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A biophysical framework of heat regulation strategies for the design of biomimetic building envelopes

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Abstract

Efficient thermoregulation solutions can be extracted from strategies found in nature. Living organisms maintain body temperature in very narrow ranges in order to survive. Organisms have adopted physiological, morphological, and/or behavioral means for thermoregulation. In some organisms, the process is achieved by skin functioning as a thermal filter, whereas in others, it is achieved by their built structures. Building envelopes separate occupied indoor spaces from the exterior environment are often considered as thermal barriers or shields. Conceiving the envelope in this way limits potentially efficient solutions, where the building envelope is considered as a medium rather than a barrier, just as in living organisms. In this context, *biomimetics*, as a design approach, provides a huge potential for innovative thermal solutions. This work focuses on the initial phase of a biomimetic design process, where a biophysical framework is established to provide an easier access to relevant analogies. It presents a structured framework of heat regulation processes to support the search for, and the selection of, appropriate strategies from the large database of nature.

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Keywords: biophysical framework; heat regulation; biomimetic; building envelopes; strategies; design.

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1. Introduction

In the context of the built environment and the need to reduce energy demands, developing more energy efficient services and technologies is essential. Buildings in general account for 40% of global energy consumption, and heating and cooling account for 50-70% of building's total energy use. Maintaining a thermal comfort condition is one of the aims of the building envelope for the enclosed spaces occupied by people. The envelope is often considered as a thermal barrier or a shield that has to be insulated to prevent heat loss and allow it to be open to dissipate heat if necessary. Conceiving the envelope in this way limits potentially efficient solutions, where the building envelope is considered as a medium rather than a barrier, just as in living organisms. Efficient thermoregulation solutions can be extracted from strategies found in nature. Living organisms maintain body temperature in very narrow ranges in order to survive, where they implement physiological, morphological, and/or behavioral means for thermoregulation. In some organisms, the process is achieved with the skin functioning as a thermal filter, whereas in others, it is achieved by their built structures. In this context, biomimetics as a design approach provides a huge potential for innovative solutions especially at the conceptual phase, where exposure to relevant examples from biology are involved [1].

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 interdisciplinary 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. Thus, the establishment of a structured framework for heat regulation is a significant initial step towards a thermal biomimetic design.

This paper focuses on the initial phase of a biomimetic design process, where a biophysical framework is established to assist analogical access. It presents an exploration model (the theoretical framework) of heat regulation strategies based on the methodology developed by Badarnah and Kadri [2]. The model is a structured platform aiming to facilitate the search for, and the selection of, appropriate strategies from the large database of nature. The model encapsulates a basic array of strategies for heat gain, retention, dissipation, and prevention; elaborates on the involved factors; and lists some examples of organisms and systems from nature that perform those. These exemplary organisms and systems are addressed as *pinnacles*[2] in this paper following Badarnah and Kadri [2].

2. Approach: biophysical information representation

The studies of biomimetic thermal solutions for buildings, in general, provide a biophysical background to some extend and present few examples that implement some of the strategies, e.g. [3, 4]. However, a systematic representation of thermal interactions and their main contribution to a system is lacking, which would assist the designer in the early stages of the design process. This section proposes a model for the representation of biophysical information to support the conceptual phase of a biomimetic development.

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[2] Literarily, a pinnacle is the summit. Badarnah and Kadri [2], define pinnacle as a representative organism or system in nature for a particular adaptation strategy. Adaptation strategies could be abstracted from an organism or a natural system (e.g. fauna, flora, nests, and ecosystems); they are addressed as pinnacles, resembling their importance and uniqueness.

During a biomimetic design process, analogies from nature are sought to solve particular design problems. Access and mapping are two basic processes to retrieve an analogue from memory and discover the relational correspondence of the elements, respectively [5]. These processes depend on the personal experience and knowledge of designers, which makes it a challenging task for designers who have a limited biological background. In order to facilitate the access to relevant analogies from the large database of nature, a systematic representation of a specific domain is essential. Organizing and categorizing the biophysical data based on hierarchical order and relational connections allows the designer to perceiving the biophysical information as a contextual map and distinguish relevant analogies [6]. Biologists, usually, analyze an organism or a system and explain the processes and factors involved to achieve a certain function. On the other hand, designers begin with an initial challenge and the desired system is unknown, where processes and factors need to be determined, as presented in Fig.1, left. This difference in the two approaches requires a unique setup that converges both.

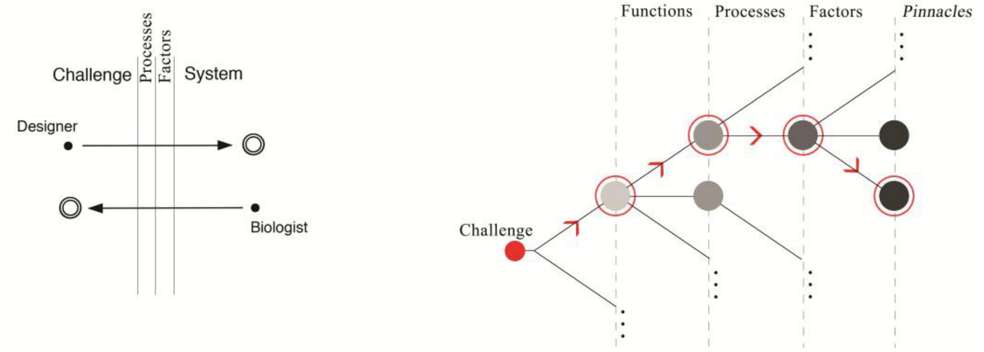

Fig. 1. Left: the biologist and the designer apply two different approaches. Right: biophysical information representation based on the exploration model of functions, processes, factors, and pinnacles, adapted from Badarnah Kadri [7].

The concept of the *exploration model* of the BioGen methodology is used in this work to map the biophysical information of heat regulation [2]. The exploration model consists of numerous data units, organized at four hierarchical levels, as presented in Fig.1, right. Each data unit contains a head keyword, which is positioned at one of the four levels and linked to other data units; different data units are linked to each other based on their association. Instead of categorizing first by organisms, the exploration model maps function data units at the first level, relevant processes at the second level, and influencing factors at the third level. The pinnacles are presented at the fourth level, and represent a specific function-process-factor combination. The classification of the biophysical information based on the functional aspects is a favourable approach for transformation in biomimetics, as systems in nature have a functional reason, and designers find it easier to establish a suitable analogy.

The following sections present heat regulation strategies in nature, their abstraction and organization in a biophysical framework, and demonstrate an application example that distinguishes a specific analogy for a particular design challenge.

3. Heat regulation in nature

Buildings, in a similar way to nature, try to maintain appropriate interior temperatures for occupant comfort. In terms of heat regulation, the same challenges can be distinguished for both natural systems and buildings, as presented in Fig. 2. This section reviews strategies and mechanisms from nature for heat gain, retention, dissipation, and prevention. The organization of the biophysical information follows the representation approach from the previous section.

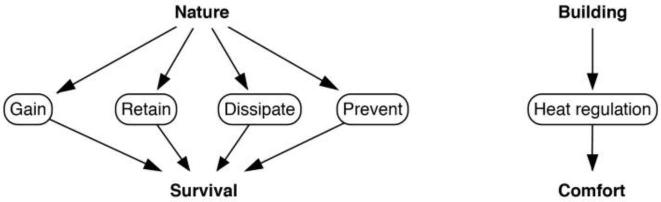

Fig. 2. Abstract analogy: heat regulation of buildings and nature.

3.1. Heat gain

Organisms gain heat from radiation and metabolic heat production. Sun radiation is the most commonly available external source for irradiative heat gain, and metabolic heat production is an internal source for heat gain.

3.1.1. Absorb radiation

Insects and reptiles use solar radiation as a source for heat gain. Color, conductance, distance from a heat source, and orientation (relative to sun) affect their rate of absorption. Dark colors absorb more radiation than bright colors, where many reptiles can change their skin color by dispersing and contracting dark pigments in their skin [8]. Enlarging the exposed area for irradiation increases heat gain as well; small organisms gain heat faster than larger ones. A proper orientation of body parts towards sunrays, e.g. spreading legs and flattening the body, increases exposed area. Overheating is avoided by changing posture, brightening skin color, and/or moving into a shaded area [9]. Even indirectly, solar radiation can be a source of heat gain. For example, cool lizards (e.g. Chuckwalla) come in close contact with a warm rock (heated by solar radiation) to increase heat gain via conduction.

3.1.2. Increase metabolic rate

An increase in metabolic rate results in increased heat production. This is achieved through muscular activity and exercise, involuntary muscle contractions (shivering), and non-shivering thermogenesis [9]. Heat production through muscular activity and exercise varies by organism and is directly tied to behavioral attributes. Shivering as heat production occurs via two types. The first type is low intensity shivering, where animals shiver at a low level for months during the cold period. The second type is the high intensity shivering, where animals shiver violently for short time during acute needs for heat production. Shivering is more efficient than exercising, since animals stay still and lose less heat to environment via convection. On the other hand, non-shivering thermogenesis results in an increased heat due to the increase in the normal metabolic rate. Non-shivering thermogenesis can be either *facultative*[3] or *obligatory*[4] [10].

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[3] Facultative refers to intended activation to increase body temperature during exposure to cold.

[4] Obligatory refers to energy generation due to metabolic rate.

3.2. Heat retention

In cold environments maintaining an appropriate *core temperature*[5] is accomplished by insulation, reduced thermal gradient, reduced metabolic rate, and reduced surface-area/volume ratio. These strategies can be morphological, physiological, as well as behavioral.

3.2.1. Reduce conduction and convection

The process of heat flow from the body to the environment is called conduction (to solids) or convection (to fluids). When insulation is high, heat transfer is low. Fur is primarily for protection and insulation; its thickness may change throughout the seasons to accommodate temperature changes. For example, in the summer the black bear loses 52% of the insulation value of its winter fur [9]. Birds use multiple strategies for retaining heat. For example, chickadees decrease conductance in the cold by raising their feathers and withdraw head and feet into the feathers (behavioral) [9]. They trap an insulating layer of air close to the body and in doing so reduce heat losses (morphological). They also allow the peripheral tissues temperature to drop while maintaining core temperature (physiological). This results in a decreased peripheral circulation, an increased insulation thickness, and enlarged volume. All these contribute in maintaining the core temperature.

Seals and whales that live and swim in the arctic and Antarctic sea have a thick layer of subcutaneous blubber for insulation, since fur loses most of its insulation (i.e. air-trapping) value in water [11]. Aquatic mammals modulate heat loss from the skin by blood bypassing the insulation [12]. Different body parts are not equally insulated, since animals need surfaces from which heat can be dissipated when required. Different thicknesses of insulating material over the body surface allow a considerable flexibility in regulating conductance [11]. Huddling is one means adopted by penguins to reduce collective surface area in the harsh environment of the Antarctic [13]. The large size of whale relative to its surface area reduces excessive heat loss in the cold water [14]. Additionally, many animals tuck in extremities like limbs during cold events in order to help with heat retention.

3.2.2. Exchange heat

The exchange of heat reduces the thermal gradient, thus retaining more heat. Heat exchangers are found in many organisms to maintain body temperature in very narrow ranges despite low ambient temperatures, e.g. circulation systems in fish and whales as well as in the tongue of baleen whales [15]. Heat exchangers can be found in blood vessels with special morphology, e.g. in whale flippers, each artery is completely surrounded by veins. This special structure arrangement results in cooling arterial blood before it reaches the periphery (where heat loss to water occurs), and in warming returning blood (venous blood) before it enters body core [16].

3.2.3. Scatter radiation

Since heat loss occurs through the surface, a strong relationship exists between heat retention and exposed surface area. Simonis, Rattal [17] provided an elaborated model on the mechanism behind the effective insulating capabilities of fur and other woolly materials. They claimed that crisscrossed fibrous material produce radiation scattering, which facilitates heat retention [17]. Fur structure, containing different sizes of hair with dense interfaces, provides the necessary multiple scattering of radiation to retro-diffuse heat [17].

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[5] Core temperature is the temperature deep within a body.

3.2.4. Reduce metabolic rate

Reduced metabolic rate leads to a decrease in body temperature, where the temperature difference between body and environment is reduced, thus less heat loss occurs. Some animals undergo hibernation in winter, where they conserve energy when food resources are limited. During hibernation body temperature drops near ambient temperature, heart slows down, and respiration rates are reduced. For example, squirrels manage their temperature set point by reducing their metabolic rate, and consequently decreasing heat generation [18].

3.3. Heat dissipation

In environment where the body temperature is higher than ambient temperature, the body may dissipate heat by convection, conduction, radiation, and evaporation.

3.3.1. Enhance convection

Convection is a major mode for heat transfer where heated fluid surrounding an object flows away from the object transferring heat. There are two types of convection: (1) natural, where the flow is created by temperature/pressure gradients; and (2) forced, where the flow is generated by mechanical sources. An example of natural convection is heated rising air. Hot air has a lower density than cooler air in the atmosphere, thus it rises. As it rises, it loses energy and cools down, which make it denser, and drops down. This creates a repeating cycle that generates wind. The forced convection involves pumps or any other mechanical force that moves the heated fluid. For example, the flapping movement of elephant ears increases airflow, which enhances convection for heat dissipation. Heat transfer is enhanced by using vibration, where perpendicular vibration to air flow is more efficient than parallel to air flow [19]. It is argued that the alternating black and white stripes of the zebra have a cooling effect due to the convective currents generated on the surface [20, 21], where temperature gradient makes the heated air (near black stripes) rise and consequently displaced by cooler air (near white stripes) creating convective currents. These currents enhance airflow over the skin, increase evaporation rates, and result in cooling.

3.3.2. Enhance conduction

Heat conduction is the transfer of heat via direct collisions of particles and kinetic energy transfer at the interface of two matters. Conduction may occur between any combination of solids and fluids. In general, conduction in fluids (especially gases) is less intensive than in solids, though conductivity increases with pressure. Material thickness, density, and surface area affect conduction: (1) the thicker the material the lower the conduction; (2) the denser the material the higher the conduction; and (3) the larger the surface area the higher the conduction.

3.3.3. Emit radiation – increase emission

Many desert organisms are primarily active at night in order to avoid the extreme heat of the day, and utilize the natural heat sink of the environment for more effective radiation emission. Since heat loss occurs through the surface, a strong relationship exists between radiation and exposed surface area. The large surface area of animals relative to their size enhances excessive heat loss to the surrounding.

3.3.4. Evaporation

When air flows over a moist surface it causes evaporation, which in turn takes a certain amount of heat from the surface. Sweating, panting, and gular fluttering are processes found in different species that increase cooling via evaporation. The capability of sweating is found in some mammals including humans, horses, camels, and some kangaroos. Gular fluttering is a process adapted by some species of birds and lizards in order to increase the rate of evaporative cooling. In this process the animal keeps its mouth open and increases air flow over moist vascular oral membranes by vibration; this in turn increases evaporation and results in increased dissipated heat [22]. Increased heat load results in increased gular fluttering [23]. Panting is also common among birds and mammals, where the rate of breathing is increased as a result of heat stress, e.g. in dogs [24].

3.4. Heat prevention

In warm environments with high radiation exposures, organisms are exposed to the risk of injury and damage [25]. Organisms prevent heat gain via various strategies, among which are decreasing radiation exposure and absorption.

3.4.1. Reduce irradiation

Many desert organisms are primarily active at night in order to avoid the extreme heat of the day. Sometimes the tendency to dissipate heat may create conflicts with heat prevention. For example, providing large surfaces for evaporation may result in large surfaces for heat gain. As a result, some morphological adaptations are distinguished among organisms to minimize heat gain and exposure to radiation. Wrinkles on the surfaces of the skin are one of the means for less radiation exposure by creating shaded regions, which provide a sufficient area for holding moisture and evaporation yet prevents too much direct exposure [26]. Since heat gain of an object has a direct relation to surface characteristics, the sum of environmental heat load on an object is directly related to surface area. Camels and other large volume animals inhabiting warm climates are less likely to absorb too much heat due to, among other factors, their smaller surface area to volume ratio (compared to small animals, larger animals have proportionately less body surface in contact with the environment - Gigantothermy).

3.4.2. Reduce absorption

Substance reflectance, color, and density have a great impact on radiation absorption. Surface color is mainly due to pigmentation, though structures formed on the surface (e.g. of a leaf or fur) may decrease absorption. For example, in the desert shrub of *Encelia Farinosa*, solar radiation absorption is minimized by the presence of dense hairs on leaves [27], which develop reflecting silvery leaves when starting to experience water stress, thus reduce the surface temperature by several degrees due to light scattering at hair layer interface [28]. However, not only the presence of hairs guarantees increased reflectance, but hairs being dead and air-filled instead of live and water filled is a significant aspect to increased reflectance [27]. The highly reflecting scales of Skink helps reducing heat load, and the fur structure of the rock squirrel results in a minimized solar heat gain [29]. In mammals and birds, skin color and hair or feather optics, are important factors for solar heat gain [30-32]. Brighter and lower density materials absorb less light than darker and denser ones.

4. Nature based framework for heat regulation

This section encapsulates the investigation of heat regulation strategies from nature, and presents them in a systematic framework, as presented in Fig. 3. The framework focuses on how certain functions for heat regulation are carried out, what processes are applied, and what exemplary organisms or systems (pinnacles) have adopted those. It is composed of numerous data units, linked to each other based on their association. Each data unit contains a head keyword that was gathered from the biophysical investigation of heat regulation, and the content is a representative state of current exploration, where it can be extended and new data at the various levels may be added in future elaborations following the same logic.

The main aim of the model is to explore possible scenarios for the design solution, and identify exemplary pinnacles. It establishes a suitable analogy between thermoregulation in nature and buildings, and provides some indications on proper aspects to adapt in the design solution, which would eliminate the study of irrelevant aspects. The framework is classified into four main groups, which are analogous to generic functions of desired building materials and systems: (1) *Functions* – analogous to the challenges of the building for heat regulation (e.g. heat gain), (2) *Processes* – presents various means by which a design solution might adapt (e.g. absorb radiation), (3) *Factors* – influential properties (e.g. surface area), and (4) *Pinnacles* – examples of organisms and systems for different function-process-factor combinations (e.g. Chuckwalla).

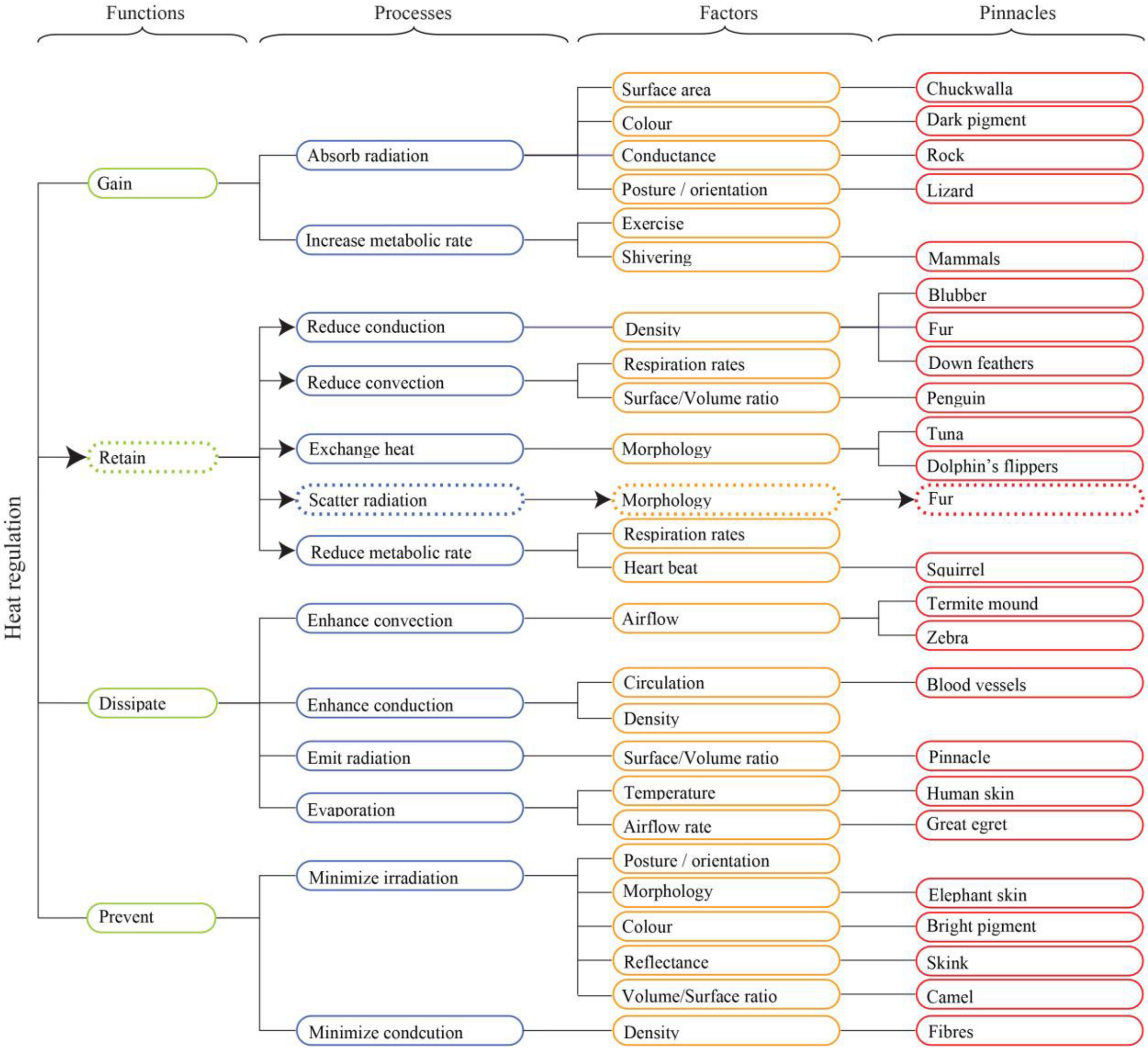

Fig. 3. Heat regulation framework for biomimetic design.

4.1. Application example: exploring possible scenarios and identifying exemplary pinnacles

Biomimetic thermal development in buildings is an emerging field, where some studies have been carried out to explore thermal strategies for potential applications [3, 4, 7, 33]. Application examples are conceptual and claim high advantages over the traditional thermal solutions, e.g. a radiative cooling roofing system estimated to be cooler than a standard roof by 4.5°C [34]; a biomimetic façade cladding material that provides higher heat retention in winter compared with a double wall facade [35]; and a spacer textile made of translucent polymer fibers that reduces heat loss by convection and radiation [36]. Several problem-based biomimetic strategies are available to facilitate design concept generation [2, 37, 38], as well as a wide array of inspirational books of strategies from nature [39-45]. Yet, a biomimetic design process remains challenging. Once the design challenge is defined, the framework provides several scenarios that lead to different relevant pinnacles. This example demonstrates the exploration of possible scenarios and the identification of exemplary pinnacles (as illustrated in Fig. 3, with arrows and dashed units):

- Challenge: reduce energy loss for heating.
- Analogy: the term “reduce energy loss” is analogous to “heat retention” in the framework.
- Processes and factors: the corresponding processes are five, and any of those or their combination can result in heat retention. For the sake of brevity, we choose “scatter radiation”, where applied morphology is a significant influential factor.
- Scenario: the resulted scenario based on our process and factor choice is *heat-retention – scatter radiation – morphology – fur*, as illustrated with dashed data units in Fig. 3.
- Pinnacles: Fur is a representative system for heat retention, where further investigation is required to determine mechanisms and features.

5. Conclusions

Organisms succeed to maintain an adequate balance between heat gain and heat loss without creating air-tightness and water-tightness. Various strategies are found in nature for heat gain, retention, dissipation, and prevention, which are accomplished by physiological, behavioral, and morphological means. The general investigation of heat regulation in nature provided a broad understanding of heat interactions, rather than limiting to a specific strategy or organism. The investigation of these interactions was summarized in an exploration model for thermoregulation, which provides different scenarios that correspond to heat related design challenges. The systematic representation of data and their relationships establishes a suitable analogy between thermoregulation in nature and buildings, and provides some indications on proper aspects to adapt in the design solution, which would eliminate the study of irrelevant aspects.

The defined challenge and degree of freedom in selecting factors and pinnacles have important consequences on the generated design concept, which provides a three-step filtering of pinnacles: (1) the defined challenge “eliminates” the overwhelming majority of irrelevant pinnacles in the exploration model, and thus increases the efficiency of selecting suitable pinnacles; (2) the degree of freedom in selecting the factors is important for optimization of the design in terms of feasibility and preferred technology to be used; and (3) the final selection of pinnacles influences the architectural aspects of the generated design.

Besides the hierarchical representation of the framework for *heat regulation*, it reveals the influence of morphology on the majority of processes and the strong relationship with surface properties. The content of the exploration model is a representative state for current exploration, where it can be extended and new data units at the various levels may be added in future elaborations.

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