Review Article: Biomimetic in Lightweight Structures: Solution for Sustainable Design

Touchaphong Srisuwan
Faculty of Architecture and Planning, Thammasat University, Pathumthani, 12121 Thailand.

e-mail: Hilary_Jackies@hotmail.com
Received 6 Jul 2019; Revised 9 Oct 2019; Accepted 7 Dec 2019
Print-ISSN: 2228-9135, Electronic-ISSN: 2258-9194, doi: 10.14456/built.2019.8

Abstract

Most of structures developed by human get inspiration from nature. Designers have often taken inspiration from nature not only for forms and aesthetics but also taken solutions to solve the design problems, called 'biomimetic approach', which could be either problem-based (from design to nature), or solution-based (from nature to design). Biomimetic relates closely with lightweight design because both of them based on natural principles: saving energy and recycling waste. The lightweight structure, in term of a material-efficient, is considered as an energy-saving and cost-effective design because the materials strengths are optimally used, then no resources are waste. The main aim of this article is to review the applications of biomimetic approaches in architecture and lightweight structure as a potential solution to sustainable design. Several case studies present various levels of applications and show how biomimetic inspiration can contribute to achieve more sustainable building design.

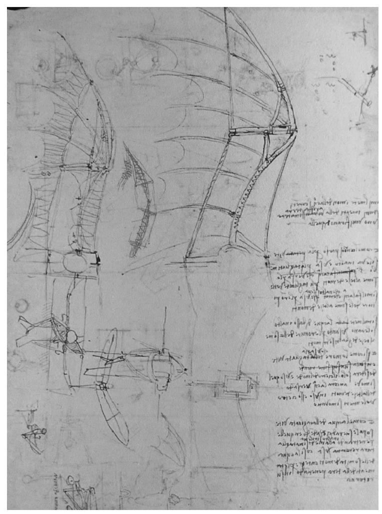
Keywords: biomimetic, bionic,sustainable, lightweight structures

1. Introduction

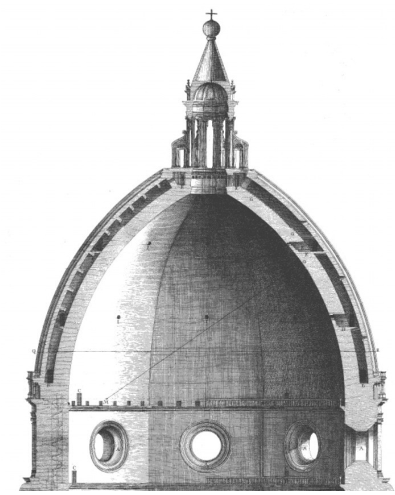
Over 3.8 billion years of evolution, plants, animals and microorganism have learned from nature to survive. During this long period of natural creation, nature creates things by two major principles: high efficiency based on minimum consumption of energy and recycling waste (Arbabzadeh, 2017). Therefore, imitating nature's form and processes leads to maximize resource efficiency and minimize the negative impact on the environmental.

The word "biomimetic ", introduced by Otto Schmitt in 1969, derives from the Greek roots bios – life and mimesis – to imitate. Its meaning is equivalent to the German 'Bionik' which are defined as activities taking information from the field of biology to technology (Gruber, 2011). It is also sometimes referred as 'biomimicry' and considered one of the most important method that approach to sustainable design solutions (Mohamed, 2018). Throughout history, human was inspired by nature to develop in science, technology and art. An early example of biomimetic was in 1482 when Leonardo da Vinci was inspired by observation of the anatomy and flying of birds and invented a flying machine (Figure 1a). This invention idea helped the Wright's brother to develop the first prototype of airplane in 1948. Another example is the dome of Florence Cathedral designed by Fillippo Brunelleschi in 1436. He created the double-shell, self supporting dome base on the studied of eggshells strength (Figure 1b). Since the late 19th century, many of architects and engineers often use biomimetics to solve the design problems. Antoni Gaudi, Spanish architect, used the forces of nature on an organism to solve the structural problems and designed the masterpiece La Sagrada Familia. Frei Otto and Heinz Isler have found a simple way to make use of the phenomenon of catenaries by using hanging models for form-finding. Later, Frei Otto combined his engineering practice through research and developed many different methods using principles of the self-organization of materials into lightweight structures.

Nowadays, there are several studies about application of using biomimetic principals, many of them reveal that mimics nature and integrates it into building design can significantly minimize a building's energy demand. Therefore, the approach of biomimetic in architecture is another way of finding design solutions by understanding and imitating the sources from nature which is considered to be a new solution to sustainable building design.



(a)



(b)

Figure 1.
(a) Drawings of Flying machine
(Source: Vinci, 1485)
(b) Double-shell dome
(Source: Brunelleschi, 1418)

2. Biomimetic and Biomorphism

It is important to make distinction between 'biomimetic' and 'biomorphism'. Biomorphic architecture uses nature as inspiration for aesthetic components to built form whereas biomimetic architecture uses nature as a model, measure and mentor, as explained by Janine M. Benyus (Benyus, 1997), to solve problems in architecture.

Many of modern architect's frequently used 'biomorphism' as architectural design approach in order to create the unconventional forms. Some examples are TWA Terminal in Kenedy airport, designed by Eero Saarinen, which imitates the figure of a flying bird (Figure 2a) and biomorphic branching columns in La Sagrada Familia, designed by Antoni Gaudi, which represents the complex shape of trees (Figure 2b).

(a) (b)

Figure 2.
(a) Eero Saarinen's TWA Terminal
(Source: Littleny, 2015)
(b) Branching Columns in La Sagrada Familia
(Source: Peacock, 2013)

(a) (b)

Figure 3.
(a) Bionic Car Inspired by Boxfish
(Source: Bartol 2008)
(b) Sto's Lotusan paint inspired by lotus effect
(Source: Baumeister, 2007)

3. Approaches of Biomimetic in Architecture

There are two different approaches in biomimetic development: from design to nature (problem-based or top-down approach) and from nature to design (solution-based or bottom-up approach). For the design to nature method, a design problem is identified and looking for solution from nature. An example of top-down approach is DaimlerChrysler's Bionic car which the boxfish form was translated into an aerodynamic car (Figure 3a). The mimicking increase efficiency of material used and consume 20% less fuel compared to similar-sized models (Bartol, et al. 2008).

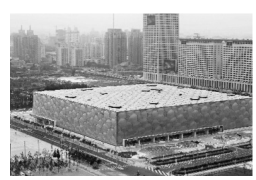
In contrast to the top-down approach (from design to nature), the bottom-up approach (from nature to design) is an observation of nature and developing further into design. StoColor Lotusan coating is an obvious example. A flat finish paint is duplicated with "Lotus-effect" idea. Consequently, the coating has self-cleaning property and highly resistant to dirt, mold and mildew. Moreover, it also offers excellent resistance to weather and UV rays (Figure 3b). Nevertheless, the bottom-up approach bases on the researches done by the biologist which often requires significantly longer times, perhaps several years, compared to the top-down approach.

Biomimetic can be applied into the architecture in three levels, organism, behavior and ecosystem, as categorized by Pedersen Zari (Zari, 2007). Within each of levels, a further five 'dimensions' of scale of mimicry exist: form, material, construction, process and function as shown in Table 1.

Table 1. Levels and dimensions of Biomimicry: a framework for understanding Biomimetic design (Zari, 2018).

5 mimic dimensions exist in building	Level of Biomimicry (Example – A building that mimics termites)		
	Organism Level	**Behavior Level**	**Ecosystem Level**
Form	The building looks like a termite.	The building look like it was made by a termite; e.g. a replica of a termite mound.	The building looks like an ecosystem (a termite would live in).
Material	The building is made from the same material as a termite	The building is made from materials that a termite builds with; e.g. using digested fine soil as the primary material.	The building is made from materials that (a termite) ecosystem is made of; e.g. uses common compounds, and water as the primary chemical medium.
Construction	The building is made in the same way as a termite; e.g. it goes through various growth cycles.	The building is made in the same way that a termite would build; e.g. piling earth in certain places at certain times.	The building is assembled in the same way as a (termite) ecosystem; e.g. principles of succession and increasing complexity overtime are used.
Process	The building works in the same way as an individual termite; e.g. it produces hydrogen efficiently through meta-genomics.	The building works in the same way as a termite mound would; e.g. by careful orientation, and natural ventilation, or it mimics how termites work together.	Building works in the same way as a (termite) ecosystem; e.g. it captures energy from the sun, stores water, etc.
Function	The building functions like a termite in a larger context; e.g. it recycles cellulose waste and creates soil.	The building functions in the same way that it would if made by termites; internal conditions are regulated to be optimal and thermally stable. It may also function in the same way that a termite mound dose in a larger context.	The building is able to function in the same way that a (termite) ecosystem would and forms part of a complex system by utilizing the relationships between processes; e.g. it is able to participate in the hydrological, carbon, nitrogen cycles, etc. in a similar way as an ecosystem.

Table 2. The applications of biomimetic in architecture: Organism level (Source: author)

Building			
	30 St. Mary Axe	Waterloo Int. Terminal	Water-cube
Inspiration	Venus Flower Basket Sponge	Pangolin	Water bubbles
Level of biomimicry	Organism	Organism	Organism
Design Application	Lattice-exoskeleton and hexagonal skin as main structure making the building more stiff and efficient than traditional high-rise.	Flexible-moving Irregular shaped glass panels response to the internal air pressure.	Cladding with ETFE cushions let more light transmission and better thermal insulation than glass.

Organism level is the approach that designer looks to the organism itself and applying its form or function to a building. Disadvantage of this level is mimicking without considering how it interacts and contributes to the context. The example buildings conducted under the organism level are London's 30 St. Mary Axe by Norman Foster, Waterloo International Terminal by Nicholas Grimshaw, and The National Aquatic Swimming Center (Water-cube) by PTW Architects (Table 2).

Table 3. The applications of biomimetic in architecture: Behavior level. (Source: author)

Building	East gate Center	Beijing National Stadium	Council House 2 (CH2)
Inspiration	Termite mound	Bird's nest	Tree's bark
Level of biomimicry	Behavior	Behavior	Behavior
Design Application	Mimicking the sophis-ticated ventilation system as a solution to keep building cool	ETFE-panels protect and provide sunlight filtration and façade openings allow for natural ventila-tion	The façades emulate a tree's bark which act as a protective layer in order to filter light and air

Behavior level is to mimicking the natural processes include the organism's behavior within its environment. The example buildings by behavior level are the Eastgate Center by Mick Pearce, Beijing National Stadium (Bird's Nest) by Herzog & de Meuron, and the Council House 2 (CH2) by Mick Pearce (Table 3).

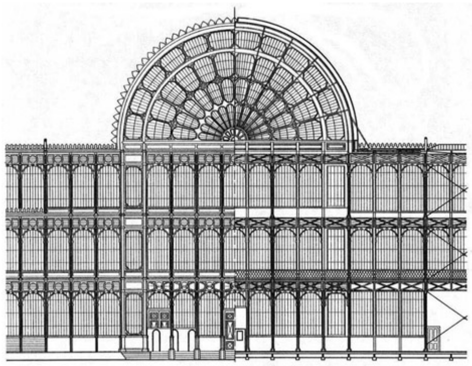
Ecosystem level is the mimicking of ecosystems as an integral part of biomimicry (Benyus, 1997). The ecosystem level can be used in conjunction with other levels of biomimicry (organism and behavior) which is an advantage to achieve more sustainable design. The remarkable examples of ecosystem based design are the Eden project by Nicholas Grimshaw and Sahara Forest Project Tunisia by Michael Pawlyn (Table 4).

Table 4. The applications of biomimetic in architecture: Ecosystem. (Source: author)

Building	 Eden project	 Sahara Forest Project
Inspiration	Soap bubbles	Namibian fog-basking beetle
Level of biomimicry	Ecosystem	Ecosystem
Design Application	Uses light three-layered cushions of ETFE as artificial enclosure in order to emulates a natural biome.	The greenhouse with eco-system is designed not only sustainable but offers a solution to restoring forests and creates renewable energy.

4. Nature-inspired in Lightweight Structures

Biomimetic ideas have been applied to lightweight structures since mid-18th century. Designers used nature-based solution in order to save material and mass of building. Consequently, several structural systems have been developed allow spans of larger distances than ever before. One example can be found at the Crystal Palace (Figure 4a), designed by James Paxton who was inspired by the leaves of giant water lily (Figure 4b). In his design, the radiating ribs are connected with flexible cross-ribs, the loads of elements can then be distributed onto rib structures. This nature-based solution is a very economical construction. There are basically four light structures derived from natural models: cable networks, pneumatics, shells and tensegrity systems.

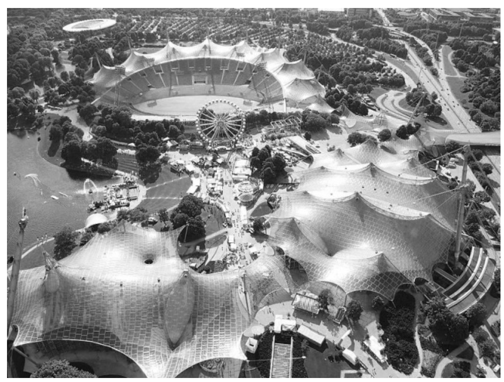


(a)

(b)

Figure 4.
(a) Crystal Palace, London by Joseph Paxton
(Source: Paxton's Crystal Palace, 1851)
(b) Giant water lily leaf
(Source: The reddit, 2019)

(a)



(b)

Figure 5.
(a) Spider's web in nature
(Source: Flickr, 2019)
(b) Olympiapark in Munich, Germany (Source: Wikimedia Commons, 2019)

4.1 Cable network structures

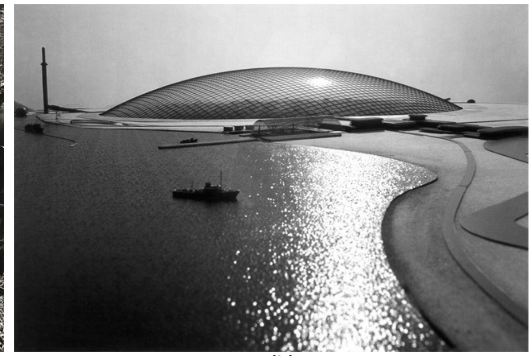
Cable-net structures has drawn from analogies of spider's web in nature (Figure 5a). The spider produces elastic-resistant webs with a minimum amount of material but extremely strong for its weight. Because of their efficiency as pure tensile structures, this made interest to Frei Otto, German architect and structural engineer, who later carried out several experiments in form-finding and designed the famous covering of the Olympia park for the 1972 Munich Olympic Games (Figure 5b). The roof shape was inspired by Alps mountain (Kim, & Park, 2018) and constructed by using cable-net structure. Since then, most cable-net roofs are largely variations of these first large-scale pioneering projects.

4.2 Pneumatics

Every living cell composes of liquid substance surrounded by a plasma membrane – the protoplasm which is the basic pneumatic structure found in nature. Like a soap bubble, its shape is stabilized by internal pressure resulting in a lot of variety of volume and shape. Other examples of such structures are found in soft fruit, egg-yolks and reptiles. The study of air bubbles is the fundamental of pneumatic building design. Many of works to investigate the potential of pneumatic structures beyond architecture was done since 1960s as proposed by Richard Buckminster Fuller, to cover Manhattan with pneumatic transparent dome (Figure 6a), whereas Frei Otto - collaborating with Kenzo Tange, Ted Happold and Ove Arup and partners – published a proposal for a covered arctic

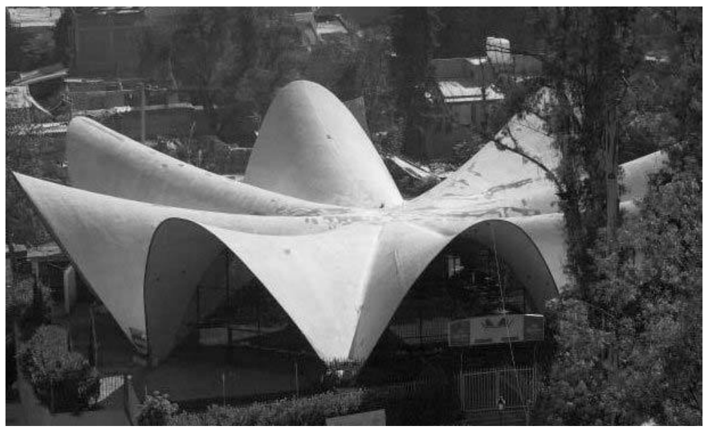
Figure 6.
(a) Pneumatic dome over Manhattan by Buckminster Fuller. (Source: Hatch, 1974)
(b) Arctic City by Frei Otto Kenzo Tange, Ted Happold and Ove Arup. (Source: Warmbronn, Bubner & Tang, 1970)

(a)

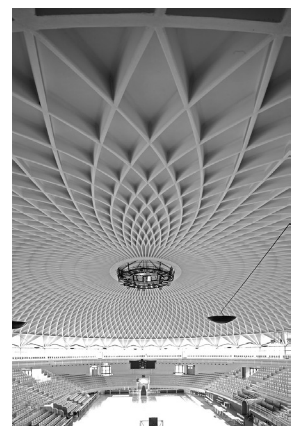


(b)

Figure 7.
(a) Restaurant in Xochimilco, Mexico by Felix Candela. (Source: Candela,1958)
(b) Palazzetto dello Sport, Rome by Pier Luigi Nervi. (Source: Nervi, 1960)



(a)



(b)

city for 45,000 people in the mining industry in 1971 (Figure 6b). Since then, air has become recognized as an important component of many structures. In recent years, pneumatic structure was developed by combination with traditional structural elements such as cables and struts to create the new structural concept called Tensairity, a modified airbeam with the same load bearing capacity as a steel beam (Luchsinger, et al. 2004).

4.3 Shells

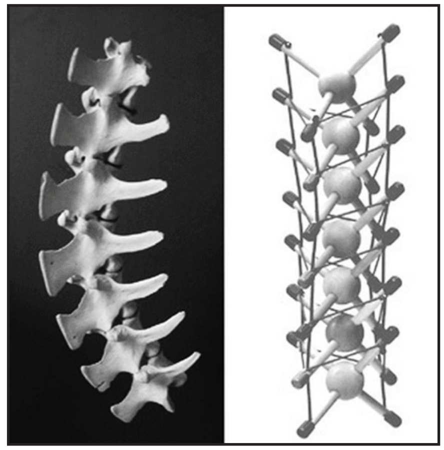
The most common and efficient structural elements in nature are shells. A shell is a structure defined by a curved surface, when the forces can flow in the direction of material it makes extremely thin construction possible. In 1952, Heinz Isler proposed the methods, based on physical modelling and experiment, to design thin concrete shell structure, while Felix Candela used the seashells as inspiration to design concrete shell for a restaurant in Xochimilco, Mexico, in 1958 (Figure 7a). Further development was made by Pier Luigi Nervi, one of the greatest structural engineer of the 20th century. He developed new shell structures, inspired from Roman and Renaissance dome architecture, by applying rib and vault system to improve the strength of the shell (Kim, & Park, 2018) as can be seen from his several design of airplane hangars. His most famous work is Palazzetto dello Sport (Figure 7b) where he used the leaves of the giant Amazon water lily as inspiration to design more efficient construction both in terms of time and overall cost.

4.4 Tensegrity Systems

Tensegrity is the balance produced between two forces – compression and tension as defined by Buckminster Fuller as "Islands of compression in an ocean of tensions" (Fuller, 1975). Tensegrity structures are self-stressing which can be found in living nature such as the system of muscles, bones and tendon of animal (Figure 8a) and the construction of vertebrates and the cytoskeleton of cells follow the principle of tensegrity system (Gruber, 2011). In contrast to manmade structures which are stabilized by gravitation compression, tensegrity stabilizes its shape by continuous tension with discontinuous compression in absence of gravity (Figure 8b). The great advantages of this kind of structures are their efficiency, lightweight and strong which make tensegrity structures an interesting solution for structural design of large spans.

5. Biomimetic Lightweight Architecture : Approach towards sustainable design

Ecological and sustainable issues are considered challenge and highly important in building design. The concept of biomimetic is in harmony with the concept of sustainability, which is about using very little energy and depends mainly on renewable energy resources, and described as an unique approach that increases the sustainability of human-designed built environment (Mazzoleni, 2013). The most common application of biomimetic into architecture is imitating the shapes from nature or biomorphism while another approach is mimicking biological processes, either problem-based (from design to nature), or solution-based (from nature to design). One of the most important indicator to evaluate the achievement of sustainable architecture through biomimetic design is energy efficiency.



(a)

(b)

Figure 8.
(a) Human spine model
(Source: Kommentare, 2016)
(b) Tensegrity sculpture: Needle tower, Washington D.C. by Kenneth Snelson
(Source: photo by author)

According to the study of Mohamed, which analyzed from three case studies, indicates that application of biomimetics into building design contribute the end product of the total energy saving (Table 5) (Mohamed, 2018). This was in consistent with the previous investigation of East gate Building in Harare, Zimbabwe, by Baird which concluded that the application of biomimetic principle into design resulted in reductions of energy use of between 17% and 52% compared to similar buildings in Harare (Baird, 2001).

Table 5. Energy efficiency results of buildings with biomimetic application (adapted from Mohamed, 2018) (Source: Mohamed, A.S.Y. 2018)

Project	The Water Cube	Council House 2	The Eastgate Centre
Biomimetic Approach	Design to Nature	Design to Nature	Design to Nature
Level of Biomimetic	Organism	Organism & Behavior	Behavior
Minimizing usage of HVAC	30%	20%	100%
Total energy saving	82%	82%	90%

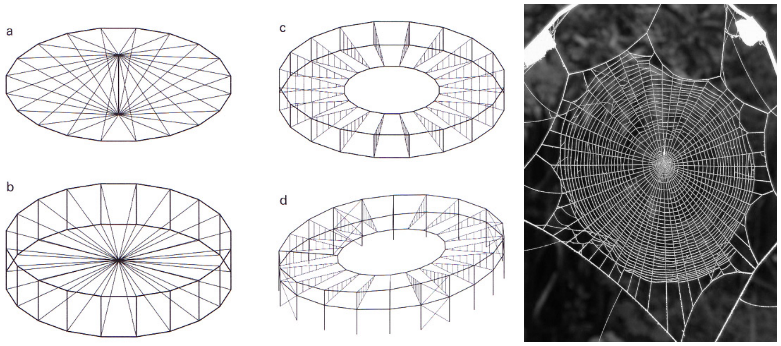


Figure 9. Radial cable networks inspired by spider webs (Source: Baukonstruktion, 2012)

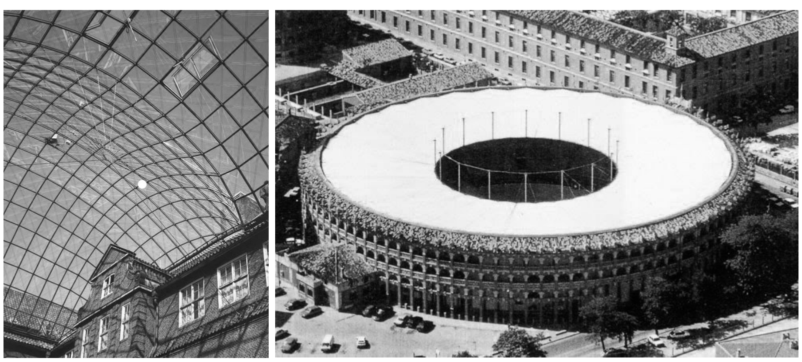


Figure 10. Spoked Wheel Structure on Old Building
(a) Hamburg City Historical Museum, Germany by Volkwin Marg and Jörg Schlaich
(Source: Marg & Schlaich, 1989)
(b) Arena Misericordia, Saragossa by Schlaich Bergermann & Partner
(Source: Schlaich Bergermann & Partner, 2010)

Research in biomimetics offers a broad knowledge towards new development of lightweight constructions (Pohl, 2006). In lightweight construction, designers can create appropriate and aesthetic expressions through efficient structures as can be seen from masterworks of Frei Otto, Renzo Piano, Herzog & de Meuron, etc. Furthermore, applications of biomimetic approaches through lightweight structures can enhance more sustainability and energy-saving potential of existing buildings. For instance, the use of analogical structure of radial cable network, or spoked wheel, from natural spider webs to cover old buildings (Figure 9).

The spoked wheel structure is an effective structural system for large span roofs and very efficient in load displacement which greatly can reduce the roof weight compared to other rigid structural system (Park, et al. 2016). Less material needed means less energy consumption in construction, this fulfils the requirements for sustainable development. Some impressive examples of spoke wheel applied into old buildings are the barrel vault, stiffened with spoked wheels, over Hamburg City Historical Museum and the spoked wheel roof of the Arena Misericordia (Figure 10a and 10b).

To conclude, through investigation of applying biomimetic technologies into architectural design, it is clear that nature has always been inspiration, sometimes also a part of, architectural design, the energy consumption level of building can be reduced by applying the biomimetic approach. Using nature as a role model to solve problems in lightweight architectural design is widely accepted that has more potential to achieve a new approach for energy efficient and sustainable design in the future.

References

Arbabzadeh, M., Etesam, I., & Mofidi, S.M. (2017). Biomimetic and Vernacular Building Design in Connection with Environment. *Eurasian J Biosci 11*, 37-44.

Asefi, M., & Afzali, Z. (2016). Environmentally Sustainable Architecture: Material-based Technological Design Approach. *Current World Environment, 11*(1), 28.

Baird, G. (2001). *The Architecture Expression of Environment Control Systems.* London and New York, Spon Press.

Bartol, I. K., Gordon, M. S., Webb, P., Weihs, D., & Gharib, M. (2008). Evidence of Self-correcting Spiral Flows in Swimming Boxfishes. *Bioinspiration & Biomimetics, 3* (1), 14001.

Benyus, J. (1997). *Biomimicry: Innovation Inspired by Nature*. New York. Harper Collins Publishers.

Dierks, K., & Wormuth, R. (2012). *Baukonstruktion.* Werner Verlag, München.

Fuller, R. B. (1975). *Synergetics: Explorations in the Geometry of Thinking*. MacMillan, New York.

Gruber, P. (2011). *Biomimetics in Architecture: Architecture of Life and Buildings*. Springer-Verlag/Wien, Germany.

Kim, J., & Park, K. (2018). The Design Characteristics of Nature-inspired Buildings. *Civil Engineering and Architecture, 6*(2), 88-107.

Lakhtakia, A., & Martin-Palma, R.J. (2013). *Engineered Biomimicry*, Elsevier Inc., Waltham, MA, USA.

Luchsinger, R.H., Pedretti, M, & Reinhard, A.J. (2004). Pressure Induced Stability: From Pneumatic Structures to Tensairity. *Journal of Bionic Engineering, 1*:141.

Mazzoleni, I. (2013). *Architecture follows Nature*. CRC Press, California, USA.

Mohamed, A. S. Y. (2018). Biometic Architecture: Creating a Passive Defense System in Building Skin to Solve Zero Carbon Construction Dilemma. *Environmental Quality (EQA), 29*, pp.1-28.

Park, K. G., Lee, D. W, & Kwun, T.J. (2016). *Mechanical Characteristics of Large Span Spoke Wheel System*. Proceedings of International Association for Spatial Structures (IASS), D1341.

Pohl, G. (2006). *Faszination Bionik: Die Intelligenz der Schöpfung*. In:K.G. Blüchel, F. Malik, SWR, & Das Erste, Verlag Bionik Media GmbH.

Schmitt, O. (1969). *Some Interesting and Useful Biomimetic Transforms*. In Proceedings of Third Int. Biophysics Congress.

Zari, M. P. (2007). *Biomimetic Approaches to Architectural Design for Increased Sustainability*. Auckland, New Zealand.

Zari, M. P. (2018). *Regenerative Urban Design and Ecosystem Biomimicry*. Routledge,New York.