

Article

Form Follows Environment: Biomimetic Approaches to Building Envelope Design for Environmental Adaptation

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Academic Editor: Maibritt Pedersen Zari

Received: 1 November 2016; Accepted: 9 May 2017; Published: 12 May 2017

Abstract: Building envelopes represent the interface between the outdoor environment and the indoor occupied spaces. They are often considered as barriers and shields, limiting solutions that adapt to environmental changes. Nature provides a large database of adaptation strategies that can be implemented in design in general, and in the design of building envelopes in particular. Biomimetics, where solutions are obtained by emulating strategies from nature, is a rapidly growing design discipline in engineering, and an emerging field in architecture. This paper presents a biomimetic approach to facilitate the generation of design concepts, and enhance the development of building envelopes that are better suited to their environments. Morphology plays a significant role in the way systems adapt to environmental conditions, and provides a multi-functional interface to regulate heat, air, water, and light. In this work, we emphasize the functional role of morphology for environmental adaptation, where distinct morphologies, corresponding processes, their underlying mechanisms, and potential applications to buildings are distinguished. Emphasizing this morphological contribution to environmental adaptation would enable designers to apply a proper morphology for a desired environmental process, hence promoting the development of adaptive solutions for building envelopes.

Keywords: biomimetics; building envelope; architectural design; morphology; adaptation; environment; heat; water; air; light

1. Introduction

Buildings account for a significant part of the total energy consumption in developed countries [1,2]. With the increasing environmental awareness and the need to reduce energy demands, developing more sustainable and resilient solutions is vital. Resilience is typically associated with the capacity of an element to recover from a change, and/or respond appropriately to variant conditions. In nature, this problem is tackled by applying strategies of *adaptation*—the process in which an organism becomes better suited to its environment, that is fundamental for efficiency and survival over the short and long terms [3]. Designing building envelopes that have the capacity to adapt to their environments will not only enhance its resiliency but also its sustainability, by requiring less energy to operate and employing resources more efficiently [4–9]. To this end, environmental adaptation strategies from nature are studied, in terms of air, water, heat, and light. These four environmental aspects were chosen amongst others because of their significant influence on occupant comfort and needs in buildings, and their immediate impact on global energy consumption.

Biomimetics is a rapidly growing discipline in engineering, and an emerging design field in architecture. In biomimetics, solutions are obtained by emulating strategies, mechanisms, and principles found in nature. Due to the multidisciplinary nature of biomimetics, designers often tackle

difficulties throughout the design process, where biophysical information is not easily accessible. One of the challenges in implementing biomimetics lies in the search for, and the selection of, appropriate strategies from the large database found in nature [10]. Thus, the establishment of a systematic way to devise adaptation solutions is a significant initial step towards a biomimetic design that is capable of regulating air, heat, water, and/or light.

In this work, considering the building envelope as an interface, we define key functions for environmental adaptation; explore how these functions are carried out in nature; and identify the morphological means that should be employed to become better suited to their environments. Furthermore, we discuss opportunities for multi-regulation, and the role of morphology in promoting the development of biomimetic applications.

2. Adaptive Building Envelopes

Buildings are structures of defined spaces that protect people and their belongings from the exterior environment, in particular harsh weather conditions, such as wind, rain, and excess of sun radiation. Buildings evolved from primitive structures providing mere shelters to sophisticated structures responding to environmental context, where various features and elements have emerged from necessity to raise comfort and quality of life [11,12]. Building envelopes, consisting of the basic elements of windows, walls, roofs, and floors, represent the interface between the outdoor environment and the indoor occupied spaces, where significant energy savings can be achieved when designing proper solutions that are responsive to specific climatic factors [13]. Environmental conditions are constantly changing and creating new challenges for building envelopes to accommodate [14]. Occupant's activities as well as environmental factors, such as air movement, humidity, temperature, solar radiation, air quality, noises, affect comfort inside buildings [15,16]. Considering the building envelope as a barrier or a shield, such as applying high resistant thermal solutions [17], limits design solutions that utilize environmental changes in their performance and create mediums to affect interior conditions more efficiently. Vernacular building solutions that reflect environmental context by utilizing prevalent winds, radiation, and temperature, promote improved energy performance of buildings [18], yet these solutions are not necessarily air-tight and water-tight. In this respect, implementing adaptive solutions that reflect environmental context can enhance the performance of building envelopes, increase occupant comfort, and potentially reduce energy demands.

Proposals for adaptive building envelopes have been emerging since the last century; some are theoretical, yet potentially applicable. A pioneering theoretical example from the 1980s is the "polyvalent wall" [19]; it consists of thin layers that are able to absorb, reflect, filter, and transfer energies from the environment. Nowadays, emerging technologies together with advanced manufacturing techniques have great potential to realize more complicated concepts [20]. These technologies, in particular information technology, enable buildings to self-adjust and respond to varying environmental conditions [20]. Mechanical services attachment and integration of advanced materials are distinguished as current means for adaptation.

Some advances in building envelope design have aesthetic and functional roles, such as the Kunsthhaus Graz by architects Cook and Fournier, where its free form envelope stands out of the surrounding traditional buildings, and the outer media skin illuminates as a response to exhibited art projects [21]; whereas a functional example is the Council House 2 Building in Melbourne by architect Mick Pearce, receiving a top green star rating, where the envelope consists of several systems that manage ventilation, water, lighting, and cooling, to enhance the sustainability and efficiency of the building [22], see Figure 1. Furthermore, advances in recent years represent a more adaptive trend in building envelope design, where responsive and kinetic principles are more prevalent [23–25]. For example, the Bio-Intelligent Quotient (BIQ) building, by Splitterwerk and Arup, consists of algae filled panels (photobioreactors) that capture heat and generate electricity [26]; and the One Ocean Thematic Pavilion, by SOMA Architecture, consists of a kinetic facade of deformable lamellas that control day-lighting [27]; see Figure 1. Despite the existing array of advanced building designs,

the majority of the building stock is static. In this paper, we propose to implement successful adaptation strategies from nature to building envelope design to facilitate adaptation to environmental conditions while employing materials and other resources more efficiently.



Figure 1. From left to right: the free form envelope of the Kunsthhaus in Graz, used with permission ©Heribert Pohl; the turbines of Council House 2 in Melbourne, courtesy of Nick Carson; the façade of the BIQ building consisting of algae filled panels, used with permission ©NordNordWest; the bending façade of One Ocean Thematic Pavilion, photos courtesy of SOMA.

3. Adaptation in Nature

Adaptation is the ability to maintain stable internal conditions while tolerating changing environmental conditions. In biology, it is called homeostasis—a fundamental characteristic in living organisms for survival. Several factors are constantly regulated by body of organisms to achieve homeostasis, including concentration of nutrients, oxygen, salts, wastes, heat, pressure, and volume [3]. Adaptation is also observed in structures built by animals [28], where immediate surroundings of organisms promote homeostasis. Adaptation occurs at various timescales: throughout the day, e.g., solar tracking by sunflowers; throughout the seasons, e.g., seasonal changes in blubber distribution and thickness in seals; and/or throughout evolution, e.g., human skin color. The changing and/or extreme conditions of the environment are significant challenges for adaptation, where different means have evolved in organisms to adapt to their environments.

3.1. Adaptation Means

Varied environmental conditions have necessitated the evolution of unique adaptation strategies in nature in terms of physiology, morphology, and behavior for survival.

- (1) Physiological adaptation is a response by an organism to an external stimulus for maintaining homeostasis. For example, certain biochemical and molecular processes enable mangroves, inhabiting inter-tidal zones along the coast, to tolerate high salinity levels [29], see Figure 2.
- (2) Morphological adaptation is a structural or geometrical feature that enhances the adjustment of an organism to a particular environment and enables better functionality for survival, such as size, form, and pattern. The special form of stem, the small and thin leaves, and the extensive root system, are examples of morphological adaptations among desert plants, see Figure 3. Such stems allow water storage and self-shading situations, small leaves reduce water loss, and extensive root systems enhance moisture collection in plants.
- (3) Behavioral adaptation is the action an organism takes for survival, such as bird migration and bee swarming. In order to cope with new conditions that the environment generates, organisms behave and respond in a certain way to complement physiological and morphological means. For example, penguins inhabiting the extreme environment of the Antarctic supplement physiological adaptation strategies with huddling, see Figure 4.



Figure 2. Left: mangrove habitat in Costa Rica. Middle: mangrove root system in direct contact with salty water. Right: the deposition of salt in the form of crystals on older leaves close to falling, courtesy of Peripitus.

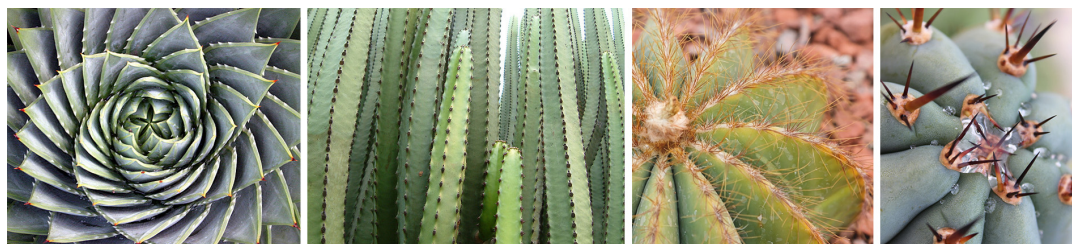


Figure 3. Morphological variations in cacti as an adaptive response to their harsh environments, photos courtesy of (from left to right): Axsom, Topinambour, Johansson, and Mattdooley40.



Figure 4. Left: a group of huddling penguins, which consists of about 2500 males, reproduced from Gilbert et al. [30]. Middle: a closer view of huddling penguins, courtesy of Australian Antarctic Division. Right: infrared image of penguin [31], photo credit: Université de Strasbourg and Centre National de la Recherche Scientifique (CNRS), Strasbourg, France.

3.2. Environmental Challenges

Living organisms and their environments are interrelated. They have developed through evolution adaptation strategies for different environmental conditions. Harsh environmental conditions, such as extremes of temperature, humidity, solar radiation, and/or pressure, pose real survival challenges to organisms. In cold environments, where the temperature gradient between body and environment is high, some organisms succeed in maintaining core body temperature within a very narrow range. Maintaining an appropriate core temperature is accomplished by radiation managing, conduction and convection reduction, and metabolic rate regulation. These strategies can be morphological, physiological, as well as behavioural. For example, birds use multiple strategies for retaining heat; chickadees decrease conductance in the cold by raising their feathers and withdraw head and feet into feathers (behavioural) [32]. They trap an insulating layer of air close to their body and in doing so reduce heat losses (morphological). They also allow the peripheral tissues temperature to drop while maintaining a stable core temperature (physiological). All these together result in a

decreased peripheral circulation, increased insulation thickness, and enlarged volume, that contributes to maintaining the core temperature in a very narrow range. In environments where ambient temperature is higher than body temperature, the body receives heat by conduction, convection, and radiation. To dissipate metabolic heat and heat gained from the environment, mammals often use evaporation, and other physiological and behavioural strategies.

Water-scarce environments pose great challenges to their local organisms. Seeking alternative sources of water through adaptation strategies is an extraordinary ability for survival. For example, in the Namib desert, one of the harshest environments on earth [33], fog represents an alternative source of water. Some organisms employ special adaptation strategies that enhance condensation on surfaces from fog events for water harvesting [34–38].

Solar radiation is a vital environmental factor that changes throughout various timescales, i.e., hours, days, and seasons. Some environments have high irradiation rates (e.g., desert), while others barely have any (e.g., deep ocean). Organisms perceive light for different purposes, such as gaining information from the surrounding environment for adequate response, or as a source of energy [39]. Adaptation strategies to light are diverse, where architecture of plants and eyes dominate in literature for unique light interception strategies.

4. Biomimetics

Biomimetics is derived from the Greek, *bios* meaning life, and *mimesis* meaning to imitate. Other used terminologies include biomimicry, bio-inspired, bionic, or bionics. In biomimetics, solutions are obtained by emulating strategies, mechanisms, and principles found in nature. Nature provides a large database of adaptation strategies that can be implemented in design in general, and in the design of building envelopes in particular. Several benefits are identified for applying biomimetics to solving building problems, such as enhancing creativity and innovation [40–42]; optimizing resource (i.e., materials and energy) use in buildings [43]; lowering pollution, benefiting health, and mitigating urban heat island effects [44]; and providing a foundation for environmentally responsive developments [45–49]. Two main approaches with various terminologies exist in biomimetics: (1) *solution-based*, where an observation of nature inspires a technological application; and (2) *problem-based*, where a solution from nature is sought for a particular engineering problem. Despite some differences in the initial phases between the two approaches, both show a similar trend in the transfer from the biological to technological domain [10].

Due to the interdisciplinary nature of a biomimetic process, the design concept generation involves three different domains: *problem*, *nature*, and *solution*, where collaborations between scientists from diverse fields are advantageous. In general, a biomimetic design process consists of the following: identify a challenge; explore natural systems; extract those that perform the required functions; analyze strategies and principles; abstract strategies; translate to a design concept; evaluate and validate the solution; and apply to solve a problem. The transformation of strategies from nature into technical solutions could become a complicated multidisciplinary process. Its complexity further increases, and often conflicts arise, when integrating a number of strategies from different systems to achieve a design solution [50,51]. Several biomimetic approaches have emerged in the last decade to assist the transitions between domains [52–54]. Yet, clear indications to architectural design are still limited.

In architecture, few explorations have been carried out to examine ways in which biomimetics is enhanced. For example, investigations of terminologies from life sciences that could have similar use in buildings [55]; analyzing ecosystem interactions for higher sustainability and optimized resource use in the built environment [43,46,56]; exploring ideas from nature for inspiration [48]; and identifying strategies of animal skins for per-formative constructions [47]. Although these explorations reveal some unique aspects from nature to inform architecture, biomimetics as an effective design tool is still a challenge. Morphology and form are the most common traits to be transferred from natural systems into architecture [57–59]. However, such traits seldom retain any function of the imitated systems from nature, and therefore hardly represent a successful biomimetic design. The main challenges remain:

the broad range of possibilities, the difficulties in the representation of the biophysical knowledge, and the challenging abstraction and transformation of relevant principles [10]. Nonetheless, the emerging biomimetic methods and frameworks for architectural applications are gaining a systematic trend to facilitate design concept generation, rather than limiting to specific examples [10,45,60–63].

In this work, we follow the systematic approach of [10,45], where solutions for environmental adaptation are sought from nature and classified based on their functional attributes. The classification of biophysical information based on functional aspects is a favorable approach for transformation in biomimetics, as systems in nature have a functional reason, thus establishing a suitable analogy is more relevant. Seeking solutions from nature involves three interrelated specialized areas; where *functions* and *morphology* are identified as key areas to promote transition between domains, see Figure 5. The following sections elaborate on these two areas, and define potential convergences to facilitate a biomimetic design process towards environmental adaptation.

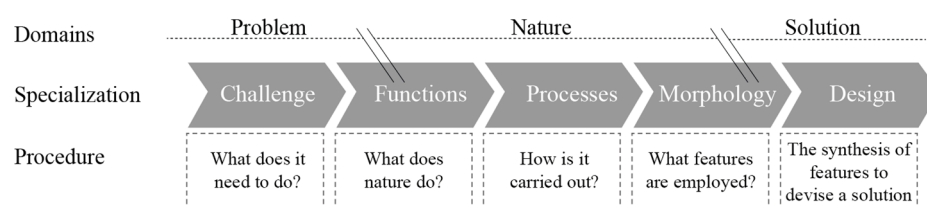


Figure 5. Diagram showing the domains of a biomimetic design process, the different specialized areas involved in addressing a challenge, the potential areas where domains intersect (i.e., *functions* and *morphology*), and the relevant procedures to solve a problem.

5. Principles of Environmental Adaptation for Biomimetic Applications

The challenging abstraction and transformation from the nature domain to the engineering domain can be carried out through identifying key categories, e.g., anatomy, behavior, and ecology [64]. Identifying levels at which Biomimicry can be applied is also important in architectural design, where information can be obtained from an organism, behavior, or an ecosystem [65]. Here, we examine adaptation strategies from several sources: organ, organism, structure, system, or behavior, such as in [45].

Both buildings and natural systems (i.e., organisms and their structures) are exposed to changing environmental conditions, which often require management of heat, air, water, and light. In some organisms, the management is accomplished through their skin functioning as an environmental filter, whereas in others, it is achieved through their built structures. Considering the building envelope as a medium, rather than a barrier, opens new avenues in design, where functional attributes are more valid. First, we define main functions relevant for both buildings and systems in nature. Then, we identify relevant processes that accomplish these functions, and put collected data into their physical and environmental contexts, altogether to be considered when applying a design solution to building envelopes.

5.1. Functional Convergences

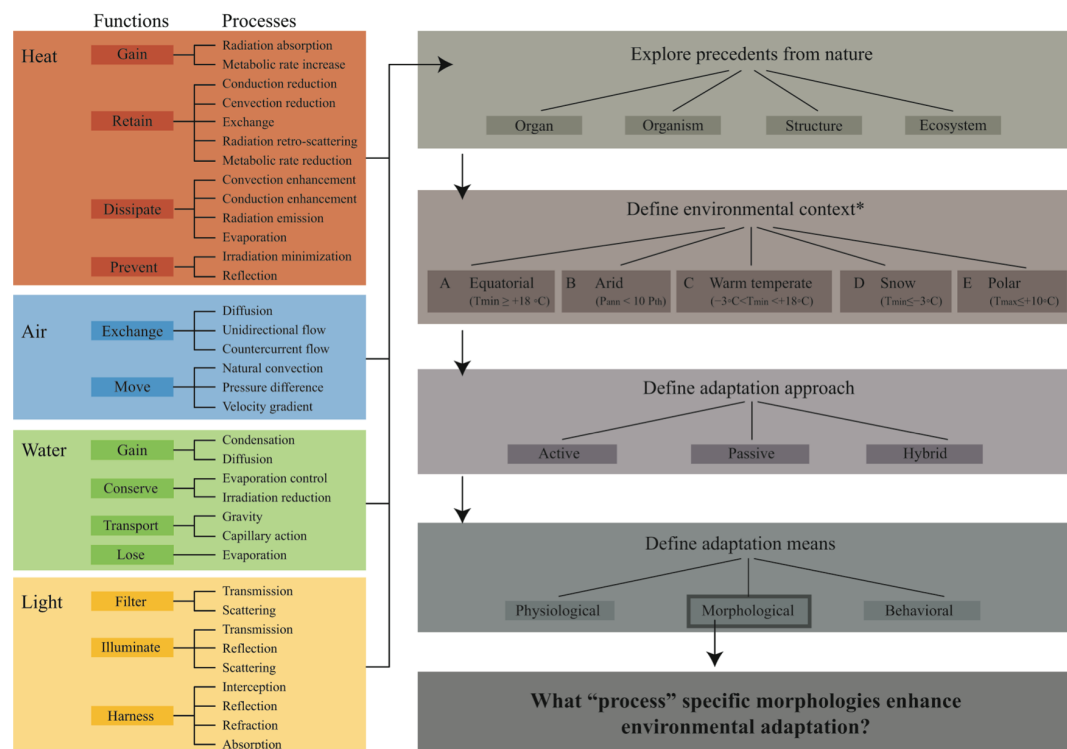
In this initial step, a functional convergence is sought. This convergence is a significant language bridge between two different domains that rarely meet and communicate. By defining the relevant functions, a more directed and focused search for strategies from nature can be carried out. Several essential environmental tasks and goals were determined for both buildings and nature, and common key functions (buildings and nature) that manipulate these challenging goals were defined and refined, see Table 1. Since the functions constitute a fundamental link between adaptation problems in buildings and potentially relevant solutions in nature, further elaboration on how some specific functions are accomplished in nature is discussed in Section 5.2.

Table 1. Identifying functional convergences (key functions) for different environmental challenges in buildings and in nature.

| Environmental Challenges | Heat | Air | Water | Light |
|--------------------------|--|---|---|--|
| Buildings | Thermal comfort Energy | Survival Oxygen supply CO ₂ supply Cooling Ventilation | De/humidification Cooling Supply Waste Distribution | Day-lighting Visual comfort Media Energy |
| Nature | Survival Thermoregulation Reproduction | Survival Oxygen supply CO ₂ supply Cooling Ventilation | Survival Thermoregulation Chemical reactions | Survival Photosynthesis Vision Communication Sensing |
| Functional Convergences | Gain Retain Dissipate Prevent | Exchange Move | Gain Conserve Transport Lose | Filter Illuminate Harness |

5.2. Environmental Processes

The identified key functions are accomplished via a series of processes that lead to adaptation, which are often based on basic laws of physics. A literature review was carried out to source out adaptation strategies found in nature for heat, air, water, and light management. These strategies were analyzed to identify unique processes applied at various environmental challenges. The list of current findings is summarized in Figure 6, and the procedure to identify adaptation means is outlined. The array of processes represents ways by which key functions are carried out, where similar approaches can be applied to buildings. In a design process, where ideas are based on functions, it is important to maintain links between physical processes and their applications. Section 6 showcases some morphological means that enhance these processes for environmental adaptation.

**Figure 6.** Combined exploration model of four environmental aspects, relevant functions, corresponding processes, and the procedures to identify morphological means for adaptation.

* According to Koppen classification [66].

5.2.1. Heat

Organisms maintain their body temperature within very narrow ranges in order to survive. Beyond generating heat metabolically, heat is transferred between animals and their environment by conduction, convection, radiation, and evaporation. These processes are carried out by organisms and/or employed in their built structures to gain, retain, dissipate, and prevent heat [67]. For example, termite mounds dissipate heat via natural convection [68], and toucans dissipate heat via radiation emission [69]. A more comprehensive overview of processes can be found in previous work of [67,70].

5.2.2. Air

Air is a significant source of oxygen and carbon dioxide for organisms, which is required, among others, to produce energy in the process of food and materials oxidation [32]. Not only organisms, but also structures built by animals need air supply and adequate oxygen concentrations. Organisms often supplement thermoregulatory strategies with air management. In order to reach the required concentrations and supplement thermoregulation, organisms and their structures are challenged with two basic functions: move and exchange, where they have employed various strategies performed mainly via natural convection, pressure differential, velocity gradients, and countercurrent flows [45]. Some small organisms obtain a sufficient amount of oxygen by diffusion via their body surface, whereas most organisms require a special respiratory system for oxygen uptake. In environments where oxygen concentrations are low, gas is exchanged via countercurrent flows [71], e.g., gills of fish [72]. Mounds, burrows, and nests utilize natural convection and velocity gradients to move air around [73,74].

5.2.3. Water

Water adaptation strategies in nature are varied, and some extraordinary abilities are found in water-scarce environments. In terms of functions, water can be gained, conserved, transported, and/or lost for thermoregulation and other chemical reactions [63]. Some organisms gain water by condensation on their body surface [34] or constructed structures [38], as well as by absorbing water vapor directly from air via skin diffusion [75]. Other organisms reduce evaporation rates [76,77] and radiation exposures for water conservation [78]. Transporting water from one region to another at a range of scales is achieved via forces of gravity or via capillary action [79], especially in venation systems [80]. Water is lost by three means in organisms [32]: cutaneous (through skin), excretory (through urine and feces), and respiratory (during gas exchange). Water evaporation from skin or respiratory organs is one of the mechanisms for thermoregulation (latent heat transfer). Several internal and external physical factors influence the rate of evaporation [32], such as vapor pressure difference, flow rate of air, temperature, surface area, and orientation.

5.2.4. Light

Organisms need light for various purposes, such as gaining information from the surrounding environment for adequate response, or for energy matters [39]. The processes of transmission, reflection, refraction, scattering, absorption, and interception are basic means to interacting with a medium for filtering, illuminating, and harnessing light in nature [62]. For example, the silver ragwort scatters light to filter and reduce incident light [81]; the Venus flower-basket illuminates by transmitting light through its intricate structure [82,83]; and some plants maximize interception to harness light [84–86].

6. Morphological Considerations for Environmental Adaptation

The environment has a significant influence on the evolution of the specific form, arrangement, and composition of natural systems [70], where morphological differentiation is often sought. In the context of the built environment, vernacular architecture is self-evident for this influence, as culture and climate have shaped buildings throughout history [12,18].

Many organisms exploit morphological and behavioral means to supplement physiological strategies for environmental adaptation. These means can significantly enhance the way specific environmental processes are carried out, often performed for different challenges simultaneously. Bones, trees, and plants are some of the elements for frequent morphological inspirations in architectural design [48,87], yet these inspirations have a limited environmental role. One of the morphological examples for functional applications is Lotusan—a self-cleaning coating used for buildings. Lotusan was inspired by the bumpy microstructure of lotus leaves that repels water and maintains a clean surface [88].

Current work distinguishes several morphological means for adaptation. These morphologies have functional tasks that are associated with specific environmental *processes*, see Table 2. For example, the presence of hexagons, spikes, and knobs on surfaces decrease the contact angle and create a thin boundary layer to enhance condensation [63], and these can be observed in some organisms inhabiting arid regions [35,89,90]. Certain morphologies can also influence other environmental challenges, such as trichomes that enhance water condensation and light scattering. The results of environmental *process* specific morphologies, their role to become better suited to the environment, and their potential application to buildings, are presented in Table 2.

6.1. Opportunities for Functional Integration in Biomimetic Design

In general, design solutions address a single function at a time. In practice, a building is exposed to multiple environmental factors and is thus required to manage heat, air, water, and light (and probably other factors), simultaneously. Moreover, the environmental factors are often highly interrelated, where the regulation of one might be dependent on the regulation of the others. As an example, in order to have a proper consideration of the humidification (water regulation) of a building interior at a targeted humidity level, one needs to take into account (1) ventilation rates (air regulation) that may continuously modify the relative humidity; (2) thermal effects (heat regulation) which is coupled with humidity in determining comfortable humidity levels; and (3) effects of solar radiation (light regulation), which are coupled with heat regulation.

Some organisms have multi-functional capabilities and are able to address multiple environmental aspects simultaneously. For example, termite mounds manage air movement and retain heat; and skink scales reflect light, conserve water, and prevent heat, simultaneously, see Table 3 for more examples. If we examine elephant skin, where water and heat regulations are addressed, then we can see in Table 2 that the same morphology associated with skin (wrinkles) promotes evaporation, radiation reflection, and convective heat loss, simultaneously. Therefore, when challenged with designing a multi-functional system, it is advised to choose morphologies with multi-functional capabilities, where integration has already been successfully assessed by nature.

6.2. Opportunities for Manufacturing

Due to the complexity of natural systems in terms of morphology and composition, biomimetic applications often tackle difficulties in transferring conceptual designs into prototypes or products. However, thanks to current trends in manufacturing techniques, complex geometries and heterogeneous compositions can be produced more easily compared with conventional methods [91]. The complex geometries that are also found in nature, e.g., variable thicknesses, lattices, and grading composites, are widely applied in additive manufacturing (AM) for product development [92]. Advances in AM can be noticed in medical applications, where customization for individuals to enhance functionality is a critical issue [93,94]. AM in buildings or mainly in construction is gaining more attention, yet successful applications are limited [95].

Despite current challenges in AM technology [96,97], addressing multi-functionality by applying specialized morphologies can be enhanced by using AM rather than conventional methods, where the combination of multiple material properties with complex geometries is feasible [98], and the control of different configurations is possible to enhance functionality [99].

Table 2. Distinct morphologies, corresponding processes, their underlying mechanisms, and potential applications for environmental adaptation. * The relevant environmental aspects involved in a process: Heat (●), Air (●), Water (●), and/or Light (●).

| Morphology | Processes (●●●●) * | Mechanism | Applications |
|--------------------|--------------------------|--|---|
| Wrinkles | Evaporation ●● | Wrinkles on the surface of the skin provide sufficient surface area for holding moisture and promote evaporation [100]. Additionally, these wrinkles create self-shaded areas for reduced heat loads and generate convective currents for enhanced heat loss. | Cooling external cladding |
| | Reflection ●● | | |
| | Convection ●● | | |
| Hexagons | Flow ● | Hexagonal micro-structuring of surfaces decreases contact angle significantly and results in a super-hydrophilic surface [89], and creates an optimal pattern of capillary water flow [101,102]. Hexagonal array of facets on a spherical plane enhances light interception [103]. | Moisture and light harvesting |
| | Condensation ● | | |
| | Interception ● | | |
| Spikes | Condensation ● | Spiky leaves create a thin boundary layer that improves water collection from fog [35]. | Moisture harvesting |
| Knobs | Condensation ● | Knobs on silk fibers attract water from humid air [90]. | |
| Grooves | Transport ● | The presence of grooves on plants surfaces provides a guided water collection and transportation [104]. Termite mounds with macro grooves enhance heat dissipation and ventilation via convection [68], and create self-shaded regions. | Water distribution, ventilation, and heat dissipation |
| | Convection ●● | | |
| | Irradiation reduction ●● | | |
| Capillaries | Transport ● | Special arrangement of integument's scales create micro-channels, a semi-tubular capillary system, over body surface to transport water via capillary forces [105] | Water transportation |
| | Diffusion ● | | |
| Fractal | Flow ●● | Fractal arrangement of flow systems is energy efficient [106,107]. The fractal network of nested loops in leaves provide an optimal transportation of fluids even at events of damage [80,108]. The fractal arrangement of Fibonacci sequence of seeds results in an efficient and compact packing for maximized light interception [85]. The fractal nanostructure of scales in butterfly wings is highly reflective [109]. | Light harnessing, light shielding, and efficient transporting systems |
| | Transport ●● | | |
| | Diffusion ●● | | |
| | Interception ● | | |
| | Reflection ● | | |
| Lamellae | Reflection ● | Closely packed ridges with horizontal lamellae and micro-ribs, highly reflects certain wavelengths [109]. Variations in film thicknesses can result in 96% absorption of the incident solar radiation [110]. | Light control and energy generation |
| | Absorption ● | | |
| Pores | Evaporation ●● | Little pores on the skin surface allow direct diffusion of condensed water [75], and moisture loss in response to thermoregulatory demands. | Humidification and cooling |
| | Diffusion ●● | | |
| Trichomes | Reflection ●● | Trichomes, microscopic fibers, enhance hydrophobicity and scatter light for reduced incident light at the interface [81]. | Reducing heat loads and harvesting moisture |
| | Scattering ●● | | |
| | Condensation ● | | |
| Mounds and Funnels | Flow ● | Mounds and funnels generate velocity gradients on the surface of ground and result in pressure gradient for wind-induced ventilation of burrows [73]. | Ventilation |
| | Velocity gradient ● | | |

Table 3. Examples of pinnacles with multi-function capabilities. The plus symbol (+) denotes the challenges carried out by pinnacles as obtained from the investigation; and the minus symbol (−) denotes that no investigation regarding the specific challenge was carried out, thus it is by no means an indication that the pinnacle is incapable of achieving the specific challenge.

| Functions | Heat | | | | Air | | Water | | | | Light | | | |
|---------------------|------|--------|-----------|---------|----------|------|-------|----------|-----------|------|--------|------------|---------|--|
| Processes | Gain | Retain | Dissipate | Prevent | Exchange | Move | Gain | Conserve | Transport | Lose | Filter | Illuminate | Harness | |
| Pinnacles | | | | | | | | | | | | | | Source |
| Termite mounds | − | + | + | − | + | + | − | − | − | − | − | − | + | Korb and Linsenmair [68,111] |
| Prairie-dog burrow | − | − | + | − | + | + | − | − | − | − | − | − | − | Vogel et al. [73], Sheets et al. [112] |
| Veins/blood vessels | + | + | + | + | + | + | − | − | + | − | − | − | − | Arens and Zhang [113] |
| Human skin | − | + | + | − | − | − | − | − | − | + | − | − | − | Randall [114,115] |
| Skink scales | − | − | − | + | − | − | − | + | − | − | + | − | − | Vrcibradic and Rocha [116] |
| Elephant skin | − | − | + | + | − | − | − | − | − | + | − | − | − | Lillywhite and Stein [100] |
| Succulent | − | − | + | + | + | − | + | + | + | − | + | − | + | Björn and Govindjee [117] |

7. Conclusions

Seeking solutions or analogies from nature is a widely growing practice in research, yet practical applications to buildings for environmental adaptation are still limited. This paper is part of a larger study effort that aims to develop new technological solutions inspired by nature to enhance the environmental adaptation capability of building systems. Attention is focused on several organisms and systems from nature that employ extraordinary techniques to withstand harsh environmental

conditions, where analogue applications to buildings are relevant. Natural systems follow special morphological configurations to create interfaces, allowing optimal interaction with their immediate environment. It turns out that morphology plays a significant role in the way an environmental adaptation is carried out in nature, and provides a multi-functional interface to regulate heat, air, water, and light. As such, morphology can be considered as an appropriate base for biomimetic applications to building envelope design for environmental adaptation.

The functional convergence is a significant language bridge between two different domains that rarely meet and communicate, where refined definition of functions enhances the search for relevant strategies from nature. The combined exploration model provides the designer with an exemplary platform for searching and selecting solutions from the large database of nature. In this paper, the functional role for environmental adaptation is emphasized by morphological specialization. For example, condensation is enhanced by elevated microstructures, such as knobs and trichomes. Furthermore, certain morphologies influence multiple environmental aspects, e.g., heat and water when applying wrinkles for evaporation. This is an important observation to consider in a design process, where the regulation of one environmental aspect can be interrelated with others.

Lastly, this paper provides an exemplary systematic representation of morphologies in their environmental adaptation context. It is hoped that designers would thus consider the underlying environmental processes of distinct morphologies at the initial stages of a design process. This would promote the development of adaptive solutions for building envelopes through morphological applications, which can be tested and validated experimentally (ongoing study) and/or numerically (e.g., [57,118]). In terms of production, complex morphologies can be produced by emerging 3D printing technologies that enable the realization of various shapes, integrations, and material gradients. Further study on relevant scaling, material properties, and suitable production methods is essential to enhance morphological applications in biomimetic design.

Acknowledgments: The author acknowledges the support from the MIT-Technion Post-Doctoral Fellowship Program. The author would like to thank the anonymous reviewers of this article for their constructive comments.

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

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