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Bio-inspired materials in the evolution of the building skins

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Abstract: We are currently addressing a significant problem all over the world which is the energy shortage combined with the issue of the high energy consumption of buildings. Within the current scenario, exacerbated by the consequences of the post-Covid19 pandemic, the Russia-Ukraine conflict, the climate change, which aggravate the situation of the energy crisis at a global level, the contribution aims to show how architects and researchers are working to find strategies for sustainable solutions in the building sector, through a paradigm shift. The innovative vision is given by the approach to biomimetic science connected to the logic of innovative materials and new technologies, such as parametric design and nanotechnologies for new bioinspired skins for building envelopes.

Keywords: Skin - Biomimetics - Building envelope - Sustainability - Energy efficiency – Comfort - Climate change - Self-healing - Self-repair

[Resúmenes en castellano y en portugués en las páginas 152-153]

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1. Introduction

The issue of sustainability has become crucial after the Seventies in the building industry, although there is a lot of confusion regarding dealing with this theme (Zhang, 2015). In general, this is due to the common belief among builders that sustainable practice is not economically viable. It is necessary to find out the balance between the growing economy, social responsibility and environmental protection to improve the quality of life of current and future generations. In this sense, there are many possible ways to achieve these goals. It has been shown that making structures more energy efficient, for instance, through the study of the correct solar orientation to obtain maximum daylight or through the use of different types of materials, such as bionic ones, leads to significant benefits, such as reducing greenhouse gas (GHG) emissions, reducing lighting fixtures or lighting needs by 30%, increasing productivity by at least 30%, saving around 70% in electricity and 50-60% in building water needs, reducing cooling needs by 5-10% and, finally, saving about 36% in energy consumption compared to traditional buildings consumption (Zakeri, 2022).
Hashim Sarkis, the curator of the 2021 Venice Biennale, investigated the need for a spatial-relational renewal as the theme of that edition entitled "How will we live together?" (Sarkis, 2021). In the exhibition, 112 participants from 46 countries put forward their proposals on how we could live together better and shortly, considering the crisis facing the planet that requires global action and a revolutionary rethinking of the way of doing architecture. Architectures have to respond to criteria of functional adaptability and to increasingly extreme and constantly changing conditions, which it is difficult to predict a priori (Di Salvo, 2020), such as the case of tragic events that may no longer be exceptional, such as pandemics, conflicts and the consequences of emergency of climate change (World Health Organization, 2018). Currently, the difficult historical moment from an environmental point of view and the pandemic consequences have made us aware that cities are not only "means for coexistence" in a stable scenario but are a process of continuous adaptation to conditions of permanent instability (Melis *et al.,* 2020). The interruption of travel from one place to another, the need for a future city where distancing, if necessary, is possible and the climate emergency has amplified discussions on alternative design models for the elements of architecture. New questions on creating products that can adapt to unpredictable events, ensuring long-term sustainability criteria, have emerged *(See Figure 1)*.

Figure 1.
17th Venice Architecture Biennale, Installation "Mutual Aid: The Politics of gaia" to cooperate harmoniously with nature.

Specifically, rethinking materials for new or existing buildings by designing bio-inspired building skins, has the dual purpose of protecting communities and taking care of the environment, with tools that we have available and that we can control in the medium term, through a multidisciplinary approach in which different skills cooperate in order to obtain lasting, adaptable and sustainable results at multiple levels. The fascinating factor is that in nature nothing happens by chance, but it is the result of a process. Remaining on the subject of forms, which is the field in which an architect can feel comfortable, the modelling of a form in nature is the result of the action of different forces. An example can clarify some mechanisms in the generation of shapes. It is assumed that waste is not allowed in nature and that the material costs because it derives from the nutrients that a plant or animal manages to recover from the environment. Being able to do better or more with the same amount of resources can be the extra point that determines the survival of one organism at the expense of another. The fight for survival is another basic principle of ecosystem balance. The optimization of specific performance is one of the most used strategies of natural organisms. In this case, since the material is precious, nature has been aiming for millennia in optimizing shapes that use as little material as possible. Within this scenario, the current continuous research and paradigmatic experiments are represented by the achievements of the research group of Achim Menges at the University of Stuttgart, which since 2012 with meteorological pavilions has demonstrated how the skin can react to stimuli from the external environment by adapting with formal and functional modifications (*See Figure 2).* As with the pine cone, bending the pavilion skin is also driven by sudden changes in humidity and does not necessarily require direct contact with water. These experimentations aim to explore a novel mode of climate-responsive architecture, based on the combination and interrelationships of material inherent behaviour, computational morphogenesis and robotic manufacturing (Krieg, 2016).

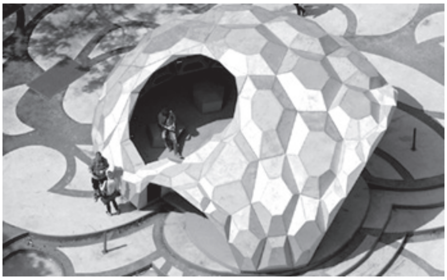

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Figure 2.
Aerial view of the built full-scale prototype of a meteorosentivive pavilion designed by Achim Menges.
Figure 3.
The Durian plant.
Figure 4.
Bioinspired plant-based design for the Esplanade Theatre in Singapore, by Michael Wilford.

1.1. Adaptive behavior

In ethology, adaptive behaviour is the strategy that generates the evolution of a species in response to changed environmental conditions. Adaptations can be read diachronically, as a change in an ecological factor and synchronically, as the realization of a new balance between organism and environment. By analogy, mechanisms of adaptation between living organisms and the environment give us a possible interpretative key of the interactions that some buildings establish with the places where they are with dominant natural characters. This makes us understand that the relationships between materials, construction technologies and the environment result from a slow and progressive dialogue between human beings and nature. An example of the influence of nature on construction is the architectural landmark such as the Esplanade Theater, inspired by the durian fruit, which opened in October 2002 in Singapore (*See Figure 3*). In the building skin, the durian-like spikes operate as sun shields *(See Figure 4)*.
Drawing inspiration from nature is not a new concept but a recurring theme in human history. When we talk about the built environment, we are also experiencing the evolution of some technical terms. What in the past was called the closure of the building is now the building envelope. And the building envelope has a skin that covers the whole building.

This makes us aware that in more sustainable technologies studies, we search for comfort through particular terms and analogies by finding definitions that make us feel closer to nature and other living beings (Di Salvo, 2018). In recent decades, this correspondence in terms has become increasingly realistic so that today it is necessary to run for cover and focus more on the cognitive tools offered by biology that, integrated with science, design and technologies, contribute to the construction and improvement of the performance of structures habitable by man.

Greenough, describing the feedback between organism and environment, states that «the law of adaptation is a fundamental law of nature in all structures», and Eildlitz, one of his students, elaborates on the subject by declaring that «in Nature, forms are the product of the environment, the environment determines function and forms are the results of function and, as in nature so in architecture, the forms must be adapted to the environment so that the resulting functions are fully expressed in the architectural organism» (Siani, 2013). The resilience of biological systems and their sustainability requires the possibility of adapting, sustaining and maintaining dynamic stability in chaotic events. Similarly, an adaptive building envelope establishes a relationship of interdependence with the external environment and conditions change over time depending on the geographical context and climate; As a result, the skin changes interact and adapt consistently, as happens in a living organism in nature. The adaptability conferred to the building organism by the biomimetic design paradigm is usually more evident in the shape of the envelope closely connected to the functional behaviour.

This contribution aims to demonstrate that as the mechanism of the evolution of Darwin's theory, also envelope-building skin can be enriched with a qualitative leap, thanks to the ability to respond, modify and improve over time resisting and finding from time to time a new balance with the surrounding environment, achieving high-performance objectives in terms of efficiency and comfort, conditioning current and future relationships with the environment and inhabitants.

2. Bio-inspired methodological approach

The methodology followed is based on the analysis of good practices of projects and significant research to demonstrate the potential of the bio-inspired approach for the construction of smarter adaptive building envelopes. In general, it is clear the need for a scientific-interdisciplinary approach that addresses the crucial contemporary issues on different ecological-environmental and aesthetic sustainability levels. We do not look at nature as an element to imitate but aim to abstract mechanical processes to explore methods and strategies implemented by natural organisms or systems to create intelligent solutions for high-performance building leather, where form and functional behaviour are two factors closely connected.

Specifically, a bio-inspired methodological approach is divided into the following phases: identify the required challenges and the results to be obtained, explore the natural reference strategy, extract and abstract the fundamental principle, build taxonomies, get

ideas, evaluate ideas, evaluate three-dimensional modelling tools, turning the best ideas into intelligent envelope designs, building physical models, evaluating, validating and determining them, making bio-inspired building skins, determining future challenges. A bio-inspired approach follows the phases according to the need of the project when the process is configured by a biological inspiration and seeks to provide a direction for the development of some biomimetic project or artefact and material. Just as species have evolved to survive and find the right balance concerning environmental conditions, the skin of the building changes and transforms, reacting like the skin of a living organism.
The contribution demonstrates the importance of the centrality of the relationship between man and building/environment/nature, underlining the importance of interaction with the place, with the construction systems, techniques, materials and new computational technologies, such as parametric design as a method to emulate the strategies of the natural system and digital fabrication, which help to define complex and performing forms. Based on the consideration that the building skin can mimic the behaviour of living beings, case studies were selected involving buildings with bio-inspired characteristics and design products as well, that could be used for the building envelope skin, emphasizing the importance of technology transfer from design to architecture. In particular, characteristics of thermoregulation, light management, self-repair and self-healing were taken into consideration. These functions were also chosen for their significant influence on energy efficiency, the containment of CO2 emissions, and comfort benefits.

3. Discussion

3.1. The skin of the building

Within this scenario, the skin is the biological paradigm, which is converted into a technical and visual element in the façade design process. The anatomical aspects of the skin find a correspondence in the façade systems through a reinterpretation of the biological functions and the building structure (*See Figure 5*) (Conzatti, 2020).

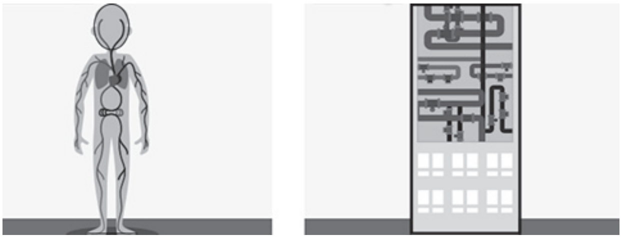

Figure 5.
Human body vs building.

One of the essential needs of the skin of the building, just as it happens through the skin of the human body, is to ensure the maintenance of comfort conditions through tools that can control and adjust parameters such as air quality, temperature, humidity, natural lighting and acoustics, reaching optimal levels for comfort, limiting the use of systems that involve the energy consumption of traditional plants. The comfort we strive for aims at mental and psychophysical well-being. Therefore, in the integrated sustainable design, the concept of envelope/closure is extended since the building skin is not a container that encloses a space but a system that connects living beings, buildings and the environment.

The skin of the building is the dynamic interface between external environmental factors and the internal needs of the occupants (Del Grosso & Basso, 2011), place of heat exchanges. Building envelope separates the space inside the building from the external one, as a kind of transformer, on one side, of which a certain number of phenomena act, including climatic ones. On the other side, these actions are transferred more or less modified according to the type of wall considered and the conditions imposed inside.

The human skin sends signals through the nerves to the brain, and then, through reactions, it self-regulates comfort conditions (Faragalla & Asadi, 2022). The building is like a living being and has a membrane, a skin, which behaves like the skin of natural organisms and, as such, can heal itself, purify the air, calibrate the brightness, regulate the temperature and respond dynamically to external environmental agents. A bioinspired sustainable building envelope is a system capable of dynamically self-regulating to changing external climatic conditions, able to produce or use clean energy by making the best use of passive resources while respecting the environment. To be efficient, the envelope of a building must reduce the heat exchanges between the inside and the outside, dampen with its inertia the most rapidly variable effects of the climate, and ensure with its permeability the hygrometric balance between the inside and the outside. It is the task of the building envelope to ensure that, despite the variability that characterizes the external environment, the conditions inside the building are comfortable in a stable manner.

3.2. New technologies

For over a decade, the design of external surfaces of buildings has acquired a strategic role in responding to increasingly complex needs, opening up to the experimentation of innovative technologies, which provide for the application of intelligent systems for the realization of bioinspired dynamic façades. Living organisms and those belonging to the plant world can capture, convert, store and process energy, water and sunlight. As a result, we heat up and cool down, creating conditions of shadow and light control dynamically and naturally. Unlike naturally occurring organisms, buildings are generally designed as static and inanimate objects. As a building's surroundings and interior conditions constantly change, there is much to learn about how nature inspiration can foster greater façade adaptability to improve building performance.

4. Good practice

4.1. A heliotropic skin for lighting capture

It has often been observed that the perfection of Nature is reflected in the bioclimatic behaviour of the leaves of green plants. The plant synthesizes and recycles its solar cells depending on the temperature of the external environment. The layers of light that convert are 10,000 times thinner than our photovoltaic cells, and the plant can still afford to throw them away every year. Many plants also move their leaves following the movement of the sun leaning towards it to collect more light or folding when the light is too strong. The ability of plants to use solar radiation from a thermal and light point of view as an energy supply is therefore unparalleled: «As far as the field of energy production using sunlight and fuel application is concerned, our technology is decidedly still in its infancy compared to the experiences of nature», Frei Otto stated (Sala & Cappellato, 2004; Liddell, 2015). The prophetic words of the architect Frei Otto expressed in the second half of the 1900s should push contemporary designers towards an exploration of the scientific Nature of the natural world and the relative ways of overcoming the problems linked to the need for survival of the factors that characterize the environment to arrive at the realization of bio-inspired or biomimetic projects.

Bioinspired projects try to exploit the following characteristics of some plants, such as tropism, phototropism and heliotropism. Tropism is the movement of an organism or part of it determined by the action of an external stimulus; phototropism is the property of an organism to orient itself concerning light; heliotropism is the property of an organism to orient itself concerning the sun. These are three characteristics of plants effectively exploited for adaptive and responsive architectural elements design. From the point of view of a new bionic approach to the project, the enclosure of the Seine Musicale in Paris, designed by Shigeru Ban and built in 2017, represents an original example of a heliotropic structure (Landa, 2017) (*See Figure 6*). The building supports a large sail 45 meters high, set on a metal grid structure and covered with a layer of 800 square meters of photovoltaic panels to maximize thermal storage and the exploitation of a renewable source of energy supply (Stehling *et al.,* 2017). Every fifteen minutes, the sail rotates like a sunflower, according to the principle of heliotropism, orienting itself and following the sun rotation and providing the whole complex with the energy necessary to achieve thermohygrometric well-being (*See Figure 7*). In general, the energy supply is covered by a connection to the district heating and cooling network IDEX, which is supplied by renewable energy up to 65%. The project represents an emblematic case because it shows the attempt to insert a building within the energy flows of the ecosystem (Usai & Stehling, 2018).

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Figure 6. The Seine Musicale in Paris. **Figure 7.** Sunflowers.

4.2. From polar bears, characteristics of thermoregulation for the buildin skin

One of the important features that the building envelope must have is to maintain thermal comfort for the occupants. The most efficient thermoregulation solutions are found in nature. Living things can physiologically manipulate their body temperature as an adaptive response to environmental changes. As in a living organism, if the thermoregulation system in a building is automatic, the user does not have to worry about managing the thermoregulation, as all the necessary climatic parameters are detected by special sensors which send information to the system and determine the consequent regulation , through the skin of the building (Best, 1982).
In recent decades, materials inspired by the thermoregulatory behavior of polar bears have been the subject of numerous researches and experiments. In fact, the fur of the white polar bear plays the role of thermal protection in the polar regions, through a gradual mutation operated by the brown bear. In reality therefore, the coat of polar bears have a very particular transparent golden hair and dark skin. The polar bear's coat is made up of translucent hollow hairs that capture the sun's rays and convey them towards the skin. The hairs appear white because the cavities scatter and reflect light. The hairs have a dual function: to capture the light rays towards the inner skin, where the skin is dark and can accumulate heat and to prevent the dispersion of the heat thus accumulated, acting as a real thermal insulation barrier (Herzog, 2005).
During the route along the fur duct, the sun's rays reflecting on the walls produce imperceptible micro-vibrations of the fur itself, producing kinetic energy which further contributes to heating the animal, which thus bears the rigid polar temperatures.
Specifically, the Transparent Insulating Materials (TIM), patented for the first time in Germany in the 1980s by Thomas Herzog with the initials TWD (Transluzente Waerme Daemmung, literally: "transparent thermal insulator") are transparent insulating materials applied on solid opaque or semi-opaque with high light diffusion capacity (Paneri

et al., 2019). They are characterized by a honeycomb capillary structure, inspired by the biological structure of polar bear fur, and, thanks to the particular material and geometric composition, they reduce radiative exchanges, blocking the convective motions of the air inside them, transforming them in heat (*See Figure 8*). The TIMs are composed of a structure of micro-cannulas in transparent plastic material protected from the outside by glass; these insulators are applied as a dark colored wall covering and work the same way as bear fur. A type of opaque envelope containing TIM called "solar wall" as well as guaranteeing a good insulating effect, thanks to the high air content and the fact that it can divide the air into small sub-volumes, has a high permeability value to solar radiation which causes the radiation itself to be able to penetrate the building envelope up to the massive internal surface but, thanks to the presence of the external glass surface, limits the dispersion of energy in the opposite direction (Wang *et al.,* 2020). The use of a transparent surface is useful not only for thermal insulation purposes, but also for the purposes of treating the external façades of buildings with attention to issues of energy sustainability and the environmental impact of buildings, with an eye to the architectural aspect.
The improvement of the performance characteristics of TIMs is given by the development of latest generation aerogels: silica aerogels either in monolithic or in granular form provide excellent thermal insulation and thus may be used as superinsulating spacer in all kinds of window systems (Fricke & Reichenauer, 2011). Characteristics such as the reduction of fragility with consequent improvement of the strength/weight ratio promote the development of the so-called superwindows, with very high insulation values. Glass with coatings and composite materials can be combined together to produce building envelopes that behave like an engineered version of the human skin, where different areas of the façade or roofing surface exhibit differentiated performance in ways, durations and times, depending on the different needs of the various parts of the building organism. These superwindows are game-changers that could change the way we think about constructing super-efficient passive or net-zero buildings (*See Figure 9*).
From an energy-saving perspective, aerogel granulate glazing systems have the potential to become a solution in not only cold climates but also hot and warm climates. These findings may contribute to new architectural techniques (Ihara *et al.,* 2015; Dörfler *et al.,* 2019).
DFAB House is a collaborative demonstrator of the Swiss National Centre of Competence in Research (NCCR) Digital Fabrication on Digital Fabrication on the NEST building of Empa and Eawag. The main components of the lightweight translucent façade are aluminium profiles, membranes, transparent insulating material and cables that limit the deflection of the exterior membrane under wind suction and assist in withstanding the forces generated between the two membranes. A crucial geometrical attribute regarding the load-bearing behaviour of the membrane system is its double surface curvature required to transfer external loads to the struts efficiently. The cavity between the two membranes is filled with aerogel. This wall build-up exposes the interior spaces to natural light and ties them to the current external condition. The thin thickness of the components and the characteristics of the materials allow the adaptability of a wide range of lightweight translucent membrane façades of complex shapes.

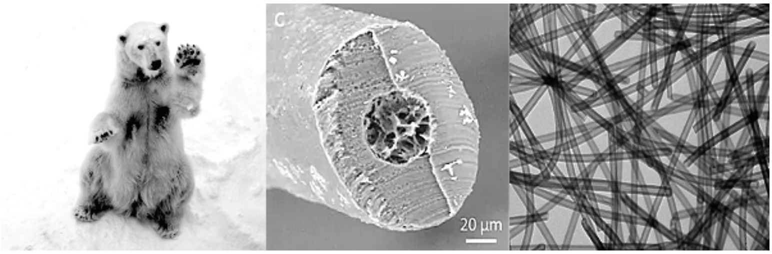

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Figure 8.
Polar bear and details of an electron microscopy of hollow bioinspired carbon tube airgel.
Figure 9.
DFAB House: translucent ETFE façade with aerogel filling.

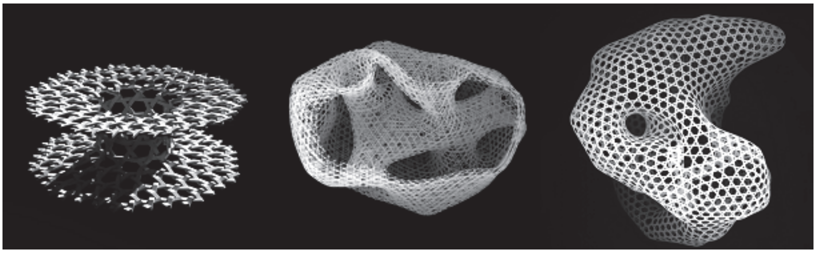
4.3. Computational design for the bio-inspired building envelope, between form and function

The logic of biological generation also belongs to computer processors, which today are the only tools capable of processing and managing complex artificial systems. The potential of computer tools is well expressed in biomimetic design, amplifying the ability to imitate. The biological model is then interpreted through mathematical functions, which can be reproduced with computers. Computational design reveals the potential for biomimetic and performance-based ecological materials development.
Exactly, as it happens for biological matter, in which the immanence of the characters is processed with a set of rules (DNA) for the determination of the organism, so, with parametric programs, it is possible to work with the relationships between the elements, to establish a set of algebraic steps that define the matrix from which a variable number of projects can be drawn (Badarnah, 2017). Exploiting the logic of parametric design for bio-inspired building façades is advantageous for *a priori* performance control. In fact, through parametric design and eco-efficiency analysis, it is possible to understand the possible optimization of the environmental impact of architectures already in the design phase. This saves time and money, helping to select the most reliable choices according to environmental and procedural sustainability criteria. Working on the bio-inspired build-

ing envelope and the solution to the specific problems can be the right strategy if the exploitation of the multiplicity matrix is foreseen for the definition of projects to be used in several building forms in environmental contexts with similar characteristics. Parametric software is used for processing complex shapes, following the principles: all systems must be soft and interdependent; all functions are parametric activity scenarios; all activities communicate with every part of the system (*See Figure 10*).

Thanks to computational design techniques, in recent years buildings with complex shapes have been created that can well represent nature. The Ayla Golf Academy and Clubhouse designed by Oppenheim Architecture in 2018, is a pavilion with a sinuous profile, it seems almost alive, not static, but in motion and seems to merge into the desert dunes. The building shape mimics Jordan's desertscape since the roof is made as a continuous wave that seems to spring directly from the ground and plunge back into it, imitating the naturally undulating motion of the sand dune forged by the wind. Local operators were trained in the use of modern spraying techniques to realize the building skin. In fact, the undulating shape of the enveloping skin of the building is made up of curved components covered with a unifying layer of shotcrete. The use of shotcrete-sprayed concrete makes the structure less porous which increases the bond strength and also helps in lowering the construction time and reduces costs as well. A traditional pigmentation technique was used for the internal surfaces, ensuring a raw and unadorned look that remains true to its inspiring context. The perforated panels in cor-ten steel, which shield some internal rooms from strong sunlight, derive from the typical Arab Mashrabiya, which is confirmed as one of the elements of Middle Eastern architectural history most used by contemporary design practice. The building establishes a unique connection with the surrounding nature and with the vibrant beauty of the Jordanian desert landscape (*See Figure 11*).

A structure that deserves mention since it was created to raise awareness of climate change is the Perpetual Spring designed by Pablo Castro of Obra Architects, a pavilion located in front of the National Museum of Modern and Contemporary Art in Seoul, which has been called «climate correcting machine» (Lynch, 2016). The pavilion is conceived as a unique prototype that demonstrates the functionality involved in the gathering of urban communities: architecture as a greenhouse machine that can be controlled by humans, helping to address and call our attention to the problem of climate change, pressing global issues. Greenhouse technology allows to create of a perpetual spring, even during autumn and winter, thanks to solar energy generated by the museum's rooftop photovoltaic panels that power the air conditioning system and information screens audiovisual. Shaped like the head of some gigantic insect, the metal pavilion is dotted with 150 polycarbonate plastic hemispheres, every 90 centimetres in diameter, which the designers likened to the eyes of an insect. These crystalline eyes favour the greenhouse effect and protrude from the pavilion's otherwise opaque metal structure as if forced to expand by a powerful internal force. They separate the indoor from the outdoor environment, providing abundant sunlight and helping to maintain the space warm during the coldest days of autumn and winter. In addition to passive solar heating, the pavilion is equipped with solar-powered automatic exhaust fans, aluminium foil curtains and a phase change radiant floor heating system. The pavilion combines architectural form and visitor experience with functionality to form a climate-correcting machine; a platform for awareness, and an invitation to concrete action (*See Figure 12*).



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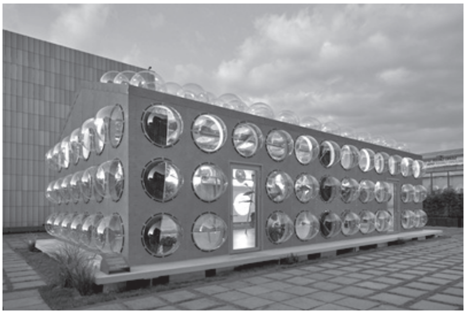

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Figure 10. Complez shapes created with parametric modeling. **Figure 11.** Ayla Club House in Aqaba, Jordan. **Figure 12.** Perpetual Spring in Seul, by Obra Architects.

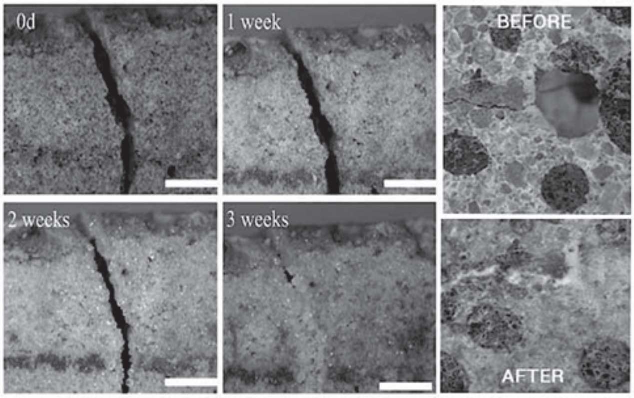
4.4. Nanotechnologies for building skin

Modern biomimicry is far from simply copying the forms of nature. It includes systematic design and problem-solving processes perfected by scientists, engineers and designers. An important factor is the continuous development of scientific knowledge and new technological tools capable of analyzing, describing and even reproducing aspects, phenomena, and processes of nature hitherto unpublished and unexplored: the contributions of nanosciences and nanotechnologies allow us to understand reality and produce artefacts at the nanoscale, through computational design software to control the parameters during the design phase of architectural products (Vezzoli & Manzini, 2008).
Nanotechnology has a wide application field precisely because it deals with aspects related to specific functions and forms for a scale of possible applications in the building sector. Moreover, nanotechnologies are born as a principle from the natural world observation: observing biological systems under a microscope has quickly turned into trying to replicate biological mechanisms even in artificial structures. The size of bio-inspired nanometric products opens up application horizons unthinkable in the past since the properties

observable at this dimension lend themselves to being used, even on a different scale, to develop processes and products characterized by increasingly performing performance for the building envelope. Therefore, thanks to nanotechnologies, today we can take inspiration from nature both for its morphological-structural aspects and for its behavioural and process models, efficient and sustainable. In fact, by manipulating the material on an atomic and molecular scale, even a simple form can contain a specific service, such as self-repair.

4.5. Self-repair and durability of cement for building skins

The ability to self-repair is to many constituent elements of living organisms, such as some vertebrate bones, shells and the exoskeleton of insects. Over the years, experiments have been carried out to obtain a more resistant type of concrete than the traditional one, with the minimum environmental impact, imitating the behaviours found in natural elements. In 2006, a team of researchers from the University of Delft in the Netherlands developed the bio concrete of the future, inspired by nature as the way to make cement more durable was found by adding simple microorganisms to the traditional mix (Ramirez, 2017). The bacteria in the mixture create a calcareous substance capable of filling the cracks in the stone material of this green concrete, eliminating the discontinuities to prevent water from coming into contact with the reinforcements. Professor Henk Jonkers described the difficulties his team of researchers encountered in developing the ingenious idea of mixing bacteria in concrete. «We invented Bioconcrete, the self-healing cement, but we needed bacteria capable of surviving in the hostile environment of cement, a dry stony material similar to rocks» (Seifan *et al.*, 2016). Another challenge that the microbiologist, who has been dealing with green cement since 2006, had to face was how the bacteria drowned in the mixture would survive for years: the microorganisms were chosen to live in the alkaline environment of the cement mass with the necessity to survive the time to fill the cracks. At first, it was thought to add sugar to the dough, which would have compromised the structure's mechanical properties. After various experiments, calcium lactate was chosen and added to the mix in bioplastic capsules containing the bacteria. Once the cracks have formed, the water dissolves the capsules releasing the bacteria that multiplicate by feeding on the calcium lactate present in the mixture and thus begin to produce crystals of calcite or limestone that repair the crack in two weeks (*See Figure 13*).
The ancient Romans had already thought about building constructions with an eternally durable structure, with a self-healing skin that behaves like a living organism, resisting attacks from external agents, water, air and sudden temperature changes. Therefore, that is why constructions, bridges, aqueducts and buildings built thousands of years ago came to us. Admir Masic, Associate Professor of Civil and Environmental Engineering at the Massachusetts Institute of Technology, has demonstrated that the secret of the resistance of ancient Roman structures is a formula based on quicklime that allows concrete to self-repair and last longer (Masic, 2023). The authoritative Science Advances Journal has just published the chemical-archaeological study by Admir Masic, confirming the scientific value.



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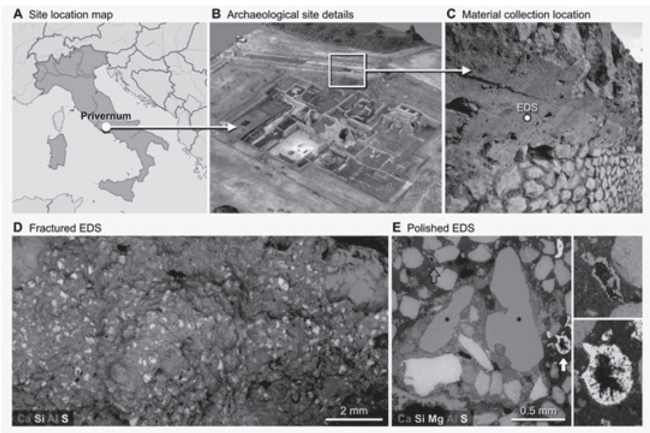

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Figure 13.
Tests on Bioconcrete.
Figure 14.
MIT, Experiments on "hot mixing" for resistant concrete.

Boston researchers have carried out experimentations to investigate the multiscale compositional heterogeneity of ancient Roman mortars and to extract design principles for modern, self-repairing, Roman-inspired concrete formulations development and testing. Specifically, ten different samples from the archaeological site of Privernum were analyzed, discovering that Roman cement is capable of self-regeneration: this is the secret of the concrete used two thousand years ago by ancient Romans. According to Masic research, everything lies in "hot mixing" or in a procedure in which a part of quicklime is added to the concrete mixture, which reacts with water and heats the mixture. This process allows the formation of lime "grains", allowing self-repair (MIT, 2023). Roman cement has always been known to contain grains of lime, but they were thought to be an impurity: for this reason, no one had ever thought that they could have such an important role. Now, Masic and his research team have created a technique that reproduces precisely that concrete and have obtained the industrial certifications of the Institute of Mechanics of Materials in Switzerland. Therefore, self-healing concrete is 50% longer durable than the traditional one and is about to enter the building market. Masic company is the start-up Dmat, which means dematerialize, precisely because it aims to "dematerialize" the eco-system of the concrete. In addition, compared with standard cement preparation, the innovative material processing emits 20% less carbon dioxide, reducing costs by up to 50% *(See Figure 14)*.

4.6. The artificial intelligence for the breathable façade: Tracheolis

A project that deserves attention for the exploitation of breathable façades is Tracheolis, designed by Doris Sung of DOSU Studio Architecture, in 2012 in Linz. The project was exhibited at the Designers of the Anthropocene, Przemiany Festival 2015 at the Copernicus Science Center in Warsaw. Doris Sung's technology-focused pavilion is a sort of kinetic façade, built around material responsiveness. The project combines cutting-edge science with great artistry, using thermo-bimetals and taking inspiration from mathematics and biology. It is a pavilion whose functioning mimics the respiratory system of the grasshopper (Sung, 2016). Insect cells get oxygen via a direct link to the air outside, a network of tubes, called tracheae let oxygen reach cells deep within the insect. Therefore, the respiration of the grasshoppers is performed using these air-filled tubes which open at the surfaces of the thorax and abdomen through pairs of valved spiracles in a complex network of windpipes. Specifically, larger insects may need to actively ventilate their bodies by opening some spiracles while others remain closed, using abdominal muscles to expand and contract the body and pump air through the system. Similarly, in the Tracheolis pavilion, the blocks draw air, using Bernoulli's principle of fluid dynamics, through an array of small holes in the surface. The air passes through the openings only when the temperature reaches a certain degree since cantilevered geometries of an innovative metal located at strategic points act as control valves, when cold the valves are closed, trapping air for insulation (*See Figures 15, 16 and 17*). These intricate geometric assemblies open and close like a field of flowers and demonstrate how solar heat energy dynamically transforms the shape and geometry of thin metal sheets to perform a range of transformations - including ventilation, light, shading, and structure - on the façades and in the construction of the building envelope. The innovative metal is a thermo-bimetal that changes shape in response to the environmental temperature. In technology, it is an elastic element, formed by the union of two layers of metals or their alloys by brazing or welding, characterized by different coefficients of thermal expansion. Adaptively, the thermo-bimetal expands and contracts with temperature swings independent of any driving electronic mechanism, therefore the bioinspired skin behaviour is essentially programmed through the exploitation of this material technology. Currently, numerous versions of the valve are being studied for implementing optimal operation in both hot and cold. The functioning of this bioinspired breathable skin could have many fields of application field in the building sector.

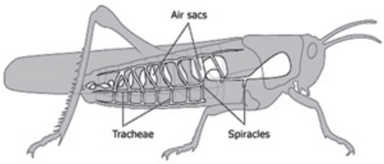

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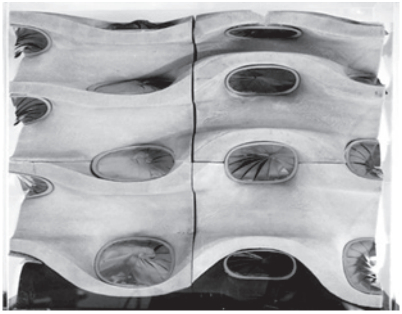
Figure 15. Grasshopper respiratory system.
Figure 16. Tracheolis.
Figure 17. Functioning Details of Tracheolis.



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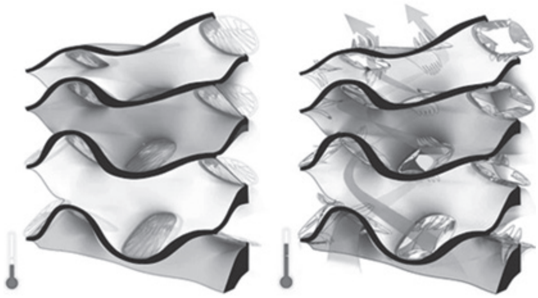

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4.7. Current experimentations and products

For years we have been trying to check and adjust existing systems when we should learn to combine new technologies with traditional ones, making the complex compact. To move building envelope technology into the future, the building skin needs to be reinvented with the help of artificial intelligence systems. This means combining multiple functions by making the building envelope skin multi-layered and active to respond to different levels of functionality which can all be incorporated into a multi-cavity façade. As demonstrated, it is possible to self-produce and manage energy, clean the air and control the light that enters to turn a building from consumer to prosumer. As far as energy saving is concerned, one of the main objectives of the building envelope is to control and supply high air quality, avoiding air stagnation which can lead to sick building syndrome and cause discomfort to the occupants. Designing innovative hybrid ventilation systems for building envelopes can lead to better indoor air quality with lower energy consumption. If the building envelope is bio-inspired, the skin breathes, behaving like a living being.
An Australian company based in Sydney, Lynx Building System has been working for years on creating healthy and intelligent buildings by bringing forward new levels of artificial intelligence, efficiency and multifunctionality of the skin of triple cavity building envelope technology. The idea is to make accessible to the construction and digital industries a new and powerful smart building skin DNA technology, enabling high levels of innovation in the functionality and performance of the building envelope. Thanks to the integration of

cutting-edge digital technologies in the building envelope, researchers have studied and created a building skin that can breathe like human skin and respond to climate change, according to an intelligent biomimetic process (Di Salvo, 2018; Geddes, 2019). Lynx has the vision to re-create the relationship natural/artificial through a holistic technological approach, with design values centred on sustainability and resiliency. The panels of the facade have been designed with small perforation venting to allow the façade to breathe and operate with "skin" sensors that measure and manage airflow, air temperature, light and humidity. The obtained results concern the mitigation of moisture and condensation of the dew point, the passive cooling of the façade, with better thermal performances that implement the quality of health of the occupants and the building, as well as minimizing the use of traditional systems.

5. Conclusions

From the study of the countless research articles concerning building leathers and from the case studies treated, it is clear that the design and creative innovation of intelligent building skins will follow a Darwinian process, according to which all the most complex and differentiated species, including man, derive from other simpler ones and through a very long series of modifications, that are transmitted and affirmed in the DNA thanks to a process of natural selection. This process, a consequence of the so-called "struggle for life", favours the most suitable elements to overcome difficulties or possible environmental changes.

Similarly, the creative innovation of intelligent building leather construction systems and applications will follow an evolutionary process that will support the most suitable configurations to survive the modifiable and unpredictable conditions of the external environment. We must also know that the twin sister of creative innovation is creative destruction to prevent many "big ideas" or intelligent building skin technologies from powering stupid building envelope technologies. The innovation of all intelligent systems and applications for building skins incorporating technologies of biomimetic inspiration must be reinforced and innovated in its set of strategies to survive continuous environmental changes and to be pertinent and practicable.

References

Badarnah, L. (2017). Form Follows Environment: Biomimetic Approaches to Building Envelope Design for Environmental Adaptation. *Buildings*, *7*(4), 40.

Best, R. C. (1982). Thermoregulation in resting and active polar bears. *Journal of comparative physiology*, *146*(1), 63-73.

Conzatti, A. (2020), The Biological Metaphor: Skin-façade analogy and biomimetic architecture. In *The City and the Skin*; Lulu: Morrisville, NC, USA.

Del Grosso, A. E., & Basso, P. (2010). Adaptive building skin structures. *Smart Materials and Structures*, *19*(12), 124011.Di Salvo, 2018 Kinetic

Di Salvo, S. (2020). Façade Solar Control and Shading Strategies for Buildings in the Mediterranean Region. In *International Journal of Environmental Science & Sustainable Development*, *5*(2), 32-47.

Dörfler, K., Hack, N., Sandy, T., Giftthaler, M., Lussi, M., Walzer, A. N., & Kohler, M. (2019). Mobile robotic fabrication beyond factory conditions: Case study Mesh Mould wall of the DFAB HOUSE. *Construction robotics*, *3*, 53-67.

Faragalla, A. M. A., & Asadi, S. (2022). Biomimetic Design for Adaptive Building Façades: A Paradigm Shift towards Environmentally Conscious Architecture. *Energies*, *15*(15), 5390.

Fricke, J. & Reichenauer, Gudrun. (2011). Thermal. Acoustical and Structural Properties of Silica Aerogels. *MRS Proceedings*. 73. 10.1557/PROC-73-775.

Geddes, G. (2016 August 5) *Reinventing the building envelope*. https://www.aechive.net/aec-business-podcast/reinventing-the-building-envelope-interview-with-gordon-a-geddes.

Ihara, Takeshi & Gao, Tao & Grynning, Steinar & Jelle, Bjørn & Gustavsen, Arild. (2015). Aerogel granulate glazing façades and their application potential from an energy saving perspective. *Applied Energy*. 142. 10.1016/j.apenergy.2014.12.053.

Krieg, O. D. (2016). HygroSkin–meteorosensitive pavilion. In *Advancing Wood Architecture* (pp. 125-140). Routledge.

Landa, M. (2017). Shigeru Ban: Exploring the limits of creativity. *Materia Arquitectura*, (15), 22-29.

Liddell, I. (2015). Frei Otto and the development of gridshells. *Case Studies in Structural Engineering*, *4*, 39-49.

Lynch, P. (2016). Thoughts about the Work of Obra Architects. In *OBRA Architects Logic : Selected Projects 2006-2016* (pp. 11–27).

Melis, A. & Medas, B. (2020) *Tecnologie avanzate per la resilienza dell'architettura e della comunità. In: Bioarchitettura: Appunti per una città sostenibile*. Nardini Editore.

MIT (2023 January). Riddle solved: Why was Roman concrete so durable? https://news.mit.edu/2023/roman-concrete-durability-lime-casts-0106.

MIT, Civil and Environmental Engineering, (2022 November 3). Admir Masic. https://cee.mit.edu/people_individual/admir-masic/

Paneri, A., Wong, I. L., & Burek, S. (2019). Transparent insulation materials: An overview on past, present and future developments. *Solar Energy*, *184*, 59-83.

Ramírez, J. D., & Guzmán, J. A. (2017). How can concrete be improved through processes that are bio-friendly to the environment and that enhance its construction qualities?. *Tekhnê*, *14*(2), 49-58.

Sala, N. & Cappellato, G. (2004). *Architetture della complessità: la geometria frattale tra arte architettura e territorio*, F. Angeli, Milano.

Sarkis, H. (2021). How will we live together?. *Statement. 17ª Biennale Architettura*.

Siani, R. (2012), *Il processo biomimetico sistemico nel progetto tecnologico di architettura. strumenti metodologici, informatici e meccanici*, Tesi Università degli Studi di Napoli Federico II, Dipartimento di Architettura Dottorato di Ricerca in Tecnologia dell'architettura e Rilievo e Rappresentazione dell'Architettura e dell'Ambiente, XXVII Ciclo.

Seifan, M., Samani, A. K., & Berenjian, A. (2016). Bioconcrete: next generation of self-healing concrete. *Applied microbiology and biotechnology*, *100*, 2591-2602.
Stehling, H., Scheurer, F., Roulier, J., Geglo, H., & Hofmann, M. A. T. H. I. A. S. (2017). From lamination to assembly-modelling the Seine Musicale. *Fabricate: Rethinking Design and Construction*, *3*, 258-263.
Sung, D. (2016) Smart Geometries for Smart Materials: Taming Thermobimetals to Behave, *Journal of Architectural Education*, 70:1, 96-106.
Usai, S., & Stehling, H. (2018). La seine musicale. In *Humanizing Digital Reality* (pp. 201-209). Springer, Singapore.
Vezzoli, C. & Manzini, E. (2008). *Design for environmental sustainability* (p. 4). London: Springer.
Wang, Y., Cui, Y., Shao, Z., Gao, W., Fan, W., Liu, T., & Bai, H. (2020). Multifunctional polyimide aerogel textile inspired by polar bear hair for thermoregulation in extreme environments. *Chemical Engineering Journal*, *390*, 124623.
World Health Organization (2018). Climate change and health. [Online]. 1 February 2018. Key facts. Available from: https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health [Accessed:22/December 2022].
Zakeri, B., Paulavets, K., Barreto-Gomez, L., Echeverri, L. G., Pachauri, S., Boza-Kiss, B. & Pouya, S. (2022). Pandemic, War, and Global Energy Transitions. *Energies*, *15*(17), 6114.
Zhang, Y., He, C. Q., Tang, B. J., & Wei, Y. M. (2015). China's energy consumption in the building sector: A life cycle approach. *Energy and Buildings*, *94*, 240-251.

Resumen: En la actualidad nos enfrentamos a un importante problema en todo el mundo que es la escasez de energía combinada con la cuestión del elevado consumo energético de los edificios. En el escenario actual, agravado por las consecuencias de la pandemia post-Covid19, el conflicto Rusia-Ucrania, el cambio climático, que agravan la situación de crisis energética a nivel global, la contribución pretende mostrar cómo arquitectos e investigadores están trabajando para encontrar estrategias de soluciones sostenibles en el sector de la edificación, a través de un cambio de paradigma. La visión innovadora viene dada por la aproximación a la ciencia biomimética conectada a la lógica de los materiales innovadores y las nuevas tecnologías, como el diseño paramétrico y las nanotecnologías para nuevas pieles bioinspiradas para envolventes de edificios.

Palabras clave: Piel - Biomimética - Envolvente de edificios - Sostenibilidad - Eficiencia energética - Confort - Cambio climático - Autocuración - Autorreparación

Resumo: Estamos atualmente abordando um problema significativo em todo o mundo que é a falta de energia combinada com a questão do alto consumo de energia dos edifícios. Dentro do cenário atual, exacerbado pelas conseqüências da pandemia pós-Covid19, o conflito Rússia-Ucrânia, a mudança climática, que agrava a situação da crise energética em nível global, a contribuição visa mostrar como arquitetos e pesquisadores estão trabalhando para encontrar estratégias para soluções sustentáveis no setor de construção, através de uma mudança de paradigma. A visão inovadora é dada pela abordagem da ciência biomimética conectada à lógica de materiais inovadores e novas tecnologias, como o projeto paramétrico e nanotecnologias para novas peles de inspiração biológica para envelopes de construção.

Palavras-chave: Pele - Biomimética - Envelopes para construção - Sustentabilidade - Eficiência energética - Conforto - Mudança climática - Autocura - Auto-reparação