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Biomimetic Building Skins: An Adaptive Approach

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Abstract

This paper provides an overview of the design of biomimetic building skins. Many types of smart and responsive building envelopes have been developed, but their improvement to achieve adaptability remains unclear and unstructured. Studies on biomimicry have formulated strategies but have failed to identify or review their technical and functional aspects in terms of architecture. Therefore, this study aims to understand biomimetic building skin designs by investigating its mechanisms, functions and materials through an adaptive approach. This study describes these biomimetic designs through theories, concepts, issues, approaches, methodologies, materials from nature, developed materials and systems in architectural applications. The study also employs systematic quantitative research to enhance the integration of biology and architecture. This research is based on an evidence review focusing on selected studies and exploration results in accordance with systematic methods and critical analyses, such as classification and comparison, to identify patterns and trends. This study provides further insights into the relationship between biological systems and building skins. It also contributes to the development of adaptive building skins based on functional aspects to overcome technical challenges and promote innovation and sustainable architectural systems.

Keywords: biomimicry; biomimetic architecture; building skins; adaptive building skins

1. Introduction

The low-carbon society development plan is gaining popularity among developed and developing countries, and this plan contributes to climate change mitigation and adaptation (Ali et al., 2013). However, Ürge-Vorsatz et al., (2012 and 2015) stated that buildings still represent a great challenge which are globally responsible for approximately 23% of the global primary energy usage and 30% of the global electricity consumption. In addition, Omrany et al. (2016) stated that 60% of the total consumed energy in buildings is accounted for space heating and cooling. Oral and Yilmaz (2003) and Wang et al., (2016) stated that building envelope plays the main role in controls energy waste in buildings and maintains internal comfort. Conventionally, a building envelope has been considered a thermal barrier to prevent heat loss or shade to control solar gain (Leatherbarrow and Mostafavi, 2002; Barbosa and Ip, 2014; Liu et al., 2017). The efficiency and performance of building envelopes have been improved in terms of energy, comfort or structure. However, most of the building envelopes are designed to provide

static design solutions (López et al., 2017). Ali et al. (2015) stated that normal solutions for building envelopes also lack the ability to adapt to contextual issues and needs.

Advancements in architecture have led to changes in traditional approaches since the last century, as stated by Le Corbusier (1991) who introduced a universal house for all climates in 1930. Zuk and Clark (1970) introduced kinetic architecture as a design field where buildings can adapt to changes through kinetics in deformable, reversible, incremental and mobile modes. However, the incapability of technology has restricted the implementation of these theories. Recently, trends in designing envelope systems, specifically façade, have involved energy efficiency by using dynamic systems by adopting layered facades; each layer functions based on a specific task, and their combination represents a complex system (Fiorito et al., 2016). Kinetic systems have different types, such as automatically controlled shutters (Wigginton and Harris, 2002), adaptive skin (Hasselaar, 2006), climate-adaptive building shell (Loonen, 2010; Loonen et al., 2013; De Boer et al., 2011), interactive architecture with robotic and kinetic design (Pan and Jeng, 2010), acclimated kinetic envelope (Wang et al., 2012), adaptive building skins (Grosso and Basso, 2013) and kinetic systems in architecture (Ramzy and Fayed, 2013). These systems aim to increase energy efficiency and enable the flexibility of occupants to control non-static buildings smartly with more flexibility than static buildings.

Nguyen and Aiello (2013) promoted the use of adaptable buildings by applying and performing automated adaptations to optimise energy consumptions. However, Berge (2011) examined the occupants with intelligent façades and found that many occupants lack interest in the capabilities of controls and suffer from 'techno stress'. Based on these systems, adaptive building skins refer to a system that reacts to users' needs and weather conditions by using automatic control concepts adjusted by users. In addition, most dynamic systems utilise mechanical actuators that require maintenance and consequently increase their susceptibility to failure (Loonen, 2010). Therefore, a new integrated system approach should be developed for future adaptive building skins.

Armstrong (2012) stated that learning from nature is the answer. Biology presents a new paradigm in various fields, such as engineering or medicine, as a novel basis for technological thinking. Biology has been integrated with architecture through biomimicry that involves nature as a massive database of mechanisms and strategies to be implemented in designs (Zari, 2007). Biological solutions can be multi-functional, complex and highly responsive and thus can replace the concept of conventional building envelopes as static to improve energy performance in a new adaptive form. This approach can help future building skins to be more responsive and adaptive to both external and internal conditions and satisfies comfort levels. Biomimicry provides many possibilities of adopting designs from nature into sustainable building systems. However, the transfer of knowledge from biology to architecture or technology is difficult. The transfer of superficial research without information from life sciences, unimaginative approach or non-scalable phenomenon can cause failure (López et al., 2017; Yuan et al. 2017).

Thus, it was found that designing building skins is impeded by uncertainty and hence can barely result in any further technical advancements in architectural designs and energy efficiency. Therefore, this review aims to establish a clear design process based on technical aspects to design adaptive building skins. This paper presents a critical review on applying adaptive building skin systems that optimise nature within the development of biomimicry knowledge in architecture.

2. Concept of Mimicking Nature

Nature has been solving many mechanical and structural problems without generating residual and active wastes (Royall, 2010). Mimicking nature requires understanding the differences between biological and technical systems. Their evolution is dissimilar: biological systems have been evolving for millions of years, whereas the technical systems have been developing for only a few hundred years. Biological systems evolved based on their genetic codes governed by natural selection, while technical systems developed based on human design for performing functions (Cohen et al., 2015). In general, functions in technical systems aim to develop a system as a result of design, while in biological systems, functions can occasionally be an unsystematic genetic evolutionary change that leads to a particular function that is not prearranged. Their differences are wide: technical systems function within extensive environments, while biological systems work within restricted living constraints.

Design from nature in the built environment can be understood in various terms, such as biomimicry, biomimetic, bionic, biodesign, biomorphic, bioutilisation, biophilia and bioderivation. Biomimicry was introduced by Frosch and Gallapoulos (1989), and they presented a special concept of resembling ecosystems by creating a balance between nature and mankind. Benyus (2002) define biomimicry as a new direction in science that links sustainable solutions and innovation with research and industry development based on an ecological criterion to evaluate the sustainability of our inventions. Benyus (1997) stated that understanding the nature as a mentor, measure and model will be crucial to appreciate the applicability of biomimicry. Benyus (2002) indicated that several explorations were conducted during the last decades to examine the development of biomimicry in architecture; one of these approaches was the investigation of terminologies by Gruber (2011) who investigated the relation of biomimicry in biology which possibly has a reciprocal use in our built environments. Pawlyn (2011) explored notions from nature. Gamage and Hyde (2012) and Zari (2010) investigated biomimicry based on ecosystem interactions.

Biomimicry levels can be categorised into three stages: (1) form, (2) process and (3) ecosystem. Benyus (1997) stated that mimicking practice undergoes three levels. The first stage is to copy the attributes of an organism, namely, appearance, visual shape, components, materials and morphological features. In other words, it means duplication of an organism's design. The second stage is to look deeper into reproducing a biological entity's development and procedures within its medium to mimic the natural processes. The third stage is a more complicated set of processes: form and processes of an ecosystem are duplicated. Mimicking is applied on a large platform where the design goes beyond the entities to identify its explicit and implicit effects in the environment. Mazzoleni and Price (2013) stated that biomimicry surpasses an analogy and executes on diverse stages, such as organism, behaviour and ecosystem.

Biomimicry ranges from architecture to material science and chemistry where it continues to provide new and innovative insights into engineering problems (Ball, 2001). The development of biomimicry has advanced and inspired over 30 years, from insects, reptiles, mammals and other organisms. In engineering perspective, biomimetic works as an instrument to solve specific problems at the conceptual levels of design (Reap et al., 2005; Alexandridis et al., 2016). Commonly, biomimicry and biomimetic are interchangeable terms; however, the latter focuses more on the technical aspect. Biomimetics is an

emerging field that has been recognised as a promising approach for a more resilient environment (Badarnah 2012; Gamage and Hyde 2012; Mazzoleni 2013; Pawlyn 2011; Zari 2010).

Biomimetic architecture seeks to remedy the errors that exist in designing efficient systems and products (Royall, 2010; EL-MAHDY, 2017). For instance, Myers (2012) presented a dramatic technique to design by incorporating living materials into elements and structures. Myers' approach pushes the concept of mimicking to integrate literally biology within buildings to create new forms. Mazzoleni (2013) explored ways of utilising animal skins for performative buildings. However, biomimetics research faces challenges in creating effective design tools in the built environment. Several academic research are conducted in this line, such as 'BioSkin' (Gruber and Gosztonyi, 2010), 'Towards the living envelope' (Badarnah and Fernandez, 2015) and 'Architecture follows nature' (Mazzoleni, 2013) that introduced a strategic methodology.

Several architectural projects utilised biomimicry; for instance, in terms of adaptive envelopes, the first project was inspired by the *valvular* pollination mechanism in *Strelitzia reginae* flower called *Flectofins* (Lienhard et al., 2011). This envelope adopts the mechanism of reversible material deformation when an external mechanical force is applied. The adaptive approach is clearly applied in adaptive exterior shading system. The second project is inspired by the research on kinematic mechanisms and plant movements, such as *Flectofins* called the One Ocean Thematic Pavilion, in Korea. A shading system adapts and responds to changing sunlight conditions during daytime (Knippers and Speck, 2012; Speck et al., 2017). The third project is based on the movements observed in spruce cones as a passive response to humidity changes called 'HygroSkin'. This pavilion uses relative humidity; the responsive capacity of its material interacts with the surroundings (Menges and Reichert, 2012). Generally, Lurie-Luke (2014) conducted a study to identify biomimetic applications in scientific discipline based on innovations, as shown in Figure 1. Results showed that the most advanced area under research are materials followed by idea and prototype of movement and materials.

Figure 1: Biomimicry applications in different areas and their development stage (Lurie-Luke, 2014)

3. Issues in implementing biomimicry in the built environment

Biomimicry is a new paradigm and emerging field in architecture and faces several issues that limit its development. For instance, the development of biomimicry in engineering and technology is limited only on certain scales to transfer technological aspects from biology to design. These limitations have narrowed the scope of inquiry that reduces biomimicry application to sustainable design (Reap et al., 2005). Nature has various mechanisms and strategies that can be adopted in biomimetic approach. Even though there are several types of biomimetic designs available, obtaining a successful design is very challenging in architecture (Zari, 2010).

Badarnah and Kadri (2015) and Lepora et al. (2013) stated that the major drawback in biomimetic design is the lack of a clear systematic methodology; the absence of design methods from the ecosystem's perspective restricts delivery of clear strategies and mechanisms from the adopted systems. Currently, form and morphology are trends to mimic nature into architecture. However, such advantage rarely possesses any function to imitate natural systems; thus, it hardly presents a successful biomimetic design.

Badarnah and Kadri (2015) stated that in architecture, three obstacles limit the implementation of biomimicry: (1) exploration and selection of strategies from nature, (2) scaling difficulties as some functions work on specific scales (e.g. nano to micro) and (3) conflict of integrated parts of the design concept.

Royall (2010) stated several issues in implementing biomimicry, such as the difficulty to segregate the approach from basic problem solving and biomimicry is frequently simplified into a linear process. Vogel (2013) indicated that mimicking technology found in nature without any adjustments creates many unsuccessful projects. El Ahmar (2011) stated several issues with biomimicry. First, biomimicry relies heavily on very specific knowledge, skills and tools. Second, design approach heavily depends on computer software. The problem relies on the gap of recognition between computers and human beings. Third, identification of the optimum material for a system requires a large number of physical tests and geometric description. Fourth is the issue of finding the relation between components. Fifth is selection of suitable algorithmic growth processes. Sixth is the recurrent interfacing with appropriate analysis applications. Seventh is the control of continuous evaluation and feedback. Therefore, Zari and Storey (2007) and Badarnah and Kadri (2015) addressed that the practical application of biomimetic methods remains elusive in architecture.

4. Approaches and classifications of biomimicry in architecture

Implementing biomimicry in architectural design has different directions and classifications. It mostly depends on the outcome obtained from research. Garcia-Holguera et al. (2016) stated that architects and researchers addressed biomimicry in architectural design based on three directions: (1) through the development of architectural courses and experimental designs (Gruber, 2011; Helms et al., 2009; Lenau, 2009), (2) advancement of design tools and methods to establish systematic and organised research (Vincent, 2003; Biomimicry 3.8 Institute, 2008; Zari, 2012; Cheong & Shu, 2012) and (3) the development of actual design models by architectural firms (Turner & Soar, 2008) and research groups (Lazarus & Crawford, 2011).

Generally, the basic design approach that has been utilised by previous researchers and practitioners were the bottom-up and top-down approaches (Gruber, 2011; Gamage & Hyde, 2012; Jan and Thomas, 2012; Aziz, 2016). Badarnah and Kadri (2015) and Garcia-Holguera et al. (2016) indicated that the first approach (bottom-up) worked as induction or indirect approach (Gebeshuber and Drack 2008) or as a solution-based approach which refers biology to design. This direction relies first on the biologist or ecologist to adapt biological properties into a human technology to find answers and then identify human design problems. The identification has to be made at particular characteristics or behaviours in an organism or ecosystem and then shape them as guidelines for developing architectural designs or industrial products (Zari, 2009). Vincent (2006) and Zari (2009) stated that the theories obtained from the bottom-up approach include adapting and evolving, self-organisation, optimisation rather than maximisation, free energy and improving the bio-sphere using of life-friendly materials and processes. Majority of these theories were implemented in industrial products till date; however, they are still limited, and some of them were unexplored in architecture.

The second approach seeks an answer from nature for a precise problem based on analogy (Gebeshuber and Drack, 2008) or a problem-based direct approach (Vattam, Helms and Goel 2009) where the approach is based on design problems and human needs to find answers in other organisms or ecosystems with similar problems (Panchuk, 2006; Baumeister, 2012). El Ahmar (2013) stated that through this approach, reaching potential biomimetic solutions is possible without collaborating with a biologist or ecologist or without an in-depth scientific understanding. However, translation of biological information into technical systems is limited due to incomplete and shallow level of scientific understanding. Research held at the Georgia Institute of Technology (Helms et al., 2009) identified the steps of conducting biomimicry research, as shown in Figure 2.

Figure 2: Two types of approaches conducted in biomimicry research (Helms et al., 2009)

Gebeshuber et al. (2009) and Gruber (2011) adopted the categorisation by Nachtigall (1997), who divided the biomimicry approach into three fields: (1) structural biomimetic such as constructions and materials in nature, (2) procedural biomimetic such as processes in nature and (3) informational biomimetic such as principles of evolution and information transfer in nature. Ayre (2004) stated that there is a difficulty in classifying biomimicry due to the complexity of biological systems and overlapping between categories. The classifications in the study are based on structures and materials, mechanisms and power, sensors and communication, behaviour and control, and generational biomimetic.

In architecture, Zari (2007) classified the concept based on two outputs. The first approach follows the direction of Ayre and Nachtigall that relied on features inspired by nature within five various design directions: (i) form (reproduce the appearance of a natural system), (ii) material (mimic the materials of natural systems), (iii) construction (structure and assembly of natural system), (iv) process (procedure of natural systems) and (v) function (actions and operations of the natural system). The second approach emphasised the nature features that are imitated in three levels: (1) organism (e.g. termite), (2) behaviour of organism (e.g. termites' performance) and (3) ecosystem by mimicking the biotic and abiotic components and interaction level between its components (e.g. termite ecosystem). Zari (2010) focused and further developed the theory on the ecosystem level through establishing a hierarchical network of interconnected processes that enlightens the complexity in nature's order.

From existing biomimicry and literature, different approaches evolved in biomimetic design, which lead to different outcomes. Most of the mimicking outcomes are applied at organism levels such as developing a material or product. Reap et al. (2005) stated that developing a product without considering its relation to the ecosystem produces a non-sustainable system, especially in life cycle analysis. For instance, applying biomimicry in a building as a system will be successful if it can imitate the natural process. This approach can drive beyond sustainability and starts to be regenerative in the built environment (Van der Ryn, 2005). Zari and Storey (2007) stated that to design within biomimicry, the ecosystem should be considered to design a sustainable system. Zari and Storey (2007) address six principles of how ecosystems operate that could be translated to any system such as building skins:

- ***Dependent on contemporary sunlight:*** use renewable and contemporary energy from the sun based on spatial and time mechanism.
- ***Optimise the system rather than its components:*** energy must transfer efficiently between systems and components as form follows the function. Energy and materials used in the same system are applied for multiple functions.
- ***Dependent on local conditions and situations:*** materials should be sourced locally and adapt to a specific environment.
- ***Diverse in components, relationships and information:*** obtaining resilience and diversity is required. Relationships are complex and operate in various hierarchies which lead to self-organisation and distribution; as a result, emergent effects will occur.
- ***Create conditions favourable to sustained life:*** Systems function as well as produce environmentally benign to improve the biosphere.
- ***Adapt and evolve at different levels and at different rates:*** obtain the balance of non-equilibrium from constant flux. An ecosystem can produce creative mechanisms when it is limited. Ecosystems can achieve the ability to be self-heal.

El Ahmar (2013) identified five principles for effectiveness: adaption, materials systems, evolution, form and behaviour and emergence. In addition, El Ahmar (2011) classified biomimicry levels in architecture into nine types: concept, process or behaviour, morphology, form, structure, skin, material, expression and symbolism. Badarnah and Kadri (2015) addressed several groups such as Biomimicry 3.8, BioTriz, Design and Intelligence Laboratory and Plants Biomechanics Group that improved design perception inspired by biomimicry. These biomimetic design strategies have differences when applied using the problem-based and the solution-based approaches. Further explanation is shown in Table 1. Each approach has three steps.

Table 1: Selected groups applying biomimetic strategy based on problem-based and solution-based approaches

5. Biomimetic methods and tools in design

Several types of biomimetic methods were developed since the last two decades (Baumeister 2012); however, their reliability for application is still challenging in architecture. The major drawback is the lack of a clear selective design procedure and the practical application of a design methodology that remains indefinable in architecture (Badarnah and Kadri, 2015). Cohen et al. (2015) mentioned that mimicking biological organisms into technical systems through function and materials need to be based on a solid platform and clear methodology.

Altshuller et al. (1999) and Spain (2003) introduced BioTRIZ as a systematically developed version of TRIZ and PRIZM which closely reflected the biological route to the resolution of conflicts and presented six fields. However, Gruber (2011) stated that building is a complex system. This method could not take the multiple interactions among building components and could be an ineffective approach in architecture (Bogatyrev et al., 2002; Vincent, et al., 2006). Hastrich (2006) introduced a helix model (design spiral). This model reflects the concept of biomimicry as a continuously evolving process with continuous

feedback and repeated fine-tuning required to adapt “organs” and “organisms” into the environment. This model works based on identification, translation, observation, abstraction, application and evaluation performed creatively. This model is suitable for teaching and practicing biomimicry. Gamage and Hyde (2012) presented the biomimicry theoretical model. This method attempts to understand the system at a micro level in both process and form. The processes is viewed as an eco-system-based design process that covers materials, synthesis of components and structures of forms as parts connecting within an ecosystem. It is designed to scale down from ecosystem to its processes for creating an innovative form.

Furthermore, Badarnah and Kadri, (2015) presented BioGen. This method is designed to generate design concepts which are divided into three sub-phases as facilitated by the design tools (exploration model), pinnacle investigation phase (pinnacle analysis) and abstraction phase (pinnacle analysing matrix and design path matrix). In each phase, a number of steps are followed: (1) identify the issue, (2) explore the natural system, (3) extract the function, (4) elaborate, (5) analyze the strategies, (6) classify, (7) abstract the strategies, (8) generate design concept, (9) evaluate then validate the solution. The drawback of this method is the limitation of transition from the concept phase to the emulation phase. Garcia-Holguera et al. (2016) introduced Ecomimetic. This method presents a conceptual approach or theoretical framework based on previous methods. The approach follows the helix model as a spiral to obtain iterative exercises for incorporating feedback. The method focuses on two levels of the abstraction and transference of biological principles. The method is divided into six phases: (1) architectural design goals, (2) ecological solution searching, (3) abstraction and representation of ecological systems, (4) correlation between ecological systems and architectural systems, (5) transference of ecosystem’s principles to an architectural system and (6) modelling and benchmarking. Recently, López et al. (2017) presented biomimetic principles for the development of adaptive architectural envelopes. This method is based on understanding plants on both macro and micro scales with specifying environmental issues. The method follows dynamic mechanisms in plants that respond to external stimuli through movement and static strategies that have multifunctional properties and surface structures of plant leaves. In this section, the existing methods are classified and summarised based on problem-based and solution-based approaches (Table 2).

Table 2: Most common methodologies that exist in the literature based on problem-based and solution-based approaches

Most of the presented methods above are theoretical especially in the field of architecture. However, Craig et al. (2008), Sheta, (2010) and Badarnah and Kadri (2015) implemented them in design to validate the methodologies. Craig et al. (2008) applied the concept of using TRIZ. PRISM, TRIZ with BioTRIZ were used to regulate the heat gain in a building envelope specifically the roof to obtain radiative cooling in hot climate based on the understanding of biological factors as shown in Figure 3. Their study identified the problem and used the matrix to uncover the main contradictions. In addition, their study employed inventive principles from the matrixes by improving the roof features, temperature and illumination intensity as well as the worsening feature such as loss of energy, temperature raised by undesired shortwave radiation and local convection. The study specified inventive principles such as colour change, parameter change, extracting the harmful part of the insulation, changing the insulation from uniform to non-uniform, thermal expansion, blessing in disguise, self-service, periodic action, mobilising the mass or the insulation to give way to the long-wave radiation and layering the long-wave

transparent membranes in multiple layers to arrest convection. In addition, they suggest external shading system, flexible shells and thin films. Sheta (2010) also applied the same approach of using TRIZ and BioTRIZ in building facades for hot climates. The study identified two problems, namely, how to regulate the heat gain through the building facades and how to protect the internal spaces from the undesired heat/cold outside, and then identified the conflict from the matrix. Subsequently, the authors identified the improving and worsening features for each conflict. Findings showed that the results from TRIZ and BioTRIZ are different, where BioTRIZ gives detailed strategies compared to TRIZ because of numerous actions which created conflicts during the design stage. These approaches showed inefficiency and required careful consideration due to conflict of decisions.

Figure 3: Diagrams of the design of roofing system based on BioTRIZ (Craig et al., 2008)

Moreover, Badarnah and Kadri (2015) presented the BioGen method to design an adaptive building envelope in arid regions using fog events that happen at dawn as a water-harvesting strategy. The model was designed based on a new exploration methodology through seven steps: (1) creating an exploration model for water regulation, (2) defining the design challenge, (3) exploring possible scenarios and identifying exemplary pinnacles, (3) analyzing selected pinnacles, (4) deriving imaginary pinnacles, (5) outlining the design concept, (6) generating a preliminary design concept and (7) estimating performance, as shown in Figure 4. This method presents its appropriateness to various disciplines as a problem solver; however, organisation and categorisation of information is a challenging process and very broad.

Figure 4: Exploration model and design path matrix for BioGen method to design an adaptive wall system

6. Mechanisms of adaptation in nature and engineering

Natural systems have developed the optimum means of protection against changing environmental conditions; thus, nature is the best source to learn adaptation. Natural systems are iterative feedback loops of continuous processes, such as thermodynamics, acoustics, and optics, which can be described as self-organisation (Kibert et al. 2002). Self-organisation is one of the main dynamic and adaptive processes for complex adaptive systems. It is a process where the internal organisation of a system adapts to the environment to develop a particular function without being managed or directed externally (Hensel, 2006).

Many studies in biology have described the adaptation process in internal organisation of natural systems by understanding the function of organisms in ecosystems (Benyus, 1997). Hensel and Menges (2008) and El Ahmar (2011) indicated that organisms use energy and materials for more than one function to maximise efficiency. Odum (1969) stated that wastes produced by one organism become the nourishment for the next in a cycle of large closed-loop systems. In addition, form in the natural systems can function given the limited resources, which means that function generates form and form directs organisms behaviour in the ecosystem within different environments (Hensel and Menges, 2007). Moreover, natural systems have always utilised energy and materials to optimise the whole system rather than the individual components (Kelly, 1994). McDonough and Braungart (2010) indicated that efficiency is different between individuals compared to the entire system, as inefficiency in an individual could be often equated to effectiveness for the whole system. As a result, the performance of natural systems does not depend on

a single parameter; however, it is based on the effectiveness of multi-parameters for optimisation and efficiency.

McCann (2000) stated that for a system to adapt to change, nature uses an insurance effect that creates a level of redundancy to allow adaptation to changing conditions at various rates. Weinstock et al. (2006) stated that biological systems are complex and respond and adapt to stresses and dynamic loadings. The form of responsiveness is nonlinear, arising from the interactions of multiple hierarchies. This response is developed and adapted based on redundancy over time, which is similar to the stochastic approach (El Ahmar, 2011). The adaptation and being responsive in the nature is different in that the former needs to have a dynamic balance in production and reprocessing of materials to generate energy, whereas the latter needs to respond to local conditions through extensive feedback loops shaped by the relationships among these organisms (Reap et al., 2005). Lopez et al. (2017) stressed on the relationship between nature and climate and indicated that climate is the main factor that influences the principles of adaptations. Designing an adaptive system in the built environment requires incorporating some levels of redundancy to allow complexity evolution over time. This redundancy creates a more responsive system to the environment which possibly will be more self-maintained (Zari and Storey, 2007).

In the engineering field, adaptive or self-adaptive concept represents systems that can acclimatise their actions to dynamic working conditions and react to environmental changes. These systems can independently alter their performance in response to alterations in their operating conditions to meet certain requirements with less energy consumption (Cheng et al., 2009). These systems based their corrective actions on sensors that function specifically to deliver information for dynamic environments. Cámara et al. (2016) stated that designing adaptive systems to be responsive to the change requires embodying knowledge about themselves. In fact, implementing knowledge on these systems is essential when decision making involves comparing alternative adaptations in real time (Cheng and Garlan, 2012; Rosa et al., 2013).

The limitation of applying adaptation depends mainly on the accuracy of analytical models that are used for decision making. Cámara et al. (2016) stated that current adaptive models in engineering fields cannot capture the underlying uncertainty and variability of such dynamic execution environments due to the low level of abstraction. Therefore, enhancing the selection of the best corrective action is crucial in adopting these systems. In addition, Cámara et al. (2016) stated that to characterise an adaptation in a genuine manner, three dimensions should be considered: (1) uncertainty in the outcome of adaptation actions, (2) context variability and (3) assumptions about the evolution of the environment during the execution of adaptations. Self-adaptation are divided into two forms: (1) a systematic method of demonstrating the influence of individual adaptation actions and (2) the behaviour of the system and its medium with a lower level of abstraction to differentiate component and connector types.

7. Inspired materials from nature

This section presents an overview of the most common natural materials that adapt with nature and possess adaptive features such as functional surfaces for animals and dynamic movements in plants through some typical characteristics of morphologies, structures and movements, as shown in Table 3 and listed below:

(i) *Adaptive Functional Surfaces*

Han et al. (2016) stated that the application views of the biomimetic functional surfaces are wide. Recently, various forms of animals' functional surfaces have been examined by professionals from several disciplines (Liu et al., 2011). These investigations helped to propose several functional surfaces which resulted due to a complex interplay between surface morphologies with physical and chemical properties. Han et al. (2016) stated that animals have adapted to produce the most efficient surfaces based on multi-functional performance. Therefore, optimising their biological solution is an inspiration for constructing adaptive synthetic surfaces. Different types of surface function and structure could be found in nature surfaces, as shown in Table 3 and Figure 5.

Surfaces for anti-wear could be found in animals with special body surface that survived in the desert to withstand wear and tear caused by the sandy wind. Understanding their properties would help to overcome material erosion and causes of damage and failure of equipment as caused by ground beetle (*Carabidae*), dung beetle (*Copris ochus Motschulsky*), earthworm (*Lumbricidae*), dung seashells and whelks, desert lizards and scorpions (Tong et al., 2012; Zhiwu et al., 2012). Surfaces for *superhydrophobicity* are special surfaces that hardly get wet and distinguished by static contact angles with water (θ_w) above 150° , such as those of water strider and *Parnassius* butterfly wing (Gao and Jiang, 2004 and Yan et al., 2011). Surfaces acting as smart adhesives could also be found in animals that produce high (dry) adhesion to support its weight with a high factor of safety, which can be found in soil-burrowing animals such as gecko (Bhushan and Jung, 2011). Surfaces for drag reduction are commonly found in underwater animals that can swim freely because of their special surface structures that have a low drag surface function, superoleophilicity in air, and superoleophobicity in water, such as those of the carp and shark skin (Liu and Jiang, 2011; Dean and Bhushan, 2010). Surfaces for anti-fogging can provide an effective protective mechanism for maintaining clear vision in a humid habitat, such as those found in the compound eyes of the *Culex pipiens* mosquito (Gao et al., 2007). Surfaces for noise reduction that generate lower sound intensity and lower frequency noise have great sound absorption property, such as the feather of the eagle owl (Chen et al., 2012). Surfaces for water capture or *superhydrophobic* patterns help to collect drinking water from fog-laden wind. One of the most famous examples is the *Stenocara* beetle in the Namib Desert (Parker and Lawrence, 2001). Optically functional surface are found in many tunable optical structures, such as *helicoidal* structure, irregular network, photonic crystal, double-facet microlens, moth eye ridge, multilayer structures, nonreflective surfaces, highly reflective surfaces that lead to advanced optical effects including dynamic structural colour, light focusing, iridescence, antireflection, ultra-whiteness and ultra-blackness, colour mixing, polarisation and broad-angle structural colour (Yu et al., 2013; Han et al., 2016). Different types of insects and animals contribute to optical novelty in design, such as the *Trogonoptera brookiana* butterfly, moth eye, sea mouse, peacock feather, male beetles *Chlorophila obscuripennis* (Coleoptera), *Papilio ulysses* butterfly and paradise whiptail (Biró et al., 2010; Izumi et al., 2010).

Figure 5: Different types of adaptive Functional Surfaces from animals (Yu et al., 2013)

(ii) Adaptive Dynamic Movements:

Plants represent one of the main players of learned biomimicry in architectural design. Plants have special features that can respond to changing environments, such as darkness, light, humidity, rainwater, fire, temperature, freezing, air movement or air quality, which make plants an inspiration of adaptive movements (López et al., 2016). For example, motion and surface structure can be learned in three ways: morphological, physiological and behavioural. Studies have shown that plants blur mechanism, material and structural borders (Dumais and Forterre, 2012; Poppinga et al., 2013). Meanwhile, other works have presented how plants transfer force, torque and motion to structural elements, and how these subsequently become associated with biologically compliant mechanisms and forms (Schleicher et al., 2015). Some plants also possess response features like tropisms or nasties, which allow them to move depending on the direction or position of external stimuli (Figure 6).

Biomimicry is represented by different types of plants. Schleicher et al. (2015) have introduced three types on the basis of plant structure and properties, namely, *Strelitzia Reginae*, *Aldrovanda vesiculosa* and *Lilium Casa Blanca*. *Strelitzia reginae* (bird of paradise flower) moves elastically, which inspired the development of a hingeless flapping mechanism particularly suited for buildings with curved glass facades that are difficult to shade (Wood, 2017). *Aldrovanda Vesiculosa* (waterwheel plant) has a fast reversible snapping motion, a type of movement that is hydraulically determined by a central surface common to plants with bidirectional mechanisms (Iijima and Sibaoka, 1981). *Lilium Casa Blanca* from the lily family is an example of a firmly packed plant with unidirectional movement; its flowers, each consisting of three outer and three inner petals, are prominently curved. López et al. (2017) introduced five plant types with motion and surface properties: (i) the hairy leaves of *Gynandriris setifolia*, which can reflect sunlight from their surface; (ii) *Echeveria glauca*, an example of a plant with crassulacean acid metabolism, which can efficiently use water (Ezcurra, 2006); (iii) *Salvia officinalis* (Sage) and *Kalanchoe pumila* (Dwarf Purple Kalanchoe), both with passive responsive and adaptive systems, which are advantageous to changing temperatures, and reflective structures for protection against excessive sunlight; (iv) the leaves of *Mimosa pudica* (Sensitive plant) with motion-sensing mechanisms linked to a signal-and-response feedback system, such that leaves fold inward upon contact to a stimuli; and (v) the seeds of many *Mesembryanthemums* and the leaves of *Rhododendron*, both with valve-like mechanisms that can use rainwater to trigger capsule launch and dispersal (Vogel, 2012).

Figure 6: Two types of plants with adaptive dynamic movements

Table 3: Most common types of materials inspired from the nature

8. Material development based on biomimetic design

Biomimetic-based materials represent majority of current research initiatives due to their wide application in many disciplines, including medicine, engineering and architecture. In the study of Lurie-Luke (2014), biomimicry-based materials are classified into four clusters: (1) smart materials that change and react in response to external stimuli; (2) surface modifications with innovative surface structures and improved

functions; (3) nature-inspired material architectures that are focused on innovative forms and structural arrangements; and (4) technologies that improve current systems by deploying specific adaptive parameters.

The first cluster is for organism-like smart materials that can change specific characteristics and parameters in response to a series of mechanical, chemical, spatial and temporal information in different environmental conditions. The group is divided into two sections: chemical stimuli and physical stimuli (Lurie-Luke, 2014). For chemical stimuli, the specific receptor of a material detects and promotes highly specific internal response. Common biomimetic applications are for pH changes and metal ion components of smart materials (Zarzar et al., 2011; Greene et al., 2008). Meanwhile, physical stimuli can range anywhere from heat to light and water content (Agnarsson et al., 2009). The second cluster are for materials with surface modifications (e.g., drag-reductive, repellent and anti-reflective properties) typical of novel designs (Wong et al., 2011). On the basis of repellent surfaces, specifically water-repellent properties, majority of plants possess highly hydrophobic surfaces that allow water to easily run off over the leaf epidermis through a waxy cuticle (Hanaei et al., 2016). Moreover, the ability of geckos to stick to different surfaces and break free easily also gives insights into well-built joints in architectural design. A gecko footpad has nanoscale, microscale and filamentous structures that can interact with any given substrate.

The third cluster is for material architectures with natural endoskeletons and exoskeletons; at the initial stages of architectural design, these materials represent the production of new materials with many potential applications. There are many good examples of natural structural adaptations that enable the construction of lightweight structures (Ali and Abdel-Ghaffar, 1995), including the two-layer *Beetle elytra* that maintain their integrity through a series of interconnecting attachments. Imitating natural photonic structures and developing new nanoscale structures can enhance the development of new structures and material properties in the field of architecture (Kolle et al., 2013). Finally, materials with technologies for targeted applications (e.g., locomotion) represent one of the largest areas of biomimicry implementation, and they are known to increase robotics and vehicle movement efficiency, and even help in the development of new types of transport (Iqbal and Khan, 2016). Mimicking provides insights into the movement principles inspired by muscular and skeletal systems. Lurie-Luke (2014) has classified biomimicry applications into three types: (1) improvements based on movement kinetics; (2) improvement-based release mechanisms; and (3) improvements based on structural configuration (e.g., energy-efficient shapes). These approaches can help improve wind technologies and innovate building designs (Vázquez, 2014).

9. Adaptive building skins

9.1 Systems and Materials for Adaptive Building Skin

This section discusses biomimetic materials for adaptive building-skin application. Generally, building skins are a complex system that requires the control of many aspects, such as heat, light, humidity and ventilation, among others. Mimicking nature for building skin designs is conducted by fully understanding the metabolism and morphology of a building, after which different approaches are considered in connection to the various elements of the building management system, such as sensors,

actuators and command wires (Wigginton and Harris, 2009). Nonetheless, Addington and Schodek (2005), Dewidar et al. (2013) and Barozzi et al. (2016) have reported that uncertainties still abound in terms of roles, responsibilities and professional accountability in contemporary architecture. Accordingly, Figure 7 summarises the definitions of the most common terms related to the field.

Figure 7: Summary of most common terms in contemporary architecture

The terms smart, responsive and adaptive concepts have been used loosely and interchangeably, which confuse many professionals (Dewidar et al., 2013; Barozzi et al., 2016). First, *smart building skins* refer to automated or largely automated self-monitoring systems similar to building management systems, which deploy integrated instruments within a building (Shabha, 2006; Brooks, 2011). Kiliccote et al. (2011) have suggested that smart building skins be regarded as a self-aware and grid-aware mechanism utilizing smart sensors that operate in four areas: (i) perception of individuals of comfort at different times of the day and year; (ii) changes in occupancy or building use; (iii) variations in occupancy characteristics; and (iv) variations in yearly average external weather conditions (Buckman et al., 2014).

Second, responsive building skin is a term frequently interchanged with ‘adaptive’ building skin. Beesley et al. (2006) have defined the term as a simple form of adaptation wherein functional and performance characteristics are similar to those of a ‘smart’ building skin, which require physical manipulation of elements. The term responsive suggests control of environmental conditions with the use of computational algorithms, thus allowing a building system to learn new concepts while educating the occupants (Cole and Brown, 2009). Kretzer (2010) developed a responsive system using *elastomeric* films, which could be deformed upon electric charging. In general, the functionality of a responsive system is larger than that of smart systems. Compared with smart systems that focus only on a specific range of climatic conditions and predictable reactions, responsive systems accommodate conditions and performance criteria that are much broader (Hasselaar, 2006; Dewidar et al., 2013).

Third, adaptive building skin refers to a *morphogenetic* evolution and real-time physical adaptation of a design in relation to its surrounding environment. The term is more complex compared with previous types, as adaptivity unite multi-scalar factors in order to reach a symbiotic energy-efficient design solution (Dewidar et al., 2013). The term adaptivity suggests solving problems with multiple parameters rather than merely responding to individual concerns. Adaptive is also a much broader concept than responsive, as the adaptive approach seeks to optimise functionality and waste reduction (i.e., energy consumption and availability of material resources). In fact, Hoberman and Happold (2010) have introduced a model called Adaptive Buildings Initiative, which helped develop several types of kinetic shading and cladding systems.

The abovementioned systems can also use smart materials to enhance their performance. In fact, smart materials play an important role in smart, responsive and adaptive building skins due to their intrinsic properties, which include the ability to change physical properties or shape without any energy source. Addington and Schodek (2005) have classified smart features in terms of ‘immediacy’ (real-time response), ‘selectivity’ (discrete and predictable response), ‘transiency’ (responsive to more than one environmental state), ‘self-actuation’ (internal intelligence) and ‘directness’ (a response is local to activating events). Many types of smart materials can function in different forms and sense environmental

stimuli, where responses can be thermal, radiant, chemical, electrical, magnetic and others. Elattar (2013) divided smart materials into three groups:

- (i) Passive smart materials work as a sensor for their inner system and the surrounding environment. All shape memory alloys and fibre optic materials fall into this category. Shape alloys respond to temperature by changing shape without analysing signals, while fibre optics act as sensors but not as actuators or transducers (Kamila, 2013).
- (ii) Active smart materials have similar properties as passive materials; however, active smart materials can also react to stimuli. For instance, *piezoelectric* materials use a feedback loop for its actuator circuit to recognise both change and initiation of appropriate response.
- (iii) Intelligent materials adapt their behaviour to circumstance. Addington and Schodek (2005) further classified this material into two groups: (1) materials that undergo change in one or more of their properties to respond directly to external stimuli, such as *thermochromic*, *magnetorheological*, *thermotropic* and shape memory, as well as photochromic materials that change colour in response to ultraviolet radiation, and (2) smart materials that transform energy from one form to another (e.g., *thermoelectric*, *electrostrictive*, *photoluminescent*, *piezoelectric* and photovoltaic materials).

9.2 Implementing Adaptivity in Building Skins

Plants offers many opportunities that inspire researchers to design various kinds of building envelopes. Plants have competed in their environment through physiological evolution, which allowed them to adapt and evolve with their surroundings. Knippers and Speck (2012) categorised adaptive natural materials of architectural systems into four main principles: (1) ***heterogeneity***, classified by the local adaptation of physical or chemical properties, as well as geometric differentiation of elements; (2) ***anisotropy***, categorised based on the principle of anisotropic fibre reinforcements; (3) ***hierarchy***, categorised based on hierarchical structure, from nanoscale to macro-scale, to achieve multilevel hierarchical construction; and (4) ***multifunctionality***, classified based on either the integration of functions into a single element or the integration of mono-functional components into multifunctional material systems. Lurie-Luke (2014) presented a variety of plant-type movement applications and innovations in response to environmental changes (Figure 8). Schleicher et al. (2015) also introduced a visual map to apply bio-inspired motion principles into technical kinetic structures (Figure 9).

Figure 8: Different possibilities of learning plant-like adaption to develop adaptive building skins (Lurie-Luke, 2014)

Figure 9: Mapping the key aspects of bio-inspired motion principles into technical kinetic structures (Schleicher et al., 2015)

To implement adaptivity in building skins, it should be aligned with physiological evolution, also referred to as the relation of plants to climate (Lopez et al., 2015a). Plant evolution and adaptation rely on three major factors: morphological, physiological and behavioural. Plant is classified by its dynamic

mechanism and static strategy on two scales (i.e., macro and micro level). Dynamic mechanism refers to plants that react to external stimuli through responsive mechanisms, namely, temperature, light, fire, darkness, water or drought. Static strategies emphasise the multifunctional properties of plant leaves (i.e., as a plant surface) to deliver more than one function and adapt to the environment, including *superhydrophobic* and light reflection (Bhushan, 2009; Gibson, 2012).

Lopez et al. (2015a) adopted the plant *stomata* concept in botany as inspiration for an adaptive wall system following dynamic mechanisms and static strategies, as shown in Figure 10. A *stomata* is a pore bordered by a pair of specialised *parenchyma* cells, which control the size of the opening and closure based on stimuli (e.g., temperature, light, carbon dioxide, drought and plant hormones) (Vogel, 2012). The functions of *stomata* include transpiration; interchange of temperature and gasses; and loss of excess water in the form of water vapor for a cooling effect. In fact, understanding how stomata operates provides adaptive solutions and their ease in adoption to architectural envelopes (Lopez et al., 2015b). Based on this lesson from nature, understanding the environment is important to cope with the challenges and realities of design work. As a start point, environmental issues related to temperature, light, humidity and carbon dioxide should be considered when transferring biology principles to architecture. Lopez et al. (2015a; 2015b) have identified the functions of adaptive architectural envelopes as follows:

- . To regulate temperature: dissipate, gain, reflect, absorb or conserve;
- . To regulate light intensity: diffuse, reflect or absorb;
- . To regulate humidity: exchange, dissipate or absorb; and
- . To regulate carbon dioxide (air quality): filter, exchange or dissipate.

Figure 10: Diagram of stomatal movement mechanism (Lopez et al., 2015a)

Designing adaptive building skins can be developed to meet adaptivity principles based on two approaches, as shown in Figure 12: (1) adaptive behaviour through dynamic mechanisms based on motion, which result in changes in the configuration (sliding, folding, creasing, expanding, rolling, hinging, fanning, inflating, rotating or curling) of the envelope, and (2) adaptive behaviour through static strategies based on material properties, including changes that directly affect the internal structure of a material, such as light reflection or absorption properties, or through the exchange of energy from one form to another.

9.3 Adaptive Materials for Adaptive Building Skin

Recently, many studies have been conducted to improve the sensing abilities and active properties of robotics. However, there have only been a few precedent literature on building skins (Čolić-Damjanovic and Gadjanski, 2016). Moving from mechanism concepts to technical implementation requires the understanding of material functions and properties. Designing adaptive building skins require low-technology and low-energy adaptive material systems. Subsequently, the selected materials should have physical properties and structures that can generate movement and adapt to real-time environmental changes. Several factors are considered in the design of adaptive systems, such as workability, responsiveness to stimulus, durability, resistance to corrosion, and achievable movements to impress force (Fiorito et al., 2016). In addition, materials must possess performative and self-actuating abilities,

innate to the system and can react to changing environmental conditions. Generally, materials that can fold, shrink or expand can respond to change, but stable enough in terms of configuration because most parts were adaptively designed.

Many examples of adaptive materials can be deduced from nature, including conifer cones with repetitive opening–closing cycles and other structural abilities in response to humidity. Lopez et al. (2015b) introduced a model for adaptive walls using adaptive materials based on dynamic mechanisms and static strategies, and classified the materials into four areas: temperature reactive materials, light reactive materials, humidity reactive materials and carbon dioxide reactive materials (Figure 11). The study reviewed and updated the literature based on the classifications below.

Figure 11: Adaptive wall system based on adaptive materials with different functions and environmental issues (Lopez et al., 2015b)

Temperature reactive materials – Several types of materials have been applied in the architectural field, such as the following: (1) *Thermo-bimetal* materials represent a self-actuating material that deforms and curves when heated or cooled based on a specific range of air temperatures. Such materials laminate two metals together with different thermal expansion coefficients (Sung, 2012), as shown in Figure 12. (2) Heat sensitive plastics are similar to *thermo-bimetal* materials with two-layer plastics and different thermal expansion coefficients that generate movement through heat-sensitive actuation (Lopez et al., 2015b). (3) Shape memory alloy is divided into thermo-responsive and magneto-responsive approach (Sun et al., 2012), where both mechanisms involve reversible martensitic transformation below transition temperature (T_s), and in effect, conserving shape memory. However, after reheating the material above transition temperatures, the original shape is recovered (Leng et al., 2011; Howes and Laughlin, 2012). (4) *Thermochromic* polymers are materials that change their original colour in reaction to temperature changes, and they are commonly used as building envelopes to improve energy efficiency (Granqvist, 2016). (5) A phase-change material is divided into four types: organic, inorganic, eutectics and hygroscopic materials (Akeiber et al., 2016), all of which have the ability to control thermal–mass behaviour and allow light reflection with absorption (Kenisarin and Mahkamov, 2016).

Light reactive materials – Several types of materials have been applied in the architectural field: (1) Phosphorescence pigments, such as conductive paints that fabricate passive and active luminous skin, which allow materials to glow in dark environments. Such materials are applied on surfaces to form conductive surfaces and create capacitance that can detect moving objects (Khoo, 2012). (2) Light responsive polymers or light-induced shape-memory polymers are polymers that undergo light-induced shape changes, which can be deformed and temporarily fixed as a new shape (Jochum and Theato, 2013). (3) Photochromic dyes allow a reversible change of colour upon exposure to ultraviolet light in the range of 300 to 360 nanometres. A full change of colour can be obtained within 20–60 seconds in sunlight. The material can change to colourless when removed from the ultraviolet light source. In other words, the materials have the potential to be mixed with others or to produce a wide range of colours, as they can also be dissolved in inks or extruded/injected into moulds and casts (Wu et al., 2016).

Humidity reactive materials – Several types of materials exist in the architectural field based on *hygroscopicity* and *anisotropy* properties of wood materials. Understanding wood properties can help shape a new type of design that can convert wood into a humidity reactive material. In principle: (1) The

cellular structure of wood always seeks to reach equilibrium moisture, which result in constant dimensional movement (Menges and Reichert, 2012). The movement in wood is similar to *Pinophyta* (conifers) where motion is triggered by external stimuli that are not related to the molecular structure of the material. Reichert et al. (2015) specified a few types of wood, such as beech (*Fagus sylvatica*), European maple (*Acer pseudoplatanus*) and cut veneer (German: *Schnittfurnier*), as shown in Figure 12. (2) Hydrogel is a smart gel that consists of an insoluble network of polymer chains that swell up when water is added; it can store large amounts of water, which is similar to the functions of natural tissue. Currently, hydrogels are utilised for bio-inspired cooling (Cui et al., 2016).

Carbon dioxide reactive materials – This type of reactive material has been applied only very recently in architectural design. Some examples include: (1) CO₂ responsive polymers, which are divided into two types, namely, carbon dioxide responsive polymers and carbon dioxide polymers for CO₂ capture (i.e., carbon dioxide is used as a green eco-trigger, and to absorb CO₂ directly from air) (Lin and Theato, 2013; Manoranjan et al., 2016), and (2) titanium dioxide, a pigment that can convert mono-nitrogen oxides into less harmful substance, such as calcium nitrate and water, and which acts as a catalyst for chemical reactions when activated by sunlight. Titanium dioxide in tiles do not change and persists indefinitely (Schattling et al., 2014).

Figure 12: Two types of adaptive materials based on temperature and humidity

Smart materials differ from adaptive materials. Smart materials have the ability to be smart, but in order to function, it requires external stimuli based on conventional energy sources. In contrast, adaptive materials can function naturally in existing environmental conditions (e.g., plants). Smart materials operate in different scales, such as sensors and actuators with separate systems. Sensors analyse variations of external stimuli and transfer information to actuators (Trolier-McKinstry and Newnham, 1993). Meanwhile, actuators provide the structure with a change in properties based on a range of external conditions (Table 4).

Table 4: Classification of materials based on smart and adaptive approach for implantation in adaptive building skins

Studies on adaptive walls have been expanding by way of the adaptive shading systems, which can track changes in sun radiation. Adaptive walls can also provide a breathing envelope to building skins, thus influencing air pressure on the surface to perform an inhaling–exhaling process; a thermo-regulating envelope by maintaining adequate balance between heat gain and heat loss without seeking air-tightness and water-tightness; and light regulating envelope to improve visual comfort of occupied space. Two examples of adaptive wall systems are presented: plant-mimicking functions (basic approach) and animal-mimicking functions using deep problem-based (top-down) approach, which represent an easy architectural approach to biomimicry.

Dewidar et al. (2013) presented a theoretical model for an adaptive wall system that can mimic nature called the Self-Active Bioclimatic Strategy (SABS), as shown in Figure 13. SABS uses algae bio-reactor panels with a kinetic responsive façade system to develop self-sensing abilities, and it adapts to environmental demands to achieve energy efficiencies. The walls of the system generate two types of

energies, namely, microalgae-cultivated energy from bioreactor panels by (i.e., utilizes waste carbon) and solar thermal energy. SABS can operate as opaque panels (shading devices), transparent panels, controlled opening systems (ventilation) and other responsive materials that provide kinetic features for the building skin. The system is controlled by integrated sensors, and its actuators operate without any use of mechanical power by adopting the ‘thermo-bimetal’ application of shape memory alloys. However, this system is limited, and it represents only a theoretical model without any validation of application.

Figure 13: Integrated approach of Self-Active Bioclimatic Strategy (Dewidar et al., 2013)

Badarnah and Kadri (2015) also proposed a wall system based on a biomimetic design, which is a theoretical model for fog-to-water collection and a water-harvesting system for building skins (Figure 14). The system was developed based on an innovative design method through several processes, including challenges, process, flow, adaption, scale, environmental context, morphological features, structural features, material features and others. The system utilises an external surface with several layers. For the water collection, the system adapts the morphological features of the bumpy *elytra* with *hydrophilic* and *hydrophobic* alternating properties for the bumps and grooves. Subsequently, water is retained on hydrophilic peaks, builds up until they reach a specific volume, and finally roll down through hydrophobic grooves. The second layer applies the Thorny devil the concept on semi-tubular capillary system, which allows water transport over the surface through a hexagonal network and capillary action to the storing chambers. The closing and opening of chambers are controlled by smart materials, which swell when saturated and shrink when dry. The system collects water at night time and releases it internally during the daytime. Similar to the previous model, this system is limited and represents only a theoretical model without any validation of its application.

Figure 14: Biomimetic wall to collect water from fog (Badarnah and Kadri, 2015)

10. Discussion

The study uncovered many aspects of biomimetic design and adaptive building skins that remedy many limitations in architectural design. Most architectural systems are limited in terms of their adaptation to user needs and weather conditions only, an approach that uses automatic control concepts with smart materials. The study found that biomimicry offers many possibilities for adaptive sustainable building designs. However, biomimetic studies face several obstacles, particularly when translating natural concepts into technical systems. Most mimicking approaches only focus on individual parts rather than the whole system. Moreover, the present study has established that applying biomimicry concepts in architecture is still in its infancy stage, as evidenced by the several levels and scales of ideas, forms relationships of architecture with the ecosystem; however, those that deal with function and process are extremely lacking. In understanding adaptation, the optimum connection between external factors (ecosystem and process) and internal factors (form and behaviour of organism) should be established to successfully approach and achieve functional systems.

Designing adaptive systems are complex and should be similar to natural systems, which deal with different factors and conditions. Beyond the typical comparison, adaptive systems should be understood at different levels (organism, behaviour and ecosystem). The present study found that past literature mainly focused on materials and ideas—not on implementation—due to lack of clear ecosystem-based systematic designs and shortage in corresponding design methods. In addition, there are also limitations

in terms of searching and selecting strategies from nature, resulting in scaling difficulties and conflict of integrated parts within design concepts. Most research attempts to understand the structural, procedural and informational aspects of biomimetics. However, there are still some difficulties in terms of classifying biomimicry concepts due to the inevitable overlap of many categories and the complexity of having to describe biological systems. Other factors have also limited the outcomes of adaptive design (i.e., bottom-up and top-down approach), which deter biologists, ecologists and designers to work effectively.

The study reviewed 18 methods and found that the most common methods in the architectural field follows the problem-based approach, which still in the development stage. Most methods are still on their theoretical concepts and models, except for few that have been applied, such as the mimicry of termites to holistic view architecture of Eastgate Centre. In addition, the study explored and explained the mechanism of adaptation in nature and engineering; addressed the mechanism and the behaviour of organisms and how they react to external and internal conditions; and explored the concept of adaptation in engineering by defining its current limitations. These explorations helped elaborate the functionality of natural materials, which served as inspiration in understanding adaptation in nature. The review found two approaches to adaptation, namely, by functional surfaces and by dynamic movements. Animals and plants represent a good source of understanding adaptation, as they give many examples and techniques to explore architectural design. Such understanding helps connect biomaterial development and the built environment. Impact evaluation can help enhance the aforementioned adaptive design models.

Understanding adaptation in a holistic view helped review the current development of architectural designs and explain the most contemporary directions of designs inspired by nature. The review delineated many issues and confusions, especially those on smart, responsive and adaptive methods in architecture. Several materials and systems following certain architectural movements were also identified; however, no clear distinctions were established in terms of their directions. Based on research, most adaptive materials are controlled by an external stimulus, which can change physical structures on the basis of direct signals or conventional energy sources to stimulate the function of a specific system. As a result, recent studies have started to redefine the design, application and functions of smart materials. Several studies have been proposed on the *stomata* and their natural behaviour, a key design on dynamic and static changes, and these have opened a new paradigm to design adaptive systems.

Finally, the study identified materials that meet the adaptation concept, and which use adaptive materials without utilizing conventional energy sources, to improve the development of the adaptive models. However, most dynamic architectural systems are designed as a responsive system, and only a few models were classified as adaptive. Findings indicate a lack of understanding of adaptation, which requires an adaption of features, behaviour or configurations with external conditions, as well as controlling internal process to recycle materials and generate energy. On this note, the most important phases to design adaptive building skins are summarized (Table 5).

Table 5: Summary of phases to obtain knowledge on how to design an adaptive building skins based on technical aspects

Conclusion

A review of biomimetic building skins to achieve adaptation was presented. Various theories, concepts, issues, approaches, methodologies, materials from nature, developed materials and systems in architectural applications based on developed models and investigative studies are discussed. The study elaborated the technical and functional aspects linking several levels of biomimicry. Such elaboration helped in the discussion and identification of adaptive building skins. In addition, the study evaluated the limitations and potentials of adaptation, which offers many application possibilities in the architectural field. The study classified and compared adaptive approaches in biological, engineering and architectural fields to create a connection between biological systems and building skins. The study achieved its aim of providing a clear design process that summarizes the development of biomimetic building skins based on the adaptive approach. In addition, the research achieved its aim of providing a clear understanding of developing adaptive building skins based on functional aspects and to overcome technical challenges and promote innovative and sustainable architectural systems.

References

- Addington, M. and Schodek, D. (2005), *Smart Materials and Technologies for the Architecture and Design Professions*, Oxford: Elsevier Architectural Press, p. 12.
- Agnarsson, I., Dhinojwala, A., Sahni, V., & Blackledge, T. A. (2009). Spider silk as a novel high performance biomimetic muscle driven by humidity. *Journal of Experimental Biology*, 212(13), 1990-1994.
- Akeiber, H., Nejat, P., Majid, M. Z. A., Wahid, M. A., Jomehzadeh, F., Famileh, I. Z., ... & Zaki, S. A. (2016). A review on phase change material (PCM) for sustainable passive cooling in building envelopes. *Renewable and Sustainable Energy Reviews*, 60, 1470-1497.
- Alexandridis, G., Tzetzis, D., & Kyratsis, P. (2016, November). Biomimicry in Product Design through Materials Selection and Computer Aided Engineering. In *IOP Conference Series: Materials Science and Engineering* (Vol. 161, No. 1, p. 012046). IOP Publishing.
- Ali, G., Abbas, S., & Qamer, F. M. (2013). How effectively low carbon society development models contribute to climate change mitigation and adaptation action plans in Asia. *Renewable and Sustainable Energy Reviews*, 26, 632-638.
- Ali, G., Bashir, M. K., & Ali, H. (2015). Housing valuation of different towns using the hedonic model: A case of Faisalabad city, Pakistan. *Habitat International*, 50, 240-249.
- Ali, H. M., & Abdel-Ghaffar, A. M. (1995). Modeling the nonlinear seismic behavior of cable-stayed bridges with passive control bearings. *Computers & Structures*, 54(3), 461-492.
- Altshuller, G., Shulyak, L., & Rodman, S. (1999). *The innovation algorithm: TRIZ, systematic innovation and technical creativity*. Technical Innovation Center, Inc.
- Appio, F. P., Achiche, S., Martini, A., & Beaudry, C. (2016). On designers' use of biomimicry tools during the new product development process: an empirical investigation. *Technology Analysis & Strategic Management*, 1-15.

- Armstrong, R. (2012). *Living architecture: How synthetic biology can remake our cities and reshape our lives*. TED books.
- Arslan, G. Y. (2014). BIOMIMETIC ARCHITECTURE A New Interdisciplinary Approach to Architecture. *ALAM CIPTA, International Journal of Sustainable Tropical Design Research and Practice*, 7(2), 29-36.
- AskNature. (2008). A project of *Biomimicry 3.8*. Accessed January 2017. www.asknature.org
- Ayre, M. (2004). Biomimicry – a review. European Space Agency ESTEC. Retrieved from http://www.esa.int/gsp/ACT/doc/BIO/ACT-RPT-BIO-GSP_BiomimeticsSpaceSystemDesign%20-%20TechnicalNote2b%20-%20Biomimicry-AReview.pdf
- Aziz, M. S. (2016). Biomimicry as an approach for bio-inspired structure with the aid of computation. *Alexandria Engineering Journal*, 55(1), 707-714.
- Badarnah, L. (2012). Towards the LIVING envelope: Biomimetics for building envelope adaptation. *Delft University of Technology*. doi, 10.
- Badarnah, L., & Fernández, J. E. (2015). Morphological configurations inspired by nature for thermal insulation materials. In *International Association for Shell and Spatial Structures (IASS) Symposium*.
- Badarnah, L., & Kadri, U. (2015). A methodology for the generation of biomimetic design concepts. *Architectural Science Review*, 58(2), 120-133.
- Ball, P. (2001). Life's lessons in design. *Nature*, 409(6818), 413-416.
- Barbosa, S., & Ip, K. (2014). Perspectives of double skin façades for naturally ventilated buildings: A review. *Renewable and Sustainable Energy Reviews*, 40, 1019-1029.
- Bar-Cohen, Y. (2006). Biomimetics? using nature to inspire human innovation. *Bioinspiration & biomimetics*, 1(1), P1. pp.1-12, available online :doi:10.1088/1748-3182/1/1/P01
- Barozzi, M., Lienhard, J., Zanelli, A., & Monticelli, C. (2016). The Sustainability of Adaptive Envelopes: Developments of Kinetic Architecture. *Procedia Engineering*, 155, 275-284.
- Baumeister, D. (2012). *Biomimicry Resource Handbook: A Seed Bank of Knowledge and Best Practices*. Missoula: Biomimicry 3.8.
- Beesley, P., Hirosue, S. and Ruxton, J. (2006), *Responsive Architectures. Subtle Technologies 06*, Cambridge: Riverside Architectural Press, p. 3.
- Benyus, J. (1998) “Biomimicry – Innovation Inspired by Nature”, Harper Collins, New York.
- Benyus, J. (2002). Mother Nature’s School of Design. *Choices for Sustainable Living*, 34-38.
- Benyus, J. M. (1997). *Biomimicry* (p. 1). New York: William Morrow.
- Berge, B. (2011). The engine is not responding. *A critique of the automatic energy-saving home. Arkitektur*, 1.
- Bhushan, B. (2009). Biomimetics: Lessons from nature – an overview. *Philosophical Transactions of the Royal Society*, 367, 1445-1486.
- Bhushan, B., & Jung, Y. C. (2011). Natural and biomimetic artificial surfaces for superhydrophobicity, self-cleaning, low adhesion, and drag reduction. *Progress in Materials Science*, 56(1), 1-108.
- Biomimicry Institute (2008). Biomimicry 3.8 Institute. (2008). Ask nature. Retrieved January, 2017, from <http://www.asknature.org/>.

- Biró, L. P., Kertész, K., Horváth, E., Márk, G. I., Molnár, G., Vértesy, Z., & Vigneron, J. P. (2010). Bioinspired artificial photonic nanoarchitecture using the elytron of the beetle *Trigonophorus rothschildi varians* as a 'blueprint'. *Journal of The Royal Society Interface*, 7(47), 887-894.
- Bogatyreva, O., Pahl, A. K., & Vincent, J. F. V. (2002). Enriching TRIZ with Biology. In *TRIZ future, 2002: Proceedings ETRIA world conference* (pp. 301-308).
- Brooks, D.J. (2011), "Intelligent buildings: an investigation into current and emerging security vulnerabilities in automated building systems using an applied defeat methodology", Australian Security and Intelligence Conference, Security Research Institute Conferences, pp. 16-26.
- Buckman, A. H., Mayfield, M., & BM Beck, S. (2014). What is a smart building?. *Smart and Sustainable Built Environment*, 3(2), 92-109.
- Cámara, J., Lopes, A., Garlan, D., & Schmerl, B. (2016). Adaptation impact and environment models for architecture-based self-adaptive systems. *Science of Computer Programming*.
- Chen, K., Liu, Q., Liao, G., Yang, Y., Ren, L., Yang, H., & Chen, X. (2012). The sound suppression characteristics of wing feather of owl (*Bubo bubo*). *Journal of Bionic Engineering*, 9(2), 192-199.
- Cheng, S. W., & Garlan, D. (2012). Stitch: A language for architecture-based self-adaptation. *Journal of Systems and Software*, 85(12), 2860-2875.
- Cheng, S. W., Garlan, D., & Schmerl, B. (2009). Raide for engineering architecture-based self-adaptive systems.
- Cheong, H., & Shu, L. H. (2012, August). Automatic extraction of causally related functions from natural-language text for biomimetic design. In *ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. 373-382). American Society of Mechanical Engineers.
- Cohen, Y. H., Reich, Y., & Greenberg, S. (2015). What can we learn from biological systems when applying the law of system completeness?. *Procedia Engineering*, 131, 104-114.
- Cole, R. J., & Brown, Z. (2009). Reconciling human and automated intelligence in the provision of occupant comfort. *Intelligent Buildings International*, 1(1), 39-55.
- Čolić-Damjanovic, V. M., & Gadjanski, I. (2016, September). Potentials of fablabs for biomimetic architectural research. In *Multidisciplinary Engineering Design Optimization (MEDO), International Conference* (pp. 1-6). IEEE.
- Craig, S., Harrison, D., & Cripps, A. (2008). Two new environmental building technologies, one new design method: infrared transparent insulation, biodegradable concrete formwork and BioTRIZ. In *Proceedings of the conference for the engineering doctorate in environmental technology. University of Surrey, UK*.
- Cui, S., Ahn, C., Wingert, M. C., Leung, D., Cai, S., & Chen, R. (2016). Bio-inspired effective and regenerable building cooling using tough hydrogels. *Applied Energy*, 168, 332-339.
- De Boer BJ, Ruijg GJ, Loonen RCGM, Trcka M, Hensen JLM, Kornaat W. (2011). Climate adaptive building shells for the future – optimization with an inverse modelling approach. In: Proceedings of the ECEEE Summer Study 2011, Belambra Presqu'île de Giens, France. – Presqu'île de Giens: Technische Universiteit Eindhoven; p. 1413–22.
- Dean, B., & Bhushan, B. (2010). Shark-skin surfaces for fluid-drag reduction in turbulent flow: a review. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 368(1929), 4775-4806.
- Decker M, Yeadon P. (2010). Projects Smart Screen: Versions I, II and III.

- Del Grosso, A. E., & Basso, P. (2013). Design concepts for adaptive multi-functional building envelopes. In *Proceedings of the 6th ECCOMAS Thematic Conference on Smart Structures and Materials, SMART 2013*.
- Dewidar, K. M., Mohamed, N. M., & Ashour, Y. S. (2013). Living Skins: A New Concept of Self Active Building Envelope Regulating Systems. *SB13 Dubai*.
- Doumpiotti, C., Greenberg, E. L., & Karatzas, K. (2010). Embedded intelligence: material responsiveness in façade systems.
- Dumais, J., & Forterre, Y. (2012). "Vegetable Dynamicks": the role of water in plant movements. *Annual Review of Fluid Mechanics*, 44, 453-478.
- Dumont, E. R. (2010). Bone density and the lightweight skeletons of birds. *Proceedings of the Royal Society of London B: Biological Sciences*, rspb20100117.
- El Ahmar, S. A. S. (2011). *Biomimicry as a Tool for Sustainable Architectural Design* (Doctoral dissertation, Faculty of Engineering, Alexandria University).
- El Ahmar, S., Fioravanti, A., & Hanafi, M. (2013, September). A Methodology for Computational Architectural Design Based on Biological Principles. In *CAADe 2013: Computation and Performance—Proceedings of the 31st International Conference on Education and research in Computer Aided Architectural Design in Europe, Delft, The Netherlands, September 18-20, 2013*. Faculty of Architecture, Delft University of Technology; eCAADe (Education and research in Computer Aided Architectural Design in Europe).
- Elattar, S. M. S. (2013). Smart structures and material technologies in architecture applications. *Scientific Research and Essays*, 8(31), 1512-1521.
- EL-MAHDY, D. (2017). Behavior Of Natural Organisms As A Mimicking Tool In Architecture. *International Journal of Design & Nature and Ecodynamics*, 12(2), 214-224.
- Ezcurra, E., Mellink, E., Wehneke, E., González, C., Morrison, S., Warren, A. & Driessen, P. (2006). Natural history and evolution of the world's deserts. In *Global deserts outlook* (pp. 1-26). UNEP.
- Fan, J., Chen, B., Gao, Z., & Xiang, C. (2005). Mechanisms in failure prevention of bio-materials and bio-structures. *Mechanics of Advanced Materials and Structures*, 12(3), 229-237.
- Fiorito, F., Sauchelli, M., Arroyo, D., Pesenti, M., Imperadori, M., Masera, G., & Ranzi, G. (2016). Shape morphing solar shadings: A review. *Renewable and Sustainable Energy Reviews*, 55, 863-884.
- Frosch, R. A., & Gallopoulos, N. E. (1989). Strategies for manufacturing. *Scientific American*, 261(3), 144-152.
- Gamage, A. U., & Wickramanayake, R. S. D. (2005). Parallels between nature and design teaching through nature studies. *Built Environment Sri Lanka*, 5(2), 1-12.
- Gamage, A., & Hyde, R. (2012). A model based on Biomimicry to enhance ecologically sustainable design. *Architectural Science Review*, 55(3), 224-235.
- Gao, X., & Jiang, L. (2004). Biophysics: water-repellent legs of water striders. *Nature*, 432(7013), 36-36.
- Gao, X., Yan, X., Yao, X., Xu, L., Zhang, K., Zhang, J., ... & Jiang, L. (2007). The Dry-Style Antifogging Properties of Mosquito Compound Eyes and Artificial Analogues Prepared by Soft Lithography. *Advanced Materials*, 19(17), 2213-2217.
- Garcia-Holguera, M., Clark, O. G., Sprecher, A., & Gaskin, S. (2016). Ecosystem biomimetics for resource use optimization in buildings. *Building Research & Information*, 44(3), 263-278.

- Gebeshuber, I. C., & Drack, M. (2008). An attempt to reveal synergies between biology and mechanical engineering. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 222(7), 1281-1287.
- Gebeshuber, I. C., Gruber, P., & Drack, M. (2009). A gaze into the crystal ball: Biomimetics in the year 2059. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 223(12), 2899–2918. doi:10.1243/09544062jmes1563
- Gibson, L. (2012). The hierarchical structure and mechanics of plant materials. *Journal of the Royal Society Interface*, 12, 106. doi: 10.1098/
- Granqvist, C. G. (2016). Electrochromics and thermochromics: towards a new paradigm for energy efficient buildings. *Materials Today: Proceedings*, 3, S2-S11.
- Greene, A. C., Trent, A. M., & Bachand, G. D. (2008). Controlling kinesin motor proteins in nanoengineered systems through a metal-binding on/off switch. *Biotechnology and bioengineering*, 101(3), 478-486.
- Gruber, P. (2011). *Biomimetics in Architecture: Architecture of Life and Buildings*. Vienna: Springer.
- Gruber, P., & Gosztonyi, S. (2010). Skin in architecture: Towards bioinspired facades. *WIT Transactions on Ecology and the Environment*, 138.
- Hanaei, H., Assadi, M. K., & Saidur, R. (2016). Highly efficient antireflective and self-cleaning coatings that incorporate carbon nanotubes (CNTs) into solar cells: A review. *Renewable and Sustainable Energy Reviews*, 59, 620-635.
- Han, Z., Mu, Z., Yin, W., Li, W., Niu, S., Zhang, J., & Ren, L. (2016). Biomimetic multifunctional surfaces inspired from animals. *Advances in colloid and interface science*.
- Hasselaar, B. L. H. (2006). Climate Adaptive Skins: towards the new energy-efficient façade. In *1st International Conference on the Management of Natural Resources, Sustainable Development and Ecological Hazards, RAVAGE OF THE PLANET 2006, RAV06* (pp. 351-360).
- Hasselaar, B. L. H. (2006, November). Climate Adaptive Skins: towards the new energy-efficient façade. In *1st International Conference on the Management of Natural Resources, Sustainable Development and Ecological Hazards, RAVAGE OF THE PLANET 2006, RAV06* (pp. 351-360).
- Hastrich, C. (2006). The Biomimicry Design Spiral. *Biomimicry Newsletter*. 4.1, 5-6.
- Helms, M., Vattam, S. S., & Goel, A. K. (2009). Biologically inspired design: Process and products. *Design Studies*, 30(5), 606–622. doi:10.1016/j.destud.2009.04.003
- Hensel, M. (2006). Towards Self-Organisational. *AD- Techniques & Technologies in Morphogenetic Design*, 5-11.
- Hensel, M., & Menges, A. (2007). *Morpho-Ecologies: Towards Heterogeneous Space In Architecture Design*. AA Publications.
- Hensel, M., & Menges, A. (2008). Designing Morpho-Ecologies. *AD-Versatility & Vicissitude: Performance in Morpho-Ecological Design*, 102-111.
- Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S., & Wood, K. L. (2002). A functional basis for engineering design: reconciling and evolving previous efforts. *Research in engineering Design*, 13(2), 65-82.
- Hoberman, A. and Happold, B. (2010). *Adaptive Building Initiative*, Available at: www.adaptivebuildings.com, (Accessed 18 May 2013).
- Hoberman, C. (2006). Transformation in Architecture and Design. *Transportable Environments* 3, 70.

- Holstov, A., Bridgens, B., & Farmer, G. (2015). Hygromorphic materials for sustainable responsive architecture. *Construction and Building Materials*, 98, 570-582.
- Howes, P., & Laughlin, Z. (2012). *Material matters: New materials in design*. Black Dog Pub Limited.
- Iqbal, J., & Khan, Z. H. (2016). The potential role of renewable energy sources in robot's power system: A case study of Pakistan. *Renewable and Sustainable Energy Reviews*.
- Iijima, T., & Sibaoka, T. (1981). Action potential in the trap-lobes of *Aldrovanda vesiculosa*. *Plant and cell physiology*, 22(8), 1595-1601.
- Izumi, M., Sweeney, A. M., DeMartini, D., Weaver, J. C., Powers, M. L., Tao, A., ... & Naik, R. R. (2009). Changes in reflectin protein phosphorylation are associated with dynamic iridescence in squid. *Journal of The Royal Society Interface*, rsif20090299.
- Jan, K., & Thomas, S. (2012). Design and construction principles in nature and architecture. *Bioinspiration and Biomimetics*, 7(1), 015002. doi:10.1088/1748-3182/7/1/015002
- Jochum, F. D., & Theato, P. (2013). Temperature-and light-responsive smart polymer materials. *Chemical Society Reviews*, 42(17), 7468-7483.
- Kamila, S. (2013). Introduction, classification and applications of smart materials: an overview. *American Journal of Applied Sciences*, 10(8), 876.
- Karamata, B., & Andersen, M. (2014). Concept, Design and Performance of a Shape Variable Mashrabiya as a Shading and Daylighting System for Arid Climates. In *30th PLEA Conference-SUSTAINABLE HABITAT FOR DEVELOPING SOCIETIES* (Vol. 2, No. EPFL-CONF-206749, pp. 344-351). CEPT University Ahmedabad.
- Kelly, K. (1994). *Out of control - the new biology of machines*. London: Fourth Estate.
- Kenisarin, M., & Mahkamov, K. (2016). Passive thermal control in residential buildings using phase change materials. *Renewable and Sustainable Energy Reviews*, 55, 371-398.
- Khoo, C. K. (2012). Sensory morphing skins. *Proceedings of the 30th eCAADe, Czech Republic*.
- Khoo, C. K., Salim, F., & Burry, J. (2011). Designing architectural morphing skins with elastic modular systems. *International Journal of Architectural Computing*, 9(4), 397-419.
- Kibert, C. J., Sendzimir, J., & Guy, G. B. (2002). *Construction ecology*. New York: Spon Press.
- Kiliccote, S., Piette, M.A., Ghatikar, G., Hafemeister, D., Kammen, D., Levi, B.G. and Schwartz, P. (2011), "Smart buildings and demand response", AIP Conference Proceedings, Vol. 1401, Berkeley, March 5-6.
- Knippers, J., & Speck, T. (2012). Design and construction principles in nature and architecture. *Bioinspiration & biomimetics*, 7(1), 015002.
- Kolle, M., Lethbridge, A., Kreysing, M., Baumberg, J. J., Aizenberg, J., & Vukusic, P. (2013). Bio-Inspired Band-Gap Tunable Elastic Optical Multilayer Fibers. *Advanced Materials*, 25(15), 2239-2245.
- Kretzer, M. (2010). *Shape Shift*, Computer Aided Architectural Design Journal.
- Kretzer, M., & Rossi, D. (2012). ShapeShift. *Leonardo*, 45(5), 480-481.
- Lakhtakia, A. Jose Martin-Palma, R. (2013). *Engineered Biomimicry*, Elsevier, USA,.
- Lawn, B. R., Lee, J. J. W., & Chai, H. (2010). Teeth: among nature's most durable biocomposites. *Annual Review of Materials Research*, 40, 55-75.

- Lazarus, M. A., & Crawford, C. (2011). Returning genius to the place. *Architectural Design*, 81(6), 48–53. doi:10.1002/ad.1319
- Le Corbusier. (1991). *Precisions on the present state of architecture and city planning: with an American prologue, a Brazilian corollary followed by The temperature of Paris and The atmosphere of Moscow*. The MIT Press.
- Leatherbarrow, D., & Mostafavi, M. (2005). *Surface architecture*. MIT Press.
- Lenau, T. (2009). Biomimetics as a design methodology possibilities and challenges. Paper presented at the International Conference on Engineering Design, ICED 2009, Stanford, CA, USA.
- Leng, J., Lan, X., Liu, Y., & Du, S. (2011). Shape-memory polymers and their composites: stimulus methods and applications. *Progress in Materials Science*, 56(7), 1077-1135.
- Lepora, N. F., Verschure, P., & Prescott, T. J. (2013). The state of the art in biomimetics. *Bioinspiration & biomimetics*, 8(1), 013001.
- Lienhard, J. (2014). *Bending-active structures: form-finding strategies using elastic deformation in static and kinetic systems and the structural potentials therein*. http://elib.uni-stuttgart.de/bitstream/11682/124/1/Diss_Bending_Active_Structures_Julian_Lienhard.pdf
- Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T., & Knippers, J. (2011). Flectofin: a hingeless flapping mechanism inspired by nature. *Bioinspiration & biomimetics*, 6(4), 045001.
- Life Architects. (2007). Air Flower. <http://www.liftarchitects.com/air-flower/>
- Lignarolo, L. E. M., Lelieveld, C. M. J. L., & Teuffel, P. (2011, December). Shape morphing wind-responsive facade systems realized with smart materials. In *Adaptive Architecture: An International Conference, London, UK, March 3-5, 2011*.
- Lin, S., & Theato, P. (2013). CO₂-Responsive Polymers. *Macromolecular rapid communications*, 34(14), 1118-1133.
- Liu, K., & Jiang, L. (2011). Bio-inspired design of multiscale structures for function integration. *Nano Today*, 6(2), 155-175.
- Liu, L., Li, H., Lazzaretto, A., Manente, G., Tong, C., Liu, Q., & Li, N. (2017). The development history and prospects of biomass-based insulation materials for buildings. *Renewable and Sustainable Energy Reviews*, 69, 912-932.
- Loonen R. (2010). Climate adaptive building shells, what can we simulate? Eindhoven (The Netherlands): Technische Universiteit Eindhoven.
- Loonen, R. C. G. M., Trčka, M., Cóstola, D., & Hensen, J. L. M. (2013). Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews*, 25, 483-493.
- López, M., Rubio, R., Martín, S., & Croxford, B. (2017). How plants inspire façades. From plants to architecture: Biomimetic principles for the development of adaptive architectural envelopes. *Renewable and Sustainable Energy Reviews*, 67, 692-703.
- Lopez, M., Rubio, R., Martín, S., Croxford, B., & Jackson, R. (2015a). Active materials for adaptive architectural envelopes based on plant adaptation principles. *Journal of Facade Design and Engineering*, 3(1), 27-38.
- Lopez, M., Rubio, R., Martín, S., Croxford, B., & Jackson, R. (2015b). Adaptive architectural envelopes for temperature, humidity, carbon dioxide and light control. 10th Conference on Advanced Building Skins. 3-4 November 2015, Bern, Switzerland. ISBN: ISBN 978-3-98120538-1

- Lurie-Luke, E. (2014). Product and technology innovation: what can biomimicry inspire?. *Biotechnology advances*, 32(8), 1494-1505.
- Manoranjan, N., Kim, J., & Woo, S. I. (2016). Amide linked conjugated porous polymers for effective CO₂ capture and separation. *Journal of CO₂ Utilization*.
- Mazzoleni, I. (2013). *Architecture Follows Nature-Biomimetic Principles for Innovative Design* (Vol. 2). CRC Press.
- Mazzoleni, I., & Price, S. (2013). *Architecture Follows Nature, Biomimetic Principles for Innovative Design*. Florida: CRC Press, Taylor and Francis Group.
- McCann, K. S. (2000). The diversity–stability debate. *Nature*, 405(6783), 228-233.
- McDonough, W., & Braungart, M. (2010). *Cradle to cradle: Remaking the way we make things*. MacMillan.
- Menges, A., & Reichert, S. (2012). Material capacity: embedded responsiveness. *Architectural Design*, 82(2), 52-59.
- Meriam, J. L., & Kraige, L. G. (2012). *Engineering mechanics: dynamics* (Vol. 2). John Wiley & Sons.
- Myers, W. (2012). Beyond Biomimicry. In W. Myers, *Bio Design* (pp. 10-17). London: Thames & Hudson.
- Nachtigall, W. (1997). *Vorbild Natur. Bionik – Design für funktionelles Gestalten*. Berlin and Heidelberg: Springer.
- Nguyen, T. A., & Aiello, M. (2013). Energy intelligent buildings based on user activity: A survey. *Energy and buildings*, 56, 244-257.
- Odum, E. P. (1969). The strategy of ecosystem development. *Science*, 164, 262-270.
- Omrany, H., Ghaffarianhoseini, A., Ghaffarianhoseini, A., Raahemifar, K., & Tookey, J. (2016). Application of passive wall systems for improving the energy efficiency in buildings: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 62, 1252-1269.
- Oral, G. K., & Yilmaz, Z. (2003). Building form for cold climatic zones related to building envelope from heating energy conservation point of view. *Energy and Buildings*, 35(4), 383-388.
- Otto F. (1971). *Convertible roofs*, INSTITUTE FOR LIGHTWEIGHT STRUCTURES, IL5, Druckerei Heinrich Fink KG, Stuttgart, 1971, pp. 6-7
- Pan, C. A., & Jeng, T. (2010, August). A robotic and kinetic design for interactive architecture. In *SICE Annual Conference 2010, Proceedings of*(pp. 1792-1796). IEEE.
- Panchuk, N. (2006). *An Exploration into Biomimicry and its Application in Digital & Parametric [Architectural] Design*, Waterloo, Ontario, Canada.
- Papanek, V. (1971). *Design for the Real World: Human Ecology and Social Change*. London: Thames and Hudson.
- Parker, A. R., & Lawrence, C. R. (2001). Water capture by a desert beetle. *Nature*, 414(6859), 33-34.
- Pawlyn, M. (2011). *Biomimicry In Architecture*. London: RIBA Publishing.
- Pesenti, M., Masera, G., Fiorito, F., & Sauchelli, M. (2015). Kinetic solar skin: a responsive folding technique. *Energy Procedia*, 70, 661-672.
- Poppinga, S., Masselter, T., & Speck, T. (2013). Faster than their prey: new insights into the rapid movements of active carnivorous plants traps. *Bioessays*, 35(7), 649-657.

- Ramzy, N., & Fayed, H. (2011). Kinetic systems in architecture: New approach for environmental control systems and context-sensitive buildings. *Sustainable Cities and Society*, 1(3), 170-177.
- RAO, C. L., LAKSHINARASHIMAN, J., SETHURAMAN, R., & SIVAKUMAR, S. M. (2003). *Engineering Mechanics: Statics and Dynamics*. PHI Learning Pvt. Ltd..
- Reap, J., Baumeister, D., & Bras, B. (2005, January). Holism, biomimicry and sustainable engineering. In *ASME 2005 International Mechanical Engineering Congress and Exposition* (pp. 423-431). American Society of Mechanical Engineers.
- Rosa, L., Rodrigues, L., Lopes, A., Hiltunen, M., & Schlichting, R. (2013). Self-management of adaptable component-based applications. *IEEE Transactions on Software Engineering*, 39(3), 403-421.
- Roudavski, S. (2009). Towards Morphogenesis in Architecture [Online]. *International Journal of Architectural Computing*, 345-374 Available from: http://dtl.unimelb.edu.au/R/H6V9SANDEJRNDYQ8FQ85I2AL3NAQF8TQ3TSLA1M5FXILP2YM5K-00585?func=dbin-jump-full&object_id=116799&pds_handle=GUEST [Accessed April 2010].
- Royall, E. (2010). Defining biomimicry: architectural applications in systems and products. In *UTSoA-Seminar in Sustainable Architecture* (pp. 1-3).
- Schattling, P., Pollmann, I., & Theato, P. (2014). Synthesis of CO₂-responsive polymers by post-polymerization modification. *Reactive and Functional Polymers*, 75, 16-21.
- Schleicher, S., Lienhard, J., Poppinga, S., Speck, T., & Knippers, J. (2015). A methodology for transferring principles of plant movements to elastic systems in architecture. *Computer-Aided Design*, 60, 105-117.
- Shabha, G. (2006), "A critical review of the impact of embedded smart sensors on productivity in the workplace", *Facilities*, Vol. 24 No. 13, pp. 538-549.
- Sheta, A. A. A. A. (2010). Biomimicry in environmental architecture: Exploring the concept and methods of the bio-inspired environmental architectural design.
- Shimomura, M. (2010). The new trends in next generation biomimetics material technology: learning from biodiversity. *Sci Technol Trends*:37:53-75.
- SOMA Architecture. (2012). Projects "thematic pavilion".
- Spain, E. (2003, November). TRIZ: uncovering hidden treasures. In *HKIVM International Conference*.
- Speck, T., & Speck, O. (2008). Process sequences in biomimetic research. *WIT Tran*, 114, 3-11.
- Speck, O., Speck, D., Horn, R., Gantner, J., & Sedlbauer, K. P. (2017). Biomimetic bio-inspired biomorph sustainable? An attempt to classify and clarify biology-derived technical developments. *Bioinspiration & Biomimetics*, 12(1), 011004.
- Sung, D. K. (2012). *Skin Deep: Breathing Life into the Layer between Man and Nature*. Los Angeles. University of Southern California.
- The Living New York, (2010), *Living Glass*, Available at: www.thelivingnewyork.com/lg/lg01.html
- The Living. (2014). Living Project "Living Glass". <http://inhabitat.com/carbon-dioxide-sensing-living-glass/>
- Tong, J., Zhang, Z., Ma, Y., Chen, D., Jia, B., & Menon, C. (2012). Abrasive wear of embossed surfaces with convex domes. *Wear*, 274, 196-202.
- Trolier-McKinstry, S., & Newnham, R. E. (1993). Sensors, actuators, and smart materials. *MRS bulletin*, 18(04), 27-33.

- Turner, J. S., & Soar, R. C. (2008, May). Beyond biomimicry: What termites can tell us about realizing the living building. In *First International Conference on Industrialized, Intelligent Construction at Loughborough University*.
- Turrin, M., Von Buelow, P., Kilian, A., & Stouffs, R. (2012). Performative skins for passive climatic comfort: A parametric design process. *Automation in Construction*, 22, 36-50.
- Ulrich, R. S. (1993). Biophilia, Biophobia, and Natural Landscapes. In S. R. Kellert & E. O.
- Ürge-Vorsatz, D., Cabeza, L. F., Serrano, S., Barreneche, C., & Petrichenko, K. (2015). Heating and cooling energy trends and drivers in buildings. *Renewable and Sustainable Energy Reviews*, 41, 85-98.
- Ürge-Vorsatz, D., Eyre, N., Graham, P., Harvey, D., Hertwich, E., Jiang, Y., & Murakami, S. (2012). Chapter 10-energy end-use: building. *Global Energy Assessment-Toward a Sustainable Future*, 649-760.
- Van der Ryn, S. (2005). *Design for life: The architecture of Sim Van der Ryn*. Gibbs Smith.
- Vattam, S. S., Helms, M. E., & Goel, A. K. (2009, October). Nature of creative analogies in biologically inspired innovative design. In *Proceedings of the seventh ACM conference on Creativity and cognition* (pp. 255-264). ACM.
- Vázquez WM. (2014). Metatectonica: further the understanding on biomimicry as one of the most important emergent theories for the future of design and architecture [Blog post]. Retrieved from <http://metatectonica.blogspot.co.uk/>, [Last accessed 11th January 2017].
- Vergauwen, A., De Temmerman, N., & Brancart, S. (2014, June). The design and physical modelling of deployable structures based on curved-line folding. In *4th International Conference on Mobile, Adaptable and Rapidly Assembled Structures, MARAS* (pp. 145-56).
- Vincent, J. (2003). Biomimetic modelling. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 358(1437), 1597–1603. doi:10.1098/rstb.2003.1349
- Vincent, J. F., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., & Pahl, A. K. (2006). Biomimetics: its practice and theory. *Journal of the Royal Society Interface*, 3(9), 471-482.
- Vogel, S. (2012). *The life of a leaf*. University of Chicago Press.
- Vogel, S. (2013). *Comparative biomechanics: life's physical world*. Princeton University Press.
- Vukusic P. (2010). An introduction to bioinspired design. *Contact Lens Spectrum*:6–13.
- Wang, J., Beltrán, L. O., & Kim, J. (2012). From static to kinetic: a review of acclimated kinetic building envelopes. *Ases confernce*. p. 4022–9.
- Wang, Y., Kuckelkorn, J., Zhao, F. Y., Spliethoff, H., & Lang, W. (2016). A state of art of review on interactions between energy performance and indoor environment quality in Passive House buildings. *Renewable and Sustainable Energy Reviews*.
- Weinstock, M., & Stathopoulos, N. (2006). Advanced Simulaiton in Design. *AD Techniques & Technologies in Morphogenetic Design*, 54-59.
- Wigginton, M and Harris, J, (2002), *Intelligent skins*, Elsevier, Oxford, UK.
- Wigginton, M. and Harris, J. (2009), *Intelligent Skins*, Oxford: Elsevier Architectural Press, p. 3.
- Wilson (Eds.), *The Biophilia Hypothesis* (pp. 73-137). Washington D.C.: Island Press.
- Wood, C. (2017) Imitating Life. *The Biologist*, 63(1):12-16.

- Wong, T. S., Kang, S. H., Tang, S. K., Smythe, E. J., Hatton, B. D., Grinthal, A., & Aizenberg, J. (2011). Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity. *Nature*, 477(7365), 443-447.
- Wu, L. Y., Zhao, Q., Huang, H., & Lim, R. J. (2016). Sol-gel based photochromic coating for solar responsive smart window. *Surface and Coatings Technology*.
- Yan, Y. Y., Gao, N., & Barthlott, W. (2011). Mimicking natural superhydrophobic surfaces and grasping the wetting process: A review on recent progress in preparing superhydrophobic surfaces. *Advances in colloid and interface science*, 169(2), 80-105.
- Yuan, Y., Yu, X., Yang, X., Xiao, Y., Xiang, B., & Wang, Y. (2017). Bionic building energy efficiency and bionic green architecture: A review. *Renewable and Sustainable Energy Reviews*, 74, 771-787.
- Yu, K., Fan, T., Lou, S., & Zhang, D. (2013). Biomimetic optical materials: Integration of nature's design for manipulation of light. *Progress in Materials Science*, 58(6), 825-873.
- Zari, M. P. (2007). Biomimetic approaches to architectural design for increased sustainability. *Auckland, New Zealand*.
- Zari, M. P. (2009). An architectural love of the living: bio-inspired design in the pursuit of ecological regeneration and psychological wellbeing. *WIT Transactions on Ecology and the Environment*, 120.
- Zari, M. P. (2010). Biomimetic design for climate change adaptation and mitigation. *Architectural Science Review*, 53(2), 172-183.
- Zari, M. P., & Storey, J. B. (2007). An ecosystem based biomimetic theory for a regenerative built environment. In *Sustainable Building Conference* (Vol. 7).
- Zari, M. P. (2015). Ecosystem processes for biomimetic architectural and urban design. *Architectural Science Review*, 58(2), 106-119.
- Zari, M. P. (2012). Ecosystem services analysis for the design of regenerative built environments. *Building Research & Information*, 40(1), 54-64.
- Zarzar, L. D., Kim, P., & Aizenberg, J. (2011). Bio-inspired Design of Submerged Hydrogel-Actuated Polymer Microstructures Operating in Response to pH. *Advanced materials*, 23(12), 1442-1446.
- Zhiwu, H., Junqiu, Z., Chao, G., Li, W., & Ren, L. (2012). Erosion resistance of bionic functional surfaces inspired from desert scorpions. *Langmuir*, 28(5), 2914-2921.
- Zuk, W., & Clark, R. H. (1970). *Kinetic architecture*. Van Nostrand Reinhold.

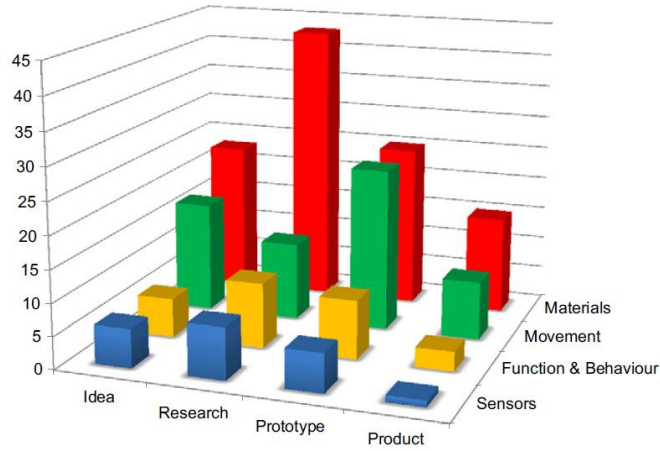


Figure 1: Biomimicry applications in different areas and their development stage (Lurie-Luke, 2014)

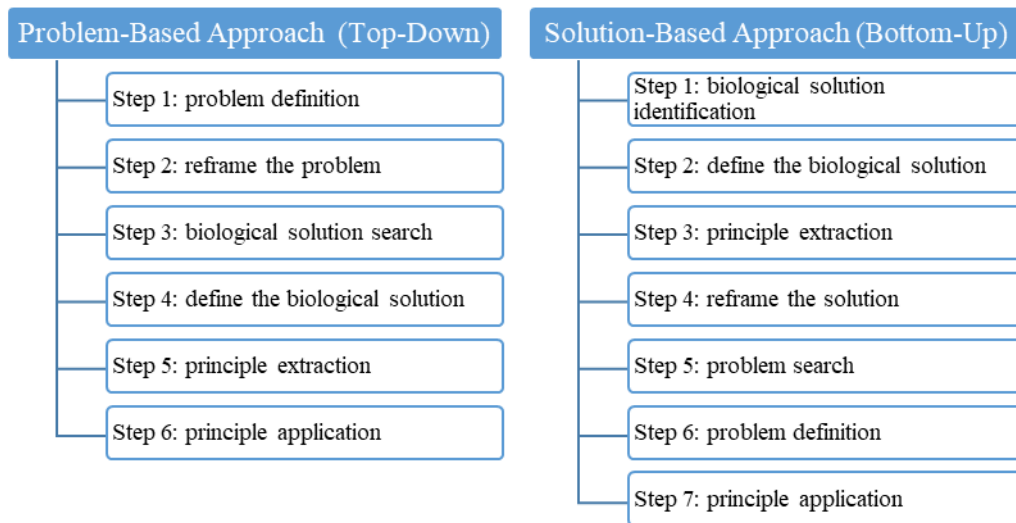


Figure 2: Two types of approaches conducted in biomimicry research (Helms et al., 2009)

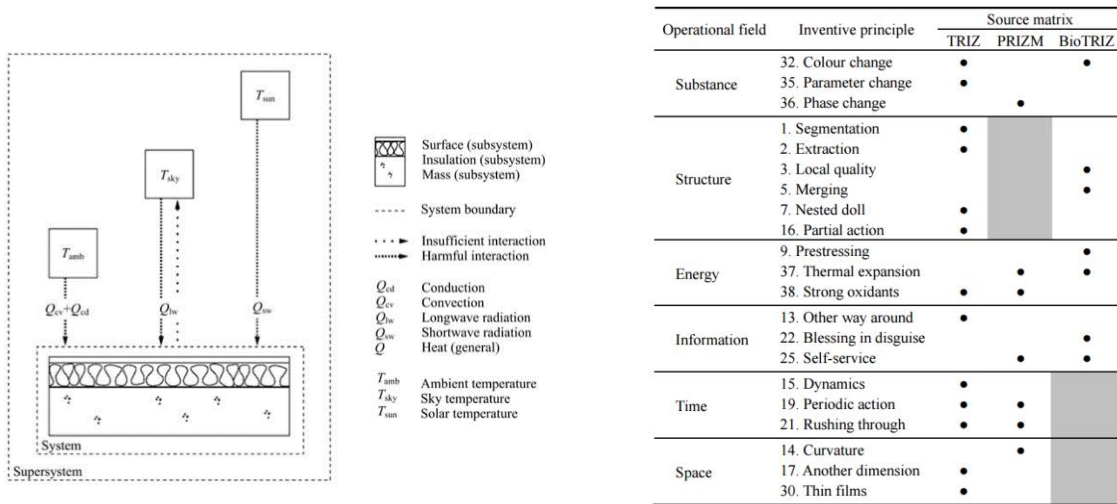


Figure 3: Diagrams of the design of roofing system based on BioTRIZ (Craig et al., 2008)

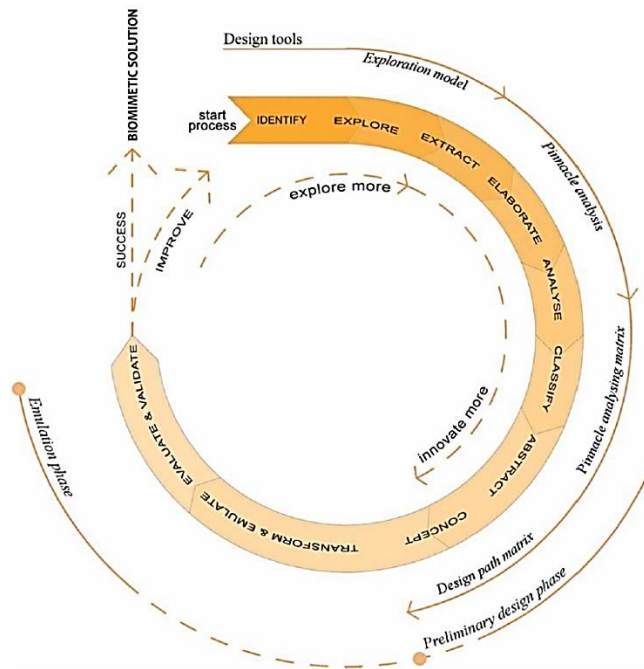
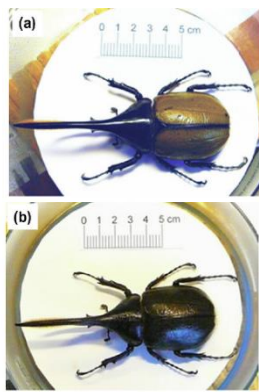
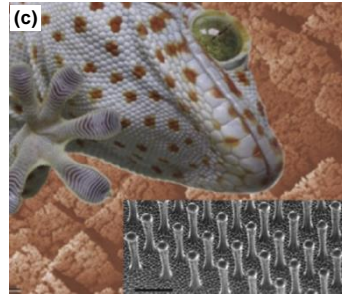


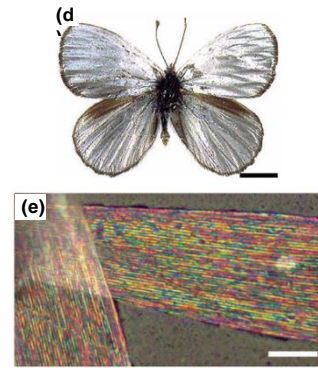
Figure 4: Exploration model and design path matrix for BioGen method to design an adaptive wall system



(a) The *Dynastes hercules* is greenish under normal condition of humidity. (b) The beetle presents a black coloration on all its body when it exposes to a level of humidity

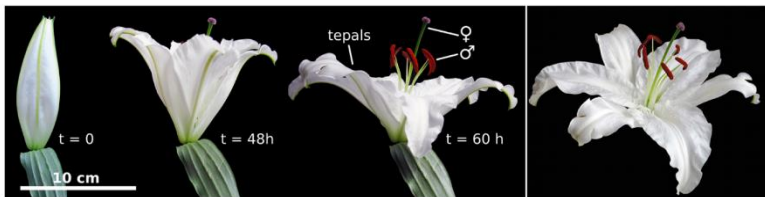


(c) The lizard *G. gecko* employs setal structures on foot (background) for attachment.



(a) *A. argenteus* specimen dorsal wing surfaces, taken in diffuse white illumination. (b) Optical microscope epi-mode image of two single structurally colored scales.

Figure 5: Different types of adaptive Functional Surfaces from animals (Yu et al., 2013)



(a) The opening movement of a lily bud is driven by differential edge growth in the petals (Schleicher et al., 2015)



(b) Reversible moisture-driven opening (dry conditions) and closing (wet conditions) of spruce cones (Holstov et al., 2015)

Figure 6: Two types of plants with adaptive dynamic movements

Kinematics & Kinetics	<ul style="list-style-type: none"> • Kinematics is the study of motion through system geometry without considering mass or external forces that may cause movement (RAO et al., 2003; Meriam and Kraige, 2012). Meanwhile, kinetics is the study of movement laws, including forces and masses, and emphasises on the relationship between motion and its causes (Lienhard, 2014).
Dynamics	<ul style="list-style-type: none"> • The study of movement, which occurs due to forces applied to an object. The term is commonly associated with moving building envelopes (Meriam and Kraige, 2012).
Retractable	<ul style="list-style-type: none"> • In architecture, the term is commonly used for textile membrane roofs, either bunched or folded; a term or expression similar to movable (Barozzi et al., 2016).
Convertible	<ul style="list-style-type: none"> • The term is mostly associated with building mobility, similar to building envelopes, that suggest change form in the short-term depending on needs and functions (Otto, 1971).
Transformable	<ul style="list-style-type: none"> • The term describes units or systems with the intrinsic property of controlled change, such as the ability to be foldable, retractable or shape-shifting (Hoberman, 2006).
Performative	<ul style="list-style-type: none"> • The term refers to systems that can mediate surrounding environment for user comfort, such as building skins. Building skin systems can control external factors in relation to predefined architectural performances (Turrin et al., 2012).
Interact	<ul style="list-style-type: none"> • The term refers to either intuitive or automatic responses to meet user requirements. Interactive building architectures use sensors to operate kinetic systems and enable intelligent materials in order to initiate change in appearance and the environment (Sung, 2012).
Smart (or intelligent)	<ul style="list-style-type: none"> • A process-related concept that conveys automatic control or operation of building envelopes, including heat loss or gain, daylighting, air ventilation and other systems. Smart systems use information technology to connect several subsystems that typically operate independently (Brooks, 2011).
Responsive	<ul style="list-style-type: none"> • In contrast to manipulate, the term responsive refers to a system moving and responding from the outside based on specific factors, thus allowing interaction with a passive environment (Hasselaar, 2006).
Adaptive	<ul style="list-style-type: none"> • The ability of a system to adjust by itself in relation to a changing environment. An adaptive system, as in the case of building skins, has the ability to adapt the features, behaviour or configuration of the external environment (Dewidar et al., 2013).

Figure 7: Summary of most common terms in contemporary architecture

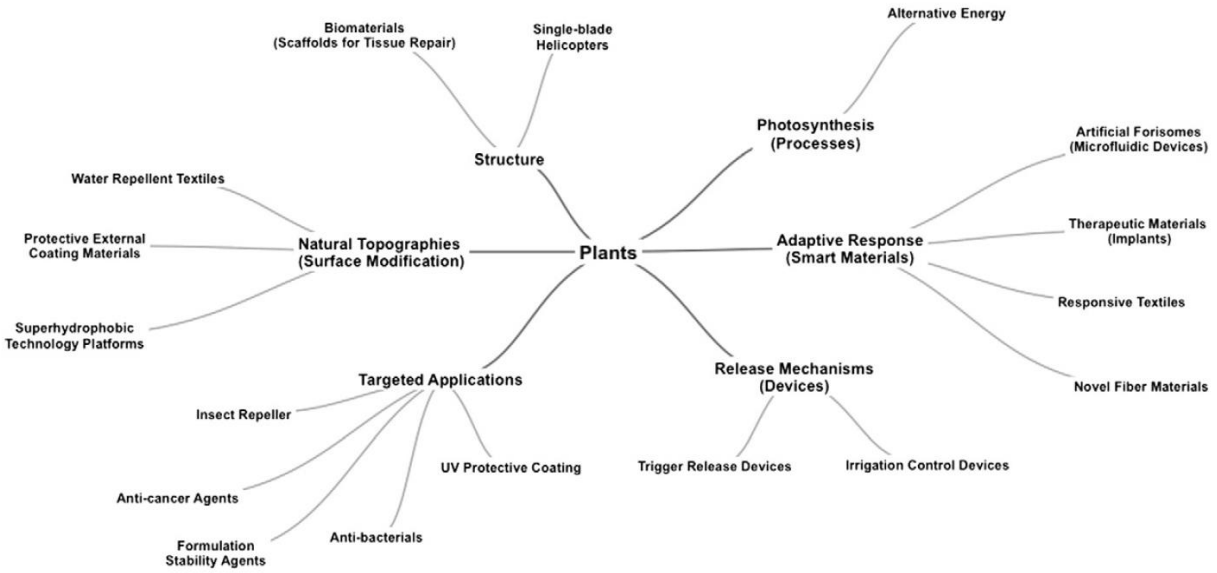


Figure 8: Different possibilities of learning plant-like adaption to develop adaptive building skins (Lurie-Luke, 2014)

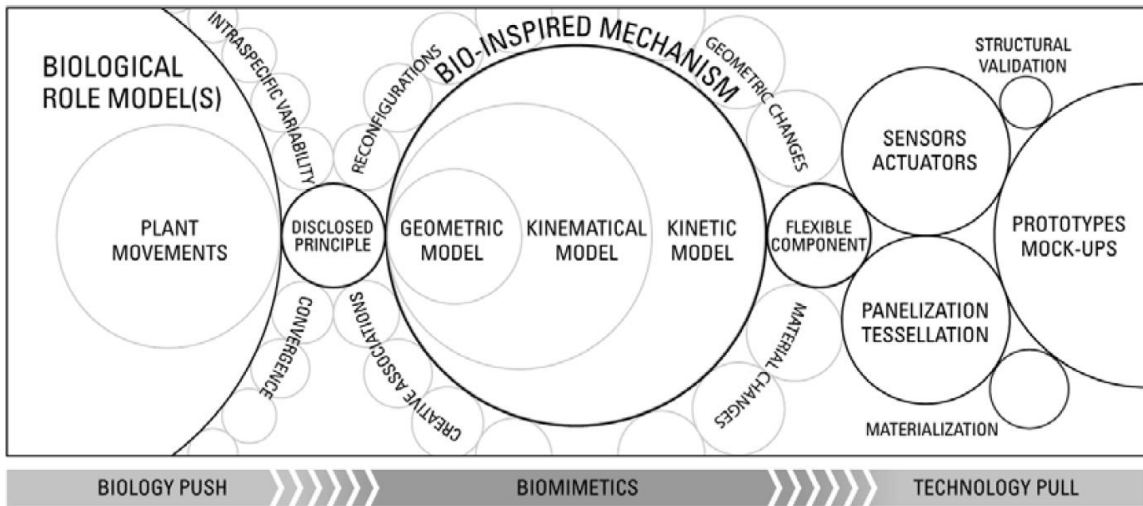


Figure 9: Mapping the key aspects of bio-inspired motion principles into technical kinetic structures (Schleicher et al., 2015)

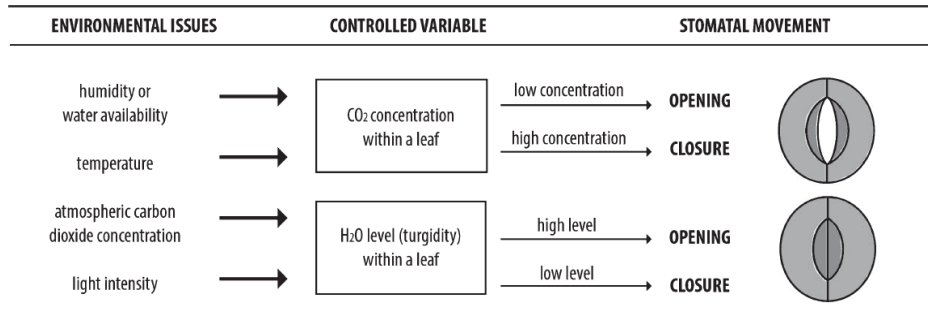


Figure 10: Diagram of stomatal movement mechanism (Lopez et al., 2015a)

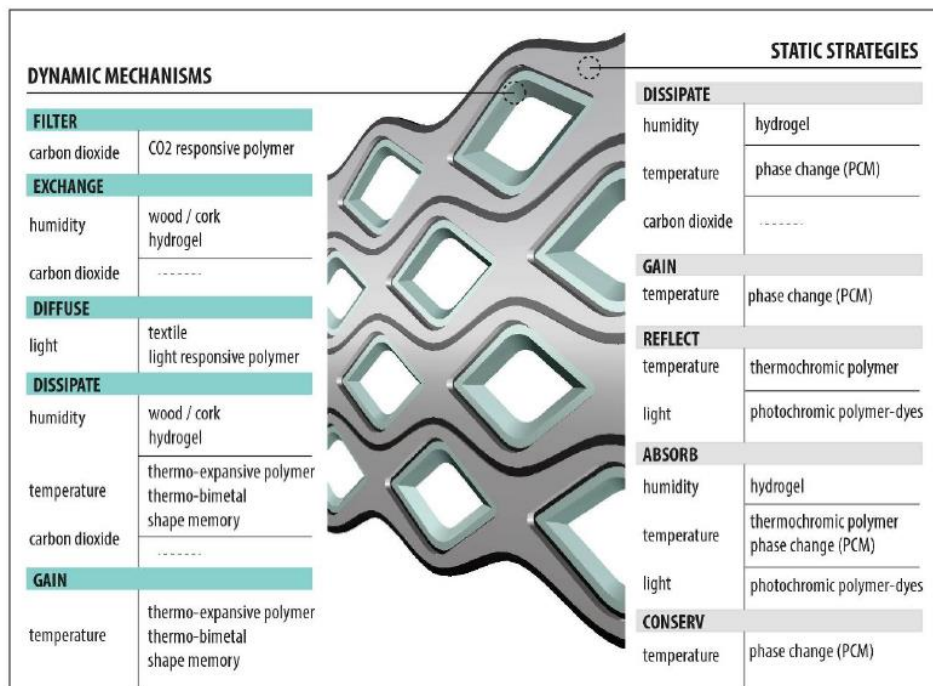
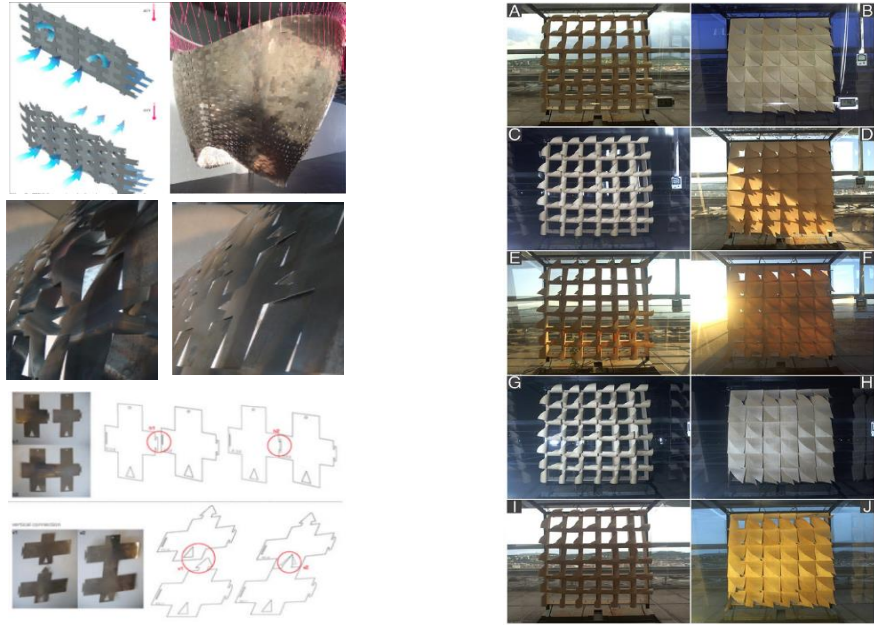


Figure 11: Adaptive wall system based on adaptive materials with different functions and environmental issues (Lopez et al., 2015b)



(a) The development of breathable façade using *thermobimetal* that operate with weather temperature (Sung, 2012)

(b) A *meteosensitive* architectural systems based on the biomimetic transfer of the hygroscopic actuation of plant cones of wooden veneer (Reichert et al., 2015)

Figure 12: Two types of adaptive materials based on temperature and humidity

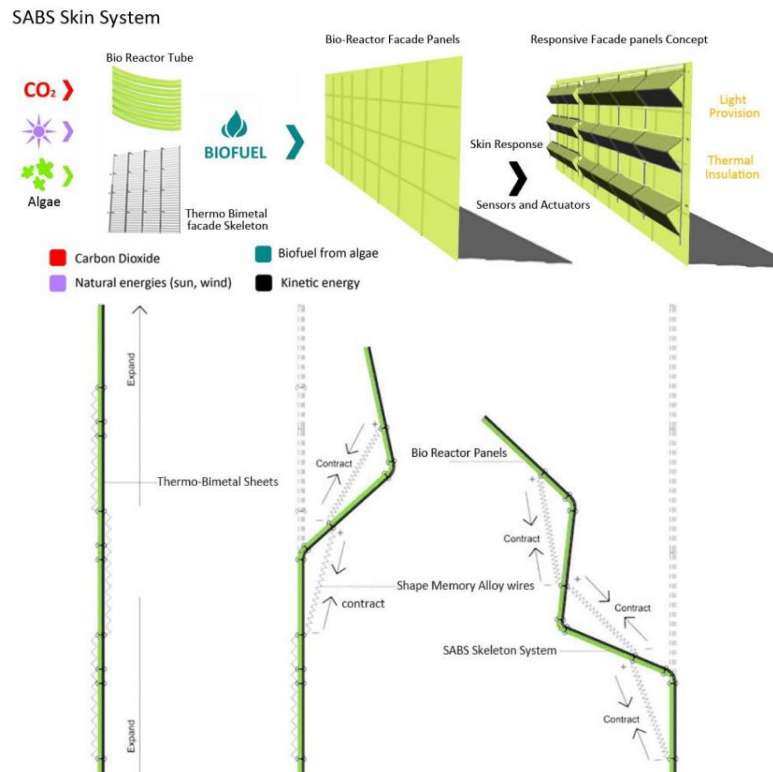


Figure 13: Integrated approach of Self-Active Bioclimatic Strategy (Dewidar et al., 2013)

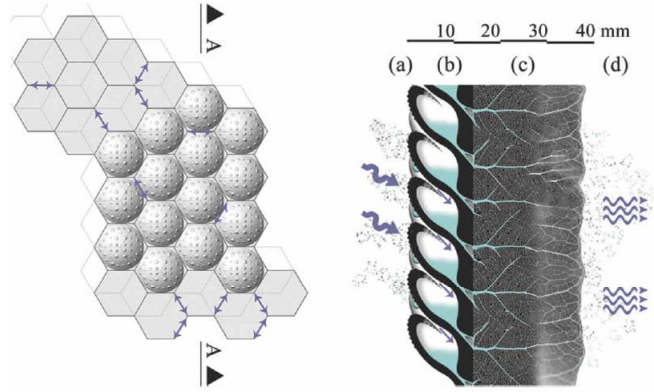


Figure 14: Biomimetic wall to collect water from fog (Badarnah and Kadri, 2015)