



**HAL**  
open science

# From Bioinspiration to Biomimicry in Architecture: Opportunities and Challenges

Natasha Chayaamor-Heil

► **To cite this version:**

Natasha Chayaamor-Heil. From Bioinspiration to Biomimicry in Architecture: Opportunities and Challenges. Encyclopedia, 2023, 3 (1), pp.202-223. 10.3390/encyclopedia3010014 . hal-04029013

**HAL Id: hal-04029013**

**<https://hal.science/hal-04029013v1>**

Submitted on 14 Mar 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Entry

# From Bioinspiration to Biomimicry in Architecture: Opportunities and Challenges

Natasha Chayaamor-Heil <sup>1,2</sup> 

<sup>1</sup> UMR MAP MAACC 3495 CNRS/MC, 23-27 rue des Ardennes, 75019 Paris, France; natasha.heil@map.cnrs.fr; Tel.: +33-751227591

<sup>2</sup> National School of Architecture Paris La Villette, 23-27 rue des Ardennes, 75019 Paris, France

**Definition:** The term “bioinspiration” defines a creative approach based on the observation of biological principles and transfer to design. Biomimicry is the recent approach, which describes a large field of scientific and technical activities dealing with an interdisciplinary cooperation between biology and other fields with the goal of solving practical problems addressing innovation or sustainable development. Architecture has been influenced by many aspects of natural and social sciences, among these, biology is currently blending into design activities. Bioinspiration has evolved and shifted architectural practices towards numerous innovative approaches through different bioarchitectural movements from the past until the present. However, there is a blur of biomimicry within bioinspiration in architecture between the direct copy of mere natural forms and the true understanding of biological principles, which is the pivot of sustainable development. The main challenge remains in the gap between the profound knowledge of biology, its related scientific fields and the creative process of architectural design, including cross-disciplinary collaboration between architects and biologists. This entry presents main bioarchitectural movements and how it leads to today’s biomimicry. It proposes to define biomimicry methodologies and how this approach applies to architectural design contexts through the study of existing case studies. The opportunities, challenges and the future outlook of the field will also be discussed.

**Keywords:** architecture; biology; bioinspiration; biomimetics; biomimicry; interdisciplinarity; analogical design process; sustainability



**Citation:** Chayaamor-Heil, N. From Bioinspiration to Biomimicry in Architecture: Opportunities and Challenges. *Encyclopedia* **2023**, *3*, 202–223. <https://doi.org/10.3390/encyclopedia3010014>

Academic Editors: Krzysztof Kamil Żur, Raffaele Barretta, Ramesh Agarwal and Giuseppe Ruta

Received: 13 September 2022

Revised: 30 January 2023

Accepted: 1 February 2023

Published: 10 February 2023



**Copyright:** © 2023 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Historically, various forms of nature were used as part of architectural decorations, as symbols, representations of religion, spiritual beliefs, political power and aesthetics [1–6]. Hitherto, the period of modern architecture, in the New World countries such as America and New Zealand, there are some buildings made in the form of animals to represent their identity, related to commercial aspects, attractions, or activities in relation to the typology of the building. Whether to reflect the role of the building, such as a fisheries department shaped like a fish [7] or just for roadside attractions zoomorphically shaped like a dog [8]. In some Oriental countries, elephants or bamboos are also used as symbolism in ‘Feng Shui’ architecture as domestic decoration for spiritual belief and fertilization [9].

Architects invariably search for new means to explore and develop their ideas, not only to achieve the design aim but also to express the culture and technologies of their time to set the standard for prospective ways of living. It is a known fact that architects often obtain inspiration from nature for various contexts in their designs [1–9]. The relationship and connection between architecture and nature is one that has brought forth many questions, criticisms and solutions. Several examples in the past demonstrate the relationship between architecture and nature. Presently, architecture moves beyond spiritual, symbolic and aesthetic uses of natural forms to more sophisticated ‘bioinspired’ performance-based building design towards sustainable development. New form of designs was introduced

several years ago which requires modern man to look at the biological functions or processes found in nature for inspiration, which are “biomimetics” or “biomimicry”. These novel bioinspired design approaches involve an understanding of natural sciences, biological processes or the entire biological ecosystem beyond only mere formal or appearance imitations [10,11].

Note that ‘biomimetics’ and ‘biomimicry’ are based on the same scientific methodology, which is an interdisciplinary design approach through the understanding of a biological role model. In particular, ‘biomimicry’ stresses the interconnectedness of systems to solve complex problem in design and today’s environmental challenges. In fact, animals and plants know how to implement strategies to adapt to their environment and their transformations develop within a sustainable ecosystem. Nowadays, technical advances at a very small scale (micro, nano) allow us to have a deeper understanding of the functioning of nature and provide a new source of knowledge and inspiration for architecture [12,13]. Admittedly, the architects have always been inspired by nature, it is still the case today and it will probably be in the future. However, we must distinguish a primarily formal bioinspiration with only an aesthetic or symbolic aim to biomimicry whose objective is innovation and sustainability. It is also necessary to distinguish among several bioarchitectural movements from the past to the present and how they lead to today’s biomimicry framework, because there is a great deal of terminological confusion due to the fact that we often associate terms from the life sciences with certain architectural design activities [14].

Nature presents such a multitude of phenomena that the length of time for research and maturation of a possibility of transfer to architectural design can be complex. Biomimetic design activities necessarily require multidisciplinary expertise involving biologists, architects and other scientific fields, which is still the main constraint within architectural design practices. Focused methodologies for analogical transfer and interdisciplinary exchanges can facilitate biomimetic design process and implementation in architecture [14–16]. Moreover, the use of computational design and digital fabrication have recently supported architects in studying and simulating biological models, helping to transfer them better into architectural design contexts [17].

This entry presents principal bioarchitectural movements and how they lead to today’s biomimicry framework. It aims to define biomimicry methodologies and how this approach applies to architectural design contexts through the study of existing case studies. The paper is divided into five sections; (1) Introduction; (2) Bio prefix in architecture; (3) Biomimetic design methodologies and tools; (4) Biological analogy and architectural design; and (5) Discussion and the outlook of the field.

## 2. Bio Prefix in Architecture

Nature has always been a source of inspiration for architecture, creating several bio-movements through historical to today’s contemporary period. Numerous terms including the prefix ‘bio’ have been associated with the architecture thus creating a great confusion and a terminological ambiguity. These closed terms have different meanings and schemes but can be grouped under the generic term ‘bioinspired’. It refers to taking inspiration from nature to create new objects or processes that do not directly use of nature in the design production.

Biomorphic architecture corresponds to a conception directly influenced by the organic forms of animals, plants and the human body [18,19]. It has its roots in the Art Nouveau movement at end of the 19th century. It is a matter of imitating nature by carrying out expressive formal and symbolic associations. For example, one might argue that Gaudi’s vaults based on his study of natural forces with the use of hanging chain models are an example of architecture whose expression and constructive configurations are borrowed from nature. Additionally, the works of Santiago Calatrava have been influenced by Gaudi. In the same way as Gaudi, forms found in nature inspired the architecture of Santiago Calatrava, such as the skeletal wing-like structure of the kinetic brise soleil of the Milwaukee Art Museum.

Presently, new computational design software and digital fabrication technology have progressed the biomorphic approach in more biological complex geometries and patterns to design and develop a number of different kinds of optimization algorithms that have been widely used in both theoretical study and practical applications, such as sand formation, variations on algorithmic tree-branching structure and snake skin patterns [20].

Biological growth or ‘metabolism architecture’ found in Japan between the late 50s and early 60s. The metabolism movement sought to create non-static architectural megastructures inspired by organic biological growth. This approach was to design building parts that can be prefabricated, replaced and removable when their lifespan is over, like living cells in an organism [21,22]. The Nakagin capsule tower, designed by Kisho Kurokawa is representative of metabolic architecture embodying the ideas of adaptability to changes in periods of time.

Bionic architecture evolved from Boolean morphology made possible by advances in digital software during the 1970s and 1980s, which focuses on the transfer of life forms and processes to building and mimicking the expressive and constructive configurations in nature. Its goal is the synthesis of nature in modern constructive technologies [23,24]. Bionic practices in architecture give rise to new forms that are functionally efficient and original in their aesthetic quality, but without regard to the principles of nature or necessarily sustainable development. Bionic architecture differs from biomorphism in that it is inspired by biological processes developed by organisms, not necessarily by forms. As seen in Greg Lynn’s Embryological House, the house transformation was animated as a living form in digital artifact [25]. Another example is Biothing of Alisa Andrasek, which shows the use of computational tools to calculate and generate forms from codes and parametric data period. It is based on genetic models and operates beyond form and geometry, using the power of self-creation and the evolution of algorithms [26]. This is also seen in the project ‘Theverymany’ by Marc Fornes that uses computational design and digital fabrication to imitate the biological self-replication process in architectural form [27].

Bioclimatic and biophilic architecture also involve the relationship between nature and building morphology. Although not considered within the bioinspiration framework, they share a paradigm shift in our relationship with nature, but are not derived from strategies found in nature as described below;

Bioclimatic architecture is a discipline of architecture whose objective is to take advantage of the conditions of a site and its environment. This architecture adapts to the characteristics and particularities of the location: its climate (or microclimate), geography and geomorphology, including its habitat. With the aim of improving the comfort and energy efficiency of the building, bioclimatic architecture uses passive strategies, techniques and constructions to heat, cool and/or ventilate the interior of a building [28,29].

Biophilic architecture is an approach to architecture that seeks to connect building occupants more closely to nature. Heerwagen and Hase [30] were the first to define various features in biophilic architecture. This design concept derives from the ‘biophilia’ philosophy, introduced by a psychoanalyst named Erich Fromm [31] who stated that biophilia is the “passionate love of life and of all that is alive” Thus, biophilic design addresses nature’s incorporation to architecture for well-being, whether vegetation or animal. In the past, biophilic architecture only referred to mere applications of vegetation in buildings, but today, this approach has a more complex design framework towards many aspects e.g., enhancing health, well-being, productivity, biodiversity and circularity [32–34].

The most recent approaches, which evolve from the bioinspiration framework are ‘biomimetics’ and biomimicry’. The two approaches have the same scientific method involving cross-disciplinary design activities and interdisciplinary collaboration between architects, biologists and relevant scientific fields. Biomimetics and biomimicry derive from the true understanding of biological science rather than appearance, beyond only mere natural form imitations. We will discuss the emergence of these two approaches and how they shift and apply to architecture and construction.

### *The Origin of Biomimetics and Biomimicry*

As described in the previous section, there have been several bioarchitectural movements but it has been more an overlapping between art and architecture taking the visual forms and direct representation from nature for architectural elements rather than inspired interpretation [35].

The term 'biomimetics' was coined by Otto H. Schmitt around 1950. During his doctoral thesis, Schmitt studied the octopus' nervous systems to create his electric circuit bioinspired medical–engineering invention. This led to his 'biomimetic concept' and established a new interdisciplinary field of biomedical engineering that he termed 'biomimetics' [36]. Biomimetic design was initially known only in small groups of medical and engineering research fields. This was the case until 1970, when zoologist Werner Nachtigall started to diffuse 'biomimetics' (in the German language, the term used is 'bionik', which is the same as 'biomimetics') in Europe, particularly in German-speaking countries. His book *Bau-Bionik: Natur-Analogien-Technik* authored with architect Göran Pohl identified the biomimetic design process as a scientific method [37]. The book was later translated into an English version *Biomimetics for Architecture & Design: Nature-Analogies-Technology* [38]. The English version precisely describes the analogical principles of transferring biological strategies or models to architectural design context.

The term "biomimicry" appeared as early as 1980, during the time of a decisive period for sustainable development. Biomimicry was popularized by the biologist and environmentalist Janine Benyus, the author of the book *Biomimicry: Innovation Inspired by Nature*, first published in 1997 [39]. Biomimicry is defined in her book as a new science that studies nature in order to observe or be inspired by it for innovation from a perspective of sustainability. Benyus suggests looking at nature as a model, measure or mentor [39].

Biomimicry has evolved the architectural design method and practice towards more innovation and sustainable awareness beyond only visual organic forms. Architect Mick Pearce has effectively demonstrated the initial use of biomimicry in his projects (during 1991–2003). He designed an innovative ventilation system inspired by the autoregulation of the termite mound to reduce energy consumption of tradition HVAC systems in several buildings in Africa. The most well-known example is the Eastgate building in Harare, Zimbabwe [40]. Whilst his projects successfully demonstrate the inspiration from nature in combination with traditional passive design strategies, Pearce was a self-taught biologist; in fact, he observed biological strategies from the termite mounds himself without any collaboration with biologists. Later on there was a claim of scientific research questioning some misleading biological principles of the termite mound as presented in the Eastgate building project [41]; however, imprecise biological knowledge did not affect the design of his bioinspired ventilation system.

Both biomimetics and biomimicry have the same core interdisciplinary design methodology but with a slight difference in relation to sustainable awareness. Biomimetics refers to an interdisciplinary design process and collaboration through the understanding of biological functions, and the abstraction and transfer of biological principles into new technical applications [36,42–48]. Initially, biomimetics involved biology–technology transfers, only with more focus on innovation than on sustainability. Biomimicry added environmental values taking nature as a model to meet the challenges of sustainable development (social, environmental, and economic) [39,49–53]. In architectural practices, the term 'biomimicry' is more widely used than the term 'biomimetics' but these two terms can be used interchangeably in academic and research groups.

The industrial sector has rapidly seized on biomimetics, which has led to innovations in different fields but has not necessarily always taken into account the challenges of sustainable development [54]. Well-known examples of existing biomimetic design applications are: a hook and loop fastener Velcro inspired by the Burdock Plant; the head of the Shinkansen train inspired by the kingfisher's beak; Lutosan coating inspired by the self-cleaning phenomenon of lotus's leaf; a reusable adhesive inspired by the nanostructured

hair of gecko's feet and the Mercedes bionic car inspired by the structural morphology of the box-fish [55].

In architecture, on the other hand, biomimetics/biomimicry is mainly perceived as a novel innovative design method inspired by nature along with a means of responding to current environmental issues. Until the present day, examples of biomimetic architecture are still rare because biomimetic design is more realizable in small scale systems or products as it is a direct transfer from biological models to technical systems. On the contrary, in architecture and construction, the direct transfer is not directly applicable due to the multi-requirements of the architectural project and its economic and social contexts [15]. The goal of biomimetic architecture is no longer simply to give form and measure to space, but also to develop synergistic relationships between the built and its environment.

Petra Gruber published the first book on *Biomimetics in Architecture—Architecture of Life and Buildings* in 2011. In her book, she addressed biomimetics in architecture dealing with classic approaches common to the overlapping between architecture and biology, the architectural interpretation of life and the notion of living architecture [14].

Until today, biomimetics and biomimicry are still mostly known and diffused in academic and research groups, rather than in architectural and construction practice, as seen in the numbers of scientific productions [14,38,51,56–64]. While examples of bioinspired architectural productions are numerous, those based on biomimetic design activity are rare. Architect Michael Pawlyn has written two editions of his book *Biomimicry in architecture*, guiding some biomimicry principles for architectural practices [65,66]. Pawlyn addresses some principles applying biomimicry toward sustainable architecture; how architects can be inspired by biological structure to design a more efficient building while using less materials and energy; how architects can learn from forest circulation to manage the water infrastructure and how architects can learn from the natural ecosystem to create waste-free production, for example.

Theoretically, there are diverse sustainable strategies that we can learn from nature. However, it is not a trivial task to transfer biological principles to artefact design application, particularly to fit the entire architectural context. Thus, theoretical frameworks, analogical transfer methodologies and tools to help facilitate the biomimetic design process and activities in the architectural field need to be focused on.

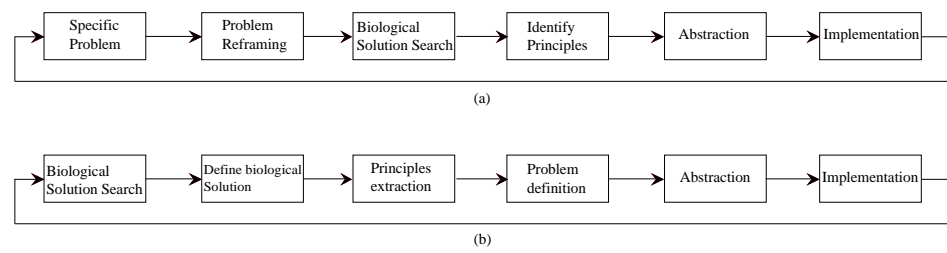
### 3. Biomimetic Design Methodologies and Tools

Some exiting/developing biomimetic design methodologies, mostly towards the engineering and industrial domain, are developed in [42,67–73]. More or less, these methodologies have a common framework as agreed by biomimetic specialists; the two approaches and the three levels of biomimicry. Some tools are also proposed to support the biomimetic design process.

#### 3.1. Process Sequences in Biomimetic Design

The biomimetic design process is bidirectional, analogical-based and interdisciplinary. Biomimetic specialists currently agree that there are two possible approaches: either we start from a design problem and we try to find strategies in nature that we could transfer to solve the design problem or we look for strategies in nature with our interest in new invention and we try to transfer them to new design methods or products [74,75]. Both approaches require a multidisciplinary activity, mainly involving designers and biologists.

The first approach starts with a human need or design problem and then examines the ways in which organisms or ecosystems in nature can solve that problem. This is a problem-oriented approach (top-down or design looking to biology). This approach is effectively carried out by designers who, after identifying the initial objectives and parameters of the design, look for solutions in the plant or animal world (Figure 1a).



**Figure 1.** Sequences of biomimetic design process: progress of a biomimetic project from biological models to biomimetic applications: (a) Problem-oriented process; (b) Solution-oriented process.

The second approach consists in identifying interesting principles, behaviors or functions in an organism or an ecosystem, and then looking for a design problem that could be addressed. This is a solution-oriented approach (bottom-up or biology influencing design). This approach is one where the knowledge of biology influences human design. It is led by people with a scientific knowledge of nature who are looking for possible applications relevant to the design (Figure 1b).

### 3.2. Levels of Biomimetic Design

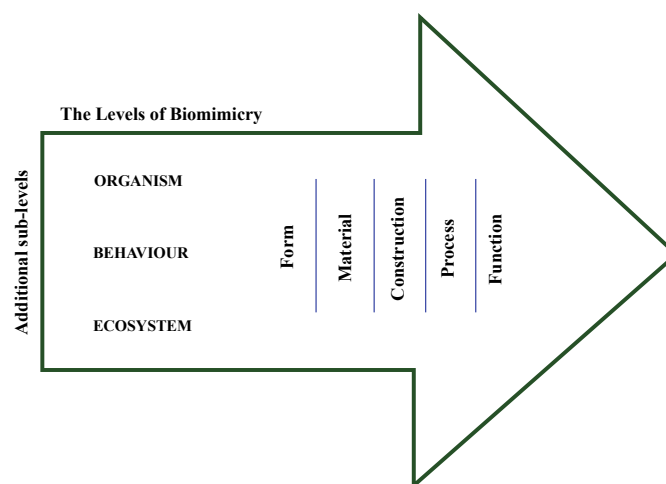
Biological role models or natural phenomenon can inspire architectural design at different levels; it can be categorized into three levels: organism, behavior and ecosystem.

The organism level refers to a specific being such as a plant or animal and may involve the imitation of a part of the organism or the whole.

The behavior level refers to the behavior of a being and may include the translation of an aspect of the organism’s behavior and possibly its relation to a larger context.

The ecosystem level is the imitation of an entire natural ecosystem and the principles that enable it to perform functions successfully.

Within each of these three levels, five additional dimensions of imitation exist. Design can be mimetic for example in terms of what it looks like (what does the form serve for an organism to survive?), what it is made of (material composition), how it is made (construction process), how it works (performance) or what it does (function) [76]. These five sub-levels are proposed by Maibritt Pedersen Zari to better facilitate the transfer from biology, in particular to architectural design contexts (Figure 2).



**Figure 2.** Three principal levels and five sub-levels of biomimicry for architectural design.

The following presents examples for each level of existing biomimetic architecture case studies.

### 3.2.1. Organism Level

The organism level corresponds to a biomimetic form, surface and material. Biomimetic design at an organism level means looking at parts of an organism how it functions to serve the organism to survive. Interesting biomimetic strategies at organism level are inspired by animal skins [57], plant surfaces [77] or organism morphology adaptations [78], for example. Most biological systems that inspire architectural design are multi-functionality, self-responsive and adaptive. These strategies are recently applied in building envelopes or façade components' design.

Examples of biomimetic architecture at organism levels are: the Esplanade theatre, Singapore (2002); the Swiss Re Building, London (2003) and Pho'liage, France (2019).

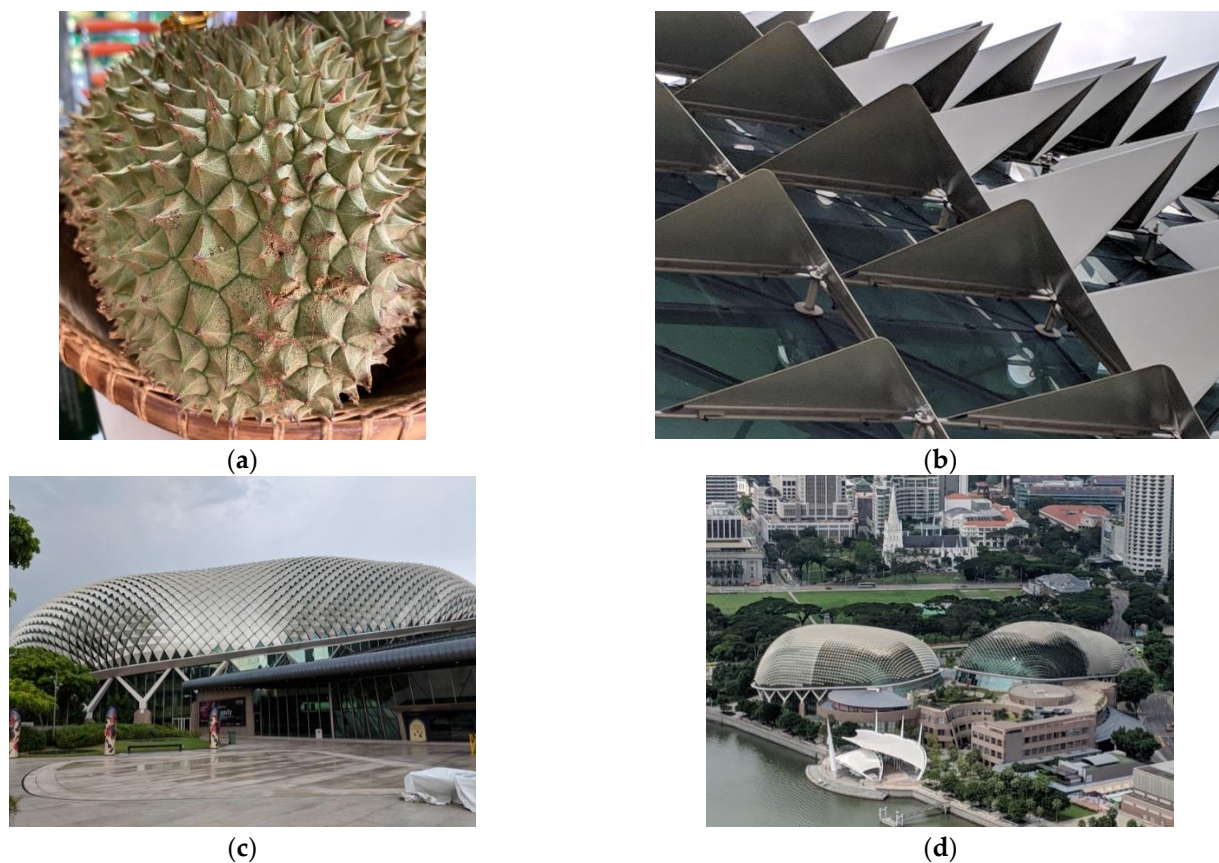
Esplanade Theatre on the Bay, Singapore [15] is a cultural performance space and concert hall. Architect Michael Wilford was asked to design a glass dome for an expressive view in all directions for the interior. However, Singapore is so close to the equator, which is a hot-humid climate, so that an entire glass dome could have allowed the interior of the building to overheat. Based on the biomimetic design framework, this project was a top-down approach starting from the 'design problem'. Wilford reframed the problem by understanding the need for 'a new skin design of the glass dome'. He initially searched for bio-role models that have a similar morphology of the glass dome and their skins that have a thermoregulation capacity to protect from the heat. Inspired by the local durian fruit shell's characteristics, Wilford proposed a new design concept of an alternative double skin envelope that can help to reduce excessive solar heat inside the building [79].

Durian fruit (*Durio zibethinus*) is composed of three layers, the outer most layer 'exocarp', the middle layer 'mesocarp' and the inner most layer 'endocarp'. The sponge-like material of the middle layer has a thermal property to help keep the durian fruit always fresh and secure inside the cocoon, while the outer layer has the spike-like characteristic that helps to protect the fruit from overheating in sun radiation (Figure 3a) [80]. The architect applied the double-skin layer strategies by replacing external triangular aluminum lamella fins varying in geometry and calculated according to the year-round sun path as the second skin on top of the glass dome (Figure 3b). There are in total 6200 aluminum fins, which have the same base dimension but are a different height so that their tips are at different angles according to the year-round sun path position to provide the maximum shading in all directions. At the same time, the fin-shading devices allow for the preservation of the view from the building's interior to the expressive view of the surrounding bay (Figure 3c).

In addition, the architect mentioned the choice of durian fruit as the bio-role model for this problem-solving design because it is also a symbolic fruit of Singapore named as 'King of tropical fruit' [81]. Thus, the bioinspired concept of the esplanade theatre has also become an iconic design feature in Singapore (Figure 3d).

The Swiss Re Building (officially 26 St. Mary Axe) is an office and a commercial building located in the Baltic Exchange district in London [15]. The particularity about this district is the strong local wind so there are not many high-rise buildings constructed in the area. The architect (Norman Foster) was asked to build one of the first commercial high-rise buildings; thus, the design of the building must have a minimum impact on the local wind environment whilst being constructed with steel light-weight structure. To achieve this problem-solving design situation, the architect team observed a marine animal that lives anchored to the deep ocean floor called the Venus' flower basket (*Euplectella aspergillum*) (Figure 4a). The silica skeleton of the Venus' flower basket sea sponge is tough and stable because multiple levels of organization each help to manage forces that help the sponge to disperse strong water currents [82,83]. Analogically to the pressure of the air around the high-rise building, the Gherkin is designed in a cylindrical form, which allows the wind to easily whip around the tower (Figure 4b). The building structure constructed in a grid form using the diagrid-architecture system inspired by the lattice-like exoskeleton of the Venus' flower basket for a strong assembly of light-weight steel structure [84]. Some of diamond-shape windows can be opened to profit from the local wind for natural ventilation to reduce energy consumption.





**Figure 3.** The Esplanade Theatres on the Bay, Singapore inspired by durian fruit shell characteristics (*Durio zibethinus*): (a) Durian fruit; (b) Esplanade theatre's envelope detail; (c) Esplanade theatre building; (d) Esplanade theatre top view. Image (a): reprinted with permission 2021 © Natasha Heil. Image (b–d): reprinted with permission 2018 © Pierre Côté.

In response to climate change, space-cooling systems account for an important part of building energy consumption. At ArtBuild Paris, Steven Ware, lead architect with a biology background, has been developing a self-responsive shading façade system inspired by nyctinasty, a nastic movement or an open-close mechanism of flowers [85]. The architect used a top-down approach in order to analyze existing dynamic shading façade systems, followed by a bottom-up approach searching for suitable strategies from nature in order to develop the functional component of autonomous shading façade system.

The Pho'liage® shading device was developed by studying the morphology and open-close mechanism of flowers according to their external stimuli (Figure 5a). The architects selected smart materials; shape memory alloy (SMA) and thermobimetal for the biomimetic design application of self-responsive shading because it only needs a small amount of energy as these smart materials react themselves to external stimuli (e.g., temperature change) [86]. The autonomous shading devices react to heat from the sun, when the exterior temperatures are above 25 °C, the blades/petals open as flowers to form a vast window curtain protecting overheating inside the building. When the temperature decreases, the petals deform to close allowing natural light to enter in to the building (Figure 5b) [87]. In this project, the architects also continued to work on form-finding of the shading system to suit with different architectural façade design contexts (different shapes and numbers of the petals) [86]. By the end of 2022, Pho'liage® will be implemented and tested in a full-scale architectural project at the new headquarters of the International Agency for Research on Cancer (IARC) building in Lyon France, a project for which ArtBuild are also lead architects (Figure 5c) [88].



(a)



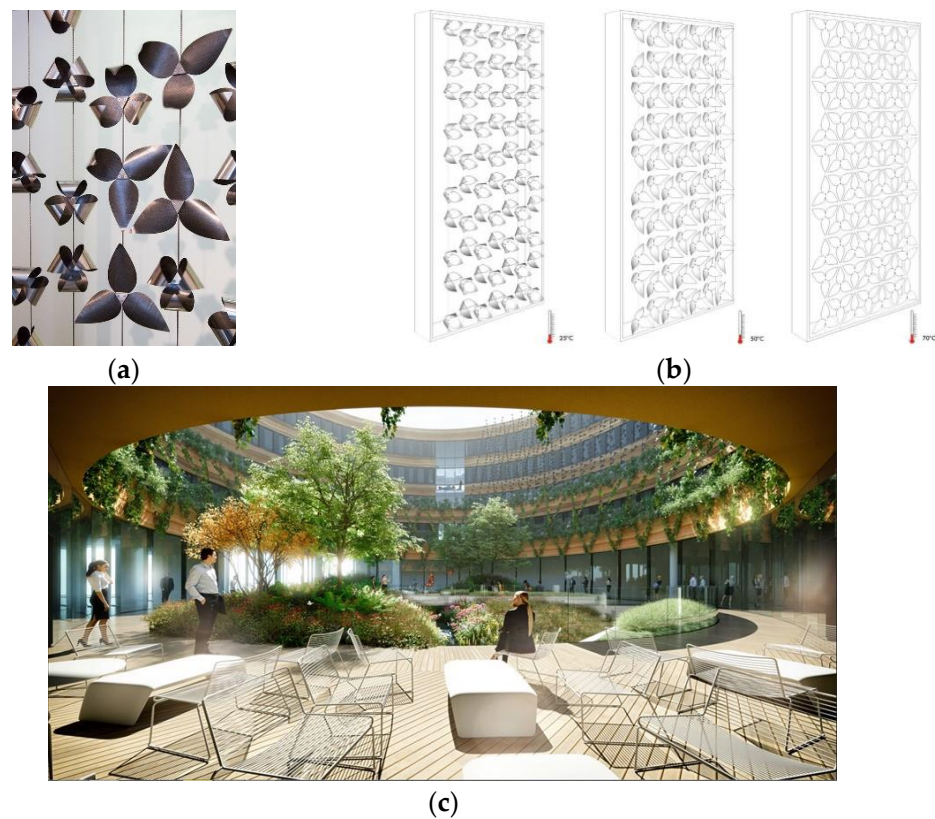
(b)

**Figure 4.** Swiss Re Building (Gherkin) inspired by Venus' flower basket (*Euplectella aspergillum*): (a) Venus' flower basket under the ocean; (b) Swiss Re Building, London. Image (a): Wikipedia. Image.

### 3.2.2. Behavior Level

The level of behavior corresponds to a biomimicry of process and performance. It is not the organism itself that is imitated but the way it behaves, observing an interacting phenomenon between the organism and its own environment. Two examples of biomimetic architecture at this level are: the NBF Osaki Building (BIOSKIN) (2011) and District 11, Skolkovo Innovation center (2017).

The architects (NIKKEN SEKKEI) were asked to design an office building in Tokyo, which can be very hot during summer. The initial idea was to create a type of 'bioskin' envelope that can passively regulate the temperature for the interior of the building once the temperature outdoors becomes too hot. The idea also related to the use of water to reduce heat by the Japanese tradition Uchimizu, which refers to the sprinkling of water in Japanese gardens and streets. During the summer period, Japanese people use Uchimizu for cooling down the area and also for other hygienic purposes [89].



**Figure 5.** Pho'liage<sup>®</sup> inspired by nyctinasty: (a) Prototype of Pho'liage autonomous shading device; (b) Simulation test of the shading device according to temperature change; (c) Simulated model of the shading device envisaged to be implemented at IARC. Reprinted with permission. 2019 © ArtBuild Paris.

Thus, the architects combined traditional culture with a biomimetic approach. The design problem was to invent a facade design that used rain water to cool down the building and the neighborhood area during the summer period. Inspired by the principle of homeostasis, the architects observed the phenomenon of human perspiration phenomenon, which is an internal physiological self-cooling mechanism in the human body to respond to the degree of heat [90]. This biological process triggered the architect to design an exterior envelope in ceramic pipe which converged in a collection system of the rainwater creating an exterior, evaporative cooling-system sprinkling water in reaction to the temperature outside. When the temperature outdoor exceeds a certain degree, the ceramic pipe will release the water vaporization for cooling the temperature of the building and at the same time this can also cool down the exterior area around the building creating a microclimate around neighboring buildings. This passive cooling system is not at all energy intensive to run; in fact, the water pump that circulates rain water through the pipes is small and activated by a tiny amount of electricity generated by solar cells installed on the building's south-facing eaves. The maximum surface temperature of this BIOSKIN system is around 12.6 °C lower than a normal facade. This biomimetic invention estimates to reduce the building's total energy consumption by about 3% by cooling air around office windows [66,91].

District 11—Skolkovo Innovation center, also known as the Russian Silicon Valley, is located at Skolkovo, near Moscow which is considered an extremely cold climate area. The architects (Béchu & Associés) were asked to design the planning of a group of housing for researchers from abroad who come to work at the center. The specification of the master plan was to design the village in a circular form so that it can create social interaction for each researchers' family. The initial design problem was to design the master plan along with the arrangement of each house in the most effective way to create a warm

microclimate within the village. The architect chose the emperor penguin's social huddling phenomenon as a bio-role model, from the perspective of a circular self-organization pattern that produces thermal regulation and heat transfer to the group of penguins helping them to survive from the extreme cold [92].

Emperor penguins live in the cold Antarctic area, where there is a storming cold wind from time to time. Once there is such an extreme cold situation, the penguins start to gather forming themselves into a group, the penguin moves from outside to inside which can allow each penguin to stay warm from time to time in order to survive. There are different self-organization patterns depending on different breeding stages [93]. Based on this phenomenon, the architect studied mathematical models of the emperor penguin's social huddling pattern; the existing mathematical models are executed by an interdisciplinary collaboration between biologist, physicist and mathematician. Based on these models [94,95] Figure 6a, the architect uses the mathematic models for the calculation algorithm of design software simulation to transpose the huddle patterns in to form-finding for each housing arrangement with maximum heat transfer between the individual houses (Figure 6b,c). This biomimetic strategy positions each house in circular form at different angles to protect from an extreme cold wind during winter and also to increase heat transfer between each housing that helps to gain 5 °C more heat inside the house [92,96,97].

### 3.2.3. Ecosystem Level

The ecosystem level is a biomimetic design that seeks to mimic network systems found in nature. It is about understanding how the relationships between species and their environment produce an ecosystem that is stable over time and therefore sustainable. Indeed, in nature, all waste generated by animals and plants is a contribution to other animals and other plants. Building networks or urban planning that would be able to emulate this natural process could work autonomously and sustainably.

The ecosystem is considered as the most complex one as to imitate the natural entire network to artefact entire network is not a trivial task. In addition, architects need to have a bigger scale of biological knowledge about how organisms interact with other organisms and with their environments, including further knowledge in the Ecology domain (biodiversity, niche construction, food web, complex network, social ecology, etc.) [98,99]. Interesting examples of architectural projects at this level are: the Sahara Forest project (2012) and the Regen Village (2016).

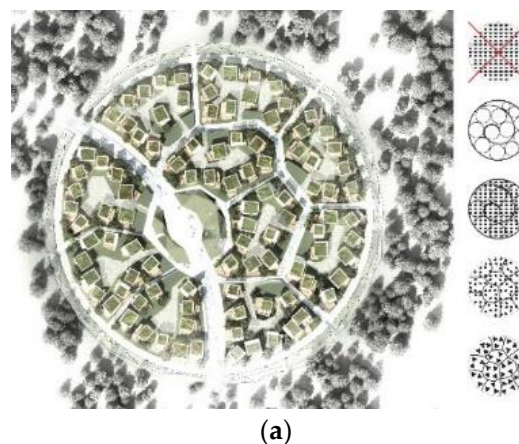
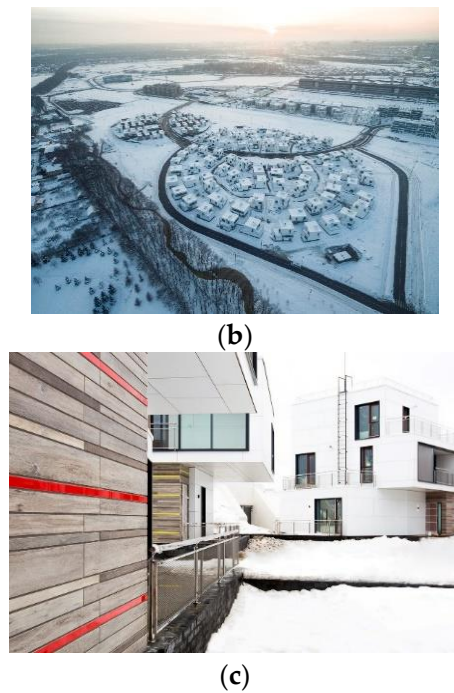


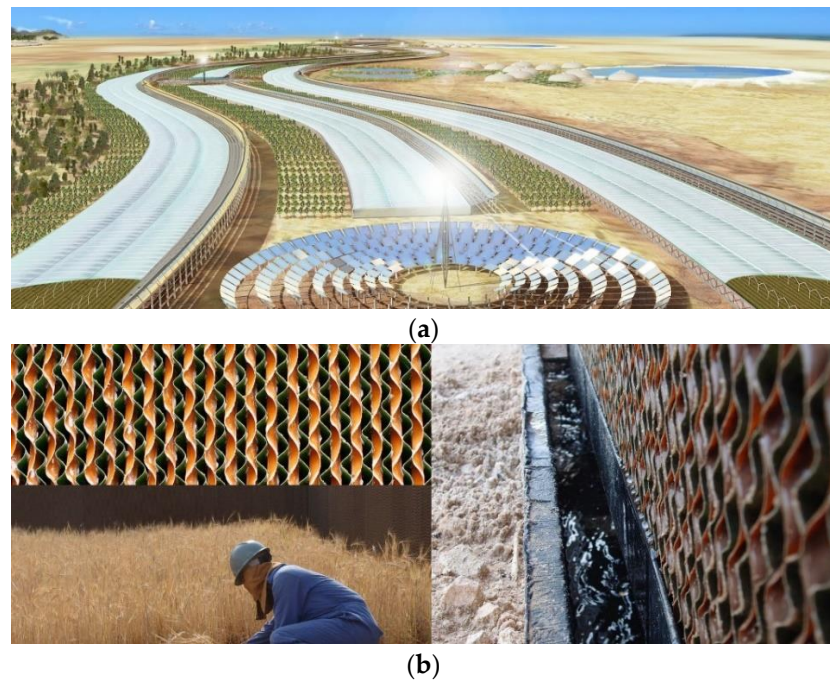
Figure 6. Cont.



**Figure 6.** District 11—Skolkovo Innovation center inspired by emperor penguin social huddling: (a) Master plan design; (b) Skolkovo village district 11; (c) Skolkovo's housings details. Images (a–c): reprinted with permission 2019 © Agence Bechu & Associés.

The Sahara Forest design aimed to recreate a new environmental solution using local resources to produce food, water and energy inspired by natural ecosystem principles (Figure 7a). The core technology was to bring seawater into the desert creating a salt extraction system to cultivate greenhouse and vegetation in desert areas (Figure 7b). The photovoltaic panels were used to collect solar power to produce electricity, including the use of algae to produce biofuels [65,66]. This large-scale urban project is one of the best examples of biomimetic design at ecosystem levels to recreate life in many abandoned desert areas for agricultural production. The project aims at rehabilitating desert areas by transforming them into a sustainable and profitable local resources. The Sahara Forest model was initially implemented in Qatar, Jordan, and recently in Tunisia and it will be tested in many other possible locations [100].

The design model of the Regen Village (regenerative village) (Figure 8a) was created by researchers at Stanford University in collaboration with the Danish architectural design firm EFFEKT. The principal concept was to design and develop a self-sufficient village model that operated in a closed-loop system [101]. The first model was built in 2016 in Almere, an outskirts' area of Amsterdam. The village was completely autonomous and environmentally friendly, which was able to produce its own energy, agriculture and recycle its own waste. After the first model in Almere, which was successfully tested and developed (Figure 8b), the Regen Village is envisaged to be constructed in the outskirts of several cities in many European countries, including The Netherlands, Germany and France [102,103].



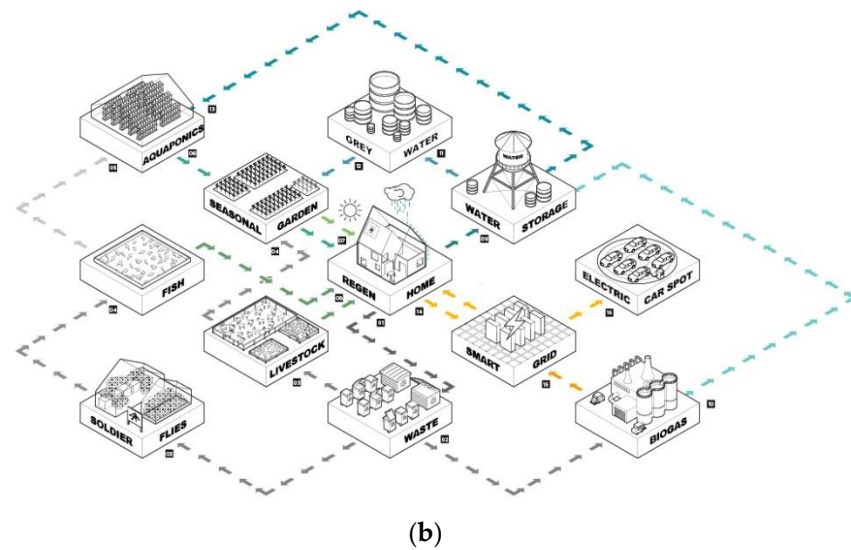
**Figure 7.** Sahara forest project inspired by natural ecosystem: (a) Sahara forest project in Tunisia; (b) Food, re-vegetation and salt water system. Images (a,b): reprinted with permission from ref. [100]. Copyright 2020 © Exploration Architecture.

Below is a summary table of all case studies according to biomimetic design framework (Table 1).



(a)

**Figure 8.** Cont.



**Figure 8.** Regen Village inspired by natural closed-loop system: (a) Simulated model of Regen Village, Almere; (b) Regen system: exchange between waste–food–water–energy. Images (a,b): reprinted with permission from ref. [103]. Copyright 2022 © EFFEKT.

**Table 1.** Summary of the case studies according to biomimetic design framework.

Case	Biomodel	Approach	Level	Sub-Level(s)
Esplanade	Durian skin	Top-down	Organism	Form, Function
Swiss Re	Venus flower basket	Top-down	Organism	Form, Process, Construction
Pho’liage	Open-close Flower	Bottom-up	Organism	Form, Process
NBF Osaki	Perspiration	Top-down	Behavior	Process, Function
Skolkovo	Penguin huddling	Top-down	Behavior	Process, Function
Sahara Forest	Ecosystem ecology	Bottom-up	Ecosystem	Process, Construction, Function
Regen Village	Close-loop system	Bottom-up	Ecosystem	Process, Construction, Function

### 3.3. Tools for Biomimetic Design

As we have seen, biomimicry, as a transfer of strategies from biology to other disciplines, is an emerging field of research that has led to the definition of meaningful concepts during the last 10 years. The development of such concepts is described by a biomimetic process comprising several steps. However, in order to overcome the challenges and facilitate the progress of the various stages, tools have been developed in various fields, such as engineering, computer science and industrial design. In the article Biomimetics and its tools [104], the researchers present an exhaustive panorama of 43 identified tools that facilitate the biomimetic design process. However, these tools still remain known mostly in research and academic groups. There is only one tool that is publicly used, which is AskNature.

AskNature [105] is an online database intended to inspire general innovators seeking information from biology that is relevant to their design challenges [106]. It is a public database of biology information categorized by function grouped in a biomimetic taxonomy. It bridges the gap between biology and various innovative fields [107]. AskNature could help to identify nature’s strategies but it is still too generic to help specify the right natural strategy to suit particular contexts and requirements in architectural design.

There are also several other tools but they have been used only in the scientific research groups, such as, Functional modeling, Natural language analysis, IDEA-Inspire software, SAPPHERE model, TRIZ and BioTRIZ. Functional modeling is a model developed by Jacquelyn Nagel, professor of engineering at James Madison University [108]. It contains

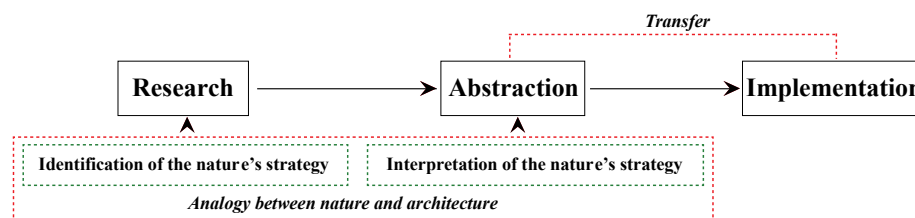
the representation of biological systems using functional models to facilitate the transfer between biology and engineering. IDEA-Inspire is designed to facilitate the stimulation of ideation through biological inspiration [109] and the SAPPHERE model is designed to help understand biological systems [110]. BioTRIZ is a fusion between biomimicry and the method of innovation TRIZ [111]. When using TRIZ, designers define their design problem as a contradiction between different requirements that require optimization of one of the 40 design parameters proposed by the method to the detriment of other requirements. The contradiction matrix developed in TRIZ allows us to discover which innovative principles among the 40 proposed have been put forward to solve the problem encountered in earlier designs. The BioTRIZ approach, based on the analysis of 500 biological phenomena, proposes a new matrix of contradictions based on biological phenomena as a means of stimulating the transfer between biology and engineering [112].

The tools presented above have mostly been tested in the scientific literature, research and academic aims. Moreover, these tools are developed towards the industrial and engineering design domains rather than architecture. The design specification, process and scale of the construction context are more complex and have multi-layers of requirements. Presently, there is still no tool to facilitate the biomimetic design process to suit architectural design and construction; it is still based on individual creative analogical design process and digital tools to support the interpretation and the transfer from biological worlds to buildings' contexts.

#### 4. Biological Analogy and Architectural Design

Biomimetic architecture is a cross-disciplinary design method between biology and architecture fields. Architect Göran Pohl and biologist Werner Nachtigall described in their book *Biomimetics for architecture and design: nature-analogies-technology* the biological principles that can be used as a source of inspiration and applied in architectural solutions. The authors specify that nature cannot be directly copied to provide architects with a wealth of analogues and inspirations to achieve a true biomimetic design in architecture [38]. Nonetheless, it is not a simple task for architects to search for biological principles, to understand and to transfer them to solve problem in their design. Pohl mentioned that the inspiration from nature should not be direct interpretation, rather it should be well abstracted within the context of an interdisciplinary analogue.

Pohl and Nachtigall identified the theory of cognition to biomimetic design process (Figure 9), signified this in three steps: Research → Abstraction → Implementation [38]. The most difficult steps for architects are 'research'—where one needs to find the most suitable biological role model to solve the design problem and 'abstraction'—where one needs to understand and translate biological principles into the architectural design context. The implementation phase relates to the use of existing design techniques, material selection and technology of the domain to achieve the best results of biomimetic application [74].



**Figure 9.** The three steps and two transitions of biomimetic design process: the selection of a biological role model, the translation of biological principles to design contexts and the implementation of a biomimetic application.

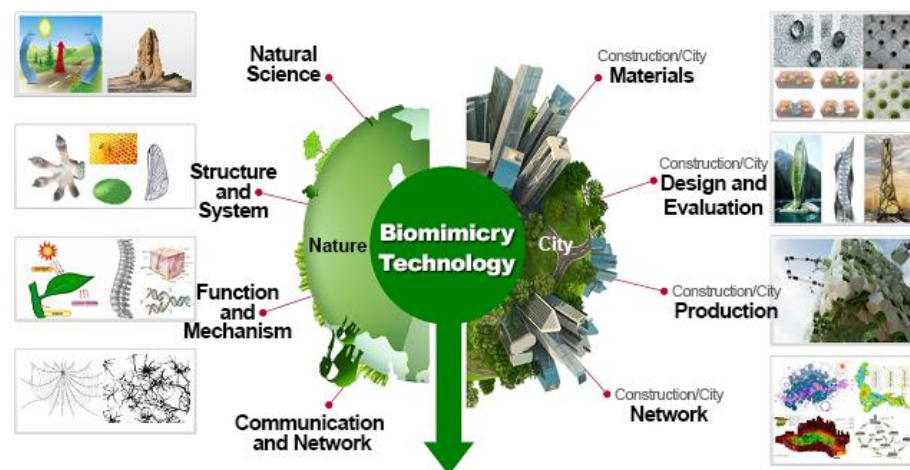
In the international standard (ISO 18458) [47], biomimetic specialists specify “abstraction and analogy” in the biomimetic design process to be a similarity in the relationships between the parameters describing two different systems. The goal is to obtain the most complete analogy possible of the relevant problem in which it is possible to recognize the



common and the different aspects in the corresponding analogies by comparing (mapping) the individual aspects. For example, mapping possible aspects from a biological system to a technical system can be functions, material, structure, shape, color, etc.

However, in the architectural domain, apart from the analogy from biological principles to design, it has other relevant contexts, such as: architectural values and design scales, to be concerned to suit the particularity of each project. It can include: climate type, location (where the building will be built), scale of design (a component, a system, a building, or an urban infrastructure), including cultural and economic contexts of each places. Thus, a direct analogy and transfer from biological systems to technical systems in the same as other domains would not fit into an architectural project; thus, other design values should also be included in the biomimetic process and implementation [113]. For example, as shown in the case studies of the Esplanade theatre and NBF Osaki, the cultural and traditional references of the local places sparked the idea and the choice of the architects to select biological models for their problem-solving biomimetic designs (e.g., Durian as a symbolic King Fruit and the Japanese tradition Uchimizu for sprinkling of water during summer).

Moreover, scalability is one of the most challenging issues in biomimetic design. In [114], the authors describe the problem of scaling biological principles to design artefacts and specify that sometimes the transfer of a biological system in nano- or micro scale is not always possible because biological structures lose their functionality when applied to different scale dimensions. In particular, in the architecture and construction domains, where most of design and applications deal at large scales; however, the transfer of functional strategies can be carried out if the rules of similarity are respected in other scales [115]. To be able to achieve the analogical transfer from the natural world to architectural world some similar contexts and scales can be compared and observed divided in four categorizations: at material scales, at building structure and system scales, at building function and production (performance) scales and at network and infrastructure scales (Figure 10).



**Figure 10.** Similar contexts and scales of transfer from nature to architecture: at material scales, at building structure and system scale, at building function and production (performance) scales and at network and infrastructure scales.

Design by analogy to biology (biomimicry), as shown in Figure 10, demonstrates the similar contexts between nature and the city starting from the material design scale, which can go down to a micro or nano scale. Normally, architects identify the specification to new materials' design but do not create the material alone, it needs a collaboration with material scientists. New bioinspired materials can be observed from a natural science phenomenon, such as, how different animals' skins or plants' surfaces interact with their environmental factors, to create a new structure or new types of properties for existing or new building materials [116,117].

Design and evaluation deals with the building structure and system. For example, we can observe how biological structures are light weight but resistant or study complex geometrical or morphological forms in nature to optimize material used for building structures [118,119].

Production relates building functions to their performances. For example, how we can learn from morphological differentiations in nature to design environmental adaptation of buildings' systems; learning from the termite mound for building thermoregulation [117], or observing biological principles for living building envelope designs [120,121].

Network scales related to city infrastructure or urban design [122,123], for example, designing traffic or transportation networks inspired by the behavior of the *Physarum Polycephal* (slime mold) [124,125].

Analogy of similar contexts and scales can help to better transfer knowledge from sources (biology) and targets (architectural design). Moreover, the architects should understand well their design problem-solving situations and other architectural relevant contexts (design brief); thus, he can select the most appropriate natural strategies and transfer the principles according to the criteria and requirements of each project particularities.

## 5. Discussion and Outlook of the Field

This article presents a bioinspiration framework in architecture, from past bioarchitectural movements until the state of development of the recent approach 'biomimicry', showing its potential for innovation along with sustainable awareness. Until the present, biomimicry methodology has been mostly known in academic and research groups. There is still a blur between biomovements and biomimicry, creating confusion among practice architects and students. Most bioarchitectural movements are often inspired by natural forms resulting from merely the direct representation of plants or animals for symbolic or aesthetic aspects. The organic and sinuous forms of flora and fauna inspired artists, architects and designers during the Art Nouveau period. They also influenced the expressive structures of biomorphic and bionic forms created by digital tools by transforming complex geometries and processes to architectural design. Instead, biomimicry was an alternative approach during the peak period of sustainability to propose a new way of designing or solving problem more innovatively and sustainably by observing at nature in a scientific manner.

The paper examines main architectural movements within bioinspiration; with bio-prefix terms, the definition and development along with examples of existing case studies. Herein, the author identifies the turn from 'bioinspiration' to 'biomimicry'. The author also presents exclusively a biomimicry theoretical framework and methodology to implement particularly in the architectural domain. Despite the nature of biomimetic design, the method should involve multidisciplinary collaboration but this cross-disciplinary activity is still challenging among architectural practices. The multidisciplinary nature of the biomimetic design method, the time required for the identification phase of a natural phenomenon that can be transferred to architecture and the difficulties in translating this phenomenon into architectural design contexts make a biomimetic design activity time-consuming. This is the reason why most biomimetic design activities are conducted mostly as part of research, academic, experimentation, preliminary prototypes [126] or demonstrating in the form of pavilions [127] rather than real-world construction.

Based on the biomimicry framework, the author has chosen the most pertinent case studies in real world construction to demonstrate how architects are inspired by natural strategies, beyond only a formal representation, to solve their design-problems innovatively and sustainably. The case studies are categorized into three main levels of biomimicry. From the study of each case studies and private interviews with the architects, the author discussed that architects captured strategies from nature to suit best the particularities of each architectural project. Architects study and understand at a good but not a profound level of how a specific biological strategy works so that they can interpret the strategy to solve the design problem. There is no use (yet) of multi biological strategies for a

design problem, which can be more interesting. Architects find it difficult to have access to profound biological knowledge and to associate several bio-strategies for the design. Moreover, as seen in the Esplanade theatre and NBF Osaki cases, the local culture and tradition also take part in the selective choices of biological role models (Durian as the Asian King Fruit, and the Japanese sprinkling of water tradition *Uchimizu*).

Biomimicry is also considered as a sustainability-driven design method based on observing nature. According to the three pillars of sustainable development—economic, social and environmental—the case studies demonstrate the use of the biomimicry approach to design various innovative building and urban systems; to reduce energy consumption in buildings (Esplanade theatre, Pho’liage, BIOSKIN); to optimize structural and material use for high-rise building (Swiss Re)- and to develop a new model of a self-sustainable villages which can produce its own food, energy, water and recycle its own waste (Regen).

The support for a better biomimetic approach is to incorporate biologists into architectural design practice, and to provide an outlook and provocation to encourage collaboration among scientists and designers, with the aim of achieving a truly interdisciplinary biomimetic team. This question was also raised in other domains [128] but it still needs more time to establish more effectively this type of interdisciplinary team. Notably, architecture incorporates more than just buildings, there are multi-layers of design phases in an architectural project, adding biological/scientific knowledge into the design practice, including how well architects perceive biological knowledge and transfer it into a specific design context are still challenging.

However, biomimicry, as we have defined it, is a practice yet to be achieved but we have seen the opportunities presented in a few case studies, as well as areas of opportunity for further research. Biomimicry, as a practice, can provide a means to cross disciplines and take advantage of blending scientific knowledge into design practices to solve today’s human problems towards environmental challenges. A new discipline ‘biomimetic architecture’ could form, though the parameters of such a collaboration depend on those willing enough to cross disciplines in this manner.

**Funding:** This research received no external funding.

**Acknowledgments:** The author would like to thank the colleagues at MAP-MAACC laboratory: François Guéna, Nazila Hannachi-Belkadi and Louis Vitalis, who have given fruitful advice and support on many important aspects of the bioinspiration framework in architectural design.

**Conflicts of Interest:** The author declares no conflict of interest.

## References

1. Montamat, B. Jules Lavirotte (1864–1929) or the Symbolist Art Nouveau. *Les Cah. Rech. Archit. Urbaine PaysagÈRe* **2021**, *32*. [CrossRef]
2. In 19th Century, Eugène Viollet-le-Duc Used ‘the Owl’ as His Symbolism of Medieval Architecture Representing Wider and Deeper Version (as He Captured the Notion That the Owl Can See in the Dark). We Can See the Owl Hidden in the Top Corner of a Column in the Churches and Other Buildings. Available online: <https://medievico.wordpress.com/2018/11/28/la-chouette/> (accessed on 30 August 2022).
3. In 17th Century, Architect Antoine Le Pautre Was Asked to Build l’hôtel De Beauvais for Pierre De Beauvais and Catherine Bellier, M. De Beauvais Asked the Architect to Use ‘Lion’ as a Symbol to Represent His Strength and at the Same Time Use ‘Ram’ to Represent His Wife (by Her Family Name) with ‘Bellier’ (Ram). The Animals Were Used as Part of the Architectural Decorations to Symbolically and Powerfully Represent Le Maître and La Maîtresse of the House. Available online: <https://www.unjourdeplusaparis.com/paris-insolite/hotel-de-beauvais> (accessed on 30 August 2022).
4. Syafrony, A.I.A. Comparison of the Significances of Garuda in Society, Arts and Architecture in Two South-East Asian Countries: Indonesia and Thailand. *J. Community Dev. Res. Humanit. Soc. Sci.* **2016**, *9*, 46–60. Available online: <https://www.journal.nu.ac.th/JCDR/article/view/1286> (accessed on 30 August 2022).
5. Evan, E.P. *Animal Symbolism in Ecclesiastical Architecture*; London, W., Ed.; Heinemann: Portsmouth, NH, USA, 1896.
6. Verma, A.; Gupta, I. The Journey of Elephant as a Decorative Element in Saharanpur Woodcraft: A Cultural Investigation. *Bharatiya Prajna Interdiscip. J. Indian Stud.* **2016**, *1*, 2.
7. National Fisheries Development Board, Located Near Hyderabad, India. Available online: [https://www.designingbuildings.co.uk/wiki/Fish\\_Building,\\_India](https://www.designingbuildings.co.uk/wiki/Fish_Building,_India) (accessed on 21 August 2022).

8. Corrugated Creations, Tirau, New Zealand. Available online: <https://weburbanist.com/2012/12/30/in-the-doghouse-again-13-odd-animal-shaped-buildings/2/> (accessed on 12 July 2022).
9. Feng Shui for Fertility. Available online: <https://fengshuitricks.com/feng-shui-for-fertility/> (accessed on 12 July 2022).
10. Recent Papers. *Biomimetics* Journal MDPI. Available online: <https://www.mdpi.com/books/book/6267> (accessed on 3 January 2023).
11. Recent Papers; *Bioinspiration & Biomimetics*; IOP Science: London, UK, 2022; Available online: <https://iopscience.iop.org/journal/1748-3190> (accessed on 28 July 2022).
12. Fratzl, P. Nature's hierarchical materials. *Prog. Mater. Sci. Sci. Direct* **2007**, *52*, 1263–1334. [[CrossRef](#)]
13. Jalil, W.D.; Kahachi, H. The implementation of nano-biomimicry for sustainable in architecture. *J. Eng. Sustain. Dev.* **2019**, *23*, 25–41. [[CrossRef](#)]
14. Gruber, P. *Biomimetics in Architecture: Architecture of Life and Buildings*; Springer: Wien, Vienna, 2011.
15. Chayaamor-Heil, N.; Guéna, F.; Hannachi, N. Biomimétisme en architecture. État, méthodes et outils. *Les Cah. De La Rech. Archit. Urbaine Et PaysagÈRe* **2018**, *1*. [[CrossRef](#)]
16. Badarnah, L. Towards the Living Envelope Biomimetics for Building Envelope Adaptation. Ph.D. Thesis, Delft University, Delft, The Netherlands, 2012.
17. Chayaamor-Heil, N. The Impact of Nature Inspired Algorithms on Biomimetic Approach in Architectural and Urban Design, Living Machines 2018: Biomimetic and Biohybrid Systems. In *Lecture Notes in Computer Science*; Springer: Berlin/Heidelberg, Germany, 2007; pp. 97–109. [[CrossRef](#)]
18. Feuerstein, G. *Biomorphic Architecture-Human and Animal Forms in Architecture*; Edition Axel Menges: Stuttgart, Germany, 2002.
19. Aldersey-Williams, H. *Zoomorphic-New Animal Architecture*; Laurence King Publishing: London, UK, 2003.
20. Agakathidis, A. *Biomorphic Structures*; Laurence King Publishing: London, UK, 2017.
21. Kurokawa, K. *Metabolism in Architecture*, 1st ed.; Littlehampton Book Services Ltd.: London, UK, 1977.
22. Koolhaas, R.; Obrist, U.L. *Project Japan: Metabolism Talks*; Taschen: Cologne, Germany, 2011.
23. Cervera, M.R.; Pioz, J. *Bionic Architecture: Learning from Nature*; Architect Publications: Barcelona, Spain, 2015.
24. Brayer, M.-A.; Migayrou, F.; Varenne, F.; Zakhama, G.L.N.; Oxman, R.; Lesne, A.; Harman, G.; Malafouris, L. *Naturaliser L'architecturei*; Archilab; Editions HYX: Orléans, France, 2013.
25. Bird, L.; LaBelle, G. Re-Animating Greg Lynn's Embryological House: A Case Study in Digital Design Preservation. *LEONARDO* **2010**, *43*, 243–249. [[CrossRef](#)]
26. Andrasek, A. *Biothing*; Editions HYX: Orléans, France, 2001.
27. Fornes, M. *Theverymany*; HYX: Orléans, France, 2010.
28. Widera, B. Bioclimatic Architecture. *J. Civil Eng. Architect. Res.* **2015**, *2*, 567–578.
29. Ávalos, J.; Villarreal, R.; Cárdenas, V.; Romero, A.C.G.L. Bioclimatic Architecture, SHS Web of Conferences. In Proceedings of the 3rd ETLTC International Conference on Information and Communications Technology (ETLTC2021), Aizuwakamatsu, Japan, 27–30 January 2021; EDP Sciences: Paris, France, 2021. [[CrossRef](#)]
30. Stankovic, D.; Cvetanovic, A.; Rancic, A.; Nikolic, V.; Stankovic, B. Biophilia in modern architectural practice: Recommendations for Serbia. *Facta Univ.-Ser. Archit. Civ. Eng.* **2019**, *17*, 133–143. [[CrossRef](#)]
31. Gunderson, R. Erich Fromm's Ecological Messianism: The First Biophilia Hypothesis as Humanistic Social Theory. *AHS* **2014**, *38*, 182–204. [[CrossRef](#)]
32. Beatley, T. Biophilic Architecture and Design. In *Handbook of Biophilic City Planning and Design*; Island Press: Washington, DC, USA, 2016. [[CrossRef](#)]
33. Tan, S.Y. From Biophilic Architecture to Biophilic Cities. In *Dense and Green Building Typologies. SpringerBriefs in Architectural Design and Technology*; Springer: Singapore, 2019. [[CrossRef](#)]
34. Barbiero, G.; Berto, R. Biophilia as Evolutionary Adaptation: An Onto- and Phylogenetic Framework for Biophilic Design. *Front. Psychol.* **2021**, *12*, 700709. [[CrossRef](#)] [[PubMed](#)]
35. Ripley, R.L.; Bhushan, B. Bioarchitecture: Bioinspired art and architecture—A perspective. *R. Soc.* **2016**, *374*, 20160192. [[CrossRef](#)] [[PubMed](#)]
36. Harkness, J. In Appreciation: A Lifetime of Connections: Otto Herbert Schmitt, 1913–1998. *Phys. Perspect.* **2002**, *4*, 456–490. [[CrossRef](#)]
37. Nachtigall, W.; Pohl, G. *Bau-Bionik: Natur-Analogien–Technik*; Springer: Berlin/Heidelberg, Germany, 2012.
38. Pohl, G.; Nachtigall, W. *Biomimetics for Architecture & Design: Nature-Analogies–Technology*; Springer: Berlin/Heidelberg, Germany, 2015.
39. Benyus, J. *Biomimicry: Innovation Inspired by Nature*; Harper Collins Publishers: New York, NY, USA, 1997.
40. Mick Peace. Available online: <https://www.mickpeace.com/> (accessed on 31 August 2022).
41. Turner, J.S.; Soar, R.C. Beyond biomimicry: What termites can tell us about realizing the living building. In Proceedings of the First International Conference on Industrialized, Intelligent Construction (I3CON) Loughborough University, Loughborough, UK, 14–16 May 2008.
42. Lenau, T.A. Biomimetic as a design methodology-possibilities and challenges. In Proceedings of the International conference on engineering design ICED Stanford University, Stanford, CA, USA, 24–27 August 2009.
43. Vicent, J.F.V. Biomimetics: Its practice and theory. *J. R. Soc.* **2006**, *3*, 471–482. [[CrossRef](#)]
44. Vincent, J.F.V. Biomimetics—A review. *Proc. Inst. Mech. Eng. Part H J. Eng. Med.* **2009**, *223*, 919–939. [[CrossRef](#)]

45. Vattam, S.S.; Wiltgen, B.; Helms, M.E.; Goel, A.K.; Yen, J. DANE: Fostering Creativity in and through Biologically Inspired Design. In *Design Creativity 2010*; Springer: London, UK, 2011; pp. 115–122.
46. Bar-Cohen, Y. *Biomimetics: Nature-Based Innovation*, 1st ed.; Taylor & Francis Group: New York, NY, USA, 2011.
47. Technical Committee: ISO/TC 266 Biomimetics ISO/TC266 18458:2015: Biomimetics—Terminology, Concepts and Methodology; ISO: Geneva, Switzerland. 2015. Available online: <https://www.iso.org/standard/62500.html> (accessed on 1 September 2022).
48. Fayemi, P.E.; Wanieck, K.; Zollfrank, C.; Maranzana, N.; Aoussat, A. Biomimetics: Process, tools and practice. *Bioinspir. Biomim.* **2017**, *12*, 11002. [[CrossRef](#)]
49. Ilieva, L.; Ursano, I.; Traista, L.; Hoffmann, B.; Dahy, H. Biomimicry as a Sustainable Design Methodology—Introducing the ‘Biomimicry for Sustainability’ Framework. *Biomimetics* **2022**, *7*, 37. [[CrossRef](#)]
50. Hayes, S.; Desha, C.; Baumeister, D. Learning from nature—Biomimicry innovation to support infrastructure sustainability and resilience. *Technol. Forecast. Soc. Change* **2020**, *161*, 120287. [[CrossRef](#)]
51. Eggermont, M.; Shyam, V.; Hepp, A. *Biomimicry for Materials, Design and Habitats-Innovations and Applications*; Elsevier: Amsterdam, The Netherlands, 2022.
52. Zari, M.P. *Regenerative Urban Design and Ecosystem Biomimicry*; Routledge: London, UK, 2019.
53. Blanco, E. Producing Benefits for Nature and Society: An Urban Design Framework Based on Ecosystem-Level Biomimicry and Regenerative Design, Doctoral thesis, National Museum of Natural History Paris, France, Defended 21/10/2022. Available online: <https://hal.science/tel-03895111> (accessed on 9 January 2023).
54. Lepora, N.F.; Verschure, P.; Prescott, T.J. The state of the art in biomimetics. *Bioinspir. Biomim.* **2013**, *8*, 013001. [[CrossRef](#)]
55. Singh, R.A.; Yoon, E.S.; Jackson, R.L. Biomimetics: The science of imitation nature. *Tribol. Lubr. Technol.* **2009**, *65*, 40.
56. Jović, B.S.; Mitić, A.D. Exploration of nature-based biomimetic approach in landscape architectural design: Parametric study of candelabra model design. *Vis. Comput. Ind. Biomed. Art* **2020**, *3*, 25. [[CrossRef](#)]
57. Mazzoleni, I. *Architecture Follows Nature: Biomimetic Principles for Innovative Design*; CRC Press: Boca Raton, FL, USA, 2013.
58. Antonioli, M. *Biomimétisme: Science, Design Et Architecture*; Loco: Paris, France, 2017.
59. Chayaamor-Heil, N.; Montas, N. Biomimetic Building Skin: Living Envelope for Contemporary Architecture. In *Book, the Power of Skin: New Materiality in Contemporary Architectural Design*; AKRIT Architecture Research Group: Madrid, Spain, 2018; Available online: <https://hal.archives-ouvertes.fr/hal-02890834/> (accessed on 31 August 2022).
60. Kuru, A.; Oldfield, P.; Bonser, S.; Fiorito, F. Biomimetic adaptive building skins: Energy and environmental regulation in buildings. *Energy Build.* **2019**, *205*, 109544. [[CrossRef](#)]
61. Cruz, E. 2021 Multi-criteria Characterization of Biological Interfaces: Towards Multi-functional Biomimetic Building Envelopes. Doctoral Thesis, National museum of natural history of Paris, Paris, France, 4 February 2021.
62. Cohen, Y.H.; Reich, Y. *Biomimetic Design Method for Innovation and Sustainability*; Springer International Publishing: Cham, Switzerland, 2016. [[CrossRef](#)]
63. Hubert, T.; Dugué, A.; Vogt Wu, T.; Bruneau, D.; Aujard, F. Exploiting the Potential of Nature for Sustainable Building Designs: A Novel Bioinspired Framework Based on a Characterization of Living Envelopes. In *Bionics and Sustainable Design*; Palombini, F.L., Muthu, S.S., Eds.; Environmental Footprints and Eco-Design of Products and Processes; Springer: Singapore, 2022. [[CrossRef](#)]
64. Gosztonyi, S. Physiomimetic Façade Design: Systematics for a function-oriented transfer of biological principles to thermally-adaptive façade design concepts. *A+BE | Archit. Built Environ.* **2022**, *4*, 1–404. [[CrossRef](#)]
65. Pawlyn, M. *Biomimicry in Architecture*, 1st ed.; RIBA Publishing: London, UK, 2011.
66. Pawlyn, M. *Biomimicry in Architecture*, 2nd ed.; RIBA publishing: London, UK, 2016.
67. Goel, A.K.; Vattam, S.; Wiltgen, B.; Helms, M. Information-processing theories of biologically inspired design. In *Biologically Inspired Design*; Springer: Berlin, Germany, 2014; pp. 127–152.
68. Nagel, J.K.S. A Thesaurus for Bioinspired Engineering Design. In *Biologically Inspired Design*; Goel, A.K., McAdams, D.A., Stone, R.B., Eds.; Springer: London, UK, 2014.
69. Chiu, I.; Shu, L.H. Biomimetic design through natural language analysis to facilitate cross-domain information retrieval. In *AI Edam*; Cambridge University Press: Cambridge, UK, 2007; Volume 21, pp. 45–59.
70. Badarnah, L.; Kadri, U. A methodology for the generation of biomimetic design concepts. *Archit. Sci. Rev.* **2015**, *58*, 120–133. [[CrossRef](#)]
71. Graeff, E.; Maranzana, N.; Aoussat, A. Biological Practices and Fields, Missing Pieces of the Biomimetics’ Methodological Puzzle. *Biomimetics* **2020**, *5*, 62. [[CrossRef](#)]
72. Fayemi, P.; Chekchak, T.; Bersano, G.; Maranzana, N.; Aoussat, A. *Biomimétisme et Supports Méthodologiques*; Techniques de l’Ingénieur: Saint-Denis, France, 2015.
73. Fayemi, P.; Maranzana, N.; Bersano, G. *Assessment of the Biomimetic Toolset—Design Spiral Methodology Analysis, Assessment of the Biomimetic Toolset—Design Spiral Methodology Analysis*; Springer: New Delhi, India, 2015; pp. 27–38.
74. Speck, T.; Speck, O. Process sequences in biomimetic research. In *WIT Transactions on Ecology and the Environment*; WIT Press: Southampton, UK, 2008; Volume 114.
75. Helms, M.; Vattam, S.S.; Goel, A.K. Biologically inspired design: Process and products. *Des. Stud.* **2009**, *30*, 606–622. [[CrossRef](#)]
76. Zari, M.P. Biomimetic Approaches to Architectural Design for Increased Sustainability. In *Proceedings of the Sustainable Building Conference, Auckland, New Zealand, 14–16 November 2007*.

77. Lopez, M. How plants inspire façades. From plants to architecture: Biomimetic principles for the development of adaptive architectural envelopes. *Renew. Sustain. Energy Rev.* **2017**, *67*, 692–703. [CrossRef]
78. Badarnah, L. *Environmental Adaptation of Buildings through Morphological Differentiation*; Advanced Building Skins: Bern, Switzerland, 2018.
79. Heil, N.; (MAP MAACC CNRS/ENSAPLV, Paris, France); Wilford, M.; (DP architecture, London, England). Private interview of the case study: Esplanade Theatre inspired by Durian. Research project BiomimArchD 2019–2021 funded by MITI CNRS, France. 2019.
80. San Ha, N.; Lu, G.; Shu, D.; Yu, T.X. Mechanical properties and energy absorption characteristics of tropical fruit durian (*Durio zibethinus*). *J. Mech. Behav. Biomed. Mater.* **2019**, *104*, 103603.
81. Subhadrabandhu, S.; Ketsa, S. *Durian: King of Tropical Fruit*; CABI Publishing: Oxfordshire, UK, 2001.
82. Aizenberg, J.; Weaver, J.C.; Thanawala, M.S.; Sundar, V.C.; Morse, D.E.; Fratzi, P. Skeleton of *Euplectella* sp.: Structural Hierarchy from the Nanoscale to the Macroscale. *Science* **2005**, *309*, 275–278. [CrossRef]
83. Woesz, A.; Weaver, J.C.; Kazanci, M.; Dauphin, Y.; Aizenberg, J.; Morse, D.E.; Fratzi, P. Micromechanical properties of biological silica in skeletons of deep-sea sponges. *J. Mater. Res.* **2006**, *21*, 2068–2078. [CrossRef]
84. Heil, N.; (MAP MAACC CNRS/ENSAPLV, Paris, France); non specific author; (Norman Forster & Partners Architecture, London, England). Private interview of the case study: Swiss Re inspired by Venus'flower basket. Research project BiomimArchD 2019–2021 funded by MITI CNRS, France.
85. Cortizo, M.; Laufs, P. Genetic basis of the “sleeping leaves” revealed. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 1474–1475. [CrossRef] [PubMed]
86. ArtBuild: Pho'liage. Available online: <https://www.artbuild.com/lab/pholiage> (accessed on 5 May 2022).
87. Charpentier, L.; Cruz, E.; Nenov, T.; Guidoux, K.; Ware, S. Pho'liage: Towards a Kinetic Biomimetic Thermoregulating Façade. In *Bionics and Sustainable Design*; Palombini, F.L., Muthu, S.S., Eds.; Environmental Footprints and Eco-Design of Products and Processes; Springer: Singapore, 2022. [CrossRef]
88. ArtBuild. Available online: <https://www.artbuild.com/work> (accessed on 5 May 2022).
89. Solcerova, A.; Van Emmerik, T.; Hilgersom, K.; Van de Ven, F.; Van de Giesen, N. Uchimizu: A Cool(ing) Tradition to Locally Decrease Air Temperature. *Water* **2018**, *10*, 741. [CrossRef]
90. Baker, L.B. Physiology of sweat gland function: The roles of sweating and sweat composition in human health. *Temperature* **2019**, *6*, 211–259. [CrossRef] [PubMed]
91. Di Salvo, S. Façade Solar Control and Shading Strategies for Buildings in the Mediterranean Region. *Int. J. Environ. Sci. Sustain. Dev.* **2020**, *5*, 32. [CrossRef]
92. Skolkovo–District 11, Bechu & Associés. Available online: <https://www.bechuetassocies.com/en/projet/skolkovo-innovation-center-district-11> (accessed on 2 September 2022).
93. Ancel, A.; Gilbert, C.; Poulin, N.; Beaulieu, M.; Thierry, B. New insights into the huddling patterns of emperor penguins. *Anim. Behav.* **2015**, *110*, 91–98. [CrossRef]
94. Waters, A.; Blanchette, F. Modeling Huddling Penguins. *PLoS ONE* **2012**, *7*, e50277. [CrossRef]
95. Zitterbart, D.P.; Wienecke, B.; Butler, J.P.; Fabry, B. Coordinated movements prevent jamming in an emperor penguin huddle. *PLoS ONE* **2011**, *6*, e20260. [CrossRef]
96. Biomimexpo 2017, Bechu Architectes, Pablo Lorenzino Talk. Available online: [https://www.youtube.com/watch?v=2FUc28E0\\_BU](https://www.youtube.com/watch?v=2FUc28E0_BU) (accessed on 18 January 2023).
97. Ronde Des Manchots Empereurs Et Constructions. Available online: <https://www.dailymotion.com/video/x6gl85r> (accessed on 18 January 2023).
98. Ecology (Wikipedia). Available online: <https://en.wikipedia.org/wiki/Ecology> (accessed on 2 September 2022).
99. Delmas, E.; Besson, M.; Brice, M.H.; Burkle, L.A.; Dalla Riva, G.V.; Fortin, M.J.; Gravel, D.; Guimarães, P.R., Jr.; Hembry, D.H.; Newman, E.A.; et al. Analyzing ecological networks of species interactions. *Biol. Rev.* **2019**, *94*, 16–36. [CrossRef]
100. The Sahara Desert Project, Exploration Architecture. Available online: <http://www.exploration-architecture.com/projects/sahara-forest-project> (accessed on 2 September 2022).
101. Drake, C. Biomimicry: Emulating the Closed-Loops Systems of the Oak Tree for Sustainable Architecture. Master's Thesis, University of Massachusetts Amherst, Amherst, MA, USA, February 2014. Available online: <https://scholarworks.umass.edu/theses/602> (accessed on 4 January 2023).
102. Regenvillages. Available online: <https://www.regenvillages.com/> (accessed on 3 September 2022).
103. EFFEKT, Regen Villages. Available online: <https://www.effekt.dk/regenvillages> (accessed on 3 September 2022).
104. Wanieck, K.; Fayemi, P.-E.; Maranzana, N.; Zollfrank, C.; Jacobs, S.R. Biomimetics and its tools. *Bioinspir. Biomim. Nanobiomater.* **2017**, *6*, 53–66. [CrossRef]
105. Biomimicry Institute AskNature—Innovation Inspired by Nature. Available online: <https://asknature.org/> (accessed on 23 August 2022).
106. Deldin, J.-M.; Schuknecht, M. The AskNature Database: Enabling Solutions in Biomimetic Design. In *Biologically Inspired Design*; Springer: London, UK, 2014; pp. 17–27. ISBN 978-1-4471-5248-4.
107. Hooker, G.; Smith, E. AskNature and the Biomimicry Taxonomy. *Insight* **2016**, *19*, 46–49. [CrossRef]
108. Nagel, J.K.S.; Nagal, R.L.; Stone, R.B.; McAdams, D.A. Function-based, biologically inspired concept generation. In *AL EDAM*; Cambridge University Press: Cambridge, UK, 2010; Volume 24, pp. 521–535.

109. Chakrabarti, A.; Sarkar, P.; Leelavathamma, B.; Nataraju, B.S. A functional representation for aiding biomimetic and artificial inspiration of new ideas. In *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, USA*; Cambridge University Press: Cambridge, UK, 2005; Volume 19, pp. 113–132.
110. Glier, M.W.; Tsenn, J.; Linsey, J.S.; McAdams, D.A. A methodology for supporting transfer in biomimetic design. In *Artificial Intelligence for Engineering Design Analysis and Manufacturing*; Cambridge University Press: Cambridge, UK, 2010; Volume 24, pp. 483–506.
111. Glier, M.W.; Tsenn, J.; Linsey, J.S.; McAdams, D.A. Methods for supporting bio-inspired design. *ASME Conf. Proc.* **2011**, *54884*, 737–744. [[CrossRef](#)]
112. Bogatyrev, N.; Bogatyreva, O. BioTRIZ: A Win-Win Methodology for Eco-innovation. *Environ. Sci.* **2014**, *3*, 297–314. [[CrossRef](#)]
113. Chayaamor-Heil, N.; Vitalis, L. Biology and architecture: An ongoing hybridization of scientific knowledge and design practice by six architectural offices in France. *Front. Archit. Res.* **2021**, *10*, 240–262. [[CrossRef](#)]
114. Perricone, V.; Santulli, C.; Rendina, F.; Langella, C. Organismal Design and Biomimetics: A Problem of Scale. *Biomimetics* **2021**, *6*, 56. [[CrossRef](#)]
115. Bechthold, M.; Weaver, J.C. Materials science and architecture. *Nat. Rev. Mater.* **2017**, *2*, 1–19. [[CrossRef](#)]
116. Wang, Y.; Naleway, S.E.; Wang, B. Biological and bioinspired materials: Structure leading to functional and mechanical performance. *Bioact. Mater. Sci. Direct* **2020**, *5*, 745–757. [[CrossRef](#)]
117. Krieg, O.D. Biomimetic Lightweight Timber Plate Shells: Computational Integration of Robotic Fabrication, Architectural Geometry and Structural Design. In *Advances in Architectural Geometry*; Block, P., Knippers, J., Niloy, J.M., Wang, W., Eds.; Springer: Berlin/Heidelberg, Germany, 2014.
118. Srisuwan, T. Review Article: Biomimetic in Lightweight Structures: Solution for Sustainable Design. *Built* **2019**, *14*, 7–16. [[CrossRef](#)]
119. Chayaamor-Heil, N.; Hannachi-Belkadi, N. Towards a Platform of Investigative Tools for Biomimicry as a New Approach for Energy-Efficient Building Design. *Build. J.* **2017**, *7*, 19. [[CrossRef](#)]
120. Xing, Y.; Jones, P.; Bosch, M.; Donnison, I.; Spear, M.; Ormondroyd, G. Exploring design principles of biological and living building envelopes: What can we learn from plant cell walls? In *Intelligent Buildings International*; Taylor & Francis: London, UK, 2018; Volume 10.
121. Cruz, E.; Hubert, T.; Chancoco, G.; Naim, O.; Chayaamor-Heil, N.; Cornette, R.; Menezo, C.; Badarnah, L.; Raskin, K.; Aujard, F. Design processes and multi-regulation of biomimetic building skins: A comparative analysis. *Energy Build.* **2021**, *246*, 111034. [[CrossRef](#)]
122. Blanco, E.; Pedersen Zari, M.; Raskin, K.; Clergeau, P. Urban Ecosystem-Level Biomimicry and Regenerative Design: Linking Ecosystem Functioning and Urban Built Environments. *Sustainability* **2021**, *13*, 404. [[CrossRef](#)]
123. Blanco, E.; Cruz, E.; Lequette, C.; Raskin, K.; Clergeau, P. Biomimicry in French Urban Projects: Trends and Perspectives from the Practice. *Biomimetics* **2021**, *6*, 27. [[CrossRef](#)] [[PubMed](#)]
124. Tero, A.; Kobayashi, R.; Nakagaki, T. *Physarum Solver: A Biologically Inspired Method of Road-Network Navigation*; Elsevier Science: Amsterdam, The Netherlands, 2005.
125. Tero, A.; Takagi, S.; Saigusa, T.; Ito, K.; Bebbler, D.P.; Fricker, M.D.; Yumiki, K.; Kobayashi, R.; Nakagaki, T. Rules for Biologically Inspired Adaptive Network Design. *Sciences* **2010**, *327*, 439. [[CrossRef](#)]
126. Knippers, J.; Nickel, K.G.; Speck, T. *Biomimetic Research for Architecture and Building Construction: Biological Design and Integrative Structures*; Springer International Publishing: Kiel, Germany, 2016; ISBN 978-3-319-46372-8.
127. Knippers, J. *Biomimetics for Architecture: Learning from Nature*; Birkhäuser: Berlin, Germany; Boston, MA, USA, 2019. [[CrossRef](#)]
128. Graeff, E.; Maranzana, N.; Aoussat, A. Biomimetics, where are the biologists? *J. Eng. Des.* **2019**, *30*, 289–310. [[CrossRef](#)]

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.