Analogical Multiplicity in Bio-Inspired Design Process

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Abstract. This study explores the integration of biomimicry into design processes by providing a closer look at architectural practice and research and proposes a categorization of bio-inspired paradigms. Noticeable clusters within biomimetic approaches in architecture that share common principles are investigated throughout the research via a series of built examples that are considered to have biological phenomena as inspiration sources. Bio-inspired design processes are investigated via a categorization to detect the depth of analogical transfer and multiplicity. The paper sets out to present the issues concerning the analogical distance, multiplicity of approaches, and the decrease in the gap between nature and human-made phenomena.

Keywords: biomimicry, bio-inspired design, analogy, abstraction, architecture

1 Introduction

Architectural design processes, with its increasingly interdisciplinary character, follow distinct routes to benefit from nature. For a deeper understanding of biological inspirations in architecture, designers concentrate on physical features of natural phenomena including well-performing formal configurations, and structural and material systems found in nature to achieve unconventional forms that behave according to a type of intrinsic logic (Hensel, 2006; Hensel et al., 2006; Menges, 2013; Pawlyn, 2011). Biological analogies had been used in architecture for a long time with a relatively superficial understanding. In the wake of technological developments and findings, alongside the rising interest in more sustainable solutions, architects orient their attention towards biomimetics in the search for deeper connections (Collins, 1978).

The developing body of research lead to insights either as design methods or as design tools and the horizon is broadened in the level of abstraction for the use of natural precedents (Pohl & Nachtigall, 2015), and accordingly new solutions are developed for emerging design and engineering problems. Formative and informative processes of nature beget inspirational ideas for architectural design (Estévez, 2005; Frazer, 1995). Nature in bioinspired design is seen as a model for creative problem-solving. We can now observe cases in which complicated design problems can be solved through inspirations from nature at different levels involving visual, conceptual, and computational aspects (Arciszewski & Kicinger, 2005). Moreover, more tangible relationships can be established between nature and architecture by carrying essential building characteristics of nature to human-made ones (Koelman, 2004) as a result of profound biological analogies used by other scientific disciplines whose solutions are also beneficial for the creative design processes of architects and engineers (Helms et al., 2009; Schmidt, 2005).

This study explores the integration of biomimicry into design processes by providing a closer look at architectural practice and research, and proposes a categorization of bio-inspired paradigms. Noticeable clusters within biomimetic approaches in architecture that share common principles are investigated throughout the research via series of built examples that are considered to have biological phenomena as inspiration sources. Selective sampling of the built examples from architectural practice is used within the body of this exploratory research. The examples, selected on the basis of emerging bioinspired concepts, are presented through analytical categories including (1) transfer of physical properties of nature as form, structure, and material; (2) transfer of performative principles of natural entities that inspire building designs by their differentiated behaviors in accordance with the conditions; and (3) transfer of systematic principles extracted from nature. Each category is presented and analyzed with different biomimetic approaches by following the emerging cases in the literature. Analogical multiplicity and its effects on the knowledge transfer from nature to design are questioned following the analysis of the categories.

2 Background

The understanding of nature as model, measure, and mentor, together with design to biology and biology to design approaches are implemented in three different biomimetic levels and are classified according to the depth of biomimicry (Zari, 2007) as follow: (1) organism level, (2) behavior level, and (3) ecosystem level. The organism level refers to form-based biomimicry attempts that mimic a specified organism entirely or a portion of it. On behavior level, a specific type of behavior of an organism is under focus (Zari, 2019). Ecosystem level involves the mimicry of another ecosystem that functions successfully in terms of components and working principles, and it is the sustainable form of biomimicry that concentrates on the process strategies or the functions in the fauna and flora of a particular place (Marshall, 2009; Zari, 2012, 2019).

The precedents show us that visual clues extracted from nature are mostly effective on formal inspiration, and are leading to spatial or typological innovation, relational information for geometry and structural performance, and material innovation (Agkathidis, 2016). Beyond mere appearance, designers particularly focus on inherent construction qualities and the processes (Gruber, 2011). Prominent authors and practitioners working in the field of architecture concentrated their attention on natural structures with their material and mechanical properties (Knippers & Speck, 2012), building principles of nature with its techniques and changeability (Menges, 2013), geometrical allowances of materials to invent new formal relations that already exist in nature (Weinstock, 2006).

Regarding the studies on the cognitive processes involved in the bioinspired design, several categorizations have been introduced to explain the biological inspirations embedded (Bhasin & McAdams, 2018; Chakrabarti, 2014; Gero, 2012; Mak & Shu, 2004; Nagel et al., 2018; Qian & Gero, 1996). Gero's function-behavior-structure (FBS) formulation approaches the issue from a perspective that design influence is inherited from a primitive element that can be either a physical or a logical entity. A primitive element to be grouped with other primitive elements can form the structural element and behaves in some specific way to achieve a specific function (Gero, 2012; Qian & Gero, 1996). Mak & Shu's idea on form, behavior, and principles explains the hierarchical relationship between each stage of the pyramid; by moving upwards in the hierarchy of the pyramid, the upper level explains the lower level's reason for existence, and each level below explains how to achieve above one by moving downwards (Mak & Shu, 2004). Bhasin & McAdams (2018) append on Mak & Shu's arguments claiming the formation process works like a mechanism and structures are depending on the materiality and dividing it into two as "materials and structures" and "mechanisms and processes". Chakrabarti's SAPPhIRE model of causality explains how an entity using physical phenomena works to achieve its functions and change the state of itself and the surrounding (Chakrabarti, 2014). It is the hierarchical ordering of 'parts', 'physical phenomenon', 'state', 'physical effect', 'organ', 'input', 'action' according to the relationships that can be constructed in between them. The SAPPhIRE model is useful for analyzing different biological entities catalog them as stimuli for the bio-inspired design of new ideas.

Based on the above literature review we have synthesized a categorization consisting of three parts. The form is accepted as a preliminary element for researchers. In theoretical approaches, it is the initial element that is perceived and related firsthand (Chakrabarti, 2014; Mak & Shu, 2004; Qian & Gero, 1996). Since it is inevitable to detach form from the structure and its materiality (Knippers & Speck, 2012; Menges, 2012; Weinstock, 2006), our framework will cover them under the topic of 'inspirations from the physical properties of nature' under three sub-categories: (1) form, (2) structure, (3) material.

The second constituent of our categorization is covered as 'process' by Nagel et al. (2018), 'behavior' by Mak & Shu (2004), 'state change' by Chakrabarti (2014), and 'performance' by Agkathidis (2016), Hensel (2006), Knippers & Speck (2012), Menges (2012) and Weinstock (2006). Process and behavior are thought of as the two inseparable measures for the part analyzing 'the performative aspects of nature inspiring building designs.' The third constituent to analyze bio-inspired design approaches is given as system and function in Nagel et al. (2018), mentioned as function in FBS of Qian & Gero (1996), Mak & Shu (2004) tackle it as principles, and Chakrabarti (2014) called it as organ or attribute. The common meeting ground of all these researchers is the systematic understanding of nature which they are trying to deal with the relations in between the parts of a system observed in nature and attempts to apply in their design as a holistic approach (Chu, 2010; Deuschle et al., 2018; Frazer, 1995). By looking at the rich literature behind it, our research will name the last major constituent of its catalog as 'building design inspirations from the systematic principles of nature.'

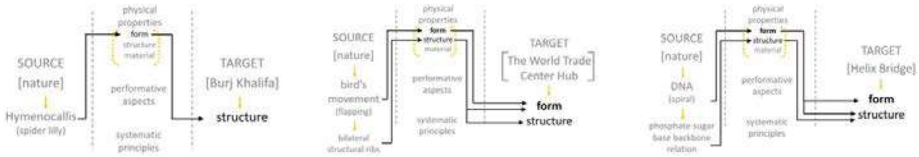
3 Bio-Inspired Design Approaches in Design Processes: A Review

A classification for architectural approaches concerning their formulation of bioinspired design is provided and analogical transfers in different stages of the conceptual design are traced via the study of the design process of key buildings. While doing that our research analyzed the prominent cases in literature focusing on the ones using text descriptions of biological phenomena together with the visual representations explaining the transfer via diagrams explaining the stages of the analogical transfer most clearly. Each category is presented with different biomimetic approaches and studied via a table set. As the bio-inspired design is based on cross-domain analogies by its definition (Goel et al., 2014), the research investigates analogical distances, analogical multiplicities, and their effects on the knowledge transfer from nature to design.

3.1 Inspirations from the Physical Properties of Nature

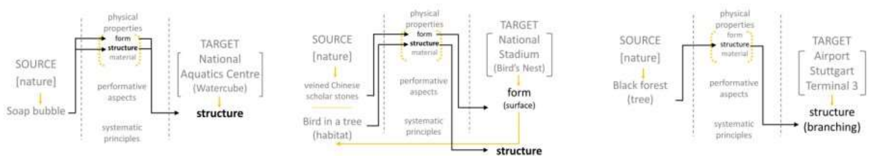
The physical properties of nature are used as a source of building design inspiration and classified into three, as the major design decisions that architects need to take into account; form, structure, and material (Estévez, 2005). We have analyzed these major chunks with examples to try to detect the similarities and differences between the analogical transfers from biology to design. The first chunk contains the buildings inspired by the forms in nature. The wide range of forms generated with minimum material and maximum performance, the formation process on how things are morphologically coming together to form an object, and their impacts on the performance of buildings are investigated through the analysis of Burj Khalifa, The World Trade Center Hub, and Helix Bridge. Burj Khalifa's design did not start with a search from the catalog of nature; however, the initial plan schema having a similar outline of the top view of a flower inspires the design team and enabled them a stylistic and structural inspiration from a real flower later (Smith, 2008). The form of Calatrava's World Trade Center Hub looking like a bird flapping its wings used biological analogies in two steps: first, the movement of a bird is transferred via the visual scene created by this movement and used as the form of the building, then the bilateral structural ribs through which the flapping effect is added to the form is achieved with two asymmetrically positioned wings (Stevens, 2016). Helix Bridge uses the shape of DNA chain as a design inspiration in the spiral form of the bridge both in micro and macro scales; the DNA helix is used as the design initiator with its form; however, the form contains also the information for the primary and secondary structural system based on the phosphate-sugar base backbone relation exist in DNA cells (Storer, 2015).

Table 1. Analogical transfer between natural phenomena and building/component design of Burj Khalifa, The World Trade Center Hub, and Helix Bridge.



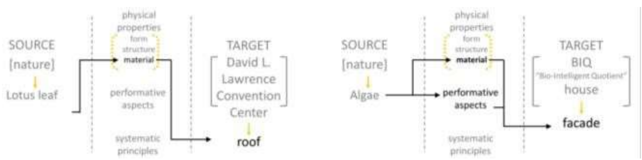
The second chunk of the physical properties concentrates on the buildings inspired by the structures of Nature which are fascinated by the complex hierarchical orders of buildings of nature constructed in multiple ways and evolving from their initial formations (Knippers & Speck, 2012). National Aquatics Centre in Beijing (The Watercube), Beijing National Stadium (The Bird's Nest), and Airport Stuttgart Terminal 3 are examined for the nonuniformity of their structures. National Aquatics Centre in Beijing – The Watercube's envelope structure is formulated by the team searching for natural equivalents addressing a similar problem. They found the solution from the physicists' works on the formation of soap bubbles with equally distributing loads and spanning distances with their inherent self-standing properties (Carfrae, 2006). Beijing National Stadium – The Bird's Nest's design is composed of two steps, Herzog & de Meuron's natural source of inspiration is the pattern of veins of the stone which is planned to be used as a surface pattern. However, the pattern reminds Ai Wei Wei of a similar one which also has three-dimensional and self-standing properties (Zhang, 2008). Airport Stuttgart Terminal 3 uses the tree-like support structures inspired from its neighboring Black Forest as if the crown of trees are carried like a roof and structural loads are transmitted through the branches and collected in the trunk (Ahmeti, 2007).

Table 2. Analogical transfer between natural phenomena and building/component design of the Watercube, The Bird's Nest, and Airport Stuttgart Terminal 3.



The third chunk covers an inseparable part of the form which is materiality. The way natural constructions use the materials contained within their body is considered as correspondences for achieving desired forms and structures with their intelligent, adaptive, and effective use of materials (Di Salvo, 2018; Menges, 2012), and sustainable and ecological solutions. Two built examples that use the materials that can transfer materialistic properties of natural precedents are David L. Lawrence Convention Center in Pittsburgh and BIQ house. The first one uses the Superhydrophobicity, which enables the Lotus plant to keep its outer surface of the leave dry and clean, to increase the sunlight gain by rinsing away the dirt (Ensikat et al., 2011), in its hydrophobic stainless-steel roof to reduce the cost of heating and cooling by controlling the solar heat gain and stabilizing the solar reflection yearlong by its always clean surface (Deuschle et al., 2018). The second one uses Photobioreactor algae in its façade system growing under specific heat and light conditions (Kim, 2013; Mora, 2014). Although analogical transfer from algae to a building component uses its material properties as design initiator; this material's performance is inseparable from it.

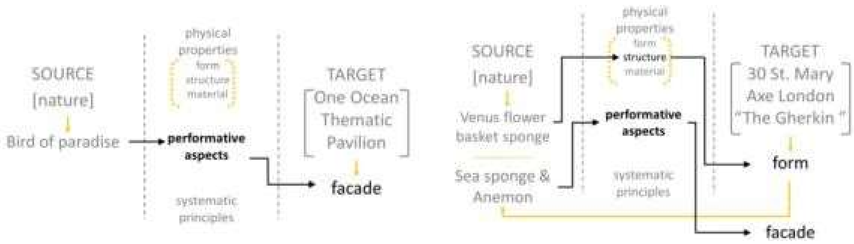
Table 3. Analogical transfer between natural phenomena and building/component design of David L. Lawrence Convention Center in Pittsburgh and BIQ house.



3.2 Performative aspects of Nature inspiring building designs

The behavioral characteristics of biological organisms are imitated mechanically in buildings systems to perform in the similar ways that natural phenomena did. These systems are intended to change their state against environmental factors like sunlight, heat, wind, rain and change their initial position according to predetermined (or tested and programmed) phases of the process. We looked at two built examples inspired from the performative aspects of the natural entities which are One Ocean Thematic Pavilion Expo 2012 and 30 St. Mary Axe: London, Swiss Re Tower – The Gherkin. One Ocean Thematic Pavilion's design inspiration comes from the kinematics found in the bird of paradise flower, an abstracted hingeless flapping device with a valvular pollination mechanism, Flectofin that is created by Knippers Helbig Advanced Engineering (Lienhard et al., 2011). The flectofin mechanism allows SOMA to achieve a modifiable and adjustable façade system to preserve interior luminosity and temperature. The design inspiration of The Gherkin comes from the Venus flower basket sponge whose exoskeleton glows like a glass lattice underwater. The tower's structure is composed of lattice arranged exoskeleton and arisen with its helical shape and diamond panelization is acquired for the enclosure. The design process of the Gherkin also includes two stepped analogical transfer from biology, the first step is used as a source of inspiration for the latter. After the form and structure are designed the breathing performance of sea sponges and anemones opening and closing the holes in their bodies for ventilation were used as a reference for the passive ventilation system achieved by the diamond-shaped glasses.

Table 4. Analogical transfer between natural phenomena and building/component design of One Ocean Thematic Pavilion and the Gherkin.



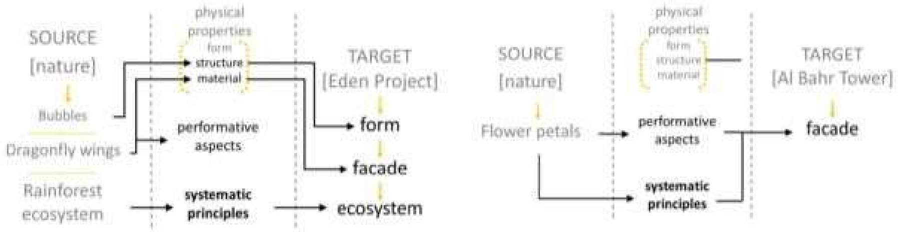
3.3 Building Design Inspirations from the Systematic Principles of Nature

The systematic understanding and representation of nature allow researchers and practitioners to join forces in the field of bio-inspired design. Researchers conduct their studies on representing natural mechanisms that are abstracted in the form of algorithms. In the design world, the algorithmic approach aims at encapsulating the relation between the shapes and their relationship between the environments. Virtual environment, as a novel form of representation, is seen as a non-physical world in which researchers can try to establish relations existing in nature as forms, structures, behaviors (Chu, 2010; Frazer, 1995).

Eden Project is one of those examples which uses the logic of nature at the ecosystem level by using multiple biological references belonging to different analogical categories operating together as a system. The initial design idea was to create a greenhouse where a vast of plants can be collected from diverse climates and live together. To achieve that bubble structures were used for their allowance to cover large span enclosures which can be self-standing, and to climatize the enclosure, ETFE panels were used for the covering by their lightness and allowance to the sunlight as in its biological analogous Dragonfly Wings (Architecture at Eden, 2016).

Al Bahr Tower uses a specific systematic principle derived from nature. Its reactive façade is using the adaptive principles of flower petals, folding and unfolding behavior in response to the sun, and reacting in the same way according to the heat gain (Cliento, 2012). The biological principle of the system was abstractly represented into design decisions as algorithmic inputs and simulated to achieve desired envelope conditions that work with the real loads of the structure.

Table 5. Analogical transfer between natural phenomena and building/component design of the Eden Project and Al Bahr Tower.

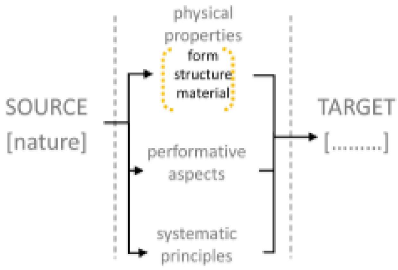


4 Discussion

The projects reviewed above were among the most striking cases from architectural practice either by opening a new path for later studies and constructions or by being the most advanced built examples. Using these prominent examples have allowed us to make a categorization of biomimetic approaches and understand analogical transfers used in different stages of design processes. The tables presented above demonstrate the benefits of making such categorization. First, the categorization shed light on the interaction inside and outside of the categories. Like nature, building forms are very much depending on the materials and specific structures. So, form, structure, and materiality are the three inseparable constituents of any construction, natural or human-made. Second, the categorization informs us about the order of precedence, which eases to understand the hierarchical and temporal relations occurring in between these categories (Table 2, 4).

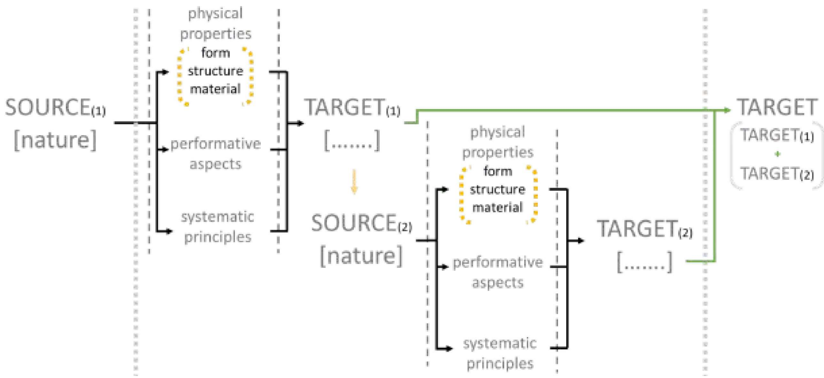
The hierarchical and temporal relations -illustrated in tables- demonstrate that the analogies constructed between natural entities and building design can use simple or compound analogies. Single stepped analogical transfer can use one or more design clues inspired by different aspects of a natural entity; however, these aspects are belonging to same thing (Table 6).

Table 6. Single-step analogical transfer between natural phenomena and building/component design.



Compound analogies are composed of multiple analogical transfers, constructing at least two analogies, or more referencing the previous one (Goel et al., 2014). Design clue or clues of a natural organism has the potential in leading to a design idea that can be reinterpreted and utilized to lead to further insights that may be considered through a different natural phenomenon (Table 7). It can be said that the depth of these analogies is deeper than the single-step analogies by looking at their level of abstraction. Moreover, including multiple and distant domain analogies can allow designers to make unexpected connections which can result in useful reinterpretations both in problem evolution and inception.

Table 7. Single-step analogical transfer between natural phenomena and building/component design.



5 Conclusion

The classification of architectural approaches concerning their formulation in bio-inspired design is examined within the body of this research. We proposed a categorization according to the initial starting point for design inspirations. The categories include inspirations from the physical properties of nature, performative aspects of the nature that inspires building performances, and inspirations from the systematic principles of nature. Rather than being a strict classification, the categorization allows for permeability, which makes it possible to evaluate biological analogies from a different perspective and understand the analogical complexity behind the design solutions.

References

Agkathidis, A. (2016). *Implementing Biomorphic Design*. 291–298.

Ahmeti, F. (2007). Efficiency of Lightweight Structural Forms: The Case of Treelike Structures - A comparative Structural Analysis. *Vienna University of Technology; Building Science & Technology*.

Architecture at Eden. (2016). The Eden Project. https://www.edenproject.com/mission/about-our-mission/architecture

Arciszewski, T., & Kicinger, R. (2005). Structural Design Inspired by Nature. In B. H. V. Topping (Ed.), *Innovation in Civil and Structural Engineering Computing* (Vol. 13, pp. 25–48). Saxe-Coburg Publications. https://doi.org/10.4203/csets.13.2

Benyus, J. M. (1998). *Biomimicry: Innovation Inspired by Nature*. Harper Collins Publishers.

Bhasin, D., & McAdams, D. A. (2018). The Characterization of Biological Organization, Abstraction, and Novelty in Biomimetic Design. *Designs*, *2*(4), 54. https://doi.org/10.3390/designs2040054

Carfrae, T. (2006, July 1). *Engineering the water cube*. ArchitectureAU. https://architectureau.com.au/articles/practice-23/

Chakrabarti, A. (2014). Supporting Analogical Transfer in Biologically Inspired Design. In A. K. Goel, D. A. McAdams, & R. B. Stone (Eds.), *Biologically Inspired Design* (pp. 201–220). Springer.

Chu, K. (2010). *TEDxBrooklyn—Karl Chu*.

https://www.youtube.com/watch?v=_5uDWFSeypM

Cliento, K. (2012, September 5). Al Bahar Towers Responsive Facade / Aedas. *ArchDaily*. https://www.archdaily.com/270592/al-bahar-towers-responsive-facadeaedas

Collins, P. (1978). The Biological Analogy. In *Changing Ideals in Modern Architecture 1750-1950* (pp. 149-158). Montreal: Mc Gill - Queens University Press.

Deuschle, F., Halliday, J., & McGuire, M. (2018). *Hydrophobic Stainless Steel Surfaces*. Facade Tectonics 2018 World Conference, Los Angeles.

Di Salvo, S. (2018). Advances in Research for Biomimetic Materials. *Advanced Materials Research*, *1149*, 28–40.

Ensikat, H. J., Ditsche-Kuru, P., Neinhuis, C., & Barthlott, W. (2011). Superhydrophobicity in perfection: The outstanding properties of the lotus leaf. *Beilstein Journal of Nanotechnology*, *2*, 152–161.

Estévez, A. T. (2005). *Biomorphic architecture*. SITES Books/ESARQ-UIC.

Frazer, J. (1995). An Evolutionary Architecture. *London: Architectural Association*.

Gero, J. S. (2012). *Artificial Intelligence in Design '00*. Springer Science & Business Media.

Goel, A. K., Vattam, S., Wiltgen, B., & Helms, M. (2014). Information-Processing Theories of Biologically Inspired Design. In A. K. Goel, D. A. McAdams, & R. B.

Stone (Eds.), *Biologically Inspired Design: Computational Methods and Tools* (pp. 127–152). Springer.

Gruber, P. (2011). *Biomimetics in Architecture—Architecture of Life and Buildings*. Springer.

Helms, M., Vattam, S. S., & Goel, A. K. (2009). Biologically inspired design: Process and products. *Design Studies*, *30*(5), 606–622.

Hensel, M. (2006). Computing self-organisation: Environmentally sensitive growth modelling. *Architectural Design*, *76*(2), 12–17.

Hensel, M., Menges, A., & Weinstock, M. (2006). Towards self-organisational and multiple-performance capacity in architecture. *Architectural Design*, *76*(2), 5–11.

Kim, K. (2013). *Beyond Green: Growing Algae Facade*. ARCC Conference.

Knippers, J., & Speck, T. (2012). Design and construction principles in nature and architecture. *Bioinspiration & Biomimetics*, *7*(1), 015002.

Koelman, O. (2004). Biomimetic Buildings: Understanding & Applying the Lessons of Nature. *Bioinspire*, *21*.

Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T., & Knippers, J. (2011). Flectofin: A hingeless flapping mechanism inspired by nature. *Bioinspiration & Biomimetics*, *6*(4), 045001.

Mak, T. W., & Shu, L. H. (2004). Abstraction of Biological Analogies for Design. *CIRP Annals*, *53*(1), 117–120.

Marshall, A. (2009). *Wild Design: Ecofriendly Innovations Inspired by Nature*. North Atlantic Books.

Menges, A. (2012). *Material Computation: Higher Integration in Morphogenetic Design*. Wiley.

Menges, A. (2013). Performative morphology in architecture: Integrative design research by the Institute for computational design. *SAJ - Serbian Architectural Journal*, *5*(2), 92–105.

Mora, V. (2014, September 3). SolarLeaf | Algae bio-reactive facade. *More Than Green*. http://www.morethangreen.es/en/solarleaf-solar-leaf-algae-bio-reactive-facade/

Nagel, J. K. S., Schmidt, L., & Born, W. (2018). Establishing Analogy Categories for BioInspired Design. *Designs*, *2*(4), 47.

Pawlyn, M. (2011). *Biomimicry in Architecture*. Riba Publishing.

Pohl, G., & Nachtigall, W. (2015). *Biomimetics for Architecture & Design: Nature - Analogies - Technology*. Springer International Publishing.

Qian, L., & Gero, J. (1996). Function-behavior-structure paths and their role in analogybased design. *Artificial Intelligence for Engineering, Design, Analysis and Manufacturing*, *10*, 289–312.

Schmidt, J. C. (2005). Bionik und Interdisziplinarität. In T. Rossmann & C. Tropea (Eds.), *Bionik: Aktuelle Forschungsergebnisse in Natur-, Ingenieur-und*

Geisteswissenschaft (pp. 219–245). Springer.

Smith, A. (2008). *Burj Dubai: Designing the World's Tallest*. CTBUH 2008 8th World Congress, Dubai.

Stevens, P. (2016). *WTC transportation hub by santiago calatrava opens in new york*. https://www.designboom.com/architecture/santiago-calatrava-world-trade-centerwtc-transportation-hub-oculus-new-york-03-22-2016/

Storer, R. (2015, July 14). *A stroll through the elegant, stainless steel double—Helix Helix Bridge, Singapore by Cox Architecture and Architects 61*. Double Stone Steel.

https://www.doublestonesteel.com/blog/design/a-stroll-through-the-elegantstainless-steel-double-helix-helix-bridge-singapore-by-cox-architecture-andarchitects-61/

Weinstock, M. (2006). Self-organisation and material constructions. *Architectural Design*, *76*(2), 34–41.

Zari, M. P. (2007). Biomimetic approaches to architectural design for increased sustainability. *Sustainable Building Conference (SB07), Auckland, New Zealand*.

Zari, M. P. (2012). Ecosystem services analysis for the design of regenerative built environments. *Building Research & Information*, *40*(1), 54–64.

Zari, M. P. (2019). *Regenerative Urban Design and Ecosystem Biomimicry*. Routledge.

Zhang, F. (2008, August 4). China's Olympic Crossroads: Bird's Nest Designer Ai Weiwei on Beijing's "Pretend Smile." *Rings Blog*. https://beijing2008.blogs.nytimes.com/2008/08/04/chinas-olympiccrossroadsbirds-nest-designer-ai-weiwei-on-beijings-pretend-smile/