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Research paper

Applications of Thermoregulation Adaptive Technique of form in Nature into Architecture: A Review

Amatalraof Abdullah[1]*, Ismail Bin Said[2], And Dilshan Remaz Ossen[3]

[1]Department Of Architecture, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor Malaysia
[2]Department Landscape Architecture, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor Malaysia
[3]College Of Architecture Engineering And Design, Kingdom University, 40434, Kingdom Of Bahrain
**Corresponding Author E-Mail: Raofa4@Yahoo.Com*

Abstract

In the last 20 years, biology has obviously been the source of countless, innovative solutions from nature in many discipline. Biomimetic is an interesting philosophy which hybrids multi-disciplinary sciences with biology. Biomimetic design is currently one of the promising fields ranging from accessing to adaptive, sustainable and energy saving solutions for the architectural and environmental challenges. This paper underlines and reviews the recent state of the art biomimetic applications to architecture, in particular, thermoregulation strategies. The review design was based on project's status that varies from executed projects, experimental models and design concepts. The study shows that biomimicking thermoregulation strategies of the nature leads to a significant energy saving and indoor thermal comfort. It is also observed that some of the architectural researches in this regard do not exceed the stage of theoretical study due to the lack of sponsorship and funding. Although there is a number of levels in respect to mimicking adaptive notions from nature such as behavioral, physiological, and morphological, architects' works are mostly confined to mimicking the functional performance of organism through its morphological configuration; physiological and morphological adaptation. The review shows that architects turn noticeably to nature's solutions as the source of zero-waste system, saving energy and controlling thermal environment.

Keywords: *Thermoregulation; biomimicry; adaptation; passive design; thermal comfort.*

1. Introduction

In December 2015, Paris Climate Conference was held to save the earth from global greenhouse emissions due to global warming. One hundred and ninety-six (196) countries agreed to gradually reduce the usage of fossil fuel and depend more on clean sources of energy such as solar radiation and wind power. This agreement from countries' decision-makers would be reflected in many sectors using energy to run day-to-day business activities thus making them more sustainable (French Ministry of Foreign Affairs and International Development, 2015).

Biomimicry is the new multidisciplinary science, which adopts these sustainable values. It is the science of emulating the genius technology of biology which works "without guzzling fossil fuels, polluting the planet, or mortgaging" the future to solve human problems (Benyus, 1997; p.2). Biomimetic architecture is one of the sciences affected by the sustainable adaptive solutions found in nature for enhancing building performance. This architecture not only copies forms in nature, but also emulates the working principles of these forms. A growing interest in this field have proven the validity of emulating nature mechanisms to generate sustainable, energy-saving solutions (Lurie-Luke, 2014; Torgal, et al., 2015).

In the last two decades, bio-inspired designs get a considerable popularity due to the advantages of bio-mimicking natural systems. They have been summarized by Zari (2012) into three motivating aspects: innovation, sustainability, and Human well-being. Firstly, biomimicry is a rich source of innovation (Pawlyn, 2011; Bonser, 2006; Benyus, 1997; Hesselberg, 2007). It contributes in inventing technological discoveries (Geim, et al., 2003; Parker, 2010; Tao, 2001), constructing resistant light structures (Lim 2009; Kozlov, et al. 2015), and designing dynamic structure (Armstrong, 2012; López, et al., 2017). Secondly, mimicking nature can result in creating sustainable designs, materials and engineering solutions (Benyus, 1997). Inspiring from strategies in nature leads to save energy, mitigate climate change (Zari, 2007; Altomonte, 2008; Morris-Nunn, 2007), recycle and eliminate waste (Memmott, et al., 2009; Pawlyn, 2011). Thirdly, it is the enthusiasm of some researchers to find out whether inspiring designs from nature standing on understanding the living world could positively affect the psychology of humans (Benyus, 2007). However, the argument of this study is about the thermoregulatory applications of adaptive techniques found in nature to buildings. In addition to their positive effects from economic, environmental, healthy facets by saving energy, reducing the adverse impacts on the environment, and providing thermal comfort, respectively.

Recently, architects turn noticeably to nature's solutions as the source of efficient structure, zero-waste system, managing water, saving energy and controlling thermal environment (Pawlyn, 2011), which are facilitated by the latest technologies (especially, computing programs). Some of the successful sample projects have been narrated by Gruber (2010), Pawlyn (2011) and Loonen (2015). Though, this paper focuses on the current literature of the biomimetic applications into architecture, particularly, thermoregulation strategies caused by morphology of the inspiration source. Thermoregulatory bio-inspired material based on their chemical

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composition is excluded in the scope of this paper. This aspect of the biomimetic design is selected for review due to the depletion of energy caused by building sector to meet the thermal comfort requirements for occupants through mechanical devices such as Heating, ventilation and air conditioning (HVAC). It is also to enlighten architects to the power of emulating natural strategies for adaptation with temperature fluctuation and design effective passive means rather than depending on electrical devices. Since this article is about thermoregulation strategies, it is essential to address an overview of heat transfer means to comprehend the thermoregulatory methods in architectural applications.

2. Heat Transfer Modes

There are two ways to describe heat regulation and control: manipulating the way of heat transfer either by heat flow enhancement or by hindrance. Heat is an energy; the heat exchange between two physical systems requires knowing the differences in their thermal energy where transfer occurs from the hot to the colder part. Thermal energy transfers by three ways; conduction, convection, and radiation. Conduction is the heat transfer mode through the collisions of body molecules, when there is no equilibrium between the temperature of its parts. In a built environment, conduction is responsible for a considerable amount of heat loss (Nasrollahi, 2009). To reduce heat dissipation through conduction, the thermal resistance value (R) of a material should be high besides using appropriate insulation and avoiding thermal bridge through construction (Brebbia, et al., 2006).

Convection occurs when a fluid flows through a solid body with a higher temperature. The nearby molecules of the fluid become a lighter in density due to heat transfer from solid making them float and replaced by other molecules of the fluid. Therefore, buoyancy is the main vector for heat energy by convection. There are two types of heat transfer by convection: natural and induced or forced convection; natural convection such as wind passes through wall, while the forced convection is caused by external forces like mechanical devices; (e.g., fans, pumps…etc.) (Bejan and Kraus, 2003). This technique as well as radiation are the running methods of heat transfer through cooling systems such as the chilling ceiling panels (Hui & Leung, 2012). To limit heat transfer by convection through the building, air flow and motion should be restricted by blocking air gaps and using air barrier materials.

Radiation is the third mode of heat transfer where the heat energy of the hot body transfers to the surroundings through electromagnetic rays (Rohsenow, et al., 1998). To avoid sun radiation, shading devices, building orientation, insulation, glazing system and photovoltaic system should be considered.

3. Biomimetic Thermoregulatory Applications Into Architecture

Building envelop is a critical part of architecture responsible for the thermal comfort and residents' well-being (Knaack at el., 2014). HVAC is widely used to offer satisfactory indoor air quality and thermal comfort. Studies show that a significant part of electrical energy is consumed by the utilities used for air conditioning; for instance, in Gulf countries, 70 % of the generated electricity is used for cooling (Sala et al., 1999). As a way of sustainable and sufficient thermoregulatory alternative method, architects tend to emulate nature's inspiring solutions. In nature, organisms adapt with the extreme variation of the environmental climatic variables through physiological, behavioral, and morphological adaptation (Dufty et al., 2002). Similarly, building is facing climatic variation and architects are required to offer a comfortable thermal indoor environment. Therefore, Benyus (2007), Gruber and Gosztonyi (2010), Badarnah (2012) and Mazzoleni (2013) insist in exploiting this analogy to solve our built environment problems.

Some of the bio-inspired projects have been executed, others were experimented as simulation models and the rest have not exceeded; the suggested bio-inspired notions are merely prototype designs. The thermoregulatory biomimetic applications ranged in scales and levels based on the inspiring solution from nature, architect's prospective of design and approach of concept's implementation. The applications might be wall's structural layers and arrangement, innovative construction units, adaptive kinetic façade, or a manipulation in the design of building's plans. The following section is a narrative description for the accessible projects, their inspiring sources, mechanisms and the validity of such bio-inspired designs. It examines the thermoregulatory applications of biomimetic strategies to projects and their potential to improve building performance by passive means.

3.1. Executed Projects

Adaptability in nature is the ability of organism to cope with the changing climatic variables such as temperature and humidity. The adaptability might be either static such as built architecture by some organisms (nests and burrow) or active like the behavioral adaptation of their bodies. On the other hand, adaptive architecture is called for the building in which some parts of it manipulatively transform in certain times of the day to manage the variation of climate (Badarnah, 2012). An example is the Heliotrope building in Freiburg im Breisgau by Rolf Disch built in 1994. The building rotates in response to the direction of the sun like the heliotrope flower which tracks the sun and gathers solar energy. The physiological emulation of motion makes the building capable of capturing 4 to 6 times of the energy needed.

Motion is one of the principles used in nature to either track sun for a solar gain or avoid its glare. In a very hot climate such as the desert of Abu Dhabi in UAE where the temperature reaches 49.2°C, avoiding sun rays is a crucial factor for designing energy efficient architecture. Since radiation is one of the effective ways of heat transfer through visible and non-visible light, blocking radiation through shading will result in hindering heat transfer thus causing the so-called passive cooling. To avoid the blazing sun of the desert, Aedas Architects designed double façade system for Al Bahar Towers. The exterior façade in Figure1 is kinetically designed to open and close in response to the movement of the sun dropping solar gain by up to 50%. The folding motion of the façade system panels is inspired from the adaptive flowers and the mushrabiyahs as a shading screen (AHR, n.d.).

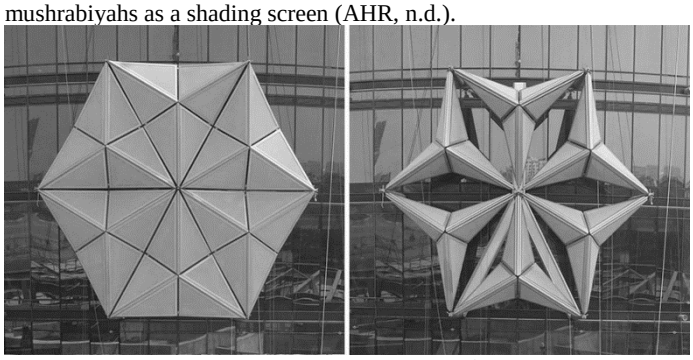


Fig. 1: Dynamic, sunlight-responding shading screen for Al Bahar Towers façade, reproduced from aedas.com/en.

Another example of adaptive architecture is Theme pavilion at Expo 2012 in Yeosu, South Korea. Under the Expo's theme, The Living Ocean and Coast, Austrian practice Soma designed kinetic façade consists of moving lamellae resembling gills. During the daytime, the reinforced fiberglass lamellae work as shading device thus controlling sunlight and overheating. However, after sunset, the intensity of lamellae movement is controlled for analogue visual effect and ventilation purposes (Soma, 2012). The performative idea of kinetic lamellae is based on lamellae performance inspired from plants. Because of this innovative shading technique, as well as using other energy renewable systems such

as solar panels and geothermal system, the building saves up to 80% of the required energy (Irvine, 2012).

The static adaptation of organism's architecture in nature is the seed notion for the well-known design of Eastgate Centre in Zimbawe by Mick Pearce in 1998. The temperature in the termite mound is stable throughout the day, 31°C; although the temperature outside fluctuates highly up to 17°C (Turner et al., 2008). The design emulates the wind-induced natural ventilation system in the mound where several long chimneys are designed to direct warm air up through the stack effect. This action induces the fresh, cold air to rise up to building's rooms through central channel connected to rooms' ground. Stack effect occurs because of the difference between indoor and outdoor air density causing air buoyancy enhanced by the air temperature differences (Lovatt and Wilson, 1994). This physiological strategy saved up to 90 % of the required energy (Marshall, 2013). Building orientation and external shading devices were considered as they play an essential role in maintaining a cool indoor temperature.

Evaporative cooling is a technique widely used as a passive way for cooling architecture. Bio-skin is the innovative bio-inspired facade system of the Sony Research and Development Office in Shinagawa, Tokyo. The building clad emulates transpiration and the Japanese traditional technique of cooling to enhance indoor cooling (Loonen, 2015). It is an intensified system of porous ceramic tubes all over the façades. The evaporation effects of rainwater collected from roof resulted to a reduction in heat load for the building and urban heat island consequences. An experimental study was done for such system, they found that the system surface temperature is lessen by as much as 12°C and 2°C around the footing of the building (Yamanashi et al., 2011).

The importance of these projects attributed to designing passive, sustainable alternatives to HVAC system. The bio-inspired designs have proven their efficiency to provide passive cooling and natural ventilation.

3.2. Experimental Models

A lot of studies have been conducted to improve indoor environment quality considering the optimal use of energy. However, the most frequent studies are focusing in building's thermal performance, energy efficiency and passive means of cooling; a review of the recent technologies of the passive cooling was narrated by Santamouris and Kolokotsa (2012). Building energy simulations are the software programs that facilitate such studies by predicting thermal performance and expecting energy consumption. The following are the bio-inspired studies using these simulations to predict the validity of research assumptions.

One of the factors that plays a noteworthy role in undesired in/outdoor heat and increases the cooling energy consumption of buildings is the convergent urban planning with a tighter spatial mutual relation between buildings (Santamouris, et al. 2007; Sakka, et al, 2012). The heat generated due to the modification of land surfaces and sun radiation reflection between buildings' surfaces and absorption of sunlight (Rizwan, et al., 2008; Oke, et al., 1991) results to the so-called Urban Heat Island (UHI). Similar heat island consequences have been observed in Galanthus nivalis flower in temperate regions. However, this flower has special mechanisms of cooling; one of the possible contributor is the retro-reflecting attribute (Han et al., 2015). The physiological and morphological attributes of this petals have been mimicked to design retro-reflective building façade. The surface design are a network of cubic-corner retro-reflective arrays which are effective to send the light back to its source. The design resulted to a reduction in the reflected solar radiation from the surrounding buildings which in turn helps to mitigate the effects of UHI as well as the energy required for cooling. It saved up to 9.8% of the cooling energy consumption of HVAC.

Furthermore, regarding the validity of design efficiency, a team of Harvard university has used experimental laboratory window model to analyze and examine their innovation. As the window is a main source responsible for energy inefficiencies regarding heat loss and gain (Bülow-Hübe, 2001), the team designed window model providing adjusted cooling and shading for indoor environment. The window consists of a transparent microvasculature layer (PDMS) made of clear silicone rubber with fluid-filled microtubes invented via using microfluidic engineering principles (Hatton et al., 2013). Water runs through the micro-channels to harvest sun heat as a solar energy and supply heated water, (Figure 2). The experimental model with 10×10 cm2 window reduced temperature by 7–9°C; the flowing water is in room temperature at 2 mL/min. The cooling degree is controlled through flow rate, and water temperature. The design was inspired from the physiological and morphological design of organism's internal vascular networks such as blood vessels cycle.

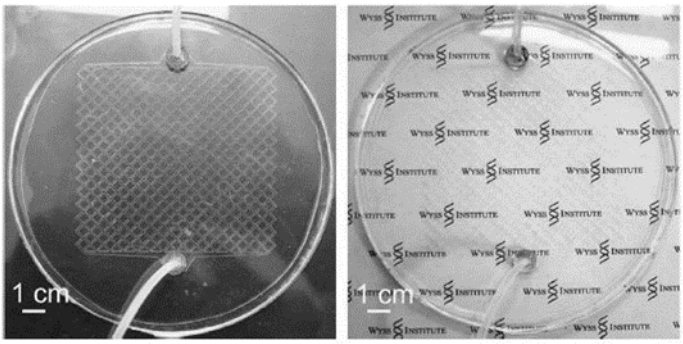


Fig. 2: The transparent fluid-filled microtubes run through the window without affecting the clarity of visibility, reproduced from Hatton et al. (2013).

Green façade is one of the techniques used in building for passive cooling. Šuklje, et al., (2013) designed a microclimatic layer of the green façade called bionic façade inspired from the vertical greenery. The artificial adaptive façade consists of panels, leaves, made of photovoltaic cells and evaporative matrices. The experiment showed that the temperature in the bionic façade and green facade reached up to 4.3 K lower than the temperatures in the microclimatic coating of the border layer at the black façade with a a little higher heat in the former. This due to the cooling effects of the bio-inspired leaves blocking radiation through shading and evaporative feature of the CaSi matrices. The bionic façade also demonstrates other advantages such as producing 6.6% of the daily electricity and reducing the ecological footprint of the building by producing less CO2 emission up to 25 times compared to the green façade.

Cooling through radiation is a known strategy used in mechanical engineering (Liao, et al., 2006; Fernandez, et al., 2015). Amaia, et al. (2017) have designed a dry cooling panel integrated to a constructive wall of a building to dissipate heat generated by the condenser of cooling system. The design is an emulation of the radiative cooling used by toucan bill and elephant pinna. As an active system, its working strategy is like the condenser heat sink of air conditioning and refrigeration equipment. Where the hot water passes through long sinuous copper pipe to increase exposed area for dissipating heat through radiation and conduction. The radiative dissipation ranges from 29.3 to 60.8% of total heat squandering with an average of 140.4 W/m2 (Amaia, et al., 2017).

3.3. Design Concepts

Going through the history of architecture, a lot of projects' configuration were inspired from forms in nature such as the form of MMAA Office Building in Qatar which simulate the form of cactus in the desert; a number of case studies have been narrated in Biomimetic in Architecture by Petra Gruber (2010). However, biomimicry is not only about emulating form in nature, but also an abstractive emulation for the smart principles and solution. Badarnah (2012) and Mazzoleni (2013) are the notable researchers in this domain who suggested some of the bio-inspired designs for the different architectural design challenge (such as ventilation, thermal regulation, water harvesting and daylight control). Yet,

this study addresses the bio-inspired, thermal proto-architectural projects and their conceptual design.

Unlike others, Badarnah (2012) integrated a number of morphological and physiological adaptive strategies of different organisms to minimize heat loss from building in cold regions. The suggested envelop wall has a number of fresh air inlets as seen in Figure 3, and the outlet of exhausted air are directed up to small chimneys above the wall. The design contains two small adjacent branching channels running along each other, one for fresh air from the outside and the other for exhausted indoor air. Due to the converged positions of these channels and the counter-current flow of the fresh air and exhausted air, the heat of the exhausted air is gradually dissipated through conductance to the adjacent channels of fresh air making it at a temperature close to room temperature. The exhausted air channel branches in the top before reaching chimneys to increase surface area for a better chance of heat exchange thus emulating termite mound surface design. The morphological design of channels arrangement was inspired from the counter-current heat exchange in dolphin's flippers for heat retention. There are other inlets for direct fresh air supply in the bottom, which can be controlled by a by-pass system utilized merely in hot days. By-pass system is an emulation to blood vessels that control flow rate through vasodilation and vasoconstriction.

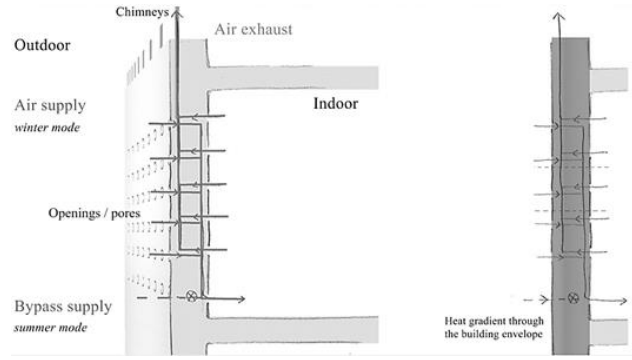


Fig. 3: Bio-inspired envelop design for heat retention in cold climate, reproduced from Badranah (2012).

Another design, Stoma Brick (SB), was suggested by Badarnah et al. (2010) for heat regulation in arid and dry climates. The facade consists of porous construction units, stoma brick, resembles leave's stoma where the design emulates the osmotic pressure changes occurring in stoma to control the openings and closing in order to aid evaporation and gas exchange. The outer layer of the SB has hairy layer similar to the hair around eye, serving as protection from sand and other particles. Then a shell shutter made of malleable material deforms based on humidity range in the air which emulate pine cone responding to the surrounding humidity. A hollow space is placed between the shutter and the inner layer which is a witty spongy section for holding moisture and enhancing evaporation process. The structure has an irrigation system through the SB to further improve evaporative cooling like sweating in human skin. The validation of the design has not yet been provided.

Due to the analogy of the organisms' skin and the building envelop as a mediator between inside and outside and the functional tasks such as thermoregulation, Mazzoleni team (2013) inspired 12 architectural kinetic envelop designs with divergent functions; though only three related thermal designs are addressed. The first design is a living unit inspired from side-blotched lizard. Lizard scales have inspired the design of the wall's units using integrated panels of different functions. The related one is the insulated panel using phase changing material (PCM) for harvesting and storing sun heat throughout the day and then releasing it at night. Lizard behavior has inspired the new sun-tracking system operated by sensors and hydraulic system. The second design is also a living unit inspired by the physiological, morphological and behavioral adaptation of polar bear of gaining and storing heat. The design emulates the polar bear hibernation method by partly embedding in the ground thus constituting insulation from the extreme climate variations. The exposed part of the unit consists of movable tubes tracking sun seasonally for light and heat accumulation and storing heat in PCM placed in the envelop for use at night. This mechanism is an emulation to the hollow bear fur directed to harvest sun. The third project is an adaptive geodesic base structure designed to reduce the heat loss from building in cold climate. It was a simulation of the anatomical reactions between Snow leopard's thick fur, body form and respiratory system. The envelope consists of multilayer structure started internally by vacuumed insulated panels and ends externally by dark waterproof membrane to observe large amount of sun heat. The structure expands or contracts to create insulating air pockets within the structural envelop.

Integrating Parametric Design of Building Information Modeling (BIMPD) with nature-based thermoregulatory mechanisms, Wang & Li (2010) have designed kinetic building envelop inspired from the morphological adaptation of the butterfly wings' honeycombed microstructure. The envelop consists of panels with hexagon structural units. In cold times, these units work as effective sun heat collectors due to the concave comb design featured by depth and dark surfaces which absorb heat and trap solar radiation reflected internally within this formation. However, in hot times, the unit form turn to flat so it reduces the expose surface and heat gain.

The last example of the biomimetic thermoregulatory applications into architecture is, SMIT, Solar Ivy project for indoor cooling through shading and sunlight harvesting. It is a building integrated photovoltaic (BIPV) system made of loose-hanging movable solar panels suspended in the exterior wall (Loonen, 2015). The design and working approach of these panels were inspired by the working approach of foliage leaves arranged to catch optimal sunlight and heat. An earlier similar design was suggested by Badarnah and Knaack (2008). The system is shading sheets supported in facades by tubular members responsible for the sheets' movability for tracking sun throughout the day. Noteworthy, the designs mentioned in this section are proto-architectural projects that have not been tested for validity.

It is manifest that further research accompanied with energy efficiency measurement is required. To optimize the existing suggested systems and to develop as well as design new inventions inspired from nature; (the countless source of innovation).

4. Discussion

Although there is a number of levels with respect to mimicking adaptive notions from nature (such as behavioral, physiological and morphological), the architect's works are mostly confined into mimicking the functional performance of organism through morphological configuration, physiological and morphological. Form in nature is not only aesthetically based, but also performs special function or multi-functions to survive and adapt with the surrounding environmental variations. Furthermore, in thermodynamics, the morphological configuration affects fluid, energy and heat flow rate which in turn affects life; therefore, exploiting such strategies, mechanisms and principles would result in the same output solutions.

The methods used by architects to achieve biomimetic architectural designs were different. However, these studies were achieved through exchange of experiences and communication with different specialists such as biologists; material and mechanical engineers. An example is the innovative glass by Hatton et al. (2013), which reduced temperature up to 9°C, is a result of a mutual study between engineers and biologist. Such communication is required for a better understanding of the working principles and guarantees a successful applicable approach for an adaptive facade.

Studying the previous designs, it is inferred that there are two kinds of adaptive biomimetic thermoregulatory applications into architecture namely: static and kinetic adaptive application. The most prominent and controversial kinetic projects of all are Mazzoleni team designs. The projects marriage between the identical mimicking of the morphological function of some organisms' skin and the smart applications of technology. The whole structures of

the adaptive envelope designs are dynamic. These designs could succeed as temporary structures for the technical aspects that need continuous maintenance to ensure flexibility of its components. The designs could hardly be understood by familiar means of architectural design, but they were constructively facilitated to be comprehended and implemented by the latest computational technology. Apparently, biomimicry with the latest technological assistance would lead to a shift of paradigm in the typical architecture from static to interactive adaptive physical structures.

Although bio-inspired techniques have proven superiority over active cooling devices, passive cooling through bio-inspired techniques in the built environment is now in its inception phase. Bio-inspired design is a safe and provident alternative for those consuming lots of fuel and indirectly destroying the biodiversity system in our planet. Capturing 4 to 6 times of the energy needed for Disch house, saving up to 90% of the required energy in Eastgate building and reducing façade surface temperature up to 12°C in Sony office and others are strong indicators that bio-mimicking organisms' mechanisms of thermoregulatory adaptations can notably reduce energy consumption and provide indoor thermal comfort.

Furthermore, bio-inspired thermoregulation strategies can excel over other air-tight thermal comfort control methods in creating an active mutual relationship between built architecture and surrounding environment (Loonen, et al., 2015). This interactive relationship referred to the different emulated adaptive strategies from nature. An example is the respiratory mechanism and the design of Sony Office by Nikken, which decrease the heat load for the building and urban heat island in the surrounding environment though the building's facades are all glass. Another example is the bio-inspired glass designed by Hatton et al. (2013), which guarantees combining between two contrary elements providing a comfortable thermal indoor environment and clear visual contact with the surrounding. In this ecological age, the biomimicry is expected to be the promising trend in many sectors including architecture (Pawlyn,2011). This is due to the unique features of the bio-inspired designs such as sustainability and adaptation with surrounding environment.

According to Benyus (2013), the co-founder of the Biomimicry Guild, the bio-inspired projects previously mentioned could be evaluated as sustainable and eco-friendly designs due to their adherence to the related life principles. Benyus named the life principles* as the evaluation tools for eco-designs. The projects in this study use renewable energy namely, sun to manage a comfortable indoor thermal environment and this meets "nature runs on sunlight and uses merely the energy it needs" principles. Moreover, some aspects of the configuration design for these projects were aimed to meet thermal function of the building design, which meets nature principle "form follows function". The bio-inspired thermal notions were selected based on the similarities of the thermal environmental variables which corresponds to "nature demands local expertise and curbs excesses from within". The evaluation in the other principles varies from one project to the other. Therefore, the biomimetic architecture is an eco-friendly design that interact passively with environment rather than gormandizing its sources or polluting its air.

It is also observed that the academic researchers in biomimetic architecture do not exceed the stage of theoretical study and computational modeling. This could be because of lack of sponsorship. The executed projects mentioned in section 2.1 have been designed by practicing architects and firms.

* life principles are "Nature runs on sunlight; Nature uses only the energy it needs; Nature fits form to function; Nature recycles everything; Nature rewards cooperation; Nature banks on diversity; Nature demands local expertise; Nature curbs excesses from within; and Nature taps the power of limits" (Benyus, 1997, p.7).

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