VII International Congress on Architectural Envelopes Biomimicry in climate adaptive building skins: relevance of applying principles and strategies.

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Abstract

There is growing interest in scientific literature and in research projects on climate adaptive building skins -CABS-. A large development of this type of building skins is expected, because of the advantages they offer over other skins, such as the improvement of environmental quality and energy efficiency, the adaptability to climate and changing uses of buildings, the ability to use low exergy sources, the potential for integrating architectural design principles with energy efficiency, the possibility of driving the research on new technologies and a greater efficiency in the use of materials. However, this development is not taking place in practice, since most projects either remain on experimental prototypes or are implemented in high budget buildings.

This paper examines the relevance of applying a biomimetic approach to the design of CABS, given the adaptive behaviour of both systems.

By studying the correlation between the functional requirements of adaptive building skins and adaptive strategies that can be found in natural organisms, we address the possible overcoming of some limits they face in their development –from design, technological, economic and social-.

The aim is to further the implementation of biomimetic principles and adaptive strategies to enhance adaptive behaviour, take advantage of the evolutionary knowledge that nature provides, derive applying principles to achieve best architectural solutions, serve as a driver of innovation in architecture and promote efficiency and sustainability in building skins, using principles such as optimality in resource management, resilience behaviour, exchange of information and energy with the environment, complexity by organization of simple elements, or multifunctionality.

Finally, biomimicry has shown to be a suitable approach, which, by putting systematic design processes into practice, yet to achieve, could promote the widespread development of climate adaptive building skins.

1 Adaptive building skins

In the current context of climate change, insecurity of energy supply, rising prices of traditional energy sources, and economic crisis, the search for solutions to improve the energy performance of buildings, particularly of the envelopes, as responsible of the exchange of energy and other flows with the environment, sets out, in order to reduce energy consumption and emissions of greenhouse gases, and achieve greater efficiency in the use of materials, by the use of adaptive building skins. This type of building skins stand out for its ability to substantially improve energy performance [1, 2].

According to the FACET project, “ideally adaptive building shells have the potential to practically eliminate the heat demand and to reduce the total heating and cooling demand by a factor 10; this is even a factor 2–3 lower compared to the very energy efficient passive house technology” [3].

This concept of adaptability of building skins has been regarded as "a necessary step towards further energy efficiency improvements in the built environment” [4] as well as an “added value on top of passive design solutions” [5], and “one of possible ways to accomplish the shift towards net zero energy buildings” [5].

Climate adaptive building skins –CABS-, have the ability to adapt themselves to environmental changes, so it’s possible to get the most out of variable weather conditions, regarding energy demand, thermal conditions, lighting, visual comfort and air quality.

The growing interest that is awakening this type of building skins comes out of the benefits that, implicitly or explicitly, are expected of them, among which include:

- Improved environmental quality: thermal, sound, visual, air, resulting in improved health and productivity at work [6, 7, 8].
- Ability to adapt individually to each user or group of users, or different functions or usage patterns, as well as changing weather conditions.
- The integration of responsive components with the rest of the building energy systems can substantially improve the energy performance of the whole building. Overall, we expect a lower energy consumption and therefore, economic expense, as well as a reduction in emissions of greenhouse gases.
- Ability to use low-exergy energy sources, facilitating the use of renewable energy.
- More efficient use of materials.
- Potential to integrate principles of architectural design concepts with energy efficiency.
- Ability to promote research and development of new technologies that combine multiple functions in one building element.

However, despite the benefits this type of building skins promise, so far its use has been limited, being confined mainly in pilot projects or in high budget buildings, due to various factors.

First, the concept of design: its dynamic character becomes adaptive building skins in a process, rather than an artifact design, so that traditional methods are inadequate and new design methods, yet to be developed, are required.

Design tools are needed, to better evaluate their behaviour at different levels, especially their performance throughout the life cycle. Simulation tools available are still insufficient to cover the variability of parameters that can be used.

Second, the technological challenge of adaptive behaviour, either because the necessary technologies to produce a kinetic behaviour may not be in an optimum stage of development, either by the challenge of producing smart materials that change their properties at the micro scale, designed bottom to top, from the desired properties and characteristics of the material.

Another technological challenge is the implementation of such systems in the industry across the board. The jump of scale, from prototypes to the industrialized production of materials and systems is still an unresolved obstacle, related to the inertia of industry and economic factors.

The development of control systems is another technological challenge with great development potential, particularly the transition from centralized to distributed models, more in line with the properties and behaviour of smart materials.

Also note the uncertainty that offer these systems in terms of behaviour in the long term, given the short time they have been in place and that the results have not always been successful.

Third, from an economic point of view, a high initial investment is needed to implement such systems in many cases. Exhaustive cost-benefit analysis, largely unrealized, are needed, because of the experimental or unique character of most existing cases, including the consideration of the entire life cycle cost (LCCA).

Finally, we mention the difficulty, for many users, of psychological adaptation to the changing behaviour of the building skins.

2 Biomimicry and adaptive building skins

Observing and learning from behavioural patterns of living organisms provide an opportunity to improve adaptive strategies of building skins. These adaptive strategies and underlying principles can be learned from nature. Indeed, living organisms have developed through evolution, a wide range of strategies to adapt to different climatic and environmental conditions. Research and analysis of these strategies and their key principles is an essential first step to transfer these strategies to adaptive building skins design. The fact that nature provides a great source of adaptive strategies requires a targeted methodology design that meets the requirements of adaptive building skins [9].

Living beings are based on principles such as energy conservation, recycling, shape optimization, use of affordable local materials, adaptation to the environment and sustainability. Although the objectives may not be the same, these principles are applicable in construction to accomplish materials and energy saving, more efficient and sustainable solutions, reduce cost or improve performance and durability [10].

It is about taking advantage of the wealth of knowledge that evolution provides, over millions of years. For every problem there is a solution that nature has provided, and in a more efficient and sustainable way than any industrial process: produce energy, collecting water or sustainably manufacturing materials. Thus, the nature becomes from a resource to use to something alive to learn from.

Another factor to incorporate biomimicry in building skins design is its role as an innovation engine in architecture: “Biomimetics in architecture is a discipline to gain innovation in architecture by using natural role models, and the comparison between animate nature and built environment creates new insights” [11].

Using biomimicry opens a whole range of application fields related to architecture, not only building skins design, such as environment design inspired by natural ecosystems, new methods of manufacturing materials, structural systems, new solutions to existing problems based on biological models, as well as improved relationship of built spaces with natural environment and, in general, with living beings.

3 Functional requirements and adaptive strategies

Typically, the adaptation of the envelopes takes place in relation to any of these physical aspects:

- Heat, related to conduction, convection, radiation and thermal energy storage.
- Optical, related to the transparency of the surfaces and the color change.
- Airflow, related to the direction and wind velocity, ventilation and air exchange, as well as variations in relative humidity.
- Water, related with water gain, evacuate or store, or regulate the moisture content of buildings.

- Electrical, such as power generation.

For each of these physical aspects, there are a number of requirements, different for each case: location, climatic characteristics, use and occupancy patterns of buildings, which determine different adaptive needs of building skins.

The functional requirements of adaptive building skins related with each of these physical aspects have a counterpart in the strategies that natural organisms use in adapting to the changing conditions of climate and environment.

The field of knowledge associated with adaptive strategies is vast and beyond the scope of this study; there are many databases that collect this knowledge, such as asknature.org, promoted by the Biomimicry Institute [12].

However, the challenge to develop a taxonomy of adaptive strategies not based on biological characteristics, but according to the functional requirements of building skins, still remains, so that this knowledge can be represented and used in building skins design.

3.1 Thermal control

Temperature regulation and homeostasis are fundamental characteristics of living beings which, using different strategies, are capable of maintaining their temperature within certain limits.

a) Gain or absorb heat: almost all living organisms rely on the sun as a heat source. Exposure to the sun allows heat gain, depending on parameters such as color, conductivity, or orientation. Poiquiloterms such as insects and reptiles, depend almost exclusively on this source of heat. Another resource is to increase the metabolic rate, in a process known as thermogenesis, through muscle activity and movement. For example, chills or repeated movements of some animals.
b) Retain, preserve or store heat. Animals turn to skin, subcutaneous fat or cavity between hairs that retains a layer of air next to the skin and thus reduce heat transfer, such as birds do. Marine mammals regulate loss by bypassing the circulatory system below the subcutaneous fat. The circulatory system of marine animals operates as a heat exchanger, yielding heat from arteries to veins before getting in touch with the outer layers of the skin. When they are not able to capture or produce enough heat, reduce their metabolic activity, sometimes for whole seasons, as the sluggishness of reptiles or hibernating bears, or modify surface/volume ratio, in order to reduce the loss per volume unit. This strategy is used by animals when wrap around themselves or when huddle collectively, as penguins.
c) Dispel heat by natural convection, as termite mounds or micro-drafts in the skin of zebras; by conduction, increasing the exhibition area, as birds do, or wrinkles in the skin of elephants, or by evaporation, with strategies such as sweating, panting or fluttering of birds.
d) Avoid heat, minimizing radiation exposure like the elephants do with the ears, which act as parasols, or minimizing the thermal load, through strategies of color and reflectance of the skin.

These strategies could be used to design building skin that function as heat exchangers, with heat and cold circulatory systems; using materials with micro-wrinkles that regulate surface weathering or by dynamic variations in color, texture or properties to generate drafts.

3.2 Lighting

Solar radiation is the main source of light. Natural organisms have developed different strategies to regulate their intensity or avoid exposure to it.

a) Adjust the light intensity by geometric structures, such as the Fibonacci series, which maximizes exposure to light; adjusting the incoming area, as the pupils of the eyes; adjusting the angle in relation to the sun, as the leaves of plants -heliotropism-; or by diffuse reflection.
b) Intercept light, as some sponges, which have a similar structure to optical fiber for continued light transmission, or by different mechanisms of refraction, reflection or absorption of light.

These could lead to the use of smart materials with different degrees of solar control, or automatic changes in the arrangement of transparent and opaque elements using geometric layouts.

3.3 Air exchange

Air exchange with the environment, consisting of oxygen uptake and release of carbon dioxide, or conversely, is vital for much of living organisms process.

a) Diffusion through the skin, increasing or decreasing surface to volume ratio, such as fish gills; regulating permeability through protective membranes in animals, or stomata in plants, or by varying gas concentration.
b) Air movement by convection caused by temperature difference in gases or liquids, or pressure difference, through the Venturi effect.

These strategies could be applied by developing smart materials with varying permeability or adjusting openings automatically depending on CO_2 concentration.

3.4 Water management

Water is essential for life, as a resource and as a medium in which biochemical reactions necessary for life take place. The organisms have developed different adaptation strategies, depending on the environment in which they are.

a) Capture water by condensation on the surface of the skin, or by vapor diffusion through the skin, especially in amphibians.
b) Transporting water using gravity, like plants that carry condensed or trapped water on the surface of leaves or thorns toward the center of the plant or the roots, or by capillarity, strategy used by trees to carry water from the roots to the leaves by successive reductions in section ducts.
c) Release water by evaporation, from parameters such as vapor pressure difference, air exchange rate, temperature, surface and orientation.
d) Conserve water, either by reducing the rate of evaporation, keeping a layer of air near the surface, like the birds or cactus spines, or by reducing exposure to solar radiation, self-protecting and providing shade in different ways: bending, reorienting, changing volume.
e) Filtering water through the skin and, more specifically, the kidneys of mammals, which act as purifying filters.

So we could develop surfaces with micro-grooves to capture and carry rain water, of surfaces which could contribute to vapor condensation.

3.5 Energy generation

Living organisms have developed different strategies related to energy management.

a) Capture energy, through photosynthesis, with strategies related to spatial distribution patterns of leaves in order to improve exposure.
b) Save energy, using mechanisms of elasticity, such as tendons, or as fat, like the humps of camels, or certain molecules.

We could think off solar energy produced by photosynthetic processes rather than silicon cells, or store energy in synthetic tendons.

4 Biomimetic principles

Within these adaptive strategies of nature, we can distinguish three levels:

- Organisms level. What is sought is the solution to particular problems mimicking the functionality of certain organisms, regardless of the context in which they occur. It is about getting an added technology to buildings, rather than a substantial modification thereof.
- Processes level. It is about getting solutions that transform the environment, studying patterns of relationship and incorporating them in the design of buildings.
- Ecosystems level. In this case, architecture and built environment is supposed to be part of a broader ecosystem, taking part in the different cycles of the planet.

The application of biomimicry is generally directed to imitate organisms, for this is its most immediate implementation. However, its real potential is not only incorporate particular strategies, but general principles that lead to solutions that are not only sustainable but regenerative. Indeed, it is to promote efficiency and sustainability in building skins, incorporating the biological principles that can be found in organisms, processes and natural systems from the initial phase of design as mandatory requirements. Thus, the number of demands on the design expands, but also serves as a guide for finding optimal solutions at different levels.

As for the principles on which organisms and natural systems are based, there are a number of features that are mostly recognized as common to biological systems.

4.1 Openness / exchange with the environment

All living organisms exchange information, matter and energy with its environment; integrating locally, taking advantage and enhancing cyclic concurrent processes, and developing relationships of cooperation and competition.

These principles could be used to promote the use of local and abundant materials in the surroundings, using renewable and available energy locally, considering the whole life cycle of materials and systems, with a "cradle to cradle" approach, or as selection criteria in the use of materials: recycled and/or recyclable, non-polluting, biodegradable.

4.2 Resource management / optimality

Organisms and natural ecosystems are characterized by optimizing available resources, following principles as multifunctionality, the development of low-energy processes with low or zero entropy, selective construction with few materials or adjustment of form to function.

Thus, the use of materials and systems with integrated functions, materials with low embodied energy, renewable and low-exergy energy sources or materials efficient by shape, not by quantity of material could be promoted.

4.3 Order / structure / growth

Living organisms are characterized by being increasingly complex systems, following the principles of self-organization, which from elements and simple rules evolve toward greater complexity; integrity through self-renewal and regeneration, or building systems bottom up, using nested elements.

In practice, we could use self-interlocking, self-cleaning and self-regenerative materials and systems, manufacturing and production systems by additive accretion or systems optimized as a whole, instead of form individual components.

4.4 Adaptability

A main characteristic of living systems is their ability to adapt to changing conditions, due to their high resilience, incorporating criteria of variation, redundancy and decentralization.

One might suggest, for example, the use of decentralized, multi-nodal, and densely interconnected control systems, so that the probability of failure is reduced, risk management is improved and resilience to unforeseen scenarios and external conditions changing is gained.

5 Conclusions

This paper has shown how the application of biomimetic principles and adaptive strategies of natural organisms, processes and ecosystems can improve the adaptive behaviour of building skins.

Indeed, the principles that rule the functioning of living organisms are applicable in architecture to save materials and energy, achieve more efficient and sustainable solutions, reduce cost or improve performance and durability, while adaptive strategies from organisms can be applied in the design of building skins, also serving as a tool for development and as innovation engine.

The application of these principles in the design of adaptive building skins, far from being a theoretical disquisition, is a practical necessity. Without respecting the principles underpinning these natural strategies, the imitation of nature is reduced to a superficial level, which can mimic a particular function, but losing the benefits that the biomimetic approach promises, where there is also a gain in sustainability.

Finally, the application of biomimicry opens many research fields; some of them integrate the ongoing research from which this paper is part, namely:

1. Development of a taxonomy of strategies according to the requirements of adaptive building skins, so that it can represent a useful biological knowledge in the design of building skins.
2. Development of a methodology to select strategies, manage conflicting requirements, and systematize the application of biomimetic approach to the design of building skins.
3. Development of modeling and simulation tools suitable to adaptive and changing behavior of adaptative building skins.
4. Prototyping and application cases which allow to compare, validate and improve this methodology in a process of continuous improvement.

Reference

[1] GhaffarianHoseini, A., Berardi, U., GhaffarianHoseini, A., Makaremi, N. Intelligent facades in low-energy buildings. *British Journal of Environment and Climate Change*, vol.2, no.4 (2012), pp. 437-464.

[2] Maile, T., Fischer, M., Bazjanac, V. Building energy performance simulation tools: a life-cycle and interoperable perspective. *Center for Integrated Facility Engineering (CIFE), working paper, 107* (2007), pp. 1-49.

[3] Loonen, R., Trcka, M., Hensen, J. Exploring the potential of climate adaptive building shells. *Proceedings of the 12th Int. IBPSA Conference*, Sydney, 14-16 November (2011), Int. Building Performance Simulation Association, pp. 2148-2155.

[4] Aschehoug, Ø., Andresen, I., editors. *Annex 44 - Integrating environmentally responsive elements in buildings*, IEA – ECBCS, 2008.

[5] Loonen, R., Trcka, M., Hensen, J. Exploring the potential of climate adaptive building shells. *Proceedings of the 12th Int. IBPSA Conference*, Sydney, 14-16 November (2011), Int. Building Performance Simulation Association, pp. 2148-2155.

[6] Heerwagen, J. Green buildings, organizational success and occupant productivity. *Building Research & Information*, vol.28, no.5-6 (2000), pp. 353-367.

[7] Haynes, B. The impact of office comfort on productivity. *Journal of Facilities Management*, vol.6, no.1 (2008), pp.37-51.

[8] Lan, L., Wargocki, P., Lian, Z. Quantitative measurement of productivity loss due to thermal discomfort. *Energy and Buildings*, vol.43 no.5 (2011), pp.1057-1062.

[9] Badarnah, L. *Towards the living envelope: Biomimetics for building envelope adaptation*, 2012. PhD thesis, Delft University of Technology, Delft, The Netherlands.

[10] Llorens D. & Ignasi, J. Zoomorfismo y bio-arquitectura. Entre la analogía formal y la aplicación de los principios de la naturaleza. *II Jornadas de investigación en construcción: Actas de las Jornadas*. Madrid: Instituto de Ciencias de la Construcción Eduardo Torroja, 2008.

[11] Gruber, P. Biomimetics in architecture [Architekturbionik]. *Biomimetics: materials, structures and processes*, pp. 127-148. Springer Berlin Heidelberg, 2011.

[12] AskNature, 2008. A project of Biomimicry 3.8. http://www.asknature.org (05/04/2015).