Renewable and Sustainable Energy Reviews 67 (2017) 692–703

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

How plants inspire façades. From plants to architecture: Biomimetic principles for the development of adaptive architectural envelopes

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A R T I C L E I N F O

Article history:
Received 15 September 2015
Received in revised form
14 July 2016
Accepted 8 September 2016

Keywords:
Biomimicry
Adaptive architectural envelopes
Energy efficiency
Plant adaptations
Climate adaptations

A B S T R A C T

Façades have an important role in the control of energy waste in buildings, nevertheless most of them are designed to provide static design solutions, wasting large amounts of energy to maintain the internal comfort. However, biological adaptation solutions are complex, multi-functional and highly responsive. This paper proposes a biomimetic research of the relationship that can be developed between Biology and Architecture in order to propose innovative façade design solutions. We focus on plants, because of plants, like buildings, lack of movement and remain subject to a specific location. Nevertheless, plants have adapted to the environment developing special means of interaction with changing external issues.

This paper provides a methodology to create a data collection of plant adaptations and a design mapping to guide the transfer from biological principles to architectural resources, as well as two design concept cases, opening new perspectives for new possible technical solutions and showing the potential of plant adaptations to environmental conditions at a specific climate. Further step is the transformation of some design concepts into technical solutions through experiments with new technologies that include multi-material 3D printing or advances in material science.

Contents

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http://dx.doi.org/10.1016/j.rser.2016.09.018
1364-0321/

1. Introduction

"Cities are part of the climate change problem, but they are also a key part of the solution." [1]. Currently cities consume the larger part of global energy and are therefore major contributors of greenhouse gas emissions. Moreover, cities' authorities have the power to act on climate change by handling urban issues in a responsible way over urban sectors such as buildings. According to European Council estimates, buildings are currently responsible for 40% of the European Union's energy consumption and 36% of its CO2 emissions and is committed to reducing greenhouse gas emissions to 80–95% below 1990 levels by 2050 [2]. This is shown by how the European Union has been developing a large number of funding building efficiency programmes for research and innovation, such as Horizon 2020 framework [3]. It proposes that energy efficiency to be raised to a higher level through '*the coherent application of passive and active design* strategies *in order to reduce the heating and cooling loads*', '*raising equipment energy efficiency*', and '*the use of renewable energies*' [4]. Some of these programmes focus on building retrofitting, or the installation of energy-efficient technologies, especially on façades. Better insulation materials, greener energy sources, more efficient financing, and better use of information and communication technology are just some of the main paths being explored [5].

The building envelope, without distinction between walls and roof, is the interface between exterior environmental factors and the interior demands of the occupants [6]. The building envelope separates the indoor and outdoor environments of a building, and is the key factor that determines the quality and controls the indoor conditions irrespective of transient outdoor [7]. Therefore, building envelopes, architectural skins or façades have an important role in the regulation and control of energy waste, since they act as intermediary filters between external environmental conditions and between external environmental conditions and the desired requirements inside. Building envelope is one of the most important design parameters determining indoor physical environment, thus affecting energy usages in buildings [8,9]. Due to this decisive role, in recent years, envelopes have been the subject of numerous studies and research around the world, always trying to achieve greater efficiency and performance, in terms of energy, comfort or structure. An increasing number of projects about improvements, challenges and possibilities in the building envelope and their impact on building energy usage, has seen significant progress in recent years, because a suitable architectural design of an envelope can significantly lower the energy usage and 'the reduction of energy consumption' and 'enhancing the indoor comfort' are the two most important goals that are necessary to be realized as the result of smart building performance [10–12].

Adaptation is the evolutionary process whereby an organism becomes better able to live in its habitat [13].

Nowadays, biology is no longer just a matter for biologists, but it is a new inspiration for technological thinking. Some of these studies have looked at nature as a source of inspiration for subsequent application to architecture. This trend known as biomimicry is a discipline that has been developing for some time in other fields, such as engineering or medicine, and it is only in recent years where we begin to see its application to architecture. Systems found in nature offer a large database of strategies and mechanisms that can be implemented in biomimetic designs.

This paper is about the transfer of plant adaptation strategies into technology for innovation. In the first part of the paper, a review of advances in adaptive architectural envelopes are presented, including those based on biomimetic principles. In addition to the built projects reviewed, other academic research works are analyzed and compared. In the second part of the paper a broad overview of plant adaptations are provided. Furthermore, novel concepts for optimizing energy efficiency in building envelopes, abstracted from plants that respond to different environmental issues, are also introduced and discussed for possible application in adaptive systems for building envelopes that respond to changing environmental conditions. To achieve the objectives of designing an adaptive architectural envelope using lessons from natural systems, the following questions have been proposed:

1. How can lessons from plant systems be utilized to create a envelope that incorporates and functions like nature?
2. Is it possible to generate design concepts for building envelopes that regulate environmental aspects, based on adaptation strategies from plants?
3. Is it possible to obtain greater energy efficiency in the construction of exterior walls in buildings by mimicking nature as opposed to building façades according to the traditional processes?

2. Adaptive architectural envelopes: a review

2.1. Adaptation

Adaptation is the evolutionary process whereby an organism becomes better able to live in its habitat [13].

Most of definitions of a building envelope establish it as an enclosure, a separation between the interior and exterior environment, that provides the following functions: support, control, finish (aesthetics) and distribution of services. However, we are more interested in the building envelope, without distinction between walls and roof, as an interface and not a separation, between exterior environmental factors and the interior demands of the occupants [6]. Building envelope as an environmental moderator [14].

The environment is constantly changing and producing new challenges to cope with. Light (solar radiation), temperature, relative humidity, rainwater, wind (air movement), noises and carbon dioxide (air quality) are the basic environmental issues affecting the building. These issues significantly affect occupant comfort demands as well as building performance. Despite the fact that the climatic characteristics of the area are variable parameters, conventional façades are largely static; so, we use large amounts of energy in order to control internal comfort. Energy consumption for space heating and cooling makes up 60% of the total consumed energy in buildings [15].

The current solutions of managing the external environmental changes have caused a great deal of energy to be wasted in heating, cooling, ventilating or lighting our buildings between quite well defined limits, while external environmental factors can change considerably, resulting in existing solutions of static building envelope and dynamic building services. In consequence, the building sector is responsible for approximately two-thirds of halocarbon and approximately 25–33% of black carbon emissions [16], in addition to the building sector used 23% of the global primary energy and 30% of the global electricity [17].

Traditionally, the building envelope has been considered as thermal barrier or shield that has to be for example, insulated to prevent heat loss or shaded to control solar gain. This approach limits more efficient solutions, where the building envelope is not considered as a barrier but as a medium. Therefore conventional solutions for façades and roofs are not designed for optimum adaptation to contextual issues and needs. As opposed to our buildings, which remain inert, living objects respond to the environment and they are able to adapt to the changing weather conditions [18]. We are interested in biological solutions to adaptation because of they are often complex, multi-functional and highly responsive. Thus, unlike static and conventional building envelopes a new adaptive architectural envelope is necessary to improve energy performance.

A summary of definitions about adaptive architectural envelopes are currently available in the literature, such as Climate Adaptive Building Shell (CABS) by Loonen [19–21]; Acclimated Kinetic Envelope (AKE) by Wang et al. [14]; Adaptive skin by Hasselaar [22]; Intelligent skin by Wigginton and Harris [23] or Adaptive building skins by Del Grosso and Basso [24]. Some of them are compiled and compared in the review's work of Fiorito et al. [25].

Within the scope of this research, the type of adaptive architectural envelopes is defined as one that responds to changing environmental conditions both interior and exterior while managing the indoor environment. Adaptive architectural envelopes have the ability to change with time through adaptation strategies to anticipate exterior environmental variations as well as interior activities and their interactions with inhabitants. We research into adaptive architectural envelopes with two main proposals: contributing to energy-saving for heating, cooling, ventilation or lighting, as well as inducing a positive impact on the indoor environmental quality of buildings. Therefore, the building envelope could be constructed, not with the traditional inert surfaces but with a "living" cladding, which could house a wide range of technologies based on the behaviour of the envelopes found in nature [26].

2.2. Advances in architectural envelopes

Traditionally external control systems have been looked for in windows and doors, through the utilization of inexpensive and easy to operate manual shading or protection devices, such as exterior louvers, blinds or sunshades.. These operable devices can control e.g. solar thermal intrusion and reduce heat gain through windows and other glazed areas [27]. Zhiqiang Zhai in his research about energy performance of ancient vernacular homes demonstrated that "considering traditions seen in ancient vernacular architecture as an approach to improving building energy performance is a worthwhile endeavor and a scientific guidance can help enhance the performance" [28].

Since the last century different design proposals for more active and less static façades have gradually emerged, kinetic façades as environmental control systems, capable of responding to different changing environmental aspects. Some of these proposals have not passed the theoretical level, such as the concept developed in 1930 by Le Corbusier: a universal house for all climates, " only one house for all countries, the house of exact breathing" [29], because of the lack of technology at that time for such a futuristic idea. Later, in 1970, William Zuk described kinetic architecture as a field of architecture in which building components or whole buildings have the capability of adapting to change through kinetics in reversible, deformable, incremental and mobile modes [30].

The Arab Institute in Paris (Fig. 1a) completed in 1987, by Jean Nouvel, was one of the first and most widely known example to employ an active façade based on automatic response to environmental sensors. The automatically controlled shutters are a technical interpretation of the traditional Arabic sun screens [19]. 25,000 solar cells, similar to a camera lens, are controlled via a computer to moderate light levels on the south façade [31,32]. In his "state of the art CABS concepts" [33], Loonen includes this envelope inside thermal-optical domain, it means adaptation causes changes in the thermal energy balance of the building and, at the same time, the adaptive behaviour influences occupants' visual perception. Although laboratory tests or scale field tests to demonstrate that the visual comfort and energy benefits can be associated with these kinetic shading systems [34,35] their considered functionality design has not validated as a successful adaptive envelope case and it would be more considered as a complex façade system. According Coelho and

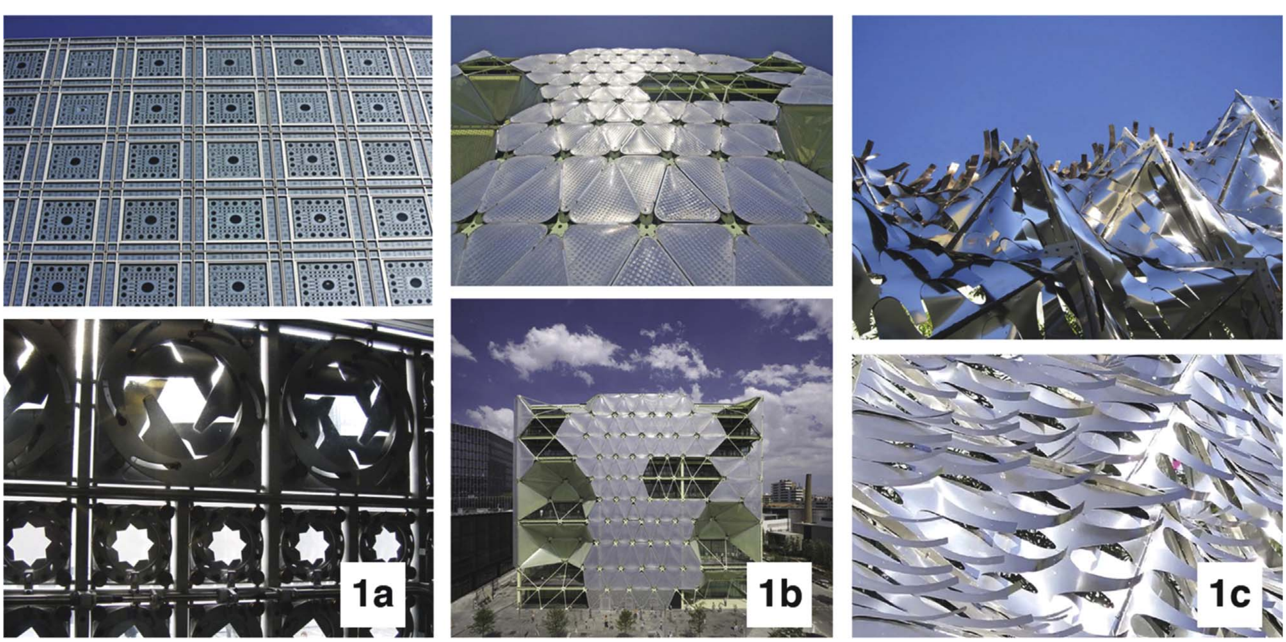

Fig. 1. Some examples of dynamic façades from recent years: (a) Arab Institute façade (b) Office Building Media-TIC and (c) Bloom installation details.

Maes' studies about shutters [36], the façade panels are noisy, tend to break easily and they are fully automated, not allowing residents in the building to have a high granularity of control over their own space. It would be about an adaptation reached by means of mechanical driven fenestration devices consuming electrical energy.

In recent years we have seen noted examples of advances in adaptive architectural envelopes, through architectural kinetics and dynamic structures. We mention here two projects, Office Building Media-TIC (Fig. 1b) by Enric Ruiz Geli (Cloud 9) and Bloom (Fig. 1c) by Doris Kim Sung, due to their experimental and innovative character.

In the first one, Office Building Media-TIC, architects designed an energy efficiency performative architecture with a "skin as an expression of energy" [37]. Building interacts with its environment through the ETFE skin, that added to a photovoltaic roof and rainwater recycling reduce carbon emissions by 95% [38]. Other buildings around the world used ETFE technology in façades: Eden in London [39], where the transparent ETFE cladding creates a microclimate; Arena in Munich [40] and National Aquatics center in Beijing [41], as iconic architectures. Unlike these other examples, in Office Building Media-TIC the adaptive envelope is created to achieve 65% CO2 reduction due to the dynamic ETFE sun filter and energy efficiency related to smart sensors. The adaptive envelope is differentiated according to southeast and southwest orientations. In the first one ETFE skin arranged in three inflatable layers in the form of a vertical cloud that filters solar radiation. The system of inflation is activated automatically by way of a network of temperature sensors. In the second one, where solar radiation is most intense, solar sun shading is achieved via a cloud through a fog system with nitrogen gas, which provides a variable shading reducing solar heat gain up to 90% [37,42,43].

The second one, Bloom by Doris Kim Sung, is a environmentally responsive installation. Bloom stitches together material experimentation, structural innovation, and computational form pattern making into an environmentally responsive installation. This envelope responds to changes in heat and light, is an sun-tracking instrument, regulating temperature and reducing the need for artificial cooling. Thermo-bimetal panels, with different coefficients of expansion, are used to regulate building temperature in a passive way. Metallic structure respond to environmental changes, curving and opening for ventilation and therefore preventing high temperatures in the interior space [44–47]. Bloom shows the potential of smart materials [48] that use environmental conditions, in this case temperature, as a green-trigger, without use electrical stimulus and the result is a sustainable responsive system able to save energy in cooling systems.

2.3. Biomimicry

The terms biomimicry and biomimetics come from the Greek words bios, meaning life, and mimesis, meaning to imitate. Biomimetics is defined as the "abstraction of good design from nature" [49] or "an emerging discipline that emulates nature's designs and processes to create a healthier, more sustainable planet" [50].

Usually it is a discipline that has been developing for some time in other fields, such as engineering or medicine, however in recent years we begin to see how several research works have been developed around biomimicry to look into new solutions in architecture. Michael Pawlyn has been a pioneering architect to apply biomimetic principles to this field and defines biomimicry as 'mimicking the functional basis of biological forms, processes and systems to produce sustainable solutions' [51]. His work looks to the natural world to seek clues as to how build more efficient structures, create zero-waste systems or produce energy for our buildings.

In recent years other research works have tried carrying out different methodologies for developing new building envelopes based on biomimetic principles. We compile some of the built projects, always in terms of adaptive envelopes and their interaction with the environment through energy exchanges and improving efficiency. The three examples are inspired by plants and they can perform movements and are, therefore, suitable for systems responsive to the continuous changing environment.

The first one is Flectofin® by ITKE [52]. Innovation is inspired by the valvular pollination mechanism in the *Strelitzia reginae* flower (commonly known as the Bird-Of-Paradise flower). Flower's inspiration comprises a reversible deformation when an external mechanical force is applied, making it a bending kinematics in nature and technical implementation resulting operates with a complete absence of technical hinges and only relies on reversible material deformation. This adaptive behaviour is abstracted and materialised as Flectofin®: a hinge-less louver system that is capable of shifting its fin 90 degrees by inducing bending stresses in the spine caused by displacement of a support or change of temperature in the lamina. One of the wide range of applications

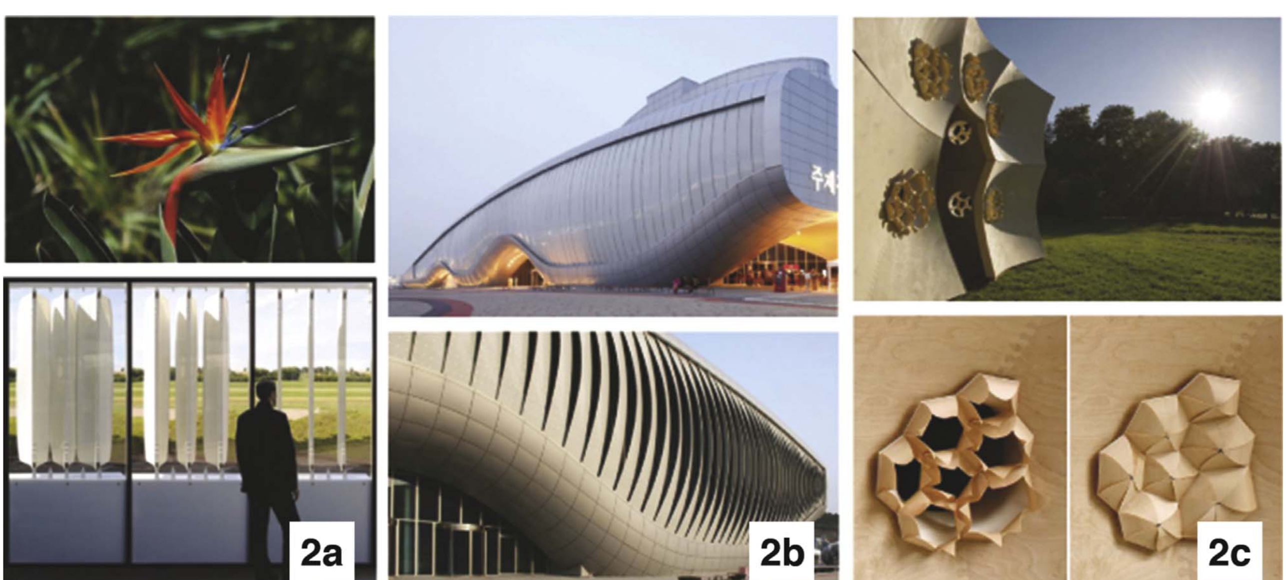

Fig. 2. Examples of biomimetic projects for adaptive architectural envelopes: (a) Flectofin® (b) One Ocean Thematic Pavilion (c) HygroSkin.

of the Flectofin® principle is as an adaptive exterior shading system (Fig. 2a) opening new possibilities for organic forms (double curved surfaces) and not restricted geometries. Functional benefits of an efficient shading system in buildings would be energy consumption reduction in mechanical cooling systems and the capturing of passive energy in winter, it means a great potential energy consumption reduction [53–57].

The second one is the One Ocean Thematic Pavilion (Fig. 2b) for Yeosu Expo 2012 in Korea, by SOMA Architecture, in collaboration with Knippers Helbig Advanced Engineering. An adaptive envelope system was developed inspired by the research on plant movements and kinematic mechanisms like the Flectofin®. A shading system, made of slightly curved plates, can adapt to light conditions and physical building conditions controlling and responding to changing sun light conditions during day [52,54,58].

Finally the third case presented is a meteorosensitive pavilion called HygroSkin (Fig. 2c) by Achim Menges in collaboration with Oliver David Krieg and Steffen Reichert. The pavilion's envelope is based on the movements observed in spruce cones as a passive response to humidity changes. HygroSkin uses the responsive capacity of the material itself, it uses relative humidity as a green trigger to interact to the environment. The dimensional instability of wood with respect to moisture content is employed to construct a weather-sensitive envelope that autonomously opens and closes in response to weather changes but neither requires the supply of operational energy nor any kind of mechanical or electronic control. The apertures respond to relative humidity changes within a range from 30% to 90%, modulating the light transmission and visual permeability of the envelope [59–65]. Research's potential, in terms of energy efficiency, has been develop an adaptive envelope that do not require any sensory equipment or electrical stimulus, based on biomimetic principles.

Through these three experimental systems we have seen the potential of biomimicry as a design tool to improve energy efficiency in buildings. Employing biomimetics as a tool in architecture will help develop a culture of active environmental design [66]. Biomimicry represents an alternative direction to reconcile energy efficiency with the need for high-quality indoor climates integrating adaptability into the building envelope, as inspired by principles found in nature. Modern construction techniques now offer ample opportunities for innovative adaptive envelopes that respond better to the environmental context, thereby allowing the façade to "behave" as a living organism [67]. It is important to note that in all cases biomimicry is not used to create an exact replica from nature but it is an abstraction and a transfer of functional principle from biology [68]. Biomimetics provides ideas to be discovered and adapted form nature's designs into sustainable building systems. The lessons from Nature are valuable to be applied as innovational technologies to carry out envelopes of the future [69]. As opposed to simply translating biomorphic elements from biology to architecture, the transfer of knowledge happens on a performative level, through the analysis of strategies in the way that problems are solved in biology and engineering [70]. However, the transfer from biology to technology is not an easy task. Julian Vincent reflects on the transfer of information between the disciplines and the procedures to identify the nature of the questions from engineering and marry them correctly with the answers from nature [71]. Possible reasons for failure of transfer could be superficial research, no information from life sciences, unimaginative approach or not scaleable phenomenon, being the consultancy from experts in life sciences the key to success [72]. Therefore, in this new way in which biology inspired approaches to design and fabrication, opportunities arise from collaborations between designers and biologist with scientist rigor [73,74].

In addition to the built projects reviewed previously, other academic research works are analyzed and compared. Theoretical studies such as "BioSkin" by Susanne Gosztonyi and Petra Gruber [75], "Towards the living envelope" [76] by Lidia Badarnah or "Architecture follows nature" [77] by Ilaria Mazzoleni, are some of the most relevant lines of research so far, where several biological principles are studied for innovative methodologies for the generation of biomimetic design concepts in building envelopes.

In "BioSkin" authors explore the potential of biomimetics to identify innovative and natural solutions to develop of novel energy efficient facades of the future [78]. A biological data base is created based on 240 biological organisms identified with potential transmission for envelopes. This resultant data base summarises in several role models from nature, comprising all kinds of animals, plants, including cellular walls, products from animals (e.g. spider silk) or phenomenon such as swarm behaviour [75,79,80].

In "Towards the living envelope" the author proposes a strategic methodology, through functional aspects and strategies found in nature, for the generation of design concepts for envelopes. This biomimetic design methodology is arranged according to four important environmental aspects: air, heat, water and light, and design concepts are generated for each of them [76]. Thus, for example, a water harvesting system is developed, based on water regulation mechanisms in nature such as animals, insects plants or even the human skin, rather than limiting to a specific strategy or organism [81]. Other example is developed, in this case a heat regulation system, based on different thermoregulation strategies in organisms that reduce energy loss for heating and increase cooling efficiency by dissipating heat excess, such as termite mounds, tuna fish, human skin or birds [82,83].

"Architecture follows nature" explores animal skin systems as they relate to building envelopes. This research provides biological inspiration for further architectural design, new building technologies and design of materials. Methodology proposed is arranged according to four selected functions in skins: communication, thermoregulation, water balance and protection. In total twelve "proto-architectural projects" or design concepts for envelopes are designed based on adaptation strategies of several animals to their climates and habitats. Thus, for example, some "proto-architectural projects" related to water balance function are presented according to animals such as Banana slug from California habitat, Dyeing dart frog from French Guiana habitat, Ochre sea star from California habitat or Namib desert beetles from Namibia habitat [77].

Unlike these studies, this research is based only on leaves of plants and their strategies of adaptation to different climates. Plants, due to their immobility as individuals, are an excellent biological material for detecting climate phenomena. Animals are rejected as source of inspiration because plants due to their immobility can not be hidden or seek protection from the elements. Plants like buildings, lack of movement and remain subject to a specific location, and they are exposed to environmental changes so they have to resist weather conditions that affect them at all times. Plants, unlike buildings, have adapted to the environment, through processes of evolution over millions of years. An in-depth analysis and evaluation of adaptation plants strategies to their environment in different climate areas is the key point of this research and this is what makes it different from other studies. These other research works, such as those about light management lessons from plants for designs that respond to light [84], features in leaves for application in shading systems [85] or a general approach to plant-inspired architectural projects [86], are based only on several morphological adaptations according to orientation, distribution and geometry parameters [87].

3. Adaptation solutions in plants

This paper only focuses on those adaptations to environment shown by plants. Plants, because of their immobility have

Fig. 3. Different types of adaptation solutions (a) Hairy leaves of *Gynandriris setifolia* (b) *Echeveria Glauca* is an example of a CAM plant (c) Leaves of *Mimosa pudica* react to contact with a rapid movement.

developed special means of protection against changing environmental issues (e.g. darkness, light, humidity, rainwater, fire, temperature, freezing, air movement or air quality). These adaptations develop over time and generations as a response to the ever changing environment. Evolution and adaptation of living organisms to their environment occurs in three main ways: morphological, a physiological and behavioural [88]. Following these types of adaptation solutions are explained through plant examples. However in the next section we will develop a second approach in terms of dynamic mechanisms and static strategies, as a part of the design methodology to facilitate the transfer from biology to architecture.

3.1. Morphological or structural

relating to an organism's shape, size, pattern or structure dependent on their particular environment, and enables better functionality for survival. An example are the hairy leaves of *Gynandriris setifolia* (Fig. 3a) These hairs, used to reflect sunlight from their surface, are an adaptation to dry and hot environments.

3.2. Physiological or functional

relating to an organism's chemical processes. An organismic or systemic response of an individual to a specific external stimulus in order to maintain homeostasis. Some plants use CAM photosynthesis, i.e. Crassulacean Acid Metabolism [88], as an adaptation to arid conditions for increased efficiency in the use of water, and so is typically found in plants growing in arid conditions [89] such as *Echeveria Glauca* (Fig. 3b).

3.3. Behavioural

relating to how an organism acts. The actions organisms take for survival. This type of adaptation is linked to a signal feedback system of signal and response, where behaviour marks an interaction between the organism and its environment. Some leaves close under various stimuli, such as *Mimosa pudica* (Fig. 3c), which folds inward as a reaction to contact.

4. Design methodology

4.1. Data collection

Analysis of adaptation plants strategies to their environment is the basis of this research. Previously we have seen a first general classification of the three main adaptations of living organisms to their environment through plant examples. However, categorization and organization of the obtained biophysical information is a challenging process and a first approach through a data collection is required in order to be able to apply solutions from nature to architectural solutions. With this classification we try to organize most examples of interest found in different climatic areas. Also, the core of this proposal is the movement resulting in two approaches, being dynamic or static. From now on we consider the ways that plants have adapted in response to challenges as dynamic mechanisms and static strategies. These two main approaches could be further divided into a macro and a micro scale. Within this first level, a second one is defined according to the environmental issues that act as green triggers (i.e. darkness, light, humidity, rainwater, fire, temperature, freezing, air movement or air quality). In summary information organized on a Data Collection uses a classification system to categorize the different ways in which plants adapt and interact with their environment. The data collection (Fig. 4) proposed organizes biological examples by adaptation according to climate type and environmental issues as well as movement approach and main biological principle.

4.1.1. Dynamic mechanisms

Plants respond to external stimuli through movement, called tropisms or nasties, according to whether the motion or response is dependent on the direction or position of the stimulus. We focus on those plants that are responsive plants, those that, exhibit rapid and reactive movements, in a timescale that we can perceive. In this way, we study how plants react to light, temperature or water changes through reactive mechanisms in the macroscopic and microscopic scales. Seeds of many *Mesembryanthemums* (Fig. 5a), dispersed thanks to a valve mechanism that uses rainwater as a trigger, and leaves of *Rhododendron* (Fig. 5b) that roll in response to temperature, are two examples of dynamic mechanisms at

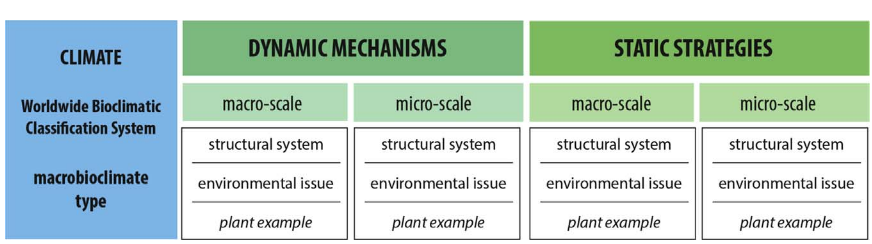

Fig. 4. Diagram showing data collection proposed.

Fig. 5. Some dynamic mechanisms: (a) Seeds of many *Mesembryanthemums* (b) leaves of *Rhododendron* and (c) stomata on the *Betula Celtiberica* leaves.

Fig. 6. Some static strategies: (a) Transparent leaves of *Fenestraria rhopalophylla* (b) Hairy surface of *Cerastium tomentosum* (c) Superhidrophobicity *Colocasia esculenta* leaf.

macro-scale. On the other hand, stomatal movements [90–92] (Fig. 5c) in response to water, light, temperature and carbon dioxide are an example of dynamic mechanisms at micro-scale.

4.1.2. Static strategies

We focus here on the multifunctional properties and surface structures of plants leaves. Plants from dry and hot environments present different adaptations to the extreme conditions of their habitats. Plant surfaces provide more than one solution for environmental conditions and can include, for example light reflection, superhydrophobic or superhydrophilic surfaces [93–95]. *Fenestraria rhopalophylla* (Fig. 6a) and *Cerastium tomentosum* (Fig. 6b) are examples of static strategies at macro-scale, with different solutions for filtering sunlight inside the plant or protecting the plant from direct sunlight and excessive evaporation in dry and hot areas. However the *Colocasia esculenta* leaf (Fig. 6c) has superhydrophobic properties also known as Lotus effect, which is self-cleaning thanks to nanoscale bumps, is a perfect example of a static strategy at the micro-scale.

4.2. Design concept generation

After a data collection to organize information of plants and how they interact with their environment, a biomimetic design methodology is suggested. This methodology leads to concept designs for adaptive architectural envelopes. A mapping (Fig. 7) is proposed to facilitate the transfer between biological information and architectural application. There are four different stages during a biomimetic process from biology to engineering: analysis, synthesis, evaluation and implementation [96]. With this mapping the first three stages may be carried out, as a basis for a possible technical implementation in the future. In order to understand how plant principles can be utilized to create adaptive architectural envelopes the proposed methodology is divided into two major stages: the first one is referred to nature and how identify adaptive strategies and mechanisms in plants in different climates. The second one is referred to architecture and how to abstract and transform the selected ideas into innovative solutions for buildings. Stage of Nature is related to more analytic and scientific concepts, and it combines with stage of Architecture that is more deductive and creative. Climate data concern directly both stages,

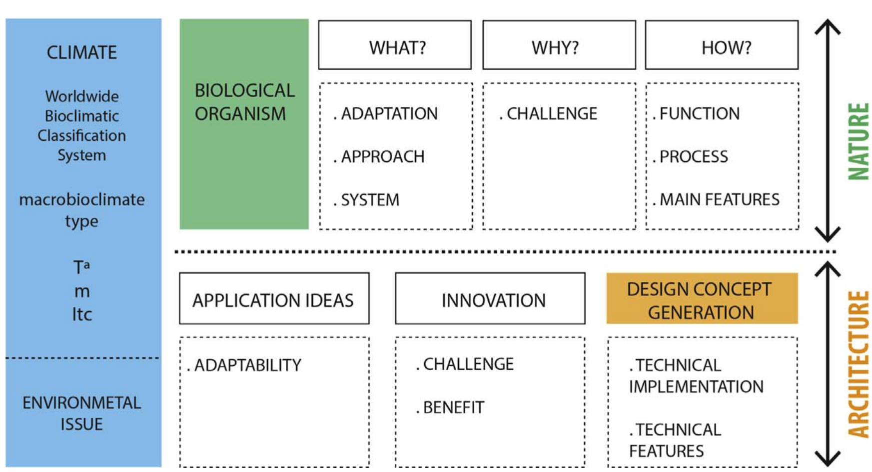

Fig. 7. Diagram showing design concept generation proposed.

nature and architecture, because of we try to achieve the adaptability in each type of environment.

4.2.1. Climate

Bioclimatology or Phytoclimatology is the ecological science dealing with the relations between the climate and the distribution of living species on the Earth. Phytosociology is the science dealing with plant communities, their relationships with the environment and the temporary processes modifying them [88]. The study of all these concepts is part of the research process in which plant communities, and their relations to the environment, and the temporal processes that modify them are analyzed. The basis of the success of plants is the ability to compete in their environment. This ability depends mainly on their physiological evolution and adaptation to the environment, so the climate context of the selected plants are described. Climatic design is one of the best approaches to contribute to the reduction of energy consumption in buildings [97]. In this way several variables are detailed, including temperature, precipitation and humidity, and this information is particularly relevant as an introductory element to the biological analysis as well as the architectural proposition.

One of the most important applications of physiological principles refers to the study of the relationships between plants and climate, with physical and physiological environmental factors and the relationships between them. All those factors mean stress to the organisms can affect their distribution. Climatic factors include intensity and periodicity of heat and light, precipitation and relative humidity, as well as wind or the periodicity and duration of the seasons. This leads us to the analysis of the distribution of plants in different geographical territories as climatic factors, or in other words Bioclimatology. Taking as a reference the Worldwide Bioclimatic Classification System [98], we focus on Europe, where we can see four of the five broad macro-bioclimate types defined: Mediterranean, Temperate, Boreal and Polar.

Climate context of the plant species is the first information described in mapping of design concept generation. This description includes the macro-blioclimate type and its main features, according to three parameters: T (yearly average temperature in centigrade degrees), m (average minimum temperature of the coldest month of the year) and Itc (compensated thermicity index). We also define the environmental issue as “green” trigger that leads this adaptation (i.e. darkness, light, humidity, rainwater, fire, temperature, freezing, air movement or air quality). This climate information is the starting point and the key of this research, because of plants have unique strategies for dealing with the climate they exist in, and we try to develop unique adaptation solutions in envelopes on buildings at different locations. Therefore, this climate data is valid both for natural stage of analysis and for architectural stage of application, and it is the main topic of this methodology.

We must select one of the biological examples at Temperate macro-bioclimate if we want to apply these adaptation principles into a building located at the same macro-bioclimate.

4.2.2. First stage: nature

This first stage provides an overview on the explored biological organisms, i.e. plants, and is organized according to three important questions: *what* is the plant adaptation analyzed, *why* that plant has performed this adaptation and *how* plant has developed these specific functions.

QUESTION 1: WHAT?

We look into general description of plant adaptation, through analysis of data such as the type of general adaptation (morphological, physiological or behavioural) or the approach and scale (dynamic mechanism or static strategy in macro or micro scale). Also, structural system is described, e.g. valve mechanisms, reflective structures or absorbing surfaces.

QUESTION 2: WHY?

Biological challenge is explored to determinate function. What challenge must that plant address to survive at that climate area? We identify a verb that directly define the biological challenge. Why does that plant need to perform this strategy?

QUESTION 3: HOW?

We study how plants develop specific functions, i.e. how a mediterranean plant manages the capture and storage of water, how is possible to avoid dehydration or survive the great changes of temperature between day and night. To understand these specific behaviors for adaptation and functional specialization, the relationship between structure, morphology and function are analyzed. From the scale of microscopic observation and using SEM (scanning electron microscope) micrographs could be useful tools for the static approaches. Most important concepts described are function, process and main feature. Function is necessary to achieve challenge required, thus we extract the functionality of mechanisms or strategies, e.g. opening, reflecting, controlling or absorbing. Function will be determinant of the design concept success. Process describes how this organism has developed these special adaptations, also it provides the understanding why this plant is able to survive on that specific climate. Finally the main feature of the performance is indicated, e.g. hygroscopicity or dense coverage.

4.2.3. Second stage: architecture

Based on the main principles for plant adaptations, in this second stage we are analogously able to abstract and transform these principles into technical solutions and further implementations for adaptive architectural envelopes. This stage is resolved with three important concepts: Application ideas, Innovation and Design concept generation.

Concept 1: Application ideas.

Application ideas suggest a kind of adaptability, i. e. dynamic adaptive envelope or static adaptive envelope. Previously we have seen how plant adaptations could be organized according to movement and environmental issues in a data collection. Adaptive architectural envelopes can be divided in two approaches as well: the adaptive behaviour could be based on a movement through dynamic mechanisms or material properties through static strategies. The first type of adaptability in adaptive architectural envelopes implies that a certain kind of observable motion is present, resulting in changes in the envelope configuration via moving parts. Examples of types of motion could be: folding, sliding, expanding, creasing, hinging, rolling, inflating, fanning, rotating or curling. In the other type of adaptive architectural envelopes, changes directly affect the internal structure of a material, also adaptability is manifested via changes in specific properties, such as light reflection or absorption properties, or through the exchange of energy from one form to another.

Concept 2: Innovation.

Building design criteria for envelopes can reduce the energy demand for the heating, cooling, ventilation or lighting systems [99], and the way to solve energy efficiency problems is through innovative solutions [100]. Challenges taken from plant adaptations to their environment can enhance innovation. Therefore, some innovation ideas are proposed according design challenges and benefits. Why is this solution design better than those existing? This concept tries to show the benefit or advantages of the biomimetic design methodology, for the design of new adaptive architectural envelopes or for refurbishment applications, compared to a standard or traditional building system in terms of energy efficiency.

Concept 3: Design concept generation.

Design concept generation comes from biological observation, so it involves an abstraction of biological terms to constructive terms. The resulting design concept is not a direct translation from particular adaptation plant, but is inspired by studying its function, morphology and nature. Innovative forms will emerge from this explorative process. Preliminary drawings and constructive details, based on analysis of adaptation plant according to previous questions, are made in order to formulate possible technical implementation. Technical application is a definition of the constructive or implementation idea and is determined by the technical features of motion, geometry, patterns or material properties.

Design concept generation must consider the comfort aspect for human behaviour in addition to their physiological needs. It is important to note that user' behaviour is a fundamental aspect to keep in mind in the overall design process of technical implementation. For example strategies for shading systems can affect the indoor comfort not only from the thermal comfort, but also for its visual implications [25]. Therefore design concepts have to satisfy not only energy performance but also occupancy satisfaction (i.e. visual and indoor comfort, acoustical performance or accessible fresh air). Interaction between system and occupants, through human factors, is basic for an efficient and successful use of the building.

5. Design cases

Design cases open new perspectives for different technical solutions for adaptive architectural envelopes, and the potential.

to carry out a new kind of bio-inspired innovation for energy efficiency.

Seeking solutions from nature for the development of new systems for adaptive envelopes is a widely growing field for innovation, yet the application to buildings is very limited. Two different theoretical design cases based on solutions adapted by plant adaptations are presented. It is hoped that these design cases will shed more light on the possible applications to buildings. Further materialization research, through new fabrication technologies and active materials [48,101], is required to test and validate the concepts and their application to the building context.

The first design case (Fig. 8) shows the possible realization of an adaptive architectural envelope from a dynamic approach. Based on the seeds of *Mesembryanthemums*, that are launched from their capsules for dispersal thanks to a valve mechanism that uses rainwater as a trigger, a smart opening-closing system is suggested for new buildings. These plants are from Mediterranean climate and when rain falls the seed capsules absorb moisture and swell, causing a star-shaped set of valves to open. A new adaptive water envelope is proposed by the material behaviour which uses rainwater as a trigger to open or close itself. This kind of solution is a dynamic mechanism which architectural benefit consists in saving or reducing the number of construction elements in windows, as well as allowing an independent and autonomous activation to adapt changing environmental conditions in buildings located at rainy cities.

Other way to improve simply and effective the energy efficiency of a building is by improving the thermal insulation of the envelope [102]. The second design case (Fig. 9) shows the possible realization of a responsive and adaptive temperature system. It has an advantage of adapting to changing temperature levels passively. Basing on some plants at Mediterranean climate, such as *Salvia officinalis* or *Kalanchoe pumila*, a reflective envelope over existing façades is suggested for refurbishment. These plants have developed reflective structures for protect themselves against excessive sunlight and temperature, by strategies of three dimensional waxes or dense coverage with air-filled hairs. This kind of solution is a static approach which architectural benefit consists in saving energy waste in cooling systems in buildings located at dry and hot cities, besides helping to reduce urban heat island.

Regarding the choice of materials to implement these design concepts it is important that they are not compromised the possible environmental benefits achieved over the biomimetic methodology. A wide range of smart materials has emerged in the recent years, such as shape memory alloys (SMA), shape memory polymers (SMP), piezoelectric materials, magnetostrictive materials, electrostrictive materials or electroactive polymers [103]. Other no-electrical smart materials, such as glass fibers, cellulose,

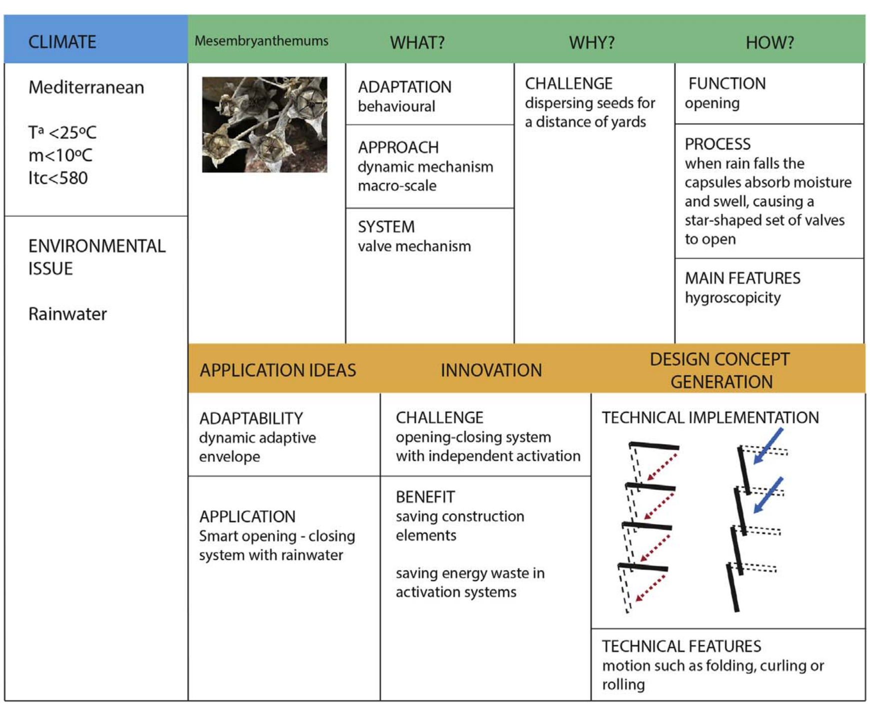

Fig. 8. Diagram of a dynamic design case for smart opening-closing envelopes by rainwater.

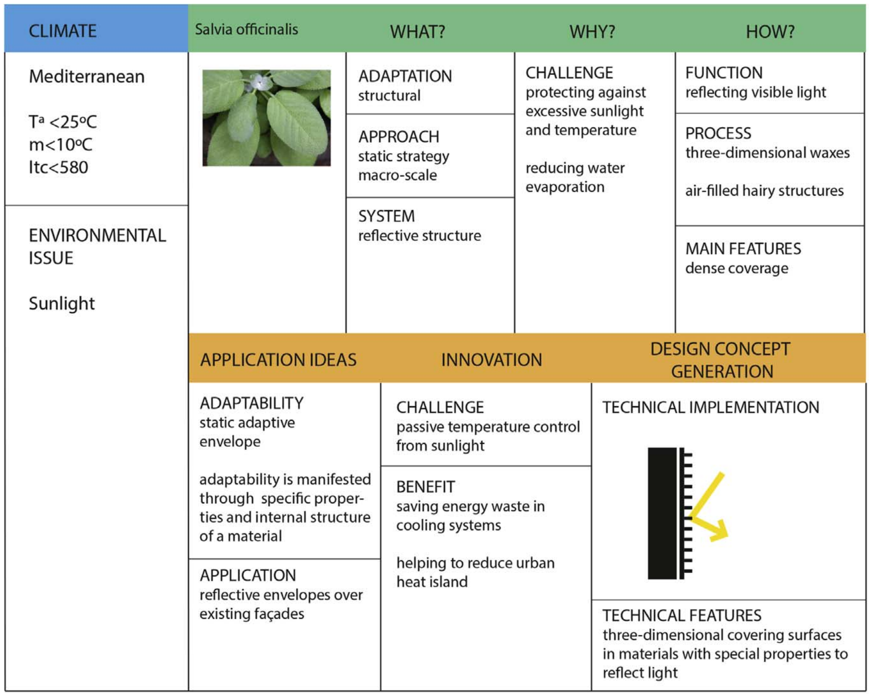

Fig. 9. Diagram of a static design case for reflective envelopes in dry and hot environments.

polymer foams or aerogel materials [104] as well as phase change materials utilized as a thermal mass or latent heat storage technologies [102,105,106] are commonly used for passive building energy savings in envelopes. The methodology presented here proposes the use of active materials to carry out challenges from nature into technical implementation. Active materials that response to external stimuli, seeking meaningful ways to bridge between the natural inspiration, plants, and the technical implementation, adaptive architectural envelopes. Active materials that are self-actuating responsive materials with innate characteristics, behaviour and performative capacity to react to environmental changing conditions that act as "green" triggers on active materials with reversible changes [48,101].

6. Conclusion

Advances in adaptive architectural envelopes could represent the future alternative to conventional building envelopes, whose static properties are not the most optimal efficiency solution. Adaptive design approaches could reduce complexity and costs wasted in heating, cooling, ventilating or lighting and thus manage significant improvements in building energy savings.

This paper provides a review of advances in adaptive architectural envelopes, including those based on biomimetic principles (built projects and academic research works) and besides proposes a biomimetic new design approach methodology for adaptive envelopes that interact with their environment, and so contribute to reduce energy demands in buildings. Novel concepts for optimizing energy efficiency in envelopes, abstracted from plants that respond to different environmental issues, are introduced for possible technical implementations. Unlike other biomimetic studies, this research is based only on leaves of plants and their strategies of adaptation to different climates. Plants like buildings, lack of movement and remain subject to a specific location, and they are exposed to environmental changes so they have to resist weather conditions that affect them at all times. An in-depth analysis and evaluation of adaptation plants strategies to their environment in different climate areas in Europe is the key point of this research and this is what makes it different from other studies. Therefore, plants strategies for dealing with the climate they exist in are studied trying to develop unique adaptation solutions in envelopes on buildings at different locations, because climatic design is one of the best approaches to contribute to the reduction of energy consumption in buildings [97].

Answering some introductory questions we can support that is possible to generate design concepts for building envelopes that regulate environmental aspects and comfort conditions, based on adaptation strategies from plants. We have carried out a mapping in order to understand how lessons from plant systems be utilized to create a envelope that incorporates and functions like nature. According our methodology several steps guide the transfer from biological principles to architectural resources. In the example part, the mapping methodology was applied to generate two design concepts, a dynamic mechanism for smart opening-closing envelopes by rainwater and a static strategy of a reflective envelope over existing façades. These design cases involve a specific study of plant adaptations to rainy or dry and hot environments to provide a new ways to save energy and reducing the number of construction elements in new buildings located at rainy climates or saving waste in cooling systems in old buildings in dry and hot cities, as well as indoor comfort considering human factors is satisfied.

Regarding whether it is possible to obtain greater energy efficiency in the construction of exterior walls in buildings by mimicking nature as opposed to building façades according to the traditional processes, this work provides several mechanisms and strategies for the design challenge. However the transformation of these into technical solutions for adaptive architectural envelopes requires a large number of studies and experiments with new technologies that include multi-material 3D printing, advances in material science and new capabilities in simulation software.

In summary, the methodology to create a data collection of plant adaptations and the design mapping from plants to architecture, open new perspectives for new possible technical solutions and showing the potential of plant adaptations to environmental conditions at a specific climate to develop adaptive architectural envelopes at the same climate.

Translation of the theoretical adaptive behaviour concepts into real living architectural envelopes that interact with their environment will be a big challenge, keeping in mind that the choice of materials for the implementations has not compromise the possible environmental benefits achieved over the biomimetic methodology. Since active materials research will take a long time to reach testing results to carry out challenges from nature into technical implementation, further research is required to test and validate the concepts and their application to the building context and their corresponding scales, expecting a different way of thinking about building construction.

The next step in the research is to continue working on the compilation of plant adaptation strategies and mechanisms to define diverse design concepts for adaptive architectural envelopes in different climate zones in Europe according to user demands inside the buildings. At the same time, possibilities of fabrication of responsive systems where multiple materials can react to the environment through deformation of active materials depending only on environmental stimulus will be investigated.

Acknowledgements

The author is grateful for financial support of her work by the nominative subsidy to the University of Oviedo for R&D projects of the 'Consejeria de Economia y Empleo del Principado de Asturias' (ref. FC-15-GRUPIN14-004). At the same time the authors would like to acknowledge the valuable comments and discussions provided by Professor Julian Vincent (University of Bath), by horticulturist Carlos Magdalena (KEW Royal Botanic Gardens, London) and horticurator Álvaro Bueno (Jardín Botánico Atlántico, Gijón).

References

[1] Kamal-Chaoui L, Robert A. Competitive cities and climate change, OECD regional development working papers no, 2. OECD Publishing; 2009.
[2] European Commission. Communication from the commission to the European Parliament, the Council, the European economic and social Committee and the Committee of the Regions. Energy Roadmap 2050, Com 2011;2011:885/2. ⟨http://ec.europa.eu/energy/energy2020/roadmap/doc/com_2011_8852_en.pdf⟩.
[3] European Commission. Communication from the commission to the European Parliament, the Council, the European economic and social Committee and the Committee of the Regions. Horizon 2020 - The Framework Programme for Research (and Innovation); 2011. ⟨http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0808&from=EN⟩.
[4] Stevanović S. Optimization of passive solar design strategies: a review. Renew Sustain Energy Rev 2013;25:177–96. http://dx.doi.org/10.1016/j.rser.2013.04.028.
[5] Skou A. Future buildings: tough and smart on energy efficiency. Research*eu results magazine, Issue 23, June 2013. CORDIS Unit, Publications Office of the European Union. ⟨http://bookshop.europa.eu/en/research-eu-results-magazine-pbZZAC13005/⟩.
[6] Del Grosso AE, Basso P. Adaptive building skin structures. IOP Sci Mater Struct 2010.
[7] Sadineni SB, Madala S, Boehm RF. Passive building energy savings: a review of building envelope components. Renew Sustain Energy Rev 2011;15(8):3617–31. http://dx.doi.org/10.1016/j.rser.2011.07.014.
[8] Oral GK, Yilmaz Z. Building form for cold climatic zones related to building envelope from heating energy conservation point of view. Energy Build 2003;35:383–8.
[9] Berkoz E, Yilmaz Z. Determination of the overall heat transfer coefficient of the building envelope from the bioclimatic comfort point of view. Archit Sci Rev 1987;30(4):117–21.
[10] Selkowitz SE. Integrating advanced facades into high performance buildings. Lawrence Berkeley National Laboratory; 2001.
[11] Selkowitz S, Aschehoug O, Lee ES. Advanced interactive facades – critical elements for future green buildings? Lawrence Berkeley National Laboratory; 2003.
[12] Lee ES, DiBartolomeo DL, Rubinstein FM, Selkowitz SE. Low-cost networking for dynamic window systems. Energy Build 2004;36(6):503–13. http://dx.doi.org/10.1016/j.enbuild.2003.12.008.
[13] Dobzhansky T, Hecht MK, Steere WC. On some fundamental concepts of evolutionary biology. 1st ed.Evolutionary Biology, 2. . New York: Appleton-Century-Crofts; 1968. p. 1–34.
[14] Wang J, Beltrán LO, Kim J. From static to kinetic: a review of acclimated kinetic building envelopes. Denver, CO; 2012. p. 4022–9.
[15] Omrany H, Ghaffarianhoseini A, Ghaffarianhoseini A, Raahemifar K, Tookey J. Application of passive wall systems for improving the energy efficiency in buildings: a comprehensive review. Renew Sustain Energy Rev 2016;62:1252–69. http://dx.doi.org/10.1016/j.rser.2016.04.010.
[16] Ürge-Vorsatz D, Eyre N, Graham P, Harvey D, Hertwich E, Jiang Y, et al. Chapter 10 – energy end-use: building.Global energy assessment – toward a sustainable future. Cambridge, UK and New York, NY, USA: Cambridge University Press; Laxenburg, Austria: International Institute for Applied Systems Analysis; 2012. p. 649–760.
[17] Ürge-Vorsatz D, Cabeza LF, Serrano S, Barreneche C, Petrichenko K. Heating and cooling energy trends and drivers in buildings. Renew Sustain Energy Rev 2015;41:85–98. http://dx.doi.org/10.1016/j.rser.2014.08.039.
[18] Armstrong R. Living architecture: how synthetic biology can remake our cities and reshape our lives. TED Books 2012.
[19] Loonen RCGM. Climate adaptive building shells, what can we simulate? Eindhoven (The Netherlands): Technische Universiteit Eindhoven; 2010.
[20] Loonen RCGM, Favoino F, Hensen JLM, Overend M. Review of current status, requirements and opportunities for building performance simulation of adaptive facades. J Build Perform Simul.
[21] De Boer BJ, Ruijg GJ, Loonen RCGM, Trcka M, Hensen JLM, Kornaat W. Climate adaptive building shells for the future – optimization with an inverse modelling approach. In: Proceedings of the ECEEE Summer Study 2011, Belambra Presqu'île de Giens, France, June 2011. – Presqu'île de Giens: Technische Universiteit Eindhoven; 2011. p. 1413–22.
[22] Hasselaar BLH. Climate adaptive skins: towards the new energy-efficient façade. WIT Trans Ecol Environ 2006;99:351–60.
[23] Wigginton M, Harris J. Intelligent skins. Oxford: Butterworth-Heinemann; 2002.
[24] Grosso AE, Basso P. Design concepts for adaptive multi-functional building envelopes. In: Proceedings of the 6th ECCOMAS thematic conference on smart structures and materials, SMART 2013: Turin, Italy; 2013.
[25] Fiorito F, Sauchelli M, Arroyo D, Pesenti M, Imperadori M, Masera G, Ranzi G. Shape morphing solar shadings: a review. Renew Sustain Energy Rev 2016;55:863–84. http://dx.doi.org/10.1016/j.rser.2015.10.086.
[26] Beesley P. Responsive architectures: subtle technologies. Canada: Riverside Architectural Press; 2006.
[27] Leatherbarrow D, Mostafavi M. Surface architecture. Cambridge, Massachusetts: The MIT Press; 2002.
[28] Zhai Z, Previtali JM. Ancient vernacular architecture: characteristics categorization and energy performance evaluation. Energy Build 2010;42(3):357–65. http://dx.doi.org/10.1016/j.enbuild.2009.10.002.
[29] Corubusier Le. Precisions: on the present state of architecture and city planning (1930), english translation.Cambridge, MA: MIT Press; 1991.
[30] Zuk W, Clark RH. Kinetic architecture.New York: Van Nostrand Reinhold; 1970.
[31] Fortmeyer R, Linn C. Kinetic architecture: design for active envelopes. Mulgrave: Images Publishing; 2014.
[32] Arab World Institute, Jean Nouvel, Projects, Paris. [Online]. Available: ⟨http://www.jeannouvel.com⟩.
[33] Loonen RCGM, Trčka M, Cóstola D, Hensen JLM. Climate adaptive building shells: state-of-the-art and future challenges. Renew Sustain Energy Rev 2013;25:483–93. http://dx.doi.org/10.1016/j.rser.2013.04.016.
[34] Lee ES, Selkowitz SE. Integrated envelope and lighting systems for commercial buildings: a retrospective. Paper presented at the ACEEE 1998 summer study on energy efficiency in buildings; 1998.
[35] Rheault S, Bilgen E. Experimental study of full-size automated venetian blind windows. Solar Energy 1990;44(3):157–60.
[36] Coelho M, Maes P. Shutters: a permeable surface for environmental control and communication. In: Proceedings of the third international conference on tangible and embedded interaction, Cambridge, UK, 2009.
[37] Media-ICT Building CZFB 22@, Barcelona, Enric Ruiz-Geli - Cloud 9, Projects, [Online]. Available: ⟨http://www.ruiz-geli.com⟩.
[38] Dent AH, Sherr L. Material innovation: architecture Media-ICT. London: Thames & Hudson; 2014. p. 180–3.
[39] The Eden Project: The Biomes, Grimshaw Architects, Projects, London. [Online]. Available: ⟨http://grimshaw-architects.com⟩.
[40] Allianz Arena, Herzog & De Meuron, Projects, Munich, [Online]. Available: ⟨https://www.herzogdemeuron.com⟩.
[41] National Aquatics Center (Water Cube), ARUP, Projects, Beijing, [Online]. Available: ⟨https://www.arup.com⟩.
[42] Geli ER. Cloud 9. Media-ICT Building, Barcelona, Actar 2011.
[43] Geli ER, Rifkin J. a green new deal, from geopolitics to biosphere politics. Barcelona, Actar 2010.
[44] Kim D. Sung Metal that breathes, TEDxUSC. [Online]. Available: ⟨http://www.ted.com/speakers/doris_kim_sung.html⟩.
[45] Bloom D. Kim Sung [Online]. Available: ⟨http://www.dosu-arch.com/bloom.html⟩.
[46] Dent AH, Sherr L. Material innovation: architecture Bloom. London: Thames & Hudson; 2014. p. 146–9.
[47] Cantrell BE, Holzman J. Responsive landscapes: strategies for responsive

technologies in landscape.Architecture. New York: Routledge; 2015.
[48] López M, Rubio R, Martín S, Croxford B, Jackson R. Active materials for adaptive architectural envelopes based on plant adaptation principles. J Facade Des Eng 2015;3(1):2015. http://dx.doi.org/10.3233/FDE-150026.
[49] Vincent J, Bogatyreva O, Bogatyrev N, Bowyer N, Pahl K. Biomimetics: its practice and theory. J R Soc Interface 2006;3(9):471–82. http://dx.doi.org/10.1098/rsif.2006.0127.
[50] Benyus JM. Biomimicry: innovation inspired by nature. 2nd ed.. New York: H. Collins Pub.; 2002.
[51] Pawlyn M. Biomimicry in architecture.London: RIBA Publishing; 2011.
[52] ITKE. Institute of building structures and structural design, bio-inspired kinematics for adaptive shading systems, Flectofin®: a hinge-less flapping mechanism inspired by nature, [Online]. Available: ⟨http://www.itke.uni-stuttgart.de⟩.
[53] Lienhard J, Schleicher S, Poppinga S, Masselter T, Milwich M, Speck T, Knippers J. Flectofin: a hingeless flapping mechanism inspired by nature. IOP Sci Bioinspiration Biomimetics 2011;6(4).
[54] Knippers J, Speck T. Design and construction principles in nature and architecture. IOP Sci Bioinspiration Biomimetics 2012;7.
[55] Lienhard J, Poppinga S, Schleicher S, Masselter T, Speck T, Knippers J. Abstraction of plant movements for deployable structures in architecture. In: Thibaut B, (editor). Proceedings of the 6th plant biomechanics conference. Cayenne: French Guyana; 2009; pp. 389–97.
[56] Schleicher S, Lienhard J, Poppinga S, Speck T, Knippers J. A methodology for transferring principles of plant movements to elastic systems in architecture. Comput Aided Des 2015;60.
[57] Bar-Cohen Y. Biomimetics: nature-based innovation. New York: CRC Press Taylor & Francis Group; 2011.
[58] Schinegger K, Rutzinger S, Oberascher M, Weber G. One ocean: theme pavilion EXPO 2012. Yeosu, Residenz Verlag; 2012.
[59] Menges A. Biomimetic design processes in architecture: morphogenetic and evolutionary computational design. IOP Sci. Bioinspiration Biomimetics 2012;7.
[60] Menges A. HygroScope – meteorosensitive morphology. In: Gattegno N, Price B, (editors). Project catalogue of the 32nd annual conference of the association for computer aided design in architecture (ACADIA), San Francisco; 2012. p. 21–4.
[61] Menges A. Material computation - higher integration in morphogenetic design, architectural design.. London: Wiley Academy; 2012.
[62] Reichert S, Menges A, Correa D. Meteorosensitive architecture: biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness. Comput-Aided Des 2014;60:50–69. http://dx.doi.org/10.1016/j.cad.2014.02.010.
[63] Krieg OD, Christian Z, Correa D, Menges A, Reichert S, Rinderspacher K, Schwinn T. Hygroskin: meteorosensitive pavilion. In: Proceedings of the Fabricate 2014 Conference Zurich; 2014.
[64] Knippers J, Menges A, Gabler M, La Magna R, Waimer F, Reichert S, Schwinn T. From nature to fabrication: biomimetic design principles for the production of complex spatial structures. In: Hesselgren L, Sharma S, Wallner J, Baldassini N, Bompas P, Raynaud J, editors. Advances in architectural geometry. Wien New York: Springer; 2012. p. 107–22.
[65] Menges A. Integrative design computation: integrating material behaviour and robotic manufacturing processes in computational design for performative wood constructions. In: Proceedings of the 31th conference of the association for computer aided design in architecture (ACADIA); 2011. p. 72–81.
[66] Gruber P. Biomimetics in architecture – the architecture of life and buildings. Vienna: Springer; http://dx.doi.org/10.1007/978-3-7091-0332-6.
[67] Loonen RCGM. Bio-inspired adaptive building skins, biotechnologies and biomimetics for civil engineering. Springer; http://dx.doi.org/10.1007/978-3-319-09287-4_5.
[68] Kennedy E, Fecheyr-Lippens D, Hsiung B, Niewiarowski PH, Kolodziej M. Biomimicry: a path to sustainable innovation. Design Issues, Summer 2015, 31. Massachusetts Institute of Technology; 2015. p. 66–73. http://dx.doi.org/10.1162/DESI_a_00339.
[69] Godfaurd J, Clements-Croome D, Jeronimidis G. Sustainable building solutions: a review of lessons from the natural world. Build Environ 2005;40 (3):319–28 ISSN 0360-1323 http://dx.doi.org/10.1016/j.buildenv.2004.05.011.
[70] Brayer MA, Migayrou F. Archilab 2013: Naturalizing architecture: Hyx, Orleans; 2013.
[71] Vincent JFV. Stealing ideas from nature, (Volume 412 of) the series International Centre for Mechanical Sciences. p. 51–8. doi: http://www.dx.doi.org/10.1007/978-3-7091-2584-7_3.
[72] Gruber P. Transfer of nature to architecture – analysis of case studies. Biological Approaches for Engineering Conference, University of Southampton, UK; 2008.
[73] Myers W. Beyond Biomimicry, Bio Design: Nature, Science, Creativity.London: Thames & Hudson; 2012.
[74] Vattam S, Helms M, Goel A, Yen J, Weissburg M. Learning about and through biologically inspired design. In: Proceedings of the Second Design Creativity Workshop, Atlanta; 2008.
[75] Gosztonyi S, Gruber P, Judex F, Brychta M, Richter S. BioSkin – research potentials for biologically inspired energy efficient façade components and systems, BioSkin Online Plattform. Project information FFG, Vienna; 2010 ⟨http://www.bionicfacades.net//⟩.
[76] Badarnah L. Towards the LIVING envelope: biomimetics for building envelope adaptation. Delft University of Technology; 2012.
[77] Mazzoleni I. Architecture follows nature-biomimetic principles for innovative design.New York: CRC Press; 2013.
[78] Gruber P, Gosztonyi S. Skin in architecture: towards bioinspired facades. WIT Transactions on Ecology and the Environment, vol. 138. WIT Press; 2010.
[79] Imhof B, Gruber P. BIORNAMETICS-architecture defined by natural patterns. PEEK project submission Austrian Science Fund FWF 2009.
[80] Imhof B, Gruber P. What is the Architect doing in the Jungle? Biornametics Springer Vienna Architecture; 2013.
[81] Badarnah L, Kadri U. A methodology for the generation of biomimetic design concepts. Archit Sci Rev 2014. http://dx.doi.org/10.1080/00038628.2014.922458.
[82] Badarnah L, Nachman Farchi Y, Knaack U. Solutions from nature for building envelope thermoregulation. In: Carpi A, Brebbia CA (editors). Proceedings of the fifth design & nature conference on comparing design and nature with science and engineering. Southampton: WITpress; 2010.
[83] Badarnah L, Fernandez JE. Morphological configurations inspired by nature for thermal insulation materials. In: Proceedings of the international association for shell and spatial structures (IASS) Symposium 2015, Future Visions, Amsterdam.
[84] Badarnah L, Knaack U. Organizational features in leaves for application in shading systems for building envelopes. In: Brebbia CA (editor). Proceedings of the fourth International design & nature conference on comparing design in nature with science and engineering. WITpress: Southampton; 2008. p. 87–96.
[85] Badarnah L. Light management lessons from nature for building applications. Procedia Eng 2016;145:595–602. http://dx.doi.org/10.1016/j.proeng.2016.04.049.
[86] Gruber P. Biomimetics in architecture – inspiration from plants. In: Proceedings of the 6th plant biomechanics conference, Cayenne; November 2009.
[87] Kobayashi H, Kresling B, Vincent JFV. The geometry of unfolding tree leaves. In: Proceedings of the Royal Society B: Biological Sciences; 1998. http://www.dx.doi.org/10.1098/rspb.1998.0276.
[88] Azcón-Bieto J, Talón M. Fundamentos de fisiología vegetal.Barcelona: McGraw-Hill Interamericana; 2000.
[89] Ezcurra E. Natural history and evolution of the world's deserts, global deserts outlook. United Nations Environment Programme 2006:1–27.
[90] Vogel S. The life of a leaf. University of Chicago Press; 2012.
[91] Martin ES, Donkin ME, Stevens RA. Stomata. London: Edward Arnold; 1983.
[92] Willmer C, Fricker M. Stomata, Volume 2 Topics in plant functional biology. Springer Science & Business Media; http://dx.doi.org/10.1007/978-94-011-0579-8.
[93] Koch K, Bhushan B, Barthlott W. Multifunctional surface structures of plants: an inspiration for biomimetics. Prog Mater Sci 2009;54:137–78.
[94] Bhushan B. Biomimetics: lessons from nature – an overview. Philos Trans R Soc 2009;367:1445–86.
[95] Gibson L. The hierarchical structure and mechanics of plant materials. J R Soc Interface 2012.
[96] Speck T. Process sequences in biomimetic research. C.A. Brebbia, Design and Nature IV. Southampton: WIT Press; 2008. p. 3–11.
[97] Omer AM. Renewable building energy systems and passive human comfort solutions. Renew Sustain Energy Rev 2008;12(6):1562–87. http://dx.doi.org/10.1016/j.rser.2006.07.010.
[98] Rivas-Martínez S. Worldwide Bioclimatic Classification System. Global Geobotany 2011;1(1). http://dx.doi.org/10.5616/gg110001.
[99] Pacheco R, Ordóñez J, Martínez G. Energy efficient design of building: a review. Renewable and Sustainable Energy Reviews 2012;16(6):3559–73. http://dx.doi.org/10.1016/j.rser.2012.03.045.
[100] Omrany H, Ghaffarianhoseini A, Ghaffarianhoseini A, Raahemifar K, Tookey J. Application of passive wall systems for improving the energy efficiency in buildings: a comprehensive review. Renew Sustain Energy Rev 2016;62:1252–69. http://dx.doi.org/10.1016/j.rser.2016.04.010.
[101] López M, Rubio R, Martín S, Croxford B, Jackson R. Adaptive architectural envelopes for temperature, humidity, carbon dioxide and light control. In: Proceedings of the 10th conference on advanced building skins, Bern, Switzerland; November 2015.
[102] Sadineni SB, Madala S, Boehm RF. Passive building energy savings: a review of building envelope components. Renew Sustain Energy Rev 2011;15:3617–31. http://dx.doi.org/10.1016/j.rser.2011.07.014.
[103] Addington M, Schodek D. Smart materials and technologies. for the architecture and design professions.Oxford, United Kingdom: Architectural Press; 2004.
[104] Fernández JE, et al. Materials for aesthetic, energy-efficient, and self-diagnostic buildings. Science 2007;315:1807. http://dx.doi.org/10.1126/science.1137542.
[105] Mavrigiannaki A, Ampatzi E. Latent heat storage in building elements: a systematic review on properties and contextual performance factors. Renew Sustain Energy Rev 2016;60:852–66. http://dx.doi.org/10.1016/j.rser.2016.01.115.
[106] Cabeza LF, Castell A, Barreneche C, de Gracia A, Fernández AI. Materials used as PCM in thermal energy storage in buildings: a review. Renew Sustain Energy Rev 2011;15(3):1675–95. http://dx.doi.org/10.1016/j.rser.2010.11.018.