Biomimetic strategies for the design of climate adaptive building envelopes: a problem-based methodological approach

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Biomimetic strategies for the design of climate adaptive building envelopes: a problem-based methodological approach

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ABSTRACT

The building envelope plays a crucial role in regulating the energy exchange between the interior and exterior environments. To reduce the energy consumption of buildings and minimise their impact on the environment, there has been a recent focus on adaptive technologies for building envelopes. The study of the adaptability of plants to their environment shows that nature has the potential to provide architectural solutions that are environmentally sustainable, energy efficient and adaptable to changing conditions. Various examples of adaptable building envelopes are evaluated and compared with examples of biomimetic building envelopes, as well as the existing methods from the literature.

After an initial exploration of nature's adaptive strategies and intelligent, self-reacting materials, a methodological approach called the bio-adaptive model (bio-AM) is presented. This model identifies the key steps for transferring plants functions to building technologies using smart materials that are able to respond to environmental factors thus emulating plant adaptation in future sustainable building solutions. Smart materials that act as both sensors and actuators enable dynamic interaction between the building and the environment, similar to the skin of living organisms. Only materials that respond to light, temperature and water triggers were considered, forming a design matrix that improves the implementation of the bio-Adaptive Model and provides a new tool for biomimetic design phases.

Research shows how smart materials can create biomimetic envelopes by regulating temperature, blocking solar radiation and responding to different environmental conditions. Although smart materials are currently used in architecture on a limited scale, this offers prospects for future research and interaction between architectural technologies, biology and materials science, leading to a more sustainable and adaptable built environment.

This research uses an interdisciplinary method to propose a design for a kinetic biomimetic system that responds to light, drawing inspiration from the functional principles of the Gazania flower. By analysing the adaptive movements of the Gazania flower in terms of its structure and functions, these observations were then used in the conceptual phase to develop the design of the biomimetic system using parametric modelling. Different alternatives for the kinetic movement were created and evaluated using daylight measurements, taking into account climate and luminance criteria. The results of the parametric simulations performed with different user positions in an office building with a temperate Mediterranean climate show that the biomimetic kinetic system effectively adjusts the natural daylight exposure in the office area. This adjustment improves energy efficiency, user comfort and mitigates glare problems. The results are consistent with the optimal ranges for climate-appropriate daylighting measurements that prevent glare and excessive heating by blocking direct sunlight. The study highlights the importance of further research, including the production of material prototypes, to verify and improve the proposed design and its implementation in practise.

HIGHLIGHTS

The main findings from this thesis are as follows:

- Six responsive functions of the adaptive envelope have been defined
- The difference between adaptive and responsive materials is clarified by introducing the concept of resilient materials
- Smart materials can be combined with responsive functions for adaptive building envelopes
- Smart materials combine the dual function of sensor and actuator through their responsiveness
- A biomimetic design matrix with smart materials is proposed
- The mechanism of plant adaptation can be applied in the field of building technology
- The Bio-AM identifies the essential phases to transfer the functions of plants to building technologies
- The bio-AM integrated with the parametric workflow of daylight simulation helps to design the light-responsive biomimetic solution;
- The different depth of the prismatic elements and the different radius of the focal region of the light-responsive biomimetic system significantly improve the daylight performance compared to a base case with a simple window without screening
- The parametric simulation allows validation and optimised configuration of the biomimetic modules
- The biomimetic approach regenerates the design process and implements sustainability

LIST OF PUBLICATIONS WITHIN THE FRAMEWORK OF THIS DOCTORAL THESIS

Journal articles (class A – Q1 – Top 10%)

F. Sommese, S. M. Hosseini, L. Badarnah, F. Capozzi. S. Giordano, V. Ambrogi, G. Ausiello (2023)
Light-responsive kinetic façade system inspired by the Gazania flower: a biomimetic approach in parametric design for daylighting
Building and Environment. Elsevier. ISSN: 1073-684X
Vol. 247, 2023, 111052. https://doi.org/10.1016/j.buildenv.2023.111052

F. Sommese, L. Badarnah, G. Ausiello (2023)
Smart materials for biomimetic building envelopes: current trends and potential applications
Renewable and Sustainable Energy Reviews. Elsevier. ISSN: 1364-0321
Vol. 188, 2023, 113847. https://doi.org/10.1016/j.rser.2023.113847

F. Sommese, L. Badarnah, G. Ausiello (2022)
A critical review of biomimetic building envelopes: towards a bio-adaptive model from nature to architecture
Renewable and Sustainable Energy Reviews. Elsevier. ISSN: 1364-0321
Vol. 169, 2022, 112850. https://doi.org/10.1016/j.rser.2022.112850

Book chapters

F. Sommese, G. Ausiello (2023) (selected for oral presentation)
From Nature to Architecture for Low Tech Solutions: Biomimetic Principles for Climate-Adaptive Building Envelope. In: Technological Imagination in the Green and Digital Transition. CONF.ITECH 2022. The Urban Book Series. Springer, Cham. https://doi.org/10.1007/978-3-031-29515-7_39

Conference proceedings

F. Sommese, G. Ausiello (2023) (selected for oral presentation)
A biomimetic approach for climate reactive building envelopesinspired by plants adaptive strategies
Colloqui.AT.e 2023. In transizione. Opportunità e sfide per l'ambiente costruito.
Edicom Edizioni. ISBN: 979-12-81229-02-0. Pagg. 1901-1908

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Edicom Edizioni. ISBN: 978-88-945937-4-7. Pagg. 115-129

G. Ausiello, M. Compagnone, **F. Sommese** (2020)
Imitare per costruire: dalla natura alla biomimetica
Colloqui.AT.e 2020 - New Horizons for Sustainable Architecture
Edicom Edizioni. ISBN: 978-88-96386-94-1. Pagg. 666-679

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Introduction

1. Research framework

Climate change is the greatest challenge facing the Planet. In order to achieve the goals of climate neutrality by 2050, various mitigation and adaptation measures are needed that affect all sectors of society. Cities are dynamically complex systems that play a major role in the increased greenhouse gas emissions globally [1]. In cities and, more generally, in the built environment, buildings account for about 40% of energy related CO_2 emissions [2][3]. To meet the Net Zero Emissions scenario and achieve international climate neutrality targets by 2050 [4], there is an urgent need to improve the energy efficiency of buildings, reduce energy demand and the negative impact on the environment, and mitigate climate change. The Architecture, Engineering and Construction (AEC) sector, which is at the heart of European policy plans [5], [6], can play an important role in developing novel technologies and innovative solutions capable of adapting to changing environmental conditions and providing comfort with lower energy demand. The energy efficiency of buildings can only be achieved by developing new design solutions for the building envelope, which is the interface between the internal and external environment [7].

The International Energy Agency's (IEA) 2022 Report [8] points out the importance of integrating high-performance building envelopes to reduce building air conditioning demand and ensure occupant comfort. The static solutions for the building envelope, which cannot react to environmental trigger, are now quite consolidated and guarantee [9], [10] a certain indoor comfort, but cannot meet the energy challenge alone. In the face of pronounced climate change [11], buildings are confronted with unusual environmental conditions - including extreme temperatures, unusual lighting conditions, and extreme precipitation that change rapidly even within a single day - for which conventional materials and techniques are not always suitable. Therefore, it is not possible to consider buildings as independent or monolithic elements, but an integral part of the environment and thus an organism endowed with life. In this way, it plays an active role in the space in which it is inserted, regulating the energy flows through the building envelope. The microclimatic conditions surrounding a building influence its energy demand [12]. It is necessary to consider the building as a living organism [13] that is related both to the environment and to the totality of biotic (living factors) and abiotic factors (no - living factors) of the ecosystem in which it is built [14]. Similar to the biological skin, the new envelope must also interact with the surrounding environment, which is constantly changing [15].

The concept of the adaptive envelope is not yet fully applied and must be part of a new design approach based on the principle of belonging to the environment. The design process is particularly complex and requires the incorporation of new systems and materials that can dynamically interact with the external and internal environment, so that its being alive can allow it to adapt to the environment and gain the benefits that come from both internal comfort and the reduction of energy consumption. The state of the art also shows that there are no standardised procedures for evaluating and testing the performance of adaptive building components.

Nature provides a large database of morphological, physiological and behavioural solutions for adaptation. Different strategies facilitate different types of adaptation in nature. Environmental changes are shaped by different variations, such as in seasonal and daily scales and geographical locations. Living organisms are connected to their habitats and develop high adaptive capacity, especially through their interface with the external environment. The skin surface may represent a complex tissue or structure (hair, skin, epidermis, cuticle, etc.) that can sense and respond to variations in environmental conditions and provide protection from extreme temperature gradients, for example [16]. The analysis of different biological strategies, such as the adaptations of plants to the environment, has the potential to provide the basic principles for the biomimetic design of climate adaptive building façades or envelopes [17].

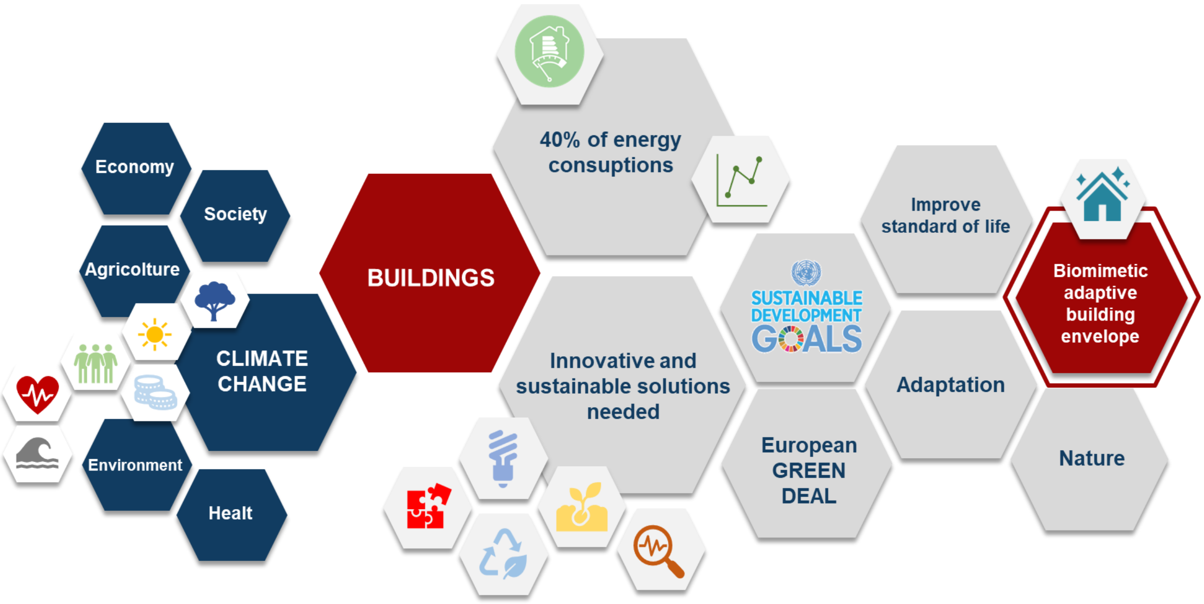

Fig. 1. Contextualization of the research

Biomimetics is a rapidly growing discipline in engineering and architecture, albeit with a limited scope in architecture. It aims to use functional solutions from nature to solve engineering problems [18]. Most applications are limited to prototypes and small pavilions using parametric modelling and digital fabrication [19]. Biomimetics has the potential to influence innovation in the AEC sector and provide efficient environmental solutions [20] [21]. In the AEC sector, interest in biomimetic architectural design has increased in recent years, with interdisciplinary interest in co-design, biology, computing and digital fabrication. Establishing clear parallels between nature and architecture for knowledge transfer could facilitate the development of environmentally sound solutions. Plants as a source of information can suggest and provide strategies that respond to variations in external conditions at different levels. Transforming natural strategies into solutions or technologies for the adaptive building envelope is still a challenge and ways need to be found and to be experiment to facilitate implementation in the AEC sector.

Fig. 2. Some examples of living skins

Fig. 3. Some examples of building skins

2. Aims and scope of the research

The aim of this work is to define a new methodological approach capable of translating the adaptation strategies of plants into solutions for architecture, through the use of smart and self-responsive materials, in order to propose biomimetic building envelope systems that adapts to the environment, differentiated for different geographical contexts. With this approach, biomimetic-adaptive building envelope solutions can be proposed that is able to passively respond to environmental trigger (water, temperature, light) by using the intrinsic properties of self-reacting materials. In this way, not only is the energy consumption resulting from the use of systems and equipment for air conditioning or for the well-being of users limited, but also a limitation of the environmental impact is ensured, which is in line with the goal of climate neutrality. After defining the new approach, the present work promotes its implementation and validation by combining it with the parametric design workflow of a biomimetic kinetic façade system inspired by the adaptation mechanisms of plants. Having achieved these goals, the purpose of this work is to provide researchers - academic and non-academic - with a reusable tool for the subsequent stages of the biomimetic design process.

3. Structure of the thesis: aims and research questions

This thesis is divided into three main steps, each of which answers a specific research question in order to achieve the aims of the thesis (Fig.4).

Step 1: *Biomimetic Adaptive Building Envelope [bio-AE]*

Research questions n.1:
How are biomimetic adaptive solutions for building envelopes developing on the international stage and what are the current trends in the scientific literature?

Aims of step 1:
This section aims to systematize the information on adaptive envelope by studying the related literature and comparing the existing examples, to define new responsive functions for adaptive envelope in accordance with different environmental parameters and to identify research gaps.

Step 2: *The bio-Adaptive Model*

Research questions n.2:
How is it possible to transfer the adaptive strategies of plants to architectural technologies in order to define building envelope solutions that can passively adapt to variable external environmental conditions?

Aims of step 2:
After examining the adaptation strategies of nature, especially plants, and defining the parallels with smart materials, this section aims to define a new "problem-based" methodological approach to move from nature to architecture through the use of smart self-responsive materials. This approach is also defined on the basis of the gaps identified when examining the biomimetic approaches already available in the scientific literature.

Step 3: *Integration of bio-AM with daylight parametric design workflow: a proposal of light-responsive facade system*

Research questions n. 3:
What is the advantage of the integration of bio-AM with parametric simulation workflow in evaluating the performance of an adaptive biomimetic solution?

Aims of step 3:
In this phase, the bio-adaptive model is integrated with the parametric design workflow, to evaluate the performance of a light-responsive biomimetic system in an office building in a temperate Mediterranean climate, parametrically modeled with the hypothesis of use of a light-sensitive shape memory polymer, studied for different occupant positions. Climate-based daylight metrics and luminance metrics are evaluated for the different kinetic alternatives developed.

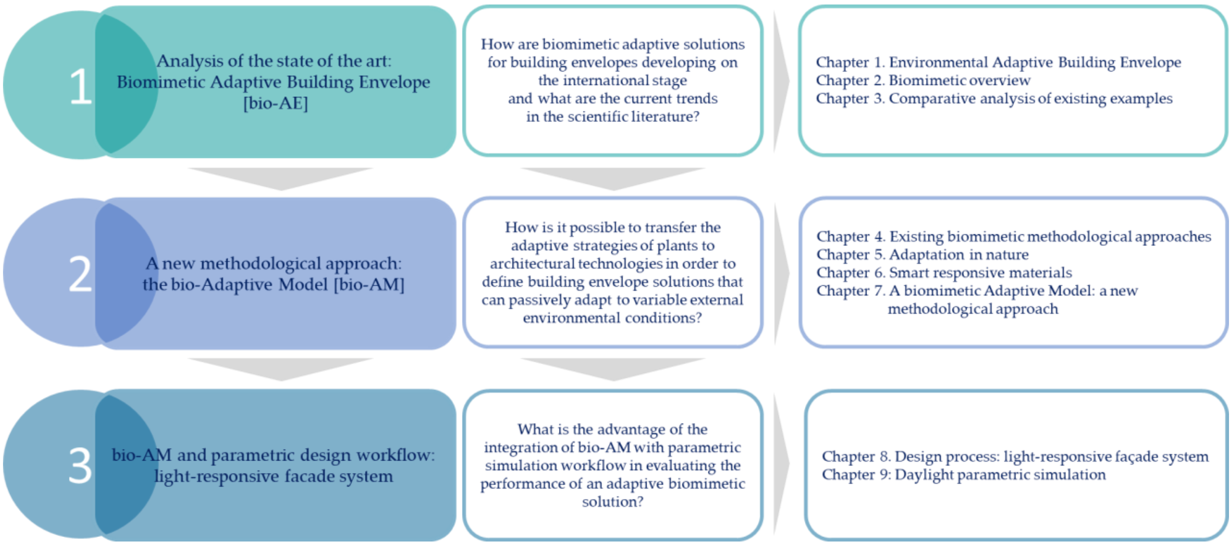

Fig. 4. General structure of the thesis and research questions

4. Approach

In this section, the methodological approach of the following research is presented. It is divided into three macro-steps, each corresponding roughly to each year of the PhD program.

Step one: *Analysis of the state of the art*

In order to define the state of the art of adaptive building envelope and related biomimetic technological solutions, the methodological approach of this research starts with the study of the international scientific literature. The most relevant scientific articles, conference proceedings, books and government reports are consulted through official websites and databases such as Scopus Elsevier, Web of Science or Google Scholar. Preference is given to the most cited articles published in high-ranking journals. As a first step, special attention is paid to government reports and action plans, including EU-COST TU 1403, a European action plan to promote the concept of adaptive facades. The best doctoral theses on the subject are also consulted.

A bibliometric analysis of biomimicry is carried out to highlight the trend of the discipline in the AEC sector, but also in other sectors, and to understand where it is more widespread and consolidated. To underline the innovation and timeliness of this study in terms of technological innovation and energy efficiency of buildings, and to highlight the response to the European Union's climate neutrality goals, a preliminary study is conducted on the Sustainable Development Goals of the 2030 Agenda and the European Green Deal.

From the study of the literature and the analysis of existing case studies (examples of adaptive and biomimetic building envelopes), the critical points and strengths are highlighted. The systematisation of adaptive envelope characteristics based on literature studies is reported to provide a complete picture of the information in terms of characteristics and performance. Six new responsive features for the adaptive building envelope are defined in this phase. An assessment of the spatial scale of the application on the building is essential, divided into: envelope, facade, facade components and materials. An in-depth study of the field of architecture is essential to understand its evolution over time and especially to highlight the differences with other bio-disciplines such as biomorphism and bio-use, which are often mistakenly used as synonyms.

Step 2: *Definition of a new methodological approach: the bio-Adaptive Model*

The aim of the biomimetic discipline, applied at AEC sector, is to transfer the functions of natural organisms to the field of engineering and architecture. For this to happen, a methodology for this transfer must be defined. Various existing methodological approaches are analysed. Among all the approaches already developed, the main reference approach is the Biomimicry Design Spiral [22], [23], proposed by Carl Hastrich in 2006 and re-proposed for the Biomimicry Institute in 2017. However, this approach only shows the six steps that need to be followed to move from biology to technology in general. It is a generic bottom-up approach that can be applied to any field.
After analysing the methodological approaches in the literature and identifying the relatively critical points, a new methodological approach is proposed: the Bio-Adaptive Model [bio-AM]. This problem-based approach consists of three basic phases that allow the transition from biology to architectural technologies according to a cyclic path. In this approach, only the biological functions of plants and their adaptation mechanisms are taken into account, because, like buildings, they are located in a specific place but are able to survive environmental stresses thanks to activated adaptation strategies; in contrast to animals, which migrate and change their location when habitat conditions are unsuitable. A preliminary study of the adaptive mechanisms of plants in different environmental contexts is conducted, together with a study of the emerging smart materials self-responsive to the main environmental factors such as light, water and temperature. By defining a biomimetic design matrix, different self-responsive materials are proposed for the definition of no-tech solutions.
The first phase of Bio-AM consists in defining the problem, the second in research in the biological field and the third in transferring the biological principles identified in the previous phases to the world of architectural technologies through an interscalar approach (scale of adaptation: envelope, façade, component, materials). If the validation is successful, a biomimetic adaptive envelope solution is obtained. If the results are negative, one has to return to phase 2 and look for a new solution in the biological domain.

Step 3: *bio-AM and parametric design workflow*

Step 3 of the research is operational and consists of implementing bio-AM through the combination of the parametric workflow. A light-responsive biomimetic façade system inspired by the nictinastic movements of the Gazania flower is propose to solve the problem of excessive solar reflection, glare and associated overheating near the façade. The use of light-responsive

polymers based on azobenzene was proposed for this system; the different reflectance values were entered into the parametric workflow.
The parametric software Grasshopper, in Rhino 7, is used to define complex geometries and facilitate modelling. It is indispensable for visual programming and generative design, and inevitably configures itself when designing dynamic environments. The use of specific plug-ins, such as Honeybee and Ladybug, associated with parametric software enables analysis in terms of Climate-based daylight metrics and luminance metrics.
Comparison with traditional envelope solutions is essential for validating the new biomimetic approach to architecture.

5. Novelty and originality

Throughout history, architects and engineers have been inspired by nature to reproduce forms and structures. These were almost always morphological imitations to reproduce the forms of natural organisms in architecture, as was the case with Art Nouveau or organic architecture. In contrast, biomimetics, imitating the functions of nature and integrating them into building technology, offers good opportunities to gear design towards sustainability and climate neutrality and thus respond to current and future challenges. The building envelope that mimics nature becomes a living envelope that can change its behaviour, properties or configuration in response to changes in the external environment.
Through adaptive strategies, the building envelope is no longer a simple element of protection and shelter or a simple element designed to provide optimal indoor behaviour and comfort. Its evolution and transformation into an adaptive dynamic element contribute to the regulation of energy flow according to the variable needs of the occupants related to the ever-increasing weather fluctuations. Moreover, the envelope will be able to respond dynamically and instantly to even the smallest climatic variations (such as cloud cover).
Given the current and future scenario of extreme climatic uncertainties and the need for environmentally friendly solutions, the focus on adaptable buildings inspired by the functioning of natural organisms enables a paradigm shift in the world of design to propose climate-relevant solutions.

6. Multidisciplinarity

Biomimetic solutions, while complex in their design, are innovative, sustainable and at the same time able to foster multidisciplinarity and collaboration between different sectors: This is increasingly required in academia to foster knowledge exchange and international collaboration. In the AEC sector, biomimetic indeed favours an approach that combines co-design, biology, computation and digital fabrication. In particular, the biomimetic approach promotes digital design and robotic fabrication through increasingly innovative techniques capable of improving the flow of the construction process, reducing production and construction times and increasing the quality of the built environment. Specifically in this thesis, which relates to the field of Techical Architecture[1], the following disciplines were involved in the multidisciplinary collaboration:

- biology[2], to study the adaptation mechanisms of plants in different climatic environments and under different environmental conditions;

- materials chemistry[3], for the study of chemical-functional strategies and responsive characteristics of shape memory smart materials;

- visual design[4], for defining evaluation criteria of climate-based visual metrics and parametric simulation.

7. Expected outcomes and climatic goals

This research proposing the bio-Adaptive Model, which defines the key stages of the transition from nature to technology, provides researchers in the construction field with a useful and reproducible tool to propose solutions inspired by nature. At the same time, the database of natural solutions and reactive materials to be used facilitates the process of identifying technologies. Bio-AM and examples of its implementation and validation can serve as a starting point for façade companies to facilitate the design and production process.
Creating clear parallels between nature and architecture for knowledge transfer could facilitate the development of ecologically adaptable building solutions. Applying a biomimetic approach to the development of adaptable and responsive envelopes favours solutions capable of limiting environmental impact by proposing technologies with low or no energy consumption. Automatisms are eliminated and environmentally friendly solutions are defined.

Fig. 5. Sustainable Development Goals by Agenda 2023 meets by biomimetic approach

The biomimetic approach and its application are in line with many of the Sustainable Development Goals of the 2030 Agenda, because by mimicking natural strategies and using responsive materials and low-tech solutions, it is possible to mitigate environmental impacts by

[1] This thesis falls within the disciplinary scientific sector ICAR-10: Technical Architectural.

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[3] Department of Chemistry of Materials and Industrial Production, University of Naples Federico II; CHIM-O7 Chemical Foundations of Technologies;

[4] Department of Architecture, Design and Media Technology. Technical Faculty of IT and Design. Aalborg University, Copenaghen.

promoting *climate action* (SDG 13) and creating *sustainable cities and communities* (SDG 11). The use of self-activating materials also leads to limiting the waste of resources and limiting pollutants, promoting the production of *affordable and clean energy* (SDG 7) and consequently creating more sustainable urban spaces that *good health and well-being* (SDG 3). At the same time, biomimetic application steers design towards the circular economy and *responsible consumption and production* (SDG 12). Above all, it favours the blue economy, which, unlike the green economy, is based on physical principles and uses techniques such as biomimetic to define a sustainable ecosystem according to the principles of nature. Finally, it promotes multidisciplinarity and *partnership for the goals* (SDG 17).

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Chapter 1

Environmental Adaptive Building Envelope

1.

1. Building envelope: the concept

The building envelope, without distinction between walls and roof, have an important role in the regulation and control of energy use because it represents the interface between outdoor and indoor environment [1][2][3][4][5]. The term envelope is used to indicate the total building enclosure and not the façade that describes only the vertical or subvertical plane of the construction [5]. In fact, contemporary architecture is characterized by complex and dynamic shapes, and it is not always evident the clear distinction between vertical wall and roof, because of a material continuity of the surfaces and of shapes. Therefore, the building envelope has not only the role of separating the space to divide the internal environment from the external one, but it also has the main role of filtering certain environmental factors ensuring good internal conditions [6]. It behaves similarly to the human skin which acts as a barrier between the external environment and the organism. In fact, in the literature, the words skin or envelope, are often used.

Sadinei defined the role of the building envelope as "*the key factor that determines the quality and controls the indoor conditions irrespective of transient outdoor conditions*" [7]. The environmental factors that broadly affect the envelope are solar radiation, precipitation, wind, temperatures, humidity, and noise [8]. These factors should be considered at the design stage to ensure indoor comfort, in particular thermal, visual, acoustic comfort, indoor air quality, and durability [9][10]. Some of these resources can also be used for energy generation. Each environmental factor can have more than one effect on the indoor environment, for example, solar radiation affects both visual and thermal comfort, as well as energy generation (Fig. 1.1). Occupant activity and environmental factors influence the comfort in the buildings, in particular: air movement, humidity, temperature, solar radiation, air quality, noise [11].

As the building envelope continues to evolve from a simple protective element to a filtering element responsible for energy flows, the performance required for indoor comfort increases. It is possible to summarise the performance of the building envelope in terms of safety, indoor well-being, aesthetic needs, durability, and energy efficiency and economy [12].

The energy requirement to assess the environmental conditions inside a building is the most common design metric for the environmental sustainability of buildings. Most of the energy consumed in buildings is due to heating/cooling requirements and is related to the characteristics of the envelope as much of the thermal energy and light transfer between inside and outside takes place through the envelope.

The constantly changing external environmental conditions create new challenges for building envelopes that require appropriate solutions in line with energy efficiency requirements. In recent years, research and development activities, about the application of components and materials for adaptive building envelopes, have been growing [13].

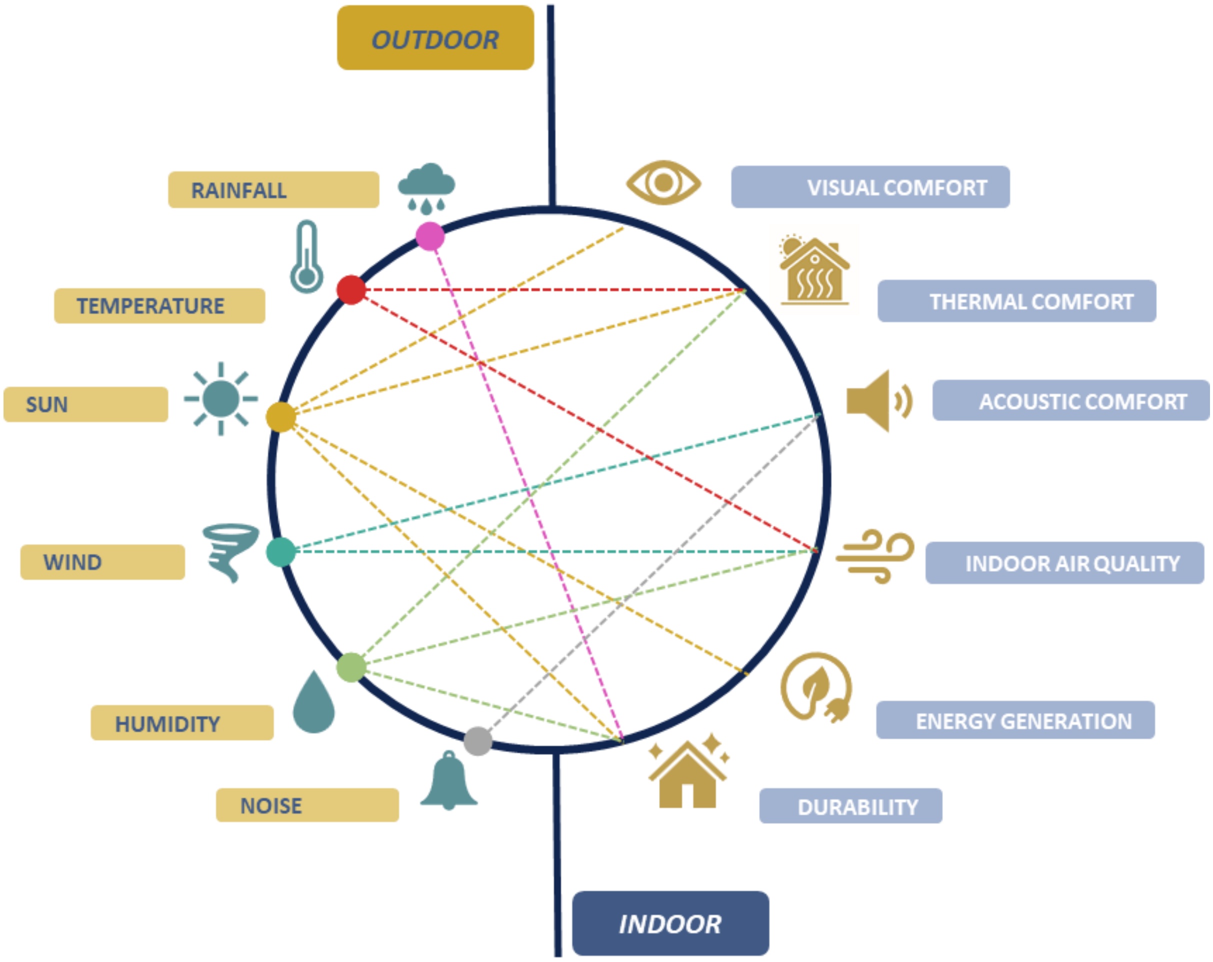

Fig. 1.1. The outdoor and indoor environmental factors that have an impact on users' comfort

2. Evolution of building envelope

Primitive buildings arose primarily in response to man's need for protection from climatic events and from the danger posed by wild animals. These were essentially shelters hewn out of rock or the tents typical of nomadic peoples, where the load-bearing function was transferred to a wooden structure while the closure was made of animal skins or tree branches and fronds.

The need for increasingly durable shelters led people to turn to new building techniques and new materials such as clay and stone as well as wood, while limiting the organisation of the interior spaces and the size of the openings.

The industrial revolution was followed by the advent of steel and glass structures and reinforced concrete, which allowed greater flexibility and articulation of interiors. Over the years, the need to use natural resources, especially natural light, to illuminate spaces, including workspaces, has led to the use of glass as a finishing element, whose characteristic structural system of columns, vaults or arches makes it possible to free the enclosing walls from their load-bearing function.

In the past, the system of vertical and horizontal closures was necessary to provide protection from rainfall and other climatic events, while the position of the building in relation to the surroundings and the cardinal points became a fundamental element for making the most of the natural resources in each area. Vernacular architecture shows that the location of the building was thoroughly studied before construction, in terms of environmental and climatic variables such as the presence of water and vegetation, exposure to wind and sun, the nature of the soil and the properties of local building materials [14]. These principles are reflected in what is now called bioclimatic architecture.
In the seventies, aware that new technologies required large amounts of energy for air conditioning, the realisation grew that fuels were not eternally available resources, and interest in thermal insulation was kindled, which gradually determined an evolution of infill solutions.
The building envelope has evolved greatly over the years, due to the increasing demands and performances to be guaranteed, but also to the evolution of available techniques and materials. Experimentation with new technological solutions marks an evolution of the building envelope from a simple protective element to a more complex system capable of optimising the interactions between the internal and external environments. The evolution may move towards increasingly dynamic surfaces that can change their performance according to the external environmental conditions and the needs of the users.

3. Environmental adaptive building envelopes: theoretical background

Various studies presented in the literature explain the concept of building envelopes that are adaptive to climate as a technological solution capable to respond to certain conditions, thus promoting higher levels of sustainability in the built environment and ensuring comfort for the occupants [15]. The main objective of an adaptive envelope is to optimize energy flows with an improvement in the performance of the building. As a result, adaptive envelope help reduce energy requirements for lighting and air conditioning, increasing air quality and comfort levels [16].

In the four years 2014-18, the European Union has activated the action plan EU COST-TU 1403, Adaptive Facades Network, that had an objective to harmonize, share and disseminate knowledge on adaptive facades and thus to facilitate sharing data and the development of technologies in adaptive facades and, more generally, in buildings with high energy efficiency [4][17][18]. The EU COST action plan defines the adaptive façade as an element of the building envelope consisting of multi-functional and highly adaptive systems capable of changing its functions over time, characteristics, or behaviour in response to performance requirements and transitional conditions, to improve the overall performance of the building.
Table 1.1 presents some of the adaptive envelope definitions in scientific literature: *Climate Adaptive Skin* (CAS) by Hasselaar [19], *Responsive Building Elements* (RBE) by IEA [20], *Living Envelope* (LE) by Badarnah [21], *Acclimate Kinetic Envelope* (AKE) by Wang [22], *Climate Adaptive Building Shells* (CABS) by Loonen [13] [23], *Adaptive Facade* (AF) by Attia [24] [25], *Responsive*

Building Envelope (RBE) by Taveres Cachat [26]. There is a lack of a general definition for the concept of the adaptive envelope, where several aspects are considered but not consistent among the different studies. The common feature is the adaptation to climatic variations but with different responses and modes. Therefore, the definitions of the adaptive systems are very broad. In this connection, one of the first aims of this study is to introduce a systematic approach to definitions about actions specifying adaptation, to give uniformity to the reading of research studies and achievements.

Table 1.1. Definition found in the literature

Year	Authors	Acronym	Definition and characteristics
2006	Hasselaar [19]	**CAS**	***Climate Adaptive Skins** can adjust their characteristics to and mediate between the changing environments. By doing so they can provide a comfortable indoor temperature, lighting level, and air quality (parameters influencing energy consumption) without excessive use of energy.* **Environmental parameters:** Internal temperature; Lighting level; Air quality. **Aim:** Reduction of energy consumption.
2009	IEA,ECBS Annex 44 [20]	**RBE**	***Responsive Building Elements**: a building component that assists in maintaining an appropriate balance between optimum interior conditions and environmental performance by reaction in a controlled and holistic manner to changes in external or internal conditions to occupant intervention.* **Boundary conditions:** Meteorological conditions; Internal heat; Pollution loads. **Responsive action:** Heat flux; Thermal storage; Permeability; Transparency. **Function:** Reject; Redirect; Store; Admit. **Requirements building and occupants:** Heating/cooling ventilation
2012	Badarnah [21]	**LE**	***Living Envelope**: is an adaptive building envelope inspired by nature that has the ability to adapt to the changes arising in the surrounding environment in order to maintain a comfort state for its occupants.* **Environmental regulation:** Air; Indoor air quality; **Functions:** Exchange; Move

			Prevent air stagnation; Heat — Thermal comfort — Gain; Retain; Dissipate; Prevent Water — Water regulation and harvesting — Gain; Conserve; Transport; Lose Light — Minimize heat gain; Maximize daylight. — Filter; Illuminate; Harness
2012	Wang et al. [22]	**AKE**	***Acclimate Kinetic Envelope:*** *capable of responding to variable climatic environment by means of visible physical behaviors of building envelope components.* **Climate sources:** — **Other:** Solar responsive — Solar radiation; Sunlight/daylight; Solar electricity Air flow responsive — Air flow; Wind electricity Other — Precipitation; Air temperature
2013	Loonen et al. [13]; [23];	**CABS**	*A* ***Climate Adaptive Building Shells:*** *has the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions, and does this to improve overall building performance.* **Relevant physics:** Thermal; Optical; Airflow; Electrical.
2018	Attia et al. [24] [25]	**AF**	***Adaptive Façade:*** *building envelopes that can adapt to changing boundary conditions in the form of short-term weather fluctuations, diurnal cycles, or seasonal patterns.* **Dynamic requirements of the occupants** **Changes in climatic conditions:** Weather fluctuations; Diurnal cycles; Seasonal patterns
2019	Tavares-Cachat et al. [26]	**RBE**	*A* ***Responsive Building Envelope*** *rely on integrated technologies that are designed to enable the building to respond to a range of triggers, using a combination of passive, active, and/or cognitive control strategies.* **User comfort** **Building energy performance** Thermal comfort;

			Visual comfort; Acoustic comfort; Indoor Air Quality Recovery and conservation of available energy; Energy buffering; Energy storage; Renewable energy integration.

4. Characteristics of adaptive building envelopes

This sub-section aims to identify the characteristics of the adaptive envelope as discussed in literature. Loonen et al. [13] summarized eight basic concepts that describe the characteristics of an adaptive envelope, starting by identifying the goal/purpose to which directly associates one or more of the above functions. Loonen proposed four physical domains (thermal, optical, electrical, and airflow) through which the interactions between internal and external environment through the building envelope occur [13]. Such interactions can be managed and controlled depending on the physical domain in terms of preventing, rejecting, or modulating solar gains, visible light or sound pressure, filtering of outside air, collecting and converting wind and solar energy [27]. Aelenei, on the other hand, simplifies interaction with the environment in four responsive functions: prevent, reject, modulate and collect [8]. Table 1.2 reports six new responsive functions (Fig. 1.2) proposed as a result of the analysis in Table 1: regulate (e.g. temperature and air), shield (e.g. cold and radiation), transfer (e.g. heat, water, light, air), reflect (e.g. radiation), store (e.g. heat and water), transform (e.g. energy). The responses depend on the input that is one of the following external environmental factors: solar radiation, temperature, humidity, wind, precipitation, and noise, which are presented in Table 1.2. Consequently, the performance of the adaptive envelope is described in terms of thermal comfort, visual comfort, acoustic comfort, internal air quality (IAQ), and energy generation. The input corresponds to an output intended as an adaptation action.

The adaptation response occurs in a variable time interval depending on the seasonal or daily cycle or other boundary conditions [13]. For the mechanisms of adaptation control, the same terminology used by Loonen [13] is preferred, which distinguishes them as extrinsic and intrinsic. The extrinsic controls refer to an envelope that adapts through response to external factors by sensors, processors, and actuators and then resume a dynamic mechanism that moves visible to the naked eye, resulting in modification of the aesthetic configuration of the envelope by folding, expanding, and/or sliding [28]. Depending on the type of control and adaptation mechanism, the level of visibility varies from a nanoscale to a macro scale. In intrinsic controls, the adaptive capacity becomes a characteristic of the envelope. The adaptation mechanism can be both static and dynamic.

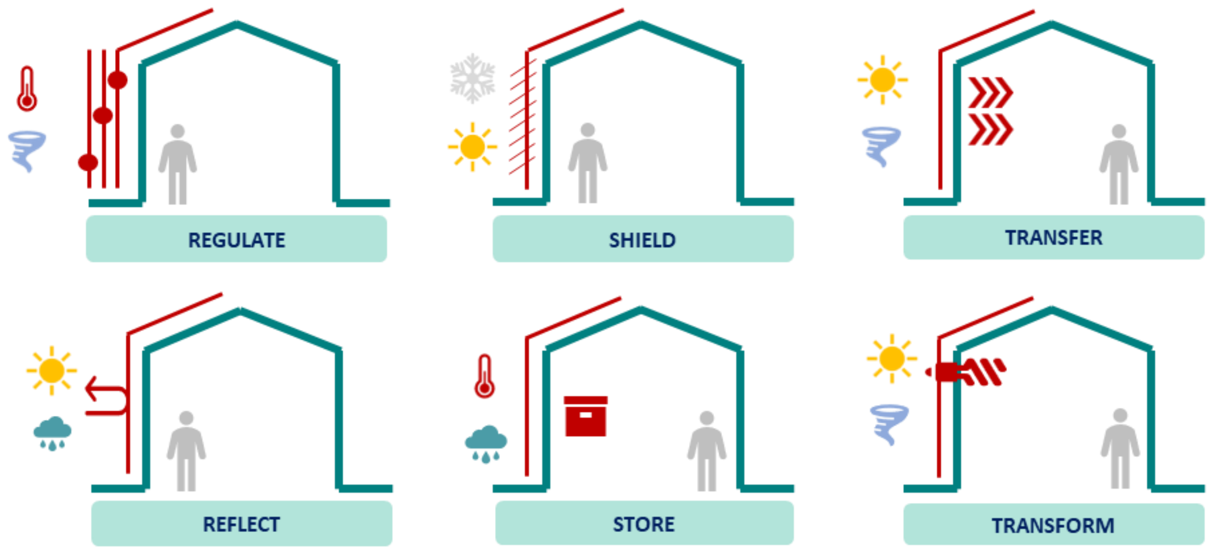

Fig. 1.2. Six responsive functions of building envelope: regulate, shield, transfer, reflect, store, transform

The adaptation response occurs in a variable time interval depending on the seasonal or daily cycle or other boundary conditions [13]. For the mechanisms of adaptation control, the same terminology used by Loonen [13] is preferred, which distinguishes them as extrinsic and intrinsic. The extrinsic controls refer to an envelope that adapts through response to external factors by sensors, processors, and actuators and then resume a dynamic mechanism that moves visible to the naked eye, resulting in modification of the aesthetic configuration of the envelope by folding, expanding, and/or sliding [28]. Depending on the type of control and adaptation mechanism, the level of visibility varies from a nanoscale to a macro scale. In intrinsic controls, the adaptive capacity becomes a characteristic of the envelope. The adaptation mechanism can be both static and dynamic. According to Lopez [28], the mechanism is dynamic when it is observable with the naked eye through a change in the material configuration, while it is static when the change is not visually observable but affects an internal property of the material that does not involve a change in the morphological configuration. A dynamic mechanism involves visible mechanisms such as expansion, rotation, curvature, and rolling that are generally manifested through automated shielding systems or through the use of smart materials, such as shape memory materials that are configured as innovative materials that respond to external stimuli by changing their properties and geometric conformation without the use of added energy. On the other hand, a static mechanism involves reflection, absorption or energy exchange, exploiting the properties of materials such as in the case of Phase Change Materials that accumulate and release thermal energy. The type of adaptation can be achieved by an interscalar approach, then either on the entire envelope or on the single components or material that constitutes the element or the envelope itself.

Table 1.2. Characteristics of adaptive building envelopes

Input Environmental external factors	Performance	Output Adaptation action	Responsive function	Responsive time	Control	Level of visibility	Spatial scale		
							Facade Systems	**Component**	**Materials**
Solar radiation	Thermal comfort	Thermal	Regulate	Seconds	Intrinsic	Nano	Curtain wall	Shading device	Thermochromic
Temperature	Visual comfort	Physical	Shield	Minutes	Extrinsic	Micro	Prefabricate module	Energy storage device	Electrochromic
Humidity	Acoustic comfort	Chemical	Transfer	Hours		Macro	Double skin facade	Air circulation device	Photochromic
Wind	Indoor Air Quality	Mechanical	Reflect	Day-night	**Mechanism**			Insulation layer	PCM
Precipitation	Energy production		Store	Seasons	Static				SMPs
Noise			Transform	Years	Dynamic				

5. Adaptive or responsive?

Several studies have investigated the concept of adaptive building envelopes resulting in different terminologies to describe it, and most frequent ones are *responsive* and *kinetic*. Hasselaar [19] suggests the difference between adaptive and reactive, specifying that reactive simply means reacting to a change (e.g. lowering the shutters or opening the windows) and not adapting to it, while adaptive implies the ability to adjust and adapt to new and changing conditions in an autonomous way. The 2009 IEA report [20] proposes the concept of Responsive Building Elements, which refers to a building component that responds in a controlled way to changes in external conditions or to occupant intervention. In Loonen [13], [23] Climate Adaptive Building Shells (CABS) are defined as shells that can reversibly change their properties in response to external environmental changes. Badarnah [21] proposes three categories for adaptation: *flexible*, *transformable*, and *responsive*, where their distinctions are based on the types of variables (e.g. spatial change), physical attributes (e.g. configuration at component or material level), and time dependence (e.g. responding to stimuli in real-time). Orhon [29] distinguishes two types of reactivity based on the type of system or response mechanism: active, when the response is carried out by automated devices capable of sensing the stimulus and implementing and regulating the technical function; passive when the function is carried out

directly by the material, which activates certain response functions autonomously, therefore without the use of technical sensing, regulation and actuation systems.
Barozzi et al. [5] propose a classification of the most common adaptive shading systems: kinematic, dynamic, retractable, transformable, adaptive and responsive. Tabadkani et al. [3] present a study in which they characterise the different types of adaptive façades (active, passive, biomimetic, kinematic, intelligent, interactive, movable, responsive, smart and switchable), including responsive façades, and limits them to those façades that require an act of reaction by changing the properties of the material or the mechanical behaviour. Santos et al. [30], [31] Auto-Responsive Technologies (ART) are defined as technologies and materials that function in an intrinsic and reversible mode because they can self-regulate as adaptive behaviour is activated by environmental stimuli with changes in the intrinsic properties of the materials. Conversely, Carlucci [32] provides an overview of smart and responsive technologies applied to building envelopes by defining adaptive technologies as a subclass of responsive technologies. The work of Menges et al. [33] focuses on embedded responsiveness, referring to the autonomous response of materials to environmental stimuli. Al-obaidi et al. [34] note that the concept of adaptation is much broader than the concept of responsiveness, as the adaptive approach optimises functionality and reduces waste. In Frighi [35], they propose a general definition of a "*smart/advanced/adaptive building*", meaning a structure that interacts with the surrounding environment through different technologies and devices, and they further elaborate that smart adaptive building envelopes have three main functions: *adjust* its performance to hourly, diurnal or seasonal variations, *adapting* to said variations at the macro level by considering the envelope as a whole or at the micro level by a single material, *controlling* the variations at the extrinsic level by sensors, processors and actuators or at the intrinsic level by the intrinsic properties of the materials [35].
From this overview, it is evident that there is no common definition in the scientific literature, as each author emphasises some concepts over others, and the terms, such as "adaptive" and "responsive", are often used interchangeably. The etymological meaning of the term *responsiveness* implies the property of reacting to something or someone [36], while the term *adaptation* implies the process of change to adapt to different conditions [37]. In the biological field, on the other hand, the term *adaptation* refers to the physiological, morphological or behavioural change of natural organisms in response to changing environmental conditions [38], while the term *responsiveness* refers to the ability of living matter to respond to a stimulus [39].

Although these terms are often used as synonyms, they imply a subtle difference that allows us to say that adaptivity is something that changes due to various conditions and therefore depends on the surrounding environment, while responsiveness is a property of a material or a system to respond to something. Therefore, an adaptive material (or system) can also be defined as responsive, but a responsive material (or system) is not necessarily adaptive. Consequently, it is possible to define responsiveness as a performance, as a property of the material that makes up the building envelope, and adaptation as a requirement in relation to the potential demands on the building envelope itself.

The ability of the adaptive envelope to respond to environmental stimuli and, eventually, return to its original configuration depending on environmental variations, allows us to link the concept of "adaptation" and "responsiveness" with that of "resilience". The term resilience (from the Latin *re-silio*, to go back, to regress), indeed, implies the ability of an element to respond to trauma, such as extreme events or variable environmental conditions, and then recover and return to its original state. In the field of biology, this concept also refers to the ability of organisms to recover their form after trauma. In the field of ecology, an ecosystem is considered resilient if it can withstand all disturbances without suffering permanent or irreversible damage and quickly returns to its initial conditions. In materials science, resilience is defined as the amount of energy that a material can absorb and then return to its original state [40]. It can thus be concluded that a resilient system or material occupies an equilibrium position between adaptive and responsive, based on its ability to return to recover after responding to a change in the environment. This concept is related to the behavior of smart materials, which are described in detail in the following sections.

6. Some examples of adaptive envelopes

In this section, some examples of adaptive building envelopes are given, representing the evolution of the building envelope compared to traditional solutions.

In particular, Jean Nouvel's 1987 Institute of the Arab World in Paris (Fig. 1.3) is the first example of an adaptive envelope [3][41]. It is often cited in the literature as an outstanding example of an adaptive kinetic envelope. The main façade, made of glass and aluminium, is characterised by a series of diaphragm that filter the light stream using photoelectric cells and can open and close like the lens of a camera on the hour, changing the appearance of the façade and the brightness of the interior spaces depending on the light [2][5][24].

In addition, two projects, Kolding Campus University by Henning Larsen Architects and Q1 Building Office by JSDW Architectures, are mentioned for their dynamic and automated shielding system.

In the first one, the Kolding Campus University in Denmark (2014) (Fig. 1.4), the architects designed a dynamic façade to control and manage light and heat, ensure an optimal climate and convey a special architectural image. The double façade consists of about 1600 triangular elements made of perforated steel that automatically adjust to the different daylight scenarios and the desired incidence of light. These elements are controlled by motors that are activated when sensors sense a certain level of light and heat. When closed, the gills lie flat against the façade, while when open they protrude from the façade itself like pointed wings.

The second building, Q1 Building Office (2014) (Fig. 1.5) by Thyssenkrupp in Essen in Germany, has a sunshade characterised by strips of different sizes made of champagne-coloured stainless steel. The approximately 400,000 horizontal lamellae rotate around 3000 vertical posts, depending on perceived pulses, outdoor temperature values and solar radiation. The lamellae are set in motion by about 1600 motors depending on the position of the sun, which is determined by a special control system, but also by the daily weather conditions, which are determined by a weather station installed on the roof of the building. In the first hours of the day, the louvres are positioned 90 % in relation to the façade, ensuring maximum opening so that light penetrates the building completely. However, in the middle hours of the day, the slats start to rotate until they reach an angle of 180 in the hottest hours, thus closing completely in front of the façade. Because the slats are spaced vertically, they block direct sunlight but still guarantee a good amount of natural light.

Fig. 1.3. Institute of Arab World, Paris

Fig. 1.4. Kolding Campus University

Fig. 1.5. Q1 Building Office

7. Advantages and limitations of the adaptive façade: summary of the state of the art

The modification of the envelope properties occurs via external sensors, actuators or control mechanisms or intrinsically via properties embedded in the material [42]. The typologies are static or dynamic, with high-tech or low-tech technologies and are applicable in different façade systems (continuous, double-skin façade, etc.) with different components and materials [43].

The analysed background configures adaptive envelope as a solution to address the urgent need for innovative and sustainable design approaches to the built environment. Adaptive envelope are configured as solutions that can dynamically respond to external environmental conditions such as light and temperature to optimise energy consumption and indoor comfort. The addressed study and literature review highlight several advantages and limitations of adaptive envelope, in line with a recent study by Borshewski et al. [44] conducted in 2023:

Advantages:

Reduction of energy demand: Adaptive envelope have the potential to significantly reduce energy consumption during the use phase of buildings. Studies, such as the one by Harder et al. [45] shows that the installation of phase change materials (PCM) can reduce the energy demand for cooling in summer by up to 50%. Other studies suggest even higher reduction rates of up to 80% [45].

Reducing emissions: While most studies have focused on reducing emissions during the operational phase, some studies also point to the potential reduction of emissions during the construction and end-of-life phases of adaptive envelope.

Cost reduction: By effectively regulating the building interior and limiting the need for excessive air conditioning, adaptive façades can lead to cost savings during the operational phase.

Increased comfort: Adaptive envelope helps improve occupant comfort by responding to occupant needs. They provide glare protection, adequate lighting, optimal temperature control, indoor air quality and privacy.

Environmental benefits: The reduced energy consumption associated with adaptive envelope helps to reduce environmental impact and resource consumption.

Aesthetic benefits: The dynamic character of adaptive façades gives buildings a new architectural quality that enhances their aesthetics and the overall urban context.

Limitations:

Complexity and interdisciplinary coordination: Designing, implementing and managing adaptive envelope involves a high degree of complexity due to their multifunctionality. This requires strong interdisciplinary coordination to ensure successful integration and performance.

Higher production costs: The incorporation of adaptive technologies often leads to higher initial production costs, which could act as a deterrent to widespread adoption.

Functionality assessment: the concept of adaptive envelope is relatively new and not yet widely used. Therefore, there is limited experience to evaluate its effectiveness.

Performance assessment [24] : Quantifying the performance of buildings with adaptive envelope is challenging due to the lack of holistic performance criteria. This includes the need for comprehensive testing, evaluation and ongoing monitoring.

Delivery process [24]: The delivery process of adaptive façades can be complex and requires careful planning and execution to ensure that the intended benefits are actually realised.

In conclusion, adaptive envelope facades are promising in reducing energy consumption, improving indoor comfort and improving the environmental performance of buildings. However, challenges related to complexity, interdisciplinary coordination, costs and performance evaluation must be addressed to promote their wider adoption and successful implementation. Therefore, the focus of this work is to explore biomimetic adaptive envelopes configured as envelopes that are able to function and respond passively to environmental triggers, as happens in nature.

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Chapter 2

Biomimetic overview

2.

1. Biomimetics overview: evolution and definitions

Humans have always looked to nature and its systems as a source of inspiration, but it is only in recent decades that the idea of making the imitation of natural processes a real discipline has grown. Able to combine nature and technology, biomimetics is a fast-growing discipline in engineering for the development of new technologies and an emerging field in architectural design [1]. Nature, through its own strategies, mechanisms and principles, is able to provide a large database of solutions and adaptation strategies. By carefully analysing the forms, structures and functional principles of natural organisms, it is possible to identify the inputs necessary for the process of abstraction and imitation.

The same etymological meaning of the term biomimetics allows us to understand the actual meaning of this discipline: It derives from the Greek *bios* and *mimesis*, meaning *life* and *imitation*, so imitation of life or nature.

The term *biomimicry* first appeared in the literature in 1969 [2], although it was preceded by the terms *biomimetics* and *bionics*, and in some cases *biomimesis.* The term biomimetic was used in the 1950s in a paper by Otto Herbert Schmitt entitled "*Some intersting and useful biomimetic transforms*", prepared for the Boston Biophysical Science Conference.

The term bionics, on the other hand, conceived in 1960 by Jack Steele, an engineer and psychiatrist in the US Air Force Medical Department, derives from the combination of the words *life* and *technology* and refers to the process of transforming the properties of biological systems into technological processes, but without specifying the scope, methodological approach or actual goal of this process [3]. Over the years, the term bionics has come to refer primarily to the field of artificial tissues and robotics, with a particular focus on the medical field [3].

In the following years, interest in the discipline has increased and some emerging figures in the field, such as biologist Janine M. Benyus[1], biology professor Steven Vogel and biomimicry professor Julian Vincent, have contributed to the consolidation of the term biomimicry.

Julian Vincent defines biomimicry as the act of borrowing or stealing ideas from nature, i.e. imitating natural models, systems and elements to solve complex human problems [4]. Janine Benyus speaks instead in her 1997 book "Biomimicry. Innovation Inspired by Nature" of consciously imitating the genius of life [5]. Benyus also speaks of nature as a model, measure and mentor. In particular:

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[1] **Janine M. Benyus**: biologist and science writer. She is co-founder of the Biomimicry Institute, a non-profit educational institution dedicated to advancing the study of biomimicry, and Biomimicry 3.8, the world's first inspired biology consultancy.

1. "*Nature as model*. Biomimicry is a new science that studies nature's models and then emulates these forms, process, systems, and strategies to solve human problems – sustainably.
2. *Nature as measure*. Biomimicry uses an ecological standard to judge the sustainability of our innovations. After 3.8 billion years of evolution, nature has learned what works and what lasts.
3. *Nature as mentor*. Biomimicry is a new way of viewing and valuing nature. It introduces an era based not on what we can extract from the natural world, but what we can learn from it"[5].

In summary, biomimetic architecture makes nature a model to be imitated by taking inspiration from natural processes. It uses nature as a benchmark or uses an ecological standard to judge the efficiency of human innovations, and finally, using it as a mentor means that nature is not consumed by taking material goods from it, but that nature is simply seen as something to learn from. Janine Benyus herself says that "the biomimicry revolution is ushering in an era based not on what we can get out of nature, but what we can learn from it" [5].

Also in the famous text Biomimicry in Architecture, author Michael Pawlyn speaks of biomimicry as a "discipline that mimics the functional bases of biological forms, processes and systems to create sustainable solutions"[2].

G. Chiesa also affirms with regard to biomimicry that it is "a recent scientific discipline concerned with the imitation and reproduction of ideas, solutions and natural processes in the artificial world [...] [6]".

The analysis of the literature thus makes it clear that biomimicry is able to combine nature and technology on the basis of the functional behaviour of living organisms by transferring them into the project through imitation. It is therefore a discipline that is able to implement sustainable and effective solutions through the analysis of natural strategies.

2. Bio-inspired design: Biomimetics, Biouse or Biomorphism?

Biomimetic design processes are based on bio-inspiration, but this does not mean that every bio-inspired design is biomimetic. The concept of "bio-inspiration" is based on a more general vision of a way of designing that is inspired by nature in all its forms (Fig. 2.1).

Very often, in the field of "bioinspired design", no distinction is made between biomorphism and biomimicry. The meaning of the term biomimicry, explained in detail in the previous paragraph, refers to projects that focus on function and are therefore able to "function" like nature. Biomorphology, on the other hand, is understood as the science of living forms and the structures of organisms. Therefore, the term biomorphism, which is composed of the Greek *bìos*, *life*, and *morphé*, *form*, refers to a model of pictorial construction that uses biological forms to "resemble" nature. In this case, the model to be imitated can be the human body (anthropomorphism), the animal world (zoomorphism) or the plant world (phytomorphism).

Both approaches, the biomorphic and the biomimetic, can coexist in an architectural project, with the difference that the first refers to a formal and aesthetic emulative expression, while the second refers to a functional emulative expression [2]. There is also the possibility that a biomimetic project does not aesthetically resemble the natural element, because what must resemble is the function to be fulfilled.

A further distinction can be made with other bio-disciplines, such as bioutilisation, which refers to the use of biological materials or living organisms in an architectural project. An example of application would be the use of wood to create a solar shading system or the use of green plants for a vertical wall with the aim of insulation and air purification. Biomimetics should not be confused with other bio-disciplines because it does not waste natural resources, but merely uses them to study their behaviour and imitate them.

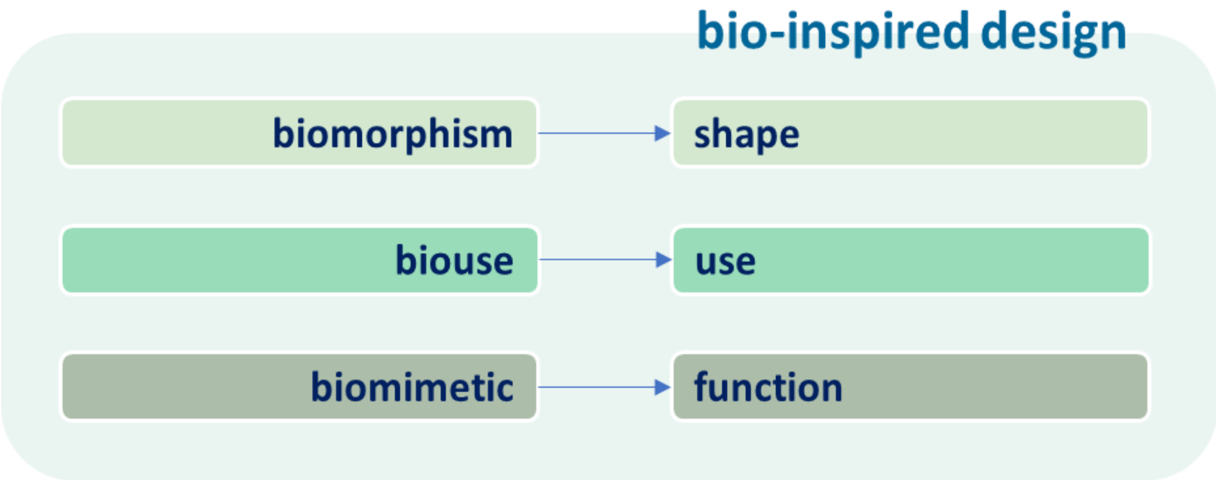

Fig. 2.1. Difference between the bio-discipline

3. Examples of biological strategies

The AskNature[2] portal offers various examples of biological strategies. One of these is the fur of the polar bear, whose function is to insulate or store heat in order to keep the animal warm; this results in a strategy of insulation (Fig. 2.2). The fur is made up of two distinct layers: a shorter and denser one that lies against the skin, and a longer and coarser one that is meant to be a transparent protective hair that, because it scatters sunlight, makes the bear's entire fur appear white. Studying the characteristics and properties of polar bear fur could help define insulation materials for buildings or more generally for human use. From the research already

[2] **AskNature**: an open-access online library for understanding nature's survival strategies and their potential to inspire human sustainable design. This website collects the world's biological intelligence, organises it by function and presents it in non-technical language so that it is accessible to all.

carried out, it appears that the protective hairs absorb infrared radiation, a part of the electromagnetic spectrum that many mammals cannot see but can perceive as heat.

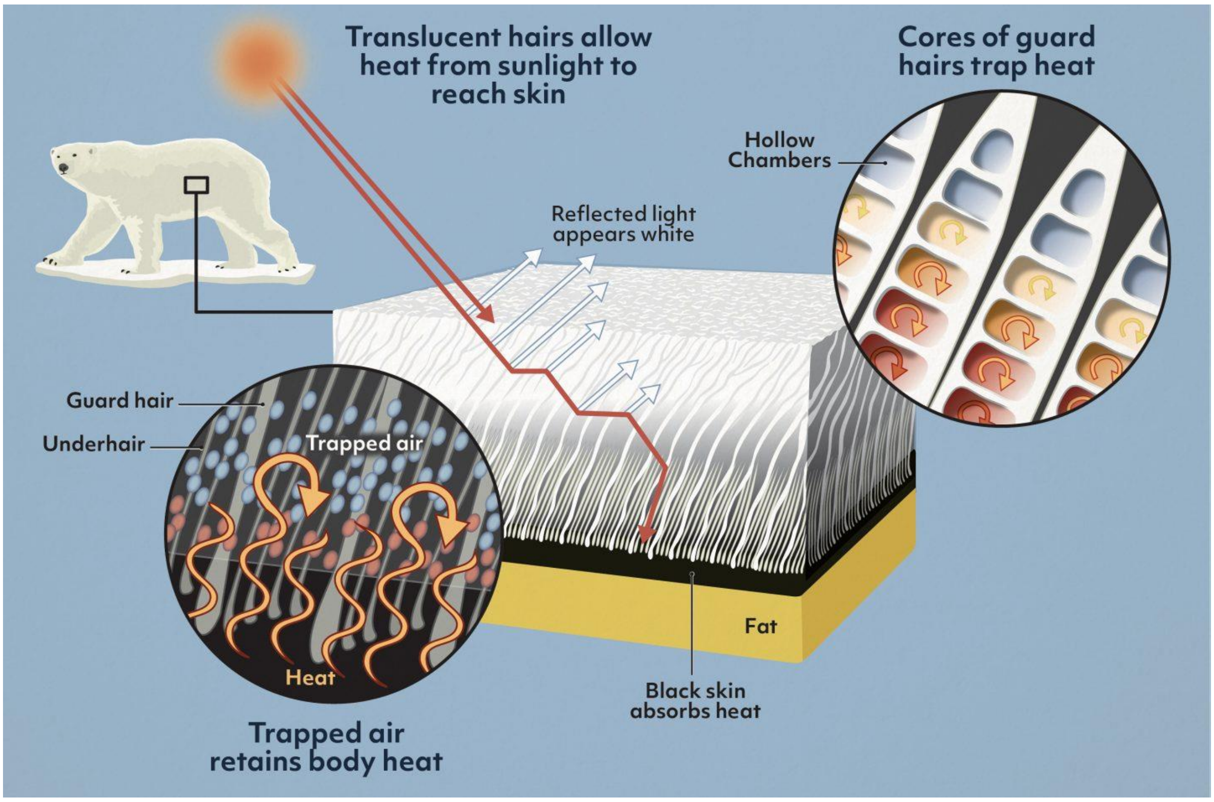

Fig. 2.2. Functional mechanism of polar bear fur: light and heat capture. Source: Mesa Schumacher by AskNature portal

Another example is defined by the shape of the beehive. Around 36 BC, the scholar Marco Terenzio Varrone noted that a hexagon inscribed in a circular figure encloses the largest space compared to other shapes such as a triangle or a square. The hexagon characterises the shape of hives not only for reasons of honey conservation or aesthetic form, but it is also the space for the development of a larva. Mathematician Thomas Hales also believed that a hexagonal honeycomb is the way to accommodate the largest area with the smallest circumference. This is good for the bees, who can produce more honey in a larger volume, but have to expend less energy to build the structure to hold the honey. By lining up several hexagons, the span can be filled in a staggered arrangement with six walls around each cavity, giving the structure a high compressive strength. The hives are also excellent heat stores, preventing the waxy structure from melting on hot days. These are therefore natural structures that guarantee efficiency, resistance and heat loss. A study conducted in 2004 by Dr Christian Pirk of the University of Pretoria showed that the temperature in the areas of the hive where the bees build up the wax is about 8°C higher than in the areas where there are no APIs. The same study also showed that the cells that have just been formed and are therefore still hot have a cylindrical shape, while after cooling they form hexagonal prisms. This happens because when the wax cools, the surface tension equalises again and the structure solidifies into a hexagonal shape.

4. Biomimetics in architecture: a background

The architectural field has been influenced by inspiration of forms, processes, and logic of the natural world. The organic forms and curved lines with predominantly plant or floral ornaments of Art Nouveau are a case in point. Biomorphic designs that mimic the formal aspects of the biological world are used in many architectural styles. Phytomorphic traces are widespread in architecture, starting with the decorations in Greek temples [7]; this makes it possible to structure not only ritual symbols but also constructive principles, such as the use of reed bundles and palm trunks as elements of construction [3]. Even Leonardo da Vinci, albeit outside the field of architecture, took his cue from nature in idealising flying machines. This was the result of an in-depth study of the flight of birds, published in Turin in 1505 in the volume "Codice sul volo degli Uccelli".

According with the definition of biomimetic, which concerns the functional emulation of natural organisms, in this section, a difference between the various types of emulation to the architectural scale is reported. Two types of emulation are proposed: morphological-structural and dynamic-functional.

4.1 Morphological-structural emulation

In morphological-structural emulation, mimesis is considered from a structural point of view. In this case, the intention to “copy” the natural function is maintained while the structural performance is ensured. In architecture, there are numerous examples of this type of imitation, especially in the architecture that preceded the 20th century.

The organic forms of the Catalan architect Antoni Gaudi are an example of structural morphological emulation, which is considered a precursor of biomimicry. In the case of the neo-Gothic Sagrada Familia (Fig. 2.3), construction of which began in October 1882, the structure of the cathedral is based on the principle of branching in the plant world: "*The tree supports the thick branches, these support the smaller branches and twigs support the leaves...*". The vault and colonnade replicate the fronds and trunks of a forest to provide a lighting and filtering system for natural light while maintaining the mystical atmosphere typical of old Gothic churches. Other imitations can be found in the spiral staircases of the Sagrada Familia, inspired by snail shells and shell spirals, and also in the towers, which recall the structures of sea sponges.

The closing infills of the great barrel vault of the Crystal Palace, designed by the English architect and botanist Joseph Paxton for the first universal exhibition in London in 1851, make it an important example of a building inspired by nature [8]. They are inspired by the structure of the Victoria Amazonia, a plant from the water lily family. Each leaf has a series of radial veins stiffened by thin transverse veins. Paxton mimics this structure for the finishing arches of the building's main façades by using iron fittings to imitate radial ribs and fins, and glass panels analogous to the leaf infills. In this way, a very light but also very resistant structure could be achieved. Konrad Wachsmann [9] explains that the Crystal Palace's large greenhouse is the first modern building inspired by the forms of nature.
Nature always provides food for thought in defining forms and geometries to emulate, as does the principle of resistance per form, which comes from the natural ribbed surfaces that make it possible to build under the banner of lightness [10]. The Italian engineer and entrepreneur Pier Luigi Nervi bases his structures on the static behaviour of elements found in nature, thus combining aesthetic value with the static-functional. He analyses shells, eggshells, leaves, calyxes and transfers the laws of nature to structures; in particular, he tries to find solutions for defining particularly efficient shell structures.
The Palazzetto dello Sport in Rome (Fig. 2.3), whose structure was designed and built in the 1950s, is defined by a large shell with ribs on the inside that radiate into the space and break with the formal paradigms of rationalism. In this work, Nervi combines the advantages of the shell structure with those of the ribbed surface to create a resistant and extremely light deck. The lower edge of the shell is corrugated to ensure greater rigidity, but also to allow light to penetrate the structure.
Frank Lloyd Wright also brings elements inspired by nature into many of his works. It is interesting to mention the tree-shaped columns of the Great Workroom of the Johnson Wax Administration Building (Fig. 2.3), built in Racine, USA, between the years 1936-1939. This structural form has demonstrated its effectiveness by resisting a load test of sixty tons, thus proving to support a load ten times greater than expected.

Fig. 2.3. left: Sagrada Familia; center: Palazzetto dello sport; right: Johnson Wax Administration Building

The architect and designer Buckminster Fuller is known for building structures inspired by the observation of radiolarians and based on the expansion of simple basic solids such as the tetrahedron, the octahedron, or any solids with as many faces as possible that can be considered similar to the geometric shape of the sphere with approximation. An emblematic example of such structures are the geodesic domes, celebrated as great architectural solutions of the 1950s. They were first built in 1948 and patented in 1954. The most famous example is the United States Pavilion at the Montreal World's Exposition of 1967. The term geodesic derives from the Greek and actually means the division of the earth into flat geometric figures that, when put together, precisely form the geodesic domes. These structures consist of a network of triangles which, when joined together, replicate a spherical shape. In fact, the sphere is divided into many triangles that are equal to each other in order to distribute the weight evenly and create a simple yet resistant structure where the compressive forces on the elements are dissipated in tension. Obviously, the thicker the triangular mesh, the larger its sides become and the closer it approaches the sphere. As a result, the weight decreases and this makes it possible to achieve much larger diameters. The fact that it is particularly resistant allows it to stand on its own. With this work, Fuller implements the principle typical of nature of "doing more with less", also known as the principle of ephemeralisation, i.e. limiting the use of material and focusing on form to achieve maximum efficiency in structural terms. One of the advantages of the geodesic dome is its high load-bearing capacity, which allows it to do without internal columns or pillars and thus to build very large covered spaces. Because it is a spherical surface, internal ventilation is excellent. Air flows continuously from the bottom to the top and centre, reducing the spread of moisture, fungi or bacteria.

4.2 Dynamic-functional emulation

The dynamic-functional emulation tends to bring the mechanisms of adaptation typical of natural organisms to architecture. The architectural organism reacts to the environment in which it finds itself and can activate autonomously dynamics that favour the adaptation conditions, just as it happens in nature. The building is therefore "living" and "intelligent", able to react to external stimuli. To ensure this is important the use of specific materials, such as natural, defined by Lopez et al. “self-activating” [11].

In this regard Kuru introduced the concept of *biomimetic adaptive building skin (Bio-ABS)* as *“a type of adaptive building skin that responds to environmental conditions by changing its morphological or physiological properties or behaviour over time to meet various functional requirements of a building and to improve its overall performance. The changing properties and behaviours of the skin are translated from biological models that offer environmentally, mechanically and/or structurally efficient strategies”* [12] .

The pinecones, which are activated according to the humidity level by exploiting the hygroscopic and anisotropic properties of the wood, are an example of self-activation. In this case, humidity is the environmental stimulus that activates the reaction. The Hygroskin pavilion designed by Achim Menges in collaboration with Oliver David Krieg and Steffen Reichert is an example of dynamic-functional architecture. This pavilion is characterized by a steel structure covered with concave panels in spruce, each of which has a circular hole for the passage of light. These openings are characterized by thin triangular petals that open and close according to the humidity in the atmosphere [13]. When the outside air is dry, the wood fibres retreat and the petals open and the holes in the structure remain open; when the air is humid, the wood fibres are relaxed; therefore, the petals are closed and the holes in the structure remain closed [13] [14] [15] [16].
Another example is given by the special system of solar shielding without hinges called "*Flectofin*" (Fig. 2.4) by ITKE that is inspired by the pollination mechanism of the flower Strelitzia reginae based on the principle of elastic deflection [17]. The final patented product is made of fibre reinforced material consisting of two large foils, like the petals of the inspiring flower, without the use of hinges. The advantage of replacing hinges with elastic deformations lies in the fusion of all mechanical elements within a single folding component. The use of fibre reinforced polymers can combine high tensile strength with low flexural rigidity, thus offering a wide range of calibrated elastic deformations [18] [19].

Fig. 2.4. Flectofin system [17]

An example of a combination of formal and functional emulation is at the scale of the building component and is represented by artificial ivy leaves. These imitate the morphology of the leaf as far as the aesthetic aspect is concerned, while for what concerns the function they behave as photovoltaic panels, therefore able to store thermal energy incidents on them [20] [21]. In addition, they can move also yielding wind energy.
Functional emulation, therefore, implies a dynamic mechanism sensitive, as the building organism or, its components, can react to external stimuli and climatic variations. This is in

line with the definition of a climate adaptive building envelope that can adapt to outdoor climatic conditions. This highlights the importance of biomimetics in favour of solutions for the building envelope, in that a functional emulation inspired by the functioning mechanisms of natural organisms allows a passive response to external environmental variations and therefore a limitation of energy consumption and mechanical tools, as in the case of other types of adaptive casings, such as a kinetic casing that requires activation mechanisms, then electricity and energy consumption.

5. Biomimetics in scientific literature

This sub-section provides an updated overview of the application of biomimetics in the various thematic areas that have been reported in scientific literature until August 2023. Researching "*biomimetics*" for "title, abstract, keywords" in Elsevier's Scopus database [22], has resulted in 58300 items, divided by Journal, Conference proceedings, and Books (Fig. 2.7). The annual production of articles on biomimetics has shown rapid growth since the 90s, confirming findings by [1]. Since 2000 publications have increased dramatically, from less than 1000 to more than 1000 per year, and in 2021 alone, some 5976 biomimetic publications were produced (Fig. 2.5). The thematic areas are led by Engineering with about 27585 publications and Material Science with about 20912 publications, followed by Computer Science (Fig. 2.8). Fig. 2.6 shows the location of items by countries: it is noted that China and the United States occupy the first places, with about 18361 and 12330 publications respectively.

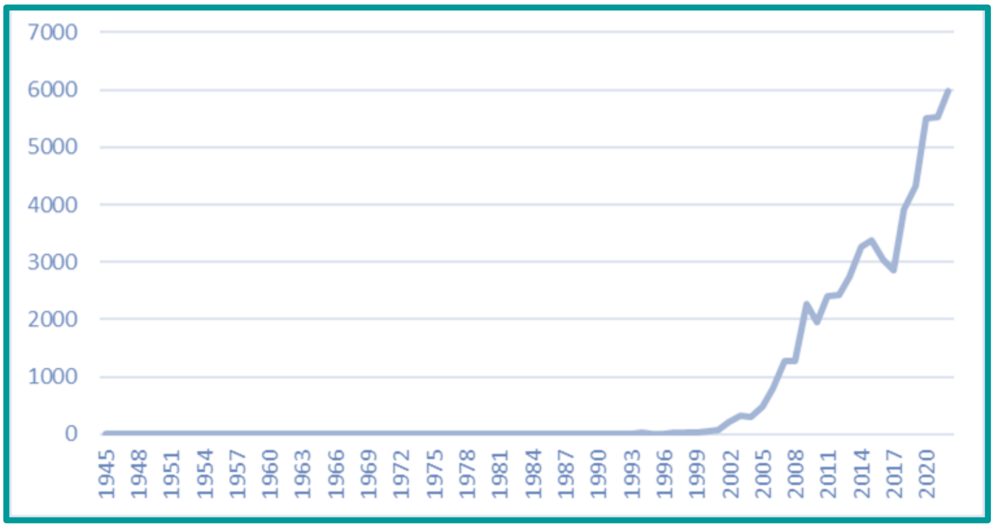

Fig. 2.5. Number of document by year

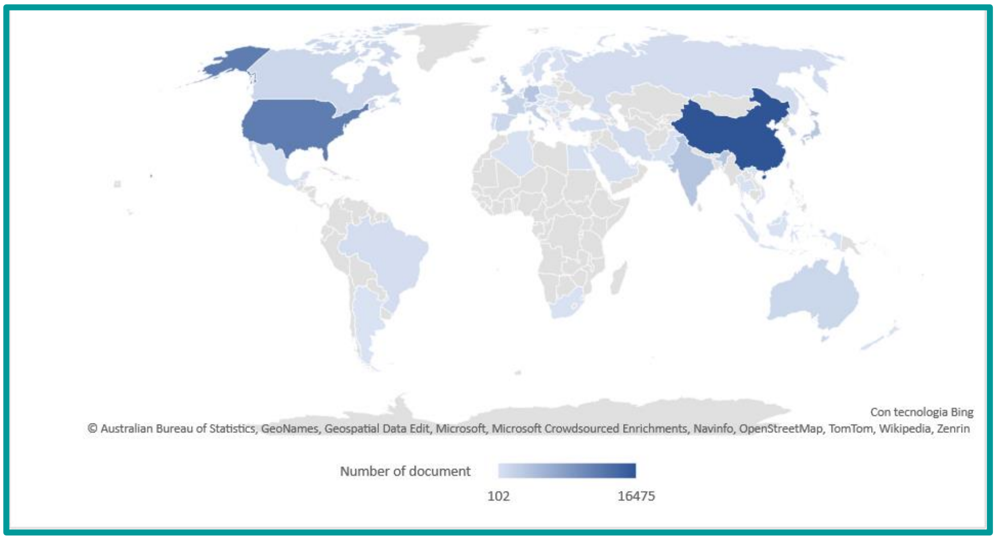

Fig. 2.6. Distribution of document by country

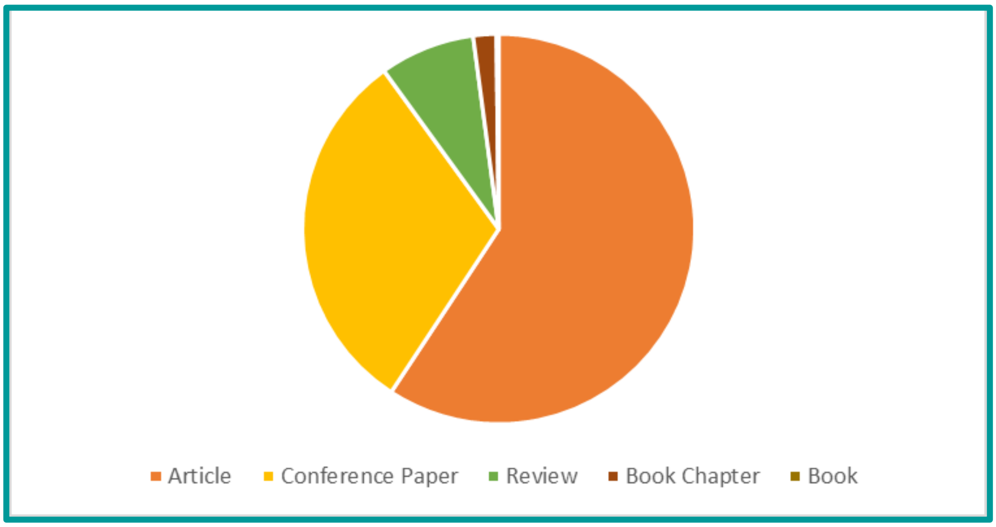

Fig. 2.7. Documeny by type

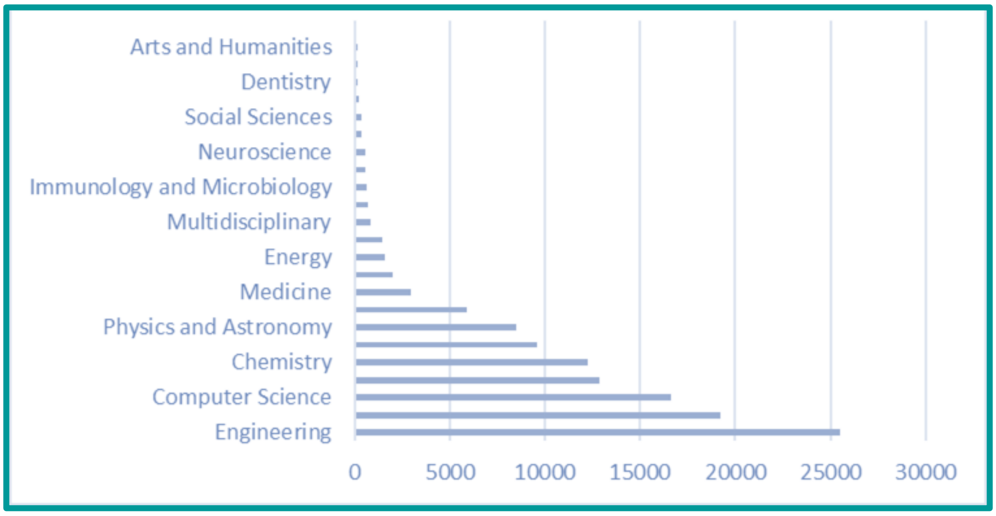

Fig. 2.8. Number of document by subject area

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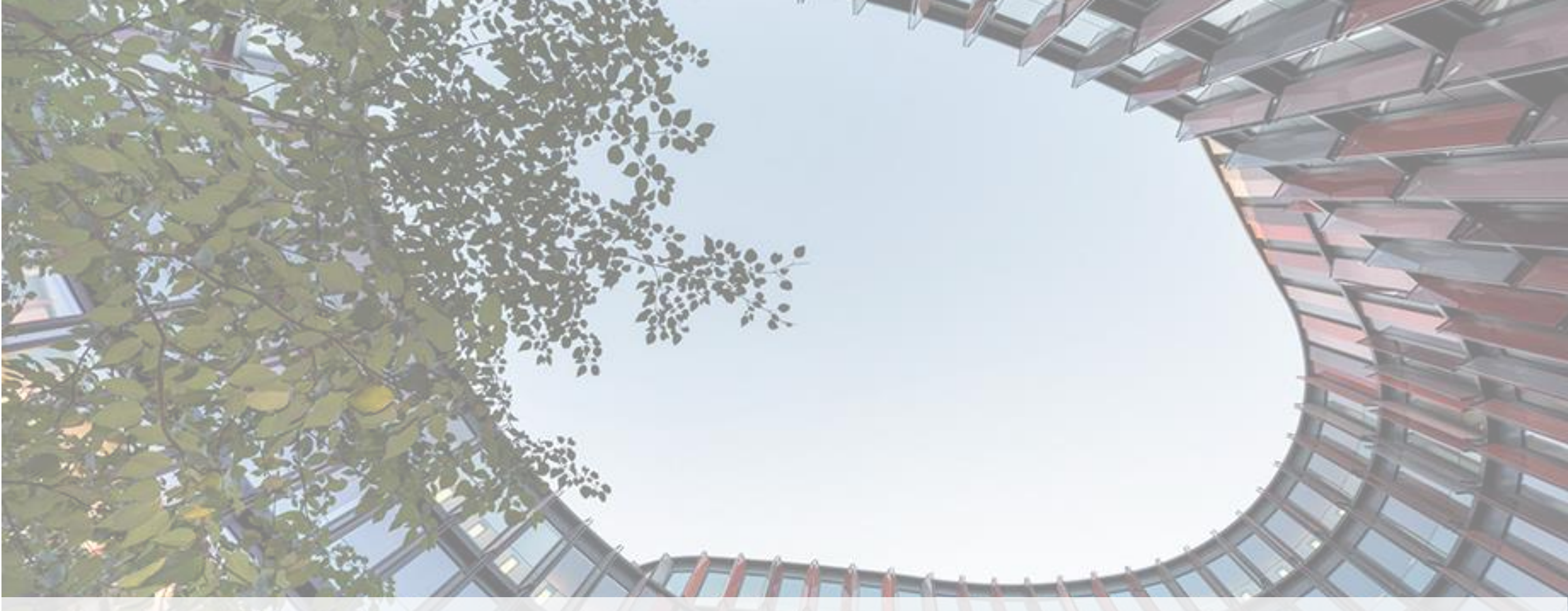


Chapter 3

Comparative analysis of existing examples

3.

In the previous chapters, the meaning of adaptive envelope (chapter 1) and biomimetic envelope (chapter 2) was clarified by organising and explaining the existing concepts in the scientific literature. In this chapter, a comparative analysis between the existing examples of adaptive envelope and biomimetic adaptive envelope is carried out using the analysis parameters described in the following sections.

1. Analysis of Adaptive Building Envelope

This study identified 25 (Fig. 3.1 – Table 1) representative examples of relevant adaptive building envelope solutions. The various examples have been classified according to the building use and the climatic context based on the Koppen Geiger classification [1].

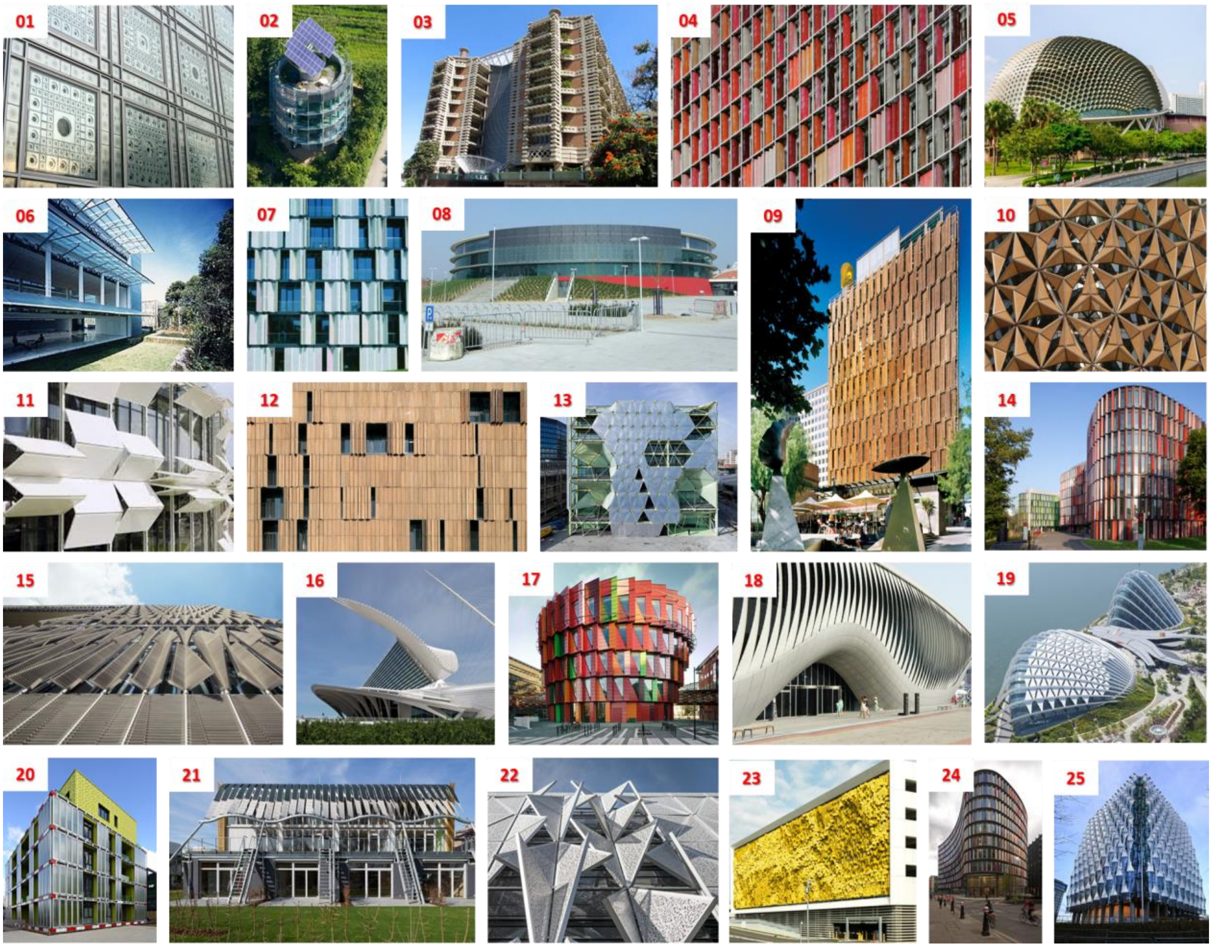


Fig. 3.1. Exemples of existing adaptive building envelope

The performance of the envelope was classified in terms of visual comfort (V), thermal comfort (T), indoor air quality (IAQ), energy generation (EG), acoustic comfort (A), and structural resistance (S); the mechanisms of adaptation were classified as dynamic if there is a movement, or as static if there is no movement [2]; the responsive functions were classified following Table 3.1 as Regulate (Reg), Shield (Sh), Transfer (Tr), Reflect (R), Store (S), and Transform (Tm); the abiotic factors that were considered are Temperature (T) air (A), light (L), and Water (W); they represent the environmental stimulus to which the building envelope adapts.

Table 3.1. Analysis of building with adaptive envelope. **Building use:** Museum (M), Residential (R), Office (O), Educational (E), Sport (S), Exposition (E), Parking (P). **Climate:** Equatorial (A), Arid (B), Warm temperate (C), Snow (D), Polar (**E). Performance:** Thermal Comfort (T), Visual Comfort (V), Acoustic Comfort (A), Energy storage (ES), Indoor Air Quality (IAQ), Structural (S). **Mechanism:** Static (S), Dynamic (D). **Responsive function :** Regulate (Reg), Shield (Sh), Transfer (Tr), Reflect (R), Store (S), Transform (Tm). **Abiotic factor**: Temperature (T), Air (A), Light (L), Water (W).

ID	Year	Case study	Designer	Building use	Climate [1]	Performance [3][4]	Responsive Function [5]	Mechanism [2]	Abiotic factor [3]
01	1987	**ARAB WORLD INSTITUTE** Paris, France	Jean Nuovel	M	Cfb	V, T	Reg, Sh	D	L
02	1993	**HELIOTROP** Freiburg, Germany	Rolf Disch	R	Cfb	V, T, ES	S, Tm	D	L
03	1996	**EASTGATE CENTER** Harare, Zimbabwe	Mick Pearce	O	Cwb	T	Reg	S	A
04	1999	**GSW HEADQUARTERS** Berlin, Germany	Sauerbruch Hutton	O	Cfb	T, A, IAQ	R, Sh	S	A
05	2002	**ESPLANADE THEATRES** Downtown core, Singapore	Dp Architects	T	Af	T	Reg, Sh	S	L, T
06	2002	**MUSEUM OF PAPER ART** Shizouka, Japan	Shigeru Ban	M	Cfa	T, V	Reg, Sh	D	A, T
07	2004	**BIOCATALYSIS LAB BUILDING TECHNICAL UNIVERSITY** Graz, Austria	Giselbrecht + Zt Gmbh	E	Cfb	A	Reg, Sh	D	A, T

08	2005	**EWE ARENA** Oldenburg, Germany	ASP Architekten		Cfb	T, IAQ	Tm, R	S	L
09	2006	**COUNCIL HOUSE 2** Melbourne, Australia	designing	O	Cfa	T, IAQ, ES	S	D	L
10	2007	**AL-BAHR TOWERS** Abu Dhabi, Arab Emirates	AHR + Arup	O	BWh	T, V	Reg, Sh,Tm, S	D	L, T
11	2007	**KIEFER TECHNIC SHOWROOM** Bad Gleichenberg, Austria	Ernst Giselbrecht + Partner	E	Cfb	T, V	Reg, Sh, R	D	L
12	2007	**CARABANCHEL** Madrid, Spain	FOA	R	BSk	V	Reg, Sh	D	L
13	2010	**ICT-MEDIA** Barcelona, Spain	Enric Ruiz Geli, Cloud 9	O	Csa	T	Reg, Sh	D	L, T
14	2010	**OVAL OFFICE** Cologne, Germany	Sauerbruch Hutton	O	Cfb	V	Reg	S	L
15	2010	**Q1 BUILDING OFFICE** Essen, Germany	JSWD Architectures et al.	O	Cfb	T, V	Reg, Sh, Tr	D	L, T
16	2011	**BURKE BRISE SOLEIL** Milwaukee, USA	Santiago Calatrava	M	Dfa	V	Sh	D	L, T
17	2011	**KUGGEN** Gotenorg, Sweden	Wingardh Arkitektonto r	U	Cfb	V, ES	Reg, Sh, R	D	L, T
18	2012	**ONE OCEAN** Yeosu-si, South Korea	Soma Architecture	E	Cfa	V	Reg, Sh, Tr	D	L
19	2012	**COOLED CONSERVATORIES AT GARDENS BY THE BAY** Singapore	Wilkinsoneyr e	E	Af	V	Tr, Reg	D	L
20	2013	**BIQ HOUSE** Hamburg, Germany	Splitterwerk	R	Cfb	ES	Tr, S, Tm, R	D	L
21	2013	**IBA SOFT HOUSE** Hamburg, Germany	360grad + Architeckten et al.	R	Cfb	V, ES	Reg, Tm, S, Tr	D	L, T

22	2014	**KOLDING CAMPUS UNIVERSITY** Kolding, Denmark	Henning Larsen Architects	U	Cfb	T, V	Reg, Sh	D	L, T
23	2014	**ESKENAZI HOSPITAL** Indianapolis, USA	HOK	P	Cfa	V	Tr, Reg	D	A
24	2015	**NEW LUDGATE** London, United Kingdom	Fletcher Priest Architects	O	Cfb	V	Sh	S	L
25	2017	**US EMBASSY** London, United Kingdom	Kieran Timberlake	O	Cfb	V	Tr, Reg, R	S	L

2. Results: adaptive envelopes

Table 3.2 presents the results of the analysis of the 25 adaptive envelopes expressed in percentages. Most of them are located in warm temperate climates (C), while only few of them are located in equatorial (A), arid (B), or snow (D) climates. The external environmental factors that are generally more widely used are the sun and in rare cases wind. Consequently, regulating and shielding are the most considered responsive functions to ensure thermal, visual, and luminous comfort conditions. The shielding systems analysed in the adaptive facades need a sensor that perceives the stimulus and an actuator that activates the system to ensure the responsive function. This study didn't identify significant solutions that draw on water or other resources. **Table 3.2.** Results of the analysis on the adaptive envelope

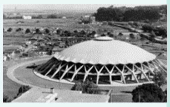
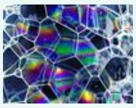
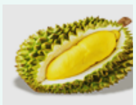
Climate		Building use		Responsive Function		Performance		Abiotic factor	
Equatorial -A	4 %	Office	28 %	Regulate	72%	Energy Storage	20 %	Light	80 %
Arid - B	8 %	Sport	8 %	Shield	60 %	Thermal comfort	56 %	Air	20 %
Warm Temp. - C	80 %	Exposure	12 %	Transfer	28 %	Visual comfort	68 %	Water	0 %
Snow -D	8 %	Residential	16 %	Reflect	24 %	Indoor Air Quality	3 %	Temperature	40 %
Polar -E	0 %	Museum	12 %	Store	20 %	Acoustic comfort	8%		
		Theater	4 %	Transform	20 %				
		University	12 %	**Mechanism**					
		Parking	4 %	Static	28 %				
				Dynamic	72 %				

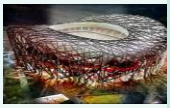
3. Analysis of Biomimetic Adaptive Building Envelope

Table 3.3 shows the analysis of 24 examples of biomimetic envelopes. The characteristics considered are the same as those already described in the previous section, as well as the source of inspiration, the stimulus, and the scale of adaptation. The stimulus is classified as intrinsic (I) intended as a self-regulation in response to environmental factors such as temperature, relative humidity, without a mechanical or energetic activation system. Conversely, if the system is activated by means of a system of sensors and actuaries, the stimulus is extrinsic (E). The scale of adaptation represents the size of the system and is defined as building (B), façade Systems (FS), component (C), material (M).

Table 3.3. Analysis of building with biomimetic envelope. **Climate:** Equatorial (A), Arid (B), Warm temperate (C), Snow (D), Polar (E). **Performance:** Thermal Comfort (T), Visual Comfort (V), Acoustic Comfort (A), Energy storage (ES), Indoor Air Quality (IAQ), Structural (S). **Scale of adaptation:** Building (B), Façade Systems (FS), Component (C), Material (M). **Responsive function:** Regulate (Reg), Shield (Sh), Transfer (Tr), Reflect (R), Store (S), Transform (Tm). **Mechanism:** Static (S), Dynamic (D). **Stimulus**: Intrinsic (I), Extrinsic (E). **Abiotic factor**: Air (A), Light (L) Water (W), Temperature (T)

	Case Study Year Name Location Designer	Inspiration	Building use	Climate	Performance	Scale of adaptation	Responsive function	Mechanism [3]	Stimulus [3]	Abiotic factor
	1851 **CRYSTAL PALACE** London, United Kingdom Joseph Paxton	Victoria amazonica 	Exposure	Cfb	S	B	-	-	-	-
	1882 **SAGRADA FAMILIA** Barcelona, Spain Antoni Gaudì	Tree 	Cult	Csa	S	B	-	-	-	-
	1936 **JOHNSON WAX BUILDING** Racine, Usa Frank Lloyd Wright	Tree 	Office	Dfa	S	C	-	-	-	-
	1951 **WOOL MILL GATTI** Rome, Italy Pier Luigi Nervi	Fungi 	Production	Csa	S	C	-	-	-	-

	1956 **SPORTS HALL** Rome, Italy Pier Luigi Nervi	Schell 	Sport	Csa	S	B	-	-	-	-
	1986 **LOTUS TEMPLE** Delhi, India Fariborz Sahba	Lotus flower 	Cult	BSh	S	B	-	-	-	-
	1996 **EASTGATE CENTER** Harare, Zimbabwe Mick Pearce	Termites 	Office	Cwb	T V IAQ	B	Reg	S	-	A
	1998 **HEMISFERIC** Valencia, Spain Santiago Calatrava	Eyeled 	Cinema	Af	V T	C	Sh Reg	D	E	T
	2001 **MILWAUKEE ART MUSEUM** Milwaukee, USA Santiago Calatrava	Bird wings 	Museum	Dfa	T	C	Sh	D	E	L
	2001 **EDEN PROJECT** Cornwall, United Kingdom Grimshaw Architects	Soap formation 	Exposure	Dfb	T S	B	S Tr Reg	-	-	T
	2002 **ESPLANADE** Singapore DPA Architects, Atelier One. Micheal Wilford	Durian fruit 	Theater	Af	T V	FS M	Reg Sh	S	-	L, T
	2003 **KUNSTHAUS** Graz, Austria Peter Cook - Colin Fournier	Bubbles 	Exposure	Cfb	T	B	Reg	-	-	T
	2006 **ORQUIDEORAMA BOTANIC GARDEN** Medellin, Colombia Plan B Arquitectos + Jprcr	Honeycomb 	Exposure	Cfb	V	C	Sh	S	-	L

	2008 **WATER CUBE** Beijing, China Ptw Et Al.	Soap formation 	Sport	Dwa	T V S	B	Reg S Tr	-	-	T
	2008 **PECHINO NATIONAL STADIUM** Beijing, China Herzog & De Meuron, Arup	Bird's nest 	Sport	Dwa	S	B	-	-	-	-
	2011 **FLECTOFIN** Stuttgard, Germany S. Schieicher ITKE Stuttgard University	Sterlitzie reginae 	'	Cfa	T V S	FS	Reg Sh	D	I	L
	2012 **HOMEOSTATIC FACADE** New York, USA Decker Yeadon	Muscle 	'	Cfb	T V	M C	Reg Sh	D	I	L, T
	2012 **ONE OCEAN** Yoesu, South Korea Soma Architecture	Sterlitzie reginae 	Exposure	Cfa	T V S	FS	Reg Sh	D	I	L A
	2012 **HYGROSKIN PAVILION** Orléans, France A. Menges, S. Reichert	Pin cone 	Exposure	Cfb	T V S	FS	Reg	D	I	T, A, W
	2013 **HYGROSKIN PAVILION** Orléans, France A. Menges, O. D. Krieg, S. Reichert	Pine cone 	Exposure	Cfb	T V IAQ	C FS	Reg	D	I	T, A, W
	2014 **LANDESGARTENSHAU EXIBITION HALL** Schwaebish Gmuend, Germany ICD, ITKE Stuttgard University	Sea urchin skeleton 	Exposure	Cfb	S	FS	-	-	-	-

	2019 **BUGA WOOD PAVILION** Heilbronn,Germany ICD, ITKE Stuttgard University	Sea urchin skeleton 	Exposure	Cfb	S	FS	-	-	-	-
	2019 **BUGA FIBER PAVILION** Heilbronn,Germany ICD, ITKE Stuttgard University	Cellulose 	Exposure	Cfb	S	FS	-	-	-	-
	2020 **PHO' LIAGE** Lyon, France ArtBuilt Studio	Flower petals 	Office	Cfa	T V	FS M	Reg Sh Tm	D	I	L T

4. Results: biomimetic envelopes

Table 3.4 presents the results of the analyses of 24 biomimetic envelopes in percentages. Most of them are located in warm temperate climates (C) and in snow climates (D), while few of them are located in equatorial (A) and arid (B). Most of the examples considered are temporary office or exhibition structures; other examples instead, are at the prototype scale. Many of the natural organisms' emulations are aimed at structural performance while others at guaranteeing indoor comfort, especially thermal and visual comfort. The latter case justifies the responsive shading and filtering functions. From this analysis emerges the evolution of biomimicry over the years.

The first examples considered, preceding the twentieth century, represent formal emulations with a structural function. In the 20th century, examples present more a functional dynamic emulation. This underlines the increased awareness about the potential of the biomimetic discipline and its application in the field of architectural technologies for adaptation purposes.

Table 3.4. Results of the analysis on the biomimetic envelopes

Climate		Building use		Scale of adaptation		Performance		Responsive function	
Equatorial -A	8 %	Office	9,5 %	Building	33 %	Structural	36 %	Regulate	45,83%
Arid - B	4 %	Sport	14 %	Facade Systems	33 %	Thermal comfort	33 %	Shield	29,17%
Warm Temp. - C	67 %	Exposure	47 %	Component	23 %	Visual Comfort	26 %	Transfer	8,33%

Snow -D	21 %	Production	5 %	Materials	11 %	Indoor Air Quality	5 %	Reflect	0%
Polar -E	0 %	Cultural	9,5 %					Store	8,33%
		Cinema	5 %					Transform	4,17%
		Museum	5 %	**Mechanism**		**Stimulus**		**Abiotic factor**	
		Theatre	5 %	Static	12.50 %	Intrinsic	25 %	Temperature	37,50%
				Dynamic	33,33 %	Extrinsic	8,33 %	Light	25%
								Air	16,67%
								Water	8,33%

5. Comparative analysis and discussion

The aim of the comparative analysis is to highlight the current trends of these technological solutions, as well as emphasizing their features and applications. Figures 3.2-3.7 shows the results of the comparative analysis of the various categories. It is evident that the examples of biomimetic envelopes of the past have the objective of emulating the morphology of natural organisms for structural functions, while more recent examples tend to mimic the behavioural or physiological function of natural organisms to ensure the ability to adapt to weather conditions. The biomimetic envelope has an added potential because it can provide in some cases the same performance as a standard adaptive envelope, without consuming much energy, enhancing a passive response to external variables and limiting the negative impact on the environment. The only adaptive casing ensures the internal comfort and well-being of users adapting to external conditions, but requires a system of sensors and actuators to activate. These, in addition to consuming energy, also entail a high cost for maintenance and management during the life cycle of the building itself.

Furthermore, the companies of façade construction, do not have all the skills suitable to design such complex systems and must resort to cooperation with companies of other sectors, such as sensors, electrical or automation more in general. To date, there are few examples of adaptive envelope, and even fewer biomimetic ones. Most adaptive envelopes have temporary, exhibition or recreational use (Fig. 3.3). The main destination of adaptive envelopes, on the other hand, is office or university offices (Fig. 3.3). These are therefore buildings that need a good level of lighting to ensure activities but, at the same time, it is necessary to reduce glare and overheating of the internal environment. This explains why adaptive envelope solutions generally dynamic shields with a filtering or shading function are (Fig. 3.5). At the same time, the analysis carried out shows that most of the applications are in climatic contexts of type C, that is in climates with warm temperatures (Fig. 3.2). This justifies that the main response functions are shading and filtering (Fig. 3.5) and the visual comfort and thermal comfort performances which are the most requested (Fig. 3.4).

The concept of adaptation for the building envelope is limited to the definition of simple shielding systems that are activated based on the climatic variations in progress but are limited to a mono-functional approach. Not only the solar factor should be considered, but all other environmental parameters should be considered and the possibility of tapping into natural resources to transform them into energy for the benefit of users. The qualitative analysis shows that only 20% of the cases analyzed have performances capable of storing energy. Otherwise, it is limited to a simple automated shielding mechanism.

The analysis regarding biomimetic envelopes identified that natural organisms, especially plants and animals, inspired the examples considered. Natural organisms have strong potential and above all, they can perform multiple functions at the same time. The biomimetic examples analyzed show that the approach is still of a monofunctional type. There are rare cases in which it is possible to find an envelope capable of performing multiple functions at the same time, as it occurs in nature. This is certainly a limit, already identified several times in the literature, not yet overcome.

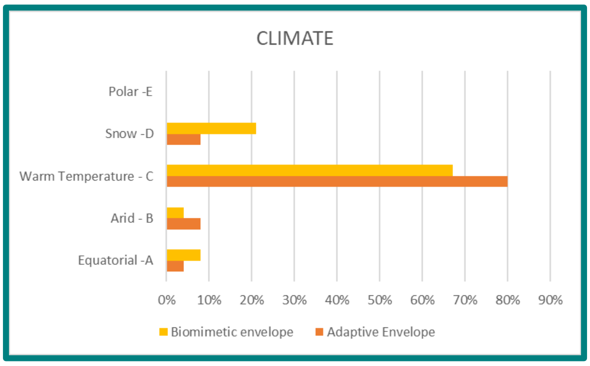


Fig. 3.2. Comparative analysis about climate

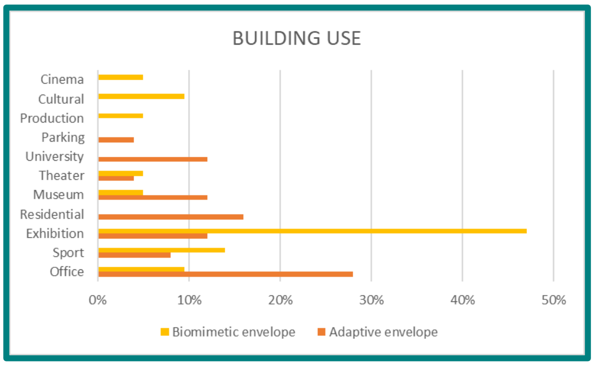


Fig. 3.3. Comparative analysis about building use

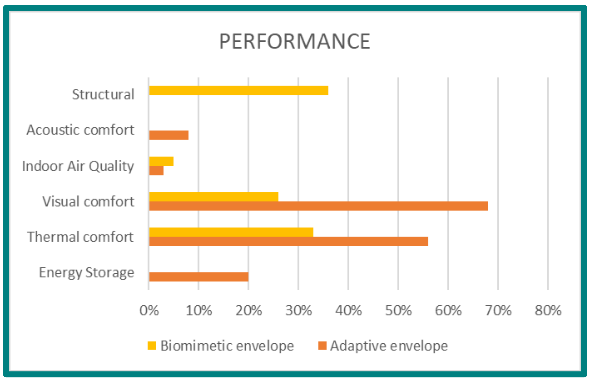


Fig. 3.4. Comparative analysis about performance

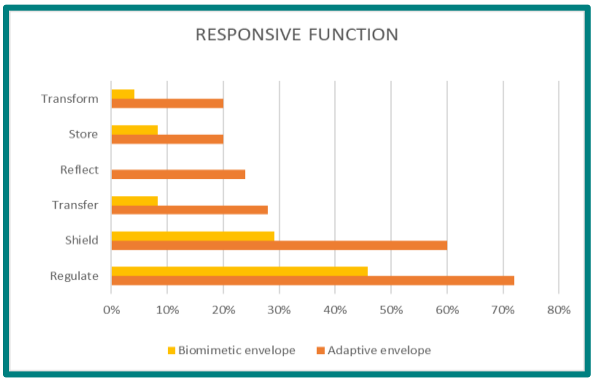


Fig. 3.5. Comparative analysis about responsive function

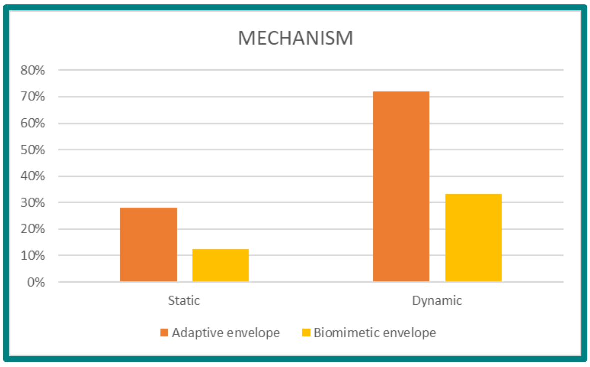


Fig. 3.6. Comparative analysis about mechanism

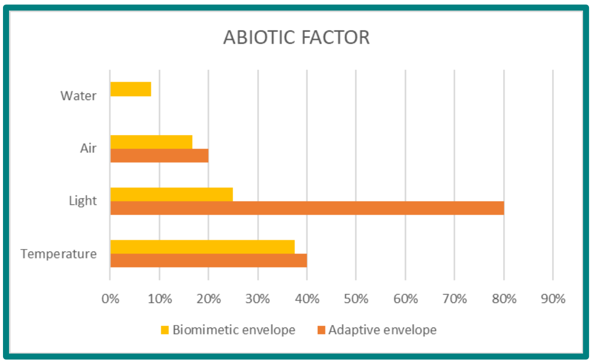


Fig. 3.7. Comparative analysis about abiotic factor

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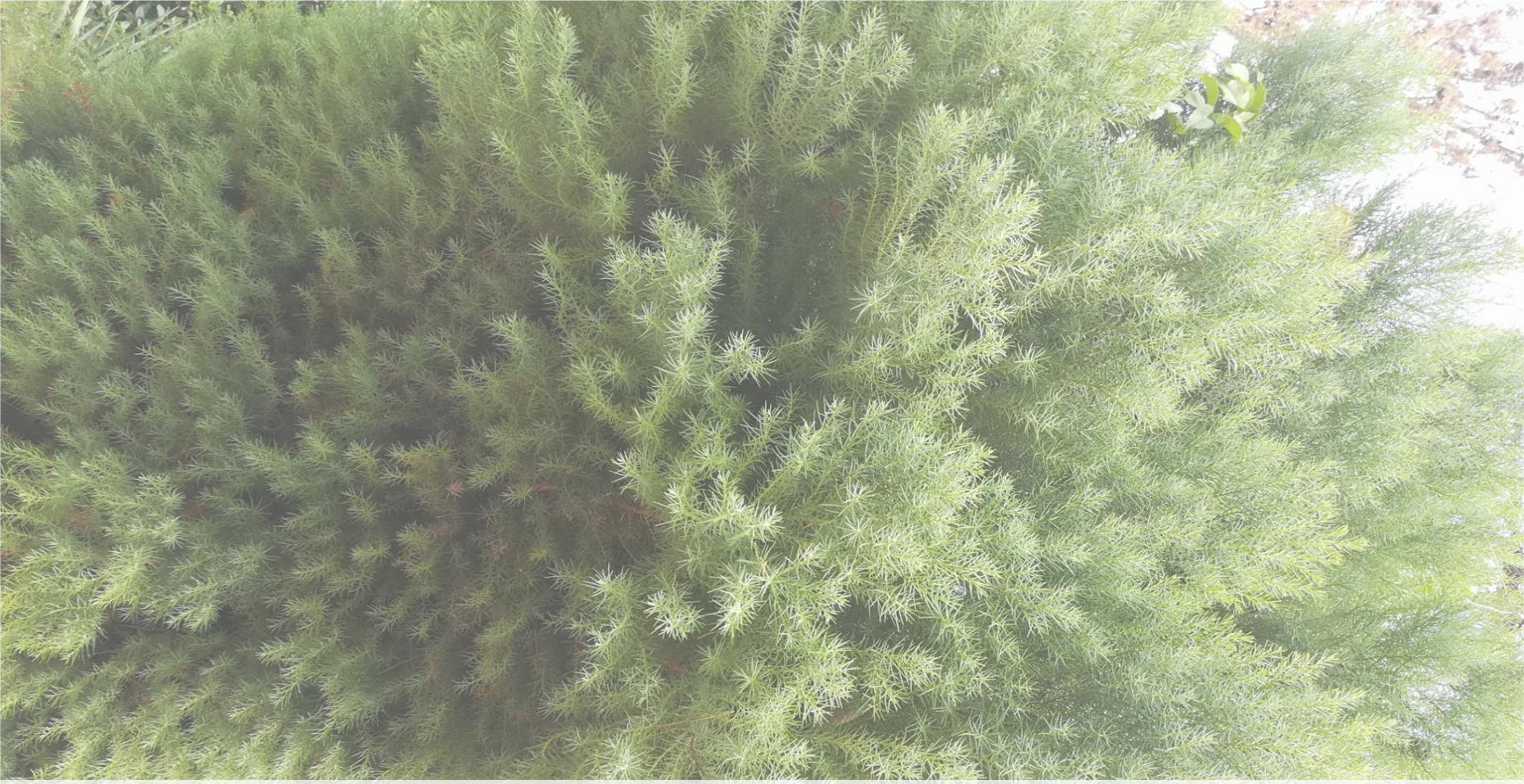

Chapter 4

Existing biomimetic methodological approaches

4.

1. Introduction

Having clarified and affirmed that the biomimetic discipline aims to transfer functional behaviours from nature to architecture, it is necessary to understand the way in which this transfer can be implemented. Various biomimetic methodological approaches to transfer from nature to architecture are presented in the scientific literature, but many of them are still general and not specific to a particular field. The multidisciplinary approach is essential to bring together the different competences with those of the sector of the biomimetic solution to be achieved. For example, the organic sector is fundamental and indispensable in all approaches. The purpose of this chapter is to analyse the different existing methodological approaches and to identify the gaps and lacunae in order to propose a new methodological approach.

Biomimetic methodological processes encompass "bottom-up" and "top-down" methodologies or a hybrid amalgamation of these paradigms.

The top-down (problem-oriented) methodology commences with the delineation of a challenge. It subsequently investigates biological solutions, aiming to extract and transmute functional principles from these solutions into the realm of technology.

The bottom-up (solution-driven) methodology revolves around discerning specific attributes within an organism or ecosystem. The intention is to extrapolate adaptation mechanisms pertinent to these attributes, thus translating them into directives for projects and technical resolutions [1].

The individual phases of each of the two methods are shown in the table 6.1[2]:

Table 6.1. Top down and bottom-up approach' phases

Top-down	Bottom-up
1. Problem articulation	1. Identification of biological strategy
2. Problem rephrasing	2. Definition of biological solution
3. Exploration of biological solutions	3. Principle extraction
4. Formulation of biological solutions	4. Solution reformulation
5. Extraction of the principle	5. Problem investigation
6. Application of the principle	6. Problem delineation
	7. Principle implementation

2. Analysis of existing approaches

In this section the most important biomimetic approaches, present in the literature, are analyzed and then compared to identify similarities and limitations of each of them. Table 6.2 shows the approaches analyzed on the basis of the framework type, problem based or solution based.

Table 6.2. Existing methodological approaches

Ref.	Biomimetic framework	Framework type	
		Problem based (top down)	**Solution based** (bottom up)
2006. 2017 Hastrich. Biomimicry Institut [3] [4]	Biomimicry Design Spiral	x	
2017 Biomimicry 3.8 [5]	Design Lens	x	
2006 Vincent et al. [6]	BioTRIZ	x	
2015 Badarnah e Kadri[7]	BioGEN	x	
2017 Lopez et al. [8]	Biomimetic principles for the development of adaptive architectural envelopes		x
2020 Kuru et al. [9]	Multi-Biomechanism approach	x	

2.1 Biomimicry Design Spiral

In 2006, Hastric proposes a top-down approach, the Biomimicry Design Spiral [3] [4] (Fig. 6.1), organised according to an outward spiralling process, with each turn of the spiral representing the full implementation of the methodology divided into five phases: 1) identify, 2) translate, 3) discover, 4) imitate; 5) evaluate. This methodology has been repeatedly adopted and revised. Notably, in 2017, the Biomimicry Institute proposes the same spiral again, but describes six steps that a design team should take when defining biomimetic solutions. The six steps are: 1) Define, 2) Biologise, 3) Discover, 4) Abstract, 5) Imitate, 6) Evaluate. The first step (define) is to define the problem or challenge to be addressed; therefore, you need to explain what kind of solution you are aiming for and to whom it is addressed. In this phase it is good to consider the context not only for defining the environmental factors and resources involved, but also for any constraints. The second phase (Biologise) is to reframe the challenges of the previous point from a biological point of view, to understand what organisms and how they manage to overcome the same challenge. The aim of this phase is to understand how nature manages to perform certain functions. On the other hand, looking for natural models with the same functions and context as the design solution and identifying the natural strategies that determine their survival is the goal of phase 3 (discover). Phase 4 (abstract) consists of analysing the features and functional mechanisms that make biological strategies effective (feature or mechanism used by an organism or ecosystem to perform a specific function) and reproducing them in non-biological form as design strategies. In phase 5 (emulate), the designer can use their professional skills to create a solution based on emulating the discovered strategy. This is the most important step in designing a biomimetic solution. At the end of the process, in phase 6 (evaluate), it is advisable to assess the extent to which the process meets the criteria and constraints of the design challenge and its adaptation to biological systems, in order to test the solution from the point of view of applicability and to understand how to optimise the project.

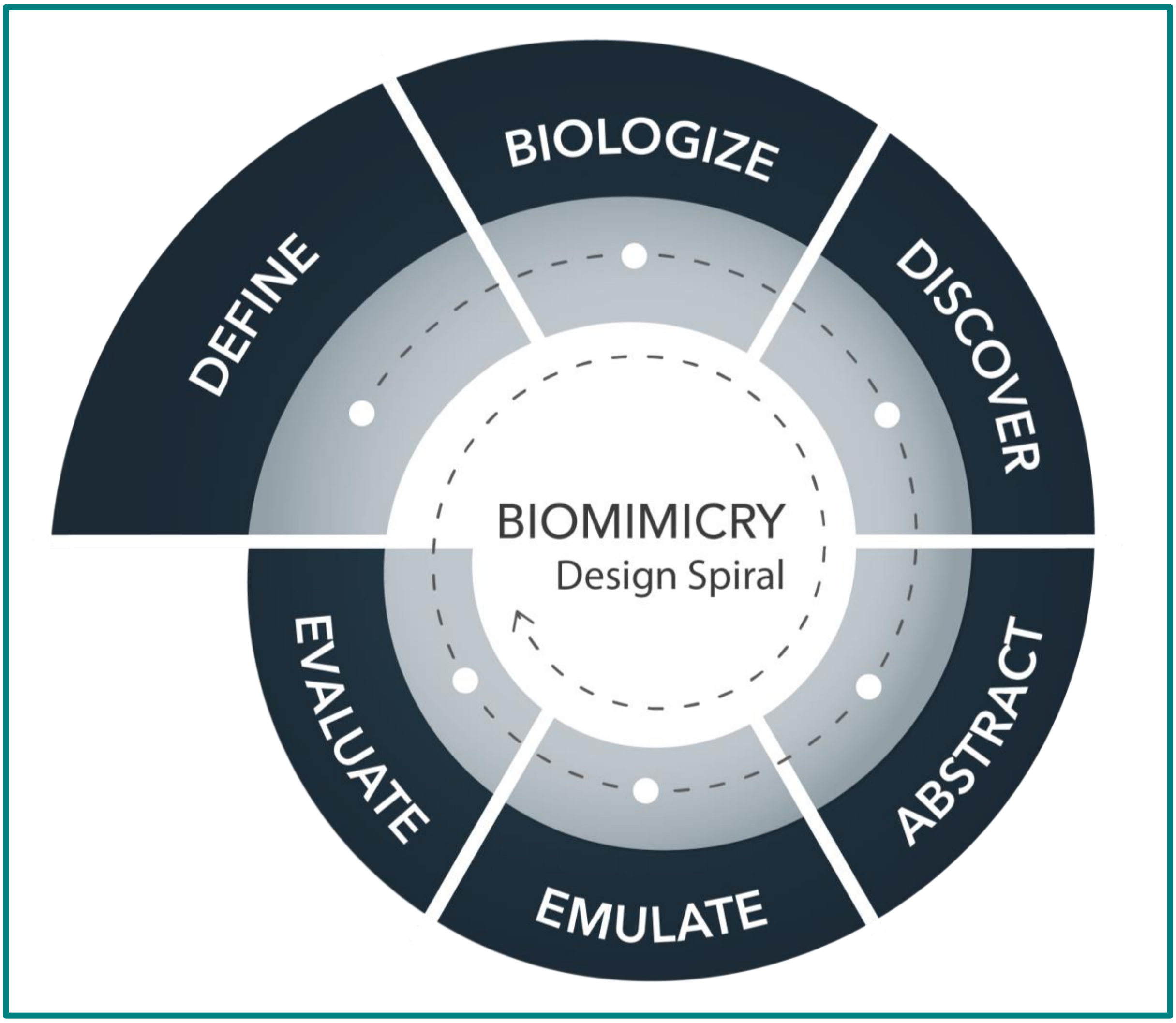

Figure 6.1. Biomimicry Design Spiral [3]

2.2 Design Lens

Biomimicry 3.8 proposes another biomimetic approach called DesignLens [5] (Fig. 6.2). This is a collection of diagrams that form the basis of the biomimetic design approach, with the aim of combining theoretical concepts with practical concepts to understand how natural elements work. The Biomimicry Design Lens presents three essential elements and defines the principles of life (Life's principles) and biomimetic thinking (Biomimicry Thinking). Life's principles are intended as lessons for design in nature, while biomimicry thinking provides context for where, how and why biomimicry fits into the process of any design discipline or scale. Biomimicry Thinking is presented in a dual framework: one that leads from biology to design, and another that leads from problem to biology. It can be concluded that Biomimicry 3.8 proposes both a bottom-up and a top-down approach. In addition, Biomimciry 3.8 also features the Biomimicry Toolbox and Ask Nature. The former is a digital resource website that provides a brief guide to biomimicry, while the latter is intended as a freely accessible online library for understanding nature's survival strategies and their potential to inspire sustainable human design. This website organises the resources by function and presents them in non-technical language to facilitate understanding for the less experienced.

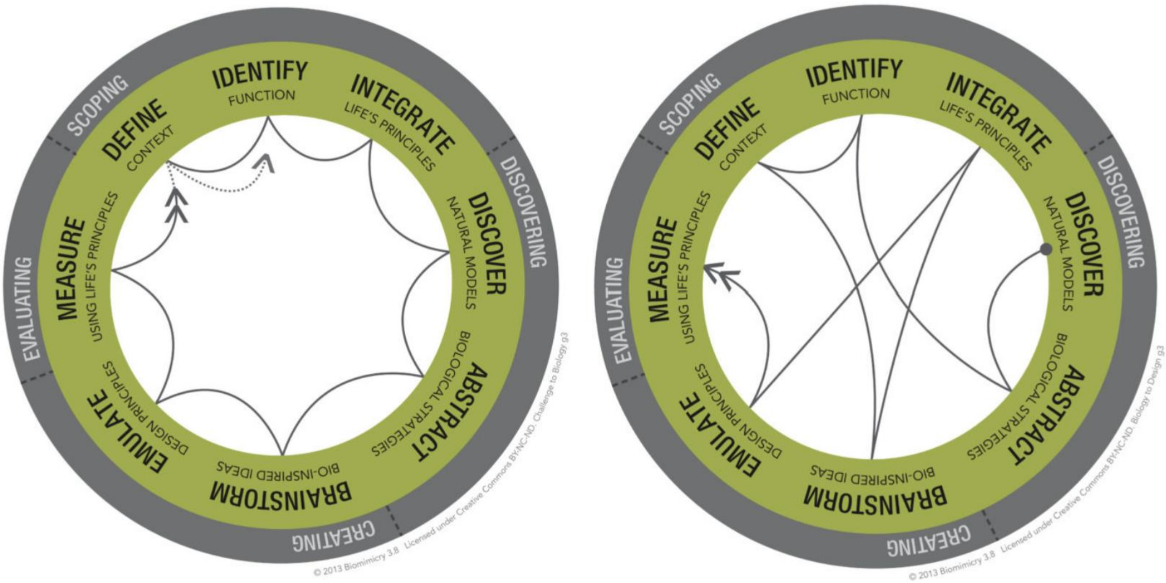

Figure 6.2. Biomimcry Design Lens [5]; left: challenge to biology, right: biology to design

2.3 BioTRIZ

Vincent et al. [6] presented BioTRIZ in 2006, a systematic technological approach to the transition from biology to technology using the Russian TRIZ method (Teorija Reshenija Izobretatel'skin Zadach, translated into English as Theory of Inventive Problem Solving). BioTRIZ is a problem-solving method that uses a database of biological data and consists of five phases. The first two phases concern the definition and analysis of the problem, respectively. The third phase compares recommended solutions from biology and the TRIZ matrix to find common analogies for the fields of biology and engineering. The fourth phase is the one that aims to establish a link between natural and engineering design. The fifth and final phase of this model recommends adding some purely technical or purely biological principles to the basic principles of the TRIZ method to create a completely new technology. Currently, the database is no longer available due to its complex implementation.

2.4 BioGEN

Badarnah and Kadri [7] proposed BioGEN (Fig. 6.3), a systematic methodology for generating biomimetic concepts by identifying successful biological adaptations in a successful database. The process of developing a biomimetic design solution involves several important steps. First, the specific challenges at stake must be identified. To do this, organisms and natural systems must be studied to find those that fulfil the required functions, known as "pinnacles" These selected pinnacles are then carefully studied to understand their strategies and principles.

In the next phase, these strategies are analysed, categorised and abstracted. By selecting appropriate strategies and striving for convergence, an initial design concept is developed. This concept is then evaluated and validated. If necessary, the process can be restarted to explore further starting points for further improvements. This problem-oriented approach enables tailor-made solutions for specific problems.

The preliminary design phase consists of three sub-phases, each supported by design tools. These phases include a general investigation of biophysics (exploration model), pinnacle analysis (pinnacle analysis) and abstraction (pinnacle analysis matrix and design path matrix). The transformation of natural strategies into technical solutions for biomimetic designs is complex and interdisciplinary, especially when strategies from different pinnacles are combined.

Therefore, a comprehensive methodology for the preliminary design phase is proposed, focusing on the exploration of pinnacles to develop design concepts. It is important to note that the emulation phase, which involves following standard codes, is separate and not covered in this methodology as it is more familiar to architects.

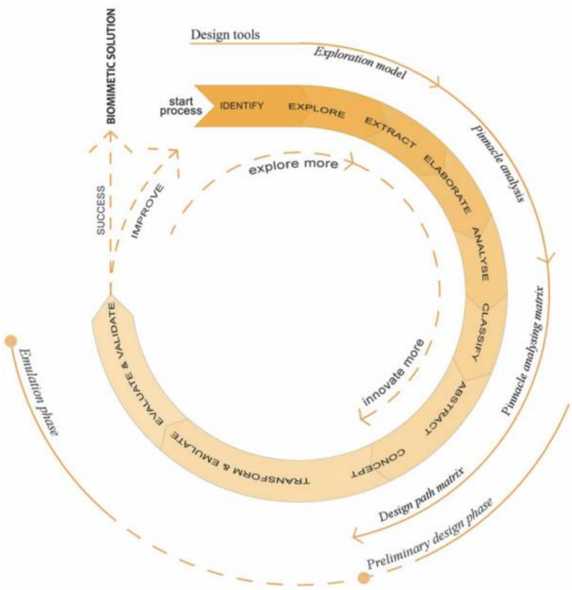

Figure 6.3. BioGEN [7]

2.5 Biomimetic principles for the development of adaptive architectural envelopes

In 2017, Lopez et al. [8] introduced a bottom-up approach named *Biomimetic principles for the development of adaptive architectural envelopes*. This approach aims to create adaptive architectural coverings by drawing inspiration from the ways plants respond to diverse environmental challenges. The authors categorized gathered biological data based on climate factors (e.g., light, humidity, temperature, air quality), movement strategies, and biological principles. Plant movements were classified into two categories: static and dynamic. Dynamic movements involve plants that swiftly react to environmental factors like light, temperature, or water levels. In contrast, static mechanisms focus on surface attributes of plant leaves, like solar reflectance or superhydrophobic properties, which function as adaptive mechanisms. The transition from biological insights to technological application involves four stages: analysis, synthesis, evaluation, and implementation. The methodology for incorporating biological solutions into adaptive architectural designs is divided into two phases. The first phase involves understanding and identifying static strategies and dynamic mechanisms across various contexts. This phase addresses three core questions: the specific plant adaptation under examination, the reasons behind that adaptation, and the evolutionary development of that particular function. The second phase concentrates on translating architectural ideas into inventive building solutions. This step encompasses three key concepts: applying ideas (e.g., employing static or dynamic strategies for building adaptability), fostering innovation (utilizing plant adaptation methods to enhance innovation, like reducing reliance on building cooling systems), and generating design concepts.

2.6 Multi-Biomechanism approach

Kuru et al. [9] proposed a top-down approach called the multi-biomechanism approach (Fig. 6.4), which focuses on engineering problems to be solved by learning from nature and consists of four phases: 1) identification of a technical problem, 2) selection of a biological solution, 3) achievement of multifunctionality, 4) development of a biomimetic strategy. The first phase is about clarifying technical issues. These include the choice of site and climate to determine outdoor conditions, the selection of a standard building scenario to determine indoor conditions, and the derivation of functional requirements from a building analysis. The main objective of this phase is to determine the technical challenges that biomimetic designs should address - a common aspect in the early phases of similar top-down methods.

The following step involves the exploration of biological tools. This involves relating the functional requirements to biological solutions in order to explore the corresponding biological mechanisms. The goal is to discover organisms that can solve the identified technical problems.

The third phase is about achieving multifunctionality by using the natural design principles of hierarchy and heterogeneity. Hierarchy and heterogeneity are exploited by examining the functions of selected organisms that span different scales and manifest themselves in different morphologies. To facilitate this, the database provides information on the hierarchical and heterogeneous mechanisms of numerous organisms.

The fourth phase involves the formulation of biomimetic strategies. In this step, functions are brought together at different scales and geometries, design configurations are created and mechanisms for adaptability are developed. This final phase culminates in the creation of a biomimetic design product.

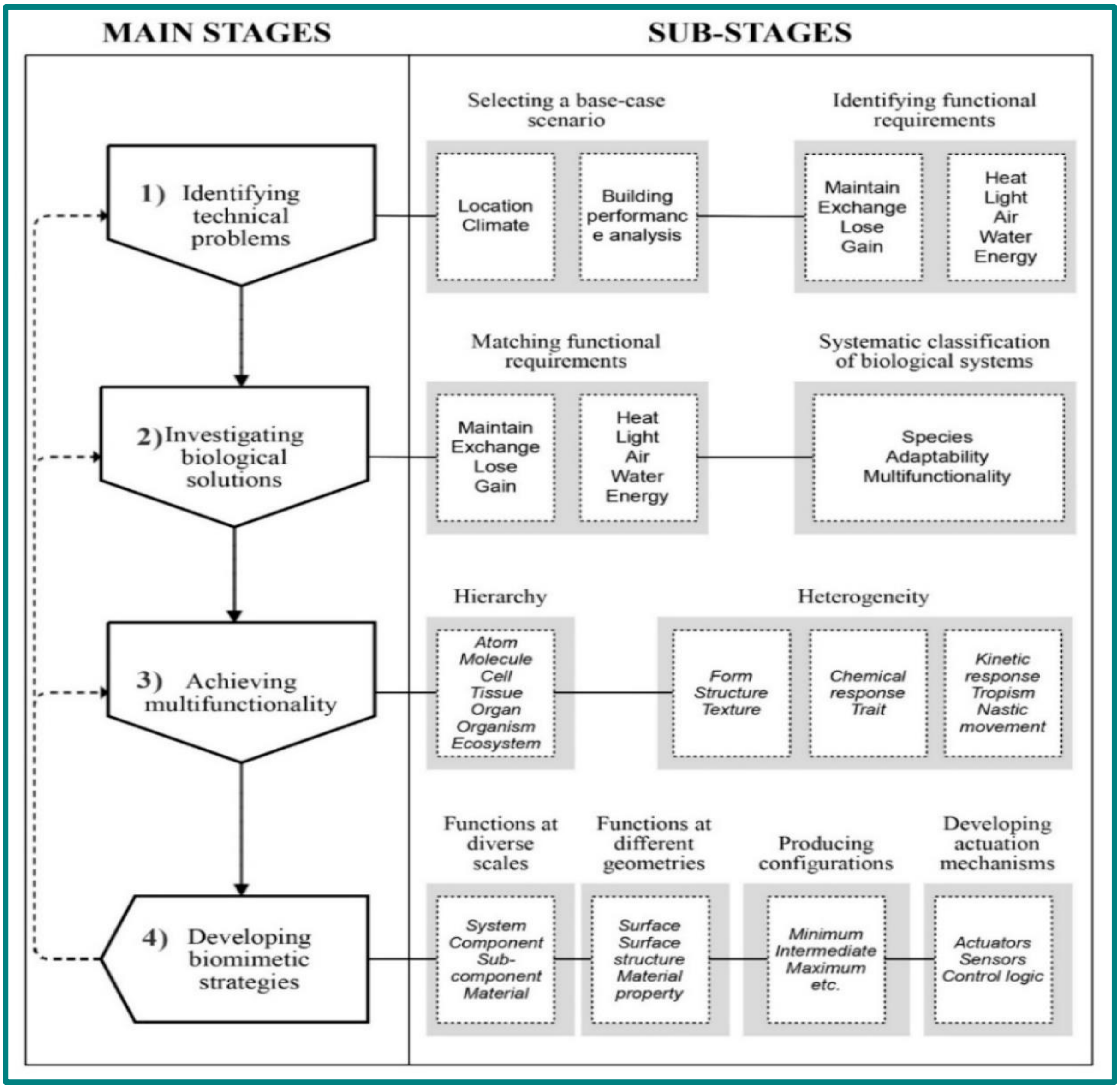

Figure 6.4. General framework of Multi-Biomechanism approach [9]

3. Synthesis and discussion

Table 6.3 provides a summary of the methods previously analysed, highlighting the type of approach, phases, strengths and weaknesses and focus of each method.

Table 6.3. Comparative analysis of existing approaches

Biomimicry Design Spiral	
Approach	Top-down approach structured in an outward spiraling process
Phases	Five or Six phases (depending on the version) - Define, Biologise, Discover, Abstract, Emulate, Evaluate
Focus	Emphasizes understanding biological strategies and mechanisms and applying them in design
Strengths	Provides a systematic approach from problem definition to evaluation. Encourages deep understanding of biological solutions
Challenges	Requires expertise in both biology and design. Evaluation phase may require substantial criteria
Design Lens (Biomimicry 3.8)	
Approach	Combines theoretical and practical concepts through diagrams and principles
Phases	Life's principles
Focus	May need additional guidance on practical implementation
Strengths	Offers a dual framework - from biology to design, and from problem to biology
Challenges	Needs additional guidance on practical implementation
BioTRIZ	
Approach	Integrates Russian TRIZ method with biological insights
Phases	Five phases - Problem Definition, Analysis, Comparison, Link Establishment, New Technology Creation
Focus	Draws analogies between biology and engineering to create new technologies
Strengths	Systematic approach for technology development. Utilizes established TRIZ method
Challenges	Database availability may be an issue. Complex implementation
BioGEN	
Approach	Problem-oriented approach to generating biomimetic concepts
Phases	Identification, Pinnacle Study, Strategy Analysis, Concept Development, Evaluation
Focus	Adopts a tailored approach for specific challenges, utilizing successful biological adaptations
Strengths	Systematic approach for technology development. Utilizes established TRIZ method

Challenges	Requires understanding of biological principles. Integration of different pinnacles can be complex
Biomimetic Principles for Adaptive Architectural Envelopes	
Approach	Bottom-up approach inspired by plant responses to environmental challenges
Phases	Four stages - Analysis, Synthesis, Evaluation, Implementation
Focus	Focuses on imitating plant movements and attributes for adaptive architectural designs
Strengths	Relatable and practical approach for architects. Specific focus on climate factors and movement
Challenges	Requires understanding of biological principles. Integration of different pinnacles can be complex
Multi-Biomechanism Approach	
Approach	Top-down approach focused on engineering problems and multifunctionality
Phases	Four phases - Problem Identification, Biological Solution Selection, Multifunctionality Achievement, Biomimetic Strategy Development
Focus	Targets technical issues, hierarchical and heterogeneous mechanisms, and adaptability
Strengths	Systematically addresses technical challenges using biological strategies
Challenges	Requires understanding of both engineering and biology. Multifunctionality synthesis can be complex

The various biomimetic methods exhibit notable distinctions and gaps in several key aspects:

Approach:

The approaches adopted by these methods exhibit a wide spectrum, ranging from top-down methodologies that begin with problem identification and move towards solution development, to bottom-up approaches that start with specific biological mechanisms and derive solutions from them.

Phases and Steps:

Each biomimetic method follows a distinct sequence of phases and steps to navigate the process of problem-solving and deriving solutions. These procedural differences reflect the diversity in how these methods translate nature's lessons into practical applications.

Emphasis:

A significant divergence lies in the emphasis of these methods. Some methods concentrate on faithfully replicating specific biological mechanisms, seeking to imitate nature's solutions directly. Conversely, others prioritize the extraction of general problem-solving strategies from nature, which can then be applied more broadly across various domains.

Resource Dependence:

Certain methods, like *BioTRIZ* and *Biomimicry Design Spiral*, might heavily rely on particular databases or resources for acquiring biological inspiration. This resource-centric aspect contributes to differences in the availability and selection of biological examples across methods.

Coverage:

The scope of these methods varies notably. While methods like *BioGEN* offer comprehensive phases for specific facets of biomimetic, others like *Multi-Biomechanism* encompass a holistic problem-solving process that integrates multiple aspects and principles.

Tools and Frameworks:

Tools and frameworks introduced by different methods play a crucial role in aiding comprehension and practical application. For instance, *Design Lens diagrams* and *Life's principles*, as introduced by *Design Lens* and *Biomimicry 3.8 respectively*, enhance the understanding of how to apply biomimicry concepts effectively.

Architectural Application:

Some methods have a distinct focus on applying biomimetic principles to architectural and engineering contexts. Notably, *Biomimetic principles for architectural envelopes* and the *Multi-Biomechanism* approach specifically address challenges and solutions within the realm of architecture, highlighting the diverse applications within this field.

In summary, these six methods vary in their approaches, focus, and complexity. The choice of method depends on the specific design challenge, the level of expertise available, and the desired outcome. Some methods provide comprehensive step-by-step processes, while others offer conceptual frameworks for understanding and applying biomimetic. Designers can select the most suitable method based on their project requirements and familiarity with biological concepts.

In terms of gaps, while each method has its strengths, there might be limitations in addressing certain types of design challenges or in providing a holistic approach that accounts for both technical and biological aspects. Additionally, some methods might be more reliant on available databases or resources, which could limit their applicability in certain situations. Moreover, the effectiveness of these methods might depend on the user's familiarity with biomimetic principles and the specific domain of application.

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Chapter 5

Adaptation in nature

5.

1. Adaptation in nature

Nature is subject to strong environmental changes, which are determined by the fluctuations of seasonal and daily cycles, as well as by various other factors such as physical geography and climate (latitude, orography, altitude, substrate, etc.). In addition, climate change, due to natural factors (solar radiation and volcanic eruptions) and anthropogenic factors (polluting gases, improper waste disposal, etc.), alters the normal climate trend and has drastic consequences for the environment, the inhabitants and the entire planet. These include: high temperatures, melting of glaciers and thus rising sea levels and coastal erosion; drought and water scarcity with damage to the production of vital daily goods; extreme meteorological events associated with hydrogeological risks, such as increasingly frequent floods. Consequently, natural organisms, plants and/or animals, must adapt to changes in their habitats through complex functional strategies in order to survive. Biological adaptation strategies are indeed particularly complex, multifunctional and reactive, but this allows nature to offer a large database of strategies and mechanisms that can be translated into biomimetic design [1]. It is therefore important to start by analysing the adaptation mechanisms of natural organisms.

In the present work, it's preferring to elaborate on the concept of adaptation in plants because, unlike animals, they are not able to move to another place when environmental conditions are unfavourable for their survival, but they still activate adaptive functional strategies. In this respect, plants and buildings coincide in the way they interact with the environment. In plants, control and tolerance of environmental factors are necessary for survival and occur via the integumentary tissue, which acts as a philtre between the internal organs and the external environment. Similarly, in buildings they are necessary for the comfort of the occupants and occur via the building envelope, which also in this case acts as a philtre between the internal and external environment. Animals, on the other hand, trigger a behavioural response that implies visible movement (e.g. migration). Plants, on the other hand, satisfy their needs through physiological and developmental responses that act on various environmental factors by regulating temperature and access to light, controlling solar energy gain and water uptake, or simply protecting themselves from the wind [2].

For example, the presence of stomata on the leaves, in addition to making possible the gaseous exchanges involved in the photosynthesis process, facilitates the gaseous exchange between the plant and the atmosphere, exchanging water vapor to decrease the internal temperatures of the plant itself during the hot [3]. Thus, stomata allow us to understand how plants respond and adapt to the environment. They activate a dynamic mechanism through flap movements in response to certain stimuli and open in response to high temperatures, light, water or humidity.

Living organisms are connected to their habitats and develop a high degree of adaptability, especially through their interface with the external environment. The interface may be a complex of covering tissues of an organ or an organism (hair, skin, epidermis, cuticle, etc.) called a "tegument" which, in addition to detecting variations in environmental conditions, has the function of protecting and attenuating the thermal gradient and detecting environmental changes to regulate body temperature, such as, in homeothermic organisms, humidity, brightness, mechanical resistance [4].

In general, the term adaptation means the ability to adapt to certain conditions and situations [5]. In biology, this term refers to the ability of living things to change their anatomical (make-up of the organism - structural morphology), physiological (metabolic characteristics) and behavioural (movement - way of acting and reacting) characteristics. It is thus a reaction to external stimuli of a biotic nature (e.g. competition, predators, parasites, pathogens) as well as to abiotic environmental factors, of which light, water and temperature are the most important.

It is therefore possible to characterize the mechanism of adaptation in three levels: morphological, physiological and behavioral [6][4][7][8][9][10] (Fig.4.1). Each of these can be classified as static or dynamic. Dynamic if there is movement, static if there is no movement. All adaptive mechanisms regulate environmental factors and develop in response to chemical or physical stimuli. By physical stimuli we mean a change in temperature, light intensity and sensitivity to abiotic stress factors; chemical stimuli refer to an internal physiological characteristic, such as a change in pH value [6].

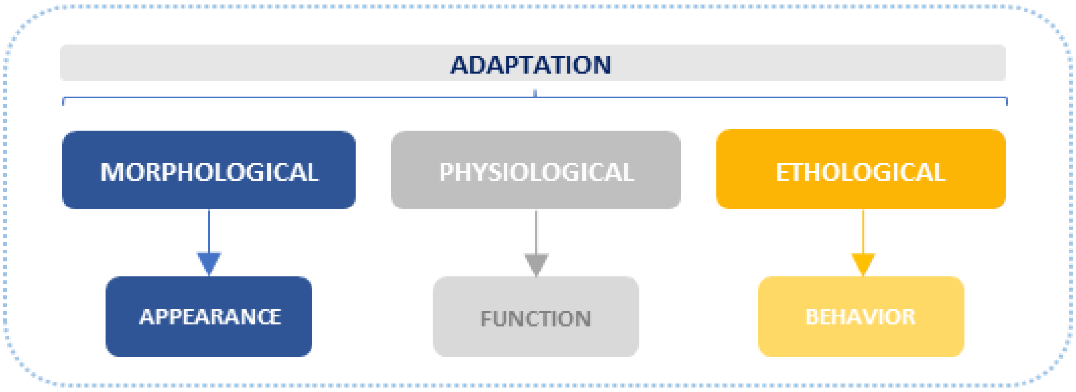

Fig. 4.1: Synthesis of the main adaptive movements of plants

Morphological adaptation: it concerns the morphology and thus the external structures of organisms that allow better adaptation to the environment or greater functionality for survival [8]. The fur of animals, which enables survival in cold climates, is an example of this. In plants, on the other hand, the particular shape of the stem, leaves or roots are adaptation mechanisms [6], [9]. The morphology of plants varies according to the context in which they live. Cacti that can survive in desert areas have leaves transformed into thorns to reduce evaporation and an enlarged stem that serves as a water reservoir (and is also the element that provides photosynthesis). The root system of cacti develops horizontally and superficially to collect the moisture present in the environment [8]. The morphological features therefore always imply an adaptive function and are not limited to the aesthetic aspect.

The importance of systems [38]

Understanding the system into which the biomimetic solution will fit appears fundamental. The universe is organised in systems ranging from natural to anthropic, organisational or technological. Each of these systems is made up of interconnected elements that are coherently organised to perform a specific function or achieve a specific purpose. They can be very large, like the Earth system, and very small, like a cell. Each system can be subdivided into subsystems consisting of lower level elements, but can also be part of a higher level super-system. No organism or element can live or exist independently of its context. This happens not only in nature but also in the anthropic world. Below is an example by Toolboox from the Biomimcry Institute of a building system that consists of many parts that interact with each other to provide performance and functionality, e.g. protection from the outside world through horizontal or vertical opaque elements, transparent elements that provide interior lighting, or the service system such as the plants. A door is a system located in the building whose function is to allow the passage of people and objects from the inside to the outside and vice versa, but also to prevent the crossing of the boundary itself. The door consists of subsystems (frame, bolt), but is at the same time part of a larger system, i.e. a supersystem (wall, building, city). One can also speak of parallel systems, which represent systems or elements on the same scale level as the analysed system (the door); in the case of a door, a neighbouring/parallel system could be a window, for example. Using the example of the door, you can understand how everything is connected. No element or organism can exist in isolation from other organisms/elements. This also applies to humans, who are dependent on the resources of the ecosystem and the associated systems, which in turn depend on the Earth system. It is therefore essential to understand the interrelationships and connections between the different systems before approaching a design challenge, especially when it comes to the field of biomimetics.

"When we try to pick out anything by itself,
we find it hitched to everything else in the Universe."
[John Muir]

Physiological adaptation: refers to changes in the metabolism of organisms. Following certain changes in the environment, some organisms begin to function differently. Physiological adaptations include hibernation or aestivation. In both cases, when the ambient temperature drops below 0 °C or exceeds 40 °C, some organisms reduce their metabolism to such an extent that they remain in a state of latency for a short or long time in order to survive the seasons that are more critical for their own ecosystem. In extremely cold climates, where the temperature gradient between the body and the environment is very high, some organisms manage to maintain an adequate body temperature by controlling heat conduction mechanisms or regulating the metabolic rate. This is due to a special physiological adaptation mechanism called homothermy, which serves to keep the body temperature constant regardless of the environment and the amount of heat generated during metabolic processes [11] [12]. This mechanism enables some organisms, such as birds or mammals, to continue to perform their vital functions even under less than optimal conditions. In birds, feathers play a fundamental role, as their classic behaviour is to ruffle their feathers to reduce heat loss. In some cases, the colour of the fur also changes, becoming lighter to blend in with the snow. This is the case with the hare or the grey wolf, which has a different colouring of the fur depending on the season, more grey in winter, more brown in summer; at the same time, the fur is thicker in the winter months and shorter in spring and summer. Other species tend instead to protect themselves by increasing their body fat, such as the seal or the polar bear. However, these solutions are not effective in all organisms. This is the case with vertebrates or invertebrate organisms that have a low metabolic rate and produce little heat. Instead, they use a physiological adaptation called heterothermy, in which the body temperature varies with that of the external environment; thus, since they are unable [1] to regulate temperature independently, they are forced to resort to alternative solutions to thermoregulate their bodies, such as solar radiation, hibernation and aestivation.

Ethological adaptation: this is the type of adaptation that develops certain behaviours for survival and involves movements. An example is migration, which is useful for animals to escape their environment when weather conditions are not ideal. In reality, even if they remain anchored to the ground, plants are also subject to certain movements that are not random but aim to achieve a certain orientation of the organism in space [13].

2. Biological investigation: plants adaptation strategies

Plants regulate their morphology and physiology in relation to the variability of the boundary conditions. The dynamic interactions between their morphology and the environment

contribute to the adaptability of the plant system. Some environmental factors greatly affect the development and growth of the plant.
Individual plant species react differently about variations in light, temperature and all other climatic factors such as rain, wind, humidity, etc. This justifies the fact that, depending on the climatic conditions of a given location, plant organisms take on different aspects and characteristics.

LIGHT: it is the only source of energy for plant organisms (it comes from the sun and reaches the earth in the form of solar radiation): it contributes to the growth of plants as it influences photosynthesis. Solar radiation is an important environmental factor that varies on different time scales (hours, days, seasons). In some environments the radiation is high (desert), in others very low (deep sea areas). Most plants can activate some physiological functions only in the presence of light.

WATER: is not only the most widespread substance on earth, but also vital for organisms. It enables the most important physiological processes such as the absorption and transport of nutrients, photosynthesis, transpiration, etc.

TEMPERATURE: influences the most important physiological functions of a plant, especially photosynthesis, respiration and transpiration. Temperature is also crucial. In winter, for example, high temperatures prevent plants from carrying out various physiological processes that will go into a stupor until spring.

3. Adaptive movement of plants

Darwin [14] was among the first to observe and describe some plant movement responses to the variation of environmental parameters. The movements of the plants can be divided into tropisms, nastie and nutations. Tropisms involve a modification of the growth pattern of the plant by changing the orientation of the plant in the direction of the stimulus. The nastie do not depend on the direction of the stimulus but are due to the variation of turgor or growth of the cell. Nutations, on the other hand, are oscillatory or rotatory movements of the organs caused by a different type of cell growth on opposite sides of the organs themselves [13]. In particular, the movements of plants are divided into spontaneous, when they are autonomous and activated for reasons internal to the organism, and induced movements, when they are caused by a stimulus. The table 1 shows the abiotic and abiotic factors and the main plant movements induced by environmental stimuli. The movements of plants and their orientations in space imply a behavioral adaptation [13].

Table 4.1. Biotic and abiotic factor and adaptive induct movements of plants

Environmental factors			Adaptive induced movements		
Level	**Biotic**	**Abiotic**	**Level**	**Sub-level**	**Stimulus**
Physical	Solar energy	Plants	Tropism	Phototropism	Light
	Temperature	Animals		Gravitropism	Gravity
	Atmospheric pressur	Micro-organisms		Hydrotropism	Water
	Rain			Tigmotropism	Contact
Chemists	Water		Nastia	Termonasty	Temperature
	Oxygen			Seismonasty	Shaking
	Minerals			Hydronasty	Water
	Water salinity			Tigmonasty	Contact

The movement of the plants is induced by the microscopic swelling of the cells. In fact, although apparently motionless, plants can move at different levels. From the roots moving into soil searching for nutrients and assuring plant stability, to the leaves and flowers that follow light direction and respond to tactile stimuli (tigmotropism), to the stomatic cells opening and closing to regulate the evapotranspiration [15]. Plant responds with movement to several stimuli such as light, humidity, temperature, and to the presence of biochemicals as in the case of allelopathy (i.e., the phenomenon by which a plant produces chemical compounds that influence the growth or the survival of other species) [16].

Plants can react to the variations in their surround by means of receptors. The existence of these receptors in some cases has only been hypothesized, as the thermoreceptor [17], [18], while others has been found and described as the photoreceptors, which allow the plant to perceive variations in the quality of light, the so-called phytochromes. Phytochromes are proteins that modify their shape by reacting at different wavelengths and thus determining the biological response to external stimuli [16].

The movements can be categorized on the base of their behaviour, some indeed are very slow and can be observed only through time-lapse observations (e.g., *Helianthus annuus* L. (Fig. 4.2.1) rotation following the sun position), others are more sudden, as in the case of the *Mimosa pudica* L. leaves (Fig. 4.2.2), whose movements can help discourage predators or reduce water loss due to evaporation; other examples of sudden movements are the modified leaves typical of the so-called carnivorous plants, that can close very fast to capture animal prey (e.g., *Dionaea* *muscipula* Soland. Ex Ellis, 2000) [19]–[21]. The movements described above are "induced" by external stimuli. To this category belong tropisms and nastic movements, depending on whether they follow directional or nondirectional environmental signals. Plant movements, such as the opening and closure of the stomata guard cells and the growth of a plant organ, are defined "spontaneous". Both "induced", and "spontaneous" movements can be reversible, when repeated one or several time (e.g., as the case of the stomata opening / closure mechanism), or irreversible, when they occur only once (e.g., as the growth of a leaf). A movement is passive when no expend of energy occurs, as hygroscopic movements, or active, as the turgor-based motions. The turgor pressure is known to be the strongest and the main mechanism responsible for plant movements; imagine for instance the capacity of some plants to drill the ground, or even the asphalt, to expose their organs to the light. The physical reason of this pressure is explained by the equilibrium of the water exchange between plant cells, and the external environment ruled by difference in water potential, turgor pressure, and cell-wall traits [22], [23].

Fig. 4.2. 1) *Helianthus annuus; 2) Mimosa pudica; 3) Vitis vinifera; 4) Mirabilis jalapa*

Plant movements may depend on various factors and have different roles; sometimes they serve for feeding, while other movements are used by plants to climb over different substrate as in the case of the tendrils of *Vitis vinifera* (L.) (Fig. 4.2.3). Specifically, tendrils are peculiar organs capable of three types of movement: circumnutation, contact coiling and free coiling, useful to get in contact and improve the support of the plant [24]. In other cases, the movements are determined by the presence/ absence or the direction of light, as in the case of phototropism; some Leguminosae species, indeed, can open their leaflets during daytime and close at night to optimize light interception and avoid excessive loss of humidity. The opening and closing of certain organs, following the circadian rhythm, are movements controlled by endogenous rhythms of the plant which respond to the need to synchronize with the external environment. Synchronization with daily rhythms has important implications for plant survival and adaptive strategies, but also for reproductive success. Some flowers, indeed, regulate their opening during the night because they take advantage of nocturnal pollinators, this is the case of *Mirabilis jalapa* L. (Fig. 4.2.4a-b) , whose pollinating insect is a nocturnal moth

[25]. Another example of synchronization with circadian rhythms comes from the nyctinastic movements of compound leaves. Most of these movements are dependent on the variations in the turgor of the thickening, called pulvinus, which is found at the base of the leflets at their anchor point to the rachis [26], [27].

Photoprotection mechanisms to reduce the amount of solar radiation collected by leaves under cold conditions is a known strategy adopted by some evergreen plants. Some of these mechanism, such as the decreasing of chlorophyll concentration [28], do not involve movements, but others do, as the case of cold induced movements. The cold induced movements are called thermonasty and act to reduce the amount of a leaf area exposed to light radiation or reduce the freezing. One example comes from the genus Rhododendron exhibiting leaf curling and rolling in response to change in temperature conditions [29]. Within this genus the species exhibiting thermonastic leaf movements show higher tolerance of cold conditions. The leaves of Rhododendron thermonastic species are susceptible to desiccation under frozen conditions, consequently, their rolling help reduce transpiration acting on the removal of the boundary layer above the leaf surface and generating a humid micro-environment around the stomata [30]. A similar leaf rolling mechanism characterizes some Poaceae, such as maize, in case of drought. In such condition, the leaves of this species roll up on themselves to reduce the evapotranspiration surface. This mechanism is mediated by the so-called bulliform cells, which plasmolyzing and determine the rolling movement [31], [32].

In other cases, as for the tulip and crocus, it has been hypothesised that the closing of flowers after temperature drop is related to the protection of the reproductive organs from being damaged by freezing or in general by unfavourable weather condition [33].

Not only the photoprotection mechanisms determine movements, in fact plants can modify the length of the petiole or the orientation of the leaves to optimize light exposure, a mechanism called "shade avoidance". The photoreceptors present in plants, the phytochromes, stimulate the mobilization of phytohormones which induce these movements [34]. The Fig. 4.3 shows a synthesis of the main adaptive movements of plants.

The relationship between plantand environment thus depends on the context and on the climate as well as on various abiotic and biotic factors. On the other hand, this relationship influences the type of morphological, physiological and behavioural adaptation. The following diagram (Fig. 4.4) presents a characterisation of the three types of adaptation. For each of them, levels and sublevels are indicated, to which the type of response is assigned. In addition, the external environmental factors (sun, water, wind, temperature and humidity) are associated with each challenge and thus represent the external stimulus that produces that specific response in terms of adaptation.

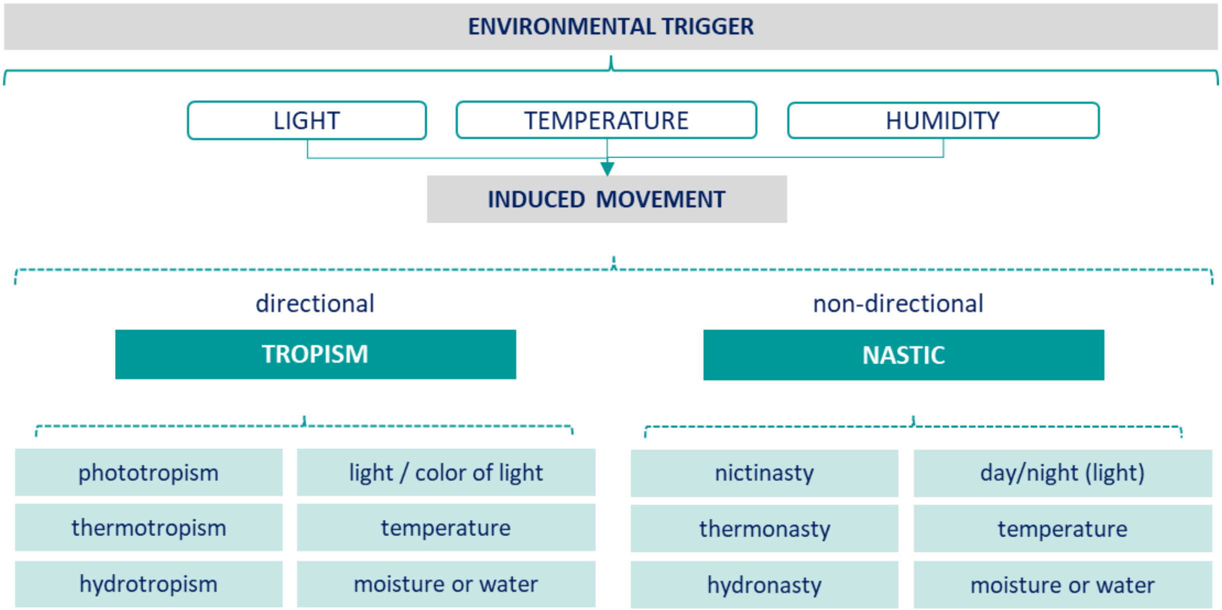

Fig. 4.3. Synthesis of the main adaptive movements of plants

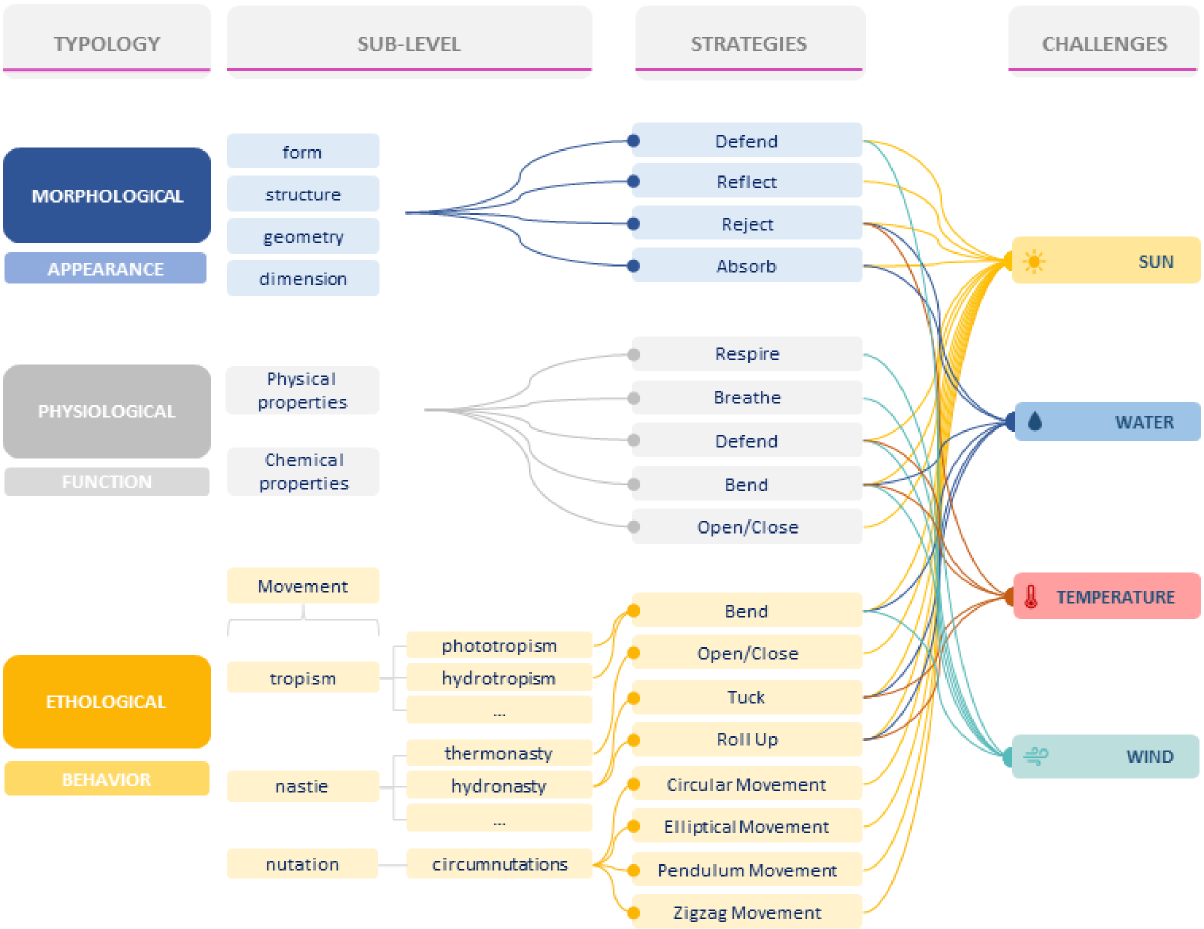

Fig. 4.4. Synthesis of the main adaptive movements of plants

4. Analysis of mediterranean and desertic climatic context plants

To further explore the adaptive mechanisms of plants, this section examines the characteristics of plants in Mediterranean and desert contexts and defines the response functions and adaptive strategies to environmental stimuli.

4.1 Mediterranean climatic context

A type of vegetation typical of the Mediterranean regions are the plants of the so-called *Macchia Mediterrarea*, whose species have had to adapt to environmental conditions characterized by mild and humid winters and hot and arid summers (Fig. 4.5). Mediterranean plants are shrubby or bushy species. Especially due to the summer dryness, Mediterranean plants have activated adaptation mechanisms aimed at reducing the loss of water through transpiration; many species have small, leathery leaves with thick, shiny cuticles, often with hair or waxy substances on the surface. The thick cuticles define robust and resistant leaves against excessive loss of water due to transpiration. Figure 2 shows some of the plants of the Mediterranean climate, classified according to the functional strategy in response to the environmental stimulus with static mechanisms. For example, *Salvia officinalis*, has leaves with a silvery coating to protect the epidermis from excessive insolation and autonomously reflect the sun's rays; or *Rosmarinus officinalis* and *Myrtus communis*, have small leaves to reduce the surface exposed to evapotranspiration.

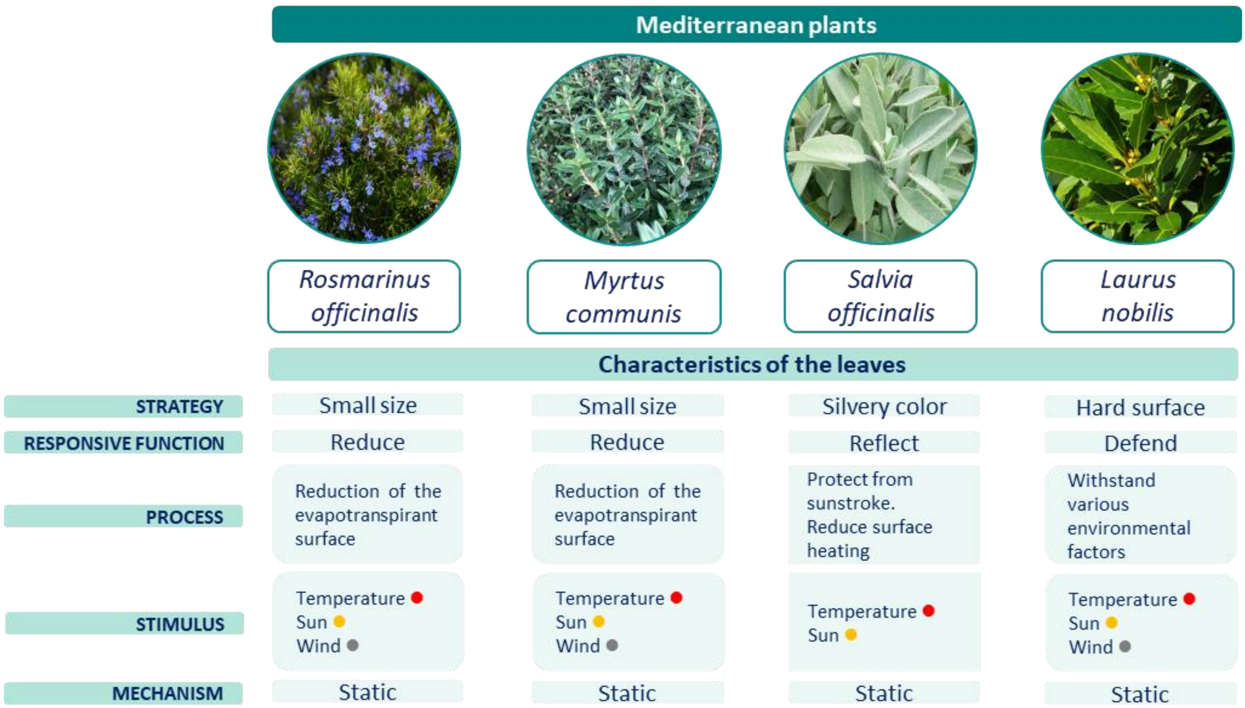

Fig. 4.5. Synthesis of the main adaptive movements of plants

4.2 Desert climatic context

Arid and semi-arid areas make up about 30% of the earth's surface and are characterized by the scarcity of water [35][36]. Due to global warming, in semi-arid and arid regions the tendency to dry out is increasingly accentuated [37]. In these climatic zones, rainfall is very rare, temperatures are high, and temperature variations are very accentuated.

The typical plants of arid and sunny areas must limit the surface exposed to the sun to avoid excessive transpiration which would lead to water loss; in fact, they tend to reduce the surface of the leaves, as well as the organ through which much of the body's liquid content evaporates. The leaves of these typical plants of arid, xerophilic contexts, are small and hard because they are protected by a thick superficial cuticle and often turn into thorns. In many cases, the stem of xerophytes swells and turns into a water reservoir that allows the plant to withstand long periods of drought.

The protective hairs, generally dead and filled with air, shiny and whitish, can guarantee total reflection of light, protecting from solar radiation and defending the plant from excessive transpiration. The intertwining of hairs, characteristic of plants in arid environments, causes stagnation of air, which, in contact with the epidermis, becomes full of moisture. Figure 4.6 shows some of the plant species typical of arid climates and their adaptation strategies.

	Characteristics of the leaves			Characteristics of the stem
	Oreocereus celsianus	*Agave americana*	*Crassula ovata*	*Echinocactus grusonii*
STRATEGY	Hairy lining	Silvery color	Waxy coating	Hard surface
RESPONSIVE FUNCTION	Absorb Store Reflect	Reflect Shield Regulate	Regulate Reflect	Store Shield
PROCESS	Retain water or moisture Protect from cold and sunlight Reflect solar radiation	Reduce surface heating by reflection	Barrier to water loss	Store water Self shading
STIMULUS	Temperature Sun Wind Water	Temperature Sun	Temperature Sun	Temperature Sun Water
MECHANISM	Static	Static	Static	Dynamic Static

Fig. 4.6. Synthesis of the main adaptive movements of plants

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Chapter 6

Smart responsive materials

6.

1. Smart materials

Smart materials are able to respond to external stimuli by changing some internal properties without requiring additional energy. In contrast to conventional materials, which exhibit inert behaviour, smart materials represent a class of materials that can sense and respond to stimuli emanating from the environment by adapting to changing environmental conditions [1]–[3]. Their mutability includes the ability to perceive, act and respond to stimuli, which is normally reserved for sensors and actuators.

Smart materials have different performance characteristics depending on the presence or absence of an external stimulus and can combine the dual function of a sensor and an actuator: the first senses the change in the external stimulus and sends it to the second, which changes the properties of the material [4] [5]. In this way, sensors and actuators are already integrated into the matrix of the material itself [6], without the need to consume additional energy [7]. Sobczyk et al. [8], in classifying smart materials, emphasise their dual use as actuators or sensors. In the sensory configuration, a smart material changes its non-mechanical properties, e.g. physical or chemical properties, in response to a mechanical stress, while in an activating configuration, a smart material deforms in response to a non-mechanical stimulus, such as a change in temperature or exposure to light [8].

In recent years, various smart materials such as shape memory materials (SMMs), piezoelectric materials, thermobimetals, thermochromics and others, have been developed [5], [9], [10]. Shape memory materials (SMMs), when exposed to certain stimuli (such as thermal, magnetic, electrical energy, light intensity, stress, etc.), can recover their original shape after near plastic deformation and distortion. The change in material properties may be perceptible to the naked eye by a change in geometric shape, or it may be imperceptible visually. In 2022, Behera [11] proposed a classification of SMMs into: Shape Memory Alloys (SMA), Shape Memory Polymers (SMP), Shape Memory Ceramics (SMC) and Shape Memory Hybrids (SMH).

Some smart materials are activated by an electrical stimulus, such as electrochromic or piezoelectric materials, but this involves additional energy consumption, with consequence on urban microclimate, in term of pollutions and gas GHG. Therefore, in this study, only responsive materials triggered by environmental parameters, such as light, temperature and/or water are investigated.

Several studies, on the application of smart materials in the fields of architecture and engineering, have been presented in the literature. Aresta [12], in 2017, presented a catalogue of materials for innovative façade components in proposing self-reactive strategies that allow facades to be autonomous and self-sufficient. Juaristi et al. [13], in 2018, presented different application configurations of smart and multifunctional materials for adaptive opaque facades. The same authors also presented a comparative analysis [14] of promising materials and technologies for the design of climate-adaptive facades, showing that the combination of adaptive technologies and smart materials can optimize the façade performance. Zarzycki and Decker [15], in 2019, present a review about the use of active materials as materials that change shape and phase. Villegas et al. [16], in 2020, provided an overview of passive and adaptive building envelope systems with active materials and defined the benefits of their application. In 2021, Sobczyk et al. [8] presented the application potential of smart materials, used as sensors and actuators, for the fields of architecture, and concluded that some of them need further research in order to be used in these field.

These studies, presented in the form of reviews of the scientific literature, refer to the potential applications of smart materials in architecture, but do not emphasise their advantage for biomimetic design. Tabadkani et al. [17], in classifying adaptive façade typologies, finds that biomimetic systems are applicable by using the intrinsic specifications of the materials as actuators to control adaptation. Contrary, Mansori et al. [18], in 2022, introduced the Material Driven Adaptive Design (MDAD) model, which moves away from systems adaptive to mechanical control and focuses on control systems based on the intrinsic responsive function of materials. In this way, it emulates the "cognitive decision-making" from the biological field and proposes a self-reactive and autonomous design through smart materials [18]. Fiorito et al. [4] provide an overview of innovative building envelopes with the integration of smart materials, paying particular attention to biomimetic principles for the movements of shape-changing solar shading devices. Al-obaidi et al [19] gave an overview of biomimetic facades and classified the adaptive materials according to their reaction to temperature, light, humidity and carbon dioxide. Lopez et al [20], [21] also propose a methodology for biomimetic design and point out some smart materials that could be used for architectural facades. Sommese et al. [22], in proposing the bio-Adaptive Model (bio-AM), based on plants adaptation strategies, have highlighted the importance of smart materials in transferring nature's responsive functions to architectural technologies. Ahamed et al. [23] proposed a classification of biomimetic materials based on their reactivity to light, temperature and humidity. Sommese and Ausiello [24] have also presented different biomimetic application examples using smart materials and classified them according to the environmental trigger (light, water, temperature, CO_2). Chayaamor-Heil et al. [25] presented an overview of nature-based materials used in architecture and construction, including biomimetic self-cleaning and self-repairing materials and bioinspired smart materials. The following subsections report on the latest applications of smart materials in the field of architecture and construction. Only materials that react to changes in temperature, light and water have been considered.

2. Temperature responsive materials

2.1 Thermobimetals

Thermobimetals consist of two laminated metal layers with different coefficients of thermal expansion, so that they bend when the temperature is increased [21], [26]. When heated, one layer expands more than the other and a bending of the material itself occurs. The greater the difference in thermal expansion, the greater the resulting displacement. A thermobimetal is defined by the American Society for Testing Materials as "*a composite material, usually in the form of sheet or strip, comprising two or more materials of any appropriate nature, metallic or otherwise, which, by virtue of the differing expansivities of the components, tends to alter its curvature when its temperature is changed*" [27].

The applications of thermobimetals in architecture are quite new and still very limited. An interesting application is the installation "Bloom" proposed by Doris Sung in 2012. As mentioned in the introduction, the reactive installation consists of about 14000 thermobimetallic plates that bend when exposed to sunlight and an ambient temperature above 21°C, thus creating a self -shading effect. In summary, the thermobimetal panels of the pavilion are closed when the temperature is low and open when the temperature is high [24], [28].

2.2 Shape Memory Alloys

Shape Memory Alloys combine shape memory properties with superelasticity; the former allows the alloys to return to their original state when heated, while superelasticity allows for high deformation [29]. The transition from the austensitic parent phase at high temperatures to the martensitic phase at low temperatures involves two main features: the shape memory effect and the superelasticity effect [11]. When the alloy is in the martensitic phase, i.e. when it is exposed to low temperatures, it tends to deform. On the other hand, when exposed to high temperatures, the alloy returns to its original shape [11], [24]. The shape memory effect can be unidirectional (one-way) or bidirectional (two-way). In the case of one-way SMA, the deformation caused by heating at the end of the first transformation cycle is permanent, i.e. not recoverable or plastic; a two-way SMA, on the other hand, has the ability to store and recover the shape of the hot phase (austenite) and cold phase (martensite) after heating and cooling, respectively [30]. Consequently, two-way SMAs can function as on/off actuators [30]. Among the applications based on Shape Memory Alloys in the architectural field, the nickel-titanium alloy (NiTi) emerges, often used as an actuator. These systems use springs or pre-compressed wires that return to their original shape after a temperature rise [16]. NiTi-based alloys have been shown to have a better shape memory effect, improve pseudoelastic effects, and have good machinability and corrosion resistance [31]. An interesting example of this application is the device called Airflow(er) for regulating the airflow and temperature [32], which was inspired by the kinetic movement of petals of a crocus flower due to the temperature difference caused by the day-night cycle. This device, in a square module, is characterized by four triangular openings connected by a shape memory alloy wire. The imitation of the kinetic reaction is ensured by the use of a wire made of a nickel-titanium-based shape memory alloy. At low temperatures, the wire deforms and opens that the four doors connected to it to allow air flow; at higher temperatures, the filament returns to its original position [24], [32]. Kuru et al. [33] transferred the mechanisms of Echinocactus grusoni to develop a photochromic folding rib morphology, with an expansion and contraction mechanism triggered by temperature differences, which activates the intelligent shape memory alloy (SMA). The totality of these morphologies, inscribed in a hexagonal shape, results in a three-dimensional photochromic glazing that regulates light and gains triggered by the sun. Fang et al. [34] presented a study on a shape memory alloy-based cladding to promote adaptive ventilation in buildings, which works according to an opening and closing mechanism; the wires of SMA are relaxed and form a closed surface when the temperature is lower than the transformation temperature, preventing the circulation of airflow in the building. If, on the other hand the ambient temperature exceeds the transformation temperature, the wires contract, the facade panel bends, and openings are created that allow the circulation of the airflow in the building.

It is evident that shape memory alloys in most cases combine the dual function of actuators and sensors. Formentini and Lenci [35] also proposed an aluminium panel for ventilated facades that responds to thermal variations using shape memory alloys; thanks to the action of Nitinol (Ni-Ti) the panel opens to allow natural ventilation in the gap between the cladding and the internal wall, while in winter it closes to allow thermal insulation of the building thanks to the resting air in the cavity.

Air Flow(er) (Fig. 5.1) is a ventilation device designed to regulate air flow and internal temperature, without the use of electricity or mechanical equipment [32]. It represents an interesting example of low-tech solutions. The design principle of the Air Flower was based on the imitation of the thermonastic movement of plant organisms, in particular the yellow Crocus Chrysanthus, that reacts in response to the increase and decrease in temperature that occurs in day-night passages [36]. Crocus flowers petals open when the temperature increases and closes when it decreases [37]. In the case of Air Flow(er), the kinetic reaction of the plant organism, due to the thermonastic movement, is guaranteed using the shape memory alloy wire. When the alloy is subjected to low temperatures (martensite) it deforms more easily and then the four doors can open to ensure the passage of air. When the alloy is subject to higher temperatures, however, it regains its original shape and then the doors close blocking the air flow.

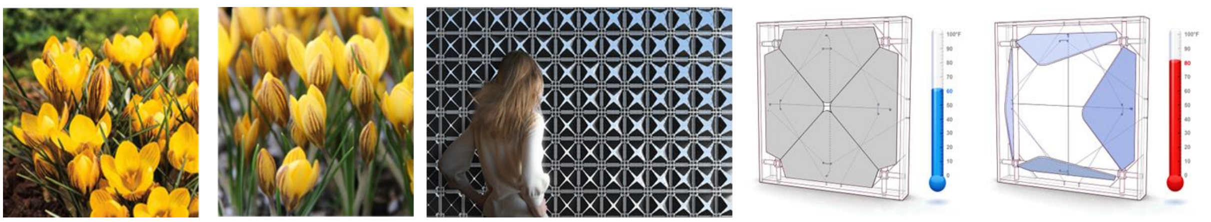

Fig. 5.1. Crocus Chrysanthus and Air Flow(er) prototype [32]

A recent study on shape-memory materials led to the definition of the prototype Pho' Liage (Fig. 5.2) by ArtBuild studio. It is a prototype of a kinetic device for shielding against natural light, which does not require human or mechanical action to activate. This system guarantees solar shielding through thermo-reactive materials and the storage of thermal energy through photosensitive materials [38]. This solution is inspired by the opening and closing mechanism of the flowers, in response to variations in the intensity of solar radiation. In particular, the reference is to the troponastic (or thermonastic) mechanism, understood as the behavioral adaptation of some plant organisms, which has allowed to define of a solution capable of reacting autonomously by exploiting the chemical-physical and environmental interaction [39]. Also this example, not consuming energy for activation, can be classified as a low-tech solution.

Fig. 5.2. Pho' Liage [38]

2.3 Thermochromics

Thermochromic materials reversibly change their colour or optical properties when exposed to temperature changes [40]. Devices with thermochromic materials adjust the transmittance according to their own temperature. When the temperature is below the critical transition temperature, the material behaves like a semiconductor and reflects less light, while when the temperature is above the critical transition temperature, it behaves like a semimetal and increases reflection [41]. In recent years, the scientific community has paid particular attention to thermochromic windows, which are able to change their state from transparent to coloured in response to temperature changes [42], [43].

Garshasbi and Santamouris [44] have provided an overview of thermochromic materials and highlighted the advantages of their application in combating urban overheating compared to conventional heat-reflecting materials. Among the state of the art thermochromic materials, Vanadium Dioxide VO_2 shows great potential as it is able to modulate the transmission of light. VO_2 allows the transition from a transparent state (low temperatures) to an opaque state (high temperatures) thanks to the thermally induced phase transition [45]. Recently, Li et al. [46] proposed an in-situ technique to fabricate a film with highly dispersed VO_2 nanoparticles (HD-VN), demonstrating the excellent light transmittance value of the film and the solar energy modulation efficiency. Sirvent et al. [47] proposed a smart materials study to investigate the feasibility of adding VO_2-based thermochromic powder with cement-based materials to develop an opaque smart material for building envelope cladding and evaluate its thermochromic performance. This study showed that the stronger modulation of reflectance was achieved with a higher dust concentration on the surface. Ke et al. [48] integrated active plasmonic vanadium dioxide VO_2 nanoparticles (NPs) into elastomers to achieve adaptive solar modulation and demonstrated high solar energy modulation and improved energy savings for buildings.

2.4 Thermo responsive polymers

Another interesting smart material studied in the scientific literature are shape memory polymers (SMPs), reactive materials that can return to their original shape in response to external stimuli [49]. Li et al. [50] proposed a new category of thermoreactive smart windows with deformable surface morphology using thermoreactive shape memory polymers and an optical coating. This butterfly wing-like smart window (BSW) is capable of reversibly transforming from an originally inclined shape to a temporarily flat shape when heated. Walter et al. [51] presented a study on the use of a thermoreactive shape memory polymer (SMP) to regulate airflow through the building envelope and provide natural ventilation, showing how this material allows autonomous adaptation to environmental conditions. Among SMPs, liquid crystal elastomers (LCEs) are ideally suited as actuators that respond to thermal stimuli, thanks to their thermomechanical behaviour [49], [52], [53]. They represent a class of anisotropic materials that combine the elasticity of rubber with liquid crystals, resulting in a change of shape when subjected to a thermal stimulus [54], [55], via a liquid crystal-isotropic phase transition. This transition can be stimulated by heat and light through photothermal or photochemical reactions [56]. Heating and cooling of LCEs leads to elongation of the material, which is often visible in the form of contraction, flexion or oscillation. LCEs are capable of acting as both sensors and actuators, autonomously. Kularatne et al. [54], suggested potential applications for LCEs as optical devices and candidate soft actuators. In a recent study, Schwartz et al. [57] presented LCEs in the context of innovations for the built environment and emphasised the possibility of their integration in the field of kinetic buildings thanks to their autonomy, which eliminates the need for motors, wiring or other external means of activation.

Thermo-bimetals are among the materials that react to the temperature difference. They refer to a double layer conformation of metal with different coefficients of thermal expansion, able to make it fold in response to the increase in temperatures [19]. The use of laser-cut bimetal lining is represented by the Bloom system (Fig. 5.3), a self-supporting paraboloid-shaped shell structure. When the shell is heated to the surface, the structure curls autonomously. In this way the curling of the shape shades and allows the passage of air and therefore allows you to ventilate specific areas. This solution emulates the mechanism of opening and closing stomata of natural organisms. Moreover, this solution is configured as a passive system because it opens and closes its slats according to solar heating, without using artificial energy [58].

Fig. 5.3. Bloom System

3. Light responsive materials

3.1 Photochromics

Photochromic materials change colour reversibly in response to changes in light intensity; they are able to pass from the transparent state to the coloured one [42].The material is activated in the presence of a light stimulus and shows a colour and reduced transparency [59]. The colour disappears when the stimulus is removed as the material returns to its original molecular configuration [60], [61]. Photochromic materials, such as glass, have advantages in terms of energy savings. In fact, in 2022, Cannavale et al. [62] presented a research article on the constructive integration of spirooxazine-based photochromic films into transparent polymethyl methacrylate matrices and showed how photochromic glass significantly reduces energy consumption compared to conventional glass. In addition, Marchini et al. [63] proposed the development of a translucent, photoluminescent smart window coating that protects against glare during the day and avoids the need for artificial lighting in the evening.

3.2 Light responsive polymers

Light responsive polymers change shape when exposed to UV rays and offer directional shape memory movements. Light-stimulated shape memory polymers must be equipped with light-sensitive functional groups or fillers such as cinnamic acid or azobenzenes, which act as molecular switches. The light does not change the temperature, but only the cross-linking density in the material matrix [11].

Back in 2006, Jiang et al. [64] dealt with the light-triggered movements of shape memory polymers and showed how they can temporarily change their shape and only return to their original and permanent form when irradiated with light of a suitable wavelength. Xue et al. [65] designed a smart sub-environmental diurnal radiative heating (SDRC) building cladding that combines sunlight-induced fluorescence, particle scattering and broadband emissivity of materials.

3.3 Photocatalytic materials

Photocatalytic materials are metallic compounds such as titanium dioxide that respond to UV radiation by oxidising the organic material they come into contact with [1].
Ausiello [66] highlights the intelligence of titanium dioxide nanoparticles, which maintain a stable appearance over time but show active behaviour in terms of their performance. The self-cleaning ability is achieved by the photocatalyst-induced change in the roughness of the surface in the nanometre range, which changes from hydrophobic to smooth and thus superhydrophilic. The process is reversible, because with the end of UV irradiation the hydrophobic states gradually become rough again. The behaviour of titanium dioxide is studied by analysing the biological behaviour of the lotus leaf, which, immersed in muddy water, always appears shiny and clean. The mechanism spontaneously triggered by sunlight is due to the presence of advancing nanoparticles that prevent the water droplets from remaining on the leaf surface, but instead allow them to slide off and carry dust or insects with them [67]. The anti-pollution effect, on the other hand, is achieved through the effect of photocatalysis, i.e. a chemical redox reaction that converts pollutants into harmless substances by accelerating the oxidation processes occurring in nature through the TiO_2 [66]. The application areas of TiO_2 range from photocatalytic cements for mortar, concrete or plaster to photocatalytic paints, floor coverings or glass with hydrophilic and self-cleaning surfaces. The Italian pavilion of Expo 2015 (Fig. 5.4) is one of the most recent examples of this solution. The interaction between concrete and titanium dioxide nanoparticles gives the surface the ability to be self-cleaning and antipollution [68].

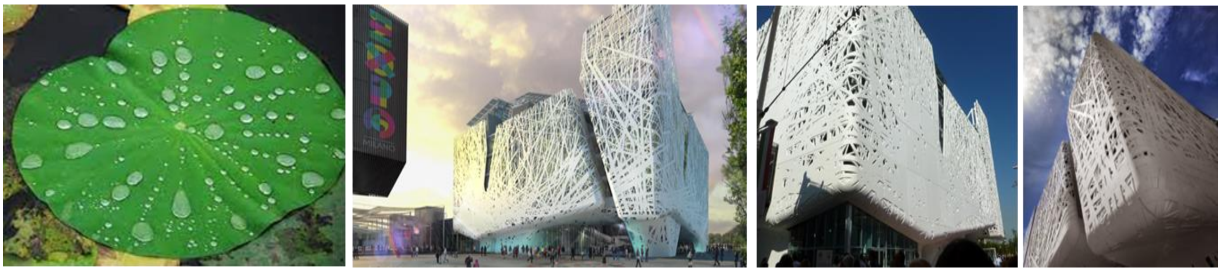

Fig. 5.4. Italian Pavilion Expo 2015

4. Water responsive materials

4.1 Wood

Wood is a natural material that, although not always counted among the intelligent materials, responds to climatic stimuli by using its hygroscopic and anisotropic abilities. This property makes it one of the most studied materials in the literature. Anisotropy is the property according to which the physical properties of the material differ in the different dimensions. Hygroscopicity refers to the ability of the material to absorb and release moisture from the environment while maintaining a particulate equilibrium. During the process of moisture absorption and release, the material physically changes; depending on the water content, the wood produces easily perceptible movements such as curvature or bending. Pinecone scales are a good example of this. During the transition from the wet to the dry state, they activate a passive bending movement caused by the swelling or shrinking of the double-layered tissues that characterise their structure [69] [70]. Plant cell walls are characterised by rigid cellulose fibrils that impede the movement of the swellable matrix; in fact, swelling occurs preferentially in the direction perpendicular to the fibrils [71]. Such organisms behave like natural actuators. Holstov et al. [72], [73] have explored the possibility of adaptive systems using wood-based hygromorphic materials, highlighting the opportunity they offer for the development of architectures that respond passively to the environment. Various experiments and application examples can be found in the literature to define meteorologically sensitive solutions capable of regulating the climatic challenges associated with the presence of water in the environment [74]. The most frequently cited projects are the Meteorosensitive - Hygroskin Pavilion and the Meteorosensitive Morphology - Hygroscope, by Achim Menges. Both projects are inspired by the passive reaction of pinecones to environmental stimuli. When the air is dry, the scales of fir cones fold outwards and release the seeds [72]; when the humidity is high, they close. Based on this behaviour, the two pavilions are examples of biomimetic design, i.e. inspired by nature. Recently, Zhan et al. [74] investigated the transfer of the principles of hygroscopic movements of plants to biomimetic building systems made of wood.

Fig. 5.5. HygroSkin pavilion. Credits: © ICD/ITKE University of Stuttgart

4.2 Hydrogel

Another material that can be named for its reaction to water absorption or evaporation is hydrogel. Hydrogel-based materials represent a group of polymeric materials with a three-dimensional structure that swell when they absorb water, thanks to the hydrophilic properties that give the material the ability to combine with and shop water [75]–[77]. Natural hydrogels have been replaced by synthetic ones because they can absorb more water [75]. Some hydrogels are sensitive to external stimuli such as temperature, light, electric fields, etc. [76]. This material can swell or shrink while acting as an actuator. Zhang et al. [78] propose a smart window model with a three-layer sandwich structure that is both electrically and thermally responsive and is able to transition from a highly transparent state to a milky white state by utilising the capabilities of the H+ and Li+ doped hydrogel HPC-PAA.

5. Summary

Table 5.1 shows the results of the literature review. The different materials described in the previous sections were classified based on the three main environmental triggers (temperatures, light, water) in order to assign to each of them a responsive function useful for biomimetic design and to create adaptive envelope solutions that can respond to the three main environmental triggers. Among the different solutions analysed, the materials that are activated independently of the effect of the temperature trigger predominate. This is especially true for the studies with shape memory alloys. The main responsive functions that smart materials have been able to ensure so far are mainly related to solar control, regulation of air flows and daylight, and thus thermal and visual comfort.

Table 5.1. Summary of the most analysed materials in the scientific literature, grouped according to the three main triggers: light, temperatures, and water. Output: Color Change (CC), Shape Change (SC), Non-Visible Change (NVC). Responsive function: Regulate (Reg), Shield (Sh), Transfer (Tr), Reflect (R), Store (S), Transform (Tm). Abiotic factor: Temperature (T), Air (A), Light (L), Water (W)

Environmental trigger	Materials	Sub-materials	Ref.	Output	Responsive function	Abiotic factor	Advantages of application
Light	Photochromic	Spirooxazine	[61], [62]	CC	Reg/ Sh	L	Limit the glare problem
	Light Responsive Polymer	Azobenzene	[64], [65]	CC/SC	Sh	L	Regulation of solar radiation
	Photocatalitic	Titanium dioxide (TiO_2)	[66]	NVC	Reg/ Tm	A	Self-cleaning Anti-pollution
Temperature	Thermobimetals	---	[28]	SC	Reg/ Sh	L/A	Modulation of solar radiation Regulation of air flows
	Shape Memory Alloys	Nickel Titanium alloy (NiTi)	[33]–[35]	SC	Reg/ Sh	L/A	Movement actuators for façade panels
	Thermochromic	Vanadium dioxide (VO_2) nanoparticles	[48], [50]	CC	Reg/ Sh/R	L	Adaptive solar modulation; Energy saving
	Shape Memory Polymers	Liquid Cristal Elastomer (LCE)	[57]	SC	Reg	A	Autonomous adaptation to environmental conditions
Water	Wood	---	[72], [79]	SC	Reg	A	Autonomous regulation of humidity
	Hydrogel	Hydrogel HPC-PAA	[78]	SC	Reg/S	W	Water absorbation

6. Discussion: advantages and limitations

The applications of smart materials in architecture are still limited; many of them are prototypes or used in small temporary pavilions. The various studies found in the literature describe the advantages of their application in building envelopes. Thus, the readiness of smart materials for biomimetic design is still at an early stage of development. Further experimental laboratory studies are needed to define the evaluation and verification stages of some parameters, including modulation, motion cyclicity, dimensions and durability. Laboratory tests and simulations with dynamic modelling software will make it possible to obtain useful feedback on the designed technological solutions before they are used in buildings. It is also necessary to examine the manufacturing techniques of these materials and the relative complexity of the production process [80].

Among the different solutions analysed, the materials that are independently activated by the action of the thermal trigger predominate. The temperature-responsive shape memory materials are the most commonly used and/or studied materials in the field of architecture. Shape memory polymers are less expensive than shape memory alloys. Furthermore, the shape memory effect can be triggered by different stimuli or by several stimuli at the same time such as temperature and humidity [81]. The scientific literature repeatedly points out that piezoelectric technologies are considered the most mature class of smart materials [82]. Nevertheless, they were excluded from this study because they are not able to react autonomously to environmental stimuli.

In many cases, smart materials are used as sensors and actuators that can activate different functions depending on triggers in the environment. In other words, they are used to control physical variables. At the same time, these solutions are configured as a possible strategy to reduce energy consumption while ensuring indoor comfort. The use of these materials leads to a reduction in the consumption of fossil fuels in buildings [83], as their ability to adapt to external conditions and their relative deformability can directly benefit indoor comfort, especially lighting levels natural ventilation, and hygrothermal comfort. The use of responsive materials favours the adaptability of the building envelope to environmental conditions and improves not only the resilience of buildings but also that of urban areas thanks to the use of environmental triggers for their activation that do not require additional energy consumption.

While smart materials have been researched in other fields for a long time, the study of smart materials in the field of architecture is still in its infancy. Therefore, it is necessary to deepen this concept by defining the possibilities and limits with regard to the state of the art.

In summary, the advantages and limitations of using smart materials can be described as follows:

- Smart materials combine the function of a sensor and an actuator by being activated by environmental triggers through the modification of their intrinsic properties;

- Self-activating smart materials can be considered as no-tech materials and therefore do not require additional automation tools for their activation, which reduces energy consumption;
- In cases where the application of these materials is appropriate, the ability to use environmental factors as a passive trigger for adaptation and the relative reduction in energy consumption means that the solution can be counted among the resilient solutions;
- The ability to change colour, shape and appearance allows not only the execution of precise functions, but also the definition of a new architectural languages that contribute to the aesthetic quality of the built environment;
- The complexity of the production system, which is not simple and immediate;
- The sporadic nature of realisations limits real-scale experimentation and slows down subsequent evaluations;
- The efficiency of application at the macro scale, because so far the main applications are at the micro and nano scale, especially in fields other than construction;
- The durability of the environmental impact of these materials during their life cycle;
- The cyclicality and repeatability of the actuation cycle to understand how often the material can ensure its reactive behaviour;
- Production and installation costs.

7. Parallels between plants movement and smart responsive materials

The adaptive parallelism between nature and architectural technologies is possible thanks to the study of the functional and adaptive strategies of plants, which, although seemingly inert, activate different strategies to survive the environmental triggers typical of their habitats.

Smart materials, thanks to their ability to respond autonomously, are configured as excellent allies for mimicking biomimetic functions and behaviours, and thus for biomimetic design. The ability to self-activate to environmental triggers enables the development of façade systems or components that provide some of the key responsive functions of a biomimetic adaptive envelope, including shielding, modulation, reflection and filtering. As plants are characterized by reversibly repeating cyclic and modular adaptive behaviour mechanisms, it is necessary to favour smart reversible or two-way materials (as in the case of some thermo responsive materials), as the process needs to be replicated over time according to variable cycles on a seasonal and daily basis. SMPs are much more deformable than SMA, which have a more limited deformation capacity; SMPs have much lower recovery stresses than SMAs, which have high stiffness [84]. Moreover, in the case of SMA and SMP, it is appropriate to consider the reversible shape change, whose studies show even weaker mechanical performance compared to the unidirectional equivalent [84].

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Chapter 7

A biomimetic Adaptive Model [bio-AM]: a new methodological approach

7.

1. The bio-adaptive model [bio-AM]: from nature to architecture

The information gained from the study of nature's adaptive mechanisms and the self-reactivity of intelligent materials is incorporated into the proposal of a new biomimetic methodological problem-base approach: the bioadaptive model [bio-AM]. The main aim of the proposed model in this study is to facilitate the transfer of responsive principles and mechanisms from nature to technological solutions for adaptive buildings. This study focuses on solutions inspired by plants due to their unique structural and morphological characteristics, where clear dynamic parallels with buildings can be established. The following sub sections explain the construction logic and the general guidelines of the bio-AM and discuss the potential integration of responsive solutions into architecture.

1.1 General outline of bio-AM

The bio-AM builds on existing problem-based approaches in biomimetic design, such as [1] and [2], and further defines specific phases to facilitate the transfer of adaptive mechanisms from nature into architecture. The iterative nature of the design process is mapped out in Fig. 7.1, where it starts with a scoping phase to define the design problem or challenge; then a research phase to investigate potential solutions from nature and select relevant features; and finally, an implementation phase to transfer knowledge, create and validate prototypes. Table 7.1 describes in more detail the various phases and steps of the process.

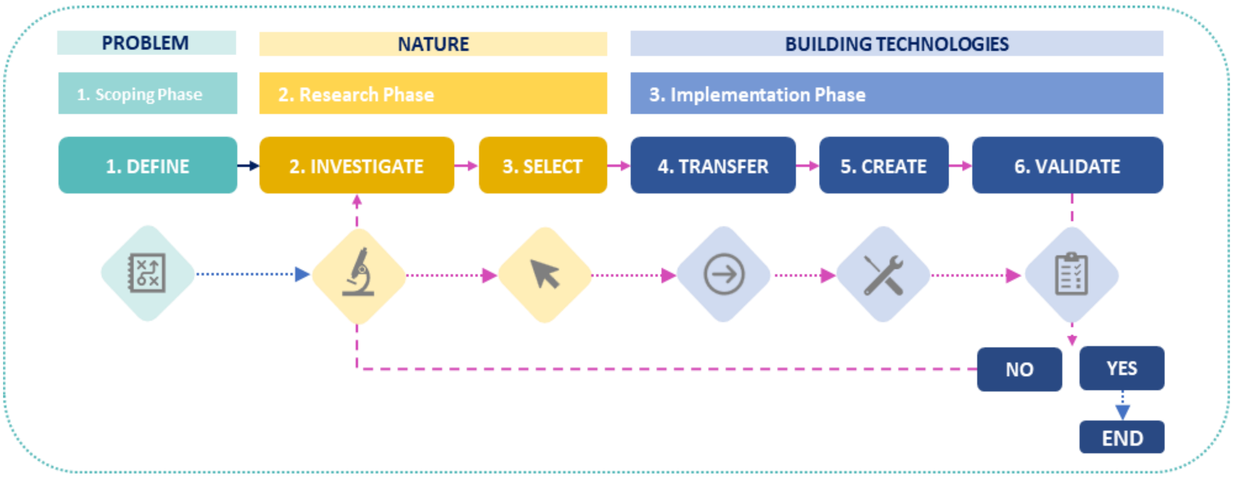

Fig. 7.1. General scheme of the bio-adaptive model (bio-AM)

Table 7.1. Description of six phase of the bio-adaptive model

Domain	Macro – phase	Phase	Procedure	Description
PROBLEM	Scoping Phase	1. DEFINE	What is the challenge?	The first step of the proposed approach is to define the problem or challenge. At this stage it is necessary to analyse the context in which the solution is to be realised, the resources available, the social and economic issues and any constraints.
NATURE	Research Phase	2. INVESTIGATE	How does nature react?	At this stage it is necessary to study the natural world to understand how natural organisms perform certain functions and adapt to certain challenges. In this phase, questions need to be asked such as: How does nature use the natural resources available in each context? What strategies does nature use to survive in a particular climate? So this is a very delicate phase. One needs the necessary time and advice from experts in the field of biology to properly understand biological strategies and classify them according to the function performed.
		3. SELECT		Having understood how natural organisms perform one or more functions, one is selected for imitation. The degree of adaptation is determined.
BUILDING TECHNOLOGIES	Implementation Phase	4. TRANSFER	How to transfer the previous informati on into technologi es?	This phase consists in transferring the adaptation solutions identified in the following phases, in the field of building technologies. Obviously, it is necessary to consider the spatial scale, the material, and the technological characteristics of the new solution. To do this you must use the professional skills of the specific thematic area of application of the solution.
		5. CREATE		Creation of a prototype in original size, in reduced scale or by simulation with advanced software (e.g. parametric software).
		6. VALIDATE		The final step is to test the proposed solution. In particular, the performance of the prototype is evaluated in terms of mechanical, physical, or chemical properties. Various simulations with advanced software are necessary to evaluate the performance and evaluate the comfort inside the building, also in terms of energy efficiency. If the test gives a negative result, it is necessary to return to phase 2 and identify a new solution.

1.2 Scoping phase: challenge and context definition

Defining the challenge is the first step in the biomimetic process. It means defining the objective as a function or strategy to which the final solution must respond. For example, understanding how to shelter from high temperatures or how to survive in snowy climates. The strategies vary according to the context in which they are applied. A strategy that works well in one context may not work in a different context. This happens because each context has varying factors and different resources availability. Therefore, it is important to understand the context in which the project will fit. From the characteristics of the context comes the challenge. For example, if the building is in a tropical environment the challenge will be to protect the occupants from high temperatures and humidity or adjust light intensity. It is crucial to consider the climate, abiotic factors and biotic factors that together make up an ecosystem. Abiotic factors are the non-living parts of an environment, such as sunlight, temperature, wind, water, and soil as well as natural events, including storms or volcanic eruptions, which are divided into chemical and physical. Biotic factors, on the other hand, are the living parts of an environment, such as plants, animals, and micro-organisms. Fig. 7.2 presents the main climatic contexts, environmental aspects, biotic e abiotic factors, and responsive functions that were considered in developing the biomimetic adaptive model in this study. Therefore, depending on the climate and the ecosystem it is possible to define the specific challenge. Having to apply the bio-AM in the field of building technologies, the challenges must be overcome by the building envelope, which acts as an adaptive interface between the internal and external environment.

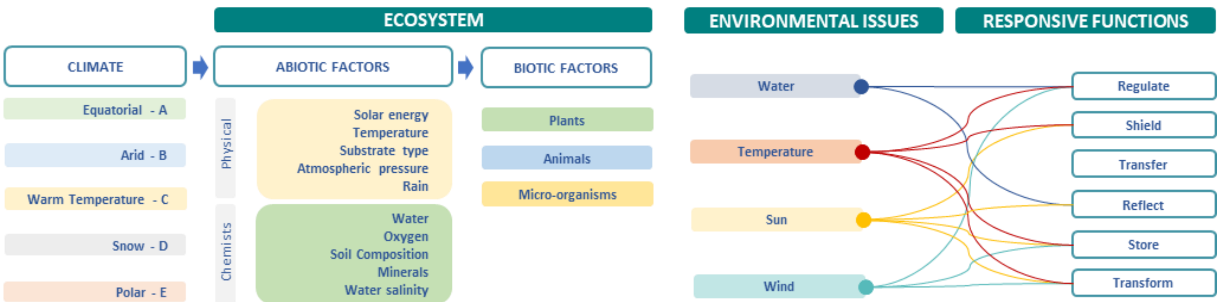

Fig. 7.2. Classification of the climatic context and of biotic and abiotic factors. Link between environmental issues and responsive functions. From left to right: five climatic zones [3]: equatorial zone (A), the arid zone (B), the warm temperate zone (C), the snow zone (D) and the polar zone (E); Factors related to ecosystem: abiotic factors and biotic factors; Environmental issues: water, temperature, sun, and wind. The responsive functions are defined to allow the building envelope to act as an adaptive interface, such as regulate, shield, transfer, reflect, store, and transform.

1.3 Research phase: adaptation in plants

The second macro-phase is to understand the biological strategies and identify the relevant mechanisms to emulate. It is therefore important to start by analysing the adaptive mechanisms that exist in nature. As mentioned earlier, plants are selected for this phase because, like buildings, they are static but have responsive adaptive qualities. Plants are excellent climate indicators. In fact, the Koppen-Geiger classification is based on the temperature and precipitation values of five vegetation groups defined by the French botanist De Cabolle [4] [5]. The five Koppen vegetation groups distinguish between plants from the equatorial zone (A), the arid zone (B), the warm temperate zone (C), the snow zone (D) and the polar zone (E). In plants, the control and tolerance of environmental factors is necessary for survival; in buildings, it is necessary for the comfort of the users.

Several studies have investigated the unique mechanisms of plants' movement, and some used these to inform new solutions [6][7][8]

Based on the adaptation mechanisms of plants analysed in the previous chapters, Fig. 7.2 provides a brief summary of the main plants and their strategies found in the literature on biomimetic building strategies, as an example of an approach to this second phase of bio-AM . Lopez [9] introduced various plants with particular properties: *Salvia officinalis* that, like all plants with hairy leaves, reflect sunlight from the surface and avoid overheating of the leaf surface; *Mimosa pudica*, whose leaves bend inward in response to physical contact [10]. La Rocca [11] describes the thermonastic movement of *Eranthis hyemalis* ; the flower petals open , during the day with increasing temperatures and remain closed ,   at night when temperatures are low. *Leontopodium alpinum*, on the other hand, is covered with a layer of down. In this case, however, the hair does not serve to protect the plant from low temperatures, but have the function of counteracting the loss of water and limit the transpiration [12]. For this reason, the *L. alpinum* , can live in arid places and subject to strong winds.

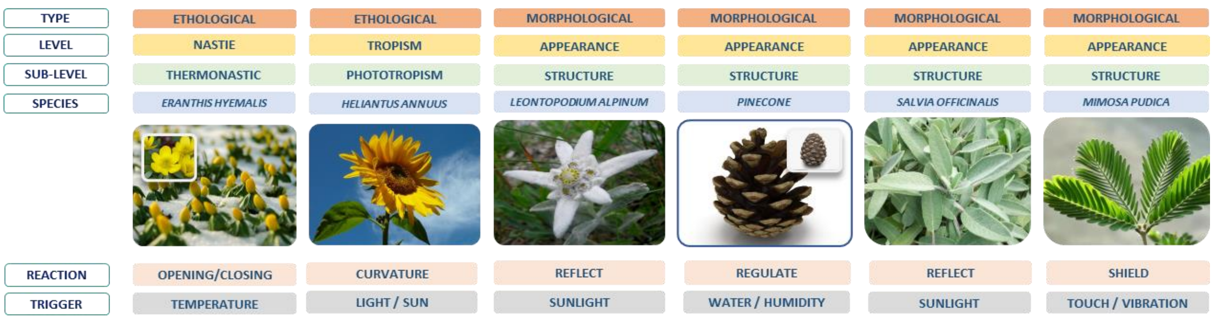

Fig. 7.3. Examples of responsive strategies and mechanisms in plants

1.4 Implementation phase: parallels of adaptation for the development of the bio-AM

The third phase aims to transfer knowledge from nature, systematically, to an adaptive solution for buildings. The context has a significant factor on the shaping of the solution, where morphological, physiological, and ethological means through appearance, function, and behaviour should be clearly defined at the early stages. The environmental factors (sun, water, temperature, wind) represent the external stimulus that induce the particular response in terms of adaptation. Several strategies and mechanisms for responsive adaptation have been identified in plants, which can be classified based on the challenge that is faced by the intended solution. An overall classification of the framework is presented in Fig. 7.4 with relation to the responsive functions.

The transfer of responsive functionalities can be facilitated by using appropriate technologies and materials. For the context of bio-AM, materials that self-adjust as a response to environmental stimuli without the need for extra energy are preferred, such as smart materials, that make possible to design architectural solutions that respond to the environment [13], thanks to a real-time response to stimuli and activate without requiring external control systems [14]. Shape memory alloys (SMA), shape memory polymers (SMP), electrochromic and piezoelectric materials are among the most widely used smart materials [15]. This work excludes smart materials based on an electrical stimulus from the model and considers only those capable of being activated through an intrinsic modification of properties. The choice of smart and self-responsive materials allows to transfer functionality from nature to technology, and to direct the design towards low energy consumption, in line with the objectives of climate neutrality by 2050.

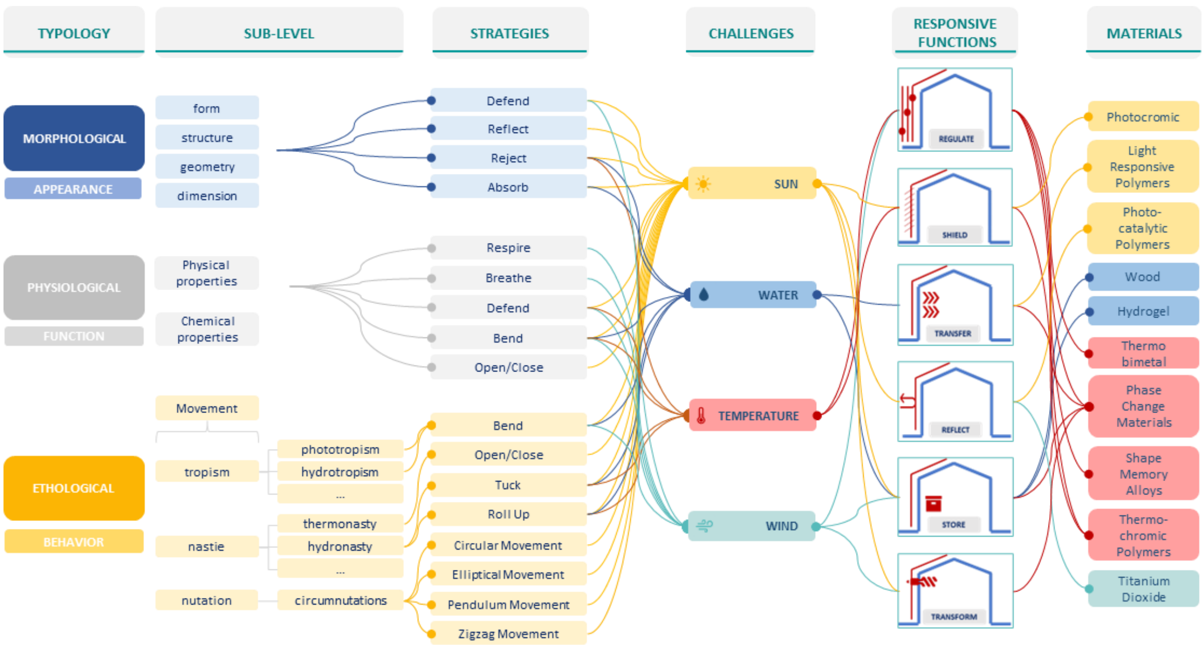

Fig. 7.4. The initial framework for developing the bio-AM

In line with the concept of the adaptive envelope, the transfer of the natural functions identified in the second phase of bio-AM can take place in technologies at different spatial levels of the building: Envelope, Façade, Façade Component or Material (Fig. 7.5). In this context, it is necessary to design the façade system, which is then transformed into technology. To do this, it is possible to create prototypes on a real scale or on a smaller scale, or to start designing a biomimetic solution, using advanced software, such as parametric modelling software, which favours design in dynamic environments. Then, the effectiveness of the proposed solution must be tested through experimental laboratory tests to evaluate the physical and mechanical properties and the response of the designed solution to environmental triggers. It is also possible to preliminarily start with parametric simulations that test the effectiveness of the proposed solution by evaluating the indoor and/or outdoor comfort parameters.

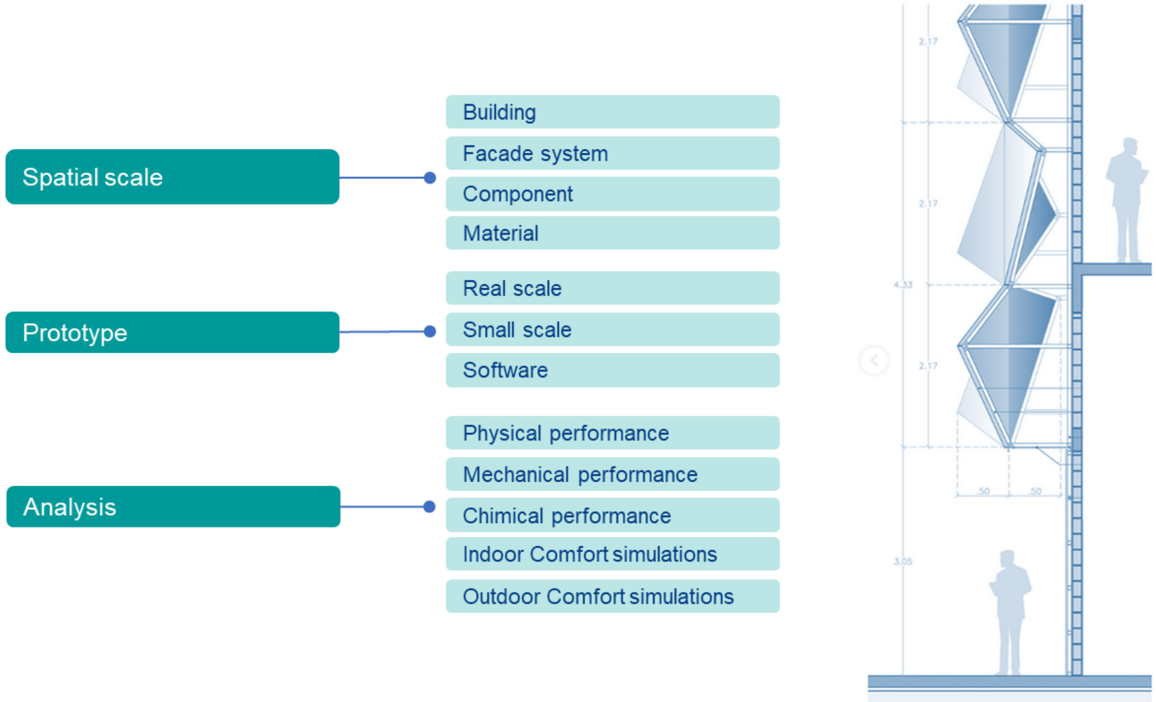

Fig. 7.5. The main three steps of implementation phase of bio-AM

2. Matrix of biomimetic design

Fig. 7.5 shows a biomimetic design matrix that helps researchers select responsive materials capable of providing a specific kinetic movement of the building façade depending on climatic factors (light, water or temperature). The matrix consists of three main lines, each relating to a climatic factor (light, temperature and water) and seven columns. Each column contains different features that apply to the study in the biological domain (phase 2 of the bio-adaptive model) and to the transfer of natural principles into technologies with smart materials (phase 3 of the bio-adaptive model). The lines between the cells indicate the connections between them and the functions that can be ensured. It is possible to read the matrix from left to right (i.e. starting from the climatic challenge) or vice versa (i.e. starting from the material). The movements of the plants and the kinetic movements were synthesised by bending, opening and closing, curving and arching. Depending on the characteristics of the adaptive building envelope, the response time can vary from seconds to hours, from daily to seasonal scales: The six response functions considered are those defined by Sommese et al. [16].

Below is an example of how to read and use the matrix in relation to the "light" challenge: assuming that a regulation function of light radiation must be ensured by a kinetic folding movement, it is possible to interpret the matrix by reading it from left to right, entering the macroline "light" and following the "folding" motion that leads to a “shape change” as output; thus, it’s possible determine that the responsive materials that can ensure this reaction are Shape Memory Polymers. Otherwise, it is possible to read the matrix from right to left to find out which responsive functions a particular material can ensure. For example, if entering "light" in the "materials" column and selecting "photochromic", this will lead to the output "colour change" and the responsive functions "regulate, shield and reflect" that the material guarantees by folding, curling, curving or expanding and contracting, depending on the choices and design needs.

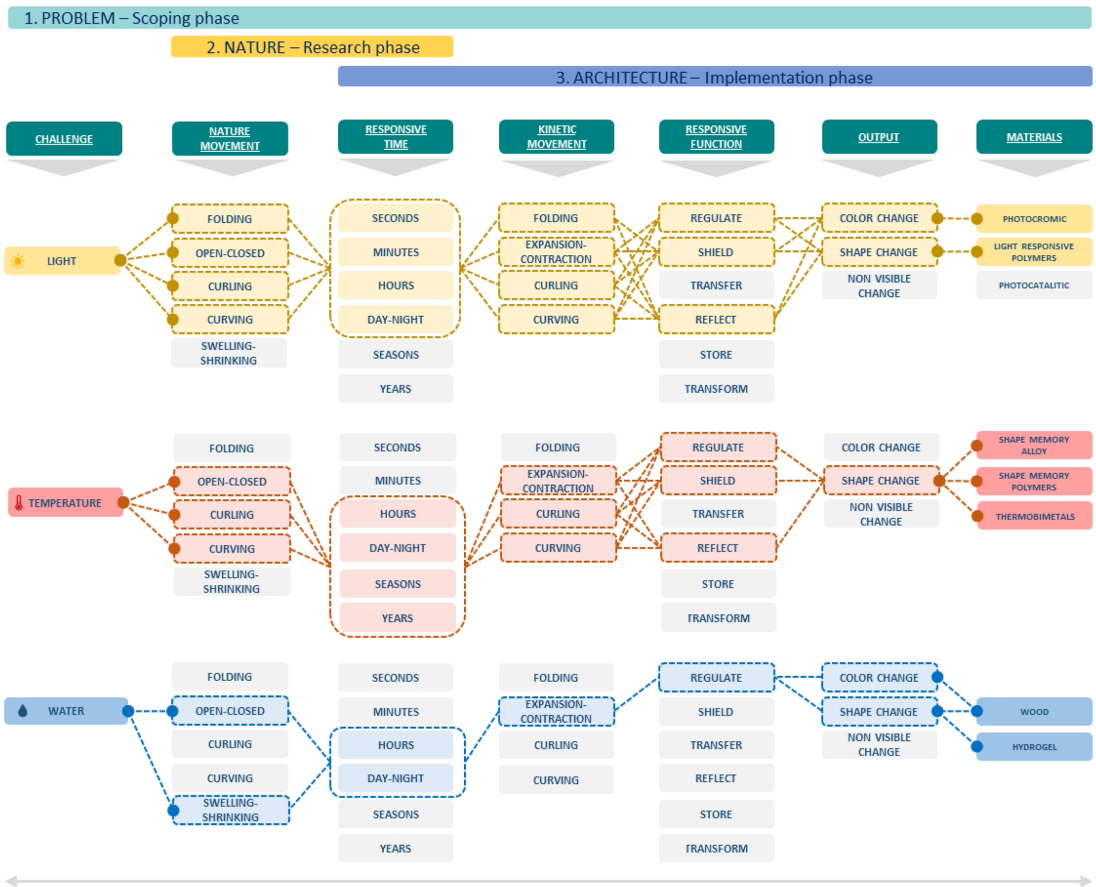

Figure 7.5. Matrix of biomimetic design based on smart responsive materials

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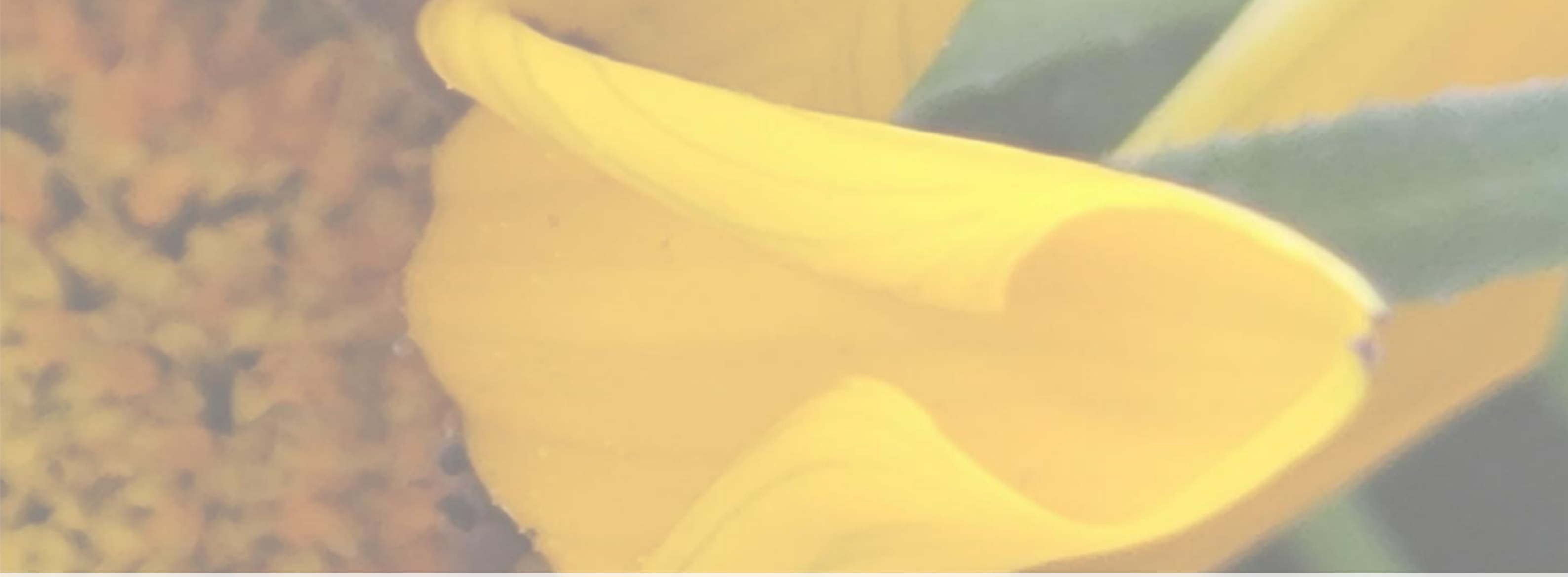

Chapter 8

Design process: light-responsive façade system

8.

1. Introduction

Ensuring optimal lighting conditions in buildings is an important aspect to consider in architectural design, as people spend most of their time indoors, where artificial light often replaces daylight [1]. The absence of daylight affects physiological functions, including the visual and well-being of users and indoor environment quality (IEQ) [2]. At the same time, the effective use of daylight is a way to reduce energy consumption of buildings [3]–[6]. The building envelope, designed as an interface to regulate the energy flows between inside and outside [7]–[10], does not always guarantee sufficient daylight conditions, which leads to problems such as glare, unwanted reflections and solar-induced overheating [11], [12]. Envelopes or façade systems are designed with static solutions that are not able to interact with seasonal or daily weather-climate variations, such as the dynamic nature of the sky and the sun [3], [5]. Given the AEC (Architecture, Engineering and Construction) sector's commitment to accelerate the transition to clean energy solutions [13] and achieve net zero emissions by 2050, dynamic solutions that interact with and respond to the environment are essential [3]. Dynamic systems continuously adapt the properties of the building envelope to environmental conditions (e.g. cloud cover) and seek to create optimal internal conditions while balancing energy targets and human factors [3], [5].

2. Kinetic biomimetic adaptive façade

This study investigates both adaptive and biomimetic solutions that exist in the international scientific literature in order to identify gaps in terms of the use of materials as well as to define more precisely other features such as kinetic movements. The identification of different solutions for adaptive and biomimetic façades found in literature and the related simulations for indoor comfort assessment, presented in Table 8.1, provide important information to identify the current gaps and propose a new solution through a multidisciplinary methodological approach. Adaptive and biomimetic façades were analysed considering climate (according to the Koppen-Geiger climate classification [14]), responsive functions [15], environmental triggers, kinetic movement and materials. Most of the examined study were mainly carried out for arid desert (Bw) and temperate steppe (Cs) climates. The predominant environmental trigger is the sun. These dynamic and interactive façades provide a double skin for the building conceived as a secondary element anchored to the main façade (generally made of glass), whose responsive functions are the control and the regulation of solar radiation to avoid glare and ensure optimal lighting conditions. In most of the cases studied, the design of adaptive façades with kinetic movements, which were used in test rooms intended mainly for offices, involved an evaluation of the quality of daylight based on various environmental criteria and parameters. Kinetic movements provide for changes in geometric configuration, two-dimensional and/or three-dimensional, such as bends, curvatures, expansions, contractions and translations.

Kinetic façades interact with occupants and improve visual comfort [16]. They benefit from different geometries, two or three-dimensional, with dynamic and complex shapes. Different methodological approaches were used in the different studies analysed, including biomimetics [17]–[21], kinetic design strategies and origami [22]–[28], to define the best configurations to improve façade performance. Parametric simulations accompanied the design of a kinetic façade through generative design strategies capable of managing complex models and shapes.

The materials used in biomimetic systems play a crucial role in their overall performance and effectiveness. Some studies do not specify the materials they use, while others rely on conventional materials like glass, metal, or plastic. However, a few studies (Kuru et al. [18] and Soliman et al. [17]) explore the use of smart materials, such as photochromic glass and shape memory alloys (SMA). Photochromic glass is a type of smart material that changes its optical properties in response to light. It can darken or change colour when exposed to sunlight. This makes it suitable for regulating light and solar radiation in biomimetic adaptive building envelopes. Shape memory alloys (SMA) are another type of smart material that can "remember" their original shape and return to it when heated. Thanks to this property, they can act as actuators and enable the opening and closing of photochromic glass flaps in the adaptive building envelope proposed by Kuru et al. [18] and Soliman et al. [17]. However, despite the promising results of these few studies with smart materials, there is still a gap in the scientific literature regarding the selection of suitable materials for biomimetic adaptive building envelopes. When selecting materials, factors such as movement, technical properties, performance, adaptability, indoor comfort, and durability over the lifetime of the building need to be considered. Mimicking nature's responsive and adaptive functions through the biomimetic discipline can be done precisely through the use of smart materials that can act as sensors and/or actuators thanks to the intrinsic properties of the material matrix itself, avoiding automated solutions that consume energy [29].

Therefore, this study proposes a design of a biomimetic kinetic façade system that interacts with the environment and is able to ensure kinetic movements in response to light by assuming the use of light-responsive shape memory polymers, the effects of which need to be accurately validated through physical prototypes, which is beyond the scope of this study, which instead focuses only on design and parametric modelling [30].

Table 8.1. Analysis of kinetic biomimetic adaptive façade. Climate [14]: Equatorial (A), Arid (B), Warm temperate (C), Snow (D), Polar (E). **Responsive function** [15]: Regulate (Reg), Shield (Sh), Transfer (Tr), Reflect (R), Store (S), Transform (Tm). **Environmental trigger**: Sun (S), Light (L), Temperature (T). **Analysis**: Thermal comfort (T), Daylight quality (DL). **Building use**: Educational (E), Office (O), Hospital (H). Tools/Software: Energy Plus (EP), Design Builder (DB), Ladybug (L), Rhinocheros (R), Honeybee (H), Design Explorer (DE), Grasshopper (G), DIVA (D).

Object	Year	Building use	Country	Climate	Responsive function	Environmental trigger	Movement	Material	Analysis	Tools/Software	Dimension	Surface	Biomimetic
Multifunction biomimetic adaptive building envelope (MBio-ABE) [17]	2023	O	Egitto New Cairo	BWh	Reg	T	Folding and rotation	Shape Memory Alloy Photochromic glass	T	EP, DB	35 cm hexagon side	3D	Yes
Adaptive facade [25]	2023	O	Belgio Brussels	Cfb	Sh Reg	T	Open-closed	---	T DL	EP, DB, L	---	2D	No
Climate responsive facade [31]	2023	H	Iran Teheran	Bsh	Sh Reg	S	Folding and basic rotation	---	DL	R, G, H	Different	3D	No
Adaptive modular facade [24]	2023	O	Australia Melbourne	Cfb	Reg	S	Folding	---	DL	R, G, L,	1mt x 1mt	3D	No
Dynamic solar shading system [19]	2022	O	---	---	Sh	S	Rotation	Colored glass and transparent materials	DL	R, G, H, L, DE	Depth: 0.25-1m Scale change: 0.50 – 0.70 L	3D	Yes
Modular dynamic façade (MDF) [26]	2021	O	Iran Yazd	Bwh	Sh	S	Folding	---	DL	R, G, H, L , EP	---	3D	No

Biomimetic kinetic shading facade [20]	2021	O	Iran Yazd	Bwh	Sh Reg	S	Curling	---	DL	R, G, D	---	3D	Yes
Bio-inspired interactive kinetic facade [21]	2021	O	Iran Yazd	Bwh	Sh Reg	S	Elastic and deformable	---	DL	R, G, D	---	3D	Yes
Interactive kinetic facade [22]	2020	O	Iran Yazd	Bwh	Sh Reg	S	Rotation	Colored glass	DL	R, G, D	---	2D /3 D	No
Biomimetic building envelope (bio-ABS) [18]	2020	E	Australia Sydney	Dfb	Sh Reg	S T	Expansion contraction	Shape memory alloy (SMA) Photochromical	T	EP	20 cm hexagon side	3D	Yes
Interactive kinetic facade [23]	2019	O	Iran Yazd	Bwh	Sh Reg	S	Scaling and translating	---	DL	R, G, D	---	2D /3 D	No
Adaptive solar facade (ASF) [28]	2019	O	Iran Teheran	Csa	Sh	--- (users)	Folding	Traslucent	DL	L, D	---	3D	No
Sun-sensitive solar shading system [27]	2018	O	Iran Teheran	Csa	Sh Reg	S	Rotation	Metal Plastic	DL	R, G, L , D	0.5 x 0.5 m rosette modules	2D	No

3. Shape Memory Polymers

Shape memory polymers (SMPs) are a class of smart materials that combine the intrinsic properties of polymers, such as high deformability, processability, versatility, and light weight, with the ability to change reversibly shape in response to environmental stimuli. Toachieve an efficient response, it is necessary to apply an external treatment (a so-called programming process) that enables SMPs to transit from a stable original shape to one or more temporary ones, and to recover the original shape by exposing the material to a selected external stimulus. Structurally, SMPs demand a stable network and a reversible switching phase. The former is responsible for the recovery to the original shape and requires a stable crystalline phase, or of chemical or physical crosslinks. Within the stable network specific molecular segments are locked, which determine the reversible switching to the temporary shape. Their working principle is based on reversible transition that can be triggered by the external stimulus. Typical reversible segments are those based on photoisomerization, molecular rearrangements (e.g.Diels–Alder reaction), physical bondings (e.g. hydrogen bonding, coordination interactions, self-assembly processes), absorption/desorption phenomena. SMPs respond to stimuli such as heat, electric field, magnetic fields, pH variation to remote sources, such as light, magnetic, microwave and ultrasound fields. The combination of these modes, enables multi-stimuli and multi-level shape memory systems, enlarging applications for advanced materials and smart devices. To achieve the goals of this study, the property of light-responsive SMPs are investigated. Light-stimulated SMPs are shape memory polymers that undergo a reversible change in their molecular and electron structures upon photo-irradiation, which in turn is responsible for a macroscopic change in their shape [32]–[34]. In fact, light is a convenient source as it enables a remote, instantaneous and precise control of the shape change by acting on the source wavelength, intensity and location. Two types of photoresponsive mechanisms are known that can transform light into mechanical energy: photothermal and photochemical. Photothermal conversion is achieved by materials that are able to convert the light into thermal energy causing deformation temporary form transition [35]. This can be due to the presence of chromophores sensitive to light and can be enhanced through the incorporation of particles, such as gold and carbon-based nanoparticles, that are able to convert efficiently absorbed light energy into heat. Photochemical effect is based on specific transition/rearrangements of molecular switches introduced in the polymer skeleton. Depending on the specific chemical structure of the active molecular segments, transitions of photo-sensitive SMPs can be reversible (cinnamic, azobenzene, spiropyran, diarylethene) or irreversible (for example, o-nitrobenzyl, coumarinyl ester, pyrenylmethyl ester).

4. Implementation of bio-AM

Based on a preliminary analysis of the scientific literature, this study investigates the movements of plants as climate adaptation strategies and then transforms them into kinetic design solutions. The following research adopts an multidisciplinary approach that combines engineering-architectural skills with those of biology and materials chemistry to develop an environmentally adaptive biomimetic façade system, extracting the principles of the biological movement of *Gazania* flowers In particular, this study is structured according to the three main phases of the bio-AM (Fig. 8.1) , proposed by Sommese et al. in 2022 [15]: scoping phase, research phase and implementation phase. It is integrated into the daylight simulation parametric workflow, which is useful for modelling and analysis of the proposed façade system.

The bio-AM is a problem-based approach which analyses the adaptation mechanisms of plants to translate them into architectural solutions and technologies assuming the use of smart materials. The first phase concerns the definition of the problem, which is the challenge that the resulting façade solution must address in terms of climate-related environmental issues. The second phase examines and selects the adaptation and behavioural strategies that plants use to meet environmental challenges and survive in their habitats. The third is about translating the principles gained from nature into adaptive solutions. Fig. 3 shows a specific framework for the implementation of bio-AM in the following study.

Phase 1: Scoping phase

As already mentioned in the introduction, the various challenges buildings face is certainly excessive solar radiation due to climate change, which often leads to glare, unwanted reflections and overheating problems for occupants. To address these issues, the first step of this study defines the development of a façade solution capable of limiting glare by adequately shielding, reflection or filtering solar radiation, while at the same time being able to illuminate the surroundings and provide adequate ventilation to limit overheating near the façade itself.

Phase 2: Research phase

In this step it is necessary to answer the question, *"How does nature react?"* [15] in order to understand how natural organisms, especially plants, deal with the above challenges. Therefore, the study of the behaviours of plants under light stimuli is carried out, favouring nastic behaviours (undirected and not dependent on the direction of the environmental stimulus). Among the different biological species studied, the *Gazania* flower was chosen because it is characterised by nictinastic movement (it follows the day/night light cycle). The morphological and behavioural analysis of the *Gazania* flower is carried out to define the morphological and kinetic principles that will be translated into kinetic solutions of great architectural impact using a parametric model in the next phase.

Phase 3: Implementation phase

The third phase involves the transfer of light-responsive, morphological and behavioural strategies of Gazania flower identified in the previous step, into building solution to propose a biomimetic façade system. To do this, the starting point is the creation of a three-dimensional computational model through software that facilitate work and design in dynamic environments. Rhino 7 software is used for modelling and Grasshopper for the parametric interface. After the parametric model is defined, it is analysed through the evaluation of parameters based on daylight metric such us: sDA (spatial Daylight Autonomy), UDI (Useful Daylight Illuminance), EUDI (Exceeded Useful Daylight Illuminance), and DGP (Daylight Glare Probability).

The plug-in of Grasshopper, Honeybee and Ladybug, was used to enter climate information and evaluate daylight performance, respectively.

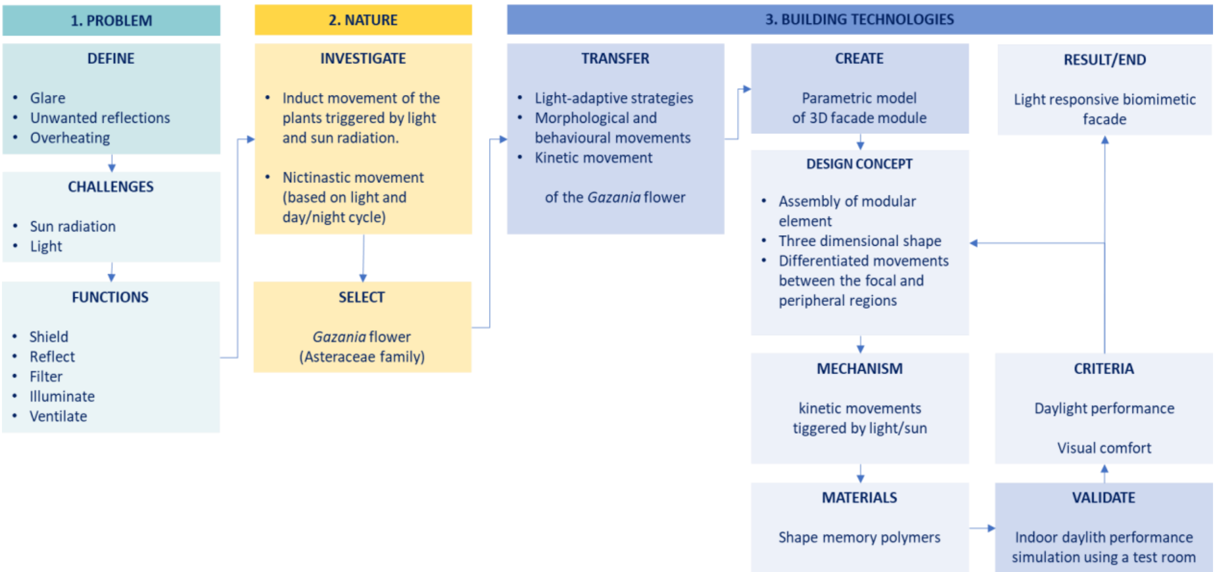

Fig. 8.1. Implementation of bio-Adaptive Model for the following study

5. Design lesson by Gazania flower: light-responsive movement

Gazania is a light-sensitive plant, belonging to the Asteraceae family. It follows nyctinastic-type induced movements. Fig. 8.2 shows the analysis of the morphological and behavioural characteristics of the *Gazania* flower. Morphologically, *Gazania* has an inflorescence characterised by tubular bundles in the central disc and ribbon-like ligulate petals in the outer radial part. From behaviour point of view, *Gazania* opens and closes the ligulate petals depending on the intensity of the light [36], [37]; the petals open and close during the night-day cycle but can remain closed when the sky is cloudy (time varying from the minute-hour scale).

When the flowers open, the petals move from a vertical position to a curved horizontal position (Fig. 8.3a-8.3b). In a cyclical and reversible process, the flowers assume a vertical position when closing from the curved horizontal, with the ends of each petal curling. Direct observation of the movement of the *Gazania* flower has thus enabled us to summarise that the two main mechanisms involve the curling of the ends of each petal along the longest axis of the petal itself and the curving as it passes from the vertical to the horizontal.

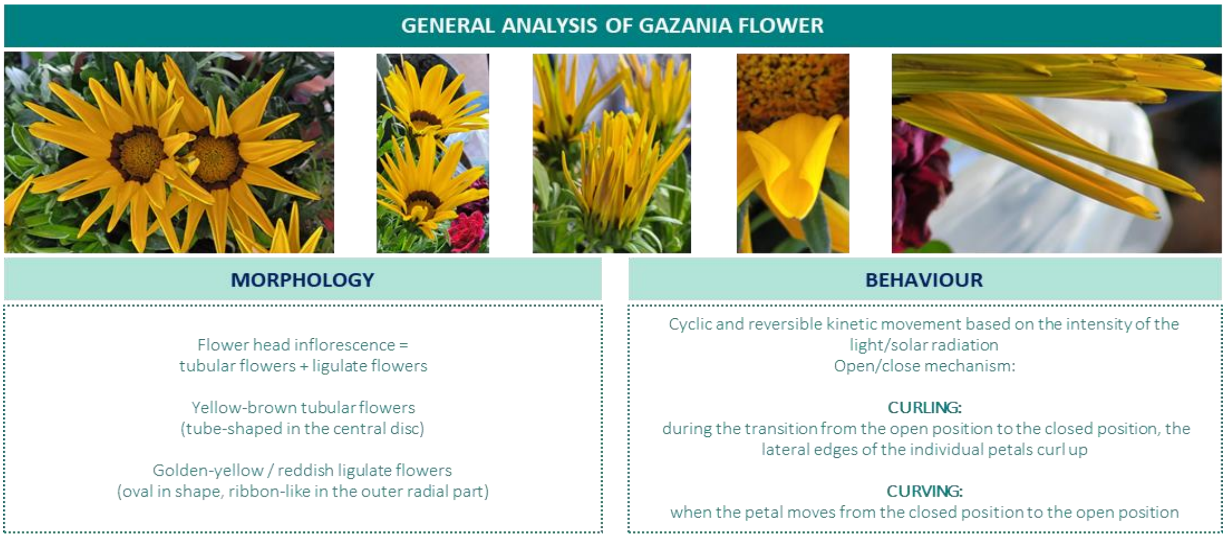

Fig. 8.2. Morphological and behavioural analysis of the *Gazania* flower

6. Design process: abstraction and development of the facade system

According to the principle of hierarchy [18], typical of biological structures, the behavioural mechanism is given by the single petal. The abstraction phase (Fig. 8.3) begins with the observation of a single petal which, when closed, assumes a three-dimensional conical shape (rolled), otherwise it assumes an extended configuration (unrolled) due to the impulse of light falling on it (Fig. 8.3c). Therefore, observing the single petal, it is possible to schematize its almost conical shape with an elementary geometric shape like the triangle. The petal of the *Gazania* keeps the extension along the vertical axis stable, while the dimensions of the horizontal axis vary according to the curvature of the edges. The curling of the petal and the subsequent unrolling by the light trigger leads to an expansion and contraction of the three-dimensional triangular element along the horizontal axis or, in any case, along the short axis of the element.

The design of the biomimetic kinetic façade system starts from the definition of a diamond triangular model that accommodates the kinetic movements and light-responsive behaviour of the flower identified as an abstraction model.

In this phase, the use of a light-responsive polymer based on azobenzene is assumed, which, after studying the literature, seems to be the best candidate for defining the kinetic movements described above, but, despite this, laboratory tests with real prototypes will be necessary to confirm its validity. In fact, among the various SMPs, the azobenzene-based systems are of particular interest for this specific study. Their photo-actuated effect is due to a reversible trans–to-cis isomerization upon radiation with UV light (λ = 366 nm UV). Trans (E) form is the most thermodynamically stable one. Heat sources, visible light (λ > 540 nm) or even storage in the dark can induce its recovery from the less stable cis (*Z*) form. During this reversible light-induced isomerization process, a variation of the geometry of N-N double bond occurs and, in turn, macroscopic properties, such as polarity, redox potential, and optical features change. When the azobenzene segments are attached to an opportunely engineered polymeric backbone, shape changes can be also observed. Therefore, functionalization of a material with azobenzenes is an effective way to amplify the light-induced nanoscopic movement to produce macroscopic structural modifications of the bulk system, thanks to a collective reorientation of azomolecules activated by light irradiation. In some cases, it could be much more convenient to use sunlight as a natural and unlimited activation source [38]. Visible light (λ=390-700 nm) in the form of sunlight or indoor illumination, is the main energy sources on earth and it is unharmful for human beings. Recently, an increasing number of advanced systems and smart devices have been developed that rely on the use of visible light for the wavelength-selective control of shape memory behavior in SMPs. By opportunely functionalizing azobenzene moieties one can tune and selectively activate the response to specific wavelength. In this way, it is possible to employ a wide range of artificial light sources, from IR to UV. Even though it is certainly more convenient to use sunlight as a natural and unlimited source of activation [38], , natural light may not be able to ensure the complete movement and shape change of the material. To avoid indoor problems due to the lack of activation of the material, a dual activation approach can be used, by designing a material which is intrinsically sensitive to both natural light and other light sources attached to the facade. To this aim, the material must be modified by grafting the molecular chain with functional groups that make the material sensitive to a specific wavelength, or by dispersing photoactive nanostructures in the matrix. In their work Leeldhar et al. [39] fabricated a graphene oxide/polycarbonate bilayer structure photoactuator and demonstrated that it could be actuated by both natural sunlight and IR source, working as a smart curtain. The actuation was reversible, fast (response time lower than 1 s) and dependent on light intensity. The described photoactuor represents a valid approach for wireless-controlled shape change facade modules responsive to dynamic daylight. In this phase, the use of a light-responsive polymer based on azobenzene is assumed, which, after studying the literature, seems to be the best candidate for defining the kinetic movements described above, but, despite this, laboratory tests with real prototypes will be necessary to confirm its validity. In fact, among the various SMPs, the azobenzene-based systems are of particular interest for this specific study. Their photo-actuated effect is due to a reversible trans–to-cis isomerization upon radiation with UV light ($\lambda = 366$ nm UV). Trans (*E*) form is the most thermodynamically stable one. Heat sources, visible light ($\lambda > 540$ nm) or even storage in the dark can induce its recovery from the less stable cis (*Z*) form. 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Recently, an increasing number of advanced systems and smart devices have been developed that rely on the use of visible light for the wavelength-selective control of shape memory behavior in SMPs. By opportunely functionalizing azobenzene moieties one can tune and selectively activate the response to specific wavelength. In this way, it is possible to employ a wide range of artificial light sources, from IR to UV. Even though it is certainly more convenient to use sunlight as a natural and unlimited source of activation [38], however, natural light may not be able to ensure the complete movement and shape change of the material.

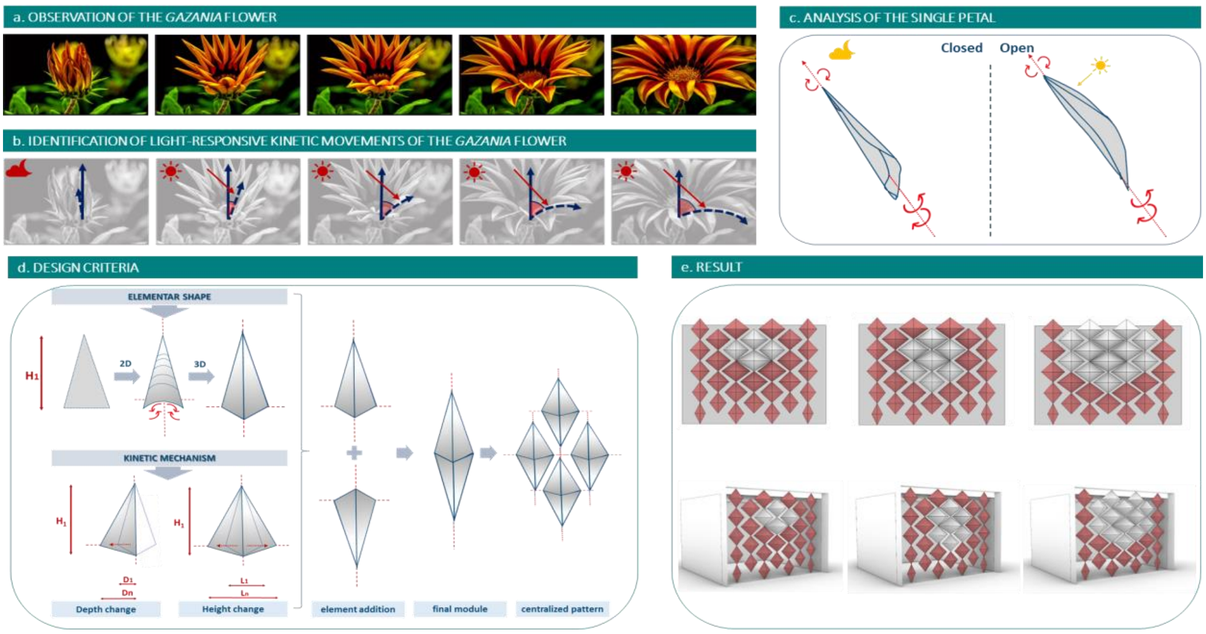

Fig. 8.3 Abstraction process. a-b) movement of *Gazania* flower: the incident solar radiation causes the opening of the flower by curling and curving movements which mark the transition from the vertical to the horizontal position. c) morphological and behavioural analysis of the single petal of the flower. d) design criteria of single facade modular element. e) Final results of biomimetic kinetic façade system: in grey Focal Region Radius (FRR), in red Peripheral Region Domain (PRD).

To avoid indoor problems due to the lack of activation of the material, you can resort to the alternative of using a dual activation system of natural light and a IR or LED light source. In their work Leeldhar et al. [39] fabricated a graphene oxide/polycarbonate bilayer structure photoactuator and demonstrated that it could be actuated by both natural sunlight and IR source, working as a smart curtain. The actuation was reversible, fast (response time lower than 1 s) and dependent on light intensity. The described photoactuor represents a valid approach for wireless-controlled shape change facade modules responsive to dynamic daylight.

7. Morphology and mechanism

Following the morphological structure of the *Gazania* flower, which has a fixed focal part and a radial part characterised by petals that move under the stimulus of light, the bio-inspired façade system is subject to periodic decentralised movements that depend on the distance of the modular element from the positioning of a sensor called the "point of attraction", which has dynamic properties determined by the dynamic sun time position and the position of the occupants. It is responsible for controlling actuation within in the focal region's center of gravity. The attraction point is understood as the intersection between the solar radiation (which varies during the day) and the position of the occupants along the vertical axis of the façade. This means that the elements placed in the central part, and thus in the focal point of the façade (Focal Region Radius – FRR (Fig. 8.4a-8.4b)), are characterised by a low degree of movement necessary to block the intense light in the occupants' field of vision; otherwise, the modular elements of the peripheral areas (Peripheral Region Domain – PRD (Fig. 8.4a-8.4b)) of the façade adopt more accentuated movements. The location of the focal point was determined using the intersection between the façade surface and a line formed by the dynamic sun positions and the occupants' positions. The days of the solstice and equinox, which occur at 9am, 12pm and 3pm, were selected as solar time positions to determine the point of attraction for implementing the kinetic configurations. Solstice and equinox days at 9, 12, 15 are assumed as representatives of sun-timing positions to create the attraction point for implementing kinetic configurations. Different hours and months make the positions of attraction point (AT) varied during the year. Based on the location of AT and radicues of focal and peripheral region, the kinetic elements get a hierarchy configuration based on depth and width changes. When exposed to light, each diamond element maintains its extension along the vertical axis, while its extension varies in width and depth along the horizontal axis.

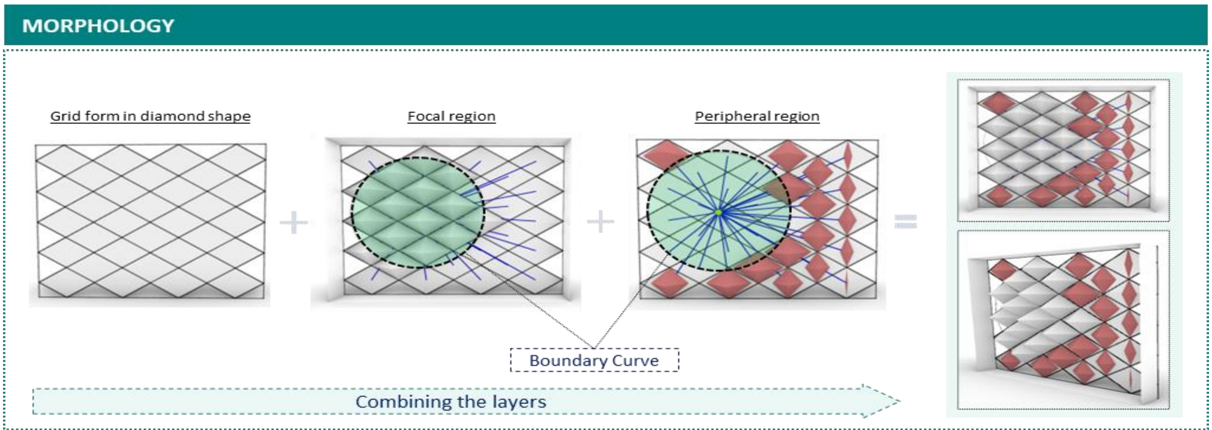

Fig. 8.4a: Biomimetic kinetic facade system development procedure: morphology

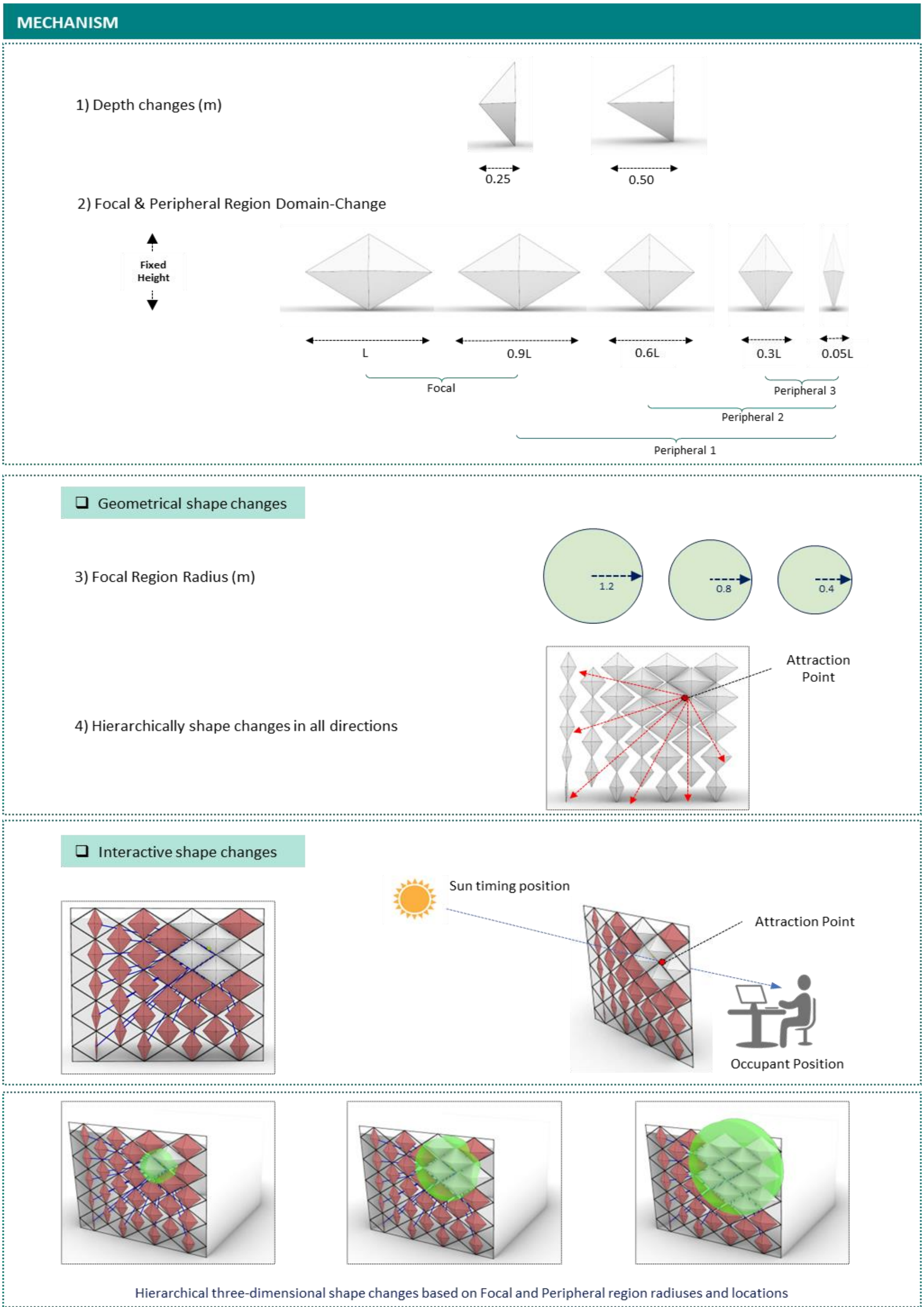

Fig. 8.4b: Biomimetic kinetic facade system development procedure: mechanism

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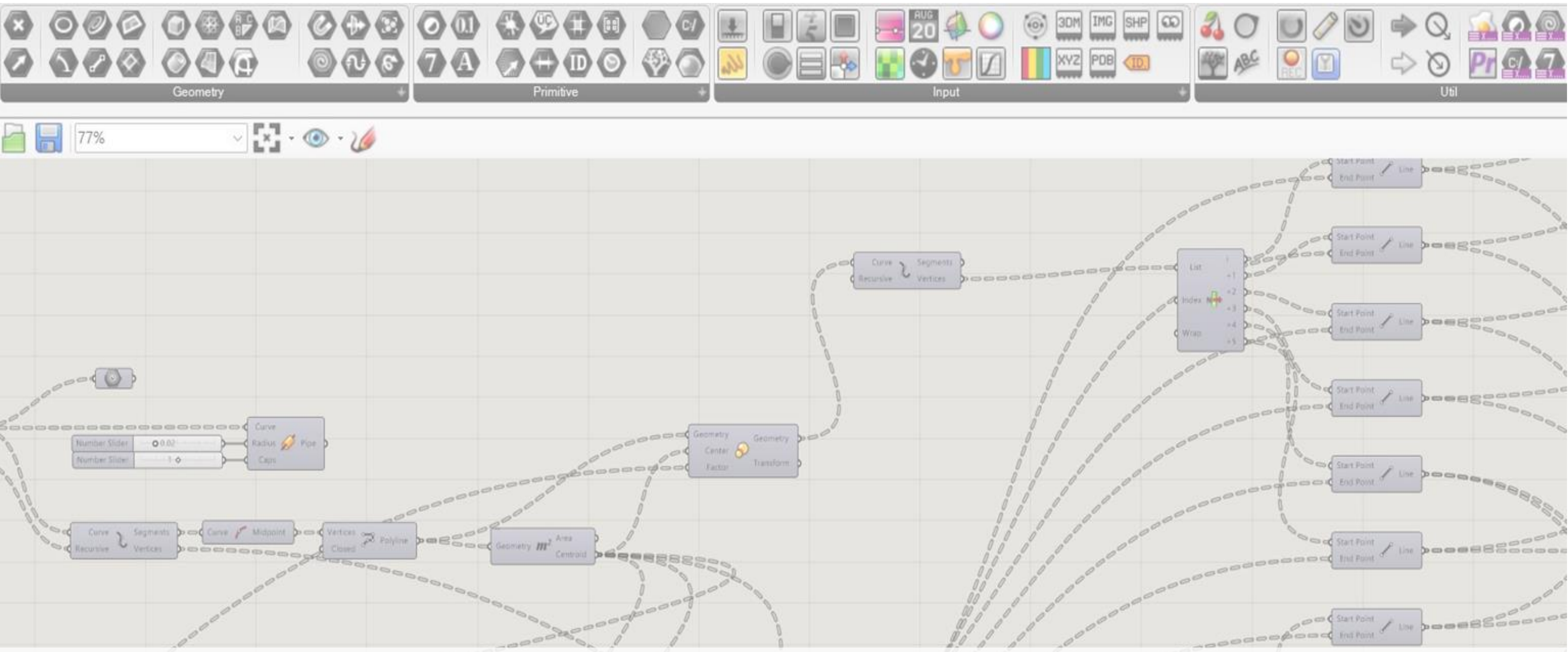

Chapter 9

Daylight parametric simulation

9.

1. Daylight performance simulation workflow

Following the study by Hosseini and Heidari [1], Figure 9.1 shows an inverse design diagram [2] that highlights the utility of the parametric algorithm to combine the morphological, material and movement parameters that characterise the design of the façade model and implement the quality of the design.

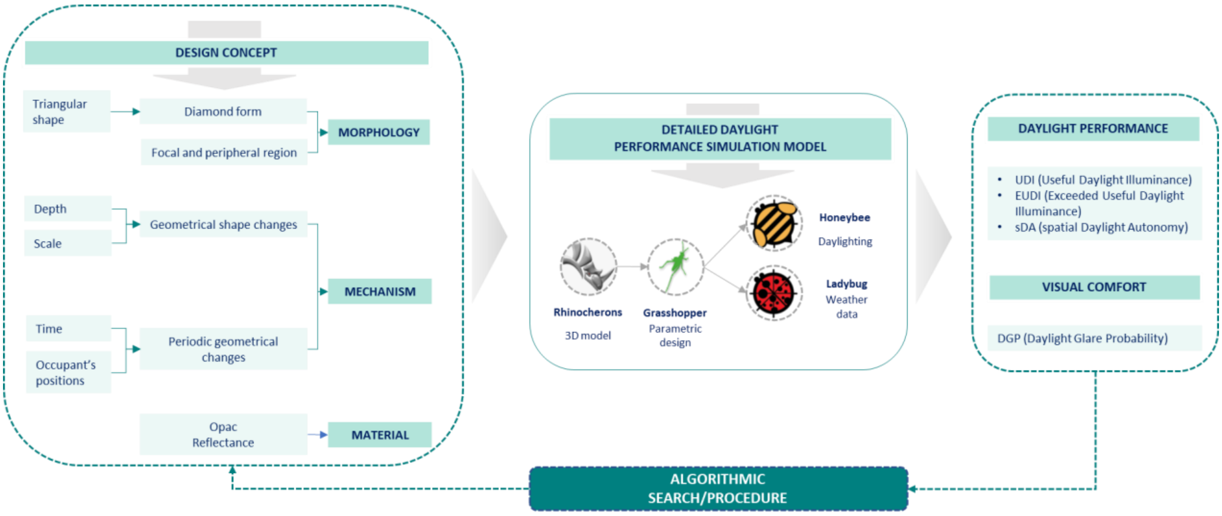

Fig. 9.1. Inverse design diagram of light-responsive biomimetic facade

As can be seen in Figure 9.1, the development of the light-responsive biomimetic façade and the associated simulations are carried out through an algorithmic and parametric modelling process using Rhino 7and Grasshopper as three-dimensional and parametric modelling tools, and Honeybee and Ladybug (Grasshopper plug-in) for climate information and daylight performance and visual comfort analysis. The simulation is performed by applying the proposed solution to an office building in Naples, Italy. According to the Koppen-Geiger climate classification [3], the city of Naples is characterised by a temperate Mediterranean climate with dry summers (Csa). The meteorological data of Naples are imported into the software via Ladybug, deriving them from the epwmap database [4]. The simulation starts by applying the light-responsive biomimetic façade to the window on the south façade of the office space with dimensions 4.40 m (width) and 5.30 m (depth) and 3.40 m (height), as shown in Figure 9.2. The building elements, floors and vertical walls, are modelled with a thickness of 0.30 m.

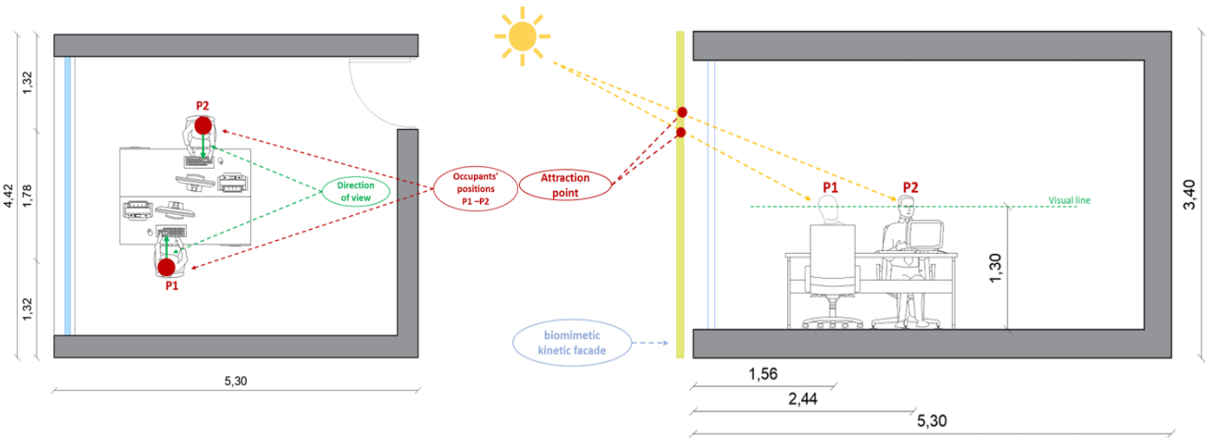

Fig. 9.2. Test room as an office building with occupant positions, direction of view, and attraction point. Left: floor plan; right: section.

2. Daylight evaluation criteria

The study conducts both annual daylight simulation and point in time simulation for several forms of the proposed kinetic façade. Climate-based daylight modeling evaluations are typically conducted for a full year at a timestep of an hour or less to represent the daily and seasonal variations of daylight. In addition, point in time simulations using luminance-based metric at solstice and equinox days are performed to evaluate occupant's visual comfort satisfaction. After analyzing the base case, and before proceeding to the analysis of the proposed biomimetic solutions, a parametric simulation is performed for a fixed shading to control the solar radiation in the room. The material properties of the fixed shading are listed in the Table 9.1.

Considering the complex inherent of the developed biomimetic forms of the study, the three-phase method has been used to conduct daylight simulation with creation of databases using Bidirectional Scattering Distribution Function (BSDF) definition [5]. The method is a reasonable choice for evaluation and optimization of external shading designs [6]. We used a software Berkeley Lab WINDOW 7.6 and Radiance genBSDF command to create BSDF file which described the behavior of light redirecting systems. The three-phase method break Flux transfer into three phases for independent simulation consisting of "sky to exterior of fenestration", "transmission through fenestration", and "interior of fenestration into the simulated space". The procedure can be described with equation 2:

$$E_{8760\times n} = V_{n\times 145} \times T_{145\times 145} \times D_{145\times 146} \times S_{146\times 8760} \qquad (2)$$

Where $E_{8760\times n}$ is hourly simulation during a year recorded at n sensor points; $V_{n\times 145}$ is the outgoing light direction from the sensor points to the fenestration system (View matrix); $T_{145\times 145}$ is Transmission Matrix relating incident window directions to exiting directions (BSDF); $D_{145\times 146}$

is Daylight Matrix relating sky patches to incident directions on window and $S_{146\times8760}$ refers to a collection of sky vectors for a whole year as Sky Matrix.

Regarding the Radiance ambient parameters, the study follows the suggested values by [6] including ambient bounces (-ab) of 5, (ambient divisions) -ad of 22400, ambient super-samples (-as) of 0, ambient accuracy (-aa) of 0, ambient resolution (-ar) of 0, and light port width (-lx) of 5e-5.

To ensure efficient visual performance indoors it is necessary to balance daylight and avoid glare. Climate-based daylight metrics, including Spatial Daytime Autonomy (sDA), Useful Daylight Illuminance (UDI) and Exceeded Useful Daylight Illuminance (EUDI), and luminance metrics, Daylight Glare Probability (DGP), are evaluated for each specific façade configuration considering different Focal Region Radius (FRR) (1.2 - 0.8 - 0.4) and two different depths of the modular element on the solstice and equinox days: 21 December, 21 March and 21 June, during the different office working hours: 9.00 - 12.00 - 15.00. The two different depths indicate that each FRR region might have two configurations, one with a depth of 0.25m and another with a depth of 0.50m. The depth refers to how much the facade elements protrude or recede from the main building surface. Table 9.2 lists the performance criteria used for the simulation. Given that the validity of the material needs to be proven through laboratory studies using physical prototypes, the reflectance properties of the shape memory polymers were obtained from relevant scientific literature [7]–[9] in the simulation phase; therefore, the reflectance values were assumed to vary between 0.05 and 0.4%.

Spatial Daylight Autonomy (sDA) is defined as "*the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone*" [10], [11]; therefore, it is necessary to achieve at least 300 lux during 50% of the hours when the building is occupied by users. When "*there is useful daylight in the back two-thirds of the space*" (UDI 100-3000 Lux) it's possible to define the UDI [11]. When UDI exceeds 3000 lux (UDI > 3000 lux), light overload occurs near the façade, known as Exceeded Useful Daylight Illuminance (EUDI) [11]. Glare is the sensation that occurs when the luminance of the field of vision is higher than that to which the eyes are accustomed, causing discomfort in vision [12]. The most commonly used metric for assessing glare is the Daylight Glare Probability (DGP) empirical method proposed by Wienold and Christoffersen [13], which gives the percentage of people disturbed by one or more sources of glare in daylit spaces [12], applying the CCD Camera based luminance mapping technology [1]. DGP (equation 1) is a function of the vertical illuminance of the observer's eye (E_v), the luminance of the glare source ($L_{s,i}$), the solid angle ($\omega_{s,i}$) and the position index (P):

$$DGP = 5.87 \times 10^{-5} \times E_v + 9.18 \times 10^{-5} \log\left(1 + \sum_i \frac{L_{s,i}^2}{E_v^{1.87}} \frac{\omega_{s,i}}{P_i^2}\right) + 0.16 \qquad (1)$$

The GDP index is associated with four domains of glare comfort [11], [14]–[16]: DGP < 0.35 *imperceptible* glare; 0.35 < DGP < 0.4 *perceptible* glare; 0.4 < DGP < 0.45 disturbing glare; DGP > 0.45 *intolerable* glare.

Table. 9.1. Properties of fixed shadings

Properties	Input value
Blade material	Steel
Blade thickness	0.03 m
Number of blades	10
Vertical spacing	0.25 m
Blade angle	30
Distance from window	*0.2 m*
Blade depth	*0.2 m*
Reflectance	0.55

Table 9.2. Performance criteria used in the parametric simulation

Performance Criteria			
Parameters	**Name**	**Unit**	**Range**
Daylight Related Parameters	Useful daylight Illuminance (100-3000 lux)	Percentage	[0-100]
	Exceed Useful daylight Illuminance (>3000 lux)	Percentage	[0-100]
	Spatial daylight autonomy	Percentage	[0-100]
Visual comfort Relate Parameters	Daylight Glare Probability	x < 0.35 : Imperceptible 0.35 < x < 0.4: Perceptible 0.4< x < 0.45: Disturbing x >0.45: Intolerable	Normalized range: [0-100]
Model Driving Parameters	Smart Material ID	Integer	[0-1-2][a] [a): 0= 0.05, 1= 0.2, 2= 0.4]
	Module Depth	Floating point number	0.25, 0.5
	Peripheral Region Domain (PRD)	Domain	(0.9-0.05),(0.6-0.05),(0.3-0.05)
	Focal Region Radius (FRR)	Floating point number	0.4, 0.8, 1.2

Model fixed Parameters	Glazing Ratio	Percentage	90
	Task Area Height	m	0.80
	Space Width	m	4.40
	Space Length	m	5.30
	Space High	m	3.4
	Single glazing direct visual transmittance	Percentage	90
	Int. Wall Reflectance	Percentage	50
	Int. Ceiling Reflectance	Percentage	80
	Int. Floor Reflectance	Percentage	20
	Ext. Ground Reflectance	Percentage	10
Time Parameters (daylight part)	Month	Integer	6-9-12
	Day	Integer	21
	Hour	Integer	9-12-15
Climate Parameters	Weather File for analysis	user-defined	temperate Mediterranean climate

3. Results

The following subsections report the results of the parametric simulations for a base case (room without shading), a static case (room with a fixed shading) and the dynamic case of adaptive biomimetic shading for both occupant positions (Fig. 9.3). Since the biomimetic kinetic façade system is activated by the position of the sun and the position of the occupants near the attraction point, parametric studies of 486 alternatives are carried out for each position of the occupant (P1 and P2), totally 972 simulations, based on different values of FRR, PRD, depth and reflectance. By comparing the metrics' values across these different zones and depths, it's possible identify the most effective configuration for optimizing daylight performance, visual comfort, and users well-being in the building.

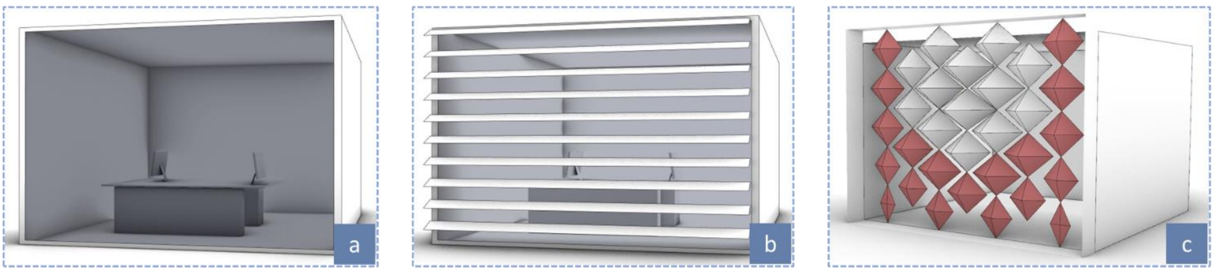

Fig. 9.3 Test room: a) base case without shading; b) static case with a fixed shading; c) dynamic case with biomimetic shading.

3.1 Base case without shading

The parametric simulation results for daylight performance for the base case (simple room with window) do not satisfy users comfort, due to an accentuated visual discomfort .

The sDA value of 100% (Fig. 9.4) shows that the room is illuminated by a sufficient amount of daylight, but the index UDI (39.55%) indicates that more than 60% of the light introduced into the work room exceeds 3000 lux, resulting in visual and thermal discomfort for users, which is also evidenced by the EUDI index value of 59.54%. Furthermore, the glare levels are considered *disturbing* (39.9%) and *intolerable* (39.9%) in most seasons, while they are considered *perceptible* (11%) and *imperceptibl*e (11%) only in a small range.

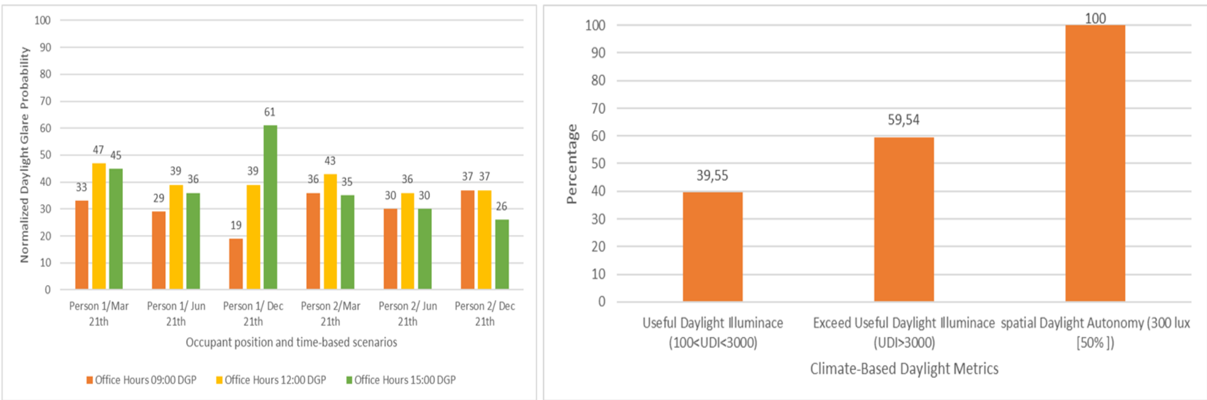

Fig. 9.4. Results of the parametric simulations related to the base case. Left: DGP values calculated on 21 March, 21 June and 21 December, at different office hours (9.00-12.00-15.00), occupant position and time-based scenarios. Right: Percentage mean of UDI, EUDI and sDA values

3.2 Static case with fixed shading

This subsection describes the results of the simulation for the case of static shielding whose material properties are listed in the previous Table 9.1. The room's sDA value of 100% (Fig. 9.5) means ample daylight with no difference from the base case. However, the UDI value of 63.15% shows that only 35% of the light exceeds 3000 lux; it is higher than the base case without shielding, and this means a more pleasant result in terms of lighting. The EUDI value of 34.82% confirms a reduction in discomfort compared to the base case without shielding (EUDI= 59.54). Furthermore, glare levels are lower than in the base case. They are always classified as *imperceptible* except in the winter season (9:00 - 21 December) where they are considered *perceptible* as they are above 0.35.

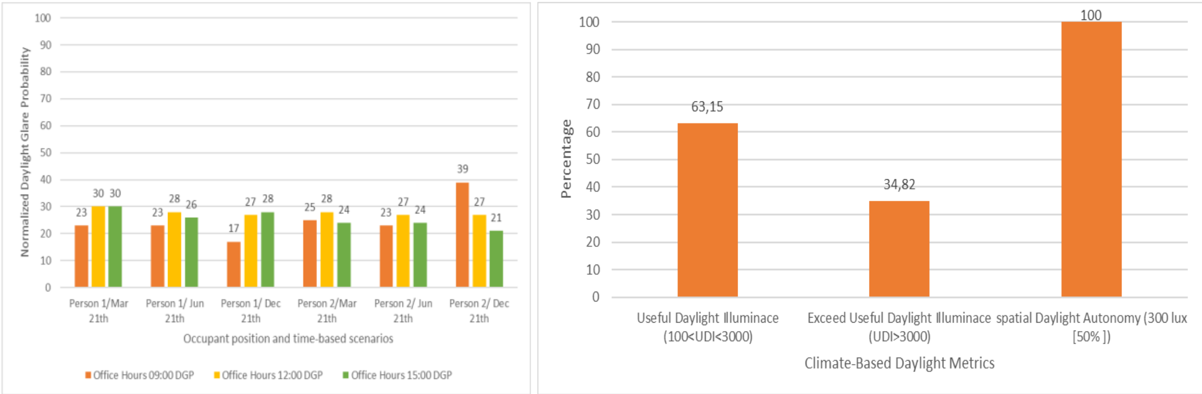

Fig. 9.5. Results of the parametric simulations related to the fixed shading case. Left: DGP values calculated on 21 March, 21 June and 21 December, at different office hours (9.00-12.00-15.00), occupant position and time-based scenarios. Right: Percentage mean of UDI, EUDI and sDA values

3.3 Biomimetic kinetic facade with different combination of FRR for occupant 1

Figure 9.6 illustrates a general analysis for position 1 that shows the high potential of the biomimetic kinetic façade for daylight performance and occupant comfort.

The kinetic facade was designed with three areas of the focal region radius (FRR= 1.2 - 0.8 - 0.4), each of which can have two different depths (0.25 and 0.50). The bar charts (Fig. 9.7) show the average values of the analysed daylight metrics. The sDA values show that the rooms are lit with a percentage of suitable daylight that ranges from 87.5% to 100%. The highest sDA values, close to 100%, are provided by FRR= 4. In particular: for the configuration with a depth of the modular element of 0.25, the sDA values are equal to 100% (in each month and hour analysed), while for the configuration with a depth of 0.50, the minimum value of sDA is equal to 98.44% (month 12, h. 15). The lowest, but still optimal, value of sDA (87.5%) is obtained by the configuration FRR=1.2 with an element depth of 0.25 (month 9, h. 15). As far as sDA is concerned, the comparison with the base case and static one shows no significant differences. In summary, the study shows that various facade configurations achieve high sDA values, which means that all configurations effectively utilize daylight to illuminate the rooms.

The kinetic biomimetic facade has had a positive impact on the UDI percentages (83.42%) compared to the base case (UDI=39.55%) and static case (UDI=63,15%), showing better comfort conditions. The values have increased, and the configuration with an FRR of 1.2 provides the highest UDI values, particularly for a depth of the element equal to 0.5. At this configuration and depth, the UDI value reaches 83.42% at month 12 and hour 15. On the other hand, the minimum UDI value of 67.4% is achieved by the FRR 0.4 configuration with a depth of 0.25 (month 12, h. 9). As a result, the EUDI values decrease significantly compared to the base (EUDI=59.94%) and static case (EUDI= 34,82%). The EUDI values vary from 30.91% (month 12, h. 9, FRR 0.4, depth 0.25) to 12.4% (month 12, h. 15, FRR 1.2, depht 0.5). Since the configuration FRR=1.2 gives the highest UDI values, it is obvious that the same configuration gives the lowest EUDI values (12.46%) for month 12 at 3 pm with an element depth of 0.5. The highest EUDI value (30.92%), which in no way affects the comfort and well-being of users during

working hours, is obtained for the configuration FRR= 0.4 with a depth of 0.25 (month 12, h. 9). The glare values there are within the optimal ranges. Only in two cases does the DGP exceed 35%, defining a *perceptible* glare condition: DGP= 36.6% (month 9, h. 12, FRR 0.4, depht 0.25) and DGP= 35.5% (month 9, h. 12, FRR 0.4, depht 0.5). The smallest DGP value is 18.82 % (month 9, h. 12, FRR 0.4, depht 0.5). Although in the base case only 39.9% caused *intollerable* glare and 39.9% caused *disturbing* glare, the presence of the biomimetic façade offers potential in terms of comfort, as glare can only be defined as *perceptible* under the above conditions, but in any case, has no negative impact on users.
The biomimetic solution offers the most favourable conditions, as it has high sDA values, low EUDI values and optimal glare values, indicating an improvement in user comfort and well-being. In summary, the biomimetic kinetic façade, analysed for position 1, is configured as the optimal solution to ensure adequate daylight in the workspace. It responds to the optimal ranges of climate-based daylight metrics and prevents glare and overheating by modulating direct sunlight. Fig. 9.7 shows the parametric exploration of 486 biomimetic kinetic façade alternatives in the different FRR and PRD combinations, using different simulation parameters with several inputs and outputs. The graph shown in Fig. 9.7 selects only the best combinations by applying the criterion of considering only the values of sDA > 80, UDI > 80, DGP < 0.35. Table 4 shows the climate-based light metrics and the luminance-based survey in the different FRR and PRD combinations for occupant 1 facing south. Table 9.3 shows the optimum daylight performance of the different FFR and PRD configurations on solstice and equinox days with UDI, EUDI and sDA values varying in the ranges 80.03 - 83.48, 12.58 - 17.13 and 84.38 - 100, respectively, while benefiting from different window-to-wall ratios (WWR) between 0.46 and 0.53.

Fig. 9.6. General analysis of daylight performance and visual comfort for position 1. Average of UDI, EUDI, SDa, WWR, DGP values for different focal region radii (FRR) (1.2 -0.8-0.4) and different depths (0.25-0.5)

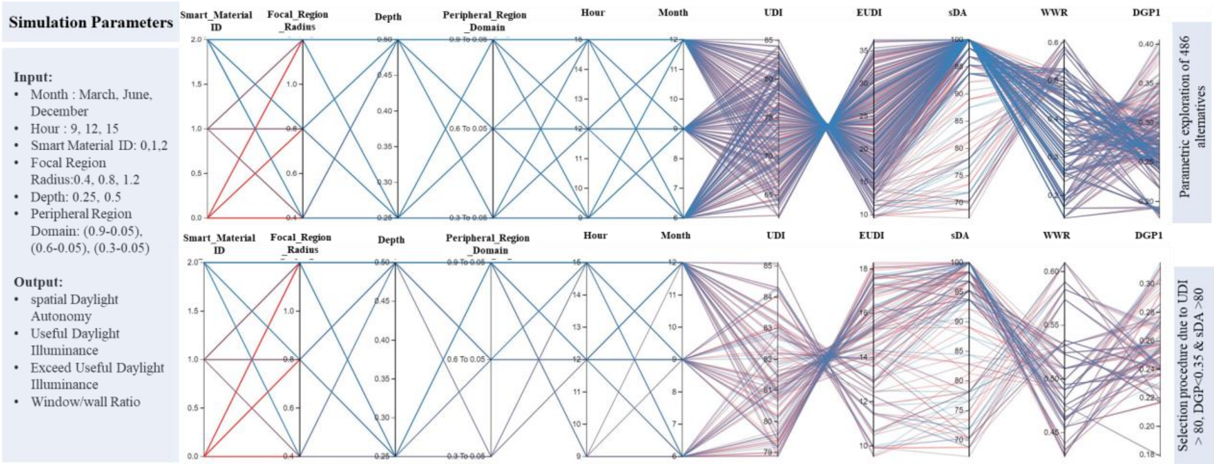

Fig. 9.7. Parametric exploration of 486 alternatives if kinetic biomimetic kinetic facade according to the occupant position 1

Table 9.3. Climate-based daylight metrics and luminance-based investigation of the most optimum Biomimetic kinetic façades with different Focal Region Radiuses (FRR) and Peripheral Region Domain (PRD) for the South direction according to the occupant position 1

Biomimetic Kinetic Façade Scenarios	Smart_ Material_ ID	Focal_ Region_ Radius	Depth	Peripheral_ Region_ Domain	WWR	UDI	EUDI	sDA	DGP1
March 21- Hour 9:00	1	1.2	0.5	0.9 To 0.05	0.47	80.17	16.76	100	0.25
March 21- Hour 12:00	1	0.8	0.5	0.9 To 0.05	0.50	82.19	13.88	98.44	0.29
March 21- Hour 15:00	2	0.4	0.5	0.9 To 0.05	0.46	81.29	15.43	98.44	0.26
June 21- Hour 9:00	1	1.2	0.5	0.9 To 0.05	0.49	81.09	15.44	100	0.23
June 21- Hour 12:00	1	0.8	0.5	0.9 To 0.05	0.49	81.45	14.65	95.31	0.28
June 21- Hour 15:00	2	0.8	0.5	0.9 To 0.05	0.50	81.64	14.30	84.38	0.24
December 21- Hour 9:00	1	1.2	0.5	0.9 To 0.05	0.479	80.03	17.13	100	0.17
December 21- Hour 12:00	1	0.8	0.5	0.9 To 0.05	0.52	83.14	12.94	95.31	0.25
December- Hour 15:00	1	1.2	0.5	0.6 To 0.05	0.53	83.48	12.58	95.31	0.21

3.3 Biomimetic kinetic facade with different combination of FRR for occupant 2

Using the same approach as for position 1, in this section the results for position 2 are anlysing. Figure 9.8 presents a general analysis for position 2 which demonstrate the high potential of the biomimetic kinetic façade for daylight performance and occupant comfort. The bar charts display the average values of the analysed daylight metrics for each of the FRR regions with their respective depths (0.25 and 0.50).

The sDA values fall within a range of 87.5% to 100%. This indicates that the room is generally well-lit with natural daylight, which is considered suitable for visual comfort and reducing the need for artificial lighting during daylight hours. The highest sDA values close to 100% are achieved with FRR=4. The depth of the modular element plays a role in the sDA values. When the depth is 0.25, the sDA values are consistently at 100% for all months and hours analysed. However, when the depth increases to 0.50, the sDA values drop slightly, with the minimum value being 98.96% (month 12, h. 15). The decrease in sDA could be attributed to reduced daylight penetration due to the increased depth. The optimal configuration is given by an FRR of 1.2 and an element depth of 0.5 that achieves a still acceptable sDA value of 87.5%. This indicates that even with a slightly reduced field of view fraction and deeper modular elements, the space still receives a considerable amount of suitable daylight.
The comparison with the base case and static case with fixed shading shows no significant differences in terms of sDA values.
The kinetic biomimetic facade has a positive impact on the UDI percentages compared to the base case (UDI=39.55%) and static case (UDI= 63,15%). The UDI percentages increase with different configurations of the facade. The highest UDI value of 81.14% is achieved with the facade having an FRR of 1.2 and a depth of the element equal to 0.5. This value is recorded at month 12 and hour 12. The lowest UDI value of 68.28% is achieved by the configurations with FRR values of 0.4 and 0.8 and a depth of the element equal to 0.25. This value is recorded at month 12 and hour 15.
The studied facade variations resulted in a significant decrease in EUDI values compared to the base and static cases. The lowest EUDI value obtained was 14.91%, and this occurred during month 12, hour 12, with FRR set to 1.2 and a depth of 0.5. This implies a higher level of occupant satisfaction and comfort during these conditions. The highest EUDI value obtained was 30.76%, and it was recorded during month 6, hour 15, with FRR set to 0.4 and a depth of 0.25. Despite being the highest value achieved, it IS still considered acceptable as it does not affect the comfort and well-being of users during working hours.
The glare values there are within the optimal ranges. The DGP values does not exceed 35% except in one case, where it reaches 35.32% (month 9, h. 12, FRR 0.4, depht 0.25). The smallest DGP value is 17.4 % (month 12, h. 9, FRR 0.4, depht 0.5). In the base case, almost 40% of the time, glare caused intolerable and disturbing glareThis implies that the biomimetic façade helps significantly reduce glare-related discomfort.
Figure 9.9 shows the parametric exploration of 486 biomimetic kinetic façade alternatives in the different FRR and PRD combinations, using different simulation parameters with inputs and outputs. The graph shown in Fig. 9.9 selects only the best combinations by applying the criterion of considering only the values of sDA > 80, UDI > 77, DGP < 0.35. Table 5 shows the

climate-based light metrics and the luminance-based survey in the different FRR and PRD combinations for occupant 2 facing south.

Table 9.1 provides information on the optimum daylight performance of various FFR and PRD configurations on solstice and equinox days. The performance metrics considered are UDI, EUDI, and sDA values that varying in the ranges 77.45 – 82.56, 13.92 – 20.37 and 92.19 - 100, respectively, while benefiting from different window-to-wall ratios (WWR) between 0.40 and 0.53.

Fig. 9.8. General analysis of daylight performance and visual comfort for position 2. Average of UDI, EUDI, Sda, WWR, DGP values for different focal region radii (FRR) (1.2 -0.8-0.4) and different depths (0.25-0.5)

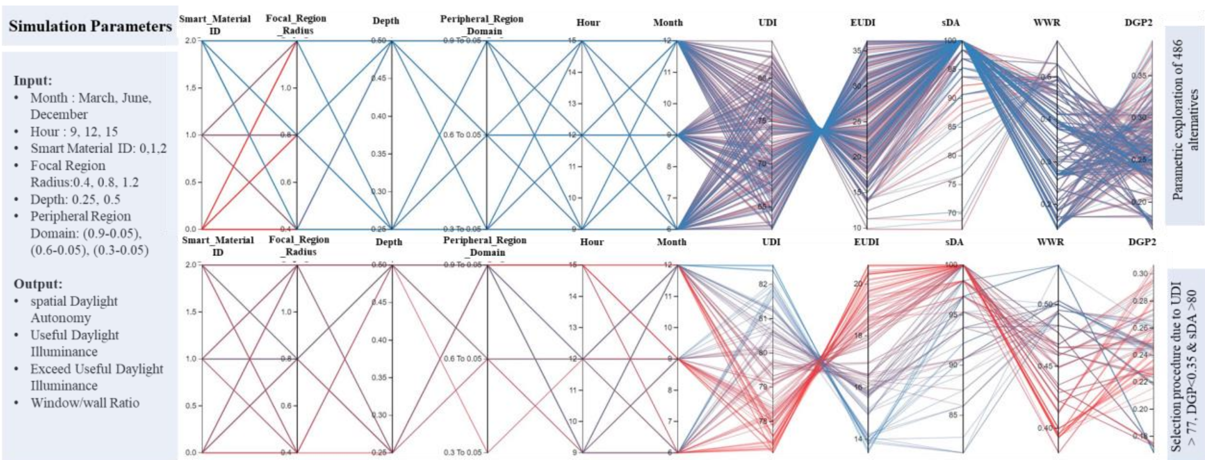

Fig. 9.9. Parametric exploration of xxx alternatives if kinetic biomimetic kinetic facade according to the occupant position 2

Table 9.4. Climate-based daylight metrics and luminance-based investigation of the most optimum Biomimetic kinetic façades with different Focal Region Radiuses (FRR) and Peripheral Region Domain (PRD) for the South direction according to the occupant position 2

Biomimetic Kinetic Façade Scenarios	Smart_ Material_ ID	Focal_ Region_ Radius	Depth	Peripheral_ Region_ Domain	WWR	UDI	EUDI	sDA	DGP1
March 21- Hour 9:00	0	1.2	0.5	0.9 To 0.05	0.50	82	13.92	92.19	0.24
March 21- Hour 12:00	0	0.8	0.5	0.9 To 0.05	0.47	80.90	15.60	96.88	0.28
March 21- Hour 15:00	1	1.2	0.5	0.9 To 0.05	0.42	78.38	19.19	100	0.23
June 21- Hour 9:00	0	0.8	0.5	0.9 To 0.05	0.46	80.9	15.61	98.44	0.22
June 21- Hour 12:00	0	0.8	0.5	0.9 To 0.05	0.46	80.67	15.81	93.75	0.26
June 21- Hour 15:00	1	1.2	0.5	0.9 To 0.05	0.53	82.56	13.48	98.44	0.16
December 21- Hour 9:00	0	0.8	0.5	0.9 To 0.05	0.48	81.04	15.67	100	0.17
December 21- Hour 12:00	1	0.4	0.5	0.9 To 0.05	0.45	80.41	16.45	100	0.26
December- Hour 15:00	1	1.2	0.5	0.9 To 0.05	0.40	77.45	20.37	100	0.23

4. Discussion

The integration of biological principles and their translation into a biomimetic design solution was enabled by the combination of the bio-AM [17], with the proposed daylight simulation parametric workflow, which represent the main novelty of this research. The morphological-behavioural analysis of the *Gazania* flower favoured the creation of modular elements that behave differently depending on their location in the focal or peripheral regions, like the radial distribution of petals around the central node of the flower. The modular elements, capable of periodic geometric movements, with different depths protruding from the plane of the façade, favour the achievement of daylight performance and visual comfort. In fact, some studies [16], [18] have shown that the interactive modification of the shape of the façade modules improves visual comfort in relation to the position of the sun and that of the occupants, thanks to their high performance.

The results of the parametric simulations show that the light-responsive kinetic biomimetic façade system is able to ensure high values of daylight performance and visual comfort compared to the base case. The setting of different material reflectance values (0.05-0.2-0.4) did not produce substantial results in the three reflectance combinations, therefore, only for safety reasons, the results were analysed considering the highest reflectance value equal to 0.4. The sDA values between the base case, the static case with fixed shading, and the kinetic biomimetic façade system do not show significant differences, while the UDI and EUDI values improve significantly and consequently also the DGP values.

The results for both positions (P1 and P2) showed improvements in UDI percentages with the kinetic biomimetic façade compared to the base case (UDI= 39.55%) and static case (UDI=

63,15%), with different configurations achieving different levels of UDI. The highest UDI values (83.42%) were attained with an FRR of 1.2 and a depth of the element equal to 0.5, while the lowest values were associated with FRR values of 0.4 (67.4%) and 0.8 (68.28%) and a depth of 0.25. The EUDI values, which flag on overheating nearby the façade, decrease by about 50% for both positions compared to the base case and static one.

The presence of the biomimetic façade system appears to significantly improve the glare conditions at both positions compared to the base case and static one. Most of the time, glare is non-perceptible or well below the threshold for discomfort, suggesting that the biomimetic façade contributes positively to user comfort. In both positions, the DGP values are generally within an acceptable range, and in position 1, the biomimetic façade significantly reduces intolerable and disturbing glare compared to the base case and static case.

However, it is important to be aware of the specific conditions and factors such as time of day, month and FRR that influence the occurrence of perceptible glare. So, the comparison with the base case shows significant differences in terms of UDI, EUDI e DGP values, that increase more than 50%. This suggests that the changes made to the facade configurations (e.g., different FRR and depth values) did have a substantial impact on the overall spatial daylight autonomy. In summary, the study demonstrates that adjusting the FRR and depth parameters can have a significant impact on occupant comfort at both positions, with some configurations providing higher UDI values and thus greater comfort and satisfaction. Overall, the results indicate that the biomimetic kinetic façade system is well-designed to put in the office room a high amount of natural daylight, promoting energy efficiency and occupant well-being. It responds to the optimal ranges of climate-based daylight metrics and prevents glare and overheating by blocking direct sunlight. The light-responsive dynamic shading solution guarantees high performance values in daylight and visual comfort compared to a solution without shading and to a solution with fixed shading. The dynamic system can adapt to optimise its performance based on real-time conditions. Another advantage of the dynamic system is that it reduces artificial lighting during working hours, resulting in energy savings and better communication with the external environment. Overall, the dynamic solution, unlike the static one, offers adaptability, flexibility and the potential to improve comfort and energy efficiency. Modelling and parametric simulations have favoured the analysis of complex geometries by adjusting the shape and depth of each module element according to the position of the sun and the occupants. In this way, the façade's response can be analysed in real time in terms of filtering and modulating sunlight, whose dynamic nature leads to problems such as glare, excessive reflection, and overheating. Furthermore, the parametric study of the best façade combinations and configurations favours the future subsequent materialisation phase of the individual façade elements, which are created considering the results of the simulation itself. Indeed, the matrix of a photosensitive memory polymer varies from case to case according to need. Therefore, before its realisation, it must be defined taking into account various characteristics and conditions (e.g. modularity, cyclicity of the desired kinetic movement, depth of expansion, etc.) as well as the reaction function to be fulfilled. Modelling and

parametric simulations therefore prove to be a preliminary stage for the future phases of material creation.
The selection of materials will be crucial in the creation of biomimetic kinetic façades, as the movement, engineering properties and performance of the materials significantly affect the adaptation and responsiveness of the façade. The integration of biomimetic and smart materials could represent an innovative approach to architecture that allows constructions to interact harmoniously with their surroundings. As mentioned earlier, concrete tests on physical prototypes are needed to test the validity of translating the biomimetic solution proposed in this study into biomimetic technologies.
In order to emphasise the novelty of this study in comparison with the architectural examples already existing in the literature or those already built, a comparative analysis is necessary.
However, most of the existing kinetic façades have a uniform movement of the façade modules, which leads to problems related to, for example, limiting the natural light entering the spaces, which could lead to the use of artificial lighting due to excessive screening.
In contrast to the kinetic façades of the Kolding Campus in Denmark, the Esplanade in Singapore and the Q1 building in the Thyssen Quarter in Germany, which are characterised by dynamic shielding systems with uniform movements of the individual modules activated by a sensor and actuation system, the kinetic biomimetic façade proposed in this study assumes to delegate the activation of its modules to the light-responsive polymer and shows an uneven distribution of the rhomboid elements depending on the point of attraction and thus on the position of the sun and the occupants.
In other examples, however, the modular shielding elements do not adopt uniform openings but vary according to their position on the façade and thus in relation to the orientation of the sun.
Although the shading solution of the Al-bahr towers has been proven to reduce solar radiation by 50% [19] while improving visibility and having an uneven distribution of façade modules at the same depth, the rhomboidal modules of the façade, inspired by the *Gazania*, can adopt different depths and openings at the same level as the façade, which greatly improves indoor performance and meets real-time needs.
So, in contrast to these solutions, the following study also considers the position of the occupants and, above all, delegates the control of solar radiation to each system module, which, thanks to its intelligent characteristics, acts as a sensor and actuator, limiting energy consumption and automation systems.
The definition of the focal and peripheral areas brings an application-functional advantage, because in the FRR configurations, the light is shielded more according to the position of the sun and the location of the occupants, to avoid problems of excessive lighting and glare near the occupants, while in the peripheral areas, the expansion and contraction of each module is reduced compared to the focal areas, to ensure an optimal percentage of natural light in the rooms that does not disturb the occupants. In fact, the results of the simulations have shown that the solution with FRR significantly improves indoor performance compared to the base case without shielding. In particular, the EUDI and DGP values increase by 50%. The

introduction of the Focal Region Radius (FRR) is thus a key parameter that plays an important role in identifying areas of the façade that require more attention in terms of solar radiation modulation.

This advantage should also be emphasised in comparison with the studies available in the scientific literature. Recently, a study by Flor et al. [20] (2022) investigated the effects of daylighting in architectural spaces with adaptive ETFE façades and showed the possibility of a significant 59% reduction in glare in the best configuration compared to the base case without double skin. A study by Norouziasas et al [21](2023) investigated the effect of automatically controlled blinds to evaluate the improvement in energy efficiency and lighting demand of an office building. Their results show that automatically controlled blinds improve the energy efficiency of an office by 19.47% and reduce the lighting demand by 2.91% compared to static shading, which also confirms the advantages of roller blinds over Venetian blinds. However, both studies lack reference to materials and configurations based on focal and peripheral areas. The FFR concept proposed in this study is in line with previous studies by Hosseini, who introduced transient sensitive areas and periodic geometric changes. In 2020 [22], he presented a kinetic design integrating rotational motion with a coloured glass composition, while in 2022 [1] he integrated the coloured glass composition with the egg carton and hexagonal lattice (FEC-CCG) at different depths and demonstrated an improvement in UDI and EUDI compared to the 2020 solution and compared to the base case without shielding, proposing the optimal solution each time. The latest solution proposed by Hosseini [1] is inspired by the biomimetic lessons of the Morpho butterfly, which has enabled the integration of morphology with coloured glass, taking into account time, sun position and occupants. In the present case, however, the morphological-functional analysis of the *Gazania* flower has not only enabled the definition of parallelism with photosensitive polymers, but also the possibility of creating a dynamic and decentralised pattern of rhomboidal modular elements that parallel the individual petals of the flower. Therefore, the bio- AM is configured as an essential tool for biomimetic design, and the biological study is a fundamental phase as it allows abstracting from the principles of nature that provide ideas for the creation of high-performance kinetic facades. Indeed, in this study, starting from the analysis of the different adaptive behavioural strategies of plants, it was possible to identify the plant species that best implement light-responsive nictinastic mechanisms in order to propose a solution capable of modulating, filtering and regulating solar radiation. BSDF definitions can also be derived from measurements of complex fenestration systems through goniophotometer testing, which necessitates the creation of a prototype and the execution of experimental measurements. However, this study was constrained to building performance simulations due to insufficient funding.

The integration of new intelligent materials could enhance the functionality of environmental systems. The shapes, colours, textures and translucency of the new materials create new relationships with the natural and/or the built environment to promote a more sustainable approach to designing environmentally responsive solutions in architecture.

5. Conclusion

The dynamic nature of daylight can cause discomfort for users due to glare, excessive reflection and overheating near the façade. Learning from the kinetic movements of the *Gazania* flower enables the development of a light-responsive biomimetic façade system capable of regulating and adapting to the dynamism of daylight to avoid the associated discomfort and reduce energy consumption from artificial lighting. Through a multidisciplinary approach, involving experts from different fields this manuscript aims to translate the bio-AM to a computational design model and apply general lessons and logics learned from the *Gazania* flower to a kinetic mechanism that respond to user's visual comfort and daylight performance requirements.

The combination of bio-AM with the daylight simulation parametric workflow provides a method that can be followed by designers to define new responsive solutions inspired by nature. Unlike conventional adaptive solutions with uniform distribution, the modules of the biomimetic kinetic system have different dimensions and depths, depending on the radius of the focal region (FFR). This configuration ensures improved performance for user comfort.

The research demonstrated excellent performance improvement compared to the base case without shading and static case with fixed shading, when considering climate-based daylight metrics and glare values, particularly for UDI, EUDI, and DGP values.

Light-responsive polymers properties were analysed and chosen as the smart materials because they could guarantee the kinetic façade system to respond autonomously to light stimuli using the intrinsic properties of the material itself. This design solution, transformed into technology, would eliminate the need for external automatic devices, leading to reduced energy consumption, maintenance costs, and management expenses.

Although parametric modeling helped identify the best façade system configuration, including FRR and modular element depth, the physical response of the smart material, its cyclicity, and modularity need to be validated through real prototypes. Thus, creating physical prototypes represents a future research horizon resulting from this study to validate the real use of shape memory polymers.

The results of this study also highlight the need for further research to refine and validate the design of the proposed energy system, particularly under different solar angles, orientations and climates. It will be necessary to collect a large amount of data and analyse it using regression analysis as a new research study.

Although the proposed solution does not seem to require additional energy input due to the use of self-responsive smart materials, it could cause high costs during the production cycle and harm the environment during the life cycle due to the chemical nature of the materials. Therefore, Life Cycle Assessment (LCA) of the light-responsive biomimetic system is configured as a fundamental future step to quantify the environmental impact, including greenhouse gas emissions, to provide useful information on their performance over time in terms of reliability and longevity, but also to assess linearity with sustainability goals. Overall, this study presents a biomimetic approach in parametric design to develop novel façade systems, by combining biological principles, materials science and architecture for more adaptable and sustainable solutions to meet real-world challenges in daylighting and indoor comfort.

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Conclusions and future perspectives

The building envelope contributes significantly to the energy consumption of buildings and has a negative impact on the environment that can be mitigated through appropriate design. Due to their static nature (in most cases), traditional solutions fail to meet the challenges of the current climate changes and crisis. Many species in nature have evolved to thrive in harsh and changing environments. Studying their adaptation strategies can help us understand how to develop solutions to withstand the effects of climate change, including high temperatures and excessive solar radiation. The adaptive biomimetic approach, applied to building envelope technologies, could reduce energy consumption for air conditioning, heating, cooling and lighting, adapting to the needs of users based on the climatic conditions surrounding the building. In this way, the building reacts passively to environmental fluctuations, similar to natural organisms.
The aim of the following thesis was to propose a new methodological approach - the bio-Adaptive Model - capable of translating the adaptive strategies of plants into adaptive envelope technologies through the use of intelligent, self-responsive materials.
Functionally and behaviourally mimicking the skins of natural organisms made it possible to draw clear parallels with the building envelope to regulate the flows of environmental parameters, including light, temperature and water.

It is possible to conclude that a biomimetic adaptive envelope:

- can change according to temperature, solar radiation or wind, reducing the need for active heating, cooling and lighting systems;
- can reduce temperature fluctuations, minimise glare and provide better natural ventilation, leading to greater well-being and productivity;
- can improve a building's resilience to climate change, as they can adapt to extreme weather conditions without manual intervention. This adaptability is particularly important in regions with fluctuating or unpredictable climates;

Biomimetic designs often result in aesthetically pleasing and unique architectural features, as elements inspired by nature can make buildings more attractive and visually appealing.

1. General overview

<u>Step 1:</u>
The first step of this work was to review the scientific literature and the state of the art on adaptive and biomimetic building envelopes, to analyse and systematise the existing information and to analyse the different examples. Several examples of adaptive envelopes were analysed to provide an overview of the progress of the application of biomimetic principles in the AEC sector, especially in the architectural field.

The analysis of adaptive and biomimetic envelopes has made it possible to define the limitations and potentials of biomimetics, with a clear potential in the architectural field for energy efficiency and environmental considerations. Nevertheless, adaptive biomimetic applications are still limited and mostly at a prototype stage. Existing examples of adaptive envelopes are limited to shading systems and limited to an emulation of structural morphologies, while only a small part of these are dynamic-functional emulations in prototypes or in temporary structures such as pavilions.

Step 2:

In the second step, following a biological study to explore and understand the functional adaptation mechanisms of plants, the study and analysis of the chemical-physical behaviour of smart self-responsive materials to the main environmental stimuli (light, temperature, water) has allowed to define the parallels between nature and architecture. The adaptation strategies of plants implement relevant mechanisms for survival and have clear analogy to buildings in terms of static location and climatic conditions.

The investigation of existing approach has highlighted the lack of a precise method that provides accurate evidence of the transition from nature to architecture, acting on a specific spatial scale of the building envelope (façade, façade component, materials). This study provided an overview of the related characteristics that were used to inform a new biomimetic model, defining the steps to move from biological principles to architectural technologies.

The need for dynamic envelopes capable of interacting with the environment, as is the case with natural organisms, has increased research into the development of advanced technologies and materials for potential applications to buildings. Smart materials are excellent candidates to achieve interaction with and responsiveness to the environment.

The ability to respond autonomously to external stimuli makes smart materials an excellent tool for biomimetic building envelopes, as they can replicate nature's adaptive functional mechanisms without requiring additional energy.

The classification of smart responsive materials, based on their response to light, temperature and water, has made it possible to create a biomimetic matrix to integrate the bio-AM. It is configured as an important tool for researchers approaching the early stages of biomimetic design, with which they can identify the smart responsive material that best fits the responsive functions required by the envelope they are designing.

Step 3:

In the third and final step of this work, the Bio-AM was integrated with a parametric simulation workflow applied to the case study of the Gazania flower, which is characterised by nyctinastic movements that vary according to the intensity of the light stimulus. These biological principles were abstracted and used to design a light-responsive facade system for an office building in a temperate Mediterranean climate, based on the hypothesis of using intelligent azobenzene-based light-sensitive materials. Since the biomimetic kinetic façade system is activated by the position of the sun and the position of the occupants near the point of attraction, parametric studies of 486 alternatives were performed for each position of the occupant (P1 and P2), totalling 972 simulations based on different values of Focal Region Radius (FRR), Peripheral Region Domain (PRD), depth and reflectance.

This study presented a novel solution to the design of a light-responsive biomimetic kinetic façade system, to ensure user comfort, control solar radiation and prevent issues caused by glare. The research followed a multidisciplinary approach, involving skills from different fields. The combination of bio-AM with the daylight simulation parametric workflow provides a method that can be followed by designers to define new responsive solutions inspired by nature. Unlike conventional adaptive solutions with uniform distribution, the modules of the biomimetic kinetic system have different dimensions and depths, depending on the radius of the focal region (FFR). This configuration ensures improved performance for user comfort.

The research demonstrated excellent performance improvement compared to the base case when considering climate-based daylight metrics and glare values, particularly for UDI, EUDI, and DGP values. The results of the parametric simulations show that the biomimetic kinetic system is well suited to provide the office space with variable natural daylight between 87,5% and 100%, promoting energy efficiency and user comfort.

Light-responsive polymers properties were analysed and chosen as the smart materials because they could guarantee the kinetic façade system to respond autonomously to light stimuli using the intrinsic properties of the material itself.

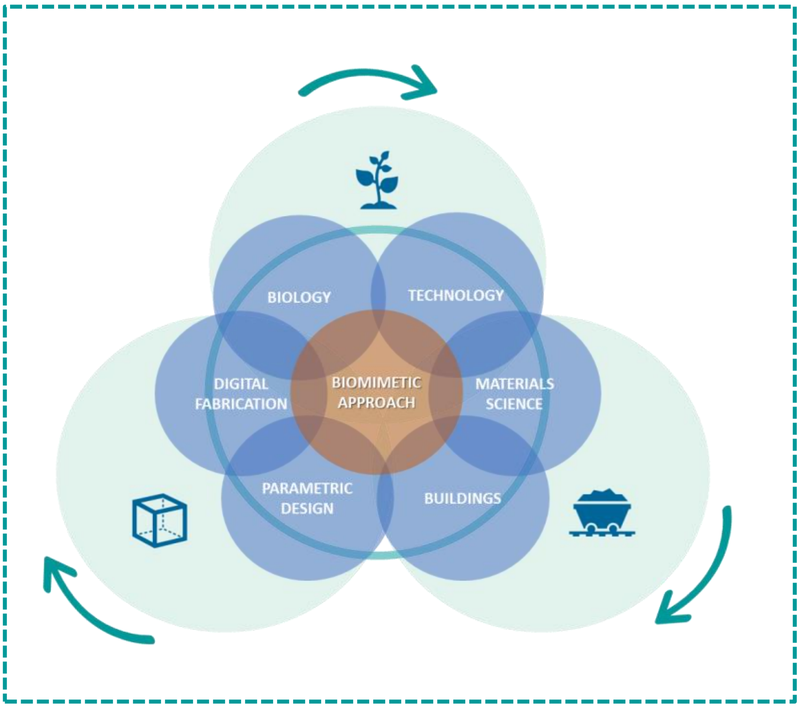

Fig.1: Multidisciplinarity of the biomimetic approach

Overall, this study presents a biomimetic approach in parametric design to develop novel façade systems, by combining biological principles, materials science and architecture for more adaptable and sustainable solutions to meet real-world challenges in daylighting and indoor comfort. This demonstrates the multidisciplinary approach that the biomimetic discipline is able to guarantee (Fig. 1).

2. Biomimetic approach and climatic goals

The biomimetic approach can play a crucial role in improving climate resilience by creating more sustainable and adaptive solutions. By mimicking the natural world, it is possible to develop innovative solutions that not only mitigate the effects of climate change, but also contribute to a more harmonious and sustainable coexistence with the environment. The aforementioned adaptive biomimetic approach can help design technological solutions that enable adaptation to changing climate conditions and thus contribute to climate change mitigation (SDG 13 – Climate Action). This contributes directly to SDG 7 (Affordable and Clean Energy) by promoting energy efficiency. Furthermore, the control of environmental parameters, such as solar radiation in the case of the Gazania flower-inspired façade system, contributes to improving the well-being of the internal environment and users (linked to SDG 3 - Health and well-being). At the same time, the use of smart and self-responsive materials that can interact with the environment without requiring additional energy is in line with SDG 12 (Responsible Consumption and Production) by promoting the use of materials that reduce energy consumption. Finally, biomimetic solutions and smart materials that can create sustainable building solutions are also in line with SDG 9 (Industry, innovation and infrastructure) as they promote technological advances and innovation in the construction sector.

3. Advantages of parametric design in biomimetic approach

Parametric design allows architects and designers to create complex geometries precisely to imitate natural forms and functions. This level of precision is essential to achieve the desired performance and aesthetics in adaptive building envelopes. Parametric design tools and algorithms can be used to optimise the shape, orientation, and behaviour of building components. This optimisation process can lead to more efficient use of materials, energy, and resources. By simulating different design iterations and testing different parameters, designers can identify the most efficient and effective biomimetic solutions for adaptive building envelopes. The proposed bio-adaptive model involves an iterative process of testing and refining ideas. Parametric design facilitates this iterative approach by allowing designers to make rapid changes and test the performance of different design options. In summary, parametric design is critical in the design of adaptive building envelopes, especially in the biomimetic one, because it enables the precise modelling, optimisation, adaptability, and customisation required to integrate biological principles and create innovative, high-performance architectural solutions. It enables designers to translate complex natural systems into functional and sustainable envelopes designs.

4. Future research horizons

The proposed initial framework for developing the bio-AM aims to facilitate the efforts towards developing solutions for adaptive building envelopes in a systematic way and implement novel design solutions for a more sustainable and resilient future. The transfer of biological principles to building envelopes that can interact with the environment is still a challenge but has the potential to change the way we design sustainable solutions and to reduce the impact on the environment, and eventually contribute to achieving climate neutrality by 2050. The proposal of the light-responsive facade system through the combination of Bio-AM with the parametric design workflow and the hypothesis of using smart self-responsive materials offers the possibility of not having to rely on external automatic devices, resulting in a reduction of energy consumption, maintenance costs and management expenses.

However, although parametric modeling helped identify the best façade system configuration, including FRR and modular element depth, the physical response of the smart material, its cyclicity, and modularity need to be validated through real prototypes. Thus, creating physical prototypes represents a future re-search horizon resulting from this study to validate the real use of shape memory polymers.

Although various studies are underway, the application of smart materials in the field of building technology remains a major challenge. Increased collaboration between experts from biology and materials science is essential to promote interdisciplinarity and achieve better results.

The approach used in this study also offers several possibilities for iteration, not only for the different and numerous replicas of natural organisms, but also for the different interactions with environmental triggers that vary according to the climatic context. This results in a complex application with a direct emulative correspondence between the building and a plant. At the same time, parametric modelling would also become more complex in the development of the biomimetic solution to define multi-layered and multi-functional solutions, where others are added to the single responsive function of the smart material, e.g. the conversion of movement into energy.

In conclusion, this study makes several recommendations for future research, including the need to develop physical prototypes to test the effectiveness of applying smart materials to building facades. As highlighted in the chapter analysing smart materials, there is a particular need to evaluate the response time and modularity of the material under specific environmental conditions. As these are solutions that anticipate future passive technologies, or rather that do not require additional energy consumption and therefore limit the impact on the environment, a future Life Cycle Assessment (LCA) would be desirable to understand the impact of these materials on the environment and the possibility of digital manufacturing should be evaluated to calculate the reduction of costs and working times. LCA would help determine whether the use of biomimetic solutions and smart materials reduces carbon emissions, energy consumption and resource use over the lifetime of the building envelope. This information is key to making informed decisions in line with sustainability goals and combating climate change. Assessing the life-cycle costs of such solutions also helps to evaluate their economic feasibility. Biomimetic solutions with smart materials, while more expensive upfront, can offer long-term cost savings through improved energy efficiency, reduced maintenance, and longer life. Assessments can help developers, builders and property owners make informed financial decisions.