15.
Morphological Differentiation for the Environmental Adaptation of Biomimetic Buildings: Skins, Surfaces, and Structures

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[NON PRINT ITEMS]

Abstract:

Morphology and form are the most common traits to be transferred from natural systems into architecture. However, such traits have seldom retained any environmental adaptation strategy of the imitated systems from nature, and therefore hardly represented a successful biomimetic design. In the last decade, more advanced solutions have emerged with promising multi-functional capabilities. In this chapter we discuss the building envelope as a medium that utilizes morphological differentiation to adapt to its environment. Implementing morphological solutions from nature that are designed for environmental adaptations such as the regulation of heat, air, water, and/or light, can enhance the performance of building envelopes, increase occupant comfort, and potentially reduce energy demands. We classify morphological solutions for buildings into three classes of skins, surfaces, and structures. Nowadays, emerging technologies together with advanced manufacturing techniques have a great potential to realize more complicated concepts. These technologies, in combination with information technology, would enable buildings to self-adjust and respond to varying environmental conditions.

Key Words: multi-regulation, multi-functional, building envelopes, adaptive, architecture, design, morphological differentiation

15.1. Introduction

The environment is in constant flux, and the need to manage these changes more efficiently in buildings is becoming more urgent. Natural systems adapt to their changing environments through morphological, behavioral, and physiological means. Seeking novel solutions by emulating strategies and principles found in nature is called biomimetics, and it is a rapidly growing discipline in engineering and an emerging field in architecture. Implementing successful adaptation strategies from nature to buildings can result in more energy efficient solutions while employing materials and other resources more effectively.

Throughout the last two decades, biomimetics have evolved from fundamental research to practical applications, providing ample contributions of innovative solutions to improve the quality of life [1; 2]. Several benefits have been identified for applying biomimetics to solving building problems, such as: investigating of terminologies from life sciences that could have similar use in buildings [3]; analyzing ecosystem interactions for higher sustainability and optimized resource use in the built environment [4; 5]; exploring functional ideas from nature for inspiration [6]; learning from termite mounds for ventilation and thermoregulation [7; 8]; identifying strategies of animal skins for performative constructions [9]; and creating frameworks and tools that bridge between the large database of nature and the needed functionalities of buildings [10; 11].

Morphology and form are the most common traits to be transferred from natural systems in architecture. However, such traits have seldom retained any environmental adaptation strategy of the imitated systems from nature, and therefore hardly represented a successful biomimetic design. The environment has a significant influence on the evolution of the specific form, arrangement, and composition of natural systems, where morphological differentiation has emerged. The special morphologies generate interfaces rather than shields, allowing the regulation of heat, air, water, and/or light.

Nowadays, emerging technologies together with advanced manufacturing techniques have a great potential to realize more complicated concepts [12]. These technologies, in particular information technology, would enable buildings to self-adjust and respond to varying environmental conditions. In the last decade, more advanced solutions have emerged with promising multi-functional capabilities. In this chapter, we address the significance of implementing morphological solutions from nature to facilitate the environmental adaptation of buildings, hence increase occupant comfort, and potentially reduce energy demands. We propose three main areas for morphological exploitations: *skins*, *surfaces*, and *structures*.

15.2. Adaptive Building Solutions

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 [13; 14]. 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 [15]. Environmental conditions are constantly changing and creating new challenges for building envelopes to accommodate.

Occupant's activities as well as environmental factors, such as air movement, humidity, temperature, solar radiation, air quality, noises, affect occupants' comfort inside buildings. Considering the building envelope as a barrier or a shield, such as applying high resistant thermal solutions [16], 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 [17], 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.

Since the 1920's new concepts started to emerge as a result of the new possibilities that the industrial revolution has brought. In particular, the proposal by Le Corbusier of an active thermal system, "the house of exact breathing", among other ideas [18; 19].

Kiesler and Greene further interrogated the need for differentiated social spatial concepts and environmental responsiveness in buildings, moving to more organic forms as speculated and demonstrated in the “Endless House” [20] and the “Living Pod” [21]. This movement has evolved with more focus on adaptive building envelopes, where more theoretical and visionary ideas continued to emerge. A pioneering theoretical, yet potentially applicable, example from the 1980’s is the “polyvalent wall” [22]; it consists of thin layers that are capable to absorb, reflect, filter, and transfer energies from the environment.

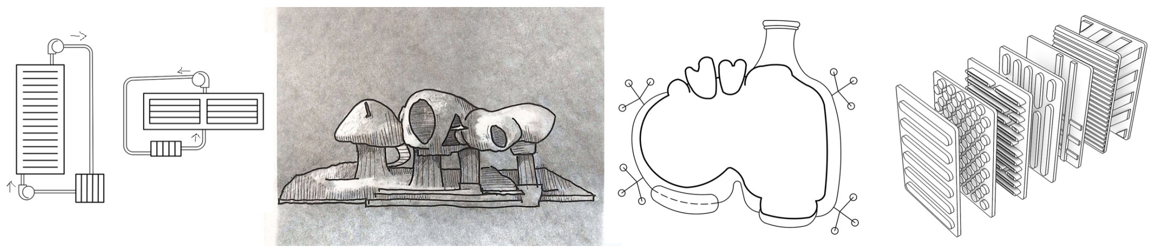

Figure 15.1. Visionary responsive and adaptive building concepts. Reproduced with permission from by Jacob Zolotovsky, adapted from original work (left to right): *the house of exact breathing* by Le Corbusier 1920’s, *Endless House* by Kiesler 1950, *Living Pod* by Greene 1965, and *Polyvalent Wall* by Davies 1981.

Emerging technologies together with advanced manufacturing techniques have a great potential to realize more complicated concepts. These technologies, in particular information technology, enable buildings to self-adjust and respond to varying environmental conditions [23; 24; 25; 26]. Some advances in building envelope design have aesthetic and functional roles, such as the Kunsthaus Graz by architects Cook and Fournier, where its free form envelope stands out from the surrounding traditional buildings, and the outer media skin illuminates as a response to exhibited art projects [27]; 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 [28], see Figure 15.2.

Furthermore, advances in recent years represent a more adaptive trend in building envelope design, where responsive and kinetic principles are more prevalent [29; 30; 31].

For example, the Bio-Intelligent Quotient (BIQ) building, by Splitterwerk and Arup, consists of algae filled panels (photobioreactors) that capture heat and generate electricity [32]; and the One Ocean Thematic Pavilion, by SOMA Architecture, consists of a kinetic facade of deformable lamellas that control day-lighting [33]; see Figure 15.2. Despite the existing array of advanced building designs and technologies, the majority of the building stock is still not responsive and adaptive to changing environmental conditions.

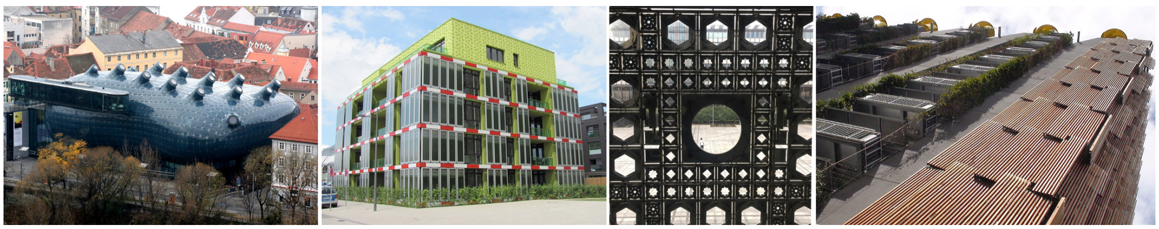

Figure 15.2. Realized adaptive and responsive solutions for buildings (from left to right): Kunsthaus Graz, photo courtesy of Marion Schneider & Christoph Aistleitner; BIQ Building with algae filled panels; the dynamic façade system of the Institute of the Arab World, Paris; CH2 building.

15.3. Environmental adaptation in nature

Living organisms and their environments are interrelated. They have developed through evolution adaptation strategies for different environmental conditions. Harsh conditions, such as extremes of temperature, humidity, solar radiation, and/or pressure, pose real survival challenges to organisms. In some organisms, the adaptive process is accomplished through their skin functioning as an environmental filter, e.g. fur, whereas in others it is achieved through their built structures, e.g. mounds [34]. Organisms employ morphological and behavioral means to complement physiological strategies for adaptation.

15.3.1. Adaptation Means

15.3.1.1 *Physiological adaptation*

Physiological adaptation is a response by an organism to an external stimulus for maintaining homeostasis. For example, certain biochemical and molecular processes enable mangroves that inhabit inter-tidal zones along the coast to tolerate high salinity levels [35]; pine cones open and close in response to humidity to protect and disperse seeds; chameleon skin shifts sacs of pigment in response to light (muscle contractions) and result in coloration changes, see Figure 15.3.

Figure 15.3. Top: (left-middle) mangrove habitat and root system in direct contact with salty water in Costa Rica, photos courtesy of Badarnah L; (right) the deposition of salt in the form of crystals on older leaves close to falling, courtesy of *Peripitus.* Bottom (from left to right): pinecones open and close in response to humidity levels; chameleon skin color changing in response to surrounding environment.

15.3.1.2 Morphological adaptation

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 for morphological adaptations among desert plants, see Figure 15.4. Such stems allow water storage and self-shading situations, small leaves reduce water loss, and extensive root systems enhance moisture collection in plants.

Figure 15.4. Top: morphological variations in cacti as an adaptive response to their harsh environments. Bottom (from left to right): whale's body morphology to reduce drag; snake's scales facilitate flexibility and movement; nautilus shell exhibits an efficient structural morphology that also facilitates movement; and hexagonal structure of wasp nest.

15.3.1.3 Behavioral adaptation

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 [36], and social insects have evolved efficient mechanisms (e.g. self-organization and stigmergy) to communicate collective needs in a responsive manner [37], see Figure 15.5.

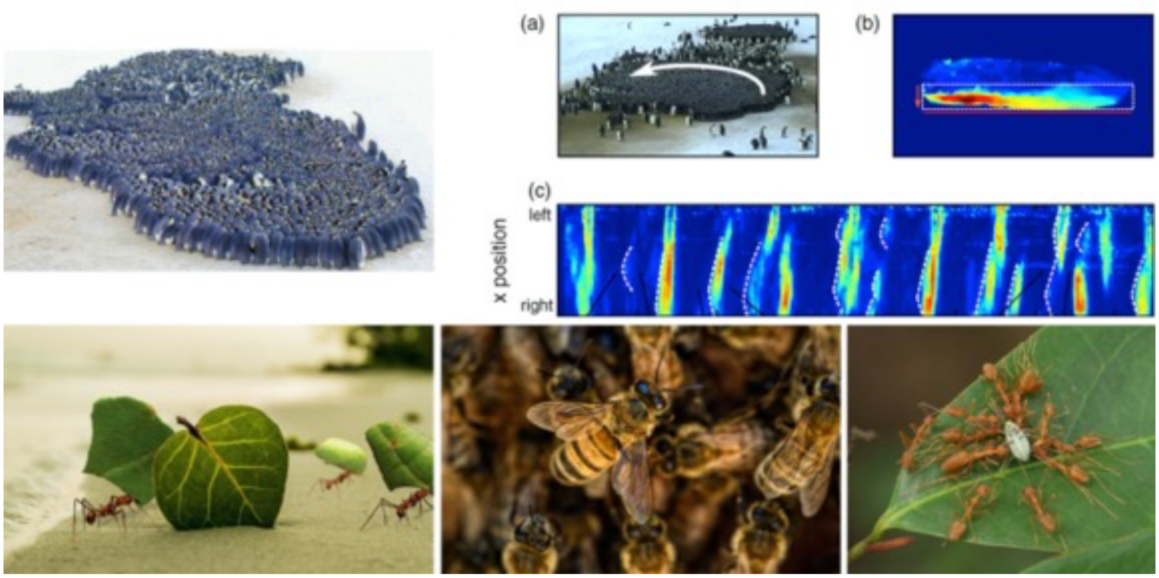

Figure 15.5. Top: (left) a group of huddling penguins, which consists of about 2500 males. Sources: Reproduced with permission from C. Gilbert, G. Robertson, Y. Le Maho, Y. Naito, A. Ancel, Huddling behavior in emperor penguins: dynamics of huddling, Physiol. Behav. 88 (2006) 479 488, with permission from Elsevier; [right (A) (C)] optical flow analysis of the traveling wave dynamics of huddling penguins,

reproduced from R. Gerum, B. Fabry, C. Metzner, M. Beaulieu, A. Ancel, D. Zitterbart, The origin of traveling waves in an emperor penguin huddle, N. J. Phys. 15 (2013) 125022, published by IOP under the terms of the Creative Commons Attribution 3.0 licence. Bottom: (left) leaf cutter ants; (middle) cooperative bee colony; (right) ants working together on a mission.

15.3.2. Environmental Regulation

Natural systems (organisms and their built structures) are exposed to changing environmental conditions, which often require the management and regulation of heat, air, water, and light, simultaneously. Adaptation strategies that regulate heat, air, water, and/or light, are accomplished via a series of processes that are often based on basic laws of physics.

15.3.2.1. Heat regulation

Organisms maintain their body temperature in 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. Organisms and their built structures regulate heat by four key functions of gaining, retaining, dissipating, and preventing [40]. The adaptation strategies can be morphological, physiological, as well as behavioral. 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 (behavioral) [41]. 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 behavioral strategies. For example, termite mounds dissipate heat via natural convection [42], and toucans dissipate heat via radiation emission [43].

15.3.2.2. Air regulation

Air is a significant source for oxygen and carbon dioxide in organisms, which are required for energy matters in the process of food and materials oxidation [41].

Organisms often supplement thermoregulatory strategies with air management. Animals construct their structures, among other reasons, for protection against extremes of climates. Gas exchange may arise as a secondary problem from creating protective walls, adding to the complexity of the structure's functional design [34]. As such, structures constructed by animals need to provide adequate air supply and concentrations of oxygen.

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 [10]. Some small organisms obtain 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 [44], e.g. gills of fish [45]. Mounds, burrows, and nests utilize natural convection and velocity gradients to move air around [46; 47].

15.3.2.3. Water regulation

Water adaptation strategies in nature are varied, and some extraordinary abilities in organisms are found in water-scarce environments. For example, the Namib Desert is one of the harshest environments on earth [48], where fog represents an alternative source of water for some organisms such as the Namib Beetle [49]. In terms of functions, water can be gained, conserved, transported, and/or lost for thermoregulation and other chemical reactions [50]. Some organisms gain water by condensation on their body surface [51] or constructed structures [52], as well as by absorbing water vapor directly from air via skin diffusion [53]. Other organisms reduce evaporation rates [54; 55] and radiation exposures for water conservation [56].

Transporting water from one region to another at a range of scales is achieved via forces of gravity or via capillary action [57], especially in venation systems [58]. Water is lost by three means in organisms [41]: 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 [41], such as: vapor pressure difference, flow rate of air, temperature, surface are, and orientation. Several morphologies are distinguished to promote water management via: condensation, transportation, evaporation, diffusion, and radiation reflection. These morphologies can influence surface functionality, among others, by decreasing or increasing contact angle for hydrophilicity or hydrophobicity (respectively), creating thin boundary layers for better water attraction, providing paths to direct water, or/and moving water around. The special form of stems, the small and thin leaves, and the extensive root system, are examples for morphological adaptations among desert plants. Such stems allow water storage and self-shading situations, small leaves reduce water loss, and extensive root systems enhance moisture collection in plants.

15.3.2.4. Light regulation

Organisms need light for various purposes, such as gaining information from the surrounding environment, communication, and/or for energy matters [59]. 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 [60]. For example, the silver ragwort scatters light to filter and reduce incident light [61]; the Venus flower-basket illuminates by transmitting light through its intricate structure [62; 63]; and some plants maximize interception by changing angles to harness light [62; 63; 64]. Succulents, canopy, under-story, and diaheliotropic plants manage light interception by applying special distributions, orientations, and forms [60]. These morphological means are sometimes enhanced by the plasticity of the plant's architecture responding to different light intensities [65].

The wide field of view of compound eyes in some insects and deep-sea creatures is achieved through the structural assembly of numerous tubes that direct light (reflection or refraction) to a specific focusing area, which exhibit a compact vision system with efficient energy consumption [66]. Some colors in nature arise due to special surface microstructures, where reflection, diffraction, and scattering of wave ranges are manipulated. These microstructures can, among others, enhance radiation absorption [67], and provide a selective vapor responsive medium [68]. Plants in particular need to adapt to different light intensities for optimal photosynthesis rates. Plants' planar area, angle of incidence, and distribution play significant roles in influencing the exposure to sun radiation [69].

15.3.3. Multi-Regulation

In design, in general, we address a single aspect at a time. In practice, buildings are exposed to multiple environmental factors and thus required to manage heat, air, water, and light (and probably other factors), simultaneously. Moreover, the environmental aspects are often highly interrelated, where the regulation of one might be dependent on the regulation of the others. For 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 change 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. Despite the existing awareness of these interrelations, multi-regulating solutions in buildings are still limited.

Figure 15.6 represents a concept model that demonstrates the interrelations between the environment, adaptation means, and regulation strategies for the environmental adaptation of organisms. This concept model attempts to configure multi-functional and multi-regulation within the dynamics of environmental adaptation as integrated cycles of the whole, inviting further study into its potential implementation in biomimetic design processes.

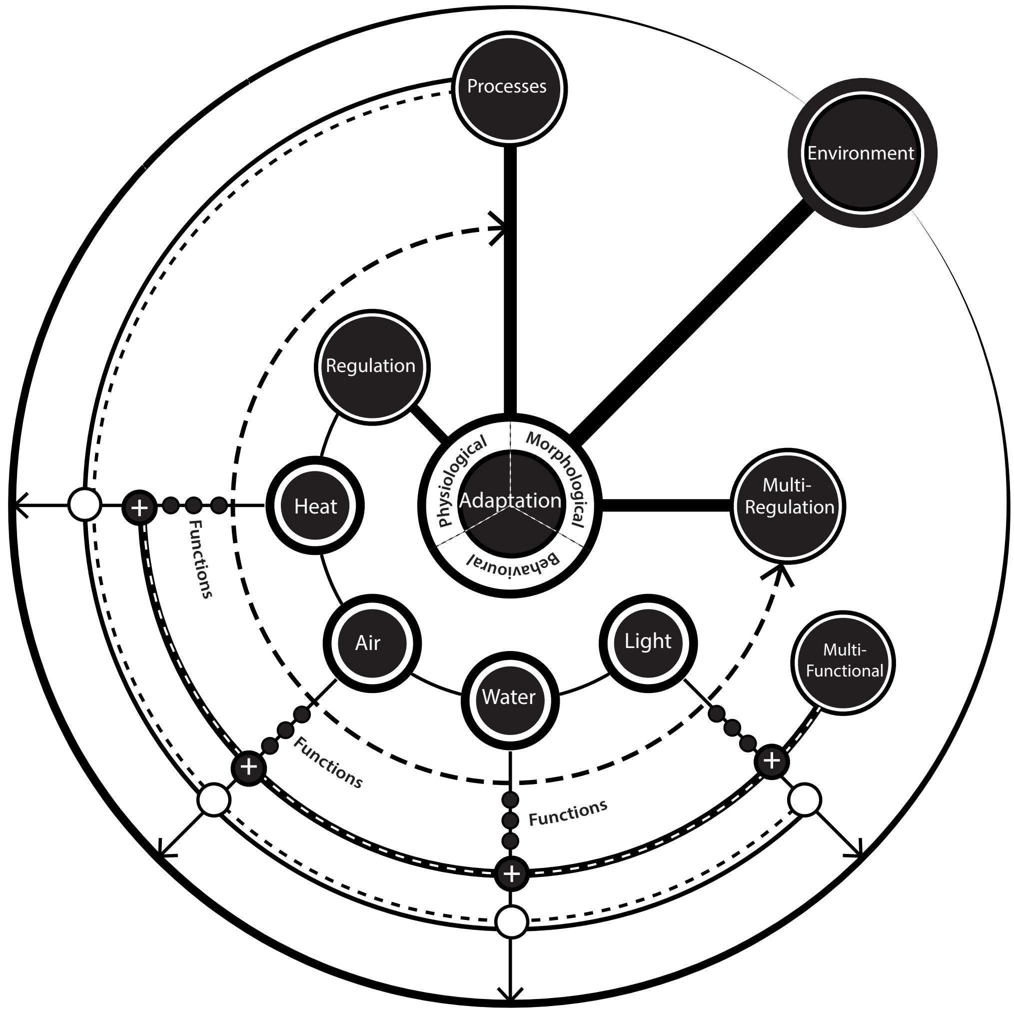

Figure 15.6. Concept model of environmental adaptation. The model maps the interrelations between the environment, adaptation means (physiological, behavioral, morphological), environmental regulation (of heat, air, water, and light), relevant functions, corresponding processes, and the cycles of multi-regulation and multi-functionality mediums. Source: Authors.

15.4. Biomimetics: functional convergences and multi-functionality

The challenging abstraction and transformation from the nature domain to the engineering domain can be carried out through identifying key categories such as: anatomy, behavior, and ecology [70]; organism, behavior, or ecosystem [71]; as well as organ, organism, structure, system, or behavior [10]. 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.

15.4.1. Functional convergences

Functional 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 tasks were defined and refined via thorough literature reviews [10], see Table 15.1.

Table 15.1. Identifying functional convergences (key functions) for different environmental challenges in buildings and in nature, and their associated processes, adapted from [72].

Environmental Challenges	Buildings	Nature	Functional Convergences	Processes
Heat	Thermal comfort Energy	Survival Thermoregulation Reproduction	Gain	Radiation absorption Metabolic rate increase
			Retain	Conduction reduction Convection reduction Heat Exchange Radiation retro-scattering Metabolic rate reduction
			Dissipate	Convection enhancement Conduction enhancement Radiation emission Evaporation
			Prevent	Irradiation minimization Reflection
Air	Air quality Ventilation Cooling Energy	Survival Oxygen supply CO_2 supply Cooling Ventilation	Exchange	Diffusion Unidirectional flow Countercurrent flow
			Move	Natural convection Pressure difference Velocity gradient
Water	De/humidification Cooling Supply Waste Distribution	Survival Thermoregulation Chemical reactions	Gain	Condensation Absorption
			Conserve	Evaporation mitigation Irradiation reduction
			Circulate	Wetting Wicking
			Lose	Evaporation

Light	Day lighting Visual comfort Media Energy	Survival Photosynthesis Vision Communication Sensing	Filter	Transmission Scattering
			Illuminate	Transmission Reflection Scattering
			Harness	Interception Reflection Refraction Absorption

For each environmental aspect a set of key functions is responsible to manage their adaptation as a response to changing conditions (Table 15.1). The array of processes represents the ways by which key functions are carried out, where similar means can be applied to buildings. In a design process, where ideas are based on functions, it is important to maintain the critical links between physical processes and their applications. In this work the critical link is morphology. Section 15.5 showcases some morphological means that enhance the accomplishment of processes for environmental adaptation.

15.4.2. Multi-functionality

Organisms in nature have multi-functional capabilities and are able to address multiple environmental aspects simultaneously. The multi-functional capabilities of systems are often enhanced by morphologies that allow several physical processes to perform simultaneously, serving as interfaces to promote multiple functions for thermoregulation, water management, ventilation, and/or light management. Table 15.2 presents several examples for multi-functional capabilities, such as termite mounds that manage air movement and retain heat; and skink scales that reflect light, conserve water, and prevent heat, simultaneously. The water and heat regulation of elephant skin, through evaporation, radiation reflection, and convective heat loss, are promoted by the same wrinkle morphology of the skin. In general, when challenged with designing a multi-functional system it is advised to choose morphologies with multi-functional capabilities, where integration has already been successfully evidenced in nature.

Table 15.2. Examples of natural systems and organisms with multi-functional 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 of no means an indication that the pinnacle is incapable of achieving the specific challenge. Adapted from [72].

Aspects	Heat				Air		Water				Light			
Functions	Gain	Retain	Dissipate	Prevent	Exchange	Move	Gain	Conserve	Transport	Lose	Filter	Illuminate	Harness	
Pinnacles														**Source**
Termite mounds	+	+	+	+	+	+	-	-	-	-	-	-	+	Korb and Linsenmair [42]; [73]
Prairie-dog burrow	-	-	+	+	+	+	-	-	-	-	-	-	-	Vogel *et al.* [46]; Sheets *et al.* [74]
Veins/blood vessels	+	+	+	+	+	+	-	-	+	-	-	-	-	Arens and Zhang [75]
Human skin	-	+	+	-	-	-	-	-	-	+	-	-	-	Randall [76]; Randall [77]
Skink scales	-	-	-	+	-	-	-	+	-	-	+	-	-	Vrcibradic and Rocha [78]
Elephant skin	-	-	+	+	-	-	-	+	-	+	-	-	-	Lillywhite and Stein [79]
Succulent	-	-	+	+	+	-	+	+	+	-	+	-	+	Björn and Govindjee [80]

15.5. Morphological Differentiation

The environment has a significant influence on the evolution of the specific form, arrangement, and composition of natural systems, where morphological differentiation is often sought, Fig. 15.7 presents some examples in different scales. Our work distinguishes several morphological means for adaptation in different contexts. These morphologies have functional tasks that are associated with specific environmental processes [72]. Table 15.3 presents some examples of certain morphological features and their potential applications for the environmental adaptation of buildings:

- **Wrinkles and Grooves** – wrinkles on the surface of the skin provide sufficient surface area for holding moisture and promote evaporation [79]. Additionally, these wrinkles create self-shaded areas for reduced heat loads and generate convective currents for enhanced heat loss. The presence of grooves on plants surfaces provides a guided water collection and transportation [81]. Termite mounds with macro grooves enhance heat dissipation and ventilation via convection [42], and create self-shaded regions. The presence of wrinkles and grooves on building skins could promote cooling by holding moisture for potential evaporation and creating self-shaded areas for reduced heat loads.
- **Capillaries** – special arrangement of integument or scales of lizards create micro-channels, a semi-tubular capillary system, over body surface to transport water via capillary forces [82]. Semi-tubular capillary systems on surfaces of structures could improve water transportation and distribution over large areas.

- **Fractals** – Fractal arrangement of flow systems is energy efficient [83; 84]. The fractal network of nested loops in leaves provide an optimal transportation of fluids even at events of damage [58; 85]. The fractal arrangement of the Fibonacci sequence of seeds results in an efficient and compact packing for maximized light interception [62]. The fractal nanostructure of scales in butterfly wings is highly reflective [86]. Fractal arrangements of flow systems in building skins could improve energy efficiency, where the presence of fractal elements at the nano-scale could also increase reflectivity and enhance light shielding.
- **Pores** – little pores on skins allow direct diffusion of condensed water [53], and moisture loss in response to thermoregulatory demands. Porous building skins could allow direct diffusion for de/humidification, and potentially promote thermoregulation.
- **Spikes, Knobs, and Trichomes** – spiky surfaces of leaves create a thin boundary layer that improve water collection from fog [87]; knobs on silk fibers attract water from humid air [88]; the microscopic fibers of trichomes enhance hydrophobicity and scatter light for reduced incident light on surfaces [61]. Spikes, knobs, and trichomes could enhance condensation capabilities of building surfaces in arid regions, by creating a thin boundary layer that improves water collection from fog.
- **Mound and Funnels** – they generate velocity gradients on the surface and result in a pressure gradient for wind-induced ventilation of burrows [46]. Variable elevations on building surfaces could generate velocity gradients on the surface resulting in pressure gradients for enhanced ventilation.
- **Hexagons** – 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 [90; 91]. Hexagonal array of facets on a spherical plane enhances light interception [92]. The hexagonal arrangement of elements in buildings such as photovoltaic cells could enhance light perception and improve energy generation. Additionally, the exploitation of hexagonal microstructures on building surfaces could enhance condensation for water harvesting.
- **Lamellae** – closely packed ridges with horizontal lamellae and micro-ribs, highly reflects certain wavelengths [86]. Variations in film thicknesses can result in 96%

absorption of the incident solar radiation [67]. The presence of micro lamellae in buildings with thickness variation could significantly improve light absorption for potential light management and enhance energy generation.

Table 15.3. Distinct morphologies, corresponding processes, and their potential applications for environmental adaptation. *The relevant environmental aspects involved in a process: Heat (H), Air (A), Water (W), and/or Light (L). Adapted from [72].

Morphology	Processes (HAWL)*	Applications
1 Wrinkles	Evaporation HW	Cooling external cladding
	Reflection HL	
	Convection HA	
2 Grooves	Transport W	Water distribution, ventilation, and heat dissipation
	Convection HA	
	Irradiation reduction HL	
3 Capillaries	Transport W	Water transportation
	Diffusion W	
4 Fractal	Flow AW	Light harnessing, light shielding, and efficient transporting systems
	Transport AW	
	Diffusion AW	
	Interception L	
	Reflection L	
5 Pores	Evaporation HW	Humidification & cooling
	Diffusion AW	
6 Spikes	Condensation W	Moisture harvesting
7 Knobs	Condensation W	
8 Trichomes	Reflection HL	Reducing heat loads and harvesting moisture
	Scattering HL	
	Condensation W	
9 Mounds & Funnels	Flow A	Ventilation
	Velocity gradient A	
10 Hexagons	Flow W	Moisture & light harvesting
	Condensation W	
	Interception L	
11 Lamellae	Reflection L	Light control & energy generation
	Absorption L	

Figure 15.7. Illustrations of different morphological adaptations from nature in different contexts.

15.6. Morphological Applications for Environmental Adaptation: Skins-Surfaces-Structures

Morphology plays a significant role in the way natural systems adapt to their environments, providing among other roles a functional interface to regulate heat, air, water, or/and light. Morphology is the most prevalent form of biomimetic applications to buildings for environmental adaptation. Below we bring successful examples of morphological strategies that are implemented in buildings to achieve multi-functional adaptation. We classified the examples by three contexts of adaptation: ***Skins*** – in-plane morphological exploitations in building envelopes, such as vascular networks, capillaries, pores, and cellular configurations; ***Surfaces*** – out of plane morphological exploitations in building envelope, such as grooves, wrinkles, spikes, knobs, mounds, and funnels; and, ***Structures*** – a spatial morphological exploitation (composition and assembly) in building envelopes, where elements are supported structurally in a way to respond to the environment, such as leaves, lattices, and lamellae.

15.6.1. Skins

In nature, living organisms use capillaries, vascular networks, and pores to manage permeability, humidity levels, and control temperature. The heat transfer in human skin is regulated by the blood flow at skin surface – the capillaries expand and increase the flow when it’s hot and contract to decrease the flow when it’s cold. In penguins, the arteries carrying heated blood to extremities are adjacent to the veins carrying colder blood from the extremities for efficient heat exchange [93]. One example of mimicking internal vascular networks for thermal regulation in buildings is the use of an artificial vascular network within windows [94] (Fig. 15.8).

The researchers have developed an artificial vascular network as a non-structural layer for a window, composed of micrometer-millimeter channels, and running over the surface of a window. It is made of optically clear silicone (PDMS) rubber with micro-channels thus allowing full transmission of visible light. This layer improves the overall energy efficiency by incorporating transparent microfluidic heat exchange layers into the window and reducing the operating temperature. It can also be used for photovoltaic applications, as it helps reduce heating by solar absorption and increase the photovoltaic efficiency.

At the Institute for advanced architecture of Catalonia (IAAC) various performative solutions for buildings have been explored by manipulating skin permeability through applying morphological variations similar to stoma and skin pores [95]. For example, the Hydroceramic project that explores the use of hydrogels as a thermally responsive in building skin [96], see Figure 15.9a – a composite skin system (comprising of hydrogel, supporting a fabric layer to diffuse water, and the supporting ceramic template) responsive to heat and water that is able to lower the temperature of an interior space by few degrees Celsius; and the water-driven breathing skin that explores mechanisms of open/close behaviors for air exchange [97], see Figure 15.9b – a semi-passive material system for hot climates consisting of sodium polycarbonate, a superabsorbent polymer, aiming to facilitate passive ventilation and cooling. The various prototypes demonstrate the potential applications of solutions at the skin context, where further investigations are needed for delicate building applications in real environments.

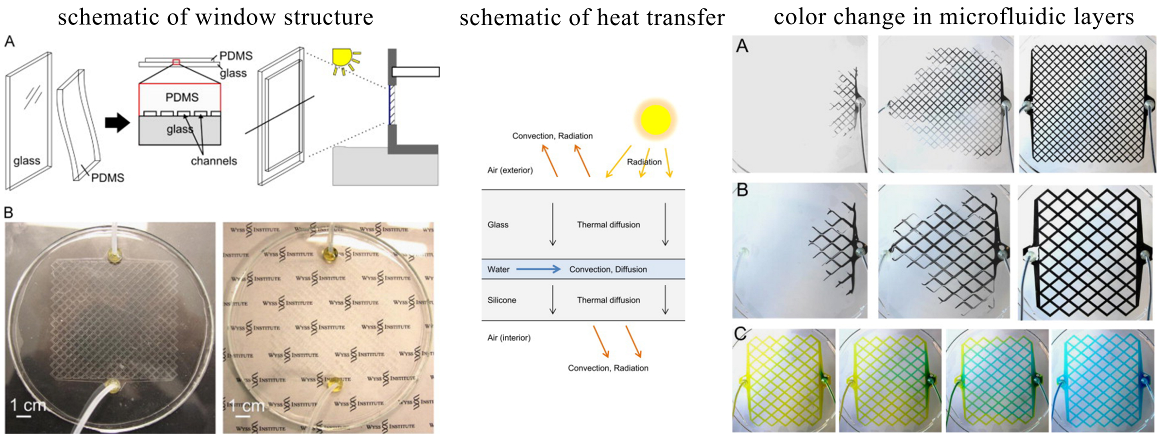

Figure 15.8. Composite window with artificial vasculature. Left: schematic of the composite window structure; Middle: schematic of heat transfer; Right: color change in microfluidic window layers. Silicone layer having a 10×10 cm^2 array of 1 mm wide channels gradually filled with black-colored water (left to right). Reproduced from [94], with permission from Elsevier.

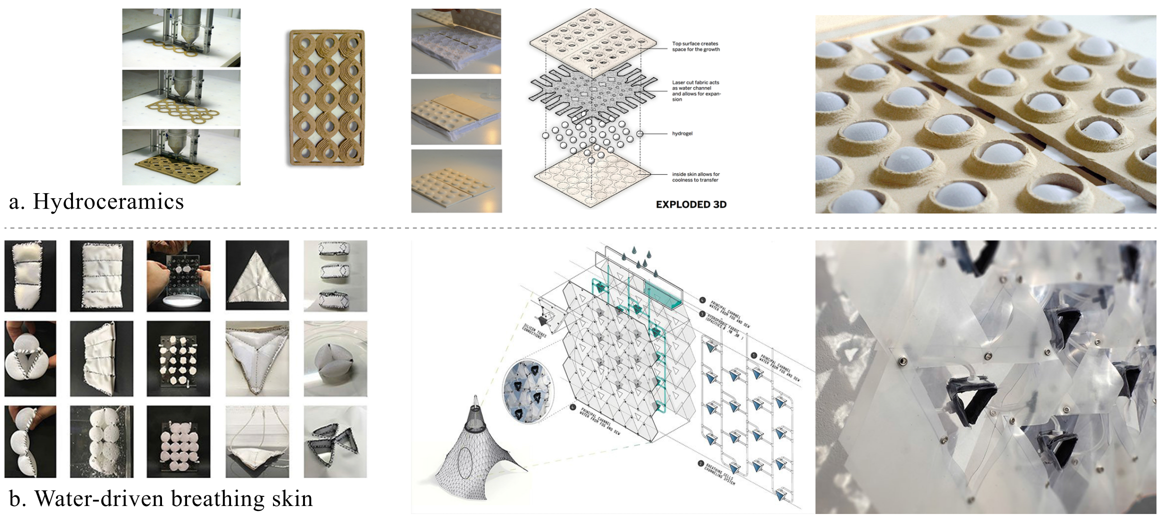

Figure 15.9. Cellular configurations. (a. Hydroceramic 2013-14) temperature control via evaporation (from left to right) – exploring clay 3D printing methods; assembly of four layers with encapsulated hydrogel; close up at the water absorbing pores. (b. Water-driven breathing skin 2016-17) ventilation via response to humidity changes (from left to right) – exploring cells variations in terms of shape, patterns, and size; schematics of the skin system; a close up to the stoma like mechanism of opening and closing. Reproduced from [96] and [97], respectively, with permission from IAAC. All images © IAAC.

15.6.2. Surfaces

In nature, morphological strategies on surfaces have a significant role for water distribution, ventilation, and heat dissipation [98]. For example, termite mounds with macro grooves enhance heat dissipation and ventilation via convection [42]. The presence of grooves on plant surfaces provides guided water collection and transportation [81]. Wrinkles and folds on the surface of the skin generate convective currents for enhanced heat transfer, and create self-shaded areas for reduced heat loads.

The façade panel in Figure 15.10 demonstrates how morphological patterns of elephant skin in the form of wrinkles have informed the texturing of a concrete facade panel to enhance cooling [99]. In this project, a series of investigations were carried out to examine the impact of a surface texture on heat loss capabilities of concrete panels through evaporative cooling. The results showed that the morphological variables of assembly and depth of texture have an impact on heat loss, and the impact of surface area to volume ratios on heat loss capabilities varies for different surface roughness. This study demonstrated the potential exploitation of morphological adaptation to buildings that could contribute to passive cooling and reduce the need for energy consuming mechanical systems.

The work by Laver *et al.* [100] is another example of informing the shape of the wall by morphological principles from natural systems, such as barrel cacti and termite mounds. Cacti ribs and termite mound ridges serve as a high mass radiator, thermal collector and self-shading mechanism. Their form facilitates processes related to radiation and convection as a response to their harsh environmental conditions and fluctuations. The researchers proposed a ceramic tile system with an articulated surface morphology that provides shading in summer and solar thermal gain in winter, see Figure 15.11. It also provides self-shading during the hot and warm months for reduced heat loads.

The TerraPerforma project (a 3D printed clay wall) explores the use of advanced manufacturing technology for the development of a climatic performative wall system [101], see Figure 15.12. For optimization, a series of physical tests and digital simulations were carried out to assess thermal conductivity and convection and simulate wind, sun, and structural behavior, resulting in a multifunctional surface morphology that improves the thermal performance of the material.

These examples demonstrate the potential impact of morphological exploitation to surfaces on the thermal performance of concrete, ceramic, and clay materials. Nature provides a large database of surface morphologies that can be extracted and abstracted for adaptive building solutions and environmentally responsive applications.

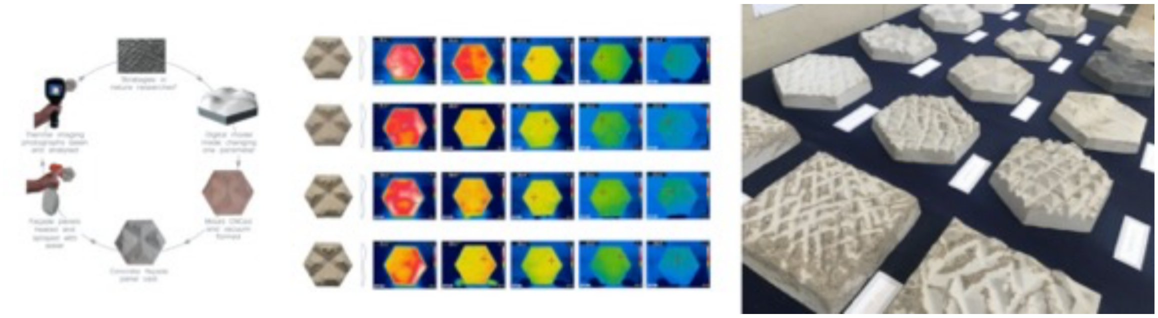

Figure 15.10. Textured façade panel [99]. (Left) investigations process: studying morphology from elephant skin, constructing a digital model, creating the physical model using CNC, forming a mold using vacuum forming around the physical model, casting a concrete panel in the mold, heating panels, watering, thermal imaging assessments; (middle) example of one of the thermal imaging comparative analysis; (right) Photograph of the resultant textured panels for the various investigations. Reproduced from [99].

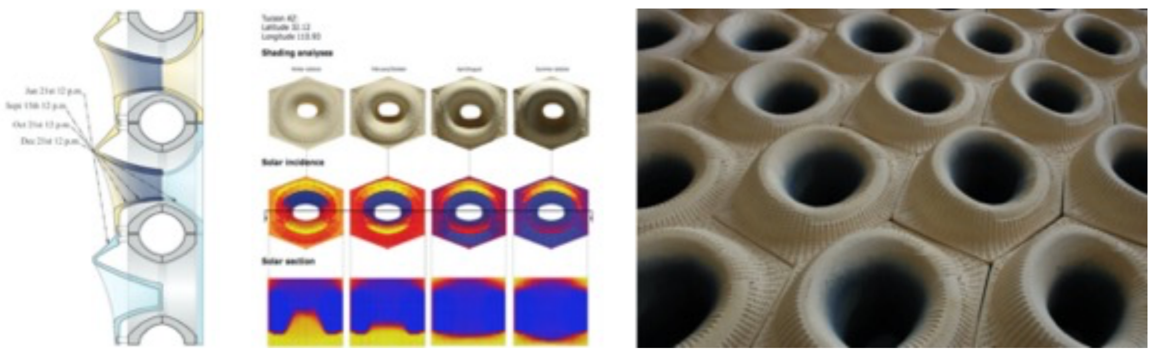

Figure 15.11. EcoCeramic CMU (concrete masonry units) [102]. (Left) diagrammatic section of the assembly showing solar angles penetrations; (middle) shading analysis and solar incidence for winter solstice, February/October, April/August, and summer solstice; (right) the assembly of the ceramic units. Reproduced from [102], images courtesy of Jed Laver.

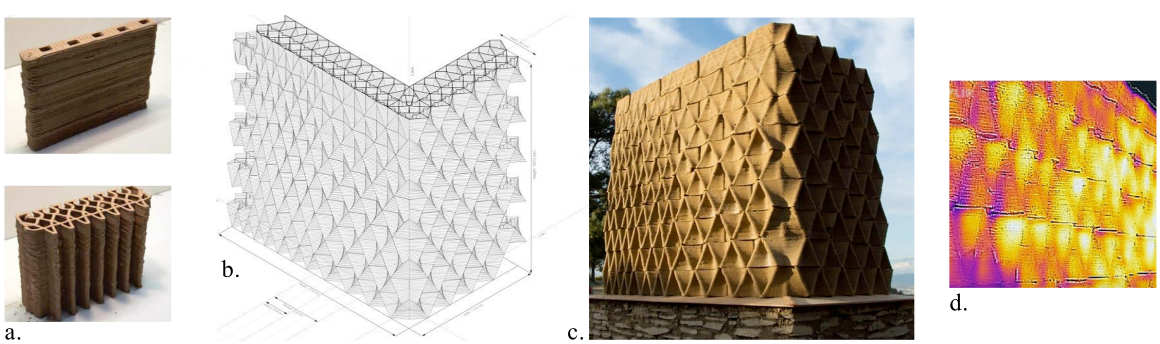

Figure 15.12. Terraperforma – a 3D printed clay wall 2016-17. (a) basic wall shape vs a manipulated wall (curvatures) with a heat sink diffuser; (b) schematic of the structure; (c) 3D printed result of a 1:1 wall; (d)

thermal image showing different temperatures throughout the curvatures. Reproduced from [101], with permission from IAAC. All images © IAAC.

15.6.3. Structures

The morphological aspects of form, arrangement, and composition have an important influence on structures in nature. The form of an organism is determined by its mechanical, environmental, and behavioral patterns obeying some laws of physics [103].

Plants have developed unique adaptive mechanisms for different climates and locations, where they can regulate the amount of exposure to sunlight by a dynamic change in leaves orientation as a response to environmental conditions. Leaf distribution and their orientation towards the sun play a significant role in the resulting efficiency of photosynthesis. Leaves' sun tracking and change of orientation is a complex response that is dependent on successful integration of multiple photoreceptors and hormonal signals [104]. The mechanism by which leaves change their orientation towards sun include non uniform curvature across the surface of the leaves, vascular bundles concentrated in certain areas, different flexibilities of the sides of a blade, leaf surfaces with specialized cell clusters.

The adaptive shading system in Figure 15.3 demonstrates a potential design solution inspired by the organizational features of leaves [98; 105]. In plants, sun tracking is achieved in two ways: leaves moving perpendicularly to the direct sun rays for a high solar irradiation and maximal rates of photosynthesis throughout the day; and leaves moving parallel to the direct sun-rays to reduce heat load, leaf temperature and transpiration rate [106]. Plants have varied leaf shapes, distributions, layering, and dynamics for environmental adaptation. The proposed shading system applies orientation principles to generate energy through the photovoltaic (PV) cells attached to the shading sheets (Figure 15.3a-b); distribution principles through the structural arrangement to allow better exposure, flexibility, and indirect light penetration for comfortable indoor climate (Figure 15.3c-d); and layering principles through their varied inclination angles and depth of position to prevent self-shading (Figure 15.3e).

The Adaptive Solar Façade (ASF) in Figure 15.14 is an example of showcasing the use of soft robotics in architecture as a dynamic solution to control the heat and shading of the façade [107]. The delicate, movable PV panels are mounted onto a lightweight framework on the façade. Like leaves, these panels are multifunctional in their roles of energy production, shading and daylight control of the interior. Access energy is stored in the form of pressurized air to be used for moving the panels when there is no sun. According to the researchers, its efficiency depends on its integration with the other building systems, such as the lighting, the heating, and ventilation [107]. For example, solar radiation captured by the façade can be used to pre-heat the interior spaces or the façade can be used to maximize the amount of light inside the rooms [107]. A key problem of ASF systems is the mutual shading of photovoltaic panels causing overheating and loss of energy. According to research using parametric simulations [108], the morphometric parameters (shape of the panels, their arrangement, spacing between them) can significantly improve the self-shading issue and maximize facade efficiency, inline with the concepts raised in [98] based on organizational features in plants.

The proposal of Grinham *et al.* [109] in Figure 15.15 is a good example of a structure that also combines skin and surface morphologies (folds, wrinkles, etc.), which mimics natural strategies for heat dissipation via convection. The researchers propose a water-based thermoregulation – a large surface with embedded copper or polymer tubing that transfers heat to and from a closed water circuit. Heat energy will be transferred between a surface and a moving fluid with different temperatures in a process known as convection. This study shows how to increase the total surface heat transfer rate of radiant systems for cooling buildings by using foldable origami surfaces with integrated water-filled tubing. The flexible layer with water-filled micro channels is sandwiched between the folding surfaces (Figure 15.5 right). Figure 15.5 demonstrates how introduction of morphological strategies such as the folds in one and then two directions improve the thermal performance by 55-67%. The researchers designed both analytical (Figure 15.5 left bottom) and physical (Figure 15.5 left top) to demonstrate this improvement.

The ITECH Research Demonstrator in Figure 15.16 showcases large-scale compliant architecture inspired by the folding mechanisms of the *coleoptera coccinellidae* (ladybug) wings [110]. The design process involved the identification of functional kinematic principles and then these were abstracted and transferred to a technical application. The folding pattern of the wings was mathematically described as *flexagons*, a common origami-folding pattern. The design outcome is composed of two adaptive folding elements made of carbon and glass fibre-reinforced plastic. An interactive control system, consisting of integrated sensors, online communication, and backend computational processing, facilitates interactive and user-controlled adaptation.

Learning from the multifunctional systems in nature, shading or heat dissipating can be single players in a multifunctional building system. The morphological adaptation of plants reviewed in this chapter as well as other strategies could be applied to shading systems to minimize self-shading, regulate solar irradiation, and increase electricity generation of PV shading systems using solar tracking. We can learn from plants the differentiation in shape, size, and distribution of leaves to apply to the photovoltaic panels. Since relative performance of the adaptive facades also depends on the season, façade orientation, and geographical location, it is worth examining plants local to the building area when designing shading systems.

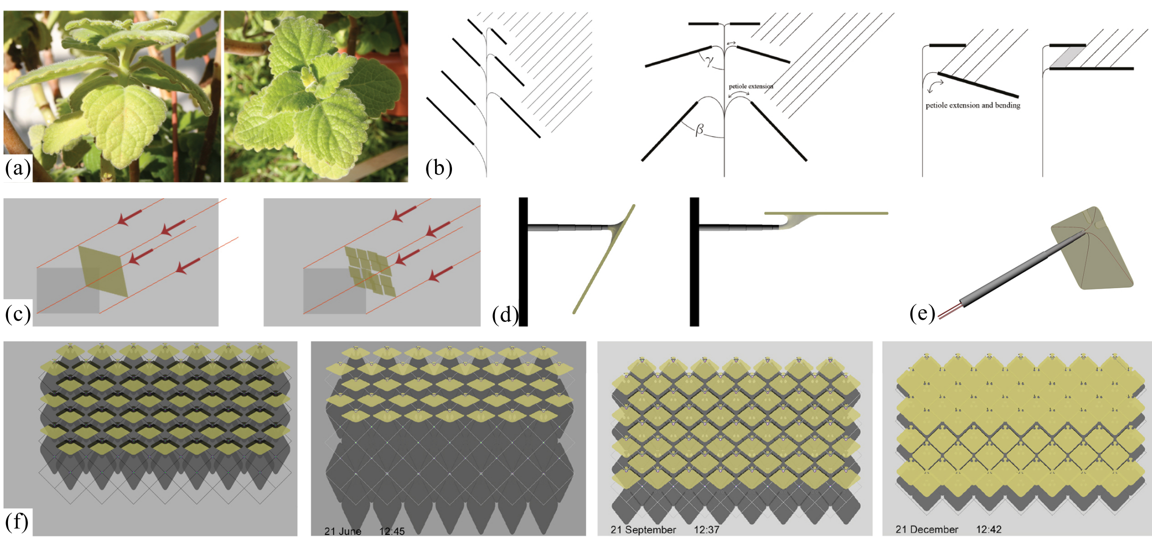

Figure 15.13. Adaptive shading system inspired by leaves: (a) leaves bend with varied sizes and angles for maximum light exposure; (b – from left to right) leaves normal to sun radiation for maximum energy gain, lower layers of leaves bend for maximum light perception and get bigger with smaller inclination ($\beta < \gamma$), leaf inclination and petiole elongation prevent self-shading; (c) the same projection area for two different surfaces of shading sheets normal to sunray (left: single flat sheet, right: the same single sheet divided into smaller pieces at different depths); (d) the shading components are connected to the frame via a tubular member supporting sheets on a flexible joint allowing rotation to follow sunrays to maximize shading and energy gain by the attached photovoltaic cells; (e) the shading component and the concept of wires to control rotation; (f) the shading results on a southern façade at different times of the year. Figures reproduced from [98; 105].

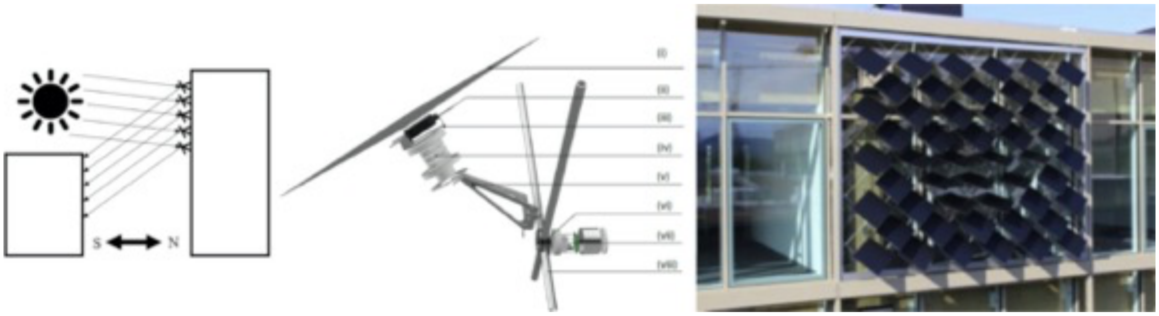

Figure 15.14. Adaptive Solar Façade (ASF). (Left) envisioned interactions between direct sunlight and buildings; (Middle) detail of the AFS panel: (i) PV panel, (ii) junction box, (iii) panel adaptor, (iv) soft pneumatic actuator, (v) cantilever, (vi) electronic and pneumatic plug, (vii) electronic shield, (viii) rod net structure incl. pneumatic tubes and wiring; (Right) The prototype ASF constructed on the House of Natural Resources at ETH Zurich. Figures reproduced from [111], with permission from Elsevier.

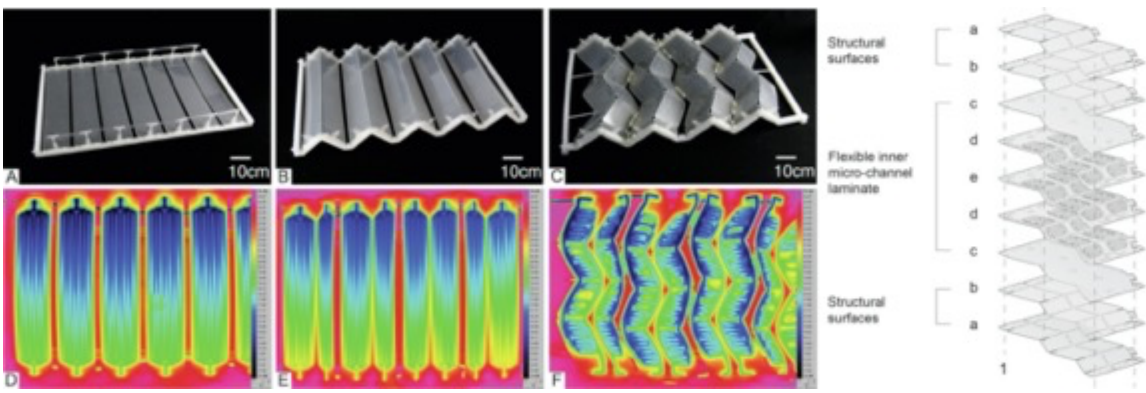

Figure 15.15. Foldable origami laminate microfluidics prototypes. Left: (A) flat (B) folded (C) zigzag. (D–F) Corresponding infrared thermal images showing discrete cooling of microfluidic water-circuit. Right: Schematic drawing of laminate device assembly: (a) 250 μm rigid polyethylene terephthalate (PET) (b) Double-sided adhesive with 50 μm PET substrate (c) 75 μm PET (d) Double-sided adhesive with 50 μm PET substrate (e) 150 μm PET (1) Alignment pins. Figure reproduced from [109], with permission from Elsevier.

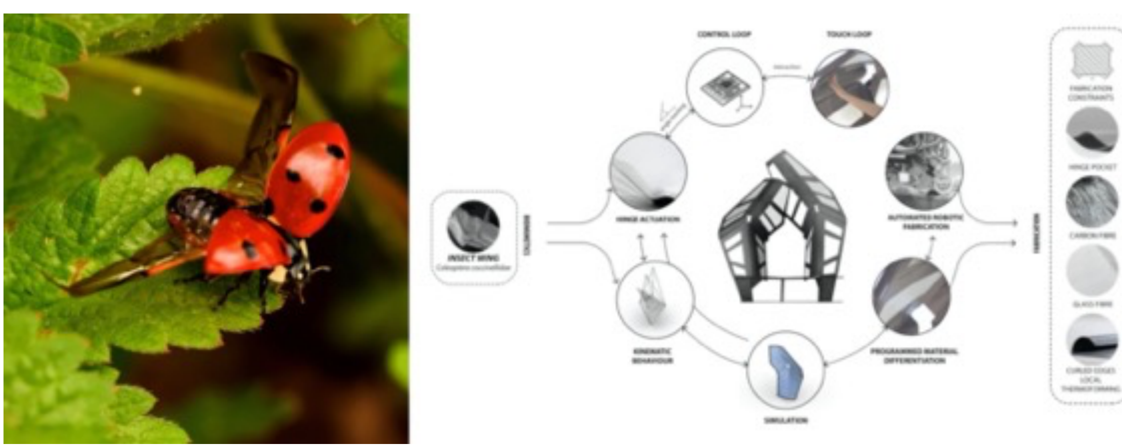

Figure 15.16. (Left) ladybug wings in open position. (Right) ITECH Research Demonstrator 2018/19: large-scale compliant architecture inspired by the folding mechanisms of the Ladybug wings. It is composed of two adaptive folding elements made of carbon and glass fibre-reinforced plastic – Figures reproduced from [110], with permission from University of Stuttgart. All images © ICD/ITKE/ITFT University of Stuttgart.

15.7. Conclusions

Environmental conditions are constantly changing and creating new challenges for buildings to accommodate. The majority of design solutions address a single function at a time. In practice, a building is exposed to multiple environmental aspects and thus required to manage heat, air, water, and light (and probably other aspects), simultaneously. Moreover, the environmental aspects are often highly interrelated, where the regulation of one might be dependent on the regulation of others. Nature is characterized by its multi-functional capabilities and many organisms are able to regulate multiple environmental aspects simultaneously.

It is evident that the skin has a significant role for adaptation, where organisms inhabiting different regions have adapted distinct morphologies for heat, air, water, and light management. In this regard, morphology can be considered as a key design element towards developing multifunctional solutions that allow several physical processes to perform simultaneously, and enhance the performance of building envelopes, increase occupant comfort, and potentially reduce energy demands. When challenged with designing a multi-functional system it is advised to choose morphologies from nature with multi-functional capabilities, where integration has already been successfully assessed by their nature.

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. The morphologies are not complicated in their nature; but rather have distinct forms, scales, and compositions. Thus, manufacturing new systems of similar functions is possible through adapting comparable physical rules at appropriate scales. The morphologies can be produced by emerging additive manufacturing technologies that enable the realization of various shapes, integrations, and material compositions. Further study on relevant scaling, material properties, and suitable production methods is essential to enhance morphological applications to the biomimetic designs of buildings.

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