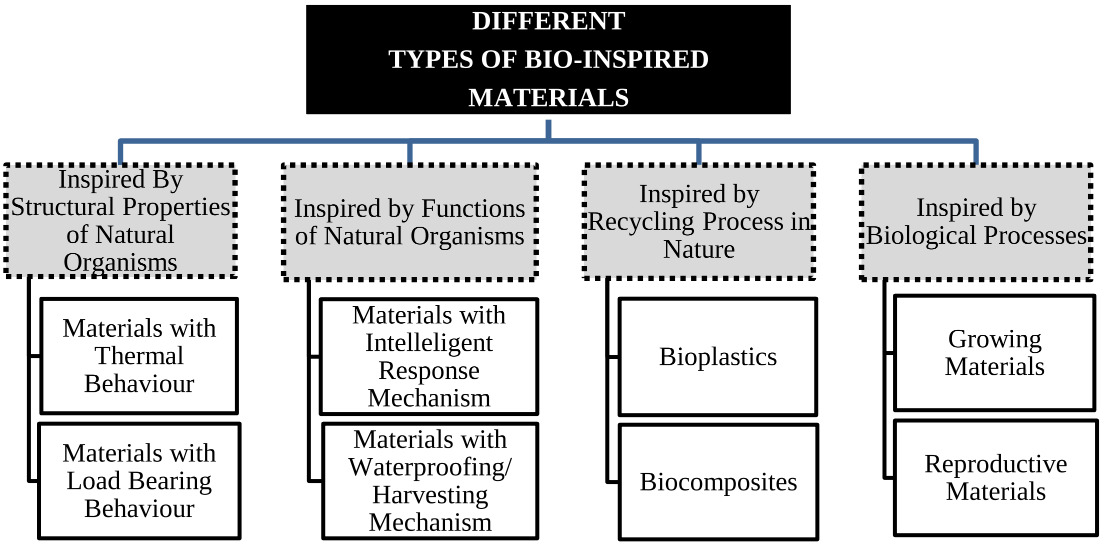


Figure (3-18) Classification of bio-inspired materials
Source: Author, adapted from Donn, M., 2019

17 Donn, M., "Bio-inspired Materials: Contribution of Biology to Energy Efficiency of Buildings", Article, Springer Nature, Switzerland, 2019
18 Op.cit

Self-assembly is the main principle used in nature to produce structural organization on all scales from molecules to galaxies. It is defined as a process whereby pre-existing parts or disordered components of a pre-existing system form structures of patterns. Examples of the self-assembling systems include weather patterns, solar systems, histogenesis (the formation and development of tissues), and self-assembled monolayers (monomolecular films). Self-assembly can occur spontaneously in nature. [19]

A major opportunity to mimic this is the prospect of growing materials for buildings by accretion or self-assembly that mimics natural processes, known nowadays as '3D printing'. 3D printing was a huge leap for designers in the digital revolution because it allows a three-dimensional computer model to be turned directly into a physical, highly accurate model. VULCAN was subsequently awarded the title of the largest 3D-printed structure in the world by Guinness World Records; Figure (3-19).[20] Different types of bio-inspired surfaces are represented in Table (3-1).

Figure (3-19) VULCAN: the largest 3D-printed architectural pavilion
Source: https://inhabitat.com, accessed April, 2020

Animals (Functional surfaces)	
Features	***Animals***
Surfaces for anti-wear	Dung beetle, ground beetle earthworm and mole cricket seashells and whelks, desert lizards and scorpions
Surfaces for super hydrophobicity	Water strider and Parnassius butterfly wing
Surfaces acting as smart adhesives	Gecko, soil-burrowing animals
Surfaces for drag reduction	Carp and shark
Surfaces for anti-fogging	Culex pipiens mosquito
Surfaces for noise reduction	Owls
Surfaces for water capture	Stenocara beetle
Surfaces for Optical function	Moth eye, Trogonoptera Brookiana and Papilio ulysses
Plants (Dynamic Movements)	
Features	***Plants***
Elastic movement	*Strelitzia reginae* (bird of paradise flower)
Reversible snapping motion	*Aldrovanda Vesiculosa* (Waterwheel plant) and Venus Flytrap
Unidirectional changes at the periphery	Flower of *Lilium Casa Blanca* (Liliaceae)
Smart opening-closing system	Seeds of many *Mesembryanthemums* and leaves of *Rhododendron*
Touch and vibration sensitivity, folds inward as a reaction to contact	*Mimosa pudica* (Sensitive plant) and Leaves of *Mimosa pudica*
Oriented and folded based on temperature	*Leucaena leucocephala* (White leadtree) and *Maranta Leuconeura* (Prayer Leaf)
Change temperature levels passively.	*Salvia officinalis* (Sage) and *Kalanchoe Pumila* (Dwarf purple kalanchoe)
Water-use efficiency	*Echeveria Glauca* is an example of a CAM plant
Reflect sunlight from hairy surfaces.	Hairy leaves of *Gynandriris Setifolia*

Table (3-1) Most common types of materials inspired from nature
Source: K.M. Al-Obaidi, 2017

19 Panchuk, N.,"An Exploration into Biomimicry and its Application in Digital & Parametric [Architectural] Design", University of Waterloo, 2006
20 Michael Pawlyn, 2016, Op.cit.

The first step is to search for the role model which can help in fulfilling the architectural target. In this case, the target is material efficiency. Cones of conifers have the hygroscopic form- changing abilities, where the cones open and close as a reaction to the environmental conditions of humidity and aridity. The cones open in dry conditions and close on moist conditions; Figure (3-20).[21]

Figure (3-20) Conifer Cones physical response
Source: Artem Holstov, 2017

a- Biological Domain

- **Experimental Phase**

Conifer Cones will be the selected biological role model; Pine cones fold their scales when it rains to prevent seeds from short-distance dispersal. The movement of spruce cones is rooted in the material's intrinsic capacity to interact with the external environment, and it shows how a structured tissue can passively respond to environmental stimuli.

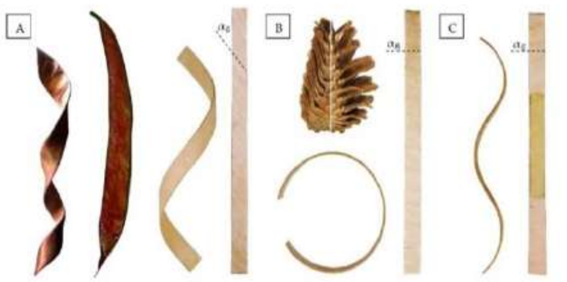


Figure (3-21) Potential shape transformations of veneers wood
Source: Artem Holstov, 2017

The outer layer, comprising of parallel, long and densely packed thick-walled cells, reacts to an increase or decrease of relative humidity by expanding or contracting, while the inner layer remains relatively stable. The resultant differential dimensional change of the layers translates into a shape change of the scale, causing the cone's scales to open or close; Figure (3-21).[22]

- **Abstraction Phase**

Cones are biological role models that work at the tissue level of complexity. It uses physical adaptation to face the environmental factor; humidity. It aims at material efficiency as an architectural target. The performance could be concluded as shape change, along with the simulated morphology of tissue Figure; (3-22).

21 Holstov, A., "Sustainable Materialisation of Responsive Architecture", Sustainability j., UK, 2017
22 Reyssat, E., "Hygromorphs: From pine cones to biomimetic bilayers", article, The Royal Society Interface J., 2009

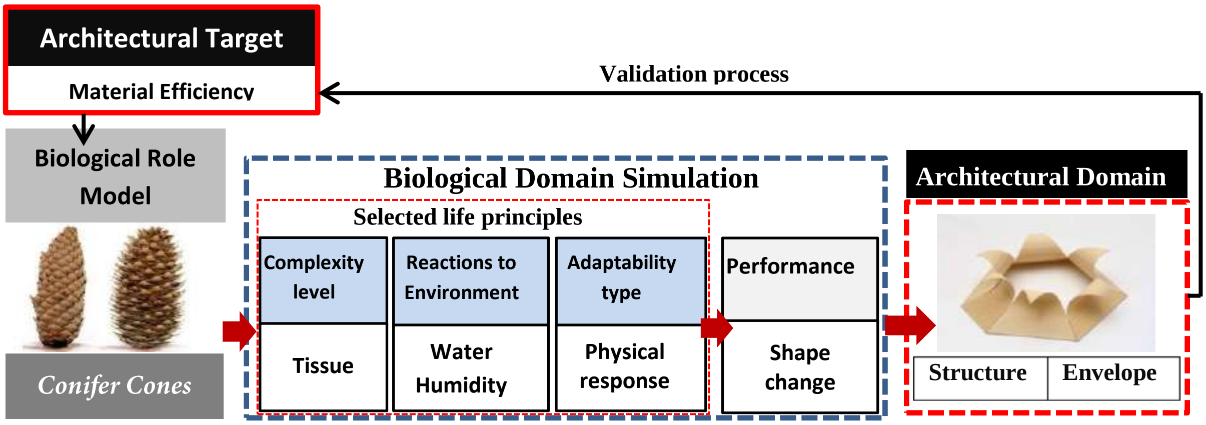


Figure (3-22) Cones abstracted principles
Source: Author

b- Architectural Domain

- **Prototyping Phase**

Programmable shape-shifting materials are observed to suggest various deformations based on behaviour. These materials are able to react to environmental stimuli including radiation, humidity and others. Shapes of hygromorphic materials can be controlled through transformations that are affected by the percentage of moisture in the air. The veneer composite element uses the reactive material properties in surprisingly simple building element that is at once an integrated sensor, energy-less actuator, and modulating flap. Integrated functionality of this type on the material level achieves complex, decentralized behaviour patterns without any control units; Figure (3-23).[23]

Figure (3-23) Reactive pavilion envelope by veneer composite element
Source: https://www.archdaily.com/, accessed June, 2020

23 Donn, M., 2019, Op.cit

3.3.3 Indoor Quality

Efficient indoor quality solutions can be extracted from strategies found in nature. Living organisms maintain body temperature, air and light in very narrow ranges in order to survive. Organisms have adapted physiological, morphological, and/or behavioural means for indoor comfort using several techniques. In some organisms, the process is achieved by skin or organ functioning as a thermal, air filter and light controller, those strategies will be discussed for all architectural targets that can achieve the indoor quality, which are represented in: indoor thermal comfort, indoor air quality and indoor visual comfort.

3.3.3.1 Indoor Thermal Comfort

Badarnah and Kadri presented an exploration model of heat regulation strategies. The model is a structured platform aiming to facilitate the search for, and the selection of, appropriate strategies from the large database of nature. The model presents a basic array of strategies for heat gain, retention, dissipation, and prevention; elaborates on the involved factors; Figure (3-24).[24]

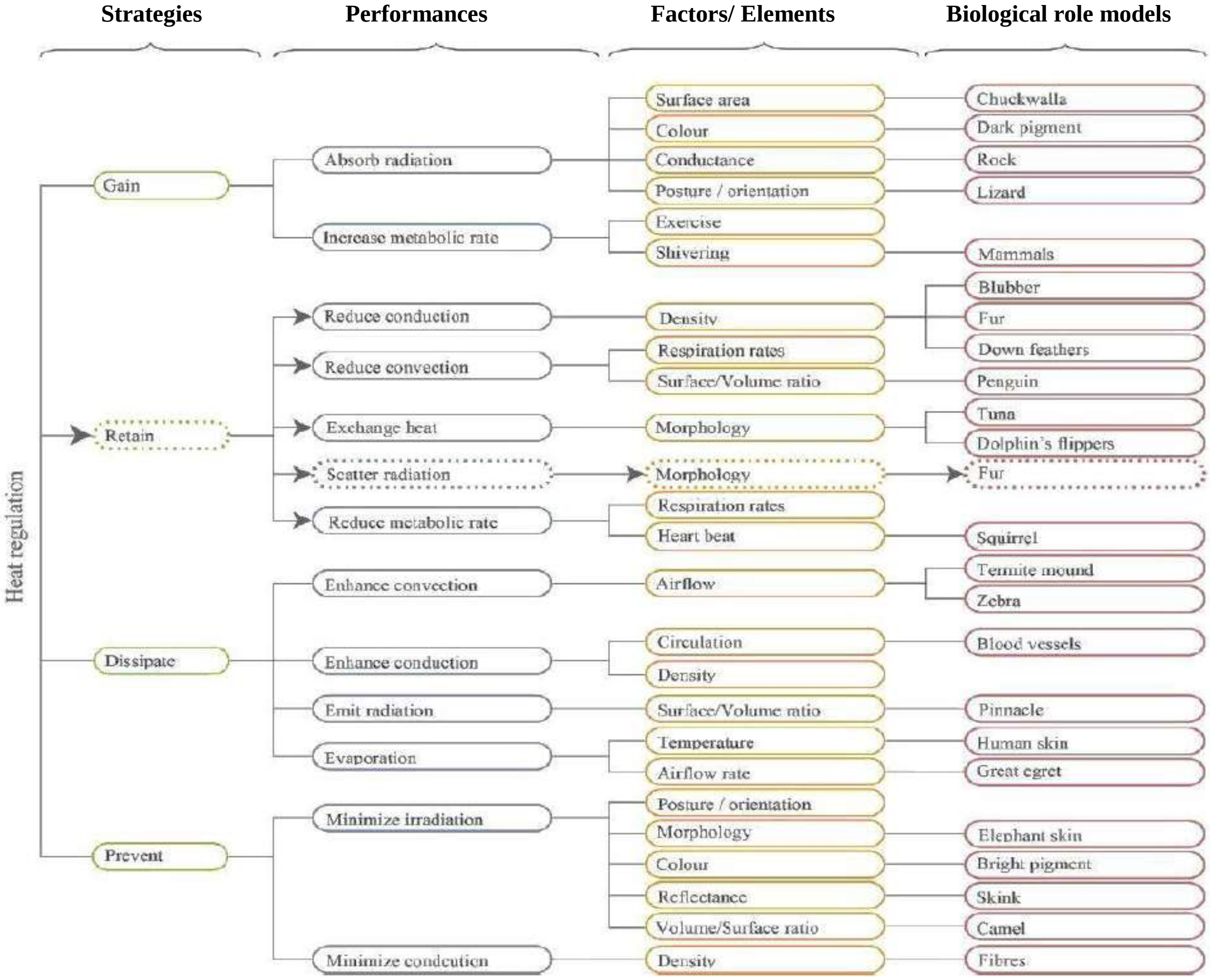


Figure (3-24) Heat regulation framework for biomimetic design
Source: Badarnah, L., 2015

24 Badarnah, L., 2015, "A biophysical framework of heat regulation strategies for the design of biomimetic building envelopes", Conference paper, Elsevier, USA, 2015

In Architectural domain, thermal regulation divided into two factors: exterior and interior elements. The exterior elements could be presented in building envelopes and structure. Building envelopes separate occupied indoor spaces from the exterior environment inspired by organisms skin. Envelopes are often considered as thermal barriers or shields by mimicking strategies from nature. Examples can be seen in the patterns inspired by nature in Masdar city, Mashrabya House, and adaptive skin response to the environmental conditions in Al Bahar towers and the Arab Cultural Institute. On the other hand, interior elements integrate with the external elements to fulfill the thermal comfort target. The bio-inspired interior elements can be seen in examples as the interior pattern, passive cooling systems and shading devices; Figure (3-25).[25]

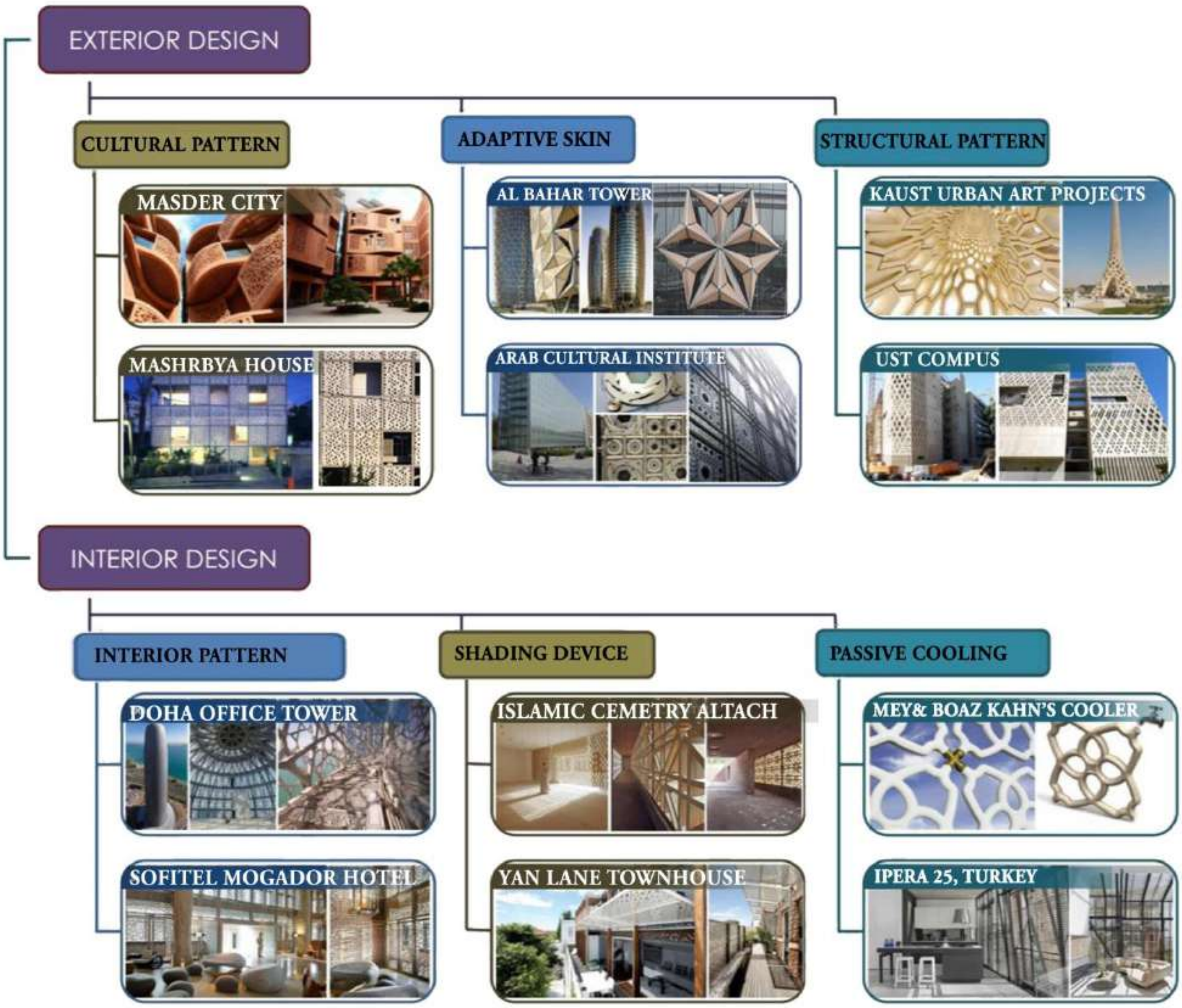


Figure (3-25) Integration between external and internal design inspired by nature for thermal regulation target
Source: Yasmin M., 2017

25 Yasmin M., "Modern Mashrabiyas with High-tech Daylight Responsive Systems", IEREK, Egypt, 2017

The first step is searching for the role model which fulfills the architectural target. In this case, the architectural target is thermo-regulation. Lizards; Figure (3-26), are role models in which thermoregulation obviously characterizes its skin pattern. Temperature regulation in lizards is achieved through a combination of both their skin characteristics and their behaviour.[26]

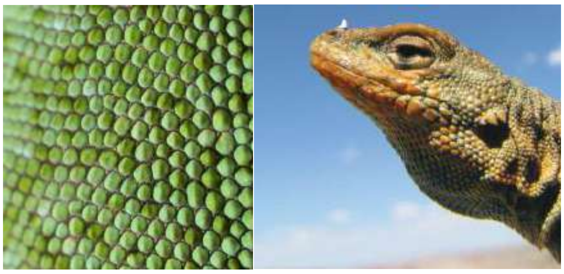


Figure (3-26) Lizards skin pattern
Source: Ilaria Mazzoleni, 2013

a- Biological Domain

- **Experimental Phase**

Ilaria Mazzoleni team designed a residence for the desert climate which mimics the behaviours of the lizard's skin by translating its physiological properties. Lizard's skin consists of two principal layers. The first is the epidermis which is the outer layer, and the second is the dermis which is the inner layer. Lizards' scales are thickenings of the epidermis and are primarily made of a horny substance called keratin, much like human fingernails.

The scales are thickenings of keratin, connected by hinges of thin keratin; they are often folded and overlap each other. Areas of the body involved in smaller movements have smaller scales to allow for increased flexibility, while large scales involved in restricted movement. The outer skin is periodically moulted and then renewed by cells in the inner skin layer. Moulting enables growth and at the same time replaces worn-out skin; Figure (3-27).[27]

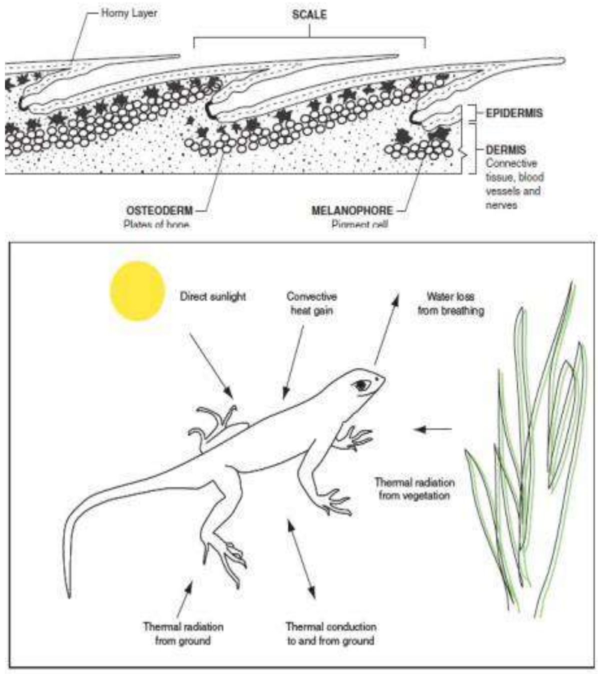


Figure (3-27) lizard's skin layers
Source: Ilaria Mazzoleni, 2013

26 Ilaria Mazzoleni, 2013, Op.cit
27 Op.cit

- **Abstraction Phase**

Lizard skin is a biological role model that works at the tissue level of complexity. It overcomes temperature as an environmental factor through physical adaptation, along with energy-efficiency to fulfill the architectural target of indoor thermal quality. The performance is concluded as colour change (camouflage) and variety of shapes along with the simulated skin tissue; Figure (3-28).

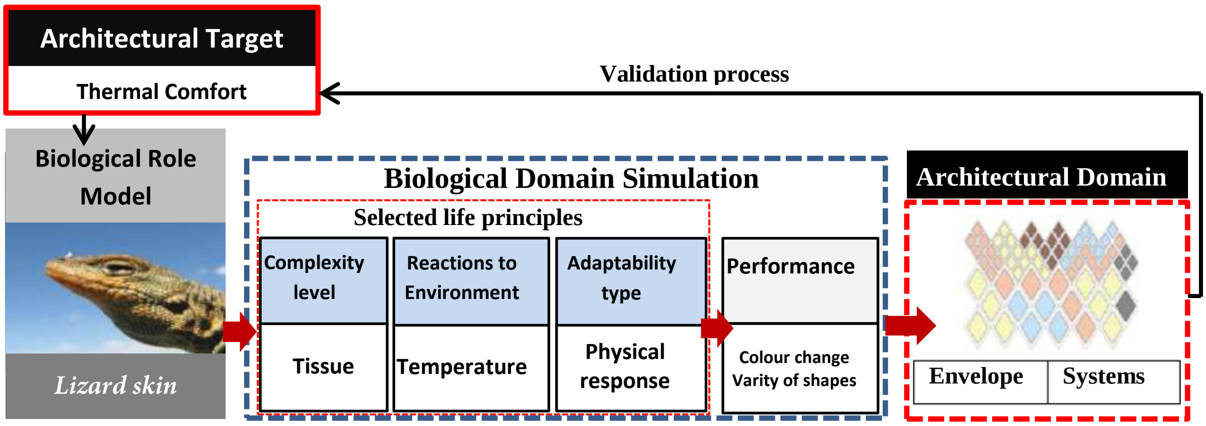


Figure (3-28) Side-blotched lizard abstracted principles
Source: Author

b- Architectural Domain

- **Prototyping phase**

The project is a small artist's retreat located in the Great Basin Desert inspired by lizard's physiological and behavioural adaptations to the desert temperature regime. The design focus on creating an enclosure system that provides 24-hour comfort for the residence during hot, dry days and sometimes very cold nights. The physiological strategies of the lizard's skin have inspired the house walls' design, while the lizard's behavioural adaptations have influenced the smart sun-tracking system actuated by a hydraulic system and sensors Figure (3-29).

The photovoltaic panel collects the sun's rays and converts them to the studio's electricity. The window panels provide views and ventilation. These panels are strategically arranged to maximize their performance; Figure (3-30).[28]

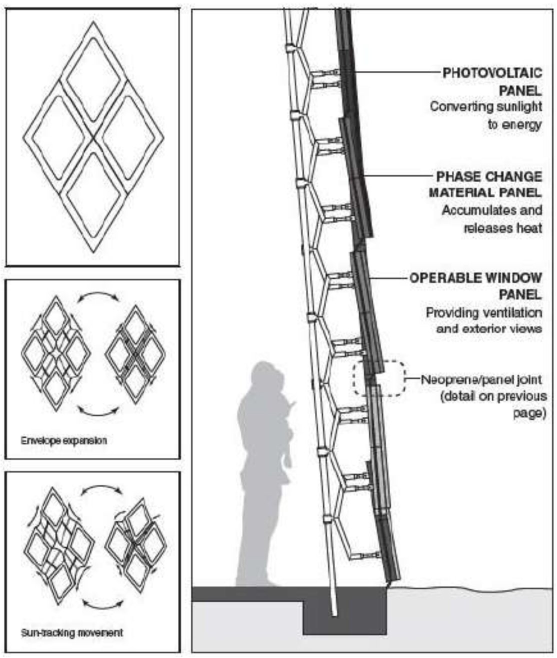


Figure (3-29) Sun-tracking envelope panels
Source: Ilaria Mazzoleni, 2013

28 https://www.media.mit.edu/projects/aguahoja/overview/, accessed April, 2020

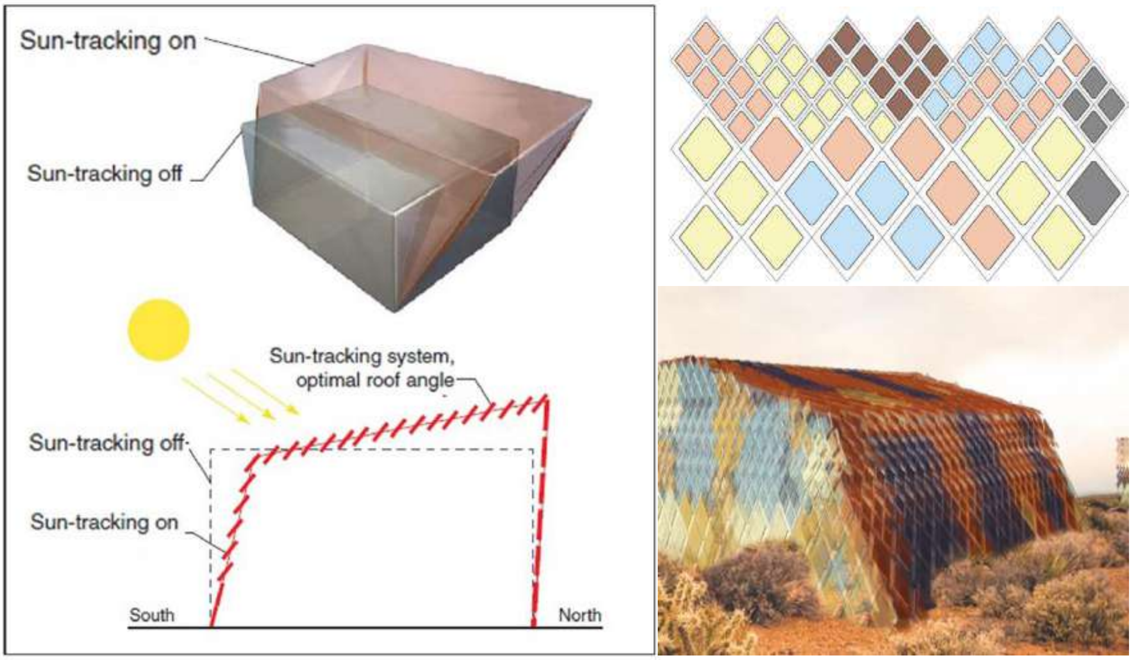


Figure (3-30) The artist studio's envelope panels inspired by lizard skin pattern
Source: Ilaria Mazzoleni, 2013

3.3.3.2 Indoor Air-Quality

The triple meaning of the word "air quality" reveals that the natural ventilation of building scan became an essential architectural design tool that leads to "breathing architecture". The above statement can be grounded on the following:

Figure (3-31) Continuous living wall system pattern
Source: Anastasia, D., 2015

1. Natural ventilation enables fresh air supply into buildings and supports the healthy breathing of the building inhabitants;
2. Natural ventilation also provides oxygen and removes air contaminants; thereby enhancing indoor air quality;
3. Supplying air into the building comprises a process that follows the laws of fluid mechanics

Therefore, the aforementioned architectural design tool is completely aligned with the concept of breathing architecture. This concept could be reached by using several strategies such as living walls and cover the building with plants; Figure (3-31).[29]

29 Anastasia, D., "Breathing architecture: Conceptual architectural design based on the investigation into the natural ventilation of buildings", Elseriver, Greece, 2015

Natural systems pay special attention to ventilation systems (air exchange), which can be found in many living organisms for different tasks. There are different strategies for ventilation and integration patterns in nature. Many living organisms have a mechanism in their body for exchanging air (inhaling and exhaling). There are four main respiratory systems appear in living organisms;

(a) Integument – where the exchange of gas occurs in the water directly through their integument;

(b) Gills – external tissues with many enfolding that increases the surface area for gas exchange. Organisms which live in water have this type of system for gas exchange;

(c) Lungs – the system is located inside the body connected to the outside by a pathway. By moving the muscles of the chest the air is sucked inside through the pathway to fill the lung. The lung has a wide surface area of gas exchange due to its tiny protrusions inside; and

(d) Tracheae – the system is divided into a lot of small tubes connected muscles and organs. This kind of system functions in bodies less than 5 cm in length. Body movements increase the diffusion of gases inside.

There are many projects inspired by Termite mounds as a function similar to human lungs. As air is pushed through the layers, the pipes within the layers become smaller and more numerous, as a filtering medium. An example of this technique is The Eastgate Centre, a large office and shopping centre in Zimbabwe which drives natural ventilation through convection inspired by the termite mounds structure; Figure (3-32).

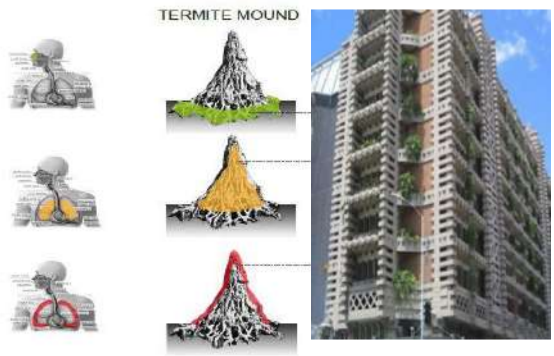


Figure (3-32) The Eastgate Centre
Source: http://blog.corkyspest.com, accessed April, 2020

The first step is searching for the role model which can help to fulfill the architectural target, which in this case the target is Air Quality. The lung is a respiratory system made of various pipes. These pipes are called bronchi through which air passes; the air then passes through various layers of pipes; Figure (3-33).[30]

Figure (3-33) Lungs, accessed June, 2020
Source: https://www.pulmonaryclinicpc.com/services/

30 Ilaria Mazzoleni, 2013, Op.cit.

a- Biological Domain

- **Experimental Phase**

Different types of airflow patterns in animal lungs. Respiration in mammals follows a tidal airflow pattern, in which air moves through a branching network of bronchi. Birds have looping bronchi, where air moves in the same direction during both inspiration and expiration through many of these bronchi. Monitor lizards have a net-unidirectional airflow pattern where air moves forward or backwards over the whole ventilatory cycle in each part of the lung; Figure (3-34).[31]

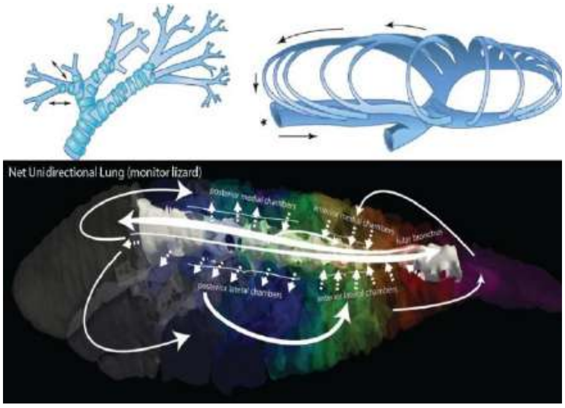


Figure (3-34) Different types of airflow patterns in animal lungs
Source: https://www.eurekalert.org, accessed June, 2020

In human lungs, every lobe is divided into multiple bronchopulmonary segments, each receiving blood from its own artery and air from its own tertiary bronchus. Human bronchi branch into smaller bronchioles, creating subdivisions of the lobes called pulmonary lobules. Each pulmonary lobule has its own large bronchiole with multiple branches. Every lobule is separated from one another by a wall of connective tissue called an interlobular septum.[32]

- **Abstraction Phase**

The lung is a biological organ that acts on the tissue level of complexity. It deals with the air of the environmental factors. It uses physical adaptation to achieve the architectural target of indoor air quality (gas exchange). The performance could be concluded as hierarchies and variety of shapes along with the simulated morphology of tissue; Figure (3-35).

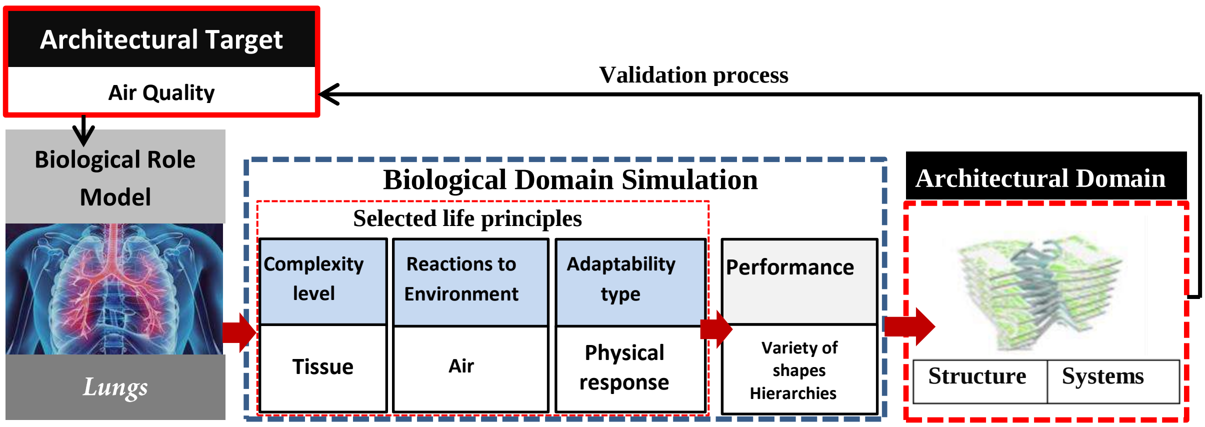


Figure (3-35) Lungs abstracted principles
Source: Author

31 https://www.eurekalert.org/multimedia/pub/219719.php, accessed June, 2020
32 https://ezra.com/lung-function-and-anatomy-the-basics, accessed June, 2020

b- Architectural Domain

- **Prototyping phase**

Edgar Street Towers designed by Iwamoto Scott architecture. It is an incredible spiralling mixed-use high rise. Its programmatic mixture serves the local neighbourhood while enhancing the public realm of lower Manhattan. Furthermore, the programmatic mixture is intended to provide spaces for living, working, art, performance, retail and a branch public library; Figure (3-36).

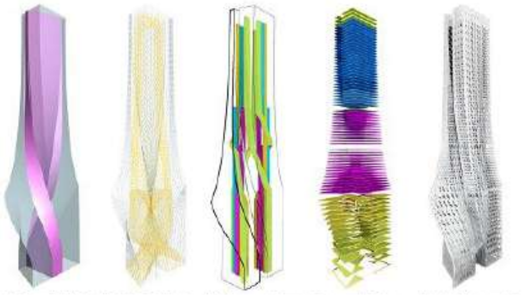


Figure (3-36) The Tower form-finding based on environmental simulation
Source: https://inhabitat.com, accessed June, 2020

The towers central branching atrium represents the main system, in which daylight is collected from above through an integrated light-transmitting fibre-optic array. Moreover, the atrium deploys bio-filtration terrariums that occupy hollow spaces within the floors, thus acting as the building's lungs to provide clean air to its occupants. By night, the light-flow is reversed, where the fibre-optic array is lit by the integrated solar-charged battery packs; Figure (3-37).[33]

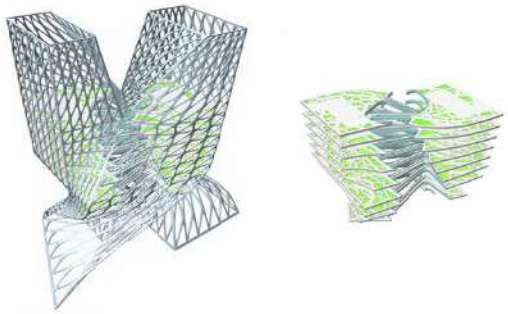


Figure (3-37) The Towers' central branching atrium
Source: https://inhabitat.com, accessed June, 2020

Figure (3-38) Edgar Street Towers Inspired by Lungs
Source: https://inhabitat.com, accessed June, 2020

33 https://inhabitat.com/spiraling-new-york-skyscraper-features-bio-filtration-lungs, accessed June, 2020

3.3.3.3 Indoor Visual Comfort

Controlling light in buildings is often handled by completely distinct systems: clear glass to admit the light, sometimes kinetic elements, such as louvers, to control sunlight and passive elements, such as light shelves, to bounce light deeper into the building. There are multiple strategies in which kinetics are manifest; (folding, expanding, sliding, shrinking and transforming) of the outer envelope to control the light into the building.[34]

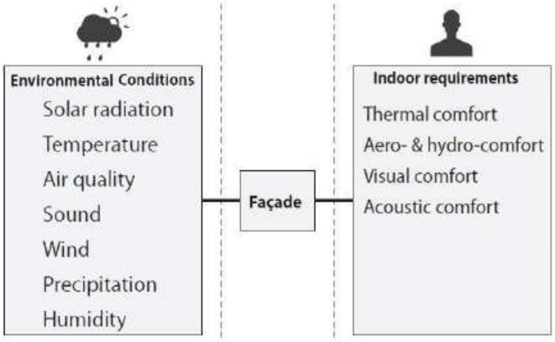


Figure (3-39) Context of environmental conditions and comfort requirements
Source: Jens Boeke, 2019

Eyes are organs of the visual system. There are different types of eye layouts could deal with light in several strategies; Figure (3-40). Indeed, any eye type can be adapted for almost any behaviour or environment. Scientifically proven that, there is a clear relationship between the environmental position and several pupil shapes. Therefore, there are several strategies could be used as a visual comfort strategy inspired by such animal eyes' behaviour as biological organisms have evolved to manage light in various ways such as; gathering light, distributing, focusing, diffusing, reflecting and refracting.[35]

Figure (3-40) The different types of eyes in animal worlds
Source: https://www.zooportraits.com, accessed June, 2020

Biomimicry can offer a plethora of solutions considering light. Bio-inspired façades have the capability to perform interdisciplinary functions including controlling daylight. Façade as a regulator element has the potential to interact morphologically with the environmental factors for controlling solar radiation. For example, "form follow environment", mimicking the extensibility of plant cell walls provides an opportunity to control dynamic daylight by an interactive transformable façade and convertible structure. Henning Larsen's university building

Figure (3-41) The intelligent skin of Henning Larsen's university
Source: https://inhabitat.com, accessed June, 2020

34 Michael Pawlyn, 2016, Op.cit.
35 Martin S., "Why do animal eyes have pupils of different shapes?", Article, Science Advances J., 2015

basically depends on intelligent skin for adaptation of building to climate; it has a facade that moves in response to changing heat and light; Figure (3-41).[36]

The first step is searching for the role model which can help to reach the architectural target. In this case, the target is visual comfort. According to the quantity of the light provided, and its distribution is crucial, the human eye adapts to the prevailing light conditions. Glare can have a negative impact on the user, it occurs as a result of direct radiation originating from the sun or artificial light sources, as well as reflections of light irradiation. Large contrasts in the lighting also lead to possible glare. Low contrasts and low shadows reduce it and promote spatial perception. Visual references to the outside contribute to the well-being of the users; Figure (3-42).[37]

a- Biological Domain

- **Experimental phase**

In visual physiology, the eye retina is known to enjoy the ability of adaptation to light. The eye pupil adopts a photo-pupillary reflex, where it adjusts the diameter of the pupil according to the intensity of light falling on the retinal ganglion cells of the retina in the back of the eye. Such reaction assists in the adaptation of vision to various light levels using the iris muscles; Figure (3-42).[38]

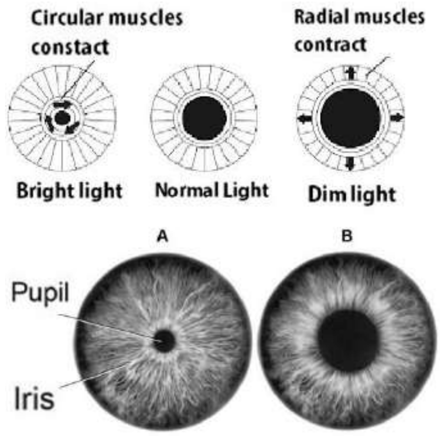


Figure (3-42) The iris muscles' reaction to light
Source: Henryk, k., 2004

- **Abstraction phase**

The eye is an organ that performs on organ level of complexity; it deals with the light of environmental factors, using physical adaptation to achieve the architectural target of visual comfort. The performance could be concluded as shape change along with the simulated morphology of tissue; Figure (3-43).

36 Morteza H.,"A morphological approach for kinetic façade design process to improve visual and thermal comfort", Article, Building and Environment J., 2019
37 Ilaria Mazzoleni, 2013, Op.cit.
38 Henryk, k., "System for measurement of the consensual pupil light reflex", Optical Application j., Poland, 2004

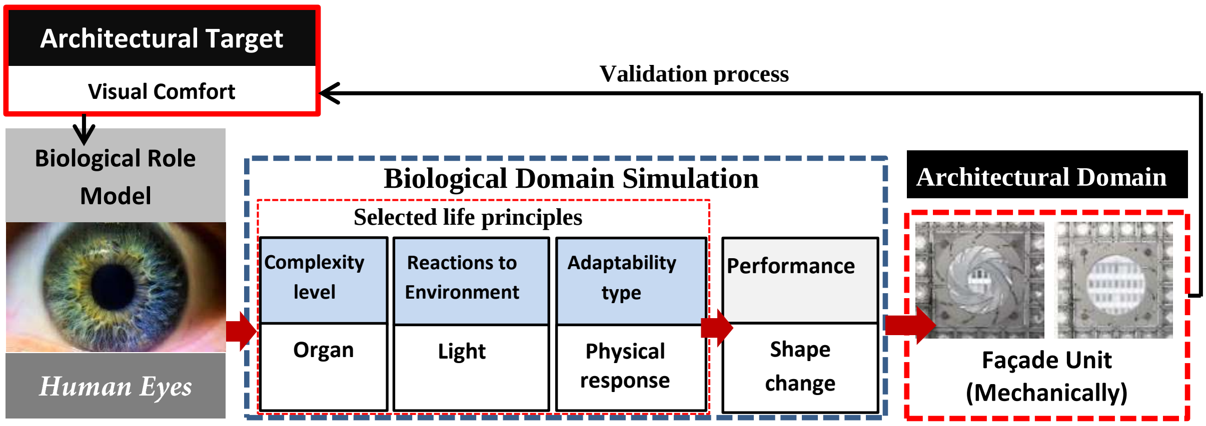


Figure (3-43) Eyes abstracted principles
Source: Author

b- Architectural Domain

- **Prototyping phase**

L'arabe du monde institute building in Paris, Jean Nouvel's work is his attention to façade detailing, and this design is no exception. The main feature and innovative element of the IMA is the advanced responsive metallic brise soleil on the south façade acting like eyes iris; Figure (3-44).

The system incorporates several hundred light sensitive diaphragms that regulate the amount of light that is allowed to enter the building. During the various phases of the lens, a shifting geometric pattern is formed and showcased as both light and void. Squares, circles, and octagonal shapes are produced in a fluid motion as light is modulated in parallel. Interior spaces are dramatically modified, along with the exterior appearance Figure (3-45).[39]

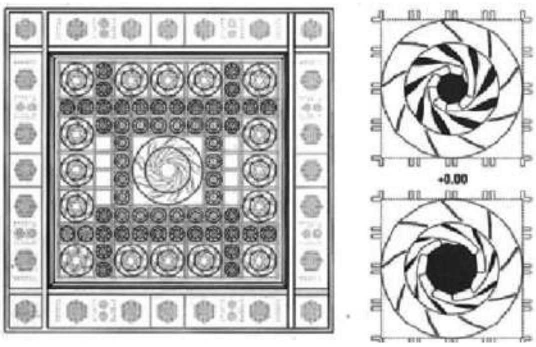


Figure (3-44) The IMA is the advanced responsive element
Source: https://www.archdaily.com, accessed June, 2020

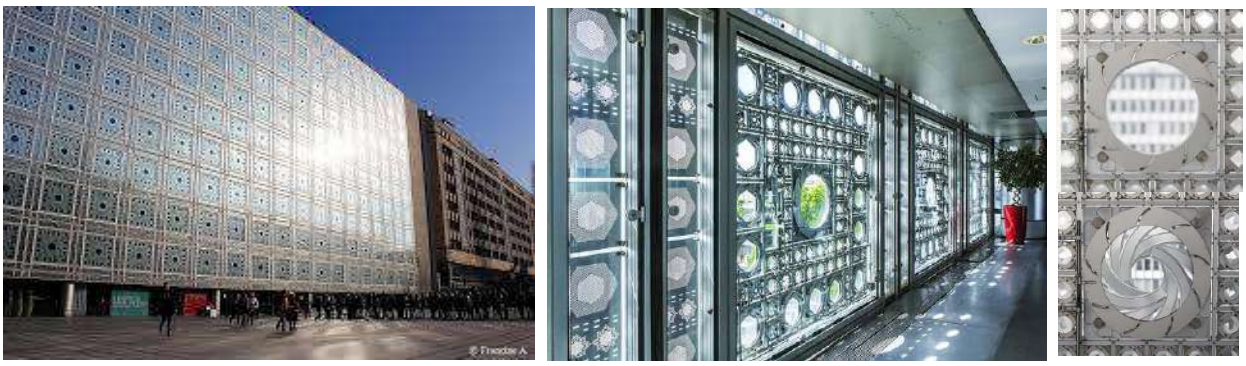


Figure (3-45) L'arab du monde institute adaptive façade
Source: https://www.archdaily.com, accessed June, 2020

39 https://www.archdaily.com/162101/ad-classics-institut-du-monde-arabe-jean-nouvel, accessed June, 2020

3.3.4 Energy Efficiency

Buildings are the front line for demand reduction itself the first step towards a solar economy. For example, building concentrated solar power plants over roughly 5 percent of the world's deserts would be enough to provide all of our energy needs. A solar economy is one that is powered entirely by forms of renewable energy:

- direct solar energy: principally photovoltaic and concentrated solar power
- indirect solar energy: wind, wave and biomass
- related natural-source: tidal and geothermal energy

Solar technologies have benefitted from biomimetic breakthroughs in lenses and geometrically optimised layouts for mirrors based on sunflowers that increase efficiency and reduce land area requirements; Figure (3-46).[40]

Figure (3-46) The Sahara Project Pv, Tunisia
Source: Michael Pawlyn, 2016

As our demand for energy increases, so must the innovative and life-friendly ways we access and use it. Nature efficiently harnesses the sun's energy for its own needs. For instance, Julian Melchiorri has recently claimed to have created a wonderful leaf made from silk. This artificially created leaf can act just like a real naturally created leaf in the presence of proper water and sunlight conditions and produces oxygen from it; Figure (3-47).[41]

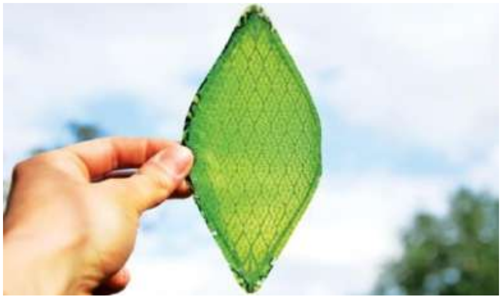


Figure (3-47) Artificial Silk Leaf
Source: https://www.julianmelchiorri.com, accessed Jan, 2020

Applying biomimetic principles to energy planning inevitably leads to the solar economy as a critical goal. This has significant implications for architects and urban designers. A 'solar economy' is one in which all our energy needs are met with renewable forms of generation. This shift is of critical importance. The contrast between human-made systems and biology would suggest four principles for biomimicry solution to energy:

a. Demand reduction through radical increases in efficiency as the first priority
b. A Source of energy that will last indefinitely
c. Resilience through diversity and distributed networks
d. Resource flows that are non-toxic and compatible with a wide range of other systems.

40 Michael Pawlyn, 2016, Op.cit.
41 M. Iman, M. Donn , Z. Balador, "Bio-inspired Materials", Springer Nature, Switzerland , 2019

The first step is searching for the role model which can help to reach the architectural target. In this case, the target is energy efficiency. Algae could efficiently produce energy, they are categorized into two groups; microalgae and macro-algae, they convert carbon dioxide into valuable compounds including biologically active compounds such as biofuels, foods, feed and pharmaceuticals [bioactive-compounds]; Figure (3-48).[42]

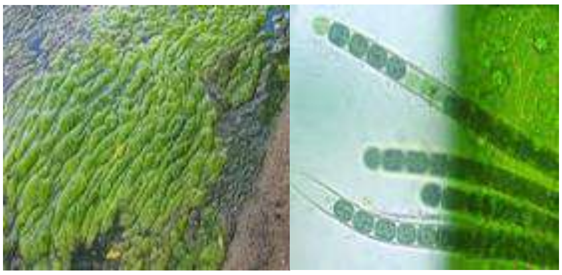


Figure (3-48) Blue Algae
Source: Elmeligy, D. 2019

a- Biological Domain

- **Experimental phase**

The Living Architecture project not just inspired by algae but it uses algae as a bioreactor, it builds an apparatus that structurally integrates biological processes into the built environment, and programs them to perform like nature as shown in Figure (3-49).[43]

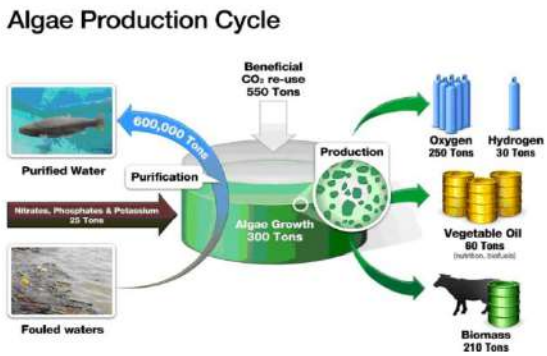


Figure (3-49) Algae production cycle
Source: http://lemarllc.com/Algae.html, accessed Nov, 2020

- **Abstraction phase**

Algae are biological Role models that perform on micro-level of complexity; it deals with air and energy and temperature of environmental factors, using chemical adaptation to achieve the architectural target of Energy efficiency. The performance could be concluded as Development Growth; Figure (3-50).

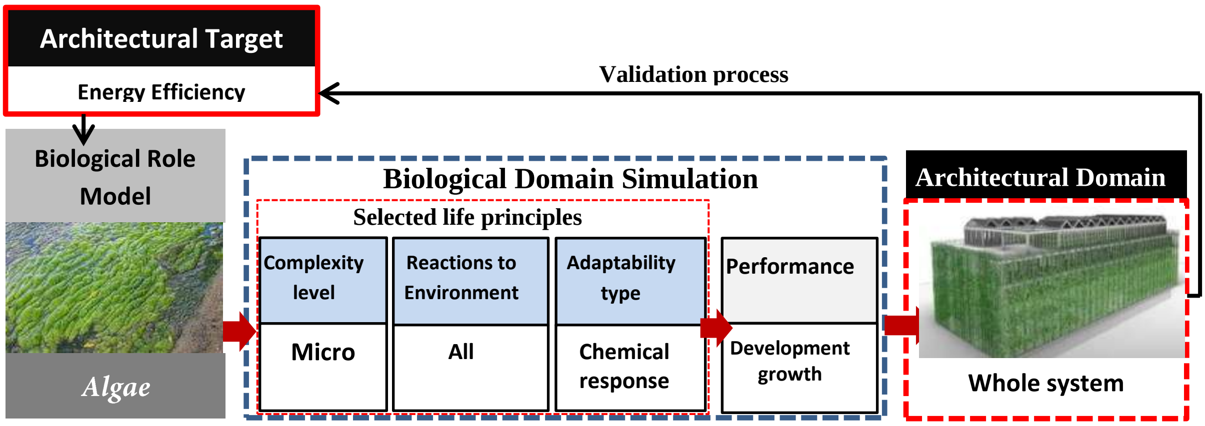


Figure (3-50) Algae abstracted principles
Source: Author

42 Elmeligy, D., "The Bio-adaptive algae contribution for sustainable architecture", BS Cairo, conference paper, 2019
43 Op.cit

b- Architectural Domain

- **Prototyping phase**

Living Architecture is revolutionary because it focuses on combined resource usage in a building, it is not just thinking about energy, but it deals with all these factors, within one combined system. The system is made of a series of interconnected microbial chambers that process waste in different ways, creating a sequence of biochemical events; Figure (3-51).

Figure (3-51) Living Architecture system
Source: LIAR, 2020

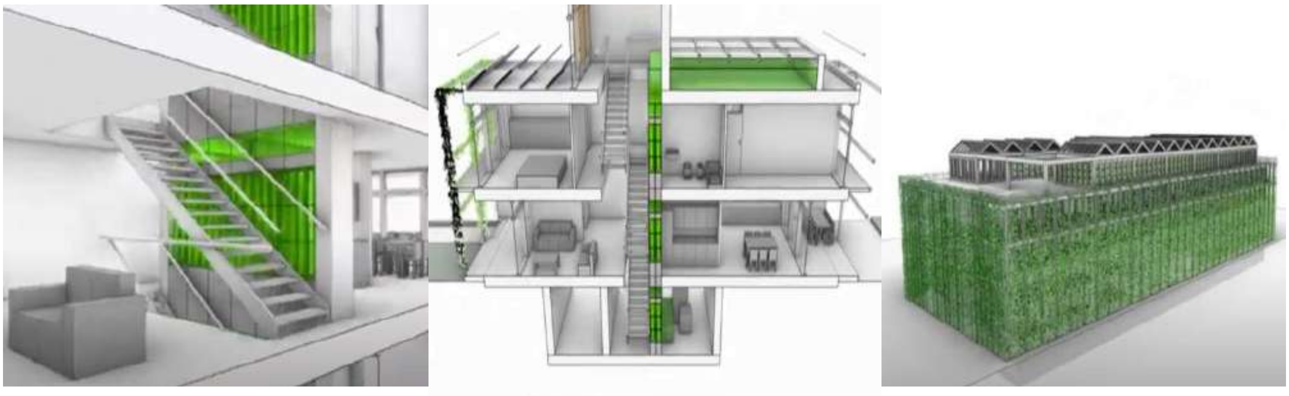


Figure (3-52) Living Architecture integrated system between interior and exterior elements
Source: LIAR, 2020

The efficiency of the conversion of light to biomass is currently 10% and light to heat is 38%. The biomass and heat generated by the façade are transported by a closed-loop system to the building’s energy management centre, where the biomass is harvested through floatation and the heat by a heat exchanger. Because the system is fully integrated with the building services, the excess heat from the photo-bioreactors (PBRs) can be used to help supply hot water or heat the building; Figure (3-52). BIQ - the world's first algae powered building, is considered to be the first building use this system; Figure (3-53).[44]

Figure (3-53) BIQ Building
Source: https://www.archdaily.com, accessed Oct, 2020

44 https://www.media.mit.edu/projects/aguahoja/overview/, accessed April, 2020

3.4.5 Water Quality

All creatures adapted to living in arid conditions have some strategies of reducing water loss. This often involves using the non-living matter to create shade, trapping a layer of air next to the organism's surface to reduce the evaporative gradient or a combination of the two.

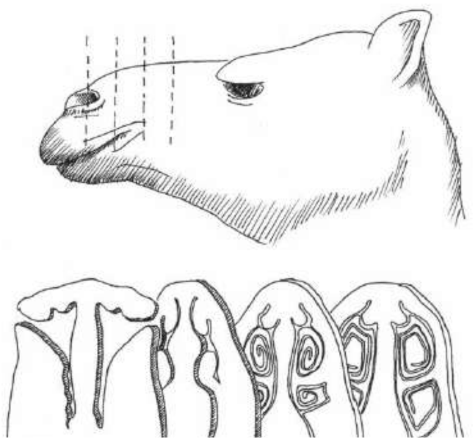


Figure (3-54) Camel's intricate nasal structures
Source: Michael Pawlyn, 2016

Camels have highly intricate nasal structures, known as turbinates, which are made from spongy bone covered with richly vascular tissue. As the camel breathes in, the tissue is cooled by the evaporation of water into the dry air. During exhalation, the humid air from the lungs passes this large area of the cool surface and much of the humidity condenses to allow reabsorption; Figure (3-54).[45]

Many living species thrive in even the driest places, with some surviving on water harvested from the fog. Due to temperatures lower than dew point in the deserts at night, water condensation also occurs from ambient. By studying living species, new materials can be developed to provide a source of freshwater from fog and condensation for communities across the globe as well as in emergency and defense applications. Inspiration can be taken from such to improve the efficiency of desalination and help purify water containing other contaminants.

Figure (3-55) The ice plant
Source: https://asknature.org, accessed June, 2020

The first step is searching for the role model which can help to reach the architectural target. In this case, the target is water efficiency. The ice plant, which is native to southern and eastern Africa, its leaves of ice plants store water in surface bladder-like cells, is named for the small, transparent bladders that cover its leaves and make the plant look like it's covered with frozen dew; Figure (3-55).[46]

45 Michael Pawlyn, 2016, Op.cit.
46 https://asknature.org/strategy/surface-cells-store-water/#jp-carousel-64000, accessed April, 2020

a- Biological Domain

- **Experimental phase**

These bladders are called epidermal bladder cells; they are modified versions of hair-like structures that cover the surfaces of many plants. Epidermal bladder cells act as numerous small reservoirs that are especially helpful during times of drought and high salinity. They retain water and also sequester excess salt to keep it away from tissues that are more sensitive to high salinity; Figure (3-56).[47]

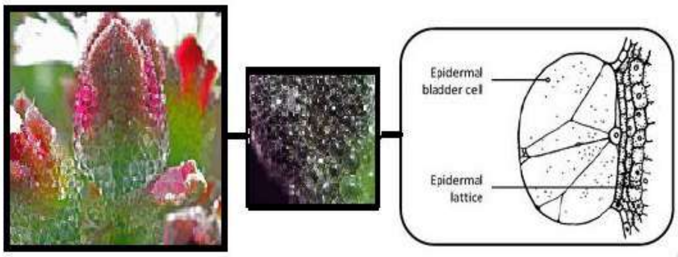


Figure (3-56) The ice plant's bladder cells
Source: Henryk, k., 2004

- **Abstraction phase**

Crystalline ice plant is the selected biological role model. It acts on the cellular level of complexity. It deals with water of environmental factors, using chemical adaptation to achieve the architectural target of water efficiency. The performance could be concluded as communication along the simulated morphology of tissue; Figure (3-57).

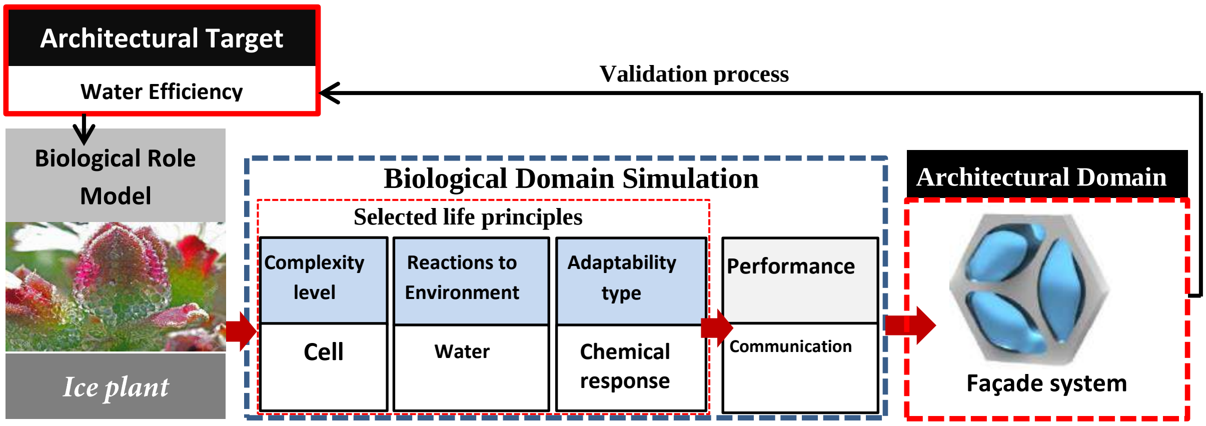


Figure (3-57) Ice plant abstracted principles
Source: Author

b- Architectural Domain

- **Prototyping phase**

The AquaWeb mimics the way that natural systems capture, store and distribute water, not just rainwater, but ambient moisture such as fog. Team NexLoop developed the AquaWeb to help urban local food producers collect, filter, store, and distribute atmospheric moisture with a modular, all-in-one water sourcing and management system. AquaWeb harnesses freely available rain and fog and uses passive strategies to distribute this water so

47 Henryk, k., "System for measurement of the consensual pupil light reflex", Optica Applicata j., Poland, 2004

that urban farms, including greenhouses, indoor vertical farms, and container farms, can save energy and become more resilient to disturbances; Figure (3-58).

Each aspect of AquaWeb's design was inspired by living systems. These include how cribellate orb weaver spider webs collect fog from the air, how drought-tolerant plants like the crystalline ice plant store water, and how mycorrhizal fungi like the Jersey cow mushroom distribute water. The team also looked to the dwarf honey bee's hexagonal nest structure for AquaWeb's efficient and modular design; Figure (3-59).[48]

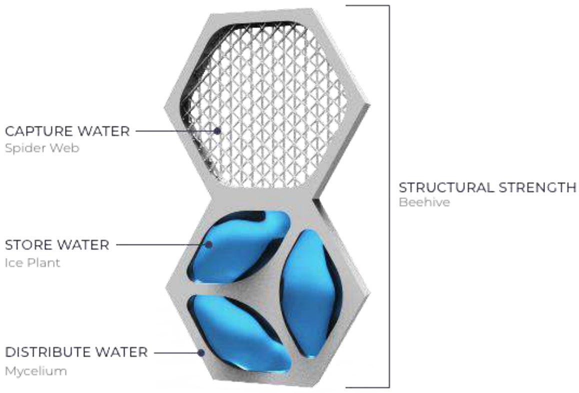


Figure (3-58) NexLoop's Aqua Web unit
Source: https://www.archdaily.com/, Accessed June, 2020

Figure (3-59) NexLoop's Aqua Web Proposals
Source: https://www.archdaily.com/, Accessed June, 2020

48 https://www.archdaily.com/162101/ad-classics-institut-du-monde-arabe-jean-nouvel, accessed April, 2020

Chapter Summary

To maintain sustainability, nature has developed a set of "principles"; complexity, propagation, growth, sensing and reacting, adaptation, metabolism, energy, self-repair, and intelligence. The selected life principles were specifically selected to be adopted for their significance in the building behaviour as; complexity level that in which level the organism behaves, reacting to the environment that dealing with the environmental factors, and the adaptability type that how the organism can adapt to the climate issues and survive.

Within the scope of building behaviour approach, biomimicry offers a wide variety of solutions derived from biological role models by embodying technologies proved to have survived previous problems with a greater economy of means. The chapter adopts the use of problem-based approach methodology, through identifying the architectural targets of building behaviour as problems and then searching the biological systems for solutions.

The architectural targets that have been identified are as follows: Structure Efficiency, Material Efficiency, Indoor Quality, Energy Efficiency and Water Quality. The architectural elements identified in order to achieve architectural goals are as follows: Structure, envelope, building systems, interior elements and materials. Biological Domain was divided into two phases. First, the experimental phase in which the selected biological role model is simulated according to the selected life principles. Second, the abstraction phase in which the specific performance of the biological role model is determined, and then it is implemented in the architectural domain in the prototype phase as an architectural element such as Envelope, Structure, Building systems, Interior elements, Materials.

As the methodology adopted by the chapter transfers biological models principles into the architectural domain. The case studies of transferring the selected life principles discuss strategies beneficial for building behaviour. This chapter aims to illustrate the performance of role models that could be transferred to the architectural domain by the analytical examples through the three mentioned phases; biological domain ‘experimental phase, abstraction phase’, then architectural domain ‘prototype phase’.

Table (3-2) discusses the influence of biomimicry on the building behaviour by identifying the potential bio-strategies for each target, studying the influence of the biomimetic strategy on each target and then discussing a successful example of using the biomimetic approach to achieve the specified architectural target. The results found that in order to guarantee interaction with environmental factors, the performance of shape change was used in different forms in the examples. The elements used to achieve architectural targets varied between systems, envelopes, materials, and structure. The influence of those strategies on the other targets will be discovered in the analytical study.

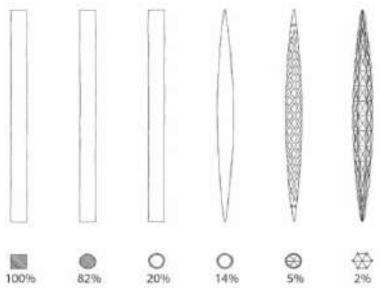
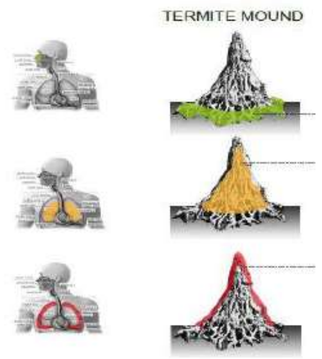
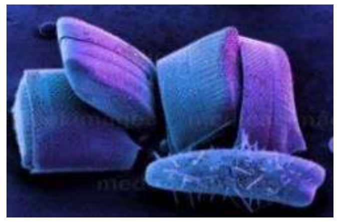
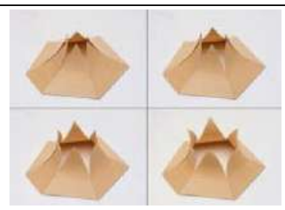
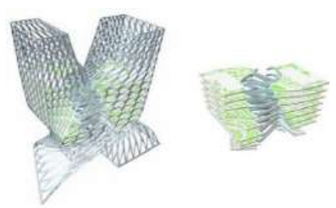
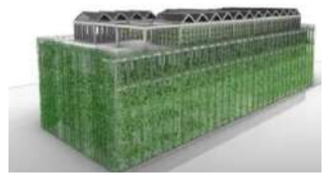
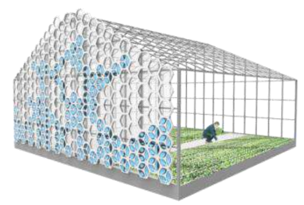
Building Behaviour Targets							
Target	Efficient structure	Material Efficiency	Environmental Quality			Energy Efficiency	Water Quality
			Thermal Comfort	Visual Comfort	Indoor Air Quality		
Bio-inspired strategies	These natural structures classified according to the type of element that they are made of (beam or surface) and whether they occur internally or externally to the shape like (skin) and hybrid elements like spongy. **Natural Structure types:** 1-The pneumatic structures 2-Shells 3-Trees 4-Webs 5-Skeletons	Bio-inspired material types: 1- inspired by structure properties of natural organism (with thermal behaviour-load bearing) 2- inspired by functions of natural organisms (intelligence response-waterproofing) 3- inspired by recycling process in nature (Biocomposite – bioplastic) 4- Inspired by biological processes (growing material-productive material)	Heat regulation strategies: 1- heat gain 2- retention 3- dissipation 4- prevention	Eyes are organs of the visual system. There are different types of eye layouts could deal with light in several strategies such as; - Gathering, - Distributing, - Focusing, - Diffusing, - Reflecting - Refracting.	There are four main respiration systems in nature: - Integument - Gills - Lungs - Tracheae	Four principles for biomimicry solution to energy: - Demand reduction - Source of energy that will last indefinitely - Resilience through diversity - Resource flows that is non-toxic and compatible with a wide range of other systems.	Bio-inspired strategies of reducing water loss: -Non-living matter to create shade -Reduce the evaporative gradient - Reabsorption - water condensation
The Influence of Biomimicry	 Weight savings Efficient structure	 3D printing Several Functional Surfaces	**External (skin)**  **Internal (systems)** - interior pattern - shading device -passive cooling	**External (skin)**  controlling daylight	 Passive natural ventilation	 -Photovoltaic solar energy	 - Improve the efficiency of desalination purify water - Water from fog
Biological Role Models	***Isthmia nervosa***  **Hierarchical structure**	***Conifer Cones***  **Bioreactor Material**	***Lizard skin***  **Variety of shapes**	***Eyes iris***  **Physical response**	***Lungs***  **Hierarchies**	***Algae***  **Chemical Bioreactor**	***Ice plant***  **Chemical Adaptation**
Architectural Elements	 Structure and material	 Material	 Envelope	 Envelope	 System	 System	 Facade System

Table (3-2) The influence of biomimicry on building behaviour targets
Source: Author

CHAPTER 4: Transfer Nature to Architecture (Methods & Tools)

Introduction

This chapter presents the link between biology field and architecture field. It is the stage in which the biological domain is transferred to the architectural domain, including principles of nature and biological performance as mentioned in chapter two. The aim of this transferring is to achieve the architectural targets of the building behaviour as mentioned in chapter three. This chapter deals with an attempt to reach how biological solutions transfer to the architectural domain from just being a text to being a digital model or an architectural element.

This chapter begins with stating the method of defining the organism, spotting it in light of the vast amount of references, the method of learning its capabilities to solve a specific architectural problem, and whether it is possible to combine the building behaviour's targets in the research phase. Therefore, the first part of this chapter will adopt using the proposed problem-based approach methodology for building behaviour, which was attained in the third chapter. Afterwards, it will discuss how to select the biological role model which could achieve the specific target, then obtain the abbreviated biological information, through which the performance can be concluded through the methodology proposed.

After this step, the problem of how to convert that performance from mere written information to the architectural domain appears. Thus, the study will address the knowledge pursuit of ways to transfer that information to the architectural field, through computational tools in the transferring domain. Additionally, examples of transforming the biological performance into digital technology will be technically presented, along with its role in the architectural formulation.

Accordingly, the main purpose of the chapter is to clarify the missing link between the biological domain and the architectural domain; Figure (4-1), focusing on tools and methods used in transferring this biological information to the technological domain, and then to the architectural domain. This will, in turn, help to conclude the design framework for this transferring process.

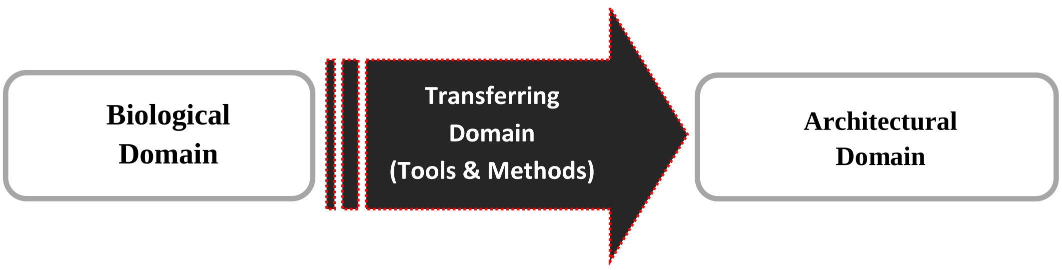


Figure (4-1) Transferring Domain between biological domain and architectural domain
Source: Author

4.1 Extraction of Biological Information for Architecture

Exploring the relevant scientific literature in the biological domain for a specific architectural target is a hard and time-consuming task, which often requires biological domain expertise. This difficulty can lead to barriers in inter-disciplinary fields of study, where an expert in the architectural domain is often a novice in the biological domain. In order to overcome those challenges, various computational tools have been developed. Recent researches in biomimetics have yielded powerful tools that allow designers to access a vast amount of biological design solutions, with no need to spend years developing their background knowledge of biology. These tools are called Computer-Aided Biomimetics (CAB) tools.[1]

4.1.1 Proposed Computer-Aided Biomimetics Support (CAB) Tools

The biologist Julien Vincent proposed the use of TRIZ to facilitate the comprehension of biological systems (Vincent, 2002; 2006; 2009). In general, Vincent works aim to extract trade-off relations that are central to many biological texts and capture information at an abstraction level that is domain-independent. Likewise, in 2004 Lindemann G. provided a structured, associative checklist to support the deduction of technical analogies from biological systems, which is based on TRIZ. Afterwards, Vincent et al. developed BioTRIZ, a reduced form of TRIZ that inventive principles to biological dialectical problems. Those trade-offs along with the abstracted concepts provide an initial filter for information retrieval, and support for the search within the biological domain. A great number of tools have been invented to provide the engineer with biological information.

Consequently, the increasing number of tools lead the architect into an unclear path as it became harder and harder to choose the appropriate; (Lahonde, 2010). In order to address this issue, in 2014, Fayemi et al. managed to sort the different tools and determine to which steps of the global biomimetic process each of them refer. Then, in 2017, Fameyi et al. analysed these tools through inter-disciplinary workshops and suggested the first unified classification for biomimetic design: the BiomimeTree. Additionally, Wanieck et al. presented a classification and analysis of more than 40 tools and categorized them into six kinds: database, taxonomy, thesaurus, ontology, algorithm and method (Wanieck, 2017). This fundamental sorting work underlined the first barrier in biomimetic development.

In 2020 Ruben Kruiper and Julian Vincent present the Focused Open Biology Information Extraction (FOBIE) dataset. FOBIE comprises 1500 manually annotated sentences taken from full-text scientific biology documents. The dataset enables training and evaluation of Relation Extraction (RE) tools that extract trade-offs from scientific biology texts. Architects in this process do not need any help from biologists, and can easily extract solutions from nature along with choosing the optimum one to apply to their design.[2]

1 Kruiper, R., "Computer-Aided Biomimetics", Conference Paper, United Kingdom, 2016

2 Kruiper, R., Vincent, J., "A Scientific Information Extraction Dataset for Nature Inspired Engineering", Conference Paper, LREC 2020, Marseille, 2020

4.1.2 Computer- Aided Biomimetics (CAB) Websites

There are several websites for extracting biological information. The research relied on two types of these websites according to their clarity to the architects. The first website is Engineering-to-BioMimetic Ontology (E2BMO); it provides the user with the opportunity to interface and extract information from both the Engineering-to-Biology Thesaurus and the BioMimetic Ontology in a way that was not possible before. It is established using the Simplified Knowledge Organization System (SKOS) as a communication tool connecting the Engineering-to-Biology (E2B) tool to the BioMimetic Ontology (BMO) tool within Protégé. Protégé is software which provides a graphic user interface to define ontologies using the Web Ontology Language (OWL). It also enables the ontology to be exported into RDF_XML format. RDF or Resource Description Framework is a format used in semantic web applications.

The homepage of the 'E2BMO' website follows a simple layout featuring a search bar and two main access points: (1) using BMO trade-off concepts and (2) using E2B functional words. Through both approaches, the user is free to choose the type of solution discovery approach they wish to pursue, then select the biological role model; Figure (4-2).[3]

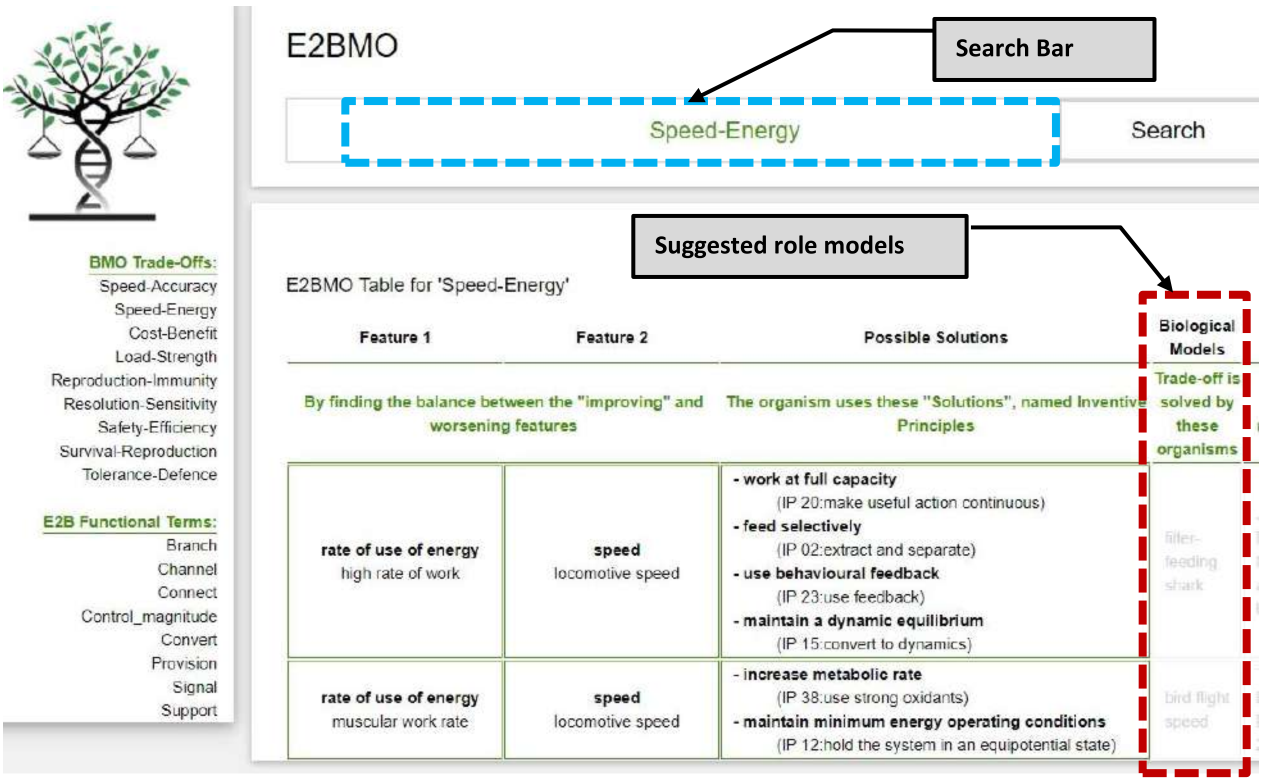


Figure (4-2) E2BMO website query result for BMO Trade-Off (Speed–Energy)
Source: https://www.uakron.edu/bric/E2BMO/index.html, accessed Aug, 2020

3 Sarah J. , Banafsheh K.," E2BMO: Facilitating User Interaction with a BioMimetic Ontology via Semantic Translation and Interface Design", MDPI journal, 2018

The second website is AskNature, it is the proposed tool in this research, which fits perfectly with the proposed problem-based approach to searching for the biological role model that can achieve the building behaviour target. It is an open-access database created by the Biomimicry 3.8 Institute (Biomimicry Institute, 2002). It lists biological organisms, strategies, functions and more general characteristics. In 2017, the database was composed of 1,671 biological strategies and 201 ideas inspired by biological phenomena. Those data are then made easily available through an intuitive search engine.

AskNature website is considered to be rich and precise as engineers did not report particular difficulties using it. Engineers might consider biological phenomena as a source of inspiration to be used during creativity steps. This website is used in searching for how nature can solve our building problems. A large database of biological models as solutions for the specific problem will be given by the website. This database allows the designer to easily choose the role model, and combine solutions and ideas. Additionally, the site presents the recent inventions and bio-inspired buildings, which simulates the same area of research. By reaching for how does nature achieve thermoregulation on Asknature website; Figure (4-3). The results show the biological models that could solve in different strategies, supported by a deep explanation for the strategy used to reach their thermoregulation. Furthermore, the site presented the implemented bio-inspired buildings and innovations which achieved thermoregulation.

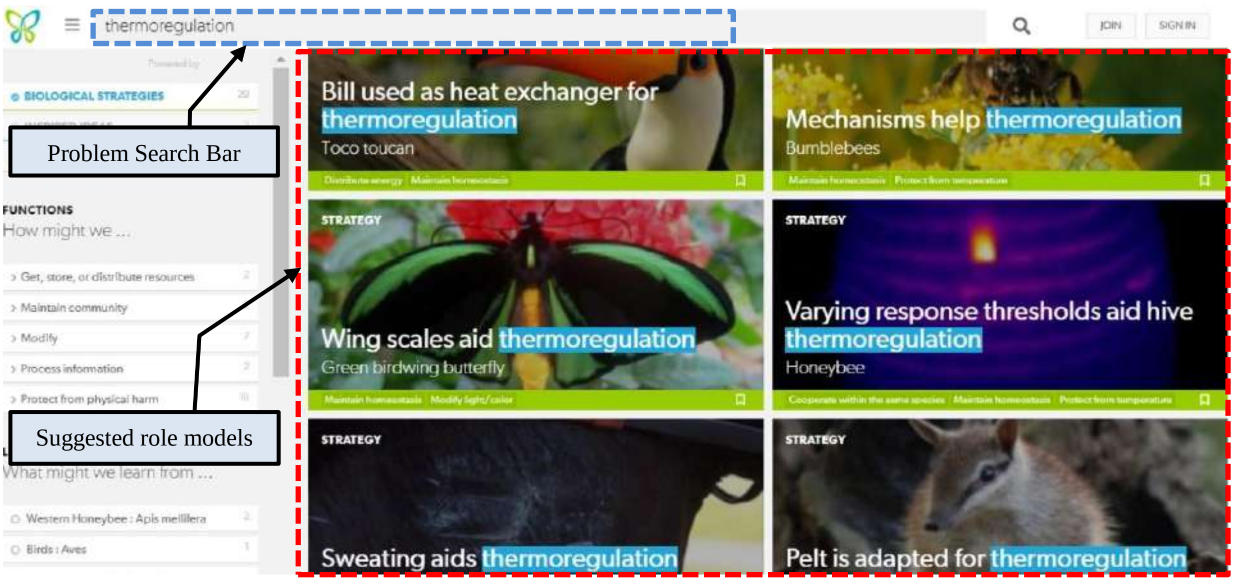


Figure (4-3) AskNature website search results for Thermoregulation as a problem
Source: https://asknature.org/, accessed Aug, 2020

After this step, the desired biological information has been obtained in the form of a text. From here begins the problem of how to convert these ideas into an architectural product, from mere words to the technological field, and not just a morphological simulation. This chapter undertakes to search for ways used in transferring the biological information into the technological domain, then to the architectural domain.

4.2 Encoding Nature Levels for Architecture

The biomimetic approach in architecture raises the question of how to transfer nature to architecture, how nature should be computerized to effectively support the process of transferring biological behaviour into architectural elements. Nature is computerized in architecture at three levels according to Toni kotnic classification; the representational level, the parametric level and the generative level.[4]

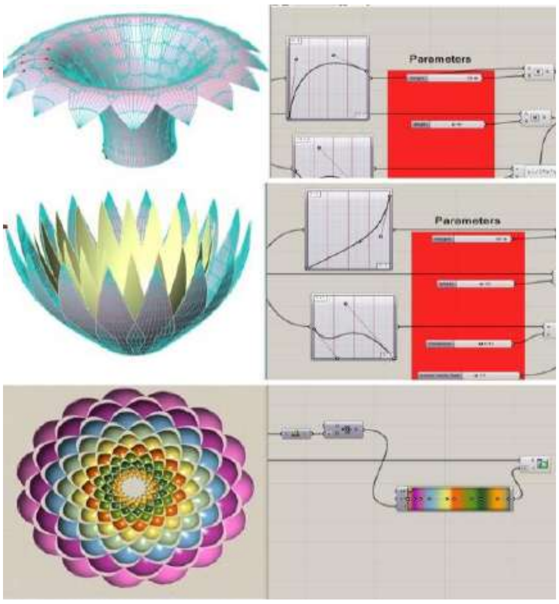


Figure (4-4) Modeling Flowers by Rhino Grasshopper software
Source: Author

4.2.1 The Representational Level

The representational level is to use the computational design in transferring nature's morphogenesis. Therefore, computer-aided design tools (CAD) helped to transfer non-linear and complex geometries existing within nature to architecture. Non-standard computational tools were introduced, as well as programming languages used for effectively applying morphogenetic operations and implementing morphological simulations.

Without these computational tools, it could be impossible to simulate such complex models. For instance, simulating flowers using Rhino Grasshopper software depends on mathematical simulations of the flowers morphogenesis; Figure (4-4). Likewise, a well-known example is the cellular automata, which was invented by von Neumann and Ulam in the 1950s. Their early applications included a biologically inspired model of self-replication. The first simulations of growing branching L-systems structures by Linden Mayer in 1968 were inspired by cellular automata. For modeling this self-replication, it was necessary to use a programming language. Figure (4-5) shows modeling the first five developmental stages of a simple branching structure using the L-system.[5]

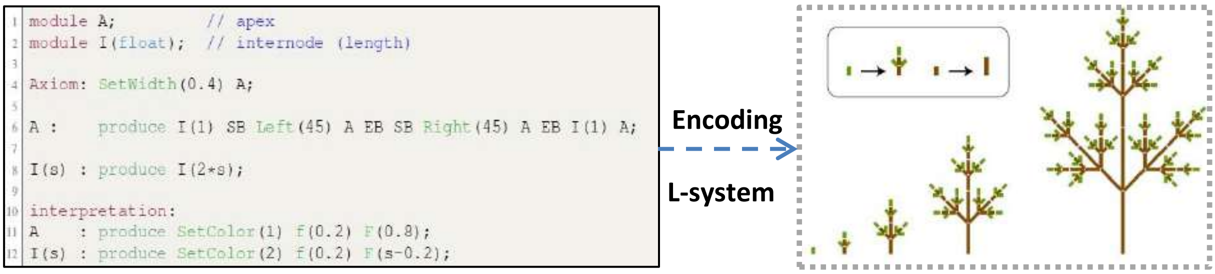


Figure (4-5) L-system constructed by C/C++ programming languages
Source: Mikolaj Cieslak, 2018

4 Kotnic T, "Digital Architectural Design as Exploration of Computable Functions", International Journal of Architectural Computing , 2007
5 Przemyslaw,P., Cieslak,M., Ferraro,P., “Mathematical Modelling in Plant Biology”, book ,Springer, 2018

4.2.2 The Parametric Level

The parametric level is one of the well-known tools for mimicking nature in architecture. The parametric design imitates natural geometries using mathematical calculations, depending on parameters given by the designer using a visual programming language such as Grasshopper engine on Rhino 3d software. For example, in 2019, Heteroptera plug-in released by Amin Bahrami, it is considered as a pre-programmed tool for mimicking agent-based behaviour. Figure (4-6) shows applying the agent-based behaviour on tower structure using Heteroptera plug-in.

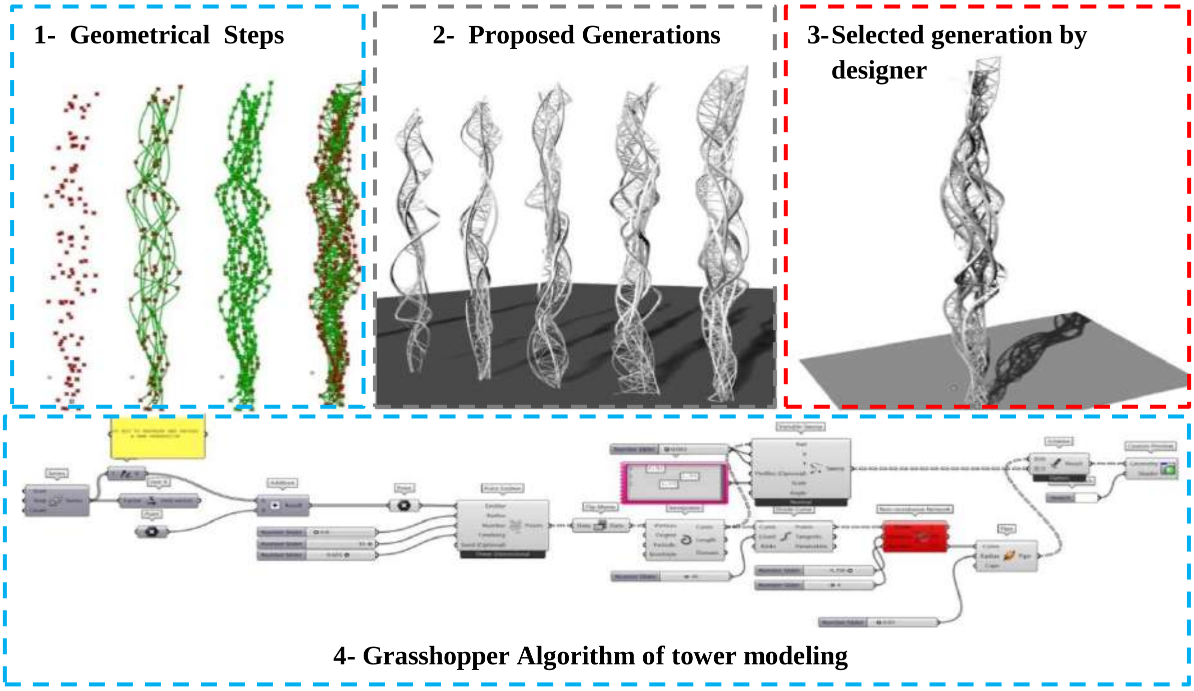


Figure (4-6) Modeling parametric tower by Rhino Grasshopper software and its HETEROPTERA plug-in
Source: Author

4.2.3 The generative Level

The generative design: its processes are well suited to the simulated behaviour and complex consequences of contemporary architectural language. Additionally, it can efficiently respond to the numerous needs targeting today's building behaviour like: structure efficiency, materialization, indoor quality, and environmental protection. In the generative level, it is necessary to know how to write algorithms that translate abstracted biological information into a language compatible with machines to perform complex calculations. Consequently, the study will focus on the generative level of encoding nature in architecture to achieve building behaviour targets.

There is no such software that can translate biological principles in the form of written text to a workable algorithm used in the design process, at least not these days, understanding the written text is an extremely hard thing to do for a computer. NLP (natural language processing) and other algorithms are progressing; however, there is a long way to go.

In order to transfer and map some principles across multi-disciplines, like from biology to architecture, information is required to be at the level of abstraction during the intermediary stage, so-called computation. Furthermore, if there is biological information selected to be transferred, the first step is to dissect it and fully understand its selected life principles. By understanding the core principles of a biological process, then it could be mapped to an algorithm and complexity can be built.

4.3 Programming Language for Encoding Nature

Algorithms are needed to encode nature, since creating architectures through algorithms is a pathway that offers immense potential. Computational design goes beyond aided design, which is traditional CAD, allowing you to articulate and control biological strategies and simulate complex behaviour. This section deals with the types of programming languages that can be used architecturally, which are two types, the first is a visual programming and the second is textual programming.

4.3.1 Visual Scripting Languages [6]

Scripting is the most recent AI tool used in architectural design. Coding helps you explore new architectural strategies and investigating how architecture can evolve and adapt to the ever-changing. There are many points of entry to start learning coding concepts and engage with the community. The wide-spread adoption of graphical programming tools, such as Dynamo works with Revit software and Grasshopper is compatible with Rhino 3D software. Additionally, it is providing a great point of entry into the world of coding for the visually-minded. As follows is a list of coding software for architects.

- **Grasshopper 3D**

Grasshopper is a visual programming language that is primarily used to build generative algorithms. It was developed by David Rutten at Robert McNeel & Associates to create 3D geometry, by dragging components onto a canvas. The outputs of these components are then connected to the inputs of subsequent components. Advanced uses of Grasshopper include parametric modeling for structural engineering, parametric modeling for architecture and fabrication, computational Japanese garden design, lighting performance analysis for eco-friendly architecture, and building energy consumption.

- **Dynamo**

Dynamo is a visual programming extension for Revit that allows you to manipulate data, sculpt geometry, explore design options, automate processes, and create links between multiple applications. Dynamo running in Revit is Sandbox, with access to the Revit model uses Revit’s authorization for cloud services. Dynamo is a tool that aims to be accessible to

6 https://www.arch2o.com/5-reasons-architects-learn-to-code/, accessed Aug, 2020

both non-programmers and programmers alike. It gives users the ability to visually script behaviour, define custom pieces of logic, and script using various textual programming languages.

4.3.2 Textual Scripting Languages

There are three levels for using textual scripting languages for encoding nature in architecture. The first is the representational level that represents complex bio-inspired forms, the second is using the script component as a parameter in a parametric design; the third is using scripting to create generative algorithms that enable coding a plug-in on software which could transfer the biological behaviour simulation into computational software.

- **Python**

Python is one of the most popular programming languages; it can be used to create scripts for parametric algorithms and other forms of complex geometry. There are a lot of resources available for anybody to get started. It is relatively easy to comprehend and can be used alongside various design software like Rhino, Grasshopper, and even Autodesk’s Dynamo.

- **VB.NET [Visual Basic .NET]**

Visual Basic is a programming language that can be leveraged to create various automation routine algorithms in AutoCAD or Revit. One can bundle a defined set of functions onto Revit by writing macros using VB. Besides, it is user-friendly; also, VB can be used to bind automation algorithms for Microsoft Office applications.

- **C#, C++**

C/C++ can be used to code a design tool from scratch. It is a bit complicated to learn. It is built on top of Microsoft’s .NET framework, just like VB.Net, and hence, shares a lot of similarities. It can also be used to compile macros in Revit and Rhino.[7]

4.4 Computational design in Biomimetic Architecture approach

The problem-based methodology for building behaviour deducted in the previous chapters will be adopted in this study. The transferring domain was added to clarify the methodology at technical level. This methodology consists of three parts. The first is the biological domain that starts with determining the selected organism that will achieve the target, then obtaining the abstracted information of that organism. Afterwards, the second part is the transferring domain. It is the transformation of biological information from mere text into a language compatible with the technological tools. The third part is the architectural

7 Op.cit.

domain, where information that has already been transferred from text to behaviour-based algorithms could be used architecturally. These algorithms are involved in computational design processes such as behavioural simulation, form-finding, environmental simulations, optimization, and fabrication. In the validation processes, an environmental simulation and optimization can be used to ensure that the simulation of biological behaviour has played its role in achieving the pre-set architectural target; Figure (4-7). Thus, the computational design tools have a great role as transferring tools in the biomimetic approach.

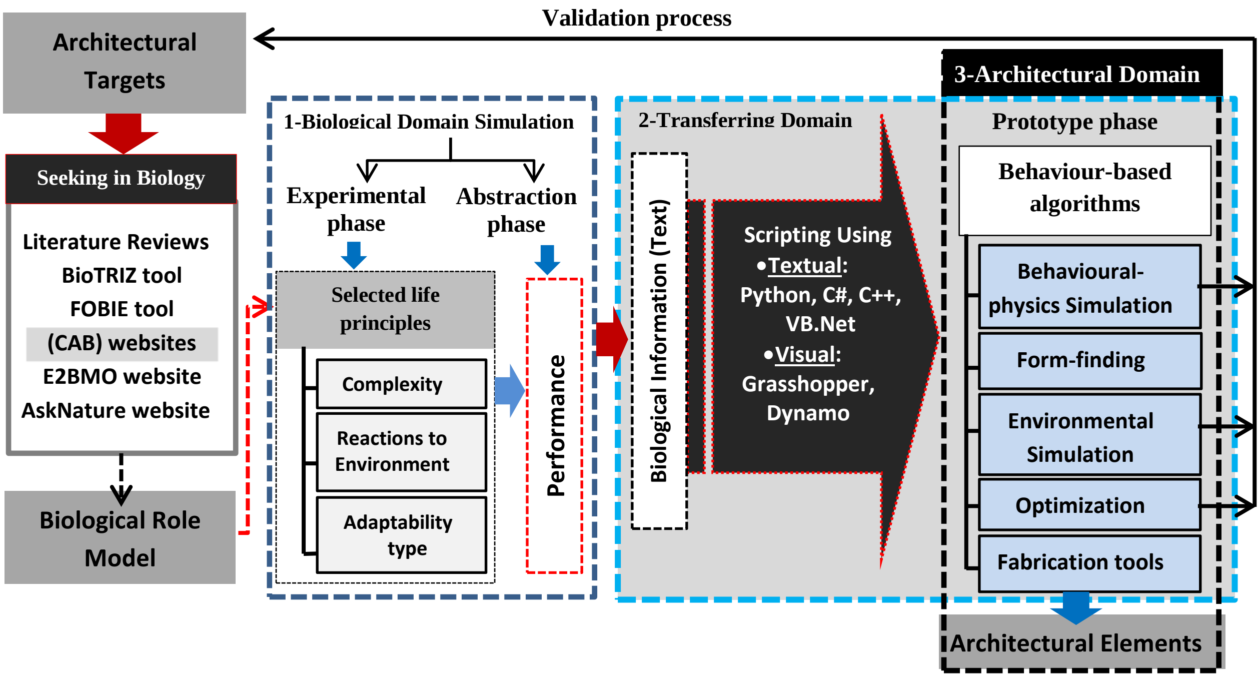


Figure (4-7) The Biomimetic Design for Building Behaviour Methodology
Source: Author

4.5 Case studies: Machine Learning and Deep Learning Algorithms in Architecture

In this part of the chapter, meaningful case studies will be presented for biological behaviour application in generative computational tools, as an attempt to understand and systematize the logic for biomimetic architecture approach by computational design. Efficient structure, thermal comfort, fabrication and materialization, were the areas chosen to reflect the specific application in biomimetic approach. Therefore, the role-models focus on behaviour simulation and structural simulations rather than on geometries. Thus, the sample of natural role models to be investigated is chosen according to the following:

- Availability of reliable mimicry in computational tools
- Exclusion of biochemistry and experimentation processes
- Expected innovative potential for spatial and architectural applications

The case studies will focus on the transferring tools for the biological information into architectural elements supported by an application on the behaviour-based algorithms achieved from this transformation. The computational processes of the case studies will be described in three steps as follows:

a- Simulation Parameters: it describes the effective variables in the computational process of the evolutionary algorithms.
b- Design Experiments: It addresses the design attempts of using the behaviour-based algorithms.
c- Encoding Workflow: It is an analytical diagram that represents a summary of the steps behind the generation of biological behaviour for each case.

4.5.1 Case study 1: Efficient Structure by AMEBA Structural Optimization

Ameba is a type of single-celled organism which is capable of changing its shape in different environments. Based on the Bi-directional Evolutionary Structural Optimization (BESO) technique, originally proposed by Professor Yi-Min (Mike) Xie, in 2019, his team at XIE Technologies has developed a topology optimization software tool called Ameba Written by C# programming language. According to their design requirements, users can apply different loading and boundary conditions to the initial design domain.

During the computational process performed by this software tool, the design domain can evolve, in a way similar to an ameba, into various shapes, and eventually reach a structurally efficient form. These evolutionary algorithms simulate the structure efficiency process of ameba behaviour. This tool has been widely used in architectural design and industrial engineering to generate physical structures that have specific properties.

In this experiment, a simple application of beam structure is presented to show how to choose the optimal shape of the beam based on topology optimization using Ameba plug-in on Rhino 3D and Grasshopper software. The main goal of this optimization is to produce lighter weight and higher structure efficiency. According to the following variables; Table (4-1): The largest load on the beam achieve more efficiency with less use of materials to, and the results are generations set of structural optimization of beam topology.

a. Simulation parameters

The **first step** is to define the parameters affecting the calculations of the optimization algorithm that achieves the required goals. The following table provides a short description of these variables; Table (4-1).

Parameter	Short description
Load 3D	Define a general load in 3D problem.
Support 3D	Define a support in the three-dimensional analysis
Opt Parameters	Define some parameters of the Optimize parameter settings. BESO algorithm. S: Sensitivity, vf: Constrained volume fraction, ert: Evolution rate, and rmin: the minimum center
Material	Define the material. In this case, the selected material is steel.

Table (4-1) Optimization parameters for AMEBA tool
Source: Author

Afterwards, the **second step** deals with the mathematical calculations of the optimization, based on loads, support values, locations, given by the designer, along with identifying the material type used. Those mathematical calculations on the initial geometry yield many generations from which it is possible to choose the optimal result suggested in the third step; Figure (4-8).

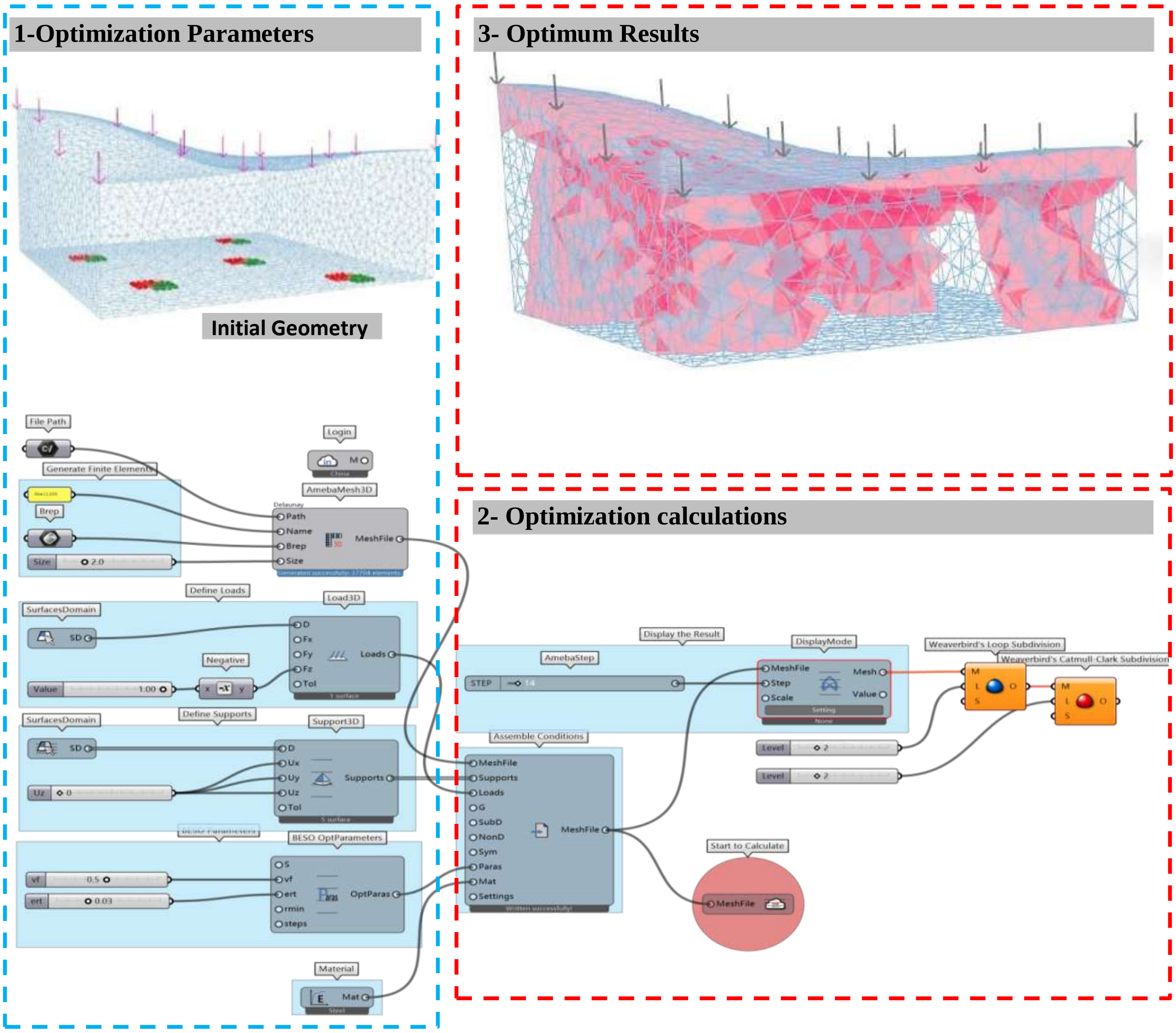


Figure (4-8) Grasshopper algorithms for AMEBA Optimization process
Source: Author

b. Design Experiments

Upon completing the calculation by the server, many files will be received (topology optimized result) numbers of alterations from the server. The analytical Graph is given by the engine; Figure (4-9), illustrates the ratio between the volume fraction, total energy and iteration number. The Volume fraction will be reduced to the appointed value according to Optimization parameters component. Total energy means the gross strain energy. Both of them score the same value in the iteration number 15. The calculated results of the optimization will be shown in the steps of generations. The selection of the optimum result will be based on this analytical graph; Figure (4-10).

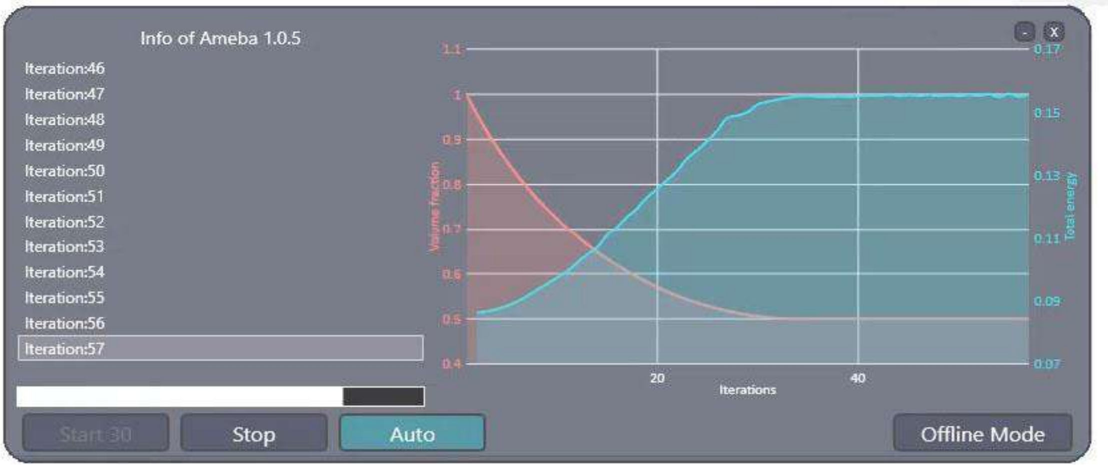


Figure (4-9) Analytical monitor graph for beam optimization results by AMEBA
Source: Author

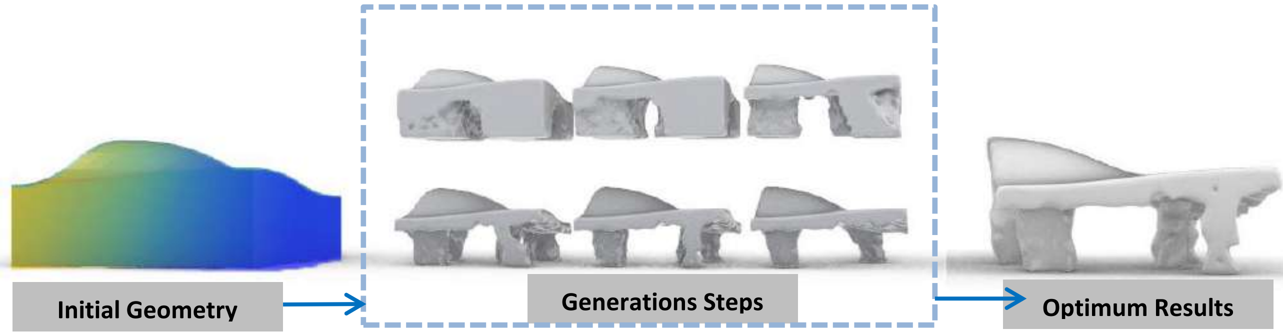


Figure (4-10) Optimization process steps
Source: Author

AMEBA software tool was DigitalFUTURES Coding Award winner Ameba, a topology optimization tool in 2020. This award is given to any digital tool that revolutionizes architectural research, practice or education by offering advanced thinking paradigm and working flow. Bio-Form workshop presented by AMEBA team Generating Biomimetic Architectural Form Based on Topological Optimization and students were required to complete a series of optimized hierarchical structure prototypes through using BESO method, application of Ameba and advanced digital modeling techniques.

The workshop outcomes; Figure (4-11), were presented by students through the workshop simulating the structural optimization on different project, for example, the Eiffel tower project abstracted and supported by AMEBA analysis and the final outcome was the optimal solution.[8]

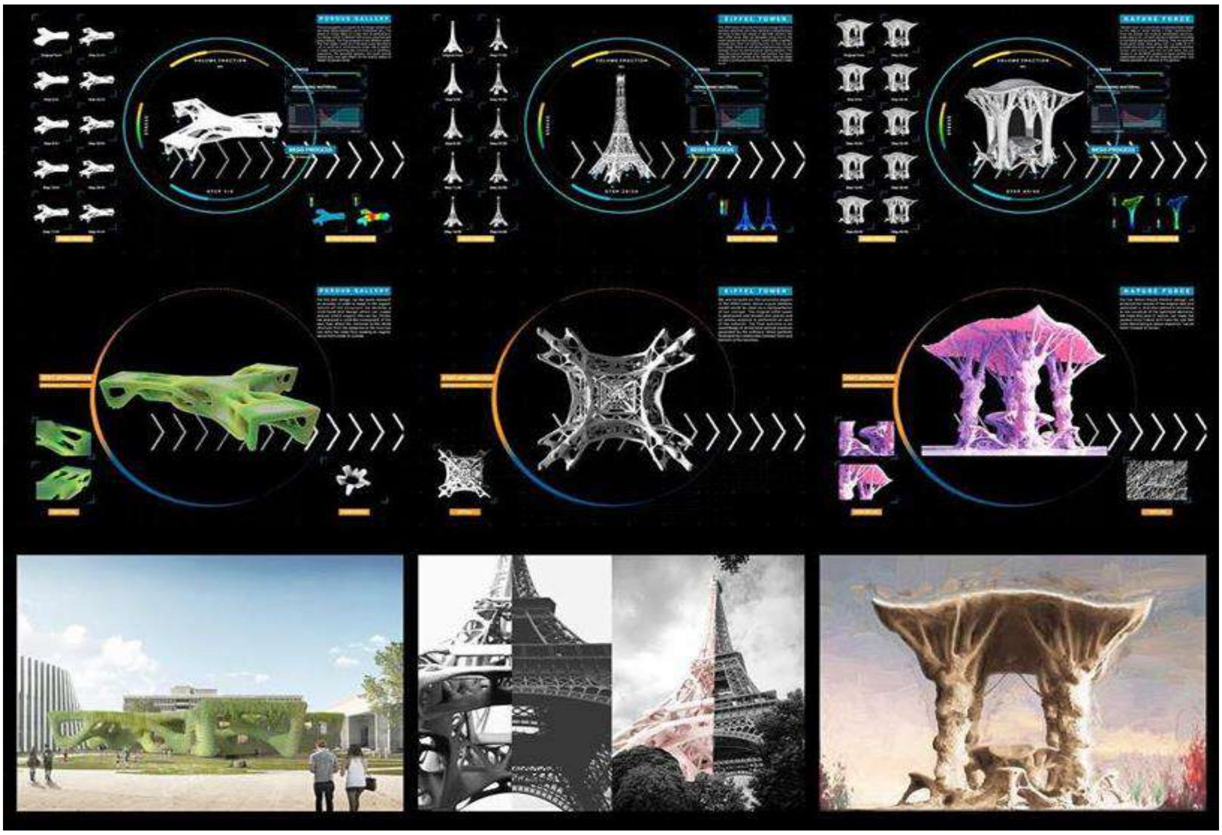


Figure (4-11) Optimized hierarchical structure prototypes using AMEBA software
Source: DigitalFUTURES, 2020

c. Ameba Encoding Workflow

According to the proposed methodology, in order to achieve the structure efficiency architectural target, the Ameba was encoded throughout a four steps workflow. The first step is to seek in the biological domain for a role model. In this case, Ameba was determined to be the biological role model. The second step is the biological domain simulation in which the biological role model is analyzed through the selected life principles to achieve the abstracted information of Ameba.

The abstracted information stated that Ameba is a single cellular organism that works at the cellular level of complexity. The environmental factor challenging the amoeba is the energy factor, which it overcomes by physical adaptation. The performance shown by the Ameba is shape change. In the third step, biological information concluded from the second step is transferred to the computational domain, using scripting. AMEBA plug-in was written

8 https://www.digitalfutures.world/, accessed Aug, 2020

using C# programming language. In the fourth step, a prototype was made in the architectural domain. A simple application of beam structure optimization was made by the author using Rhino 3d, Grasshopper visual scripting and Ameba plug-in software tools, in order to verify the ability of the Ameba plug-in's behaviour -based algorithms to fulfill the architectural target; Figure (4-12).

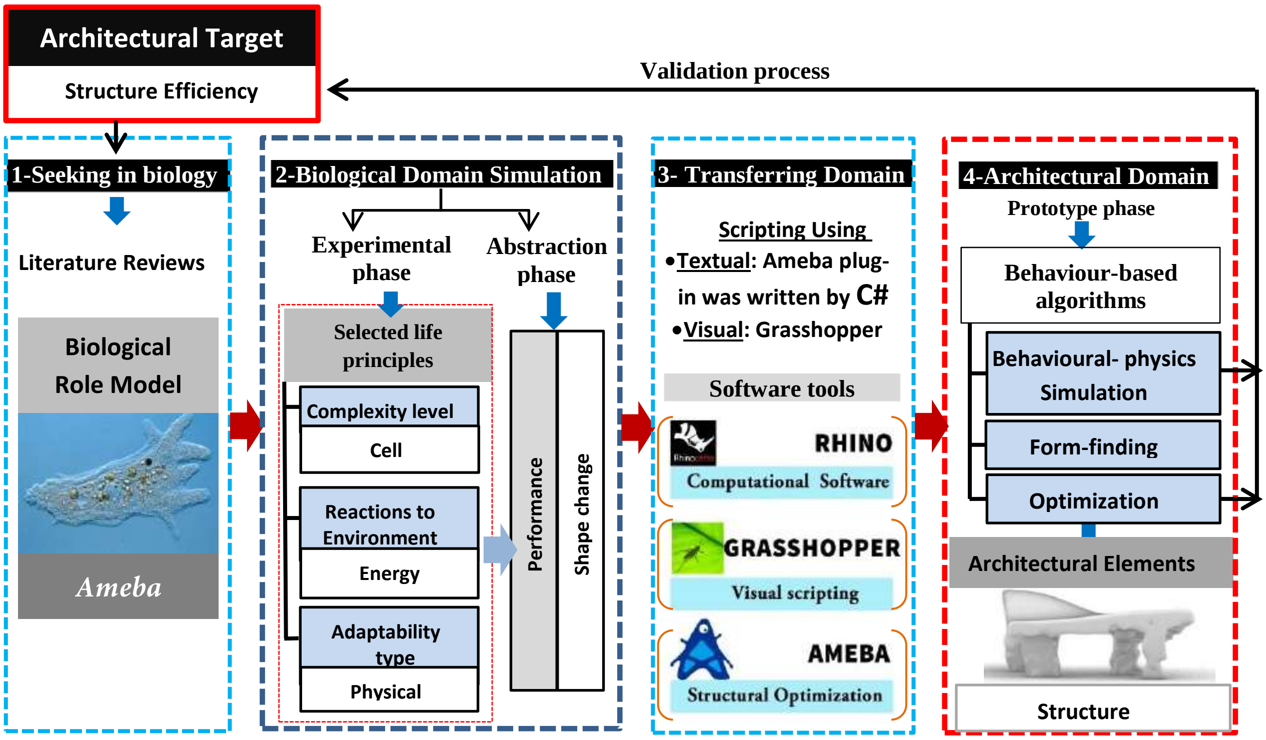


Figure (4-12) Ameba Encoding workflow Diagram
Source: Author

The results suggested an optimized structure based on mathematical calculations made using the parameters given. The parameters were the initial geometry of the beam, the maximum loads, support surfaces, and the materials used in the beam. In the validation process, the analytical graph is obtained from the engine, providing analysis for the generation through which the optimum result that will achieve the structure efficiency can be decided. Results also included fulfilling sub-objectives, such as behaviour physics and form-finding were achieved during the optimization process.

4.5.2 Case study 2: Thermal Comfort by WALLACEI multi-objective optimization

In biology, the phenomenon of evolution is the change in the characteristics of a species over several generations and depends on the process of natural selection. Evolution depends on the presence of genetic variation. In a community, it affects the physical properties (phenotype) of an organism. Individuals of a species exhibit a variation in physical properties. This difference is due to differences in their genes. Organisms with characteristics best suited to their environment survive, find food, avoid predators and fight disease. These individuals are more likely to reproduce and pass on their genes to their children.[9]

WALLACEI software tool is an evolutionary multi-objective optimization engine, which is based on the phenomenon of evolution written by C# in 2018. It was named after Alfred Russell Wallace, who was, among many other titles, a geographer, a naturalist, and an explorer, who independently proposed the theory of evolution by natural selection at the same time as Charles Darwin. WALLACEI is founded on the research conducted by Mohammed Makki during his doctoral studies at the Architectural Association under the directorship of Dr. Michael Weinstock; and has been developed by Mohammed Makki, Milad Showkatbakhsh and Yutao Song.[10]

The following experiment is a simple application on WALLACEI plug-in, and an attempt to understand and systematize the logic of WALLACEI and its optimization process parameters. This was done by defining a structured network in a bounding box, selecting three important locations in box's edges, and then trying to find how these important locations could be connected one by each other. This optimization resulted in the shortest walk for these locations according to the following variables; Table (4-2), the initial geometry, gene-pool, the minimum length between the three locations will be the objective, the phenotype is physical geometries which will be influenced by the optimization.

a. Simulation parameters

The **first step** is to design the problem that needs to find the optimum solutions by calculating the optimization algorithm that achieves the required goals. The following table provides a short description of these input parameters; Table (4-2):

Parameter	Short description
Genes	Genes are comprised from sliders or gene-pools.
Objectives	Fitness Objectives are values contained within a 'number' component. In this case, the minimum length between the three locations will be the objective.
Data	Any data type to be saved for every solution in the population
Phenotype	Define the geometries will be influenced by the optimization then will be exported by the solver

Table (4-2) Optimization parameters for WALLACEI engine
Source: Author

Afterwards, the **second step**, it deals with the mathematical calculations of the optimization, based on the parameters given by the designer, which includes the network, geometries, the three important locations, and the identifying the minimum length. After doing those calculations on the initial geometry, the engine gives many generations supported by analytical simulation. This analytical information helps to select the fitness result in the **third step**; Figure (4-13).

9 Anatoly L.," The Beauty and Fascination of Science", springer, Russia, 2020
10 https://www.wallacei.com/about, accessed Aug, 2020

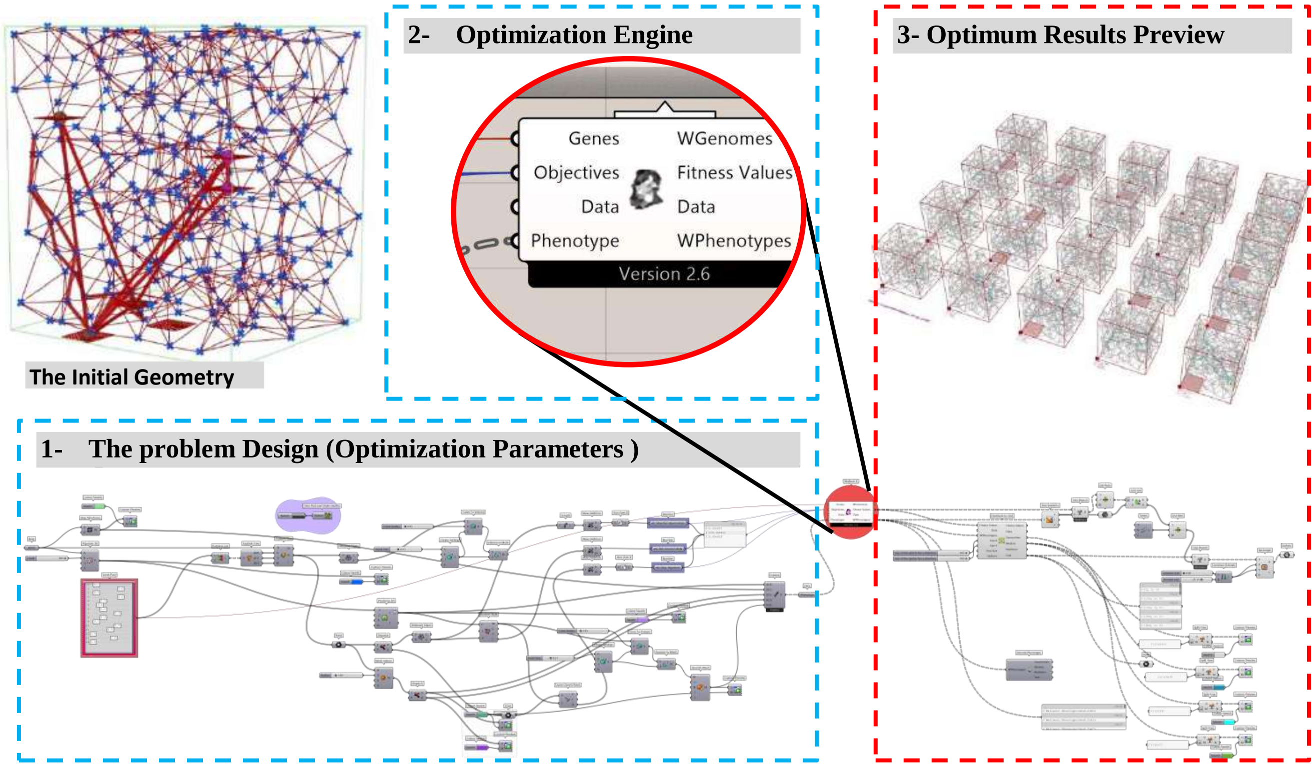


Figure (4-13) Grasshopper algorithms for WALLACEI Optimization process
Source: Author

Upon completing the calculations by the engine, the selected number of generations will be received (evolutionary optimized results) from the server. Then WALLACEI analysis visualises the diamond fitness chart for the selected solution, draws the fitness value charts for all the solutions in the population, and then draws the Standard Deviation and mean value Trendline for all generations in the population; Figure (4-14).

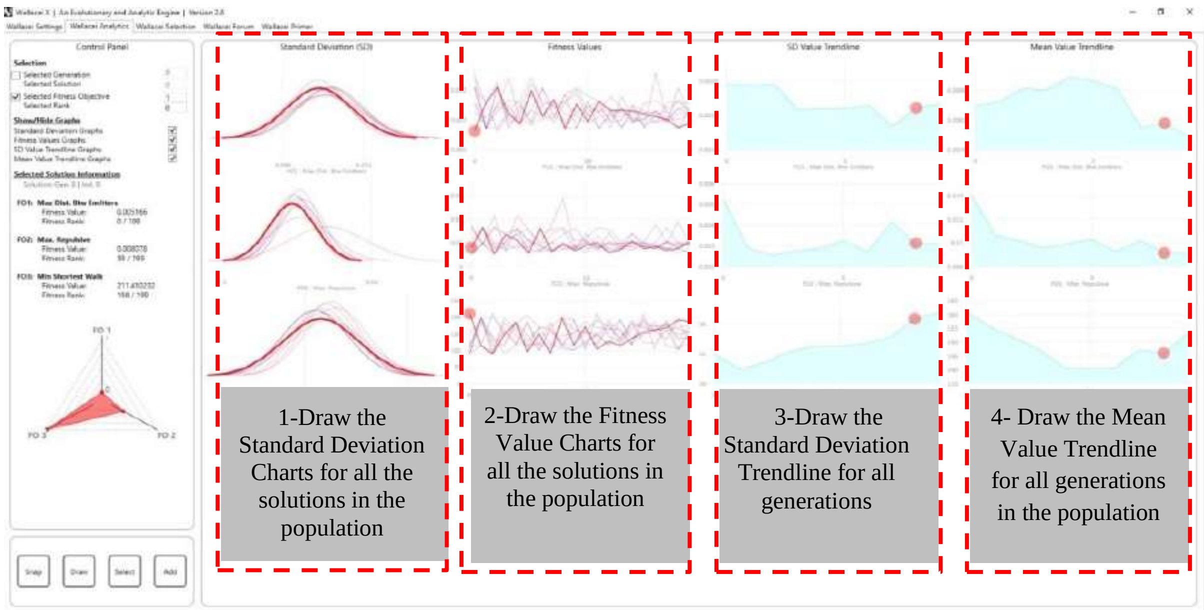


Figure (4-14) WALLACEI analysis for Optimization process
Source: Author

b. Design Experiments

In Milad Showkatbakhsh and Saam Kaviani experiment, the application was made on ALbahar envelope optimization to achieve thermal comfort target; Figure (4-15). Based on the results of the surveys on the evaluation of adaptive facades, 60% of the users are uncomfortable with the natural light that is received through the skin.[11] This was the reason for choosing this project. The complexity of the skin and the simplicity of the form of the towers were the reason to investigate the skin to morphology relationship in this experiment.

Figure (4-15) Al Bahar tower responsive façade
Source: https://www.re-thinkingthefuture.com, accessed Aug, 2020

The experiment shows that the effectiveness of the skin, in terms of blocking the excessive solar radiations as well as providing a good view to the outside area, relies on the elements that are considered as the variable values of the shapes of building skin such as the number of modules, offset size, extrusion size. The experiment is mimicking homeostasis phenomena which are the state of internal, physical and chemical stability maintained by living systems.[12]

The process of setting up the variables and development is illustrated in Figure (4-16). The hexagons are chosen as the skin system in this experiment as an example to show that even complex geometries can take advantage of homeostatic principles.

The fitness objectives that are driving the generative simulation are as follow, given the complexity of the design problem, the experiment was limited to 25 individuals per generation with a total number of 300 generations. The resulted analysis showed that the ratio of the skin to the entire buildings for each iteration.

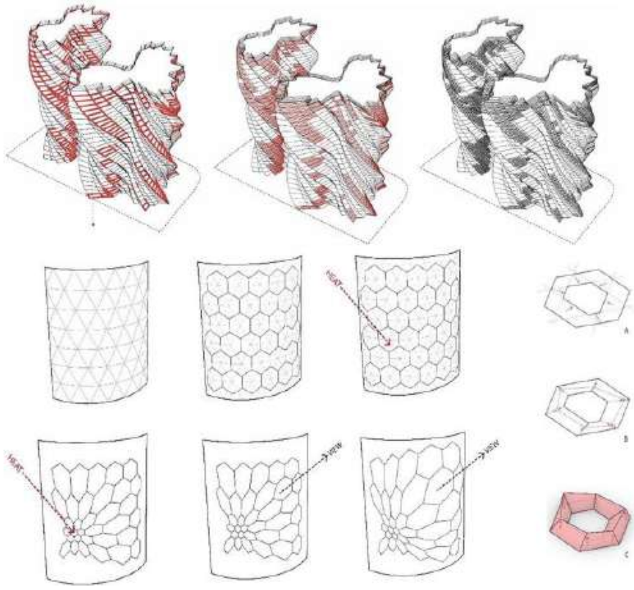


Figure (4-16) The Algorithmic setup of the proposed skin system
Source: Showkatbakhsh, M., 2020

11 Attia, S., "Evaluation of adaptive facades: the case study of Al Bahr towers in the UAE.", Q Science Connect ,2018
12 Showkatbakhsh, M., Kaviani, S. "Homeostatic generative design process: Emergence of the adaptive architectural form and skin to excessive solar radiation", Article, IJAC, UK, Aug 2020

The investigation concluded that the generative design system produced a set of design proposals with morphological characteristics that showed better performance based on the measurement criteria, compared to the case study at a significant level. The first step was identification and period of analysis; the second step was using agent-based simulation for users' analysis by PEDSIM plug-in on Rhino and Grasshopper software.

The analysis indicated that the most used area on the floor, the third step is overlying the most sun-exposed with the most user-visited areas. finally, the last step of the problem design is selecting the parts of the skin causes solar radiation exposure, then running the evolutionary optimization to obtain the results of the optimized envelope, in order to achieve the thermal comfort target based on the environmental simulation during the evolutionary algorithmic optimization by WALLACEI engine; Figure (4-17).

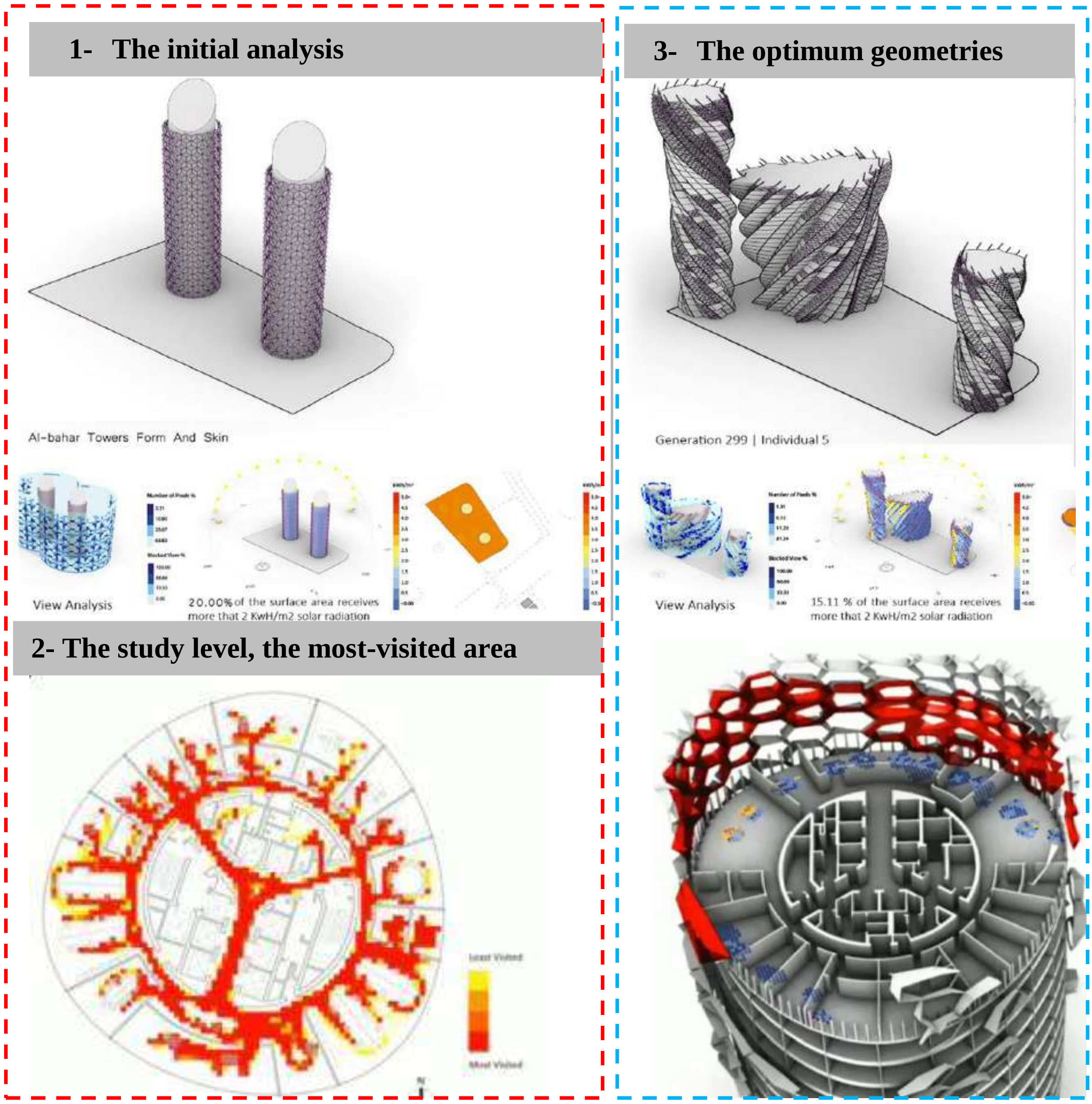


Figure (4-17) Albahar proposals by WALLACEI engine
Source: Showkatbakhsh, M., 2020

c. Evolutionary genes Encoding by WALLACEI Workflow

According to the proposed methodology, in order to achieve structure efficiency target for the first experiment by the author, the thermal comfort for the second experiment by Milad Showkatbakhsh and Saam Kaviani, the WALLACEI encoding workflow went through four main steps. The first step is seeking in the biological domain to identify the organism that achieves that target. In this case, the evolution theory was determined to be the biological role model, as it achieves multi-objective for organism surviving. The second step is the biological domain simulation, in which the biological role model is analyzed through the selected life principles to achieve the abstracted information of Evolutionary genes.

The abstracted information of Evolutionary genes according to the biological simulation suggested that genes work at the molecular level of the complexity. It reacts to all the environmental factors as needed, and in that case study, provided by Milad and Saam simulates temperature and adapts physically. The performance could be defined to be shape change and shape variety.

Afterwards, the third stage, it is the stage of transferring this biological information to the computational domain by scripting. C# was the programming language used in writing WALLACEI plugin. The fourth step is the prototyping in the architectural domain. An application of Albahar project optimization has been made by Milad and Saam using Rhino 3d, grasshopper visual scripting, PEDSIM plugin and WALLACEI Plug-in software tools in order to verify the ability of those behaviour-based algorithms of evolutionary genes to achieve the identified architectural target; Figure (4-18).

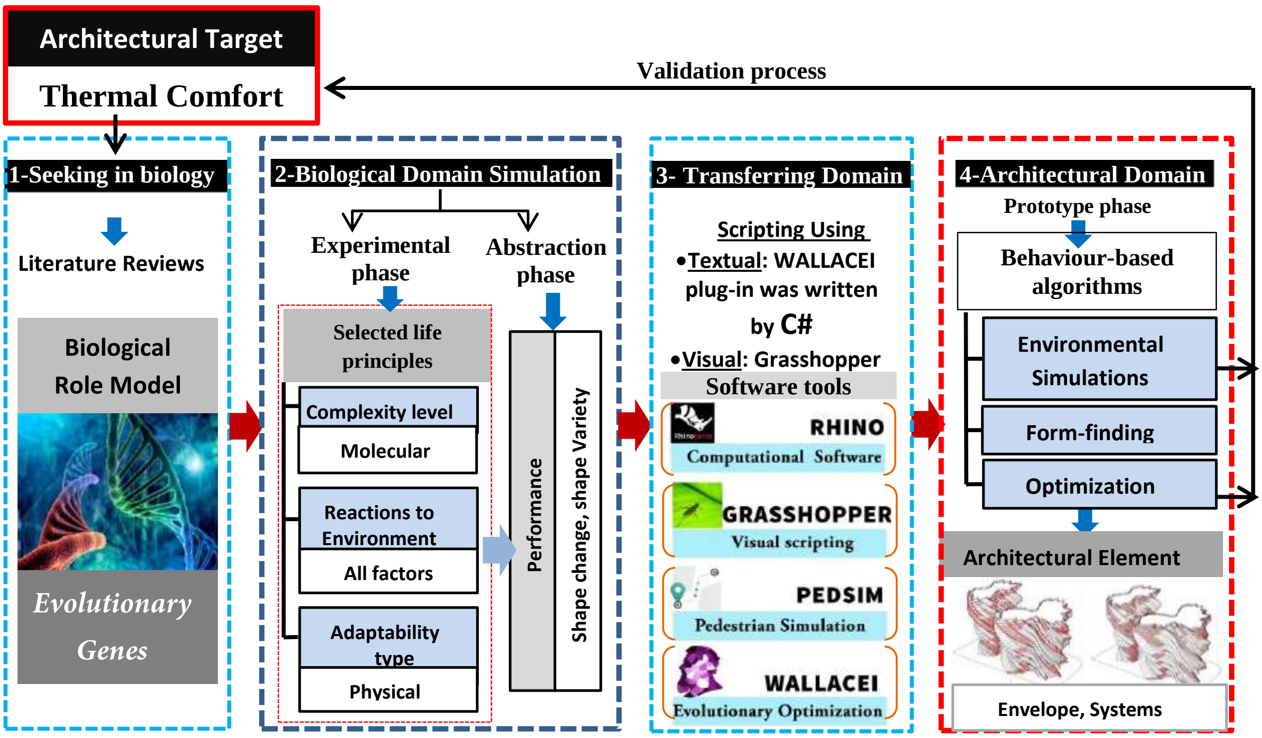


Figure (4-18) Evolutionary Genes Encoding workflow Diagram
Source: Author

The results found that the optimized proposals are produced based on the mathematical calculations of the given parameters such as level of the study, period of analysis, the most sun-exposed, the most user-visited areas, and the fitness objectives. In the validation process, the analytical graphs given by WALLACEI analysis simulate the generations and show that the optimum results fulfilled the thermal comfort target better than the original shape. Additionally, sub-objectives have been achieved, such as behavioural physics simulations and form-finding during the optimization.

4.5.3 Case study 3: Multi-proposed Agent-based simulation by CULEBRA engine

Agent-Based Modeling (ABM), a relatively new computational modeling paradigm, is the modeling of phenomena as dynamical systems of interacting agents.[13] It is responsible to modeling Stigmergic Systems in nature such as swarm intelligence and social insects. Stigmergy is a consensus social network mechanism of indirect coordination, through the environment, between agents or actions. The principle is that the trace left in the environment by an action stimulates the performance of the following action, by either the same agent or a different one. In that way, subsequent actions tend to reinforce and build on each other, leading to the spontaneous emergence of coherent, apparently systematic activity.[14]

CULLEBRA software tool is an evolutionary multi-agent based engine by Luis Quinones based on the phenomenon of Stigmergic mechanism in social insects written by C# programming language (Wrapper around Culebra Java library) in 2017. It is a 2D and 3D Multi-Object Behaviour library focused on hybrid system interactions with custom Visualization, Data, and performance features. It’s a Rhino grasshopper plugin; it contains a collection of objects and behaviours for creating dynamic multi-agent interactions.[15] It depends on behavioural simulation of the organisms which is the main target of Biomemitic approach. These Behaviours include flocking Behaviour, Wandering Behavior, and Noise Behavior. Figure (4-19), is the application of the different behaviour types obtained by CULLEBRA plug-in. The application represents 2D patterns of the different behaviour given by the author using Rhino and grasshopper software.

This experiment is a simple application trying to understand and systematize the logic of CULEBRA plug-in and its generation process parameters. By defining the tracking geometry, selecting spawn locations in box’s edges, apply their initial setting, select the values for the initial speed and maximum speed and force for the move setting, and then select the behaviour from CULEBRA library. In this experiment, the selected behaviour is flocking and tracking the mesh.

13 http://www.scholarpedia.org/article/Agent_based_modeling, accessed Sep, 2020
14 Luís Correia, "On the role of stigmergy in cognition",Progress in Artificial Intelligence, Springer, 2017
15 https://www.food4rhino.com/app/culebra, accessed Aug, 2020

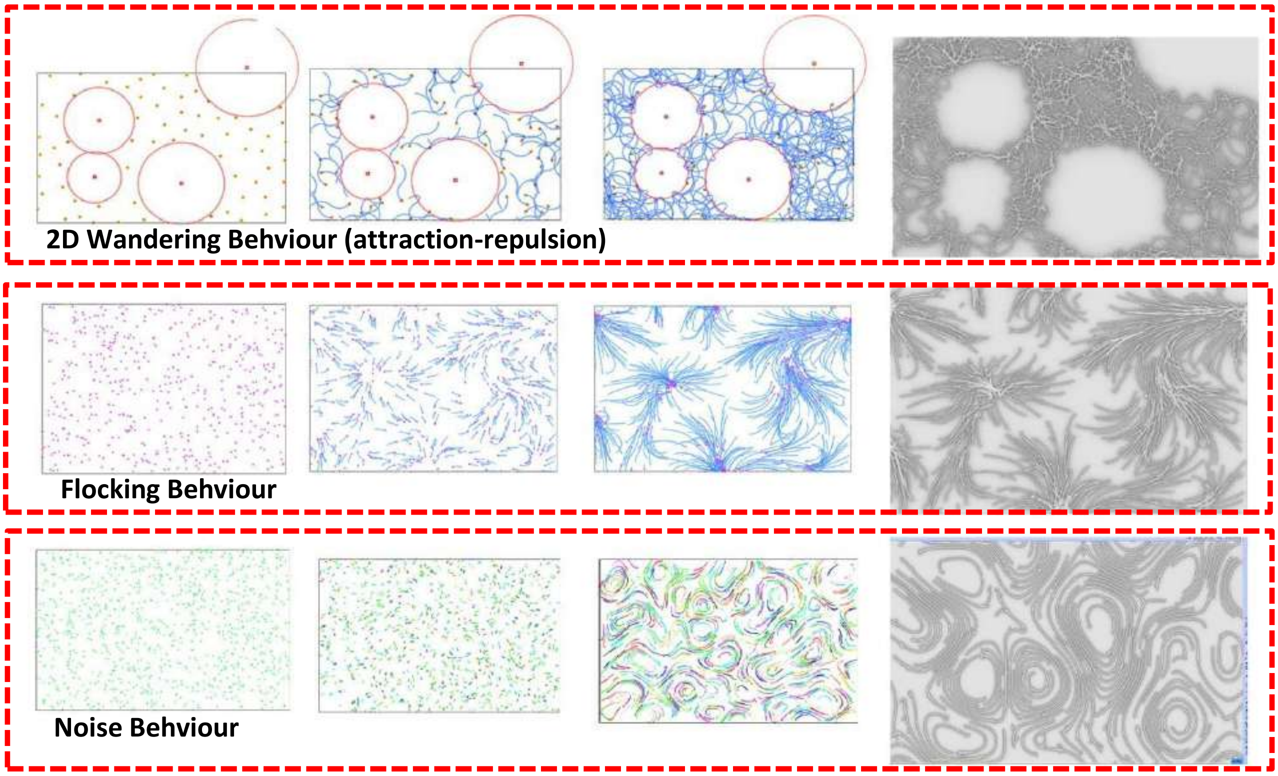


Figure (4-19) Behaviour types simulated by CULLEBRA Plugin
Source: Author

a. Simulation parameters

The first step, design the surface that needs to which the process will take place on it, then apply the parameters setting by which the calculations of the generative algorithms will achieve the required goals. The following table deals with a short explanation of these input parameters; Table (4-3):

Parameter	Short description
Int settings	Deals with the initial agents, their locations and value in 2D or 3D
Move setting	Decide agents initial speed, maximum force and velocity
Behavioural setting	The controller behaviour from CULEBRA library
Visual setting	Define the geometries display options
Reset	For Reseting the behavioural simulation

Table (4-3) Generative simulation parameters for CULEBRA engine
Source: Author

After that, the second step deals with the mathematical calculations of the behavioural-based algorithms, based on the previous parameters given by the designer on the initial geometry. The engine gives the behavioural simulation for the given setting supported to reset simulation and the ability of reset the parameters to select the fitness result by the designer in the third step; Figure (4-20).

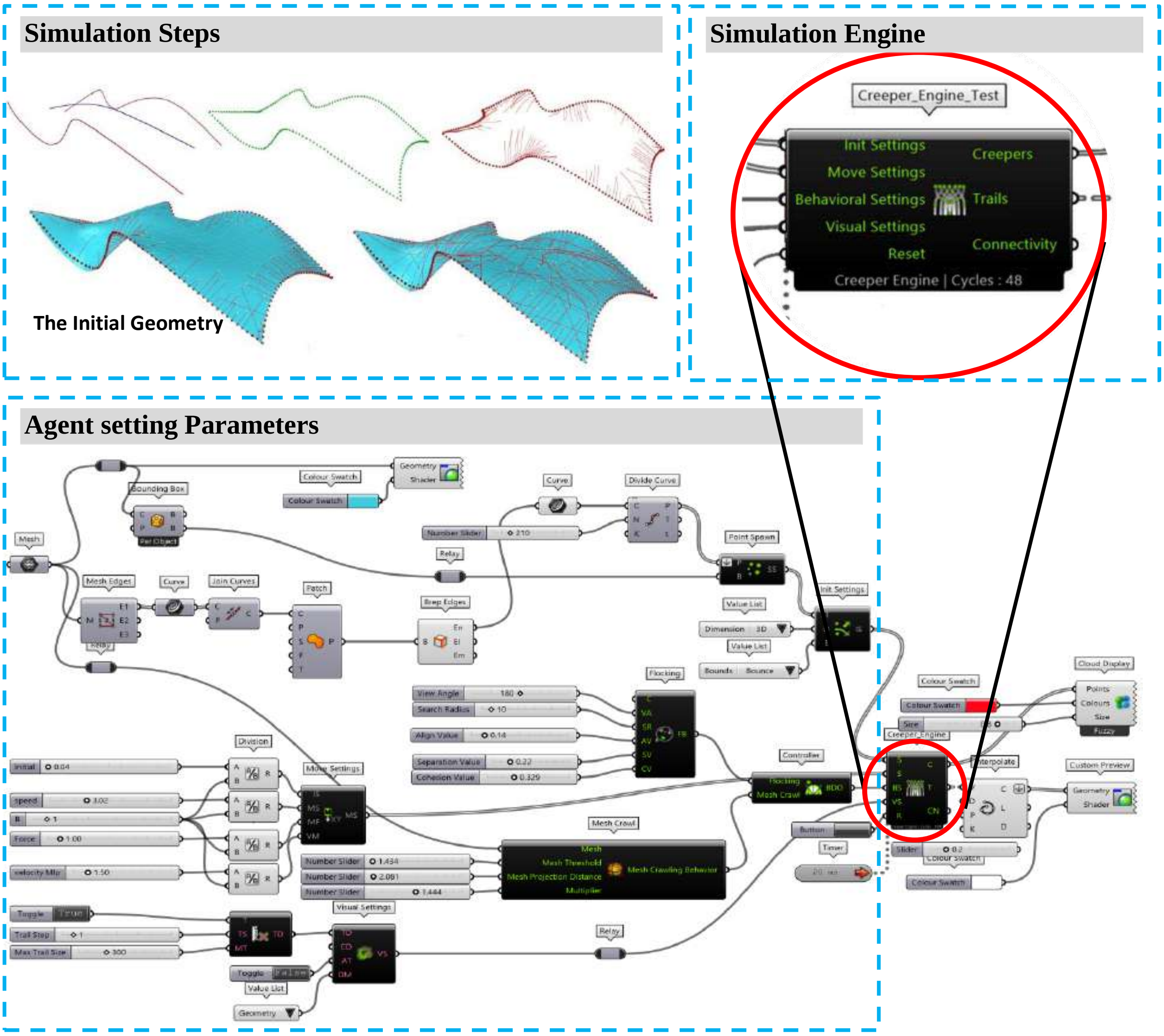


Figure (4-20) Grasshopper algorithms for CULEBRA behavioural simulation process
Source: Author

b. Design Experiments

This creeper engine results in the behavioural simulation. This behaviour simulation can be used in multi purposes such as thermal regulation in terminate social insect, swarm structure, and swarm urbanism. The target in this experiment; Figure (4-21), will be structure and material efficiency by mimicking spider's behaviour in the pavilion structure; Figure (4-22).

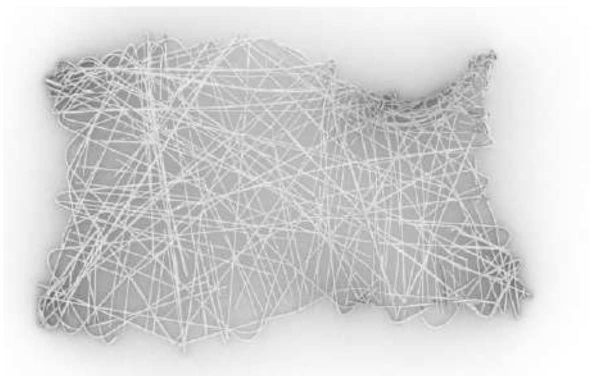


Figure (4-21) Swarm structure layout of the pavilion using CULEBRA software tool
Source: Author

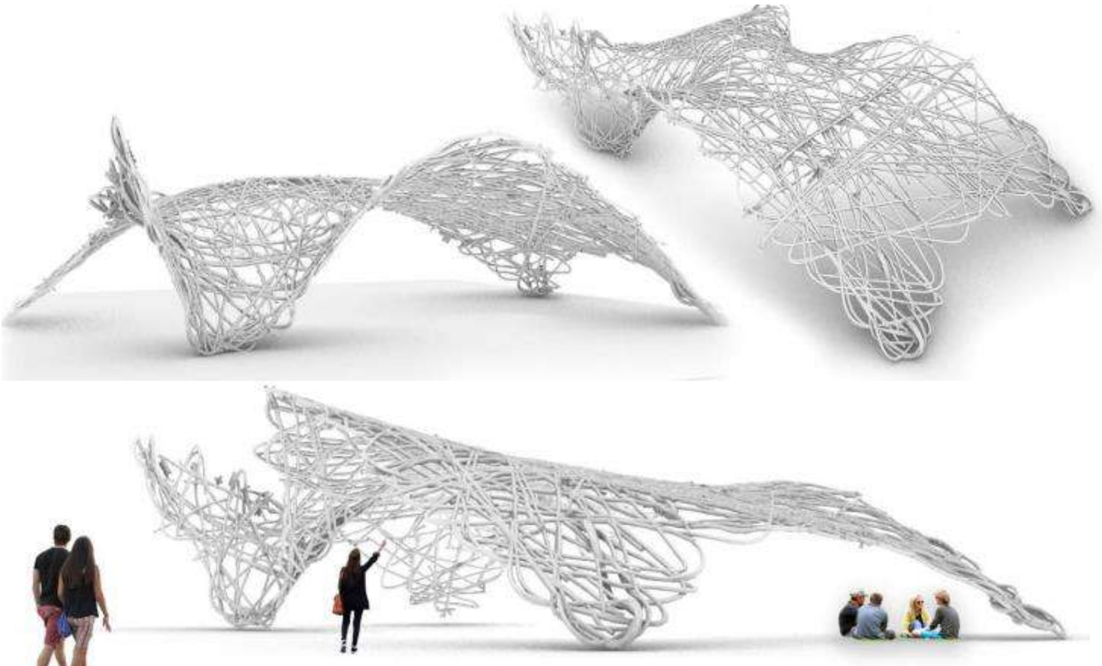


Figure (4-22) Efficient material and structure for the pavilion by CULEBRA software tool
Source: Author

In Jan Petrš master thesis experiment, a skyscraper was designed for which the vehicular traffic is not needed. It is replaced by PRT (personal rapid transit) whose rails lead directly to the individual floors. In terms of urban planning, the idea of the gradual expansion of the network with such PRT solved structures is essential. The shape of the building is based on paths linking facilities to the skyscraper. These railways were designed by swarm intelligence to save energy consumption by vehicular traffic. Movement of the flock, in this case, Boids, was captured and wrapped by mass; Figure (4-23).[16]

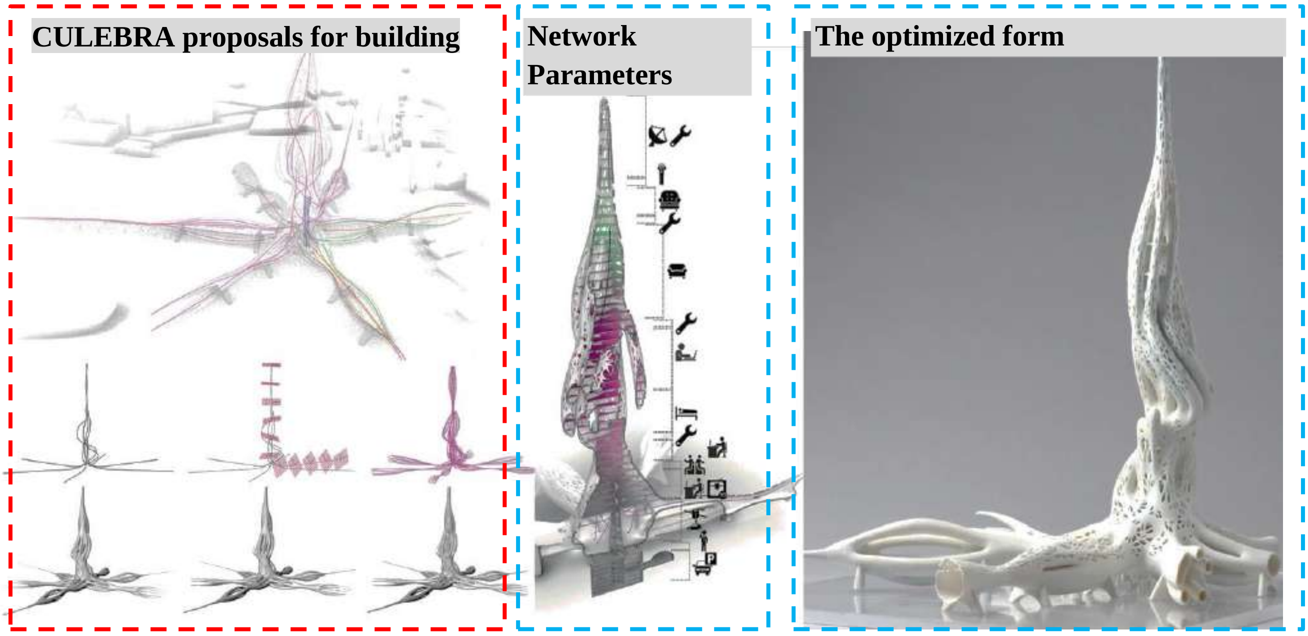


Figure (4-23) Swarm tower by Jan Petrš based on swarm behaviour
Source: http://janpetrs.com, accessed, Sep 2020

16 http://janpetrs.com, accessed Sep, 2020

c. Social insect Encoding by CULEBRA Workflow

According to the proposed methodology, in order to achieve material efficiency and structural efficiency targets for the first experiment made by the author and the energy efficiency for the second experiment by Jan Petrš, the CULEBRA encoding workflow followed four main steps. The first step is to seek in the biological domain for a role model. In this case, social insects were determined to be the biological role model. The second step is the biological domain simulation in which the biological role model is analyzed through the selected life principles to achieve the abstracted information of social insects.

The abstracted information of social insects according to the biological simulation suggested that genes work at ecosystem level of the complexity. It reacts to all the environmental factors as needed, adapting physically. The performance shown by social insects is shape change and growth. In the third step, biological information concluded from the second step is transferred to the computational domain, using scripting. CULEBRA plug-in was written using C# programming language. In the fourth step, a prototype was made in the architectural domain. A simple application of pavilion optimization was made by the author using Rhino 3d, Grasshopper visual scripting and CULEBRA plug-in software tools, in order to verify the ability of the CULEBRA plug-in's behaviour -based algorithms to fulfill the architectural target; Figure (4-24).

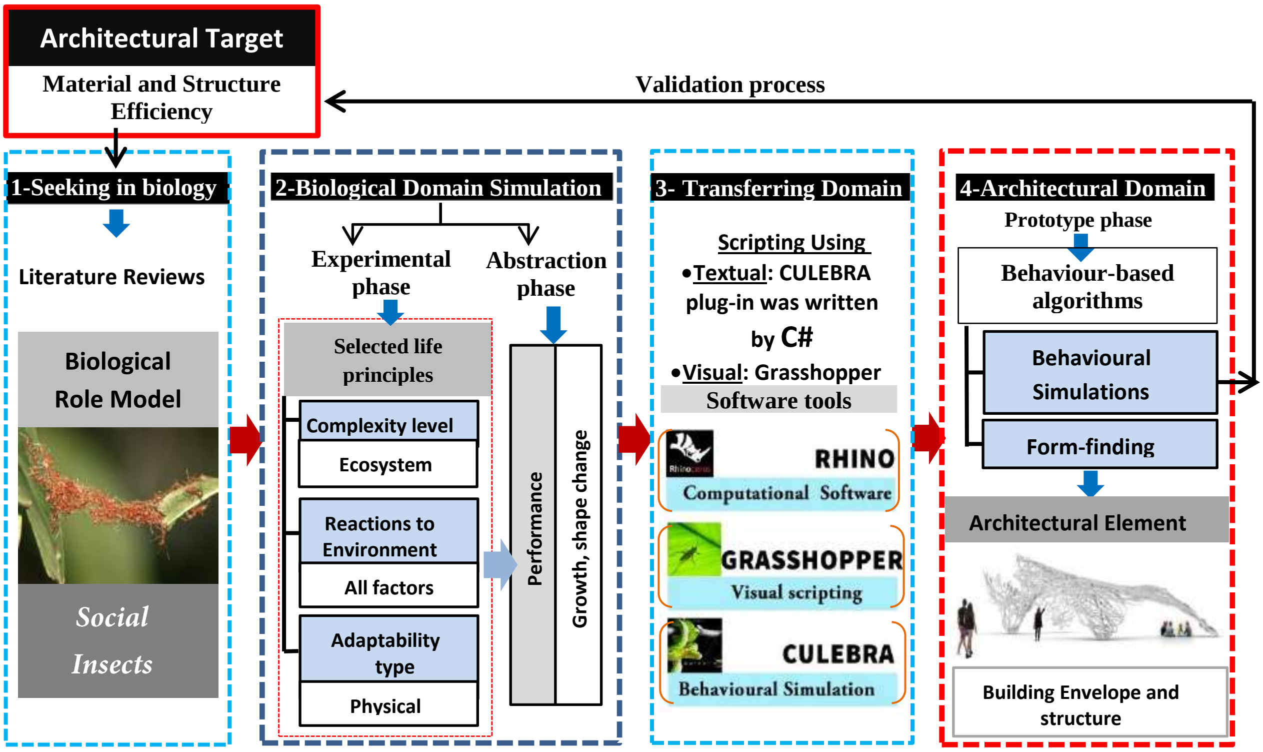


Figure (4-24) Social Insects Encoding workflow Diagram
Source: Author

The results suggested an optimized structure based on mathematical calculations made using the parameters given. The parameters were the tracking geometry, the initial setting of agent locations, move setting, the speed settings and the controller behaviour. In the validation process, the generative results given by CULEBRA simulate the behaviour and show that the optimum result will achieve the structure efficiency. Results also included fulfilling sub-objectives, such as form-finding of the building during the simulation process.

4.5.4 Case Studies Discussion

After applying the methodology proposed by the researcher for analyzing the case studies, Biomimetic Design Workflow for Building Behaviour was concluded, which can be summarized in four primal stages, as follows:

1- After defining the architectural target to be achieved, **the first stage** will begin which is seeking in the sources of the biological domain, determined either from previous research, literature review or by using CAB software such as BioTRIZ, FOBIE or by using websites such as E2BMO or AskNature websites through them that the biological role model will be determined.

2- **The second stage** is simulating the biological information obtained from the biological domain sources. This stage divided into two phases the experimental phase where the role model is simulated by the selected life principles, which in turn infer the biological performance in the abstraction phase that will be mimicked.

3- After obtaining the biological information in written form, **the third stage** begins, which is the transferring domain from mere text to the architectural domain. The transferring domain is responsible for scripting that information using programming languages, whether visual as Grasshopper and Dynamo, or in textual such as Python, C#, C++ and VB.net.

4- Biological information reaches the transferring domain in a behaviour-based algorithmic form, and thus **the fourth stage** is using those algorithms in the architectural field and reaching an architectural element that achieves the desired target in the prototype phase. This can be validated using the analysis provided by these algorithms.

Chapter Summary

According to the previous chapter, the problem-based approach methodology for building behaviour produced by the researcher is the methodology for transfer the abstracted life principle deducted from chapter two. This methodology raised the questions of how to transfer these principles into an architectural element. For this reason, this chapter aims to clarify the problem-based approach methodology by adding the transferring domain that is responsible for transferring these principles.

The chapter starts with the biological domain sources which provide the designer with the biological information needed and helps in selecting the biological role model. Furthermore, the chapter overviewed the use of scripting in architecture. The role of computational design in biomimetic approach has been discussed in terms of translating the biological morphogenesis, the parametric level, and then the generative level of computational design.

Biomimetic Design Workflow for Building Behaviour could be achieved by analyzing the selected case studies. The Biomimetic Design Workflow for Building Behaviour could be summarized in four primal stages; first, seeking in biology for the biological role model; second, the biological domain simulation; third, the transferring domain which is responsible for transferring the biological information into the architectural domain; fourth, the prototyping in architectural domain. These stages can be applied to any architectural target for the building behaviour, and this will be the problem-based approach workflow. The starting could be from the identification of the biological model, and thus it will be a solution-based approach workflow. The next part will be the application on this Biomimetic Design Workflow for Building Behaviour to verify the results.

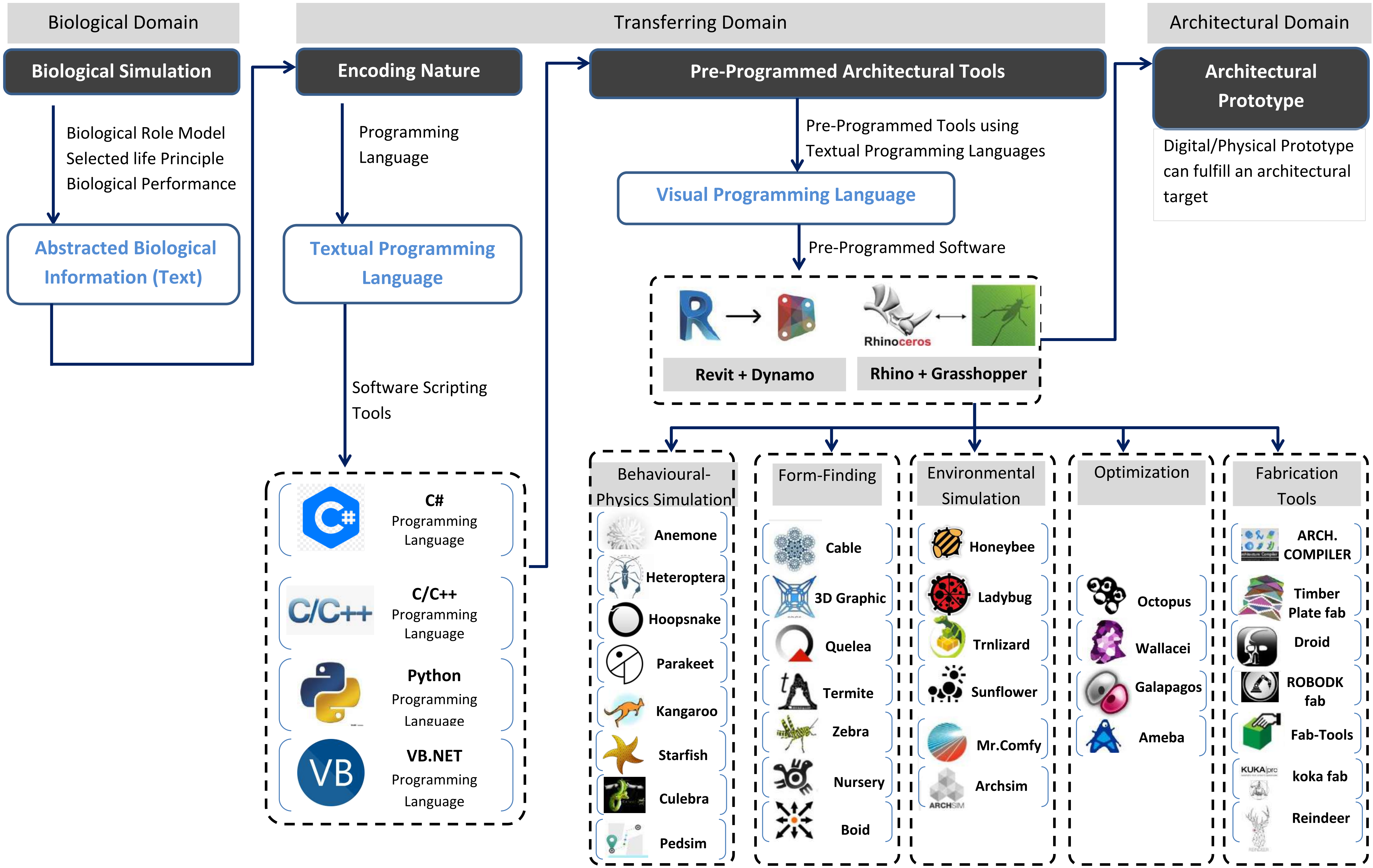


Figure (4-25) Transferring Domain Framework and Recent Tools classification
Source: Author

CHAPTER 5: Application of the Biomimetic Design Framework for Building Behaviour

Introduction

This chapter represents the application of the methodology proposed by the author to fulfill two main aims. The first aim is to verify the results through presenting an example for the utilization of the Biomimetic Design framework methodology for Building Behaviour. It also helps to acquire a hands-on experience for the digital model and fabrication of physical models through all the steps, starting from defining the building behaviour target till the implementation stage, for inevitable further explanation and to clarify the methodology. Furthermore, in order to reach those aims, the primal four stages of the biomimetic design framework will be applied to design a responsive façade, which could react to environmental factors such as temperature, daylight, and humidity. Additionally, human gestures could be used as input data for this physical response.

The application moves along the design framework stages, starting with defining the architectural targets to be achieved. The first stage will be seeking in the biological domain for the role model and gathering data. In the second stage, data abstraction will be made. In the third stage, domain transfer was made by programming the biological information. In the fourth stage, validation was made, and digital and physical prototyping was presented. The application experimentations are collaborations between biological, mechanical, and architectural fields. The fabrication phase took place at Trim Academy and Fab Lab Egypt fabrication labs in Cairo. Finally, the architectural application of a responsive façade for the proposed methodology was introduced.

5.1 The First Stage: Seeking in Biological Domain

In this application, the required building behaviour targets were identified. The first target to be achieved is indoor quality by providing thermal comfort and visual comfort through the response for environmental factors such as temperature, daylighting and humidity. The second target is that human gestures could be used as input data for this physical response, in order to make it controllable by users to avoid limitations to control the light and temperature and reaching the highest levels of comfort.

AskNature website is used in this experiment for searching the biological domain for response target to be achieved in the building and how nature can give suggestions for that target. A large database of biological models is available. The researcher selected the biological role model according to the short description provided by the website, as shown in Figure (5-1). Upon investigating how nature responds to the environmental conditions, *Mimosa pudica* was found to reach this target by the physical response to protect itself. Based on the in-depth explanation provided by the site, the required biological information has been obtained. Then the second stage begins, which is to simplify that information into the abstracted principles to be mimicked.

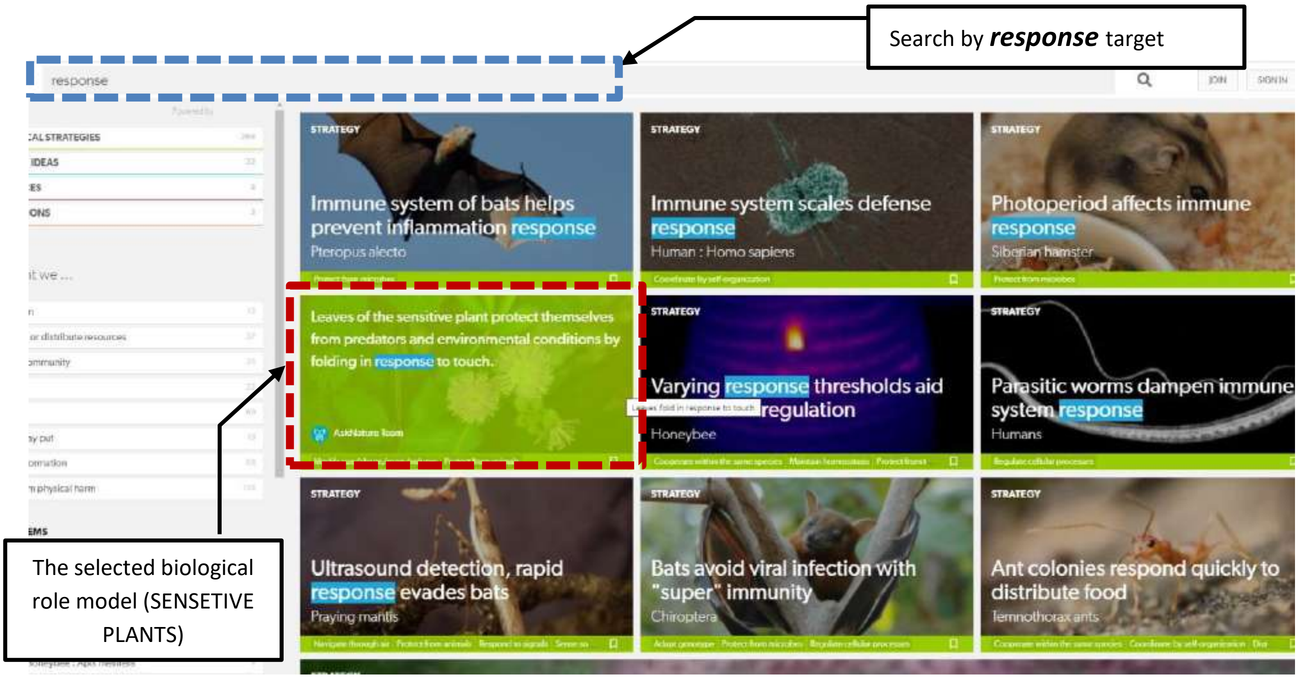


Figure (5-1) AskNature website search results for Response as a required target
Source: https://asknature.org/, accessed Aug, 2020

5.2 The Second Stage: Biological Domain Simulation

The first step is searching for the role model which can help to reach the architectural target. In this case, the target is self-responsive façade. *Mimosa pudica* Figure (5-2) is one of the role models where the self-responsive is a very obvious characteristic in their bio-cellular structures. There is a change in the concentration gradient of potassium and chloride ions within the two types of cells (flexor and extensor cells) in the plant that respond to heat, light, humidity and physical movement. The biological domain simulation will pass through two phases. The first phase will be the experimental phase for data gathering in the previous experiment on the mimosa plant, then the abstraction phase of this principle to be mapped into an algorithm.

5.2.1 Experimental Phase

Mimosa Pudica, known as the sensitive plant, is affected by another organism, with leaves drooping on itself and stems drooping. This rapid folding is supposed to prevent herbivores and insects from eating the plant. The plant appears smaller, while at the same time displaying sharp spines on the stems. The following image shows the Night Body at Night.[1]

Figure (5-2) Mimosa Pudica plant
Source: https://asknature.org, accessed Sep, 2020

1 https://asknature.org/strategy/leaves-fold-in-response-to-touch/, accessed Sep, 2020

The movement of Mimosa Pudicaraises arises the question of how does this dramatic movement happen? How does a plant sense the external touch from the start? Based on the measuring experiment Figure (5-3) of the Action Potentials generated at the stem/petiole joint of Mimosa plants by using Plant Spiker-Box, the hat plants can generate electrical impulses. Hard-working scientists have hypothesized that small red mechanoreceptor cells on the underside of the leaves respond to mechanical disturbance. This initiates electrical impulse (Action Potential) propagation along the rachis, which results in the plant movement behaviour we observe.[2]

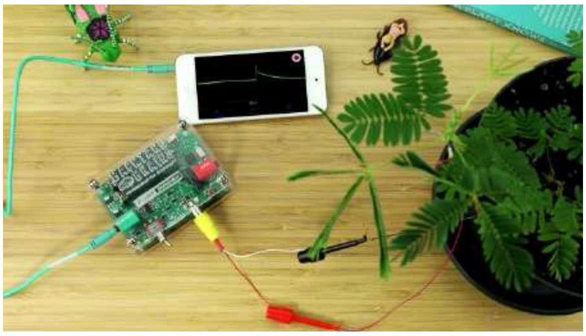


Figure (5-3) Measuring experiment for Mimosa Pudica movement
Source: https://backyardbrains.com, accessed Sep, 2020

5.2.2 Abstraction Phase

Mimosa is a biological role model that performs on Cellular-level of complexity. The environmental factor challenging Mimosa is temperature and light. It uses physical adaptation to achieve the architectural target of indoor quality by providing thermal and visual comfort. The performance could be deduced as a shape change by folding mechanism; Figure (5-4).

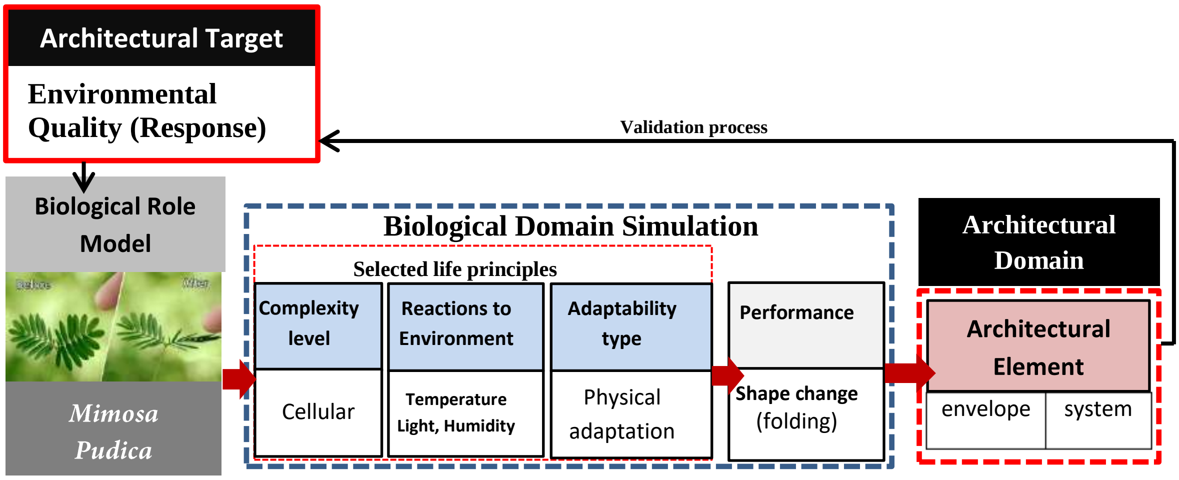


Figure (5-4) Mimosa abstracted principles
Source: Author

In order to transfer and map Mimosa principles, a level of abstraction must exist in the process as the previous stage, and then the intermediary stage where the computation will start. So, the next step is to transfer this biological information of Mimosa folding response by attractors into the transferring domain by using scripting. After fully understanding its components and the selected life principles, it could be mapped to an algorithm and builds its complexity in the next stage.

2 https://backyardbrains.com/experiments/Plants_SensitiveMimosaPudica, accessed Sep, 2020

5.3 The Third Stage: Transferring Domain

This application is attempting to turn the behaviour of the sensitive plant to an architectural element. By utilizing the previous abstracted life principles and systematize its physical behaviour logic to main principles to be transferred in this application as follows: folding as a physical reaction, the sensitivity to environmental conditions and physical movement response.

The transferring domain role will be presented in this application in the digital prototyping, by using the visual programming language Grasshopper on Rhino software which will go through design processes produced in the next part. Then the physical prototyping will be coded using textual programming C for scripting Arduino code which is responsible for the mechanism variables.

5.3.1 Digital Prototyping

The hexagonal pattern is used to clarify the difference between form mimicry and behaviour mimicry, as the hexagonal cells is a simple imitation for this hexagons pattern in nature, working at the organism level of complexity; Figure (5-5). Conversely, the mimicking of the performance of shape change regarding the physical adaptation works on the cellular level of complexity for the sensitive plant behaviour.

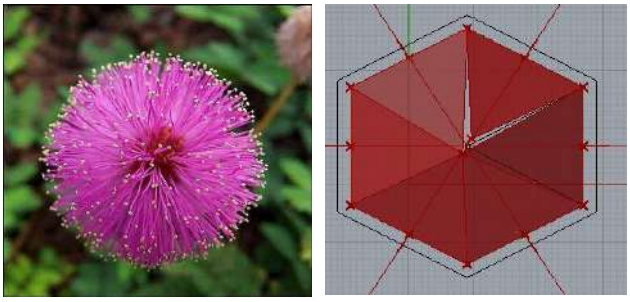


Figure (5-5) Abstracted form for Mimosa pudica flower
Using Rhino GH software
Source: Author

The logic underlying the hexagonal mathematical geometry is that hexagonal tessellation is considered the result of the abstracted form of the flower that made using the algorithm on Grasshopper in the next step. The prototype mechanism is mimicking Mimosa pudica flower blooming and process, there are several types of flower blooming mechanism; Figure (5-6). The application will be mapped to an algorithm using Rhino and grasshopper software tool by considering the Patel of the flower as a triangular planer; Figure (5-7).

Figure (5-6) Flower Blooming
Source: https://www.123rf.com, accessed Sep, 2020

- **Design Parameters**

The first step is to design the surface on which the process will take place, and apply the parameters setting by which the algorithms will achieve the required goals. The following table deals with a short explanation of these input parameters; Table (5-1):

Parameter	Short description
Hexagonal points	The describes the number of cells which will be generated
Opening size	The remapped scale affected by the closet point
Boundary	The initial geometry frame for the façade
Closet point	In this application will define as the stimulus place

Table (5-1) Geometrical parameters for the self-responsive façade
Source: Author

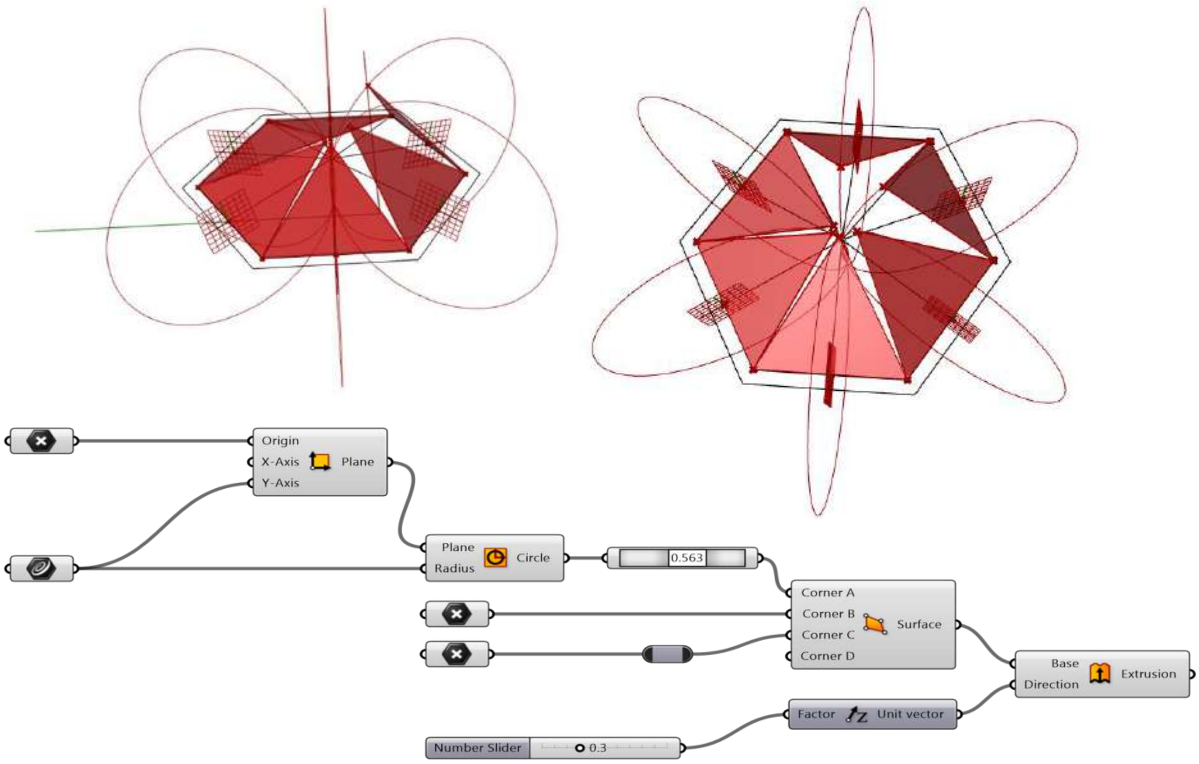


Figure (5-7) Digital prototype for the facade unit inspired by Flower blooming
Source: Author

The façade openings are affected by these attractors, whereas the sizes of the openings are distributed based on the places with the stimuli, as the openings change their size to adapt to distance, physical motion, light, humidity and temperature variance, by closing the units in the places exposed to impacts, while opening it after the stimulus is gone. That mechanism simulated plants that are sensitive to environmental factors and physical motion. Whereas environmental factors are not stable, the façade must be kinetic and must have the ability to react to ever-changing factors. The six flower petals considered as the triangular planer rotating around an axis for each triangular plan, using the algorithm on Rhino and Grasshopper; Figure (5-7) and repeat this algorithm for each triangular plan.

The digital prototyping indicated the potential scenarios for the façade unit affected by the strange attractors for each triangular planer. In order to avoid the environmental limitations, physical response for human gestures could be added as input data in the physical prototyping in the fabrication stage. The next stage is the implementation of the selected unit as a hands-on experience and testing how to transfer the sensitive plant principles into a physical model.

5.3.2 Physical Prototyping

This stage is a fabrication framework that focused on the physical model for the self-responsive unit of the facade. Each unit of the digital façade model will have the same component of the physical unit prototype. Simplification of the physical prototype into a regular shape with a view to reaching a fabrication framework that could be implemented on any irregular shape.

5.3.2.1 Mechanism Design

By mimicking Mimosa pudica flower blooming process, motion characteristics of the deployable-foldable mechanisms could be deducted in both processes: the folded and deployed states; Figure (5-8). The form of the flower will be abstracted into polygon geometry, as the flower frame and the triangle as the petal of the flower distributed around the rack in a circular array; Figure (5-9).

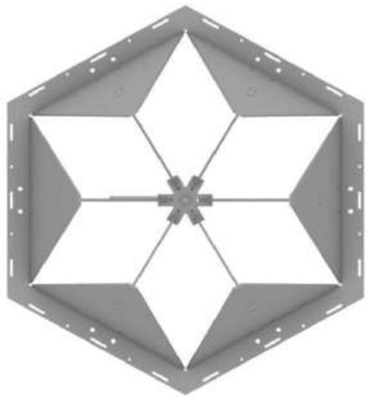


Figure (5-8) The abstracted mechanism inspired by flower petals
Source: Author

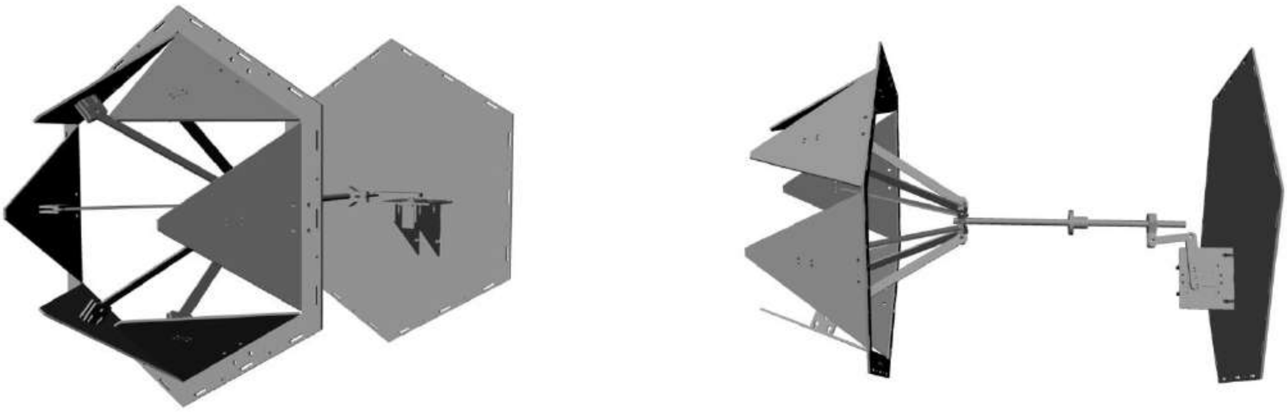


Figure (5-9) Mechanism digital prototype using Rhino Grasshopper software
Source: Author

The deployable- foldable mechanism is affected by an external stimulus. Therefore, the first step in its fabrication is designing the folding mechanism. In selecting the desired unit, SOLIDWORKS software was used to be able to perform the mechanical design and engineering. This software supports the design by providing motion analysis to be able to validate the motion possibilities. In this application, linear-motion bearing is used in the unit mechanism; it's a linear slide designed to provide free motion in one direction. Additionally, to control the triangular units folding angle, the deployable-foldable mechanisms could be used; Figure (5-10).

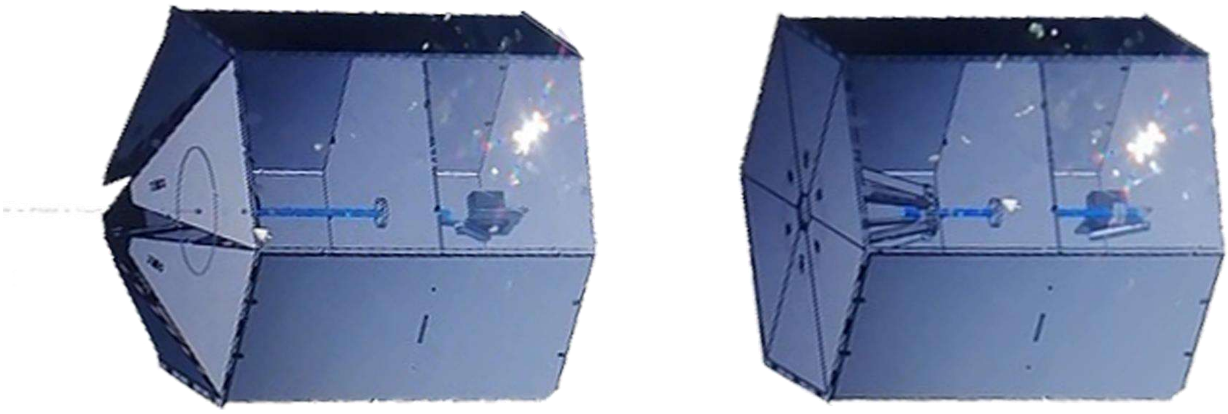


Figure (5-10) Mechanism simulation using SolidWorks software
Source: Author

5.3.2.2 Self-Responsive Unit's Components

The self-responsive unit consists of three main types of components for mimicking the mechanism inspired by the flower blooming: the façade components, mechanism components, and the tools used in the physical prototyping as the following:

a- The Façade Components

The façade outer surfaces consist of the unit frame that will play the role of the hinges support and sensors locations. Furthermore, the polygon geometry is divided into 6 triangular deployable units according to the selected unit number of edges; Figure (5-11).

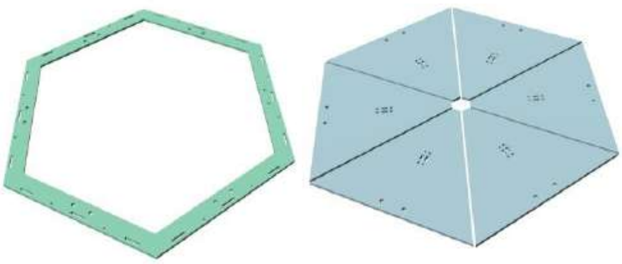


Figure (5-11) The façade outer surface components
Source: Author

b- The Mechanism Components

The unit mechanism components are consist of six arms, each arm is responsible for folding the triangular unit connected to it, then the polar hinges component attached by arms, and different types of hinges to smooth the motion of the unit. All these components are assembled with the linear bearing guide that connected to the motor; Figure (5-12).

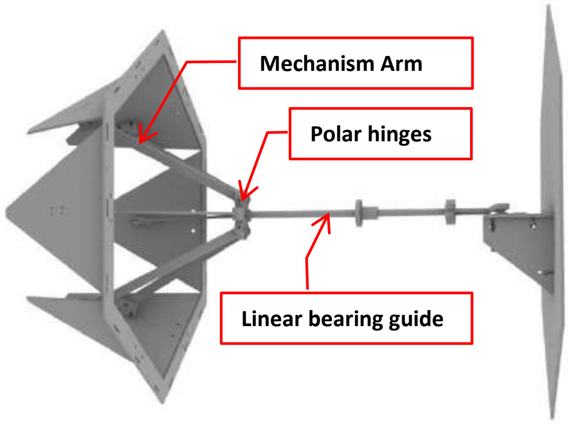


Figure (5-12) The façade unit's mechanism components
Source: Author

The self-responsive façade unit connects with one servo motor, light level sensor, temperature sensor and ultra-sonic for distance measuring sensor. The behaviour of the façade elements is detected by those sensors and the physical input. The units perform a role in integrating environmental sensor data and physical form to formulate a combined conceptual design, mimicking the movement of sensitive plants in the early façade design process. This mechanism is suitable for the regular unit and the irregular unit; Figure (5-13).

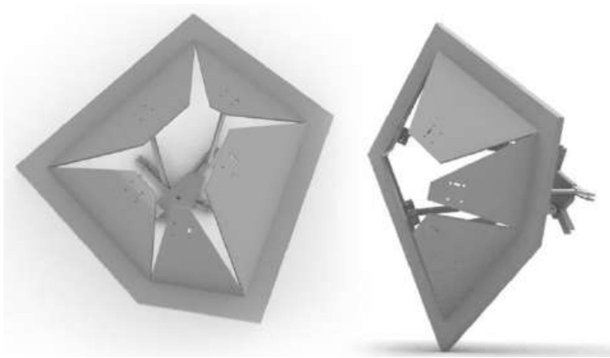


Figure (5-13) The irregular unit mechanism
Source: Author

c- The Tools used in the Physical Prototyping

The following Table (5-2) presents the equipment that was used during the fabrication process and describes their role in manufacturing as follows:

Tool	Name	Function
	**Servo Metal Gear MG995 For RC Model and Robot Torque: 13 kg-cm**	Servo engine maybe a gadget that contains an encoder, which changes over the mechanical movement (turns of the shaft) into computerized beats translated by a movement controller. It also contains a driver; and in conjunction, they make up a circuit that administers the position, torque and speed.[3]

3 https://clr.es/, accessed , Sep 2020

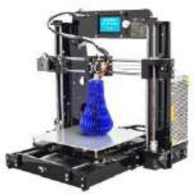
	**Arduino Uno R3**	Arduino Uno is a microcontroller board based on the ATmega328P (datasheet). It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator (CSTCE16M0V53-R0), a USB connection, a power jack, an ICSP header and a reset button.[4]
	**Light Sensor Module with LDR and OP-amp amplifier 3-wire Optical Sensitive Resistance Module**	The light sensor is a passive device that converts this “light energy” whether visible or in the infra-red parts of the spectrum into an electrical signal output. Light sensors are more commonly known as “Photoelectric Devices” or “Photo Sensors” because the convert light energy (photons) into electricity (electrons).[5]
	**LM35DZ Temperature sensor**	A temperature sensor is an electronic device that measures the temperature of its environment and converts the input data into electronic data to record, monitor, or signal temperature changes.[6]
	**UltraSonic Sensor**	An ultrasonic sensor is an electronic device that measures the distance of a target object by emitting ultrasonic sound waves, and converts the reflected sound into an electrical signal.[7]
	**3D printing machine**	3D printing machines are additive manufacturing machines that specialize in making custom parts with accuracy.
	**Laser Cutting Machine**	Laser cutting machines are a tool used in a wide range of industries for precision cutting and designing projects. The laser cutting machine emits a high powered laser beam to either cleanly cut or etches a specific design on materials such as steel, plastic or wood.[8]

Table (5-2) Equipment used during the fabrication process
Source: Author

4 https://store.arduino.cc/usa/arduino-uno-rev3, accessed Sep, 2020
5 https://www.electronics-tutorials.ws/io/io_4.html, accessed Sep, 2020
6 https://www.fierceelectronics.com/, accessed Sep, 2020
7 Op.cit.
8 https://www.shapecut.com.au/, accessed Sep, 2020

5.3.2.3 Fabrication Process

In this stage, the façade unit is turned from a digital model into a physical model, by using the CAM tools (Cad Aided Manufacturing) such as 3D printing and laser cutting machines. In this application, the 3d printing machine was used for printing the polar hinges component and the connection between the linear bearing and server motor; Figure (5-14), Then the rest of the component of the model remain unrolled to be prepared for laser cutting; Figure (5-15).

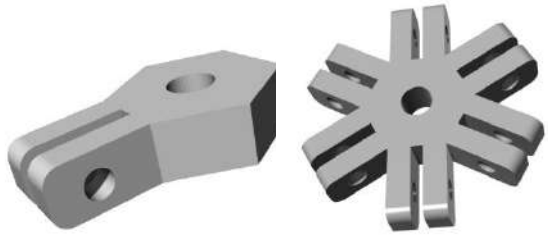


Figure (5-14) Preparing the components for 3D printing
Source: Author

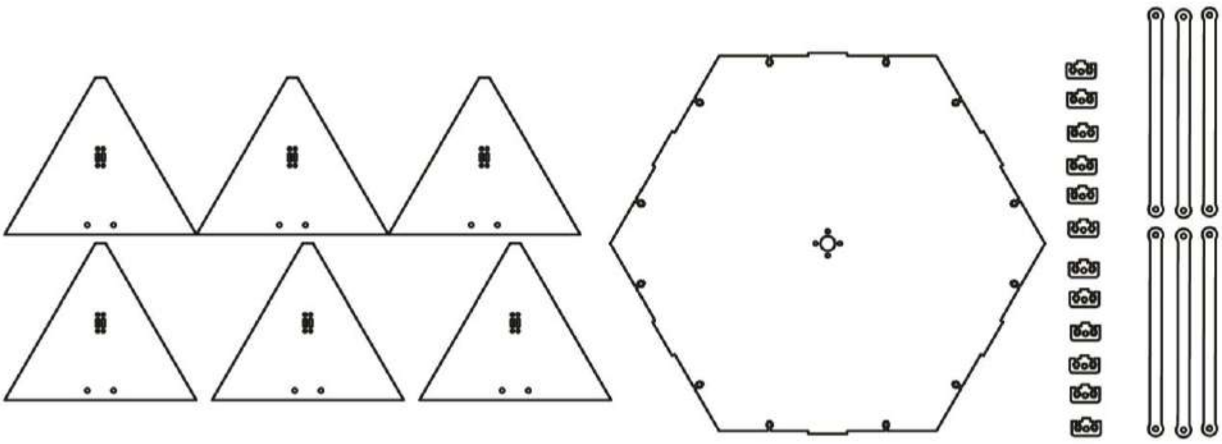


Figure (5-15) Preparing the components for laser cutting
Source: Author

Then the second step deals with the external stimuli calculations for Hexagonal pattern. Based on the parameters given by microcontroller, these external attractors performed to the façade provided the behaviour mechanism which affects the façade movement (physical stimuli), which acts as a strange attractor. The Arduino allows re-setting of the parameters and the selection of the fitness results by the designer. This behaviour will equally provide environmental quality targets.

In order to transfer the sensitive plant behaviour to the physical model, a programming language will be used to write the algorithm for the physical model by adding sensors such as light and temperature sensors and Ultra-Sonic sensor. The ultra-sonic sensor is responsible for measuring the distance and uses the human physical movement as an input in the movement process; Figure (5-16).

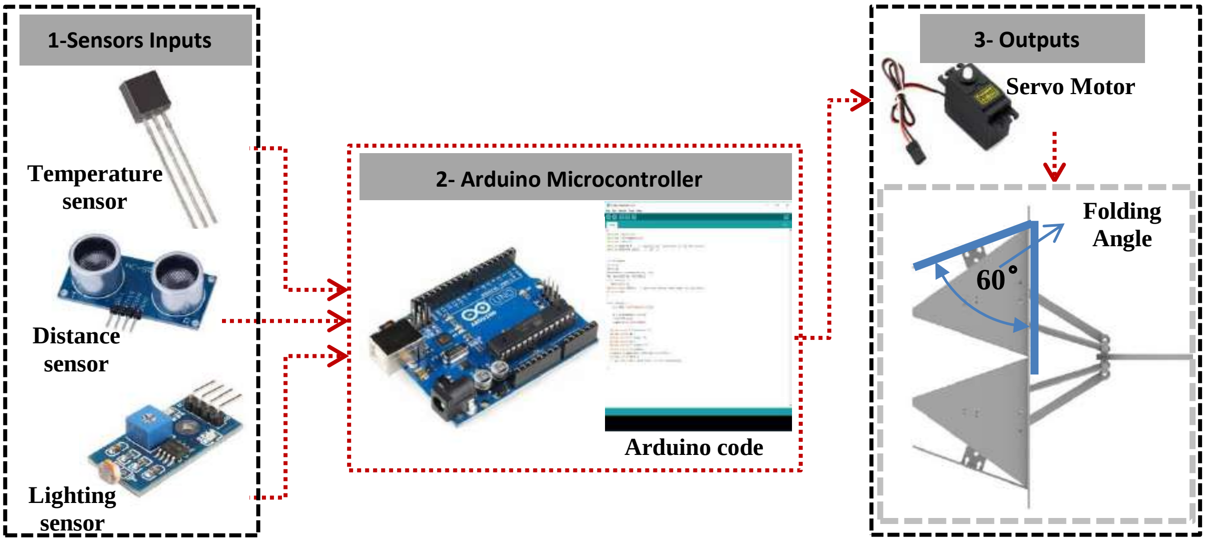


Figure (5-16) The Self-Responsive Façade Unit framework
Source: Author

The unit's microcontroller was coded using C programming language by Arduino IDE software by determining the humidity, temperature, light, and distance as input variables, and the angle of the triangle unit movement as an output, and then the serial monitor gives a reading sheet for the variables as in the Figure (5-17).

```
#include <Servo.h>
#include <Ultrasonic.h>
#include "DHT.h"
#define DHTPIN 8     // Digital pin connected to the DHT sensor
#define DHTTYPE DHT11   // DHT 11


int x,light;
float t;
Servo m;
Ultrasonic ultrasonic(10, 11);
DHT dht(DHTPIN, DHTTYPE);
void setup() {
   dht.begin();
Serial.begin(9600);  // put your setup code here, to run once:
m.attach(9);
}

void loop() {
    t = dht.readTemperature();

    x = ultrasonic.read();
    if(x>300)x=0;
    light=analogRead(A0);

  Serial.print("distance= ");
  Serial.print(x);
  Serial.print(" Temp= ");
  Serial.print(t);
  Serial.print(" Light= ");
  Serial.println(light);
  if(x<10||light>500||t>50){m.write(70);}
  else{m.write(180);}
  // put your main code here, to run repeatedly:

}
```

Figure (5-17) Arduino code for sensors values
Source: Author

5.3.2.4 Assembly Process

In order for the prototype to be as Self-responsive, sensors are integrated as part of the kinetic system. In order for the system to respond to different light levels, temperature degree and distance, light, temperature, and distance sensors are used. The sensors are programmed to detect different environmental conditions based on the lux measurement for lighting, temperature degree, and distance by the meter. The data output from the sensors let the triangle unit change their angle and respond to fully open, semi-open, and fully closed Figure (5-18).

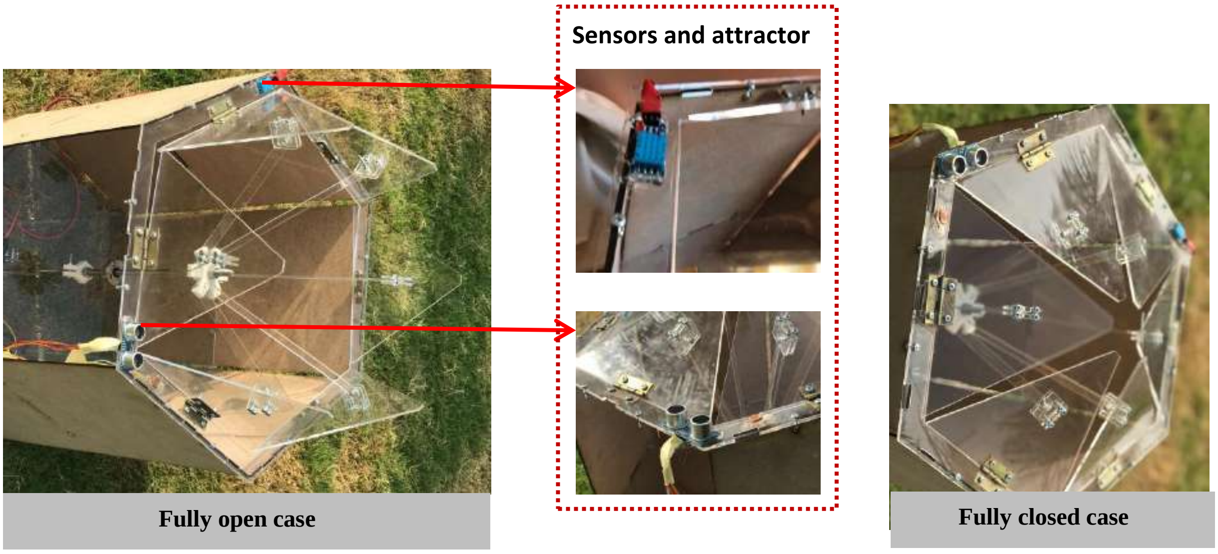


Figure (5-18) The physical prototype for the responsive façade
Source: Author

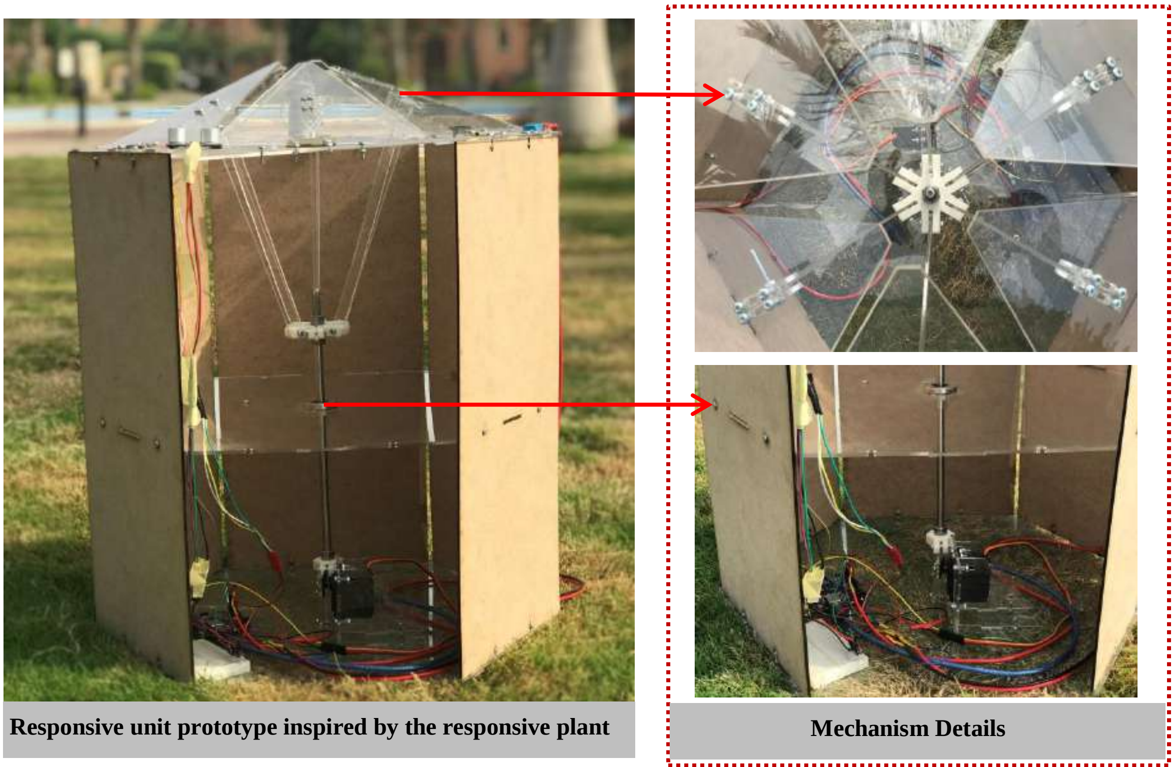


Figure (5-19) The physical prototype mechanism details
Source: Author

5.4 The Fourth Stage: The Architectural Domain

By scripting the sensitive plant's behaviour using the two types of programming languages for various targets. The plant principles have been transferred from a mere text of biological information into digital prototyping for the responsive façade, as an architectural element affected by the environmental factors and physical stimuli that will fulfill the building behaviour targets of Environmental quality as a responsive element; Figure (5-20).

This strategy which mimicked the sensitive plant allows the facades to react based on appropriate environmental conditions available in the space. Additionally, this responsive facade unit reacts to human gestures to be controllable by users. The validation process is to verify the ability of the fabricated prototype to respond to the environmental condition. This will be done through a hands-on experiment on the physical unit by exposing it to various stimuli; Figure (5-20) presents various scenarios for the same units under those stimuli and after their demise.

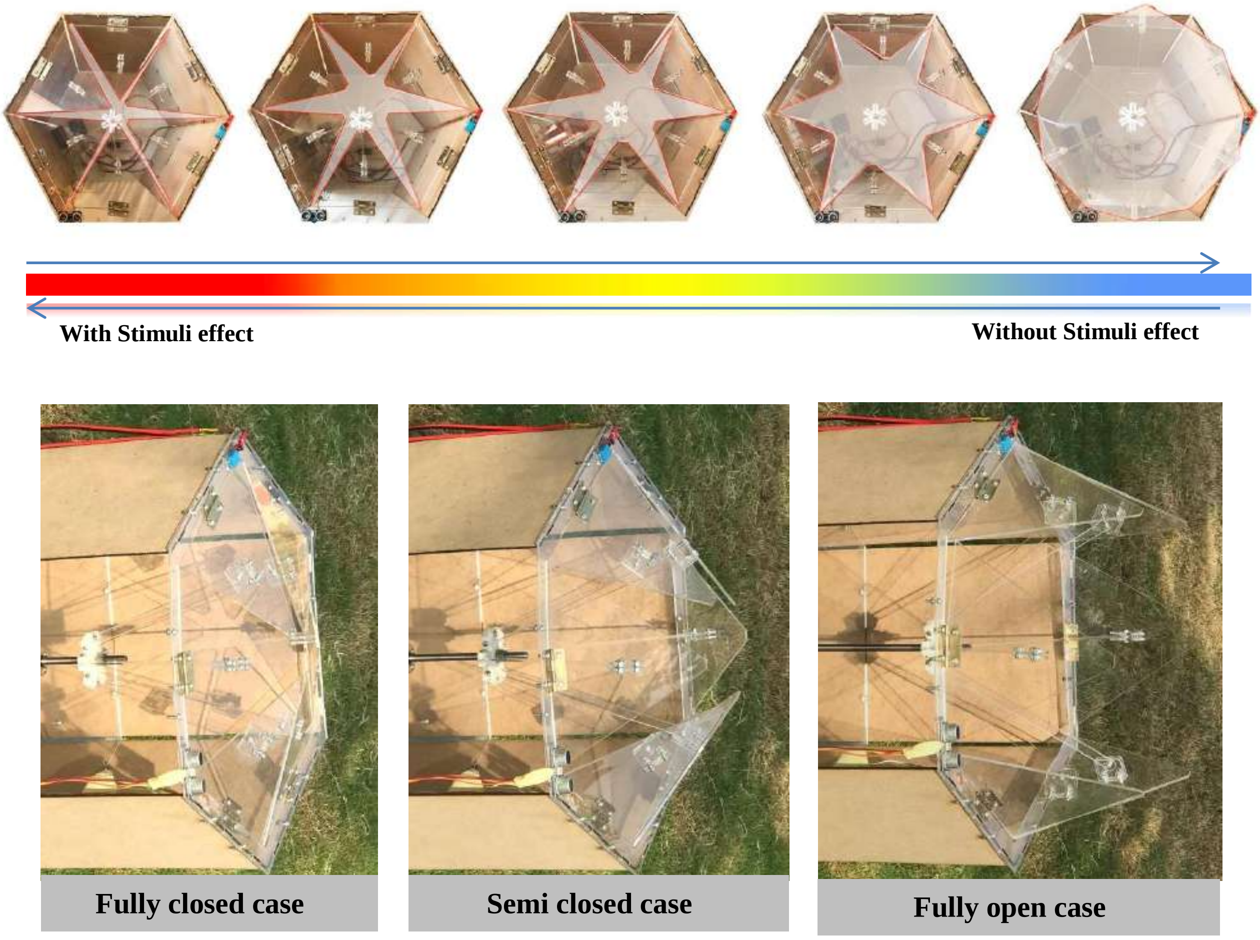


Figure (5-20) The Physical prototype of the responsive façade experiment
Source: Author

The result of this experiment indicated that the unit efficiently responded to various environmental factors and the physical stimuli through the programmed Arduino code. Additionally, the parameters or the variables within the Arduino programming can be changed, where a single unit can be programmed in several ways to react to various environmental conditions. By using the Ultra-sonic sensor that could calculate the distance and use the human movement as an input, the problem of the lack of control the façade by the user will be solved.

5.5 The Application of Mimicking Mimosa Plant Framework

According to the methodology proposed for the problem-based approach, the framework will go through the following steps. The architectural target will be defined, which in this case is the indoor environmental quality by the responsive unit. The first step will be searching for the biological domain using the Ask Nature website. The Mimosa plant was defined as the biological role model in this case study. The second step is analyzing the biological role model using the selected life principles. Mimosa works at the cellular level of complexity. The environmental factor challenging the Mimosa is temperature and light through physical adaptation. The performance concluded from the sensitive plant and its flower blooming was shape change (folding).

Consequently, the third stage involved transferring that biological information to the computational domain by scripting. The visual programming language Grasshopper on Rhino 3D software has been used in scripting the digital prototyping, starting by generating the hexagonal pattern, and then transferring the behaviour of the plants on the façade affected by the environmental stimuli. The physical prototyping went through several steps, starting by the mechanism design to transfer the foldable-deployable kinetic system of the flower blooming to the façade mechanism system by using Solid Works software.

In order for the façade unit to be responsive, sensors were attached and programmed using the textual programming language C in writing the microcontroller Arduino code. The fourth step involves the architectural domain, where an application of the responsive façade unit has been made by the researcher using Rhino 3d, grasshopper the visual scripting, SolidWorks software and the textual programming language C. After that, the validation process was carried out by experimentation the efficiency of the façade unit to fulfill the identified architectural target. The results found that the unit efficiently responded to various environmental factors and the physical stimuli as programmed in the Arduino code; Figure (5-21).

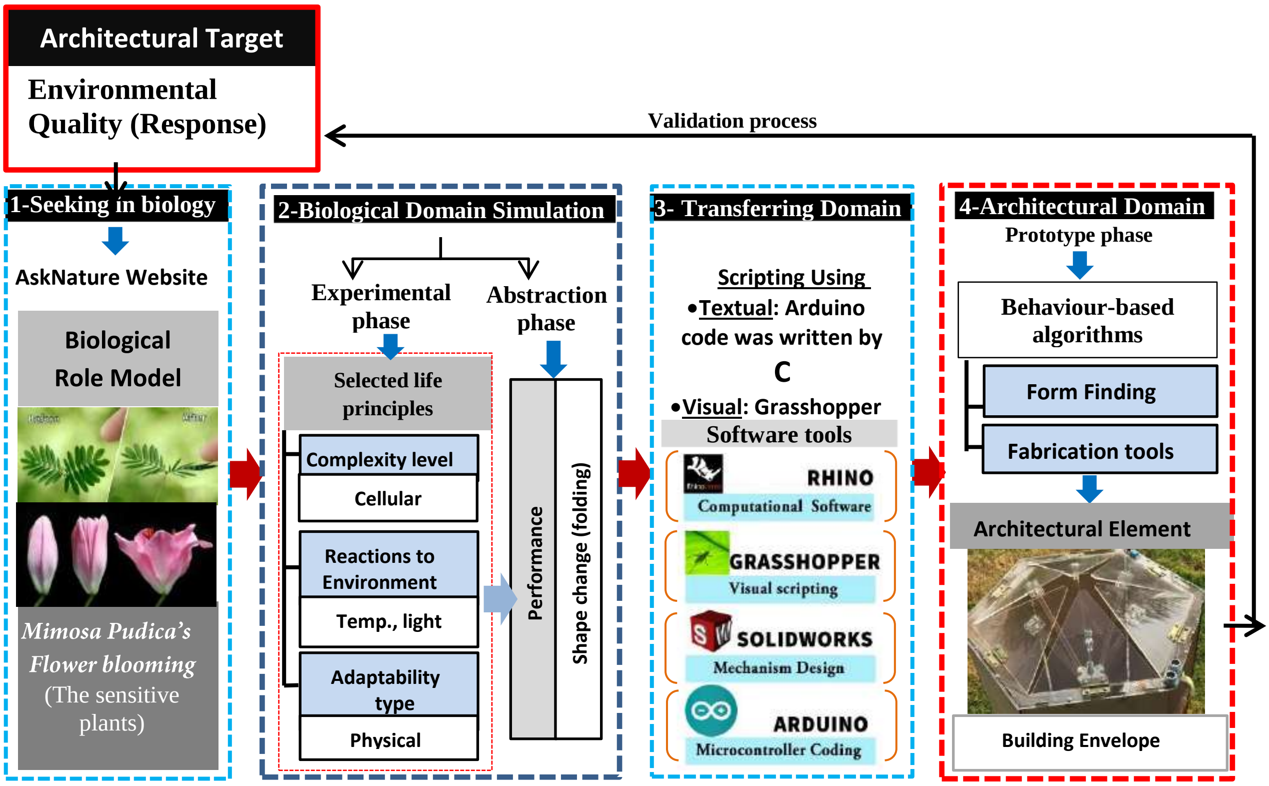


Figure (5-21) Mimosa Pudica's Flower blooming
Encoding framework Diagram
Source: Author

This practical application is a prototype for a responsive facade unit made to evaluate the application of such an approach to building behaviour. In fact, such practical experimentation helped in setting a clearer and more defined design framework from the conceptual stage to the implementation stage. The main finding concluded from this diverse and wide-ranged study was that the proposed framework is not meant to be strictly followed, but to be flexibly adopted as a guiding schema. Worth mentioning that the purpose of the application/outcome of this prototype is not the design of the responsive unit; rather than being the processes in which the design and the fabrication go through.

Chapter Summary

The fifth chapter represents the application of the proposed methodology, aiming to reach a hands-on experience for digital model and the fabrication of physical model through all the steps, starting from defining the building behaviour target till the implementation stage, for the inevitable explanation and to clarify the methodology. Furthermore, design and implement a prototype of a responsive facade unit and a digital and physical prototype is introduced to validate the proposed biomimetic design framework.

In order to transfer the sensitivity of the plant to the façade unit to be responsive, sensors were attached and programmed using the textual programming language C in writing the microcontroller Arduino code. In the architectural domain, an application of the responsive façade unit has been made by the researcher using Rhino 3d, grasshopper the visual scripting, SolidWorks software and the textual programming language C. After that, the validation process was carried out by experimentation the efficiency of the façade unit to fulfill the identified architectural target. The results found that the unit efficiently responded to various environmental factors and the physical stimuli as programmed in the Arduino code. These results represented the success of the Biomimetic Design Framework for Building Behaviour in transferring the behaviour of biological role model to the building behaviour in the form of the architectural elements using the four-staged framework.

CHAPTER 6: Measuring the Influence of Biomimicry on the Building Behaviour

Introduction

Efforts have been exerted by architects to deliver truly remarkable projects leading to a successful bio-morphic architecture based on bio-mimicry with the assistance of the digital revolution. However, this does not necessarily imply their successful transfer of the performance of living systems to building behaviour.

This will be the primary concern of this chapter; it adopts the verification of this success. The benefit gained from mimicking biological role models will be investigated through the criteria established to measure the success rate achieved by the design, especially at the behaviour level. Also, the fulfillment of building behaviour targets will be verified.

6.1 The Aim and Methodology

This chapter uses an analytical methodology to identify and comprehend selected case studies using the evaluation criteria. Create a model to measure the extent of the benefit of simulating biological role models in building behaviour in order to achieve the following aims:

1- Determining the most successful design characteristics inspired by nature that achieved building behaviour targets.

2- Developing future design standards by ensuring that nature is transferred to buildings as a behaviour rather than a mere form, thus increasing building efficiency.

6.1.1 Determinants of Selected Case Studies

The selection process adopted by the researcher in selecting the projects that will be subjected to the analysis as case studies is based on the following selection criteria:

1- Samples selection to be biomimetic buildings based on the simulations of biological performance.
2- The building utilized life principles for mimicking whether in form or in behaviour.
3- The buildings should be designed by senior architects or winning buildings in architectural competitions
4- Established recently in the last 15 years.

6.1.2 Measuring Criteria Analysis Model

In this part, a set of criteria were developed based on the study's elements, and then these criteria were applied to measure the extent of benefit from the imitation into three main dimensions; **First**, the biological domain, it divaricated into four dimensions; **Second** the architectural domain, it divaricated into two dimensions; **Third** the transferring domain, it divaricated into two dimensions. The relative weight was distributed based on the importance of each criterion to achieve the desired targets of building behaviour through simulation. Thus the criteria for the architectural domain will be the greatest value. The criteria are applied to selected case studies as the following:

- **Biological Domain Criteria (Deduced from Chapter Two)**

  a. Biomimetic approaches: Solution-based, Problem-based.
  b. Levels of Biomimicry: Organism, Behaviour, Ecosystem.
  c. Selected life principles: Adaptability, Environmental reactions, Complexity type.
  d. Biological role models performance: Color Change, Growth, Deployment, Shape Change, Variety of shapes, Hierarchies, Self-healing.

- **Architectural Domain Criteria (Deduced from Chapter Three)**

  a. Building behaviour targets: Structure Efficiency, Material Efficiency, Indoor Quality (Thermal Comfort, Visual Comfort, and Air Quality), Energy Efficiency, and Water Quality.
  b. Building behaviour elements: Structure, Envelope, Building systems, interior elements, Materials.

- **Transferring Domain Criteria (Deduced from Chapter Four)**

  a. Computational design levels: The representational level, the parametric level and the generative level.
  b. Computational design tools: Behavioural-physics simulation, form-finding, environmental simulation, optimization and fabrication.

6.2 Case Studies

The following is the analytical study of the selected case studies. In order to measure the influence of biomimicry and classify building types based on the benefit of the biological simulations, buildings varied between local and international building. The researcher selected five international and five local biomimetic buildings to identify the current global and local situation in Egypt for the use of biological simulation in architecture.

- **International Case studies**

The international case studies are samples of biomimetic buildings based on simulating biological performance, these buildings utilized life principles for mimicking whether in form or in behaviour and should be designed by senior architects or for buildings that won architectural competitions. These case studies established recently in the last 15 years.

6.2.1 Case Study 1: Yeosu Oceanic Pavilion

Oceanic Pavilion is a floating marine designed by Emergent Architecture and Kokkugia for the Yeosu 2012 Expo in Korea; Figure (6-1), which will provide another showcase of amazing architecture once the Shanghai Expo has wound to a close. Intended as a centerpiece for the expo, the Oceanic Pavilion is considered a biomimetic building, it is s celebration of the ocean as a living organism and the co-existence of human culture and ocean ecosystem.

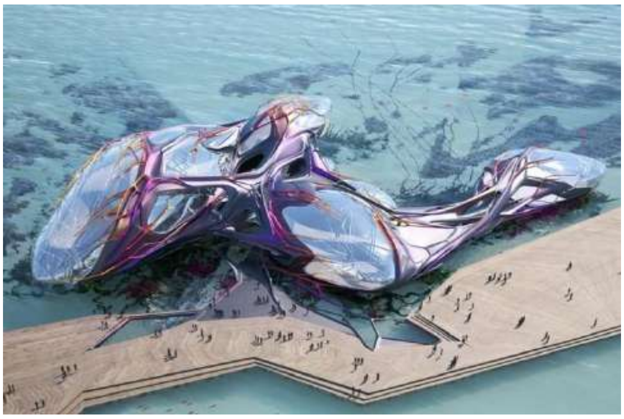


Figure (6-1) Yeosu Oceanic Pavilion
Source: http://cargocollective.com, accessed Oct, 2020

The building is based on an aggregation of soft membrane bubbles merged together with a hard monocoque shell, both being characterized by patterns of surface articulation. This aggregation system inspired by the heart veins system; Arteries carry blood away from the heart while veins carry blood into the heart. Heart veins system works on organ level of complexity; it uses physical adaptation to air as an environmental factor. The performance could be deduced as hierarchies and growth along with the simulated morphology of tissue; Figure (6-2). [1]

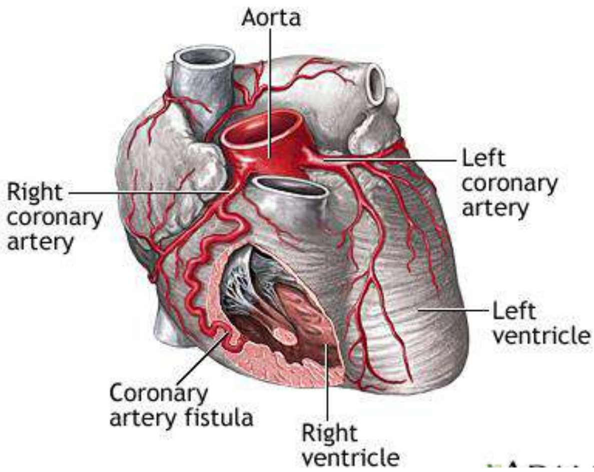
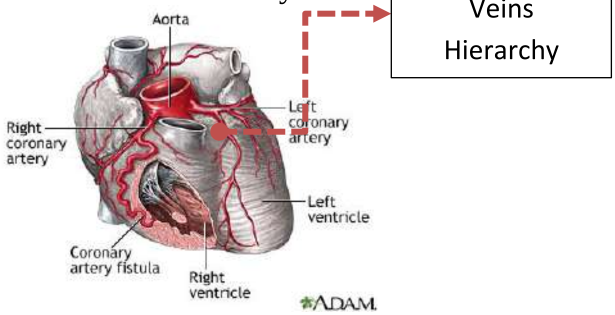
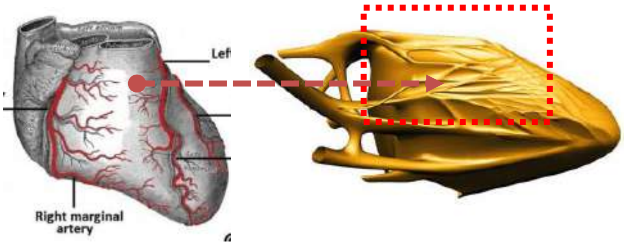
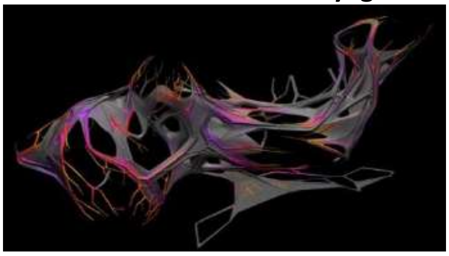
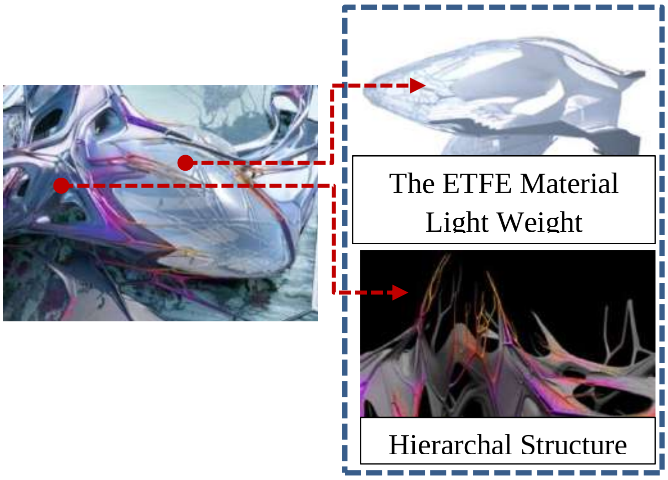


Figure (6-2) Heart veins system
Source: https://teachmeanatomy.info, accessed Oct, 2020

1 https://inhabitat.com/oceanic-pavilion-for-yeosu-expo/yeseou-oceanic-pavilion-2/, accessed Oct, 2020

<table>
<tr><td colspan="2">Project / Analysis Criteria</td><td colspan="2"></td><td>Yeosu Oceanic Pavilion
Emergent Architecture and Kokkugia
Korea
2012</td></tr>
<tr><td rowspan="16">Biological Domain</td><td colspan="2">Biological Role Models</td><td>√</td><td>Heart veins system</td></tr>
<tr><td rowspan="2">Biomimetic Approaches</td><td>Solution based</td><td>---</td><td rowspan="2">Searching for the biological role model to fulfill the structure hierarchy.


This aggregation system is inspired by the heart veins system.</td></tr>
<tr><td>Problem based</td><td>√</td></tr>
<tr><td rowspan="3">Biomimetic Levels</td><td>Organism</td><td>---</td><td rowspan="3">• Mimicking the aggregation growth of veins as the micro-armatures spread out over the structure like veins.
• The micro-armatures called Mohawks spread out over the structure like veins.

</td></tr>
<tr><td>Behaviour</td><td>√</td></tr>
<tr><td>Ecosystem</td><td>---</td></tr>
<tr><td rowspan="3">Selected life principles</td><td>Adaptability</td><td>√</td><td rowspan="3">• The Building mimics the heart veins system on organ level of complexity; it uses structure adaptation.</td></tr>
<tr><td>Environmental Reactions</td><td>---</td></tr>
<tr><td>Complexity type</td><td>√</td></tr>
<tr><td rowspan="8">Biological role model performance</td><td>Colour Change</td><td>---</td><td rowspan="8">• Using Emergent growth of veins to generate the hierarchical structure.
</td></tr>
<tr><td>Growth</td><td>√</td></tr>
<tr><td>Deployment</td><td>---</td></tr>
<tr><td>Shape Change</td><td>---</td></tr>
<tr><td>Variety of shapes</td><td>---</td></tr>
<tr><td>Hierarchies</td><td>√</td></tr>
<tr><td>Self-healing</td><td>---</td></tr>
<tr><td>Communication</td><td>---</td></tr>
</table>

Architectural Domain	**Building Behaviour (Target)**	**Structure Efficiency**	√	• Hard monocoque shell, both being characterized by patterns of surface articulation. • Used the ETFE membrane bubbles to allow natural daylight. • Provide a bit of a thermal barrier and insulation. • Remarkably lightweight.  **ETFE Material allow Daylight**  **Hierarchal Structure**
		Material Efficiency	√	
		Thermal Comfort	---	
		Visual Comfort	---	
		Indoor Air Quality	---	
		Energy Efficiency	---	
		Water Quality	---	
	Building Behaviour (Element)	**Structure**	√	• This building used the structure and envelope elements to fulfill the Structure efficiency architectural target. • Using ETFE Material as an architectural element to increase material efficiency. 
		Envelope	√	
		Building systems	---	
		Interior elements	---	
		Materials	√	• Soft membrane bubbles merged together with a hard monocoque shell. Patterns of surface articulation.

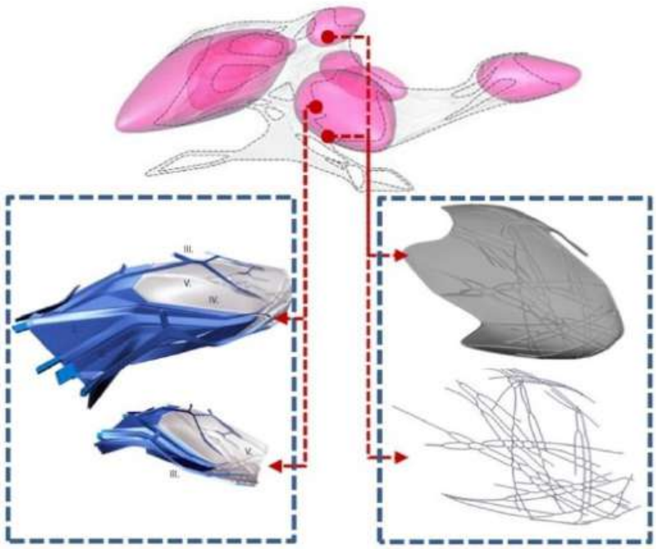
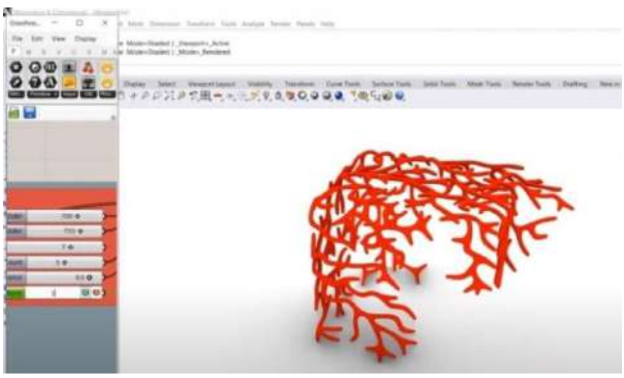
Transferring Domain	**Computational Design Levels**	**Representational Level**	---	• The digital prototype is modeled using the generative tool of PARAKEET Plug-in to generate the veins' hierarchy structure.
		Parametric Level	---	 **Hierarchy Structure** **Glass pattern**
		Generative Level	√	• Digital Prototype for Pavilion Venation Structure using PARAKEET Plug-in. • The ETFE Material Glass Pattern Digital Prototype using Rhino GH. • The design was developed through the exploration of messy computation.
	Computational Design Tools	**Behavioural Physics Simulation**	√	• This pavilion is generated by a behavioural physics simulation using Rhino 3D and Grasshopper and their plug-in PARAKEET.
		Form-Finding	√	
		Environmental Simulation	---	
		Optimization	---	
		Fabrication	---	• Digital Venation using PARAKEET plug-in on Rhino GH.

Table (6-1) Yeosu Pavilion Analysis using Measuring Criteria
Source: Author

6.2.2 Case Study 2: Floating Brazilian Pavilion for Dubai Expo 2020

Brazilian architect Gabriel Kozlowski has unveiled the design for the Dubai Expo 2020 in Dubai. The floating pavilion; Figure (6-3) gently sits on undulating walls, which provide free public circulation on the ground floor, to project "an inverted topography" of the city. Designed with renowned stenographer Gringo Cardia, the pavilion is inspired by one of the greatest technological achievements of Brazil: the improvement of the Direct Planting System over the straw. This agricultural technique protects the soil and maintains the ideal thermal conditions for cultivation.[2]

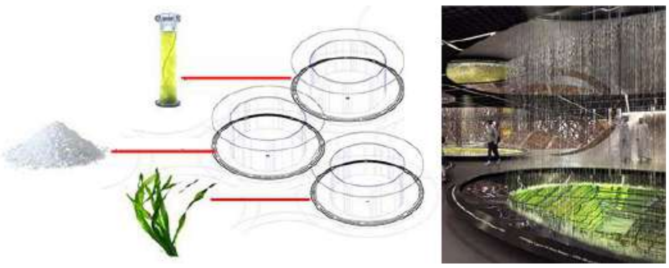
Figure (6-3) Floating Brazilian Pavilion in Dubai
Source: https://worldarchitecture.org, accessed Oct, 2020

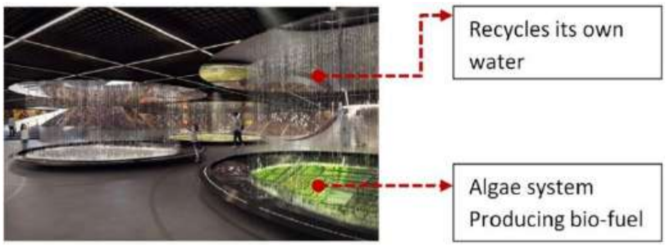
The pavilion conceptually mimics Straw; they are an agricultural byproduct consisting of the dry stalks of cereal plants after the grain and chaff have been removed. The pavilion generates form like straw; Figure (6-4), and mimics the behaviour of this scheme through its layered arrangement; soil, the entanglement of protection, productivity, presenting itself as both a building and a symbolic image of the signs of progress.

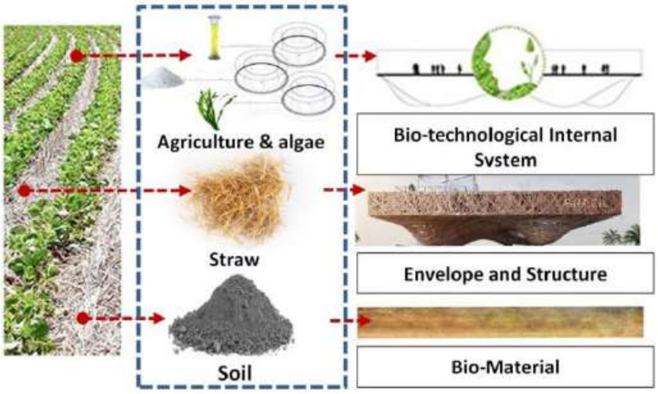
Figure (6-4) Straw Arrangement
Source: https://en.wikipedia.org, accessed Oct, 2020

The pavilion's design decisions are based on technological advances in sustainability, both of construction and of performance. The walls are combined with the soils of each biome and surrounded by totems containing the seeds of their native species, narrating a tactile history of the foundations of our country through colours and textures. In this pavilion, there is no distinction between outside and inside, between building and exhibition, between sustainability and technology, all together form a single sensory-cognitive experience.[3]

2 https://worldarchitecture.org/architecture-news/epfpz/gabriel-kozlowski-unveils-design-for-floating-brazilian-pavilion-for-dubai-expo-2020.html, accessed Oct, 2020
3 Op. cit.

Project / Analysis Criteria				Floating Brazilian Pavilion Gabriel Kozlowski Dubai 2020
Biological Domain	Biological Role Models		√	Straw Agriculture
Biological Domain	Biomimetic Approaches	Solution based	√	• Inspired by the agriculture strategies for generating energy and sustainable systems 
Biological Domain	Biomimetic Approaches	Problem based	---	
Biological Domain	Biomimetic Levels	Organism	√	• Generates form and structure from straw on the organism level.  • Mimics straw agriculture system productivity on behaviour level.
Biological Domain	Biomimetic Levels	Behaviour	√	
Biological Domain	Biomimetic Levels	Ecosystem	---	
Biological Domain	Selected life principles	Adaptability	√	• It depends on the bio-material which reacts to all environmental factors using chemical adaptation on micro-level of complexity.  This material consists of the rammed earth mixed with reinforced concrete.
Biological Domain	Selected life principles	Environmental Reactions	√	
Biological Domain	Selected life principles	Complexity type	√	
Biological Domain	Biological role model performance	Colour Change	---	Using growth and communication in the internal agriculture system and the algae system. 
Biological Domain	Biological role model performance	Growth	√	
Biological Domain	Biological role model performance	Deployment	---	
Biological Domain	Biological role model performance	Shape Change	---	
Biological Domain	Biological role model performance	Variety of shapes	---	
Biological Domain	Biological role model performance	Hierarchies	---	
Biological Domain	Biological role model performance	Self-healing	---	
Biological Domain	Biological role model performance	Communication	√	

<table>
<tr><td rowspan="12">Architectural Domain</td><td rowspan="7">Building Behaviour (Target)</td><td>Structure Efficiency</td><td>√</td><td rowspan="7">
• Laminated timber as a structure.
• Renewable material that sequesters carbon.
• Produces its own energy.
• Recycles its own water.
• Doesn’t use air conditioning.
• Flow of air through an open façade.


• The use of air conditioning unnecessary by combining the constant flow of air through an open façade, with the humidity of running water and of the vegetation under the shadow.
</td></tr>
<tr><td>Material Efficiency</td><td>√</td></tr>
<tr><td>Thermal Comfort</td><td>√</td></tr>
<tr><td>Visual Comfort</td><td>√</td></tr>
<tr><td>Indoor Air Quality</td><td>√</td></tr>
<tr><td>Energy Efficiency</td><td>√</td></tr>
<tr><td>Water Quality</td><td>√</td></tr>
<tr><td rowspan="5">Building Behaviour (Element)</td><td>Structure</td><td>√</td><td rowspan="5">
This building used renewable material, internal cooling system, structure and envelope elements to fulfil the architectural targets.


The building explores the plastic potential of laminated timber as a structure - renewable material that sequesters carbon rather than releasing which lowers its energy of production and the absorption of heat.
</td></tr>
<tr><td>Envelope</td><td>√</td></tr>
<tr><td>Building systems</td><td>√</td></tr>
<tr><td>Interior elements</td><td>√</td></tr>
<tr><td>Materials</td><td>√</td></tr>
</table>

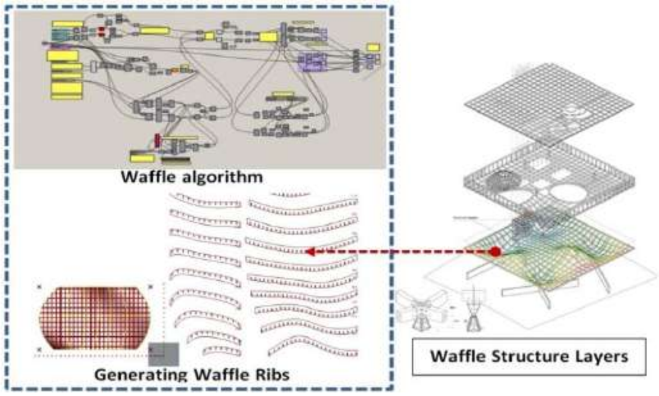
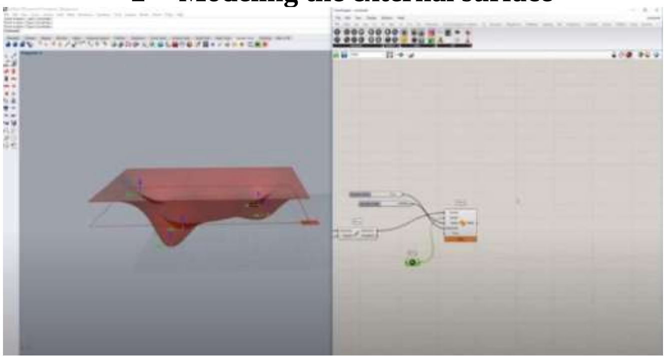
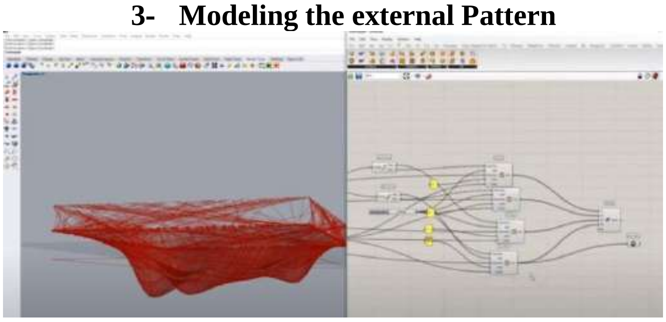
Transferring Domain	**Computational Design Levels**	**Representational Level**	---	• Bio-inspired pattern using the parametric tools on Rhino GH based on the parameters of iso-curves GH component. • Waffle structure using fabrication tools on Rhino GH
		Parametric Level	√	
		Generative Level	---	
	Computational Design Tools	**Behavioural Physics Simulation**	---	This digital model divided into Three steps; • first, the waffle structure using fabrication tools on Rhino GH • Second, modeling the surface • Third the modeling bio-inspired pattern using the parametric tools on Rhino GH
		Form-Finding	√	**1- Waffle structure Digital Model** 
		Environmental Simulation	---	
		Optimization	---	**2- Modeling the external surface** 
		Fabrication	√	**3- Modeling the external Pattern** 

Table (6-2) Floating Brazilian Pavilion Analysis using Measuring Criteria
Source: Author

6.2.3 Case Study 3: Council House 2 Office Building

Council House 2 (CH2); Figure (6-5) is a 10-storey office building for about 540 City of Melbourne staff, located at 240 Little Collins Street, Melbourne Australia that was officially opened in August 2006. it is a multi-award winning and inspirational building that has reduced CO2 emissions by 87%, electricity consumption by 82%, gas by 87% and water by 72%.[4] CH2 has been designed to copy the planet's ecology using the natural 24-hour cycle of solar energy, natural light, air and rainwater, to power, heat, cool, and water the building.[5]

Figure (6-5) Council House 2 (CH2) in Dubai
Source: https://designinc.com.au, accessed Oct, 2020

This case study will focus on using multi-target strategies, as the building used multiple bio-inspired strategies for each architectural target and each facade has its own appropriate strategy. The building has improved staff effectiveness by 4.9% and will pay for its sustainable features in a little over a decade. Additionally, it is the first building in Australia to achieve a six-star rating from the Green Building Council of Australia.

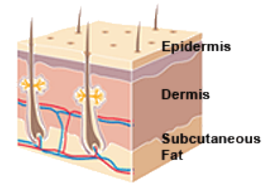
Biomimicry was a large component in designing the building. The heating, ventilating, and cooling system (HVAC) is designed with strategies taken from a termite mound. In the termite mound; Figure (6-6), the cool wind is drawn into the base of the mound, via channels and the 'coolth' is stored using wet soil. As the wark air flows out of the mound via vents in order to keep a stable temperature in mounds. Another strategy used taken from nature is the skin system. The façade is composed of the outer skin and inner skin. Additionally, it mimics the aesthetic and function of bark in the eastern façade for protecting the indoor quality.

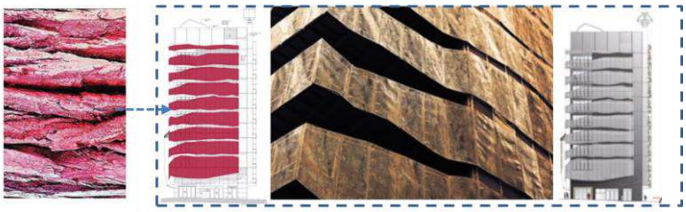
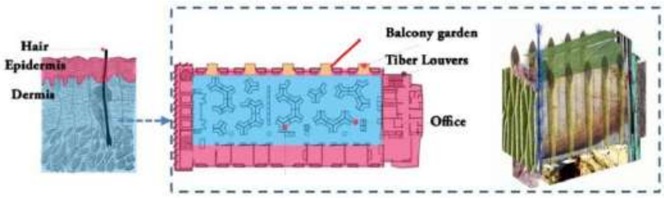
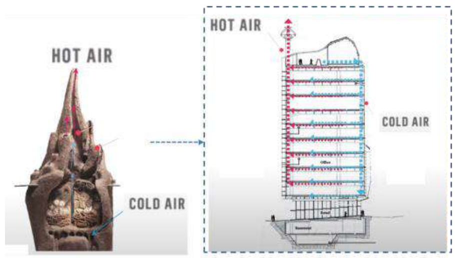
Figure (6-6) Termites' Mound
Source: https://earthlymission.com, accessed Oct, 2020

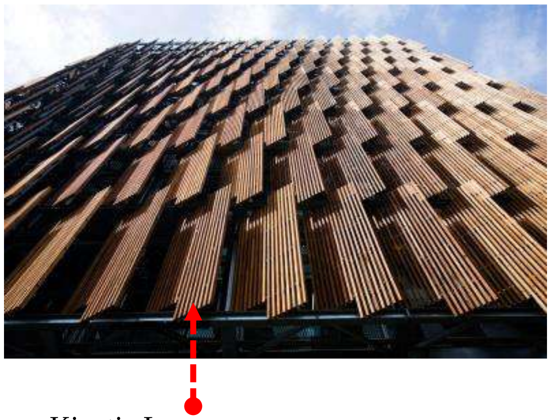
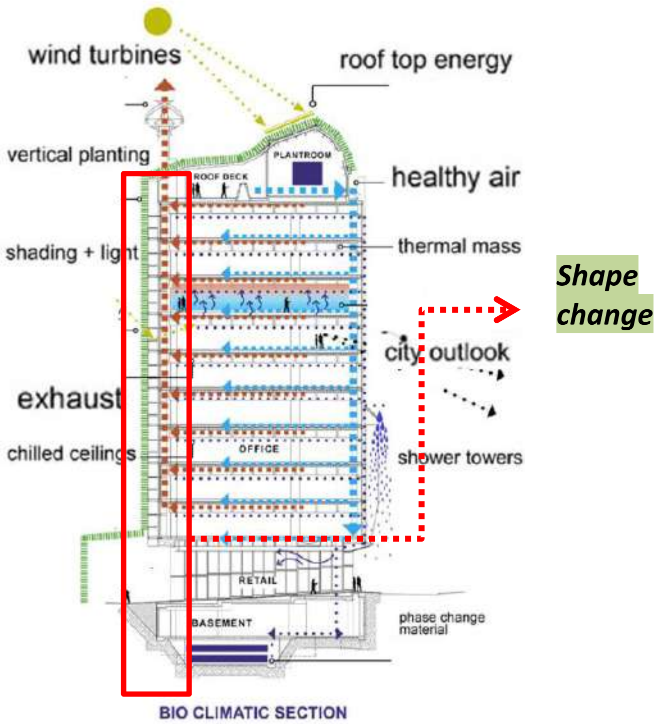
4 Paul Bannister, "COUNCIL HOUSE 2 (CH2) IN REVIEW", Conference Paper, AIRAH Conference, Australia, 2013
5 https://www.c40.org, accessed Oct, 2020

<table>
<tr><td colspan="4">**Project**
Analysis Criteria</td><td>
Council House 2 (CH2)
Mick Pearce
Melbourne, Australia
2006</td></tr>
<tr><td rowspan="6">**Biological Domain**</td><td colspan="2">**Biological Role Models**</td><td>√</td><td>Termites' mound, the skin system and bark</td></tr>
<tr><td rowspan="2">**Biomimetic Approaches**</td><td>**Solution based**</td><td>√</td><td rowspan="2">• (HVAC) is designed with strategies taken from a termite mound.
• The skin system. The façade is composed of an epidermis (outer skin) and dermis (inner skin).
• Mimics the aesthetic and function of bark in the eastern façade

Mounds

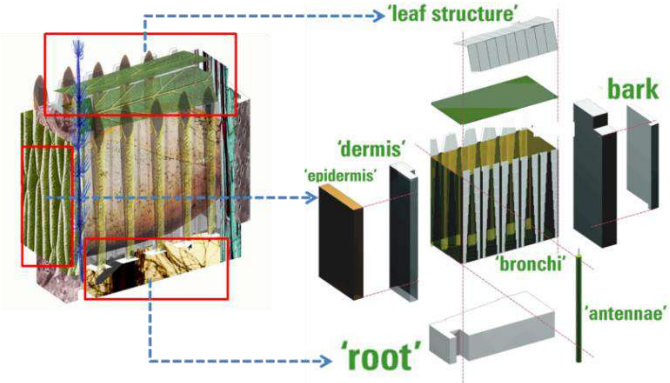
Bark


Human Skin</td></tr>
<tr><td>**Problem based**</td><td>---</td></tr>
<tr><td rowspan="3">**Biomimetic Levels**</td><td>**Organism**</td><td>√</td><td>• The building generates form from the aesthetic of bark on organism level in the eastern façade.
</td></tr>
<tr><td>**Behaviour**</td><td>√</td><td>• Mimics the skin system on behaviour level

</td></tr>
<tr><td>**Ecosystem**</td><td>---</td><td>• The building mimics HVAC system from mounds

</td></tr>
</table>

Biological Domain	**Selected life principles**	**Adaptability**	√	• It depends on both the physical adaptation in the western façade mechanically. • It reacts to all the environmental factors: Heat, energy, light, and air • It mimics the bark on the organism level of complexity, the human skin on the culler level of complexity, and the termite mounds on the eco-system.
		Environmental Reactions	√	
		Complexity type	√	Kinetic Louvers
	Biological role model performance	**Colour Change**	---	Using shape change performance in the kinetic façade and communication in the internal HVAC system.
		Growth	---	
		Deployment	---	
		Shape Change	√	
		Variety of shapes	---	
		Hierarchies	√	
		Self-healing	---	
		Communication	√	**Communication in the internal HVAC system**

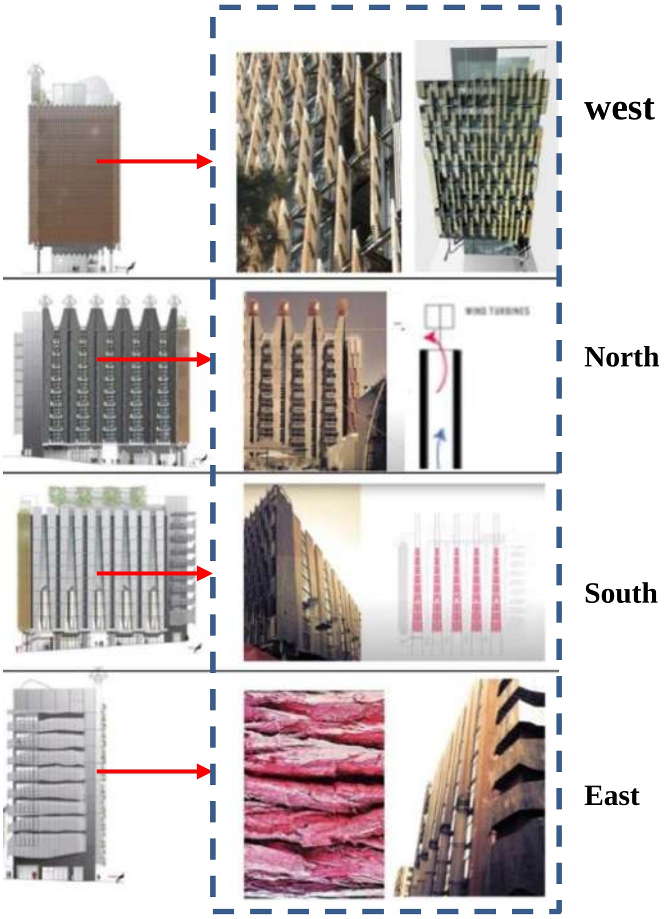
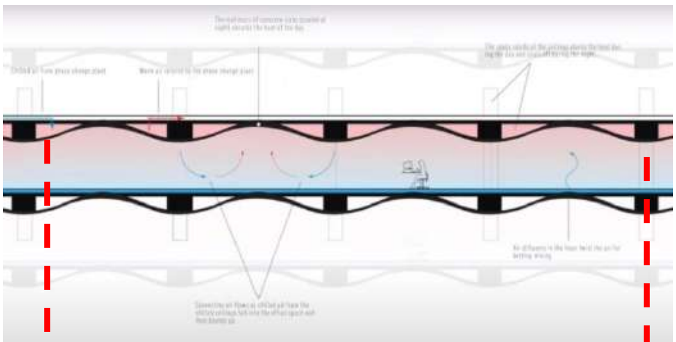
<table>
<tr><td rowspan="10">Architectural Domain</td><td rowspan="7">Building Behaviour (Target)</td><td>Structure Efficiency</td><td>√</td><td rowspan="7">

• Deliver **fresh air** to each floor at a low level
• Help reduce glare by their splayed plan profile
• Taper in elevation to allow greater light to the lower levels of the building
• Change in concrete colour from north to south to optimize thermal load
• Help carry vertical landscape down the façade
• the use of recycled concrete and timber, waste-water harvesting and cogeneration of power
• CH2 achieved the structure efficiency, material efficiency, the indoor environment quality, energy efficiency and water quality as it acts as the living organism



• Building system acts like living organism consists of complex element inspired by human skin, termites mounds and the photovoltaic panels on the roof inspired by leaves
</td></tr>
<tr><td>Material Efficiency</td><td>√</td></tr>
<tr><td>Thermal Comfort</td><td>√</td></tr>
<tr><td>Visual Comfort</td><td>√</td></tr>
<tr><td>Indoor Air Quality</td><td>√</td></tr>
<tr><td>Energy Efficiency</td><td>√</td></tr>
<tr><td>Water Quality</td><td>√</td></tr>
<tr><td rowspan="3">Building Behaviour (Element)</td><td>Structure</td><td>√</td><td rowspan="3">

• The building uses the The heating, ventilating, and cooling in building system.
• Serve as solid external wall elements – optimizing the Extent of glass
• used recycled timber material
• Each elevation deals with the environment by the suitable strategy.
• Produces its own energy
</td></tr>
<tr><td>Envelope</td><td>√</td></tr>
<tr><td>Building systems</td><td>√</td></tr>
</table>

Architectural Domain	**Building Behaviour (Element)**	**Interior elements**	√	
		Materials	√	The building is depending on the internal system for cooling.  The internal cooling system  Chilled ceiling Internal Gardens

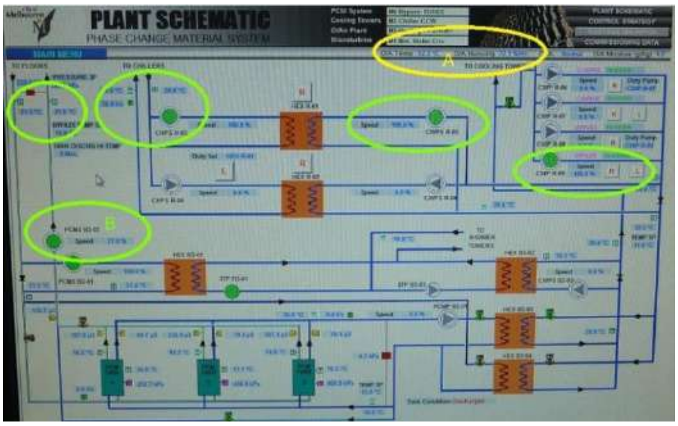
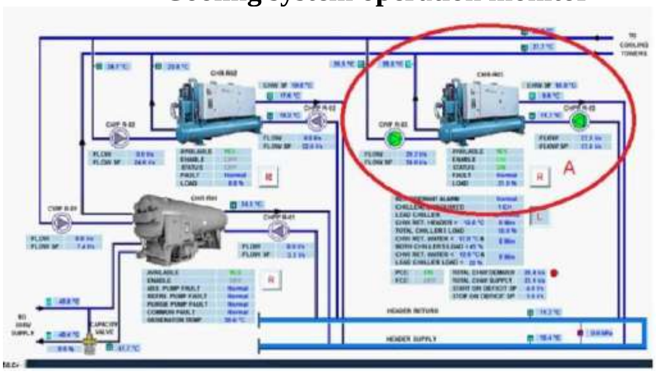
Transferring Domain	**Computational Design Levels**	**Representational Level**	---	The building used behaviour-based algorithms for environmental simulation optimization and in the fabrication process, and then used it in the operating process.
		Parametric Level	---	
		Generative Level	√	
	Computational Design Tools	**Behavioural Physics Simulation**	---	• The mechanical monitors for the mechanical systems  **Cooling system operation monitor**  **Chilled water system operation monitor**
		Form-Finding	---	
		Environmental Simulation	√	
		Optimization	√	• The building used the programming language for operating the kinetic façade for coding the microcontroller to operate louver according to the data given by the building's weather station.  **Kinetic façade tracking the sun**
		Fabrication	√	

Table (6-3) CH2 Office building Analysis using Measuring Criteria
Source: Author

6.2.4 Case Study 4: GSA Office Building Retrofit

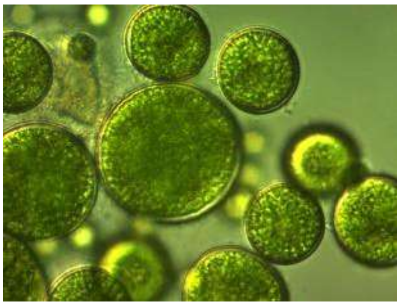
HOK and Vanderweil utilized microalgal PBRs to power the Net Zero building as a retrofit solution for the 46-year-old federal office building in downtown Los Angeles, the GSA office building. The Net Zero retrofit solution; Figure (6-7), the winner of the International Algae Competition and Metropolis Magazine's Next Generation Design Competition 2011, was introduced in order to reduce building emissions by 30% by 2020.[6] This case study will focus on using multi-target strategies, as the building mimicked algae for energy efficiency, water efficiency and indoor air quality. In addition, the internal atriums are inspired by the light beams in the upper canyon for visual comfort.

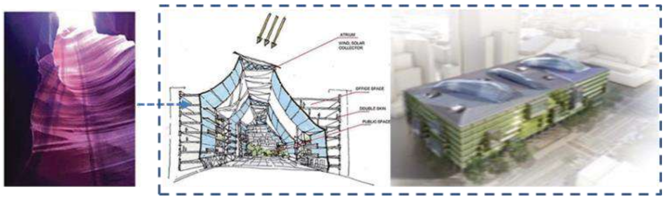
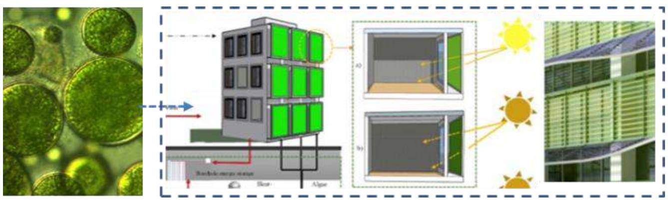
Figure (6-7) GSA Office Building Retrofit in Los Angeles
Source Mohammad, G., 2018

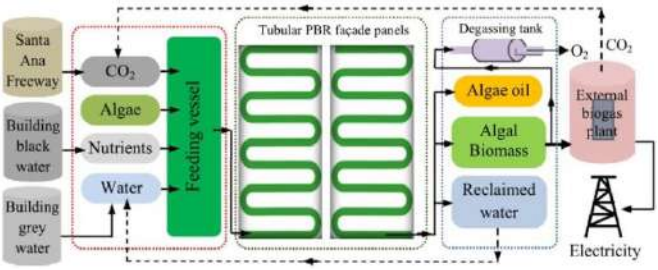
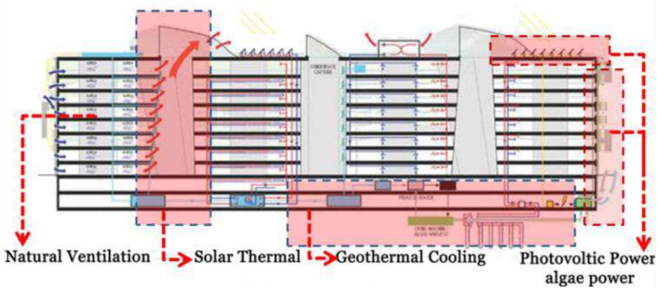
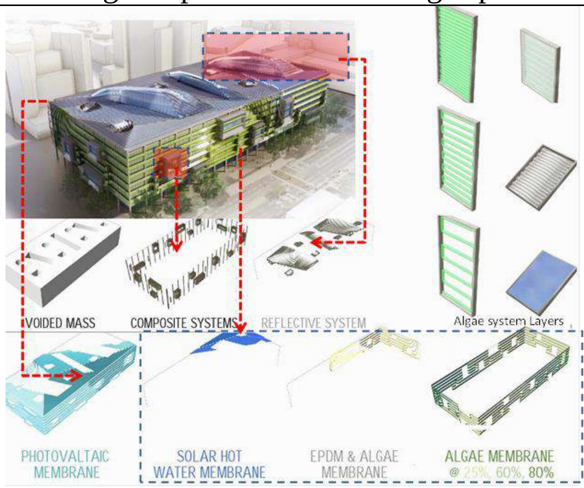
Algae Systems; Figure (6-8) integrates a suite of technologies into a process that grows native algae species to provide cost-effective wastewater treatment, removing CO2 from the atmosphere and yielding only clean water, carbon-negative bio-fuels, and fertilizers as its end products.[7] The microalgae PBRs cover 25,000 ft2 of the GSA building's envelope with a modular network of tubular PBRs. The PBRs capture sunlight, absorb CO2, release O2, and produce lipids for fuel production on site. Simultaneously, the PBRs provide the interior spaces with sun shading.[8]

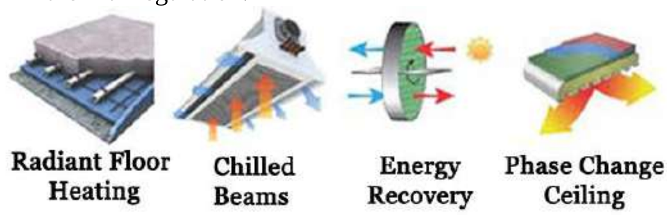
Figure (6-8) Algae façade system
Source: https://www.thefifthestate.com.au, accessed Oct, 2020

6 Mohammad, G., "Microalgae: Prospects for greener future buildings", Article, Elsevier J., Egypt, 2018
7 https://www.bfi.org, accessed Oct, 2020
8 Stoller, P., "Exploring the feasibility of algae building technology in NSW", Conference paper, Elsevier J., Sydney, 2016

<table>
<tr><td colspan="4">Project / Analysis Criteria</td><td>
GSA Office Building Retrofit
HOK and Vanderweil
Los Angeles
2011</td></tr>
<tr><td rowspan="9">Biological Domain</td><td colspan="2">Biological Role Models</td><td>√</td><td>Algae and Upper Canyon</td></tr>
<tr><td rowspan="2">Biomimetic Approaches</td><td>Solution based</td><td>---</td><td rowspan="2">• The existing GSA Office Building has energy consumption issues; therefore, HOK and Vanderweil used the problem-based approach to seek for the solution and to power the Net Zero building.
• The internal atriums mimicked the upper canyon for visual comfort target.

Algae

Canyon</td></tr>
<tr><td>Problem based</td><td>√</td></tr>
<tr><td rowspan="3">Biomimetic Levels</td><td>Organism</td><td>√</td><td rowspan="3">• The building generates the internal atriums form inspired by Canyon

• Mimics Algae system on behaviour level
</td></tr>
<tr><td>Behaviour</td><td>√</td></tr>
<tr><td>Ecosystem</td><td>---</td></tr>
<tr><td rowspan="3">Selected life principles</td><td>Adaptability</td><td>√</td><td rowspan="3">• It depends on the bio-reactor algae system which adapts chemically for all environmental factors and works on the micro-level of complexity</td></tr>
<tr><td>Environmental Reactions</td><td>√</td></tr>
<tr><td>Complexity type</td><td>√</td></tr>
</table>

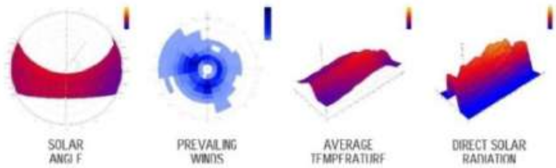
	Biological role model performance	**Colour Change**	---	• Using growth performance in algae system  The microalgae photo bioreactor system of the Process Zero Retrofit building
		Growth	√	
		Deployment	---	
		Shape Change	---	
		Variety of shapes	---	
		Hierarchies	---	
		Self-healing	---	
		Communication	---	
Architectural Domain	**Building Behaviour (Target)**	**Structure Efficiency**	---	• The PBRs capture sunlight, absorb CO_2, release O_2, and produce lipids for fuel production on site. • Provide the interior spaces with sun shading.  • Building integrated system of internal and external elements provide the building with natural ventilation, solar thermal, geothermal cooling and photovoltaic and algae power.
		Material Efficiency	√	
		Thermal Comfort	√	
		Visual Comfort	√	
		Indoor Air Quality	√	
		Energy Efficiency	√	
		Water Quality	√	
	Building Behaviour (Element)	**Structure**	---	
		Envelope	√	
		Building systems	√	

<table>
<tr><td rowspan="2">Architectural Domain</td><td rowspan="2"></td><td>Interior elements</td><td>√</td><td rowspan="2">
• This building used bio-reactor material, internal cooling system, envelope elements to fulfil the architectural targets.
• The building depends on the interior elements for thermal regulation.


</td></tr>
<tr><td>Materials</td><td>√</td></tr>
<tr><td rowspan="8">Transferring Domain</td><td rowspan="3">Computational Design Levels</td><td>Representational Level</td><td>---</td><td rowspan="3">The retrofit proposal has made according to behaviour-based algorithms used for the environmental simulation and optimization</td></tr>
<tr><td>Parametric Level</td><td>---</td></tr>
<tr><td>Generative Level</td><td>√</td></tr>
<tr><td rowspan="5">Computational Design Tools</td><td>Behavioural Physics Simulation</td><td>---</td><td rowspan="5">
The building retrofit workflow done using computational design divided into three steps;
• First, gather information about the existing building and the environmental simulation.

• Second, Generate the digital model based on the environmental optimization parameters

• Third, analysis the building behaviour of the retrofit proposal and comparing with the existing situation



</td></tr>
<tr><td>Form-Finding</td><td>---</td></tr>
<tr><td>Environmental Simulation</td><td>√</td></tr>
<tr><td>Optimization</td><td>√</td></tr>
<tr><td>Fabrication</td><td>---</td></tr>
</table>

Table (6-4) GSA Office Building Retrofit Analysis using Measuring Criteria
Source: Author

6.2.5 Case Study 5: Palazzo Italia Pavilion for Milano Expo 2015

In Expo Milano 2015, Italy's pavilion had an air-cleaning facade designed by Roma studio Nemesi & Partners to resemble tree branches represents an urban forest. Palazzo Italia's facade, a mixture of cement and titanium dioxide, captures nitrogen-oxide pollution and converts it into a harmless salt that easily rinses off the walls when it rains; Figure (6-9). Palazzo Italia also consumes 40 percent less energy than a conventional building of its size and emits zero air pollution.[9]

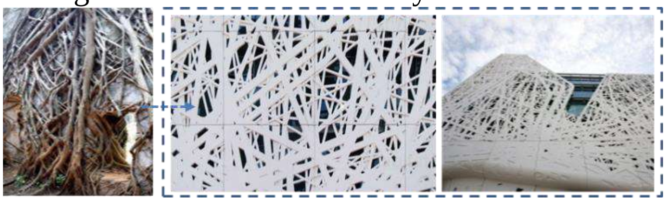
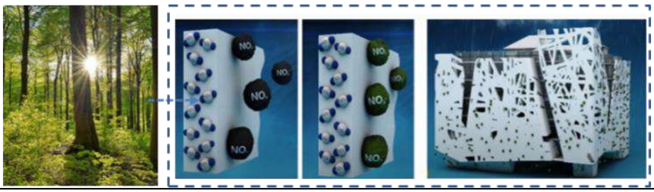
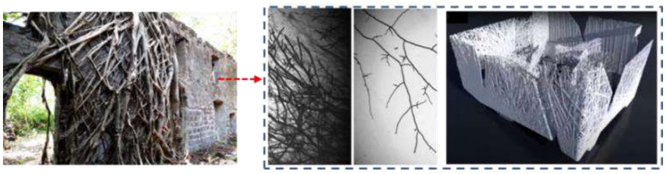
Figure (6-9) Palazzo Italia Pavilion in Italy
Source: https://designinc.com.au, accessed Oct, 2020

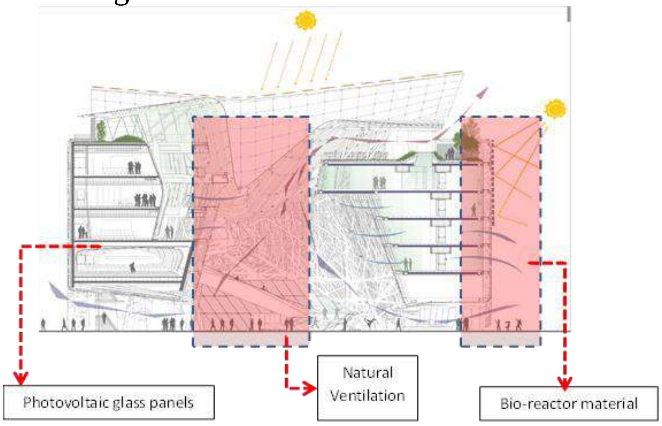
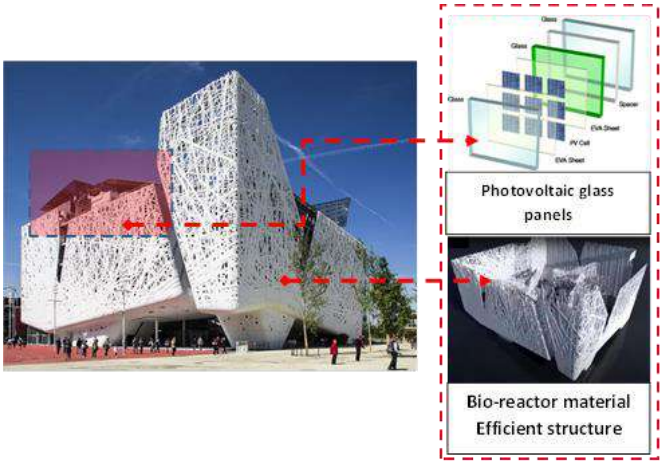
This case study will focus on using material-based strategy, as the building used bio-inspired material for air cleaning like forest branches to achieve the indoor air quality architectural target. In addition the facade's intricate alternation between solid and void results in a dappled light and shadow effect across the internal square to achieve the visual comfort target. The building used the contribution of photovoltaic glass in coverage and photocatalytic properties of new concrete for the outer casing to achieve a sustainable energy building almost zero.

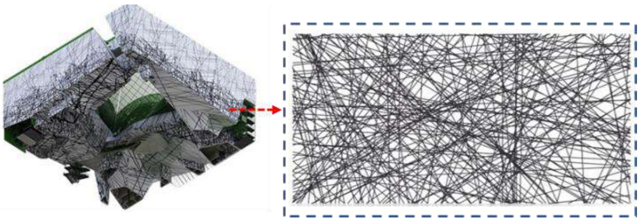
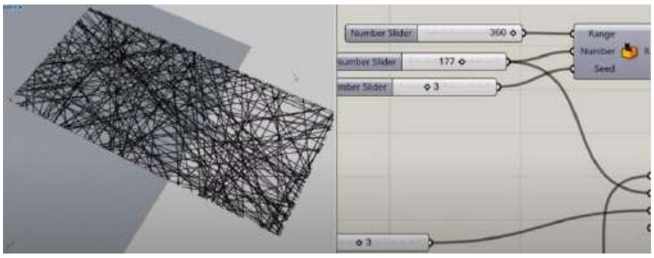
The architectural concept of the Italy Pavilion project by Nemesi & Partners is an urban forest; Figure (6-10). Palazzo Italia is inspired by a natural architecture in which the branched weave of the external "skin" of the building generates alternations of light and shadow and solids and voids, creating a scenario that refers to works of Land Art. The external "skin" of the building evokes the artistic concept of through the image of a petrified forest.

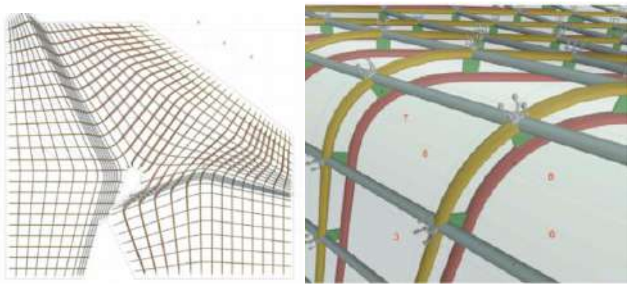
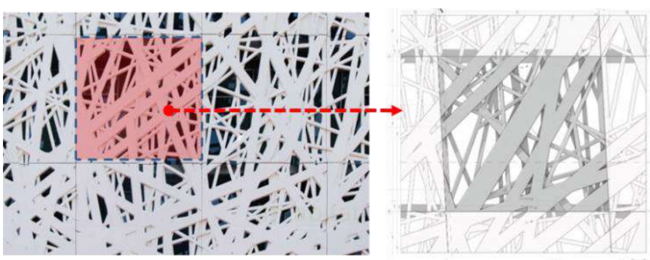
Figure (6-10) Petrified Forest Roots
Source: https://earthlymission.com, accessed Oct, 2020

9 https://inhabitat.com, accessed Oct, 2020

Project / Analysis Criteria				 Palazzo Italia Pavilion Nemesi & Partners Roma studio Italy 2015
Biological Domain	**Biological Role Models**		√	Petrified Forest Roots
	Biomimetic Approaches	**Solution based**	---	• The designer used the bio-reactor material to solve the air pollution problem. • The Palazzo Italia is inspired by the growth of the branched weaved and petrified forest roots.
		Problem based	√	 Petrified forest roots
	Biomimetic Levels	**Organism**	√	• The building generates the external skin form inspired by the growth of weaved roots on the organism level of biomimicry. 
		Behaviour	√	• It mimics the air filtration of the urban forest on the behaviour level. 
		Ecosystem	---	
	Selected life principles	**Adaptability**	√	• It depends on the bio-reactor material which adapts chemically for the air of the environmental factors and works on the atomic level of complexity.
		Environmental Reactions	√	
		Complexity type	√	
	Biological role model performance	**Colour Change**	---	• The building mimics deployment performance of the branches form generation.  • Branching form generation based on the deployment performance.
		Growth	---	
		Deployment	√	
		Shape Change	---	
		Variety of shapes	---	
		Hierarchies	√	
		Self-healing	---	
		Communication	---	

Architectural Domain	**Building Behaviour (Target)**	**Structure Efficiency**	√	• The facade's intricate alternation between solid and void results in a dappled light and shadow effect provide the interior spaces with sun shading  • Using natural ventilation • Photovoltaic glass and photocatalytic concrete produce power.
		Material Efficiency	√	
		Thermal Comfort	√	
		Visual Comfort	√	
		Indoor Air Quality	√	
		Energy Efficiency	√	
		Water Quality	---	
	Building Behaviour (Element)	**Structure**	√	This building used bio-reactor material to achieve the indoor air quality, and efficient structure, and Photovoltaic glass for energy efficiency target.  Building Elements
		Envelope	√	
		Building systems	---	
		Interior elements	---	
		Materials	√	
Transferring Domain	**Computational Design Levels**	**Representational Level**	---	• The digital modeling of the pavilion is according to behaviour-based algorithms to generate the form of the external façade and the alternation between solid and void results in a dappled light and shadow effect. • The implementing phase of the pavilion used the fabrication tools for paneling the façade and used the pre-fabricated cement panel in I-lab in Italy.
		Parametric Level	---	
		Generative Level	√	

<table>
<tr>
<td rowspan="5">Transferring Domain</td>
<td rowspan="5">Computational Design Tools</td>
<td>Behavioural Physics Simulation</td>
<td>---</td>
<td rowspan="5">This pavilion used the computational design process in three stages;
• First, generating the external façade form using Rhino Grasshopper 3D.

• Afterwards, verify by the environmental simulation
• To achieve the alternation between solid and void that results in a dappled light and shadow effect.


• Second, the building waffle scripting for modeling the structure

• Third, the fabrication process and it is divided into two steps the first one modeling the paneling façade to be fabricated
</td>
</tr>
<tr>
<td>Form-Finding</td>
<td>---</td>
</tr>
<tr>
<td>Environmental Simulation</td>
<td>√</td>
</tr>
<tr>
<td>Optimization</td>
<td>---</td>
</tr>
<tr>
<td>Fabrication</td>
<td>√</td>
</tr>
</table>

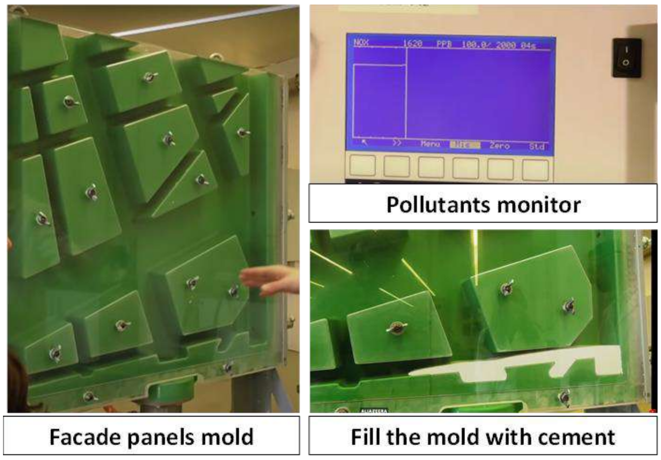
Transferring Domain		**Fabrication**		Then the pre-fabrication inside the I-Lab in Italy and the pollutants monitor for calculating the pollution reduction in the air.  Pre-fabrication process in I-Lab Italy

Table (6-5) Palazzo Italia Pavilion Analysis using Measuring Criteria
Source: Author

- **local Case Studies**

The local case studies are samples of biomimetic buildings in Egypt. These case studies will focus on the biomimetic approach outcomes in Egypt that utilized the biomimicry for mimicking whether in form or in behaviour and should be designed by senior architects or for buildings that won architectural competitions. These case studies established recently in the last 15 years.

6.2.6 Case study 6: The Yard in New Cairo, Egypt

In Egypt 2017, The Yard Mall Designed by AI Designs in Egypt, it awarded in cityscape global awards in 2017. The Yard is a commercial mall that contains shops, administrative units, and restaurants and cafes. It lends a modern touch using hard edges, royal colours and modern lighting to the genuine soul of historic arenas, feel the containment and space, the modernity and nobility, smoothness and adequacy, truly balanced design that is very welcoming, prestigious and futuristic looking. The core concept behind the design is the connection with the power of nature, The Yard is completely outdoor with uncut sky scenery of the beautiful morning sun rays and night celestial sparkles. This irresistible scene is mixed with the ambience of ongoing water features; Figure (6-11).

This case study will focus on the results of local projects in Egypt that have used the biomimetic approach, using the measuring criteria on the building to validate the utility of using this approach in design. In this design, the external shade and columns are inspired by the tree morphogenesis and the facade's pattern is inspired by the tree branches. The building used local material such as pure granite floors and soft marble walls.[10]

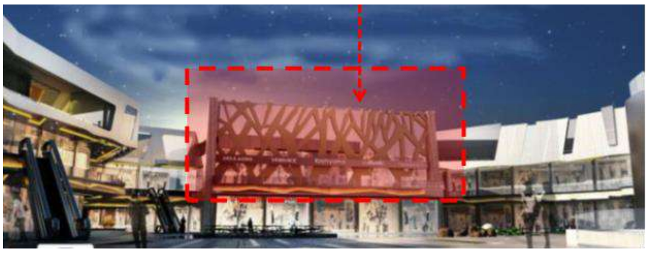
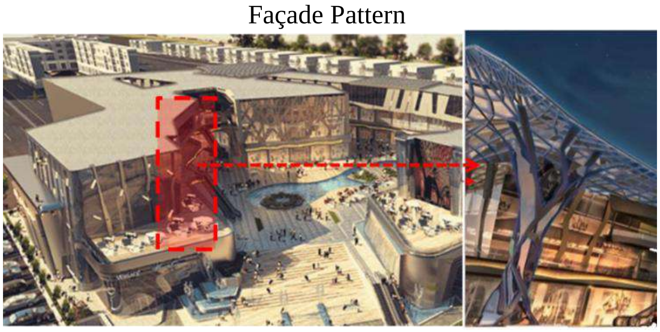
Figure (6-11) The Yard Mall
Source: http://www.theyard-eg.com, accessed Oct, 2020

The architectural concept of The Yard Mall project by AI Designs is the connection with the power of nature. Yart Mall is inspired by the tree branches; Figure (6-12), in the external facade of the building, and it inspired the external columns from the tree structure.[11] The tree was the selected biological role model in this case study. Trees play a significant role in reducing erosion and moderating the climate. They remove carbon dioxide from the atmosphere and store large quantities of carbon in their tissues. Trees work on the tissue level of complexity, deal with all the environmental factors such as light, temperature, energy and water. Trees adapt chemically and their performance could be defined as growth, hierarchy, self-healing and communication.[12]

Figure (6-12) Tree branches
Source: https://www.123rf.com, accessed Oct, 2020

10 http://www.theyard-eg.com/page/concept, accessed Oct, 2020
11 Op. cit.
12 https://en.wikipedia.org/wiki/Tree, accessed Oct, 2020

Project / Analysis Criteria				 The Yard Mall AI Designs New Cairo, Egypt 2017
Biological Domain	**Biological Role Models**		√	Trees' Branches
	Biomimetic Approaches	**Solution based**	√	• The building mimics the aesthetic of tree branching  Tree Branches
		Problem based	---	
	Biomimetic Levels	**Organism**	√	• The building inspired the form of the external façade from the branching of the tree morphology on organism level.  • The column inspired by tree structure on the organism level 
		Behaviour	---	
		Ecosystem	---	
	Selected life principles	**Adaptability**	---	• Tree adapts chemically to the environmental factor but the building did not benefit the ability of the tree in the building behaviour.
		Environmental Reactions	---	• Tree reacts to all the environmental factors: Heat, energy, light, and air but the building did not benefit from the behaviour of the tree towards the environmental factors
		Complexity type	√	• It mimics tree on the organism level of complexity, as it mimic the external shape of tree branches

Biological Domain	**Biological role model performance**	**Colour Change**	---	The building did not mimic the behaviour of the tree, whether its interaction with the environment or its internal behaviour behind that formation
		Growth	---	
		Deployment	---	
		Shape Change	---	
		Variety of shapes	---	
		Hierarchies	---	
		Self-healing	---	
		Communication	---	
Architectural Domain	**Building Behaviour (Target)**	**Structure Efficiency**	---	The building did not achieve any architectural target from the mimicry as it used the tree morphology as false aesthetes' motifs of the tree's branching, neglecting the behaviour behind this formation.
		Material Efficiency	---	
		Thermal Comfort	---	
		Visual Comfort	---	
		Indoor Air Quality	---	
		Energy Efficiency	---	
		Water Quality	---	
	Building Behaviour (Element)	**Structure**	---	• The building used the normal, local material such as pure granite floors and soft marble walls. • It mimics the tree branches simple form on the envelope.  Façade Pattern  False Column
		Envelope	---	
		Building systems	---	
		Interior elements	---	
		Materials	---	

Transferring Domain	**Computational Design Levels**	**Representational Level**	√	In this case study, it was used the representational level in this building to just imitate the external shape of the tree structure manually as a facade pattern.
		Parametric Level	---	
		Generative Level	---	
	Computational Design Tools	**Behavioural Physics Simulation**	---	This building did not use the behaviour-based algorithm to generate the form of tree branches that results in the simple imitation of the false aesthetes' motifs from the tree's branching. This was the result of neglecting the behaviour underlying this formation.
		Form-Finding	---	
		Environmental Simulation	---	
		Optimization	---	
		Fabrication	---	

Table (6-6) The Yard Mall Analysis using Measuring Criteria
Source: Author

6.2.7 Case study 7: The Gate Residence in Heliopolis District, Egypt

In the heart of this New Cairo, the Gate Residence is an innovative design idea of Green Building, representing the combination of Trees and Building and metamorphosing the city into a vertical, green, dense and hyper-connected ecosystem. The main objective behind this urban proposal is to raise awareness of green sustainable architecture to fight against global warming in order to maintain an eco-friendly Earth for the next generation.[13]

The project shows a high ambition in green energy and technology. A solar roof covering the shopping area, green terraces and sky villas partially unifies architecturally the whole complex. This roof provides the possibility of maximizing green energy; providing shadow where necessary, thus decreasing the demand in mechanical ventilation. This roof is also the support for the solar panels and solar heating tubes, and for the green vertical gardens ; Figure (6-13).

Figure (6-13) The Gate Residence
Source: https://www.123rf.com, accessed Oct, 2020

This case study will focus on the creation of an iconic sustainable building in Cairo that would express the future of the city Victorious. This case study used multi-target strategies to create a sustainable landmark in New Cairo by transforming this efficient building mass, multiplying the perspective views towards the streets, into a huge urban oasis. This design awarded the green certification of LEED Gold Plus.

13 http://vincent.callebaut.org, accessed Oct, 2020

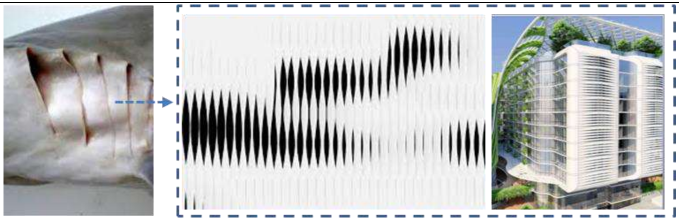
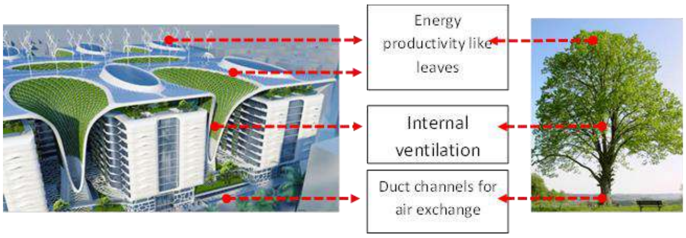
In this design, the designer mimicked nature in each element with its suitable strategy, as the facades are inspired by the gills of fish acting as sunshades. Inside the patios, the facades are developed with a voronoï structure presenting organic shapes inspired by the structure of a coral reef with a progressive density from the bottom to the top. The Mega trees are the strong sculptural identity of the project but are first conceived to ventilate naturally all the basement spaces and to refresh naturally the patios and the inner street; Figure (6-14).[14]

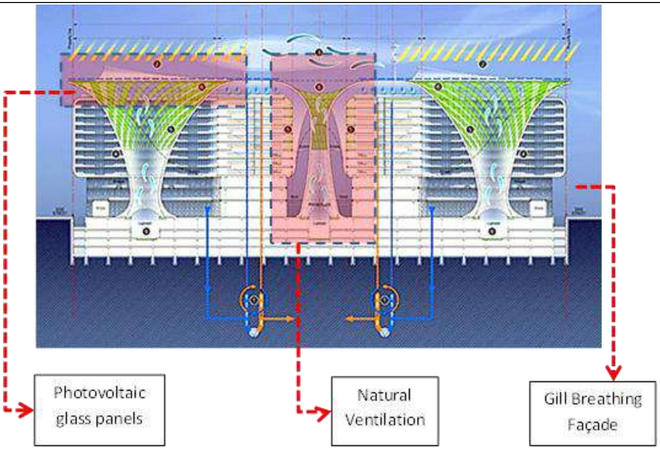
Figure (6-14) Coral Reef
Source: https://eurekalert.org, accessed Oct, 2020

<table>
<tr><td colspan="4">Project / Analysis Criteria</td><td rowspan="1"></td></tr>
<tr><td colspan="4"></td><td>The Gate Residence
Vincent Callebaut
Heliopolis District, Cairo,Egypt
2015</td></tr>
<tr><td rowspan="6">Biological Domain</td><td colspan="2">Biological Role Models</td><td>√</td><td>Tree, Coral leaves and Shark gills</td></tr>
<tr><td rowspan="2">Biomimetic Approaches</td><td>Solution based</td><td>---</td><td rowspan="2">In order to fight against global warming, the designer stated a green sustainable architecture, representing the combination of Trees and Building.
  
Tree — Coral leaves — Shark gills</td></tr>
<tr><td>Problem based</td><td>√</td></tr>
<tr><td rowspan="3">Biomimetic Levels</td><td>Organism</td><td>√</td><td rowspan="3">• The building generates the external pattern of the facades inside the patios from the voronoï structure inspired by the structure of a coral reef on the organism level of biomimicry.

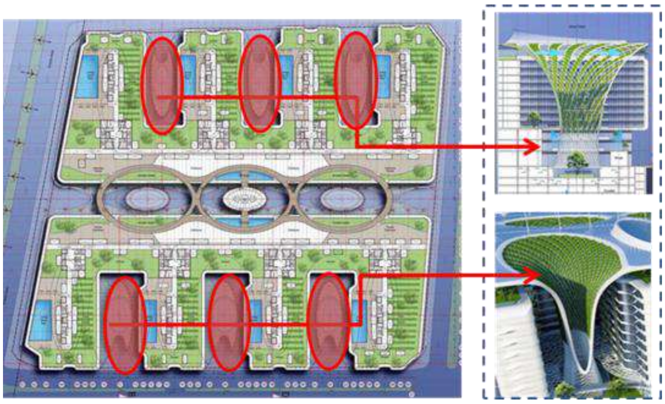
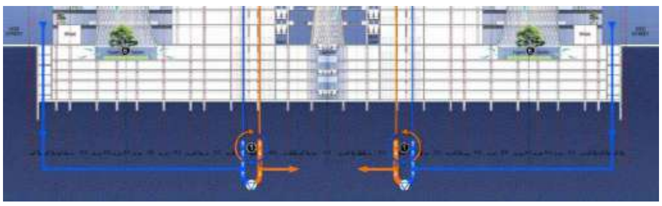
• The building generates the external façade of the facades are inspired by the gills of fish acting as sunshades on behaviour level.</td></tr>
<tr><td>Behaviour</td><td>√</td></tr>
<tr><td></td><td></td></tr>
</table>

14 Op. cit,

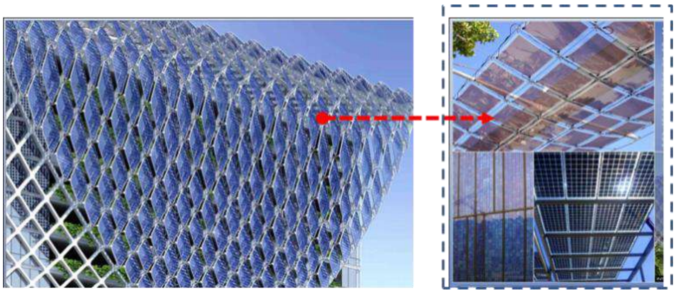
Biological Domain	**Biomimetic Levels**	**Ecosystem**	---	 • Mega trees mimic tree on behaviour level, as they are designed to naturally ventilate all basement areas and to naturally renew patios and inner streets. 
	Selected life principles	**Adaptability**	√	• It depends on the performance of trees, agriculture systems, photovoltaic systems and the fogger system which adapts chemically to deal with air, temperature, energy and water of the environmental factors and works on the cellar level of complexity.
		Environmental Reactions	√	
		Complexity type	√	
	Biological role model performance	**Colour Change**	---	The building mimics hierarchies and communication performance of the tree in the whole building system. 
		Growth	---	
		Deployment	---	
		Shape Change	---	
		Variety of shapes	---	
		Hierarchies	√	
		Self-healing	---	
		Communication	√	
Architectural Domain	**Building Behaviour (Target)**	**Structure Efficiency**	√	The design depends on the integration between internal and external systems to maximize the efficiency of the building. • The design enhanced performance of thermal mass (cooling, cool storage) • It ventilates naturally all the spaces (improved airflow control, reduced draughts).
		Material Efficiency	√	
		Thermal Comfort	√	
		Visual Comfort	√	
		Indoor Air Quality	√	

<table>
<tr>
<td rowspan="4">Architectural Domain</td>
<td rowspan="2">Building Behaviour (Target)</td>
<td>Energy Efficiency</td>
<td>√</td>
<td rowspan="2">

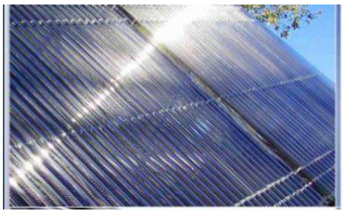
It combines Passivhaus principles and renewable energy technology to assure 50% of energy saving.
It ventilates naturally all the spaces.
Solar water heating systems are designed to deliver hot water in all the wet areas.
</td>
</tr>
<tr>
<td>Water Quality</td>
<td>√</td>
</tr>
<tr>
<td rowspan="2">Building Behaviour (Element)</td>
<td>Structure</td>
<td>√</td>
<td rowspan="2">The design depends on the integration between internal and external systems as the following;

1. The Wind-catchers transformed into mega trees in the middle of each green patios.

2. The Passive Geothermal Cooling System integrated along with each core with the vertical shafts.
</td>
</tr>
<tr>
<td>Envelope</td>
<td>√</td>
</tr>
</table>

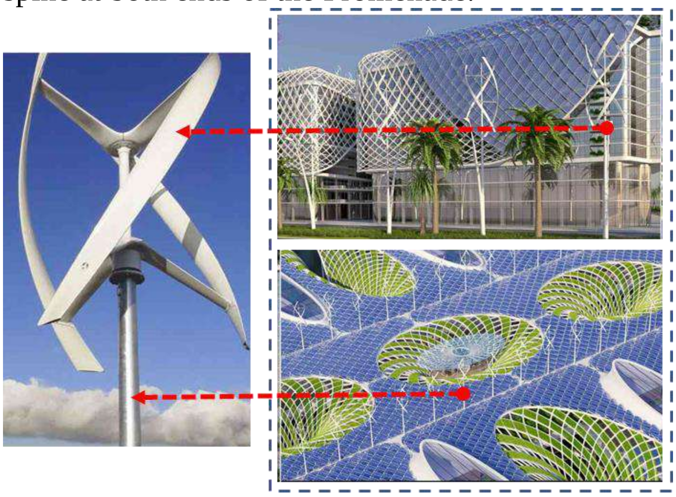
<table>
<tr>
<td rowspan="3">Architectural Domain</td>
<td rowspan="3">Building Behaviour (Element)</td>
<td>Building systems</td>
<td>√</td>
<td rowspan="3">
3. The Solar Photovoltaic Cells covering all the solar roof and the west and east facades.



4. The Solar Heater Tubes located on the roof above each core.




5. The Wind Turbines integrated along the axial spine at both ends of the Promenade.



6. The Roof Food Gardens covering the whole complex improving the thermal inertia of the roof.


7. The Living Walls growing along with the 9 Mega trees as a Structure and the Fogger system for the automatic watering refreshing the atmosphere.
</td>
</tr>
<tr>
<td>Interior elements</td>
<td>√</td>
</tr>
<tr>
<td>Materials</td>
<td>√</td>
</tr>
</table>

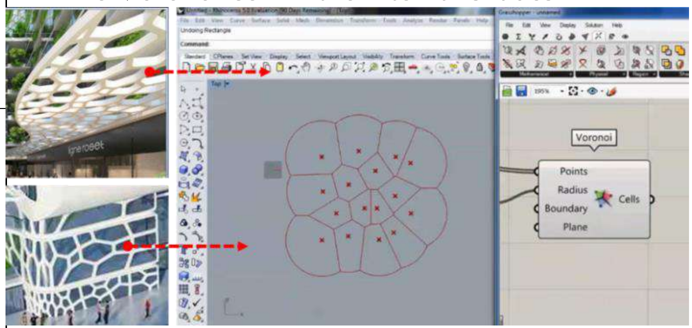
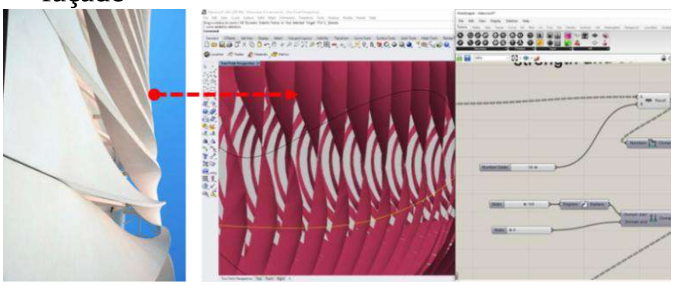
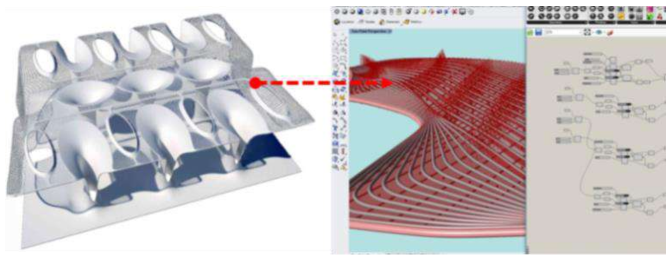
		Materials		
Transferring Domain	**Computational Design Levels**	**Representational Level**	---	• The digital modeling of the design is according to behaviour-based algorithms to generate the form of the external shade using the parametric level of computational design. • Using the generative design approach in environmental simulation.
		Parametric Level	---	
		Generative Level	√	
	Computational Design Tools	**Behavioural Physics Simulation**	---	The building used form-finding algorithms in the computational design process for the digital prototype. • The Voronoi cell in the internal shades  • The twisted ribbon surfaces for the external façade  • Using the mathematical mesh surface that unfolds above all the building volumes to generate the shade 
		Form-Finding	√	
		Environmental Simulation	√	
		Optimization	---	
		Fabrication	---	

Table (6-7) The Gate Residence Analysis using Measuring Criteria
Source: Author

6.2.8 Case study 8: La Capital Mall in New Capital, Egypt

La Capitale Mall; Figure (6-15) is located in compound LaCapitale which is located in a prime location in the new administrative capital of Egypt, Pyramids development established the design of the la capital mall in 2020. Pyramids development company established the design of the la capital mall in 2020. it is considered as a commercial, administrative and medical mall. The mall inspired its façade pattern by the Voronoi cell tesselation which could found in nature clearly, as well as in dragonfly wings pattern.[15]

Figure (6-15) La Capital Mall in Egypt
Source: https://pyramidsdevelopments.com, accessed Oct, 2020

The architectural concept of The La capital Mall project by Pyramids company is an attempt to create a form inspired by nature. The Voronoi cell in the dragonfly wing pattern was the role model in this case study. In mathematics, a Voronoi diagram is a set of points is dual to its Delaunay triangulation. The Voronoi diagram is named after Georgy Voronoy.[16] Dragonfly wings; Figure (6-16), are composed of a thin cuticular membrane that is supported by a system of veins. The veins are hollow branching tubes that form the supporting framework, which often have cross-connections that form closed "cells" within the membrane. The microstructure represents the evolutionary relationship between form and function of wings, as well as revealing basic principles of insect wing mechanical design. Additionally, the of the pattern has mechanical properties to keep their flyability.[17]

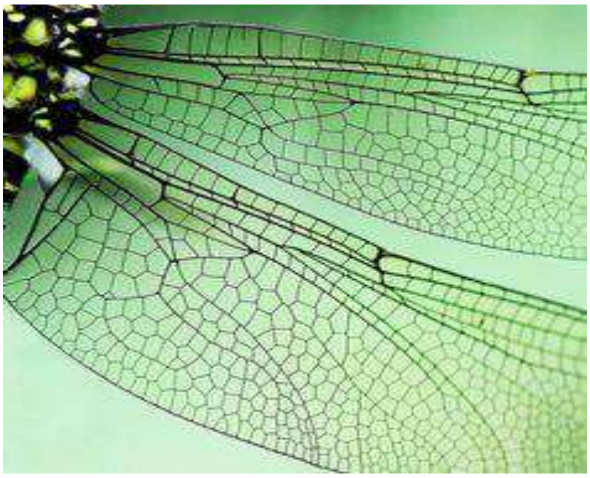
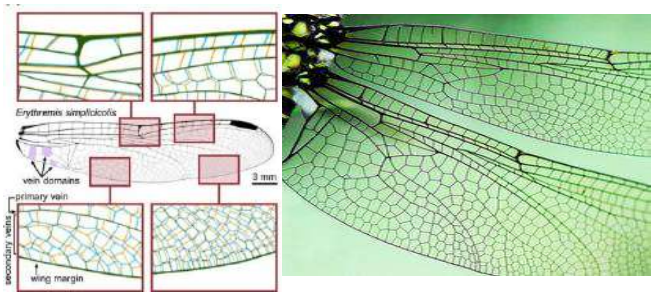


Figure (6-16) Dragonfly wing pattern
Source: Jiyu, S., 2012

15 https://pyramidsdevelopments.com, accessed Oct, 2020
16 https://en.wikipedia.org, accessed Oct, 2020
17 Jiyu S., "The structure and mechanical properties of dragonfly wings and their role on flyability", Article, Elsevier, 2012

Project Analysis Criteria				La Capitale Mall Pyramids Development New Capital, Egypt 2020
Biological Role Model	Biological Role Models		√	Dragonfly wing pattern
	Biomimetic Approaches	Solution based	√	• The building mimics the aesthetic of dragonfly wing pattern.  The Voronoi pattern on the wing
		Problem based	---	
	Biomimetic Levels	Organism	√	• The building inspired the form of the external façade by the tessellation of the dragonfly wing pattern on the organism level 
		Behaviour	---	
		Ecosystem	---	
	Selected life principles	Adaptability	---	• Dragonfly wing adapts chemically and physically for their fly ability. It reacts to the air of the environmental factors but the building did not benefit the ability of the dragonfly in the building behaviour.
		Environmental Reactions	---	
		Complexity type	√	• It mimics the pattern on the organism level of complexity, as it mimics the external shape of the dragonfly wing
	Biological role model performance	Colour Change	---	The building did not mimic the dragonfly wings behaviour, whether its interaction with the environment or its internal behaviour underlying that formation
		Growth	---	
		Deployment	---	
		Shape Change	---	
		Variety of shapes	---	
		Hierarchies	---	
		Self-healing	---	
		Communication	---	

<table>
<tr><td rowspan="12">Architectural Domain</td><td rowspan="7">Building Behaviour (Target)</td><td>Structure Efficiency</td><td>---</td><td rowspan="7">The building did not achieve any architectural target from the mimicry, as it used the Voronoi pattern as false aesthetes' motifs from the dragonfly wing's pattern, neglecting the behaviour behind this formation.</td></tr>
<tr><td>Material Efficiency</td><td>---</td></tr>
<tr><td>Thermal Comfort</td><td>---</td></tr>
<tr><td>Visual Comfort</td><td>---</td></tr>
<tr><td>Indoor Air Quality</td><td>---</td></tr>
<tr><td>Energy Efficiency</td><td>---</td></tr>
<tr><td>Water Quality</td><td>---</td></tr>
<tr><td rowspan="5">Building Behaviour (Element)</td><td>Structure</td><td>---</td><td rowspan="5">The building used the normal, local material
It mimics the simple form of Voronoi pattern on the envelope.

Façade Pattern

Voronoi Façade Pattern</td></tr>
<tr><td>Envelope</td><td>---</td></tr>
<tr><td>Building systems</td><td>---</td></tr>
<tr><td>Interior elements</td><td>---</td></tr>
<tr><td>Materials</td><td>---</td></tr>
</table>

Transferring Domain	**Computational Design Levels**	**Representational Level**	√	In this case study, it was used the representational level in this building to just imitate the external shape of the Voronoi pattern in the dragonfly wing manually as a facade pattern.
		Parametric Level	---	
		Generative Level	---	
	Computational Design Tools	**Behavioural Physics Simulation**	---	This building did not use the behaviour-based algorithm to generate the form of Voronoi pattern, therefore, that results in the simple imitation of the false aesthetes' motifs from the Voronoi pattern. This was the result of neglecting the behaviour underlying this formation.
		Form-Finding	---	
		Environmental Simulation	---	
		Optimization	---	
		Fabrication	---	

Table (6-8) La Capitale Mall Analysis using Measuring Criteria
Source: Author

6.2.9 Case study 9: Business Park, New Cairo, Egypt

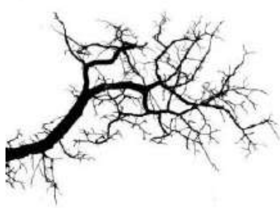
Business Park; Figure (6-17), is locate in New Cairo which is located in the Commercial City Center. offers standalone offices set within a fully-integrated business compound. Inspired by the structue of tree branching, the project supports the presence of medium to large enterprises that are in need of their own unique identity.[18]

Figure (6-17) Business Park in Egypt
Source: Author

The concept of BUSINESS PARK, mimicking the external form of the tree branching integrated by wide area of glass in order to provide an unprecedented final product. Branching is a detailed pattern that looks similar at any scale and repeats itself. It takes a simple rule and applies it over and over again, resulting in complex shapes. Tree branching; Figure (6-18), can help to understand seemingly complex behaviour inside the tree.[19]

Figure (6-18) Tree Structure
Source: https://www.123rf.com, accessed Oct, 2020

18 www.elgabalyarchitects.com, accessed Oct, 2020
19 https://en.wikipedia.org, accessed Oct, 2020

Analysis Criteria / Project				Business Park Tamer El Gabaly New Cairo, Egypt 2006
				
Biological Role Model	Biological Role Models		√	Trees' Branches
	Biomimetic Approaches	Solution based	√	• The building mimics the aesthetic of tree branching   Tree Branches
		Problem based	---	
	Biomimetic Levels	Organism	√	• The building inspired the form of the external façade from the branching of the tree morphology on the organism level. 
		Behaviour	---	
		Ecosystem	---	
	Selected life principles	Adaptability	---	• Tree adapts chemically to the environmental factor but the building did not benefit the ability of the tree.
		Environmental Reactions	---	• Tree reacts to all the environmental factors: Heat, energy, light, and air but the building did not benefit from the behaviour of the tree towards the environmental factors
		Complexity type	√	• It mimics tree on the organism level of complexity, as it mimics the external shape of tree branches
	Biological role model performance	Colour Change	---	The building did not mimic Leaf's behaviour, whether its interaction with the environment or its internal behaviour behind that formation.
		Growth	---	
		Deployment	---	
		Shape Change	---	
		Variety of shapes	---	
		Hierarchies	---	
		Self-healing	---	
		Communication	---	

Architectural Domain	**Building Behaviour (Target)**	**Structure Efficiency**	---	The building did not achieve any architectural target from the mimicry, as it used the Voronoi pattern in leaves as false aesthetes' motifs, neglecting the behaviour underlying this formation.
		Material Efficiency	---	
		Thermal Comfort	---	
		Visual Comfort	---	
		Indoor Air Quality	---	
		Energy Efficiency	---	
		Water Quality	---	
	Building Behaviour (Element)	**Structure**	---	• It mimics the tree branches simple form on the envelope.  False Façade Pattern
		Envelope	√	
		Building systems	---	
		Interior elements	---	
		Materials	---	
Transferring Domain	**Computational Design Levels**	**Representational Level**	√	In this case study, using the representational level in this building was in order to just imitate the external shape of the tree structure manually as a facade pattern.
		Parametric Level	---	
		Generative Level	---	
	Computational Design Tools	**Behavioural Physics Simulation**	---	This building did not use the behaviour-based algorithm to generate the form of tree branches, therefore, that results in the simple imitation of the false aesthetes' motifs from the tree's branching. This was the result of neglecting the behaviour underlying this formation.
		Form-Finding	---	
		Environmental Simulation	---	
		Optimization	---	
		Fabrication	---	

Table (6-9) Business Park Analysis using Measuring Criteria
Source: Author

6.2.10 Case study 10: Medical Park Premier, New Cairo, Egypt

The Medical Park Premier is the first fully serviced medical compound in Egypt by AI Designs. It was shortlisted for Cityscape Egypt Awards 2018. Medical Park Premier adopts a whole new vision that goes beyond providing clinical care and it expands to include World-Class hospitals as well, forming an enormous medical compound that serves health care providers and beneficiaries in a whole new way; Figure (6-19).[20]

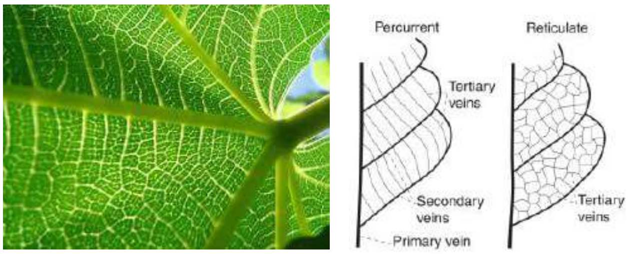
Figure (6-19) Medical Park in Egypt
Source: Author

The external façade inspired by the hierarchy in the Voronoi pattern in leaves merged by significant glass area; Figure (6-20). Leaves are the most important organs of most vascular plants. Green plants are autotrophic, meaning that they do not obtain food from other living things but instead create their own food by photosynthesis. They capture the energy in sunlight and use it to make simple sugars, such as glucose and sucrose, from carbon dioxide and water.[21]

Figure (6-20) Voronoi Pattern in leaves
Source: microlivingjohanna.blogspot.com, Accessed Oct, 2020

The shape and structure of leaves vary considerably from species to species of plant, depending largely on their adaptation to climate and available light, but also to other factors such as grazing animals (such as deer), available nutrients, and ecological competition from other plants. Considerable changes in leaf type occur within species.[22]

20 https://www.b2b-egy.com, accessed Oct, 2020
21 https://en.wikipedia.org, accessed Oct, 2020
22 https://en.wikipedia.org, accessed Oct, 2020

Project / Analysis Criteria				
Project / **Analysis Criteria**				Medical Park AI Designs New Cairo, Egypt 2018
Biological Role Model	**Biological Role Models**		√	Leaves Pattern
	Biomimetic Approaches	**Solution based**	√	• The building mimics the aesthetic of leaves pattern.  Leaves Pattern
		Problem based	---	
	Biomimetic Levels	**Organism**	√	• The building inspired the form of the external façade from the hierarchy in leaves' pattern morphology on the organism level. 
		Behaviour	---	
		Ecosystem	---	
	Selected life principles	**Adaptability**	---	• Leaves adapt chemically to the environmental factor but the building did not benefit the ability of the tree.
		Environmental Reactions	---	• Leaves react to all the environmental factors: Heat, energy, light, and air but the building did not benefit from the behaviour of the tree towards the environmental factors
		Complexity type	√	• It mimics Leaves on the organism level of complexity, as it mimics the external shape of its Voronoi pattern
	Biological role model performance	**Colour Change**	---	The building did not mimic the tree's behaviour, whether its interaction with the environment or its internal behaviour behind that formation.
		Growth	---	
		Deployment	---	
		Shape Change	---	
		Variety of shapes	---	
		Hierarchies	---	
		Self-healing	---	
		Communication	---	

Architectural Domain	**Building Behaviour (Target)**	**Structure Efficiency**	---	The building did not achieve any architectural target from the mimicry, as it used the pattern of leaves as false aesthetes' motifs, neglecting the behaviour underlying this formation.
		Material Efficiency	---	
		Thermal Comfort	---	
		Visual Comfort	---	
		Indoor Air Quality	---	
		Energy Efficiency	---	
		Water Quality	---	
	Building Behaviour (Element)	**Structure**	---	• It mimics Voronoi pattern in a simple form on the envelope.  False Façade Pattern
		Envelope	---	
		Building systems	---	
		Interior elements	---	
		Materials	---	
Transferring Domain	**Computational Design Levels**	**Representational Level**	√	In this case study, using the representational level in this building was in order to just imitate the external shape of the Voronoi pattern manually as a facade pattern.
		Parametric Level	---	
		Generative Level	---	
	Computational Design Tools	**Behavioural Physics Simulation**	---	This building did not use the behaviour-based algorithm to generate the form of Voronoi pattern, therefore, that results in the simple imitation of the false aesthetes' motifs from leaves' pattern. This was the result of neglecting the behaviour underlying this formation.
		Form-Finding	---	
		Environmental Simulation	---	
		Optimization	---	
		Fabrication	---	

Table (6-10) Medical Park Analysis using Measuring Criteria
Source: Author

6.3 Discussion

Upon reviewing the analysis, Biomimicry was implemented in various projects whether in form or in behaviour with varying values. The study granted points for each of the projects subjected to the analysis based on the building behaviour targets fulfilled. These points were granted based on the criteria set from study elements by the researcher. So, the ratio derived from total score points for each project was determined, enabling measuring the success rate of each project in implementing bio-mimicry. The relative weight of the measuring criteria was distributed based on the importance of each criterion to achieve the desired goals of building behaviour through simulation. Therefore, the architectural targets of the building behaviour in the architectural domain have the largest value in these criteria as they are the first priority. The second priority will be the architectural element, achieved by imitation, and then the transferring domain and the biological domain simulation are the same values which are considered to be the tools and methods in the mimicry process. Whereas, the organism level of biomimicry and the representational level of computation has the least value as both of them will achieve simple imitation outcomes.

Table (6-11,12) present the data collection and analysis of the criteria applied to the selected international and local case studies. These tables show the application of measuring criteria to analyze each project, i.e. defining the used biomimetic approach and level of biomimicry, specifying the life principles and performance transferred to the designs, listing the building behaviour targets achieved through the building elements given, and pinpointing the used tools and methods in the transferring domain. Conclusions drawn from the comparative analysis was conducted between projects, presented within the table. This analysis will help to reach some kind of generalization about the evaluation of success factors of the biomimetic projects. The common characteristics could be identifying for successful biomimetic projects which can then be used as standards for future projects.

Project / Analysis Criteria			Relative Weight	Case Study 1	Case Study 2	Case Study 3	Case Study 4	Case Study 5
				Yeosu Oceanic Pavilion	**Floating Brazilian Pavilion**	**Council House 2 (CH2)**	**GSA Office Building Retrofit**	**Palazzo Italia Pavilion**
								
				Korea, 2012	Dubai, 2020	Australia, 2006	Los Angeles, 2011	Italy, 2015
Biological Role Model	**Biological Role Models**		-	Heart veins system	Straw Agriculture	Mound, skin and bark	Algae and Upper Canyon	Petrified Forest Roots
Biological Role Model	**Biomimetic Approaches**	**Solution based**	1	---	√	√	---	---
		Problem based	1	√	---	---	√	√
	Biomimetic Levels	**Organism**	1	---	√	√	√	√
		Behaviour	2	√	√	√	√	√
		Ecosystem	2	---	---	---	---	---
	Selected life principles	**Adaptability**	2	√	√	√	√	√
		Environmental	2	---	√	√	√	√
		Complexity type	2	√	√	√	√	√
	Biological role model performance	**Colour Change**	2	---	---	---	---	---
		Growth	2	√	√	---	√	---
		Deployment	2	---	---	---	---	√
		Shape Change	2	---	---	√	---	---
		Variety of shapes	2	---	---	---	---	---
		Hierarchies	2	√	---	√	---	√
		Self-healing	2	---	---	---	---	---
		Communication	2	---	√	√	---	---
Architectural Domain	**Building Behaviour (Target)**	**Structure Efficiency**	5	√	√	√	---	√
		Material Efficiency	5	√	√	√	√	√
		Thermal Comfort	5	---	√	√	√	√
		Visual Comfort	5	---	√	√	√	√
		Indoor Air Quality	5	---	√	√	√	√
		Energy Efficiency	5	---	√	√	√	√
		Water Quality	5	---	√	√	√	---
	Building Behaviour (Element)	**Structure**	4	√	√	√	---	√
		Envelope	4	√	√	√	√	√
		Building systems	4	---	√	√	√	--
		Interior elements	4	---	√	√	√	--
		Materials	4	√	√	√	√	√
Transferring Domain	**Computational Design Levels**	**Representational**	1	---	---	---	---	---
		Parametric Level	2	---	√	---	---	---
		Generative Level	3	√	---	√	√	√
	Computational Design Tools	**Behavioural Simulation**	2	√	---	---	---	---
		Form-Finding	2	√	√	---	---	---
		Environmental Simulation	2	---	---	√	√	√
		Optimization	2	---	---	√	√	---
		Fabrication	2	---	√	√	---	√
	Evaluation Criteria		100	**40%**	**75%**	**80%**	**65%**	**63%**

Table (6-11) International Case Studies Comparison, Source: Author

Project / Analysis Criteria			Relative Weight	Case Study 6	Case Study 7	Case Study 8	Case Study 9	Case Study 10
				The Yard Mall	**The Gate Residence**	**La Capitale Mall**	**Business Park**	**Medical Park**
								
				Egypt, 2017	Egypt, 2015	Egypt, 2020	Egypt, 2017	Egypt, 2018
Biological Role Model	**Biological Role Models**		-	Trees' Branches	Tree, Coral leaves and Shark gills	Dragonfly wing pattern	Trees' Branches	Leaves Pattern
	Biomimetic Approaches	**Solution based**	1	√	---	√	√	√
		Problem based	1	---	√	---	---	---
	Biomimetic Levels	**Organism**	1	√	√	√	√	√
		Behaviour	2	---	√	---	---	---
		Ecosystem	2	---	---	---	---	---
	Selected life principles	**Adaptability**	2	---	√	---	---	---
		Environmental	2	---	√	---	---	---
		Complexity type	2	√	√	√	√	√
	Biological role model performance	**Colour Change**	2	---	---	---	---	---
		Growth	2	---	---	---	---	---
		Deployment	2	---	---	---	---	---
		Shape Change	2	---	---	---	---	---
		Variety of shapes	2	---	---	---	---	---
		Hierarchies	2	---	√	---	---	---
		Self-healing	2	---	---	---	---	---
		Communication	2	---	√	---	---	---
Architectural Domain	**Building Behaviour (Target)**	**Structure Efficiency**	5	---	√	---	---	---
		Material Efficiency	5	---	√	---	---	---
		Thermal Comfort	5	---	√	---	---	---
		Visual Comfort	5	---	√	---	---	---
		Indoor Air Quality	5	---	√	---	---	---
		Energy Efficiency	5	---	√	---	---	---
		Water Quality	5	---	√	---	---	---
	Building Behaviour (Element)	**Structure**	4	---	√	---	---	---
		Envelope	4	√	√	√	√	√
		Building systems	4	---	√	---	---	---
		Interior elements	4	---	√	---	---	---
		Materials	4	---	√	---	---	---
Transferring Domain	**Computational Design Levels**	**Representational**	1	√	---	√	√	√
		Parametric Level	2	---	---	---	---	---
		Generative Level	3	---	√	---	---	---
	Computational Design Tools	**Behavioural Simulation**	2	---	---	---	---	---
		Form-Finding	2	---	√	---	---	---
		Environmental Simulation	2	---	√	---	---	---
		Optimization	2	---	---	---	---	---
		Fabrication	2	---	---	---	---	---
	Evaluation Criteria		100	**9%**	**76%**	**9%**	**9%**	**9%**

Table (6-12) Local Case Studies Comparison, Source: Author

6.4 Analytical Study Results

Using a set of criteria deduced from the study element for measuring the influence of biomimicry on the building behaviour of selected case studies. Those case studies are selected based on the determinants put by the researcher. Case studies varied between local and international buildings. Following is a discussion of the results of the analytical study; contains the deducing simulation efficiency, the effective factors on the biomimetic project's efficiency.

6.4.1 Deducing Simulation Efficiency

The evaluation found that all of these examples benefited from biological simulations in varying proportions, and so the examples will be classified into three categories as the following:

- First, the multi-strategy building succeeds in transferring the life principles and deals with the building as a whole system. It was as successful as 80% in productive regenerative design and achieving building behaviour targets. In Case Studies 2, 3 and the local project 7, the building relies on multi-target strategies as it simulates the appropriate biological role models on the behaviour level of biomimicry for each architectural element and takes advantage of its ability to deal with the environment; Figure (6-21).

Figure (6-21): (a) Floating Brazilian Pavilion, Dubai; (b) Council House 2 (CH2), Australia; (c) The Gate Residence, Egypt

- Second, the Material-Based building succeeds in transferring the life principles and deals with the building as a material-based system. It mimicked the biological role model on the behaviour level and achieves a bio-reactor material; however, it did not affect the whole building system, neglecting one or more of architectural elements and targets. Therefore it was a medium success rate of 65% and 63%. In Case Studies 4 and 5, both of them are considered to be Material-Based buildings, however, the building did not achieve all the architectural targets although the deep mimicry of the biological role models; Figure (6-22).

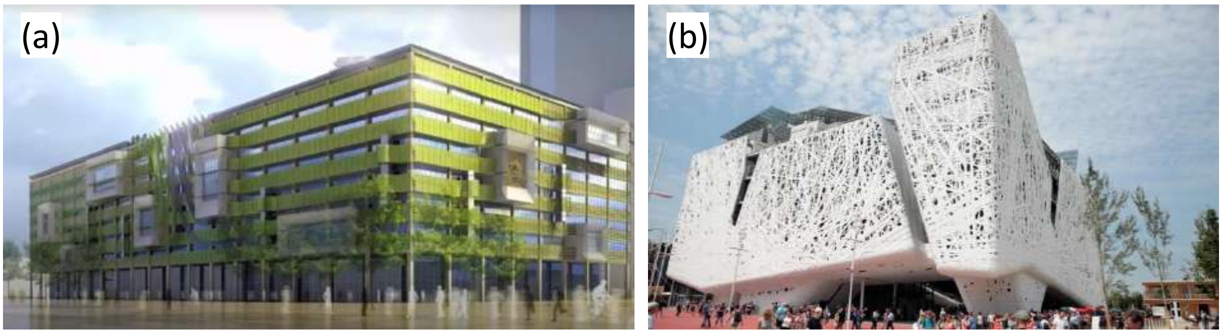


Figure (6-22): (a) GSA Office Building Retrofit, Los Angeles; (b) Palazzo Italia Pavilion, Italy

- Third, Structure-Based building succeeds in transferring the life principles and deals with the building as a structure-based system. It mimicked the biological role model on the behaviour level and achieves an efficient structure; however, it did not affect the whole building system, neglecting the rest architectural elements and targets. Therefore it has achieved a low success rate of 40%. In Case Study 1, it is considered to be Structure-Based buildings, however, the building did not achieve all the architectural targets although the deep mimicry of the behaviour physics of the biological role model; Figure (6-23).

Figure (6-23): Yeosu Oceanic Pavilion, Korea

- Fourth, Form-Finding building fails to convey the life principles into the building's behaviour and deals with the building as an external facade without integrating other architectural elements. Simulations were used to transfer the external morphology of the biological role model only. Its success rate to achieve the building targets was very weak 9%. Case Studies 6, 8, 9 and 10, are local projects in Egypt that rely on the representational level of the computational design which could not transfer the behaviour underlying the morphology. Therefore, their outcome results in the simple imitation of the false aesthetes' motifs from the morphology of the biological role models; Figure (6-24).

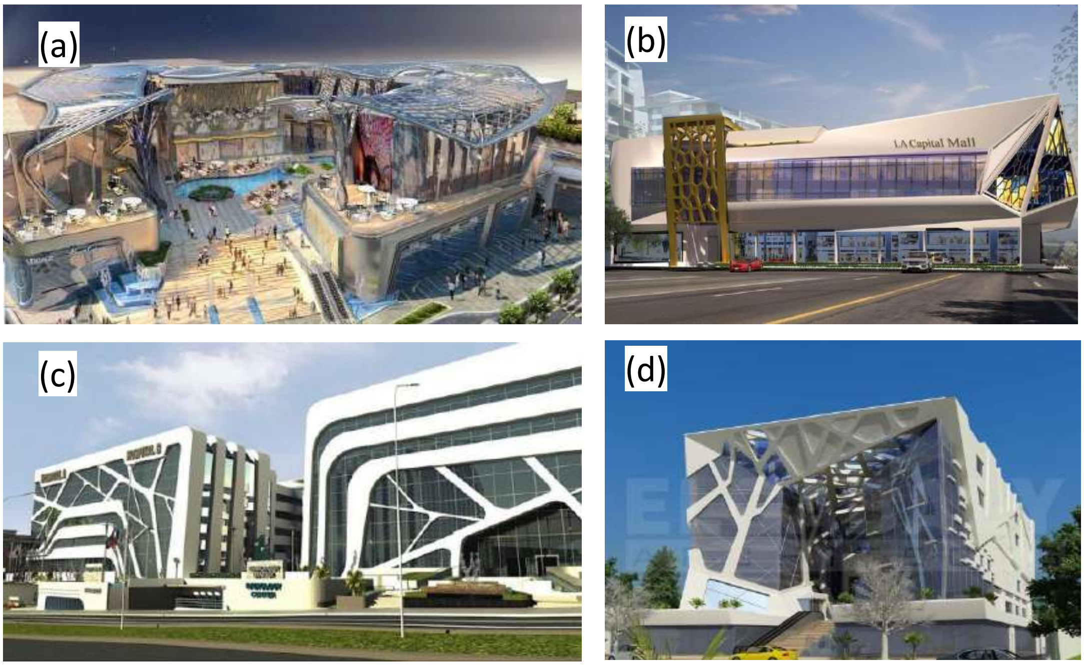


Figure (6-24): (a) The Yard Mall, Egypt; (b) La Capitale Mall, Egypt; (c) Medical Park, Egypt; (d) Business Park, Egypt

6.4.2 The Effective Factors on the Biomimetic Project's Efficiency

Comparative analysis showed the most influencing factors on the project's success, based on the common characteristics of the most successful projects in achieving building behaviour's targets, as the following:

- The choice of the biomimetic approaches, whether problem-based or solution-based, does not affect the success of the project as long as the architectural goal is specified.
- Determining the selected life principles affects in a very considerable way, as:

  a. Choosing the type of adaptation as kinetic, whether chemical response or physical response, guarantees its interaction with environmental factors, and thus achieving a large percentage of the desired goals, such as the first, second, and fourth projects.
  b. As for choosing a static adaptation such as form or structure, it does not interact with the environmental factors and thus does not achieve a large percentage of the required goals, such as in Case Studies 1, 6, 8, 9 and 10.
  c. It was found that the deeper complexity level, the closer the simulation to the performance of the organism, where simulation of tissue, micro and organ level in the Case studies 2, 3 and 7.
  d. The simulation on the organism level of complexity in the Case study 1, it is superficial and simulates the form only, and therefore there were no successes in facing environmental factors.

e. Living organisms do multi-function performance at the same time, and consequently, therefore it has become necessary to use a holistic view and deal with the organism as a whole system.

- Dealing with the building as a whole system, such as a living organism, guarantees to achieve multiple targets of the building behaviour.
- Material-based approach achieved more targets than mimicking the organism mechanically.
- Structure-based approach achieved the architectural targets related to the structure efficiency such as material efficiency but did not affect the other architectural targets.
- Bio-morphic approach got the lowest percentage of achieving the building’s targets.
- Previous studies lack adequate knowledge of the technological tools used to transfer the biological performance of living organisms to the building behaviour. This results in the simple imitation of the false aesthetes’ motifs in Egypt, where local projects in Egypt rely on the representational level of the computational design that could not transfer the behaviour underlying the morphology. Third, Structure-Based building succeeds in transferring the life principles and deals with the building as a structure-based system.

Chapter Summary

Measuring the influence of imitation of the biological role models in building behaviour using measuring criteria and comparative analysis revealed the common effective factors for their success and failure in transferring nature to building behaviour. The determinants of the selected case studies adopted by the researcher that they are 10 projects international and local biomimetic buildings based on biological performance simulations. These building utilized life principles for mimicking whether in form or behaviour and should be designed by senior architects or for buildings that won architectural competitions, developed recently in the last 15 years.

Measuring criteria were developed based on study's elements, and then applied these criteria for measuring the efficiency of the biological simulation into three main dimensions; **first**, the biological domain, it divaricated into four dimensions; **second** the architectural domain, it divaricated into two dimensions; **third** the transferring domain, it divaricated into two dimensions. The relative weight was distributed based on the importance of each of the criteria to achieve the desired goals of building behaviour through simulation.

The results deduced that there are four classifications for these building based on how biomimetics are used in the design; **first**, the multi-strategy building succeeds in transferring the life principles and deals with the building as a whole system. **Second**, the Material-Based building succeeds in transferring the life principles and deals with the building as a material-based system. **Third**, Structure-Based building succeeds in transferring the life principles and deals with the building as a structure-based system. **Fourth**, Form-Finding building fails to convey the life principles into the building's behaviour and deals with the building as an external facade without integrating other architectural elements.

Besides, the results of the comparative analysis showed that the most influential factor in the success of the project, based on the common characteristics of the most successful projects in achieving building behaviour's targets.

CHAPTER 7: Results and Recommendations

Introduction

The main aim of the study is closing the technical gap in biomimetic architecture approach, through integrating the biomimetic approach with the technological tools in a clear design framework which is concerned with transferring the biological strategies to the building behaviour to achieve its targets. In order to fulfill the aforementioned purpose, an analytical and experimental methodology will be adopted. In this final chapter, the research presents the final results and general recommendations of the study elements, represented in the following:

7.1 Results

In this part, the chapter presents the results which deduced from the study through the study elements, into three parts; The results of the theoretical part, The Experimental Study and Application Results, and the results of the analytical part are as the following;

Part I: The Results of the Theoretical Part

Following is a discussion of the results of the theoretical study; First, the motivations behind shifting the use of biomimetic approach; Second, the biological domain simulation as the first factor of the three major factors of the study; Third, Architectural Domain Parameters; Fourth, the influence of biomimicry on the building behaviour.

1- Shifting from Biomimicry for Form-Finding to Regenerative Approach

- By observing the environmental motivations behind the trend of biomimicry, these motivations emphasized the necessity to shift from inspiring the external shapes of nature to mimic the behaviour of the living organisms.

- The significant bio-inspired innovations timeline in various fields, starting from Da Vinci flight till the contemporary innovations, clarified that Biomimicry has already solved many problems in several fields by mimicking the performance of the organisms. Those strategies can be useful in architecture, where Biomimicry can produce advanced architectural elements such as structure, sensors renewable systems in building behaviour, etc.

- The biomimetic architecture was highlighted in the historical timeline of utilizing the Biomimicry in architecture throughout the history, it explained that nature was used as a source for forms and geometries while neglecting the functions and processes underlying these forms, which led to the emergence of projects that looks like nature but do not function like nature.

2- Biological Domain Simulation

- There are a large number of biological roles models that can be mimicked in architectural design, which leads to the difficulty of identifying and analyzing the organism to be used in the architectural domain, so it was necessary to identify the analytical elements that could facilitate the possibility of dealing with them. These elements are represented by:

  a) **Selected Life Principles**: the most promising selected life principles- that are architecturally achievable and could deal with building behaviour- have been identified. Those were sensing, reacting to all environmental factors, complexity, and adaptability type.

  b) **Biological Role Model Performance**: based on the database provided by the “Growing as Building” project, the same organism can manifest several performances at the same time to achieve the goal of survival. In addition, common performances were observed in most organisms, such as growth, shape change, colour change, deployment, and variety of shapes, hierarchies, self-healing and communication.

- By reviewing the methodologies that have been put forward by biologists in previous studies, the methodology which presented by Juilen Vincient has been adopted with its development and linking to the architectural domain by the researcher, in order to reach abstracted biological information that could be converted into architectural ideas. This methodology divided into three phases as the following:

  a) Biological Domain Phases

  - **Experimental phase**: The study of biological strategies used by the biological model in order to survive.

  - **Abstraction phase**: The abstraction of relevant knowledge resulting from the biological simulation into arranged groups during the experimental phase.

b) Architectural Domain Phase

- **Prototyping phase:** Testing the capabilities of those potential strategies and developing prototypes whether physical or digital models, using architectural software.

- The biological simulation elements have been reached to extract and conclude strategies that can improve the efficiency of the building behaviour. By using this analytical process, the abstracted biological information can be obtained which can be transformed into architectural elements.

3- Architectural Domain Parameters

- The building behaviour parameters are determined, it could be divided into; First, the architectural targets of the building behaviour; Second, the architectural elements that can achieve those targets are identified. In order to achieve the architectural targets through Biomimicry, a clear methodology has been defined linking the biological domain with the architectural domain. Those deducted parameters represented in:

a) **Building behaviour architectural targets:** The targets which are responsible to enhance the efficiency of the building behaviour as the following:

- Efficient structure
- Efficient Materials
- Indoor Environmental Quality
  (Thermal comfort-Visual comfort- Indoor air quality)
- Energy efficiency
- Water efficiency

b) **Building behaviour elements**: The elements which are responsible to fulfill the architectural targets, as the following:

- External Components: The elements which are responsible for the external barriers of the building such as Envelope and Structure.

- Internal Components: The internal systems which are responsible for the building operation such as Building systems (i.e., mechanical, electrical, etc.), Interior elements and Materials.

4- The Influence of Biomimicry on Building Behaviour

Selected case studies have been analyzed for each architectural target using the proposed methodology of the problem-based approach by the researcher. The methodology of the problem-based approach consists of three phases; biological domain ‘experimental phase, abstraction phase’, then the architectural domain ‘prototype phase’. The results revealed that:

a) The potential bio-inspired strategies for each architectural target:

- Natural Structure types: The pneumatic structures, Shells, Trees, Webs and Skeletons.
- Bio-inspired material types: inspired by structure properties of natural organism (with thermal behaviour- load bearing); inspired by functions of natural organisms (intelligence response- waterproofing); inspired by recycling process in nature (Biocomposite – bioplastic); Inspired by biological processes (growing material- productive material).

- Environmental Indoor Quality strategies;
  - Heat regulation strategies: heat gain, retention, dissipation and prevention.
  - Visual comfort and dealing with light in several strategies: Gathering, Distributing, Focusing, Diffusing, Reflecting and Refracting.
  - The four main respiration systems in nature for indoor air quality: Integument Gills, Lungs and Tracheae.

- Four principles for biomimicry solution to energy:
  - Demand reduction
  - Source of energy that will last indefinitely
  - Resilience through diversity
  - Resource flows that is non-toxic and compatible with a wide range of other systems.

- Bio-inspired strategies of reducing water loss: Non-living matter to create shade, reduce the evaporative gradient, Reabsorption and water condensation.

b) The influence of biomimicry on each architectural target:

- Weight savings and efficient structure.
- Discover 3D printing and Several Functional Surfaces.

- External and internal (systems): interior pattern, shading device and passive cooling.
- External skin controlling daylight
- Passive natural ventilation
- Photovoltaic solar energy
- Improve the efficiency of desalination purify water and water from fog

c) The effective performance of the biological role model on the architectural target:

- The Hierarchical structure is the most effective performance to fulfill the structure efficiency target.
- Bioreactor Material (shape change) is the most effective performance to fulfill the material efficiency target.
- Variety of shapes, Physical response and Hierarchies are the most effective performances to fulfill the indoor environmental quality.
- Chemical Bioreactor (Growth) is the most effective performance to fulfill the energy efficiency target.
- Chemical Adaptation (communication) is the most effective performance to fulfill the water efficiency target.

PART II: The Experimental Study and Application Results

Following is a discussion of the results of the experimental study and the application; First, closing the technical gap in biomimetic architecture approach; Second, the Biomimetic Design Workflow for Building Behaviour; Third, the application of Biomimetic Design Workflow for Building Behaviour.

1- Closing the Technical Gap in Biomimetic Architecture Approach

Highlighting the technological tools that used in transferring the abstracted biological information from mere text to an architectural element, these tools have been identified through the following steps;

- **First**, identifying the tools that can be used to achieve the biological information and determine the biological role model to be simulated as the following:

  a) Computer-Aided Biomimetics Support (CAB) Tools such as; Bio-TRIZ matrix software, BiomimeTree and FOBIE dataset.
  b) Computer-Aided Biomimetics (CAB) Websites such as; E2BMO and AskNature website.

- **Second,** Encoding Nature from textual information to the architectural software using the technological tools,

  - The role of computational design in biomimetic approach has been discussed, in translating the biological morphogenesis.

  - Adopting Toni kotnic classification of the computational design levels in architecture; the representational level, the parametric level and the generative level.

  - Using Programming Languages for Encoding Nature: this is the way for transformation the biological information from mere text into a language understood by the technological tools. the programming languages types are textual programming language and visual programming language.

- **Third,** case studies of machine learning and deep learning algorithms in architecture have been analyzed; those case studies are meaningful applications of biological behaviour simulation in the computational tools. This helped to understand and systematize the logic for biomimetic architecture approach using the computational design.

2- The Biomimetic Design Workflow for Building Behaviour

By applying the proposed methodology by the researcher for analyzing the case studies of the computational design, Biomimetic Design Workflow for Building Behaviour was deduced, which can be summarized in four primal stages, as the following:

- After defining the architectural target to be achieved, **the first stage** will be started, is seeking in the sources of the biological domain, which are determined either from previous research, literature review or by using CAB software such as BioTRIZ, FOBIE or by using websites such as E2BMO or AskNature websites, through them, the biological role model will be determined.

- **The second stage** is simulating this biological information obtained from the biological domain sources. This stage divided into two phases; the experimental phase is to simulate this role model by the selected life principles, which in turn infer the biological performance in the abstraction phase that will be mimicked.

- After obtaining the biological information in written form, **the third stage** begins, which is the role of the transferring domain from mere text to the architectural domain. The transferring domain is responsible for scripting that information using programming languages, whether visual as Grasshopper and Dynamo or textual such as Python, C#, C++ and VB.net.

- Biological information arrives at the transferring domain in Behaviour-Based algorithmic form, and thus **the fourth stage** is using those algorithms in the architectural domain and reaching an architectural element that achieves the desired target in the prototype phase. This can be validated using the analysis provided by these algorithms.

3- The application of Biomimetic Design Workflow for Building Behaviour

This practical application is a prototype for a responsive facade unit made to evaluate the application of such an approach to building behaviour. In fact, such practical experimentation helped in setting a clearer and more defined design framework from the conceptual stage to the implementation stage. Worth mentioning that the purpose of the application/outcome of this prototype is not the design of the responsive unit; rather than being the processes in which the design and the fabrication go through. In this application, the proposed design framework has been followed in the following steps:

- **The first step** is searching the biological domain using the Ask Nature website. The Mimosa plant was defined as the biological role model in this case study.

- **The second step** is analyzing the biological role model using the selected life principles. Mimosa works at the cellular level of complexity. The environmental factor challenging the Mimosa is temperature and light through physical adaptation. The performance concluded from the sensitive plant and its flower blooming was shape change (folding).
- **The third stage** involved transferring that biological information to the computational domain by scripting. The visual programming language Grasshopper on Rhino 3D software has been used in scripting the digital prototyping, starting by generating the hexagonal pattern, and then transferring the behaviour of the plants on the façade affected by the environmental stimuli.

- **The fourth step** involves the architectural domain, where an application of the responsive façade unit has been made by the researcher using Rhino 3d, grasshopper the visual scripting, SolidWorks software and the textual programming language C. After that, the validation process was carried out by experimentation the efficiency of the façade unit to fulfill the identified architectural target.

The results of the application found that the unit efficiently responded to various environmental factors and the physical stimuli as programmed in the Arduino code. These results represented the success of the Biomimetic Design Framework for Building

Behaviour in transferring the behaviour of biological role model to the building behaviour in the form of the architectural element (facade unit) using the four-staged framework.

PART III: The Results of the Analytical Part

Following is a discussion of the results of the analytical study; first, measuring the influence of biomimicry on the building behaviour; second, the effective factors on the biomimetic projects efficiency.

1- Measuring the Influence of Biomimicry on the Building Behaviour

Using a set of criteria deduced from the study elements for measuring the influence of biomimicry on the building behaviour of selected case studies. Those case studies are selected based on the determinants put by the researcher. Case studies varied between local and international buildings. The evaluation of these case studies found that; all of these examples benefited from biological simulations in varying proportions, and so the examples will be classified into four categories as the following:

- First, the multi-strategy building succeeds in transferring the life principles and deals with the building as a whole system. It was as successful as 80% in productive regenerative design and achieving building behaviour targets.

- Second, the Material-Based building succeeds in transferring the life principles and deals with the building as a material-based system. It mimicked the biological role model on the behaviour level and achieves a bio-reactor material; however, it did not affect the whole building system, neglecting one or more of architectural elements and targets. Therefore it was a medium success rate of 65% and 63%.

- Third, Structure-Based building succeeds in transferring the life principles and deals with the building as a structure-based system. It mimicked the biological role model on the behaviour level and achieves an efficient structure; however, it did not affect the whole building system, neglecting the rest architectural elements and targets. Therefore it has achieved a low success rate of 40%.

- Fourth, Form-Finding building fails to convey the life principles into the building's behaviour and deals with the building as an external facade without integrating other architectural elements. Simulations were used to transfer the external morphology of the biological role model only. Its success rate to achieve the building targets was very weak 9%.

2- The Effective Factors on the Biomimetic Projects Efficiency

The comparative analysis showed the most influencing factors on the project's success, based on the common characteristics of the most successful projects in achieving the building behaviour's targets, as the following:

- The choice of the biomimetic approaches, whether problem-based or solution-based, does not affect the success of the project as long as the architectural goal is specified.
- Determining the selected life principles affects in a very considerable way, as:
    - Choosing the type of adaptation as kinetic, whether chemical response or physical response, guarantees its interaction with environmental factors, and thus achieving a large percentage of the desired goals, such as the first, second, and fourth projects.
    - As for choosing a static adaptation such as form or structure, it does not interact with the environmental factors and thus does not achieve a large percentage of the required goals.
    - It was found that the deeper complexity level, the closer the simulation to the performance of the organism, where simulation of tissue, micro and organ level.
    - The simulation on the organism level of complexity is superficial and simulates the form only, and therefore there were no successes in facing environmental factors.
    - Living organisms do multi-function performance at the same time, and consequently, therefore it has become necessary to use a holistic view and deal with the organism as a whole system.
- Dealing with the building as a whole system, such as a living organism, guarantees to achieve multiple targets of the building behaviour.
- Material-based approach achieved more targets than mimicking the organism mechanically.
- Structure-based approach achieved the architectural targets related to the structure efficiency such as material efficiency but did not affect the other architectural targets.
- Bio-morphic approach got the lowest percentage of achieving the building's targets.
- Previous studies lack adequate knowledge of the technological tools used to transfer the biological performance of living organisms to the building behaviour. This results in the simple imitation of the false aesthetes' motifs in Egypt, where local projects in Egypt rely on the representational level of the computational design that could not transfer the behaviour underlying the morphology.

7.2 Recommendations

The research presents the general recommendations for the biomimetic approach in order to enhance the future designs, represented in: Recommendations for using the biomimetic approach to enhance the building behaviour efficiency, Recommendations for future studies in developing the biomimetic approach in architecture and Recommendations for the architectural education process, as the following:

1- Recommendations for using the biomimetic approach to enhance the building behaviour efficiency

- Transferring the principles of life and deals with the building as a whole system.
- Using a much deeper level of complexity than that was simulated by external shapes and skin's pattern.
- Using kinetic adaptability which guarantees the interaction with environmental factors
- Dealing with the Bio-reactor approach to produce the regenerative design that can face climate change and achieve sustainability.
- Using the multi-strategies approach in mimicking the biological role model to achieve productive and regenerative design.
- Using the specific tools for the biomimetic approach which guarantees transferring the biological behaviour of the biological role model to the architectural designs.

2- Recommendations for future studies in developing the biomimetic approach in architecture

- Efforts should be made to establish an architectural database of biomimetic strategies.
- Further studies should be made to focus on the biomimetic approach tools in architecture and the architectural interpretations of the life principles technically.
- New approaches may be considered in which the benefits of a microcontroller can be combined with an intelligent material-based intervention. This may result in establishing a new era in the material industry.

3- Recommendations for the architectural education process

- Integrated science laboratories must be established in universities in order to obtain more efficient results.

- Encourage carrying out educational programs that provide coordination between researchers from different disciplines.

- Giving students the opportunity to implement their ideas of learning 'Biomimicry in Architecture' and applying its principles in their design projects in order to enhance the building behaviour efficiency.

- Encourage using digital fabrication tools to verify the design ideas through physical prototypes (Make to Learn) and to get accurate results.

Conclusion

This study went through the three main elements of the biomimetic approach in architecture represented in; the biological domain, architectural domain and transferring domain. The study went through a literature review to clarify that the biomimetic approach throughout history was using nature as a source of form not function. This thesis indicated that the importance of biomimicry as a sustainable methodology to enhance building behaviour.

Dealing with nature in the biomimetic approach could be summarized in two ways. The first is to use solutions from nature and benefit from them Solution-Based approach, and the second is to use architectural problems and search for solutions from nature that serve them Problem-Based approach. This study adopts the problem-based approach in order to solve the problems of building behaviour. The researcher proposed an analytical methodology which could be used for simulating selected case studies named the problem-based approach methodology. This methodology consists of three processes; first, is to search for the biological role model criteria; second, is the abstraction of the results. The third is the Implementation in the architectural domain.

The study deduced the analysis elements for the biological domain which could be used for simulating the biological role model to reach the abstracted information. This abstracted information transferred into architectural elements using the highlighted technological tools in the study. The study answers the question of how to transfer nature to architectural from mere text into architectural element through an experiment of the implementation of a responsive façade unit. The experimental application described the design, fabrication process of transferring the life principle of a biological role model to the architectural domain.

Finally, the analytical study of measuring the influence of biomimicry on the building behaviour efficiency using measuring criteria and comparative analysis revealed the common effective factors for their success and failure in transferring nature to building behaviour. The results revealed the biomimetic design framework that could be used to guarantee reaching a successful design which could fulfill the building behaviour targets.

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الملخص

يسلط البحث الضوء علي الجانب التطبيقي والعملي لكيفية التكامل بين التخصصات المختلفة تحديدا بين علم الاحياء و التطور التكنولوجي وتأثيرهما في مجال العمارة، حيث تتناول هذه الأطروحة توضيح مفهوم محاكاة الطبيعة في الهندسة المعمارية لغرض الوظيفة بالأضافة إلي التشكيل وذلك بهدف تحقيق أنظمة بناء مستلهمة من الطبيعة مستدامة والتي يمكنها أن تحسن كفاءة سلوك المبني. اقتصر هذا النهج سابقا في المجال المعماري على التقليد السطحي فقط بدون النظر إلي الدوافع وفهم الآليات الحاكمة وراء هذا التشكيل مما ترتب عليه وجود تأثير سلبي على الأداء الوظيفي للمبني والذي أدى إلى عدم نجاحه في تحقيق مبادئ الاستدامة كهدف رئيسي.

وبالنظر إلي الإسهامات المتعددة المتعلقة بموضوع الدراسة، قدم بعض المهندسين المعماريين مشاريع مختلفة كان الدور التقني فيها عامل رئيسي لظهورها وذلك بفضل الثورة الرقمية والتطور الهائل في دور الحاسب الآلي في العمارة. حيث ظهرت العديد من الأمثلة التي يظهر فيها تداخل التصميم المعماري مع علوم الهندسة الحيوية تلك التي استخدمت الطبيعة كمصدر اساسي للتشكيل. تعبر تلك الأمثلة عن مدي التطور الحاصل في نتاج و توليد التكوينات المختلفة، ومع ذلك ، فإن هذه الامثلة لا تعني بالضرورة أنها نقلت سلوك الأنظمة الحية بنجاح إلى سلوك المبني فمن الممكن ان المصمم قام بمحاكاة السلوك البيولوجي من اجل الحصول علي تكوينات جديدة و معقدة رغم التعمق في محاكاة السلوك للكائن الحي. لكن هذا التشكيل لا يكفي لتحسين كفاءة سلوك المبني، فعلي الرغم من تمكن المتخصصين حالياً في تفسير سلوك والظواهر المرتبطة بعلم الأحياء إلا أن كانت تتمثل الأولوية الأولى لمحاكاة الطبيعة في التصميم المعماري في نقل التشكيل الحيوي دون النظر إلي طرق التكيف التي تطورت في الكائنات الطبيعية والتي نتج عنه ذلك التكوين، بمحاكاة تلك الطرق يمكن الوصول إلى أنظمة لسلوك المبني لديها القدرة علي التكيف وفقاً للمتغيرات البيئية المختلفة.

تهدف هذه الأطروحة بشكل أساسي إلى إنشاء إطار عمل للمحاكاة الحيوية يهدف إلي نقل سلوك الكائنات الحية إلي سلوك المبني وفق المتغيرات البيئية المختلفة، والذي يُمكن للمهندسين المعماريين اعتماده لتصميم وتطوير أنظمة المحاكاة الحيوية. وبناءاً علي ذلك، تم تحقيق هذا الغرض من خلال إنشاء إطار عمل للمحاكاة الحيوية متعدد المراحل ، كنتيجة حتمية للجمع بين إطار تصميم المحاكاة الحيوية التقليدية والجوانب التكنولوجية مع الأخذ في الاعتبار نقل نهج المحاكاة الحيوية من الإطار النظري إلى الإطار العملي عن طريق تسليط الضوء على الأدوات والأساليب التكنولوجية المستخدمة لتطبيق المحاكاة الحيوية مثل البرمجة النصية والمرئية.

ومن أجل التحقق من إطار العمل المقترح ، قام الباحث بعمل مرحلة تجريبية بالاشتراك مع فريق عمل مكون من متخصصين في علم الميكاترونيك وعلم الأحياء. حيث قام الباحث في مراحلة التطبيق العملي بتنفيذ نموذج مبدئي لوحدة او نموذج للواجهات المستجيبة يمكن تكرارة علي اسطح الواجهات المختلفة بحيث يكون متجاوب مع العوامل البيئة المتغيرة باستخدام البرمجة النصية و المرئية، ففي البداية قام الباحث بجمع المعلومات البيولوجية عن الكائن الحي الذي تم اختياره للمحاكاة، ثم تم نقلها إلى نموذج رقمي من أجل الاستفادة منه في المجال المعماري باستخدام الأدوات التكنولوجية، وأخيراً مرحلة التصنيع الرقمي من أجل تقييم تطبيق هذا النهج وتأثيره علي سلوك المبني. ساعدت هذة التجربة العملية في وضع إطار تصميم أوضح وأكثر تحديدًا بداية من مرحلة الفكرة التصميمية وصولاً إلى مرحلة التنفيذ. كانت النتيجة الرئيسية المستخلصة من هذه الدراسة هي وضع إطار أكثر وضوحاً لمحاكاة الطبيعة وإسهاماتها في تحسين أداء المبني . من أجل التحقق من تأثير المحاكاة الحيوية علي أداء المباني تم استخدام معايير قياسية مستنتجة من عناصر الدراسة و تطبيقها في الدراسة التحليلية علي مجموعة من المشاريع المختارة بناءً على المحددات التي وضعها الباحث. تنوعت حالات الدراسة بين المباني المحلية والعالمية. اوضحت الدراسة التحليلية السمات المشتركة للمشاريع الناجحة في نقل السلوك الحيوي إلي سلوك المبني لتحقيق الأهداف المعمارية وتحسين كفاءة أداء المبني، مما ساعد علي تحديد العناصر الأكثر تأثيرا في نهج المحاكاة الحيوية علي نجاح المبني لتحسين أداءه الوظيفي والتي يمكن الاستفادة منها في التصميمات المستقبلية.

قسم الهندسة المعمارية
كلية الهندسة بشبرا
جامعة بنها

إقرار الأمانة العلمية

أقر انا: هاله سيد محمود سيد عامر، الموقع بأن هذه الرسالة بعنوان: " محاكاة التشكيل الحيوي في التصميم المعماري" اقدمها إلى كلية الهندسة بشبرا جامعة بنها للحصول على درجة ماجيستير العلوم الهندسية في الهندسة المعمارية، هى من صميم عملى الشخصى نتيجة لبحثى الخاص بإستثناء ما ورد بالمراجع العلمية، كما أقر بأن الإقتباسات الواردة بها لم تتعدى المصرح به وأن جميع راجع الرسالة مصادر المعلومات بها موضحة كل فى موضعه، كما أقر بعلمى بكافة إشتراطات الأمانة العلمية وحقوق الطبع والملكية الفكرية وقد إلتزمت بها، كما أقر بأن هذه الرسالة لم يسبق تقديمها لجهة آخرى، وهذه إقرار منى بكل ما ذكر.

تحريرا فى ....../......./٢٠٢٠م

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عنوان الرسالة : محاكاة التشكيل الحيوي في التصميم المعماري

قسم الهندسة المعمارية
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محاكاة التشكيل الحيوي في التصميم المعماري

رسالة مقدمة من

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كجزء من متطلبات الحصول على درجة ماجستير العلوم الهندسية في الهندسة المعمارية

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