2017

Biomimetic Renewable.pdf

Hazreena Hussein
Karam M. Al-Obaidi
Muhammad Azzam Ismail
A. M. Abdul Rahman

Available at: https://works.bepress.com/hazreena/63/
Biomimetic building skins: An adaptive approach

Karam M. Al-Obaidi, Muhammad Azzam Ismail, Hazreena Hussein, Abdul Malik Abdul Rahman

A R T I C L E   I N F O

Keywords:
Biomimicry
Biomimetic architecture
Building skins
Adaptive building skins

A B S T R A C T

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 a 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.

1. Introduction

The low-carbon city and society development plan is gaining popularity among developed and developing countries, and this plan contributes to climate change mitigation and adaptation. In recent years, adaptive building skins 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 a 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.

http://dx.doi.org/10.1016/j.rser.2017.05.028
Received 16 January 2017; Received in revised form 6 April 2017; Accepted 10 May 2017
1364-0321/ © 2017 Elsevier Ltd. All rights reserved.
most of the building skins refer to a system that reacts to users’ needs and weather conditions by using automatic control concepts adjusted by users. In addition, it was found that most dynamic systems utilise mechanical actuators that require maintenance and consequently increase their susceptibility to failure [119]. As a result, a new system should be developed for future adaptive building skins.

Armstrong [15] 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 [191]. Biological solutions can be multifunctional, 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 [121,189].

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 skins 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 [151]. 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 [42]. 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 [62], and they presented a special concept of resembling ecosystems by creating a balance between nature and mankind. Benyus [28] 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 [27,29] stated that understanding the nature as a mentor, measure and model will be crucial to appreciate the applicability of biomimicry. Benyus [28] 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 [73] who investigated the relation of biomimicry in biology which possibly has a reciprocal use in our built environments. Pavlyon [143] explored notions from nature. Gamage and Hyde [64] and Zari [193] investigated biomimicry based on ecosystem interactions.

Biomimicry levels can be categorised into three stages: (1) form, (2) process and (3) ecosystem. Benyus [29] 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 [127] 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 [22]. 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 [148,9]. Commonly, biomimicry and biomimetic are inter-changeable 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 [126,143,19,193,64].

Biomimetic architecture seeks to remedy the errors that exist in designing efficient systems and products [151,58]. For instance, Myers [133] 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 [126] explored ways of utilizing 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’ [74], ‘Towards the living envelope’ [20] and ‘Architecture follows nature’ [126] that introduced a strategic methodology.

Several architectural projects utilised biomimicry; for instance, in terms of adaptive envelopes, the first project was inspired by the valcular pollination mechanism in Strelitzia reginae flower called Flectofins [113]. 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 [102,161]. 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 [130]. Generally, Lerue-Luke [124] conducted a study to identify biomimetic applications in scientific discipline based on innovations, as shown in Fig. 1. Results showed that the most advanced area under research are materials followed by idea and prototype of movement and materials.

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 [148]. Nature has various mechanisms and strategies that can be adopted in biomimetic approach. Even though there are several types of biomimetic designs
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 [194] and Badarnah and Kadri [21] 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. [67] stated that architects and researchers addressed biomimicry in architectural design based on three directions: (1) through the development of architectural courses and experimental designs [109,73,79], (2) advancement of design tools and methods to establish systematic and organised research [175,16,196,41] and (3) the development of actual design models by architectural firms [167] and research groups [106].

Generally, the basic design approach that has been utilised by previous researchers and practitioners were the bottom-up and top-down approaches [18,64,73,91,160]. Badarnah and Kadri [21] and Garcia-Holguera et al. [67] indicated that the first approach (bottom-up) worked as induction or indirect approach [68] 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 [192]. Vincent [175] and Zari [192] 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 [68] or a problem-based direct approach [172] where the approach is based on design problems and human needs to find answers in other organisms or ecosystems with similar problems [141,25]. El Ahmar [55] 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

---

**Fig. 1.** Biomimicry applications in different areas and their development stage [124].

Available, obtaining a successful design is very challenging in architecture [193].

Badarnah and Kadri [21] and Lepora et al. [111] 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 perspective restricts delivery of clear strategies and mechanisms from

**Fig. 2.** Two types of approaches conducted in biomimicry research [79].
Table 1

<table>
<thead>
<tr>
<th>Problems Applying Biomimetic Strategy Based on Problem-Based and Solution-Based Approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomimetic 3.8</td>
</tr>
<tr>
<td>Steps</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Problem Definition</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Exploration and Investigation</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Solution Development</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Technological Domain</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

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. [148] 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 [171]. Zari and Storey [194] stated that to design within biomimicry, the ecosystem should be considered to design a sustainable system. Zari and Storey [194] address six principles of how ecosystems operate that could be translated to any system such as building skins:

1. **Dependent on contemporary sunlight**: Use renewable and contemporary energy from the sun based on spatial and time mechanism.
2. **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.
3. **Dependent on local conditions and situations**: Materials should be sourced locally and adapt to a specific environment.
4. **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.
5. **Create conditions favourable to sustainable life**: Systems function as well as produce environmentally benign to improve the biosphere.
6. **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.

Gebeshuber et al. [69] and Gruber [73] adopted the categorisation by Nachtigall [134], 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 [17] 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 [191] 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 [193] 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.

Ecosystems can achieve the ability to be self-heal.
El Ahmar [56] identified five principles for effectiveness: adaption, materials systems, evolution, form and behaviour and emergence. In addition, El Ahmar [55] classified biomimicry levels in architecture into nine types: concept, process or behaviour, morphology, form, structure, skin, material, expression and symbolism. Badarannah and Kadri [21] 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.

5. Biomimetic methods and tools in design

Several types of biomimetic methods were developed since the last two decades [25]; 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 [21]. Cohen et al. [42] 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. [13] and Spain [159] 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 [73] 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 [34,176]. Hastrich [78] 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 [64] 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, Badarannah and Kadri, [21] 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 evaluation phase. Garcia-Holgaira et al. [67] 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. [121] 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).

Most of the presented methods above are theoretical especially in the field of architecture. However, Craig et al. [45], Sheta, [155] and Badarannah and Kadri [21] implemented them in design to validate the methodologies. Craig et al. [45] 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 Fig. 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 conviction. In addition, they suggest external shading system, flexible shells and thin films. Sheta [155] 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.

Moreover, Badarnah and Kadri [21] 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, (4) deriving imaginary pinnacles, (5) outlining the design concept, (6) generating a preliminary design concept and (7) estimating performance, as shown in Fig. 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.

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 [100]. 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 [80].

Many studies in biology have described the adaptation process in internal organisation of natural systems by understanding the function of organisms in ecosystems [29]. Hensel and Menges [82] and El Ahnar [55] indicated that organisms use energy and materials for more than one function to maximise efficiency. Odum [136] 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 [81]. Moreover, natural systems have always utilised energy and materials to optimise the whole system rather than the individual components [95]. McDonough and Braungart [129] 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 [120] 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. [181] stated that biological systems are complex and respond and adapt to stresses and dynamic loadings. The form of responsibility 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 [55]. 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 [148]. Lopez et al. [121] 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 [194].

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 [40]. These systems based their corrective actions on sensors that function specifically to deliver information for dynamic environments. Câmara et al. [37] 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 [150,39].

The limitation of applying adaptation depends mainly on the accuracy of analytical models that are used for decision making. Câmara et al. [37] 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

<table>
<thead>
<tr>
<th>Operational field</th>
<th>Invention principle</th>
<th>Source matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TRIZ</td>
</tr>
<tr>
<td>Substance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Information</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Diagrams of the design of roofing system based on BioTRIZ [45].

\[ T_{\text{sun}}, T_{\text{sky}}, T_{\text{amb}} \text{ Ambient temperature, Sky temperature, Solar temperature} \]
crucial in adopting these systems. In addition, Cámara et al. [37] 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.

7.1. Adaptive functional surfaces

Han et al. [76] 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 [117]. 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. [76] 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 Fig. 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 [165,198]. Surfaces for superhydrophobicity are special surfaces that hardly get wet and distinguished by static contact angles with water ($\theta_w$) above 150°, such as those of water strider and Parnassius butterfly wing [65,188]. 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 [32]. 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, superoleophobicity in air, and superoleophobicity in water, such as those of the carp and shark skin [117,48]. 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 [66]. 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 [38]. 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 [142]. Optically functional surfaces 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 [190,76]. Different types of insects and animals contribute to optical novelty in

---

**Fig. 4.** Exploration model and design path matrix for BioGen method to design an adaptive wall system [21].
design, such as the *Trogonoptera brookiana* butterfly, moth eye, sea mouse, peacock feather, male beetles *Chlorophila obscuripennis* (Coleoptera), *Papilio ulysses* butterfly and paradise whiptail [33,90].

### 7.2. 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 [121]. 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 [145,53]. 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 [153]. Some plants also possess response features like tropisms or nasties, which allow them to move depending on the direction or position of external stimuli (Fig. 6).

Schleicher et al. [153] have introduced three types on the basis of plant structure and properties, namely, *Strelitzia reginae*, *Aldrovanda Vesiculosa* (Waterwheel plant) and Venus Flytrap. *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 [185]. *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 [89]. *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. [121] 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 [59]; (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

### Table 3

Most common types of materials inspired from the nature.

#### Animals (Functional surfaces)

<table>
<thead>
<tr>
<th>Features</th>
<th>Animals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Surfaces for anti-wear</td>
<td>Dung beetle, ground beetle earthworm and mole cricket seashells and whelks, desert lizards and scorpions</td>
</tr>
<tr>
<td>2. Surfaces for super hydrophobicity</td>
<td>Water strider and <em>Parnassius</em> butterfly wing</td>
</tr>
<tr>
<td>3. Surfaces acting as smart adhesives</td>
<td>Geckos, soil-burrowing animals</td>
</tr>
<tr>
<td>4. Surfaces for drag reduction</td>
<td>Carp and shark</td>
</tr>
<tr>
<td>5. Surfaces for anti-fogging</td>
<td>Culex pipiens mosquito</td>
</tr>
<tr>
<td>6. Surfaces for noise reduction</td>
<td>Owls</td>
</tr>
<tr>
<td>7. Surfaces for water capture</td>
<td>Stenocara beetle</td>
</tr>
<tr>
<td>8. Surfaces for Optical function</td>
<td>Moth eye, <em>Trogonoptera Brookiana</em> and <em>Papilio ulysses</em>, <em>Sea mouse</em>, Peacock feather, male beetles (Coleoptera), and Paradise whiptail</td>
</tr>
</tbody>
</table>

#### Plants (Dynamic Movements)

<table>
<thead>
<tr>
<th>Features</th>
<th>Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Elastic movement</td>
<td><em>Strelitzia reginae</em> (bird of paradise flower)</td>
</tr>
<tr>
<td>2. Reversible snapping motion</td>
<td><em>Aldrovanda Vesiculosa</em> (Waterwheel plant) and Venus Flytrap</td>
</tr>
<tr>
<td>3. Unidirectional changes at the periphery</td>
<td><em>Flower of Lilium Casa Blanca</em> (Liliaceae)</td>
</tr>
<tr>
<td>4. Smart opening-closing system</td>
<td><em>Seeds of many Mesembryanthemums</em> and leaves of <em>Rhododendron</em></td>
</tr>
<tr>
<td>5. Touch and vibration sensitivity, folds inward as a reaction to contact</td>
<td><em>Mimosa pudica</em> (Sensitive plant) and Leaves of <em>Mimosa pudica</em></td>
</tr>
<tr>
<td>6. Oriented and folded based on temperature sensitivity</td>
<td><em>Leucaena leucocephala</em> (White leadtree) and <em>Maranta Leuconeura</em> (Prayer Leaf)</td>
</tr>
<tr>
<td>7. Change temperature levels passively.</td>
<td><em>Salvia officinalis</em> (Sage) and <em>Kalanchoe Pumila</em> (Dwarf purple kalanchoe)</td>
</tr>
<tr>
<td>8. Water-use efficiency</td>
<td><em>Echeveria Glauca</em> is an example of a CAM plant</td>
</tr>
<tr>
<td>9. Reflect sunlight from hairy surfaces.</td>
<td><em>Hairy leaves of Gynandriris Setifolia</em></td>
</tr>
</tbody>
</table>
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 [177] as shown in Table 3 and listed below:

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 [124], 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 [124]. 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 [197,72]. Meanwhile, physical stimuli can range anywhere from heat to light and water content [2]. The second cluster are for materials with surface modifications (e.g., drag-reductive, repellent and anti-reflective properties) typical of novel designs [186]. 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 [75]. 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 [12,54], 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 [103]. 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 [88]. Mimicking provides insights into the movement principles inspired by muscular and skeletal systems [60]. Lurie-Luke [124] 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). Generally, these classifications can help improve design approaches and innovate building skins [173].

9. Adaptive building skins

9.1. Systems and materials for adaptive building skins

Generally, building skins are a complex system that requires the control of many aspects, such as heat, light, humidity and ventilation, among others. Applying adaptivity in building skins requires various elements of the building system, such as sensors, actuators and command wires to be efficiently correlated with the approach of nature such as metabolism and morphology. [183]. Nonetheless, Addington and Schodek [1], Dewidar et al. [51] and Barozzi et al. [24] have reported that uncertainties still abound in terms of roles, responsibilities and professional accountability in contemporary architecture. Accordingly, Fig. 7 summarises the definitions of the most common terms related to the field.

The terms smart, responsive and adaptive concepts have been used loosely and interchangeably, which confuse many professionals [24,51]. 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 [154,35], Kilicote et al. [101] 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 [36].

Second, responsive building skin is a term frequently interchanged with ‘adaptive’ building skin. Beesley et al. [26] 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 [43]. Kretzer [104] 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 [77,51].

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 [51]. 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 [84] 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 [1] 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 [57] 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 memory alloys respond to temperature by changing shape without analysing signals, while fibre optics act as sensors but not as actuators or transducers [93].

(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 [1] 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., thermolectric, electrostrictive, photoluminescent, piezoelectric and photovoltaic materials).
9.2. Implementing adaptivity in building skins

Plants offer 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 [102] 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 [124] presented a variety of plant-type movement applications and innovations in response to environmental changes (Fig. 8). Schleicher et al. [153] also introduced a visual map to apply bio-inspired motion principles into technical kinetic structures (Fig. 9).

To implement adaptivity in building skins, it should be aligned with physiological evolution, also referred to as the relation of plants to climate [122]. 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 [31,70].

Lopez et al. [122] adopted the plant stomata concept in botany as inspiration for an adaptive wall system following dynamic mechanisms and static strategies, as shown in Fig. 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) [177]. 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 [123]. 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. [122,123] have identified the functions of adaptive architectural envelopes as follows:

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

Designing adaptive building skins can be developed to meet adaptivity principles based on two approaches, as shown in Fig. 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 skins

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 [44]. 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 [61]. 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 they must be stable enough in terms of configuration to utilise their implementation in adaptive models.

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. [123] introduced a model for adaptive walls using adaptive materials based on dynamic mechanisms and static strategies, and classified the materials in to four areas: temperature reactive materials, light reactive materials, humidity reactive materials and carbon dioxide reactive materials (Fig. 11). The study reviewed and updated the literature based on the classifications below.

9.3.1. 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 [162], as shown in Fig. 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 [123]. (3) Shape memory alloy is divided into thermo-responsive and magneto-responsive approach [163], where both mechanisms involve reversible martensitic transformation below transition temperature (Tₜ), and in effect, conserving shape memory. However, after reheating the material above transition temperatures, the original shape is recovered [110,87]. (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 [71]. (5) A phase-change material is divided into four types: organic, inorganic, eutectics and hygroscopic materials [3], all of which have the ability to control thermal–mass behaviour and allow light reflection with absorption [96].

9.3.2. 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 [97]. (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 [92]. (3) Photochromic dyes allows a reversible change of colour upon exposure to ultraviolet light in the range of 300–360 nanometres. A full change of colour can be obtained within 20–60 s 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 [187].

9.3.3. 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 [130]. 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. [149] specified a few types of wood, such as beech (Fagus sylvatica), European maple (Acer pseudoplatanus), and cut veneer (German: Schnittfurnier), as shown in Fig. 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 [46].

9.3.4. 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 [116,125], 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 [152]. 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.
conditions (e.g., plants). Smart materials operate in different scales, such as sensors and actuators with separate systems. Sensors analyze variations of external stimuli and transfer information to actuators [166]. Meanwhile, actuators provide the structure with a change in properties based on a range of external conditions (Table 4).

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 features based on a range of external conditions (Table 4).

Dewidar et al. [51] presented a theoretical model for an adaptive wall system that can mimic nature called the Self-Active Bioclimatic Strategy (SABS), as shown in Fig. 13. SABS uses algae bio-reactor panels with a kinetic responsive façade system to develop self-sensing properties based on a range of external conditions. The walls of the system generate two types of energies, namely, microalgae–cultivated energy from bio-reactor panels by (i.e., utilises 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. In fact, [8] has introduced the world’s first bio-reactive façade that generates renewable energy from algal biomass and solar thermal heat, however, SABS is limited, and it represents only a theoretical model without any validation of application.

Badarnah and Kadri [21] 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 (Fig. 14). The system was developed based on an innovative design method through several processes, including challenges, process, flow, adaptation, 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 concept on semitubular 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.

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

<table>
<thead>
<tr>
<th>Smart Materials (Source of activation is conventional energy)</th>
<th>Stimulus</th>
<th>Projects and References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Glass fiber reinforced polymers (GFRP)</td>
<td>Mechanical force</td>
<td>Ocean Pavilion [158]</td>
</tr>
<tr>
<td>2. Fiberglass-reinforced plastic</td>
<td>External mechanical forces</td>
<td>Flectofin [102]</td>
</tr>
<tr>
<td>3. Shape Memory Alloy (SMA) actuators</td>
<td>Heat source provided through electrical current</td>
<td>Solar Kinetic [144]</td>
</tr>
<tr>
<td>4. Elastic Polymer Material with Shape Memory Alloy (SMA) actuators</td>
<td>Heat source provided through electrical current</td>
<td>Blind [98]</td>
</tr>
<tr>
<td>5. Shape memory alloy wires to open and close the facade panels</td>
<td>Heat source provided through electrical current</td>
<td>Air flow(ers) [114]</td>
</tr>
<tr>
<td>6. Shape memory alloys and more recent shape memory polymers</td>
<td>Electricity</td>
<td>Homeostatic [49]</td>
</tr>
<tr>
<td>7. Silicone surface embedded with Dynalloy Flexinol wires</td>
<td>Heat source provided through electrical current</td>
<td>Living glass [164]</td>
</tr>
<tr>
<td>8. Shape morphing smart materials (Shape Memory Alloys and Shape Memory Polymer)</td>
<td>Heat source provided through electrical current</td>
<td>Sun shading [115]</td>
</tr>
<tr>
<td>9. Thermoplastic resin matrix, reinforced by glass fiber strands with Shape Memory Alloys</td>
<td>Heat source provided by solar radiation</td>
<td>Piraeous Tower [52]</td>
</tr>
<tr>
<td>10. Polypropylene sheets</td>
<td>Mechanical Force</td>
<td>Curved-line folding [174]</td>
</tr>
<tr>
<td>11. Combination of custom optics and phase change material</td>
<td>Heat source provided by solar radiation</td>
<td>Shape Variable Mashrahiya [94]</td>
</tr>
<tr>
<td>12. Cardboard, glass fibre reinforced polymers (GFRP) and poly(methyl methacrylate), silicon rubber and thermoplastic resin with Shape Memory Alloys</td>
<td>Mechanical Force and Heat source provided through electrical current</td>
<td>Shape morphing solar shadings [61]</td>
</tr>
<tr>
<td>13. Electro-active polymer (EAP)</td>
<td>Electricity</td>
<td>Shapeshift [305]</td>
</tr>
</tbody>
</table>

### Adaptive Materials (Source of activation is environment)

<table>
<thead>
<tr>
<th>Adaptive Materials</th>
<th>Stimulus</th>
<th>Projects and References</th>
</tr>
</thead>
<tbody>
<tr>
<td>14. Thermo-Bimetal</td>
<td>Temperature Reactive</td>
<td>Sung [162]</td>
</tr>
<tr>
<td>15. Heat sensitive plastics</td>
<td>Temperature Reactive</td>
<td>Lopez et al. [123]</td>
</tr>
<tr>
<td>16. Shape memory alloys</td>
<td>Temperature Reactive</td>
<td>Sun et al. [163]</td>
</tr>
<tr>
<td>17. Thermochromic polymers</td>
<td>Temperature Reactive</td>
<td>Granqvist [71]</td>
</tr>
<tr>
<td>18. Phase Change Material (PCM)</td>
<td>Temperature Reactive</td>
<td>Kenisarin and Mahkamov [96]</td>
</tr>
<tr>
<td>19. Phosphorescence pigments</td>
<td>Light Reactive</td>
<td>Khoj et al. [39]</td>
</tr>
<tr>
<td>20. Light Responsive Polymers</td>
<td>Light Reactive</td>
<td>Joschum and Theato [92]</td>
</tr>
<tr>
<td>21. Photochromic dyes</td>
<td>Light Reactive</td>
<td>Wu et al. [187]</td>
</tr>
<tr>
<td>22. Wood: beech (Fagus sylvatica), European maple (Acer pseudoplatanus), and cut veneer</td>
<td>Humidity Reactive</td>
<td>Menges and Reichert [130]; Reichert et al. [149]</td>
</tr>
<tr>
<td>23. Hydrgel</td>
<td>Humidity Reactive</td>
<td>Cui et al. [46]</td>
</tr>
<tr>
<td>24. Carbon dioxide responsive polymers</td>
<td>Carbon Dioxide Reactive</td>
<td>Lin and Theato [116]</td>
</tr>
<tr>
<td>25. Carbon dioxide polymers for CO2 capture</td>
<td>Carbon Dioxide Reactive</td>
<td>Manoranjan et al. [125]</td>
</tr>
<tr>
<td>26. Titanium dioxide</td>
<td>Carbon Dioxide Reactive</td>
<td>Schattling et al. [152]</td>
</tr>
</tbody>
</table>
**Fig. 13.** Integrated approach of Self-Active Bioclimatic Strategy [49].

**Fig. 14.** Biomimetic wall to collect water from fog [21].
### Table 5
Summary of phases to obtain knowledge on how to design an adaptive building skins.

<table>
<thead>
<tr>
<th>Steps</th>
<th>Phases</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Biomimetic levels</td>
<td>(1) Form (organism), (2) Process (behavior), (3) Ecosystem</td>
</tr>
<tr>
<td>2</td>
<td>Biomimetic Approaches</td>
<td>Bottom-up and Top-down</td>
</tr>
<tr>
<td>3</td>
<td>Biomimetic Classification</td>
<td>Concept, Process or Behavior, Morphology, Form, Structure, Skin, Material, Expression, and Symbolism.</td>
</tr>
<tr>
<td>5</td>
<td>Mechanisms of Adaptation</td>
<td>Nature: (1) dependent on contemporary sunlight, (2) optimize the system rather than its components, (3) dependent on local conditions and situations, (4) diverse in components, relationships, and information, (5) create conditions favorable to sustained life, (6) evolve at different levels and at different rates, (7) self-organization, (8) creates a level of redundancy.</td>
</tr>
<tr>
<td>6</td>
<td>Adaptive materials in nature</td>
<td>Adaptive Functional Surfaces: (1) surfaces for anti-wear, (2) surfaces for super hydrophobicity, (3) surfaces acting as smart adhesives, (4) surfaces for drag reduction, (5) surfaces for anti-fogging, (6) surfaces for noise reduction, (7) surfaces for water capture and (8) surfaces for optical function.</td>
</tr>
<tr>
<td>7</td>
<td>Biomaterials development</td>
<td>Adaptive Dynamic Movements: (1) reversible snapping motion, (2) unidirectional changes at the periphery, (3) smart opening-closing system, (4) touch and vibration sensitivity, folds inward as a reaction to contact, (5) oriented and folded based on temperature sensitivity, (6) change temperature levels passively, (7) water-use efficiency and (8) reflect sunlight from hairy leaves.</td>
</tr>
<tr>
<td>8</td>
<td>Adaptive behavior in building skin</td>
<td>(1) Temperature Reactive, (2) Light Reactive, (3) Humidity Reactive and (4) Carbon Dioxide Reactive</td>
</tr>
<tr>
<td>9</td>
<td>Adaptive materials in architecture</td>
<td>Dynamic mechanism: sliding, folding, creasing, expanding, rolling, hinging, fanning, inflating, rotating or curling.</td>
</tr>
<tr>
<td>10</td>
<td>Adaptive Systems</td>
<td>Static strategies: morphological features as density, pattern or geometrical strategies and change in materials properties as reflection, absorption or change energy from form to another.</td>
</tr>
</tbody>
</table>

### 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, especially those systems that deal with function and process. 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

---

**1487**
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 an adaption 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 summarised (Table 5).

11. 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.

Acknowledgements

The authors would like to thank the Ministry of Higher Education (MOHE) in Malaysia and the University of Malaya for providing financial support and facility for this research through Fundamental Research Grant Scheme (FRGS) (FP063-2016).

References

[44] Craig S, Harrison D, Crapps A. Two new environmental building technologies, one new design method: indoor transparent insulation, biodegradable concrete composite and BioTRIZ. In: Proceedings of the conference for engineering...


