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BIOMIMICRY AS A SUSTAINABLE DESIGN METHODOLOGY FOR BUILDING BEHAVIOUR

Hala S. Aamer[1], Ahmed F. Hamza[2], Mohamed khairy[3], Islam Ghonimi[4]

[1]Demonstrator, Architectural Engineering Department, Faculty of Engineering at Shoubra, Benha University
[2]Professor, Architectural Engineering Department, Faculty of Engineering at Shoubra, Benha University
[3]Professor, Architectural Engineering Department, Faculty of Engineering at Shoubra, Benha University
[4]Associate Professor, Architectural Engineering Department, Faculty of Engineering at Shoubra, Benha University

Abstract
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. Among the modern tools used to tackle the building functionality and climate-related problems is biomimicry. Aiming to enhance self-sustainability, widen ecological building elements, and boost building behaviour efficiency, bio-mimicry draws from nature mimicking the life principles of biological role models which have proved to overcome similar challenges; thus, reaching building behaviour's targets. The paper specifically discusses the embodiment of bio-mimetic strategies into building behaviour elements that increases building behaviour efficiency.

Keywords: *Bionics, adaptation, Biophilia, Bioinspiration, Biomimetics, Biomimicry, Form Finding, Genetic Algorithms, Biological Role Model, Regenerative Design, Building Performance*.

1. Introduction
Obviously, today's world is heavily struck by climate change. Challenging as it seems, the impact of climate change reached scientific, economic, social, and political aspects, expected to continue to be witnessed for years ahead. Man-made premises are held accountable for climate change-related issues such as excessive waste production, energy overconsumption and greenhouse gas emissions. Therefore, reversing such harmful effects became vital through re-connecting to nature as a source of thinking system. Currently, a paradigm shift can be witnessed in various fields, especially architecture and material science led by biomimicry which is inspired by nature's life principles. Climate change problem can be tackled by endless solutions through integrating nature simulation into architectural elements.

1.1 Research Problem
Reviewing discipline of the literature, despite claiming being bio-inspired an environmentally-friendly, designs solely relying on the envelope of the buildings have failed to maintain the principles of sustainability. Drawing from the external inspiration from nature rather than implementing the internal behaviour of living organisms, the problem thus arose from the simple imitation of nature. This paper is an endeavor to link building behaviour and bio-mimicry as a tool for sustainable design.

1.2 Research Aim
The primary purpose of this paper is to reach criteria for measuring the success rate of the bio-inspired design, to verify the design utilization of mimicking the biological role models in building behaviour.

1.3 Research Methodology
In order to fulfill the purpose aforementioned, explanatory and analytical methodology will be adopted through five stages; **first** starting with a literature review of the history of biomimetic architecture; **second,** explore biomimetic design approaches and levels of biomimicry; **third,** explore nature's life principles; **forth** analyze examples of architectural interpretation of life criteria into building behaviour systems; which looking for functions, behaviour, and ecosystems within the living systems and implement same into building designs to reach architectural targets; and **fifth** using measure criteria to identify the rate of utilization of biomimicry for selected projects.

2. Biomimicry Origins
Bio-mimicry means the imitation of life, the word coming from a combination of the Greek roots bios (life) and mimikos (imitation) according to Benyus's [1] definitions. In 2002, Janine Benyus defined Bio-mimicry as the study of nature's most efficient processes and systems that has evolved over 3.8 billion years of survival on earth and implementing these to solve human problems. Waste management and resource rationalization can be solved through mimicking natural processes.
As stated by Werner Nachtigall, Bionik is a German term originally comes from The English word "bionics",

coined by the US Air Force major J.E. Steele at "Bionics Symposium: Living prototypes – the key to new technology" conference in 1960, it is confirmed a mixture of "biology", "technology" or "electronics". In German, the term "Bionik" finds a very expressive reinterpretation in the first and last syllables of Biologie [Biology] and Technik [Technology].

From a historical standpoint, the term Bio-mimetic was first introduced in 1917 by Otto Schmitt in his book titled "On growth and Form". Considered as the founder of biomedical engineering, Schmitt also contributed to the field of biophysics. Schmitt claimed that nature has long been a source of inspiration back to the Stone Age. Upon tracking the bio-mimicry timeline, we can see various bio-inspired inventions; starting Leonardo Da Vinci Flight 1452- 1519 till the modern innovations Figure (1).

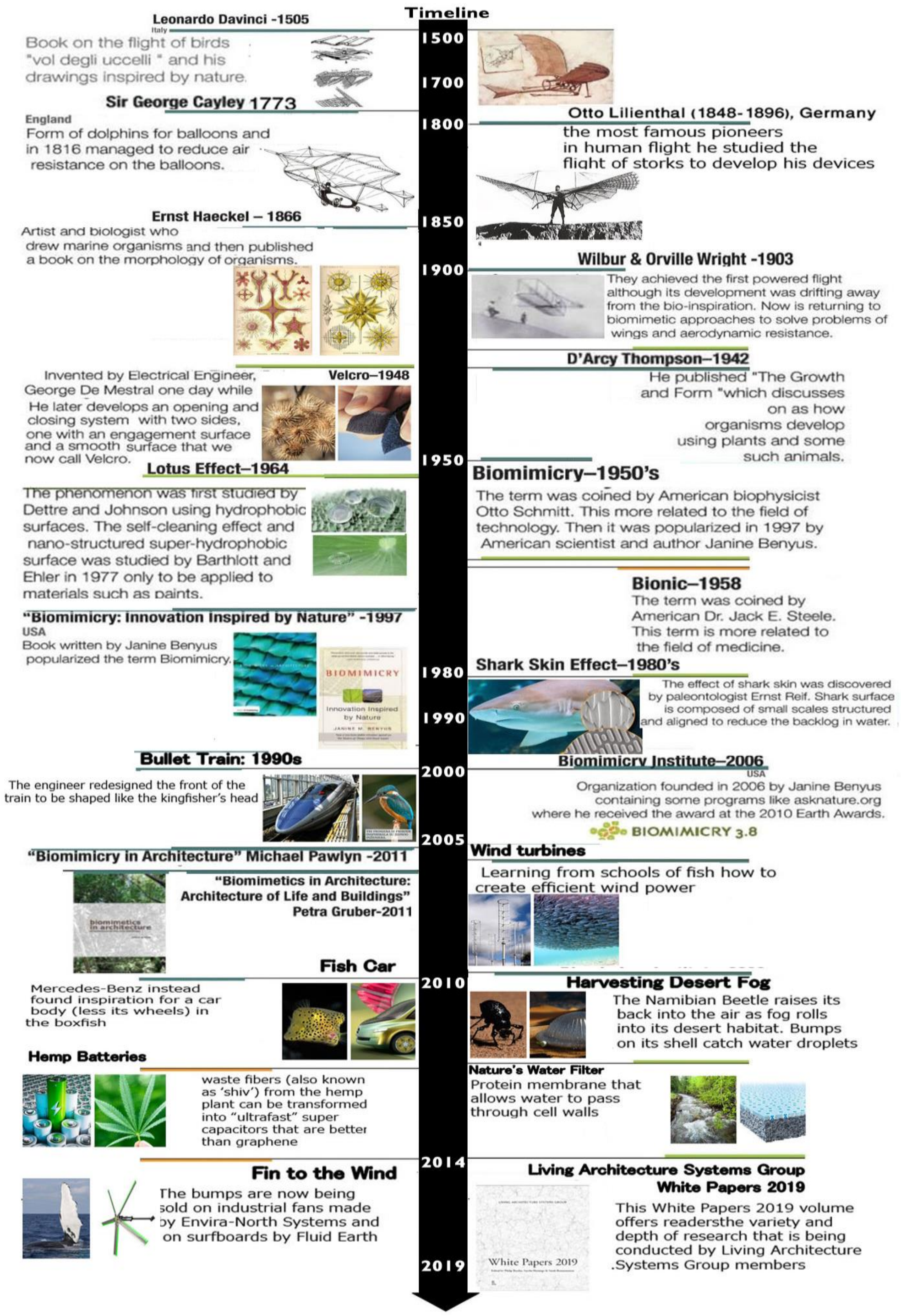
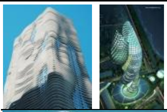
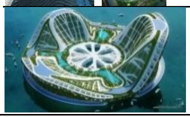


Figure (1): Bio-inspired Innovations Time line
Source: Edlyn García La Torre 2013, developed by Author

3. Biomimetic Architecture Background

Throughout human history, architecture has been inspired by nature, most prominent example of which is biomorphism. Additionally, ancient Egyptians, Greeks, and Romans all implemented natural motifs in their designs, where the resulting example can be seen in the tree-inspired columns [2]. Historical background of architecture indicated that throughout history nature has been used as a source of form-finding. However, various architecture projects look like nature but don't work like nature. Biomimetic architecture timeline Table (1) presents the using bio-mimicry in architecture throughout history.

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

Classification	Time Period	Location	Example	Description	Image
Pre Industrial Revolution Rock-Cut Architecture	1400 BC	Egypt	**Ancient Egyptian Architecture:** Luxor temple columns	During this period we find Egyptian columns that have the common features like plant stems , India Buddhist temples and shrines were actually carved into caves and mountain, decorated floral ornamentations in the Baroque and Rococo periods and Medieval period: masonry vaults [3]	
	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	**Geometry of Nature:** • Golden Section • Spirals in Architecture • Chaos Theory and Architecture • Construction lightness • Curved Surfaces with Girders (Sea shell) • Folded Structures • Ernst Haeckels Tables of Marine • Hexagonal design inspired by nature • Cable structures inspired by 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 buildings.	
	21th Century AD	World wide	**Futuristic** LILYPAD Ecopolis		

4. Biological Domain

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

Biomimetic provides a wide variety of approaches. Worth mentioning, the biomimetic design process is utilized as an integrated system, not as separate elements. Two approaches have been identified for the application of Biomimicry as the following [4]:

1- Problem-Based Approach: is concerned with the design problem and then examines the methods in which organisms or ecosystems overcome the problem.
2- Solution-Based Approach: identifies a particular characteristic, behaviour, or function within an organism or ecosystem then look for the design problem that could be addressed [5].

4.2 The Three Levels of Biomimicry

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 [6]. This paper will focus on behaviour level for sustainability, which is concerned with a deep understanding of biology.

4.3 Nature's life principles

For the purpose of maintaining sustainability, nature has developed a set of "principles"; complexity, propagation, growth, sensing and reacting, adaptation, metabolism, energy, self-repair, and intelligence [7]. 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 behave, Reacting to environment that dealing with the environmental factors, and the adaptability type that how the organism can adapt to the climate issues and survive.

In Petra Gruber, Barbra Imhof, and Vincent j. project titled "Growing as Building", a growing database was created of the most common biological performance of biological role models by simulating 37 role models, define the biological performance as; change color, growth, shape change, variety of shapes, hierarchies, self-healing, and communication.

This paper will adopt the biomimetic design approach workflow which goes through the following steps in Figure (2).

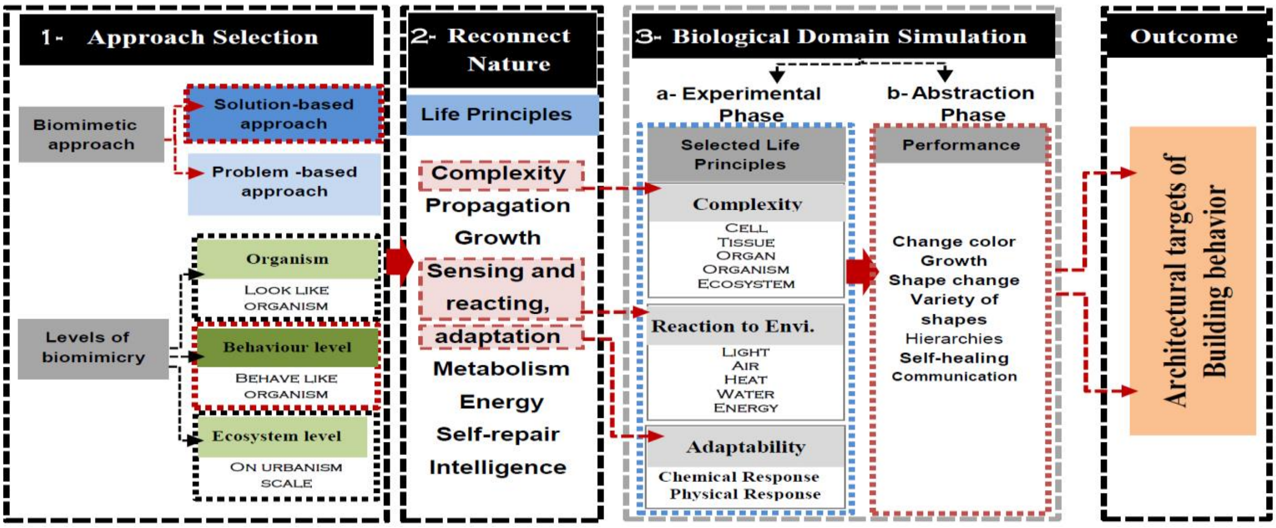


Figure (2): The Biomimetic Design Approach Workflow
Source: Author

5. Potential Strategies offered by Biomimicry to implement in Building Behaviour

Within the scope of building behavior 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 paper 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 architectural domain in prototype phase as an architectural element such as: Envelope, Structure, Building systems, Interior elements, Materials) Figure (3).

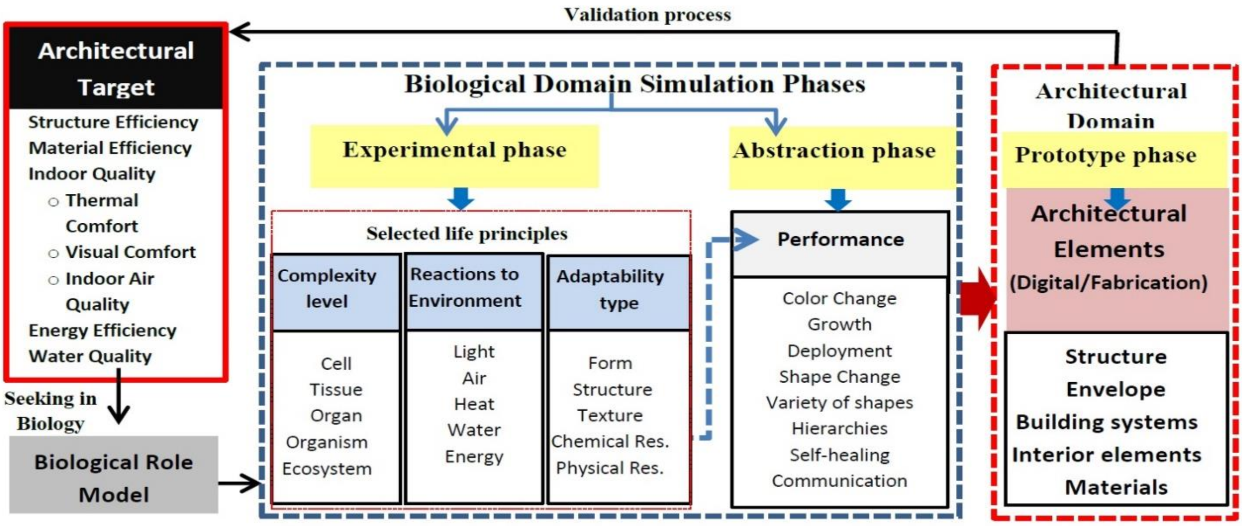


Figure (3): Problem-based Approach Methodology
Source: Author

6. Case Studies

As the methodology adopted by the paper transfers biological models principles into the architectural domain. The case studies listed below discusses strategies beneficial for building behavior. The aim of this section is 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', and architectural domain 'prototype phase'.

- Case study 1: Algae - BIQ building
- Case study 2: Eyes - L'arabe du monde institute
- Case study 3: Conifer Cones - Programmable Veneer composite element

6.1 Case Study 1: Edgar Street Towers

The first step is searching for the biological role model that can help to reach the architectural target, in this case, the target is Indoor Quality and energy efficiency, Algae will be the selected biological role model, second is the abstraction of the results, and then is the Implementation in architectural domain for BIQ building example as the following:

6.1.1 Biological Domain

- **Experimental phase**

Algae, convert carbon dioxide into valuable compounds including biologically active compounds such as biofuels, foods, feed and pharmaceuticals (bioactive-compounds) [8]

- **Abstraction phase**

Algae are a biological Role model that performs 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 deduced as a development growth Figure (4)

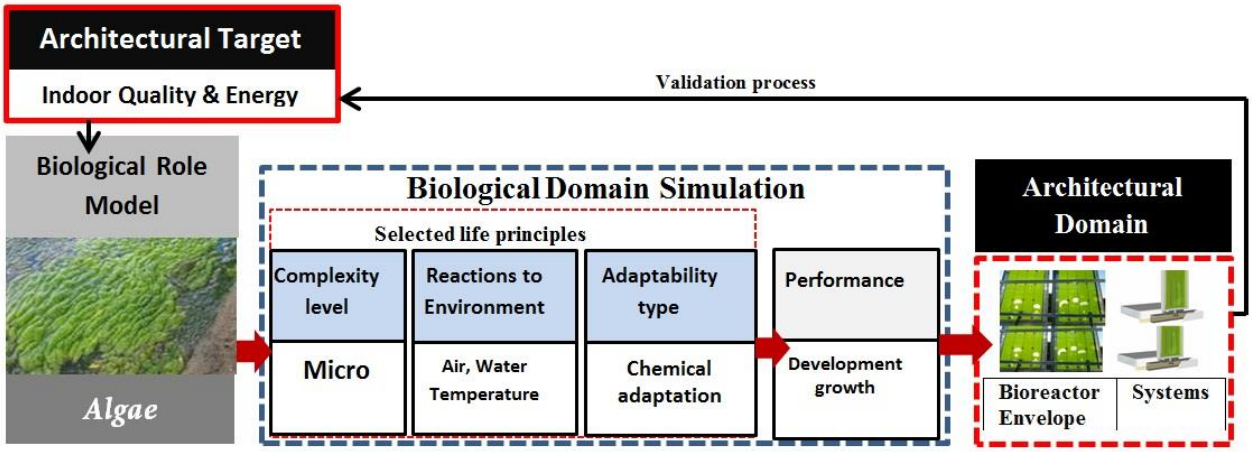


Figure (4): Algae abstracted principles
Source: Author

6.1.2 Architectural Domain

- **Prototyping phase**

Architecture witnessed revolutionary change upon the introduction Living Architecture concept. Rather than addressing factors such as energy, water re-use, or organic waste management individually, combined resource usage is implemented throughout the building through a single combined system [9].

Figure (5): Living Architecture system
Source: LIAR, 2020

Figure (6): BIQ building
Source: https://www.archdaily.com/, Accessed July, 2020

Through such a system, waste is managed in various ways in a series of interconnected microbial chambers, creating a sequence of biological events. The heat and biomass generated by the façade are transported by a closed-loop to the building's energy management center Figure (5). BIQ building [10] in Germany considers being the first algae powered building Figure (6).

6.2 Case study 2: L'arabe du monde institute

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, Eyes will be the selected Biological role model, second is the abstraction of the results, and then is the Implementation in architectural domain for L'arabe du monde institute example as the following:

6.2.1 Biological Domain

- **Experimental phase**

In visual physiology [11], 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 (7).

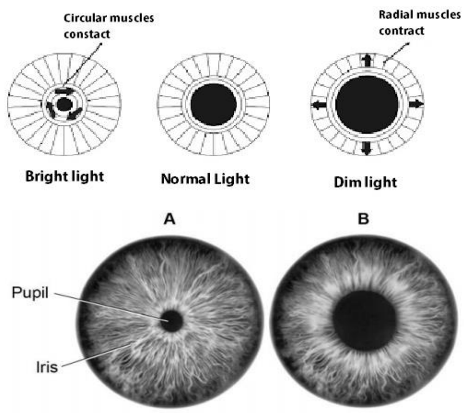


Figure (7): The iris muscles action during the PLR
Source: Henryk, k., 2004

- **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 deduced as shape change along with the simulated morphology of tissue Figure (8).

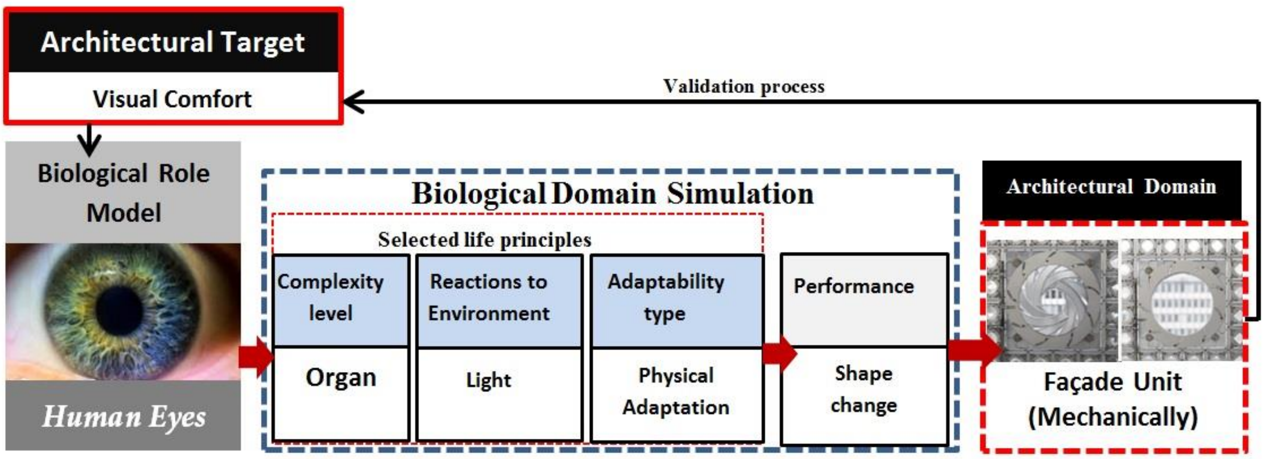


Figure (8): Eyes abstracted principles
Source: Author

6.2.2 Architectural Domain

- **Prototyping phase**

Famous for his attention to details within façades, Jean Nouvel [12] utilized an innovative element- IMA- in designing L'arabe du monde institute building in Paris. In imitation to the eye retina, responsive metallic Soleil was installed on the south façade acting like eyes iris Figure (9).

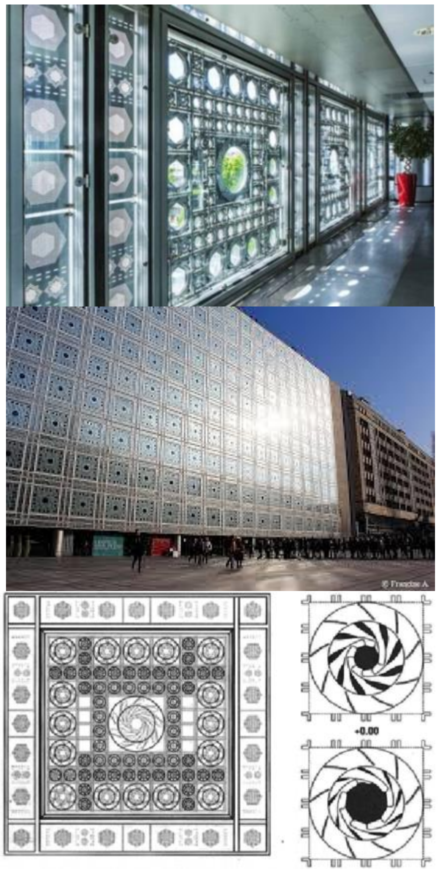


Figure (9): L'arab du monde institute adaptive façade
Source: https://www.archdaily.com/, Accessed June, 2020

6.3 Case study 3: Veneer composite element

The first step is searching for the role model which can help to reach the architectural target in this case the target is Material efficiency, Conifer Cones will be the selected Biological role model, second is the abstraction of the results, and then is the Implementation in architectural domain for veneer element example as the following:

6.3.1 Biological Domain

- **Experimental phase**

Figure (10): Potential shape transformations of veneers wood
Source: Artem Holstov, 2017

Cones of conifers [13]: with its hygroscopic form-changing abilities, The cones open and close as a reaction to the environmental conditions of humidity and aridity, where the cones open in dry conditions and close on moist conditions Figure (10).

- **Abstraction phase**

Cones are a biological role model that presents tissue level of complexity. It uses physical adaptation to humidity as an environmental factor in providing material efficiency as an architectural target. The performance could be deduced as shape change along with the simulated morphology of tissue Figure (11).

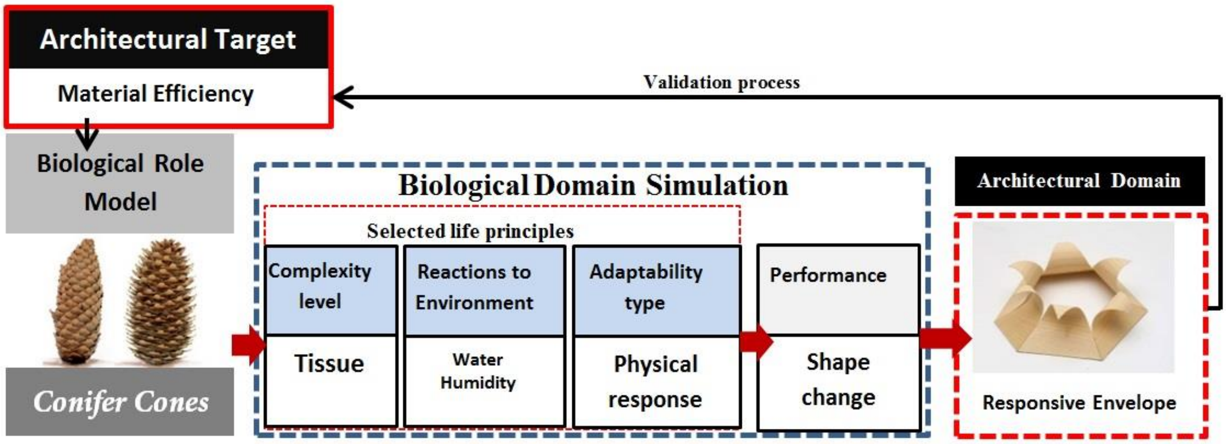


Figure (11): Cones abstracted principles
Source: Author

6.3.2 Architectural Domain

- **Prototyping phase**

The veneer composite element [14] uses the reactive material properties in surprisingly simple building element that is at once an integrated sensor, energy-less actuator, and modulating flap. An integrated functionality of this type on the material level allows complex, decentralized behavior patterns without any control units Figure (12).

Figure (12): Reactive envelopes by veneer composite element
Source: https://www.archdaily.com/, Accessed June, 2020

7. Measuring the extent of benefit from the imitation of biological role models in building behavior

Efforts have been exerted by architects to deliver truly remarkable projects leading to successful bio-morphic architecture based on bio-mimicry with the assistance of digital revolution. However, that doesn't necessarily mean their successful transfer of the performance of living systems to building behaviour.

This will be the main concern of this paper; it adopts the verification of this success. The benefit gained from mimicking biological role models will be investigated via the criteria developed for measuring the success rate achieved by the design, especially at the behaviour level. Also, the fulfillment of building behaviour targets will be verified. This will, in turn, helps in developing future design standards by ensuring that transferring nature to buildings as behaviour rather than a mere form, thus increasing building efficiency.

7.1 Methodology of measuring the extent of benefit from biomimicry

This paper uses an analytical methodology to identify and comprehend the selected case studies using the evaluation criteria, in order to identify the most successful bio-inspired design characteristics that achieved building behavior targets.

A set of criteria were developed based on the study's elements; it contains biomimetic approaches, levels of biomimicry, selected life principles, biological role model performance, and the deduced building behavior targets and elements, the fabrication type.

7.2 Determinants

The selection process adopted by the researcher in choosing the projects that will be subjected to the analysis as case studies are based on the following selection criteria: Samples selection to be biomimetic building, based on biological performance simulations, and utilized life principles for mimicking whether in form or in behavior, and developed recently in the last 10 years.

7.3 Criteria analysis

In this part the research applied criteria of measuring the extent of benefit from the imitation into two main dimensions: the biological domain and the architectural domain, then it divaricated into seven dimensions. The relative weight was distributed based on the importance of each of the criteria to achieve the desired goals of building behavior through simulation. Thus the largest value will be for the architectural domain criteria. The criteria are applied to selected case studies like the following:

7.3.1 Biological domain

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 and Communication.

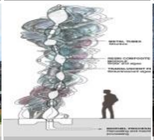
7.3.2 Architectural domain

a. Building behaviour targets: Structure Efficiency, Material Efficiency, Indoor Quality (Thermal Comfort, Visual Comfort, Air Quality), Energy Efficiency, Water Quality
b. Building behaviour elements: Structure, Envelope, Building systems, interior elements, Materials
c. Fabrication type: Mechanically, Bio-reactor, Programmable

7.4 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. The score points were granted based on the criteria set by the researcher. The ratio derived from total score points for each project was determined, enabling measuring the success rate of each project in implementing bio-mimicry.

Table (2) presents the data collection and analysis of the criteria applied to the selected case studies. The table shows the application of measuring criteria to analyze each project, i.e. defining the used bio-mimic approach and level of bio-mimicry, specifying the life principles and performance transferred to the designs, listing the building behaviour targets achieved through the building elements given, and pinpointing the fabrication type. 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 bio-mimetic projects which can then be used as standards for future projects.

Case Studies / Measuring Criteria			Rate Wieght	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6
				BIQ Building	E. crispata-building	L'arabe du monde institute	Veneer Pavilion	Yeosu Oceanic Pavilion	Bundle House
									
Biological Domain	Biological Role Model		-	Algae	E. crispata	Eyes	Cones	Emergent	Water
	Biomimetic Approaches	Solution based	1	---	---	---	√	√	√
		Problem based	1	√	√	√	---	---	---
	Biomimetic Levels	Organism	1	---	---	---	---	---	---
		Behaviour		√	√	√	√	√	√
		Ecosystem	4	---	---	---	---	---	---
	Selected life principles	Adaptability	3	Chemical	Chemical	Physical	Physical	structure	Form
		Environmental reactions	3	Air- water	Energy	Light	Humidity	---	---
		Complexity type	3	Micro	Tissue	Organ	Tissue	Organism	Ecosystem
	Biological role model performance	Color Change		√	√	---	---	---	---
		Growth		√	√	---	---	√	---
		Deployment	5	√	---	---	---	√	---
		Shape Change		---	---	√	√	---	---
		Variety of shapes		---	---	---	---	---	√
		Hierarchies		---	---	√	---	---	---
		Self-healing		---	---	---	---	---	---
		Communication		---	---	---	---	---	---
Architectural Domain	Building Behaviour (Target)	Structure Efficiency	7	√	√	√	√	√	√
		Material Efficiency	7	√	√	---	√	√	---
		Thermal Comfort	7	√	√	---	√	---	---
		Visual Comfort	7	√	√	√	√	---	---
		Indoor Air Quality	7	√	√	---	√	---	---
		Energy Efficiency	7	√	√	---	√	---	---
		Water Quality	7	√	√	---	---	---	---
	Building Behaviour (Element)	Structure	4	---	√	√	√	√	√
		Envelope	4	√	√	√	√	√	√
		Building systems	4	√	√	---	---	---	---
		Interior elements	4	√	---	---	---	---	---
		Materials	4	√	√	---	√	---	---
	Fabrication Type	Mechanically	2	---	---	√	---	---	---

		Bio-reactor	4	√	√	---	---	---	---
		Programmable	4	---	---	---	√	---	---
	Criteria Evaluation		100	88%	88%	43%	77%	35%	28%

Table (2): Measuring Criteria application
Source: By Author

8. Results, Analysis and Recommendation

Following is a discussion of the results of the analytical study; contains measuring of the success, the deduced common characteristics of successful projects, and then the recommendations to enhance the building behaviour using a biomimetic approach.

8.1 Measure of the success

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:

- The first is successful in transferring the principles of life and deals with the building as a whole system; it was successful in a large percentage up to 88% in produced regenerative design achieving the goals of the building behavior.
- The second is successful in analyzing the principles of life, but it was transferred to one component of the building, so it was a low success rate 43%, 35% although the deep understanding of life principles.
- The third is that it used simulation to transfer the surface shape only; its success rate to achieve the building goals was very weak 28%.

8.2 The Effective Factors on project's success

Comparative analysis showed the most influencing factors of the project's success, based on the common characteristics of the most successful projects in achieving building behaviour's targets of building behaviour, 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 the fifth and sixth projects.
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 1st: 4th project.
d. The simulation at the ecosystem and organism level of complexity in the 5th and 6th project, 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 behavior.
- The results revealed that the dynamically responsive façade involves mechanical systems that have operational problems such as microcontroller maintenance, noise, and energy consumption.
- Material-based approach achieved more targets than mimicking the organism mechanically.
- Bio-reactor approach got the highest percentage of achieving the building's targets.

8.3 Recommendations for using biomimetic approach to enhance building behaviour

- 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
- New approaches may be considered in which the benefits of a microcontroller can be combined with an intelligent material-based intervention.
- Dealing with the Bio-reactor approach to produce a regenerative design that can face climate change and achieve sustainability.

9. Conclusion

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 paper indicated that the importance of bio-mimicry as a sustainable methodology for building behavior.

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 paper adopts problem-based approach to solve problems of building behaviour by analytical methodology for selected case studies through three process; The first is to search for the biological role model criteria. Second is the abstraction of the results. Third is the Implementation in design and technology. The analysis of case studies revealed the following:

• Living organisms operate at a level of complexity much deeper than that which delivered by external shapes and skin's pattern as some organisms operate at the tissue level and others on the micro-level, etc. This is the reason for reaching projects that look like nature but do not work like nature and it may not do the required role.

• Living organisms do multi-function performance at the same time, and consequently, they produce many levels of adaptation, and therefore it has become necessary to use a holistic view and deal with the organism as a whole system.

Measuring the extent of benefit from the imitation of biological role models in building behavior 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 that the kinetic responsive façade which involves mechanical systems has operational problems such as microcontroller maintenance, noise, and energy consumption.

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