Advanced Building Skins
Adaptive architectural envelopes for temperature, humidity, carbon dioxide and light control

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Abstract

In this paper, the authors present research into active materials for adaptive architectural envelopes that adapt to environmental changes, as a result of the application of biomimetics on the development of a new type of exterior walls for buildings.

Plants have developed adaptation strategies for thermal comfort conservation, water management or air exchange with neither supply of external energy nor any kind of mechanical or electronic control. The transformation of these strategies into technical solutions for adaptive architectural envelopes requires a large number of studies and experiments with new technologies that include multi-material 3D printing and advances in material science. We focus on temperature, humidity, carbon dioxide and light as the main environmental issues or “green triggers” to be managed by the adaptive architectural envelope through several active materials, in which responsive capacity is embedded in the structure of the material itself. These active materials include: hydrogels, thermo-expansive polymers or photochromic polymers, with capabilities such as programmable actuation, sensing, self-transformation and operables in 3D printer technologies. In summary, this paper presents some results of experiments in active material behaviours as actuators for innovative and low-tech design strategies, without electrical stimulus.

Keywords: active materials, adaptive envelopes, biomimicry, low-tech, climate adaptations.

1. Biomimicry: from plants to architecture

1.1. Introduction

Nowadays cities consume the larger part of global energy and are therefore major contributors of greenhouse gas emissions [1]. Moreover, cities have key competencies to act on climate change through their responsibilities over urban sectors such as buildings. So much so that latterly European Union has been developing a large number of funding building efficiency programmes for research and innovation trying to problem-solve these issues, such as Horizon 2020 framework. Some of these programmes focus on building retrofitting, or the installation of energy-efficient technologies, especially on façades. Façades have an important role in the regulation and control of energy waste, since they act as intermediary filters between external environmental conditions and inside users and functional requirements. Due to this decisive role, in recent years façades or architectural envelopes have been the subject of numerous studies and research, always trying to achieve greater efficiency and performance in terms of energy, comfort or structure [2][3][4].

The multiple environmental and climatic characteristics of the area are variable parameters, while those concerning internal comfort in buildings are largely static; so, we use large amounts of energy to pump heating, or cool, ventilate and light our buildings between quite well defined limits, while external environmental factors can change considerably. The existing solutions to these problems tend to have a static building envelope and dynamic building services. Therefore conventional solutions for façades are...
not designed for optimum adaptation to contextual issues and needs. However, biological solutions to adaptation are often complex, multi-functional and highly responsive. 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 [5]. An adaptive architectural envelope is one that responds to changing environmental conditions both interior and exterior while managing the indoor environment. Adaptive architectural envelopes should have adaptation strategies to anticipate exterior environmental variations as well as interior activities and their interactions with inhabitants. Office Building Media-TIC by Enric Ruiz Geli (Cloud 9) [6] [7] and Bloom by Doris Kim Sung [8] are noted examples of adaptive architectural envelopes. Through technological innovation we investigate an architecture that continuously changes in response to external stimuli and the application of biomimetics to the development of adaptive architectural envelopes according to plant adaptation strategies. Advances in technology have opened new avenues for design; we can more effectively mimic nature’s language [9].

This paper is organised in three main sections. In the first one, motivations for application to biomimetic principles from plants to architecture are explained, as well as concepts such as adaptation and why plant adaptation principles are the basis of this research. The second section is related to how convert these inspirational mechanisms of plants into technical implementations for adaptive architectural envelopes. A selection of functions and possible active materials is proposed, according to the environmental issues defined: humidity, temperature, carbon dioxide and light. Finally, in the third section some experiments about active materials are described.

1.2. From plant adaptation principles to adaptive architectural envelopes

As it was said before, façades have been the subject of numerous studies and research during last years, and some of these studies have looked at nature as a source of inspiration for subsequent application to architecture [10][11][12][13][14]. This trend also known as biomimicry or biomimetics, and it is defined as the ‘abstraction of good design from nature’ [15] or ‘mimicking the functional basis of biological forms, processes and systems to produce sustainable solutions’ [16]. Systems found in nature offer a large database of strategies and mechanisms that can be implemented in biomimetic designs. Although it is a discipline that has been developing for some time in other fields, in recent years we have begun to see how several research works have been developed around biomimicry to look into new solutions in architecture. Some of them try different methodologies for developing new building envelopes based on biomimetic principles, such as “Towards the living envelope” [17] or “Architecture follows nature” [18]. Unlike these studies, this research is based only on plants and their strategies of adaptation to different climates.

We only focus on those adaptations to environment shown by plants. Plants, like buildings, lack movement and remain subject to a specific location, so they have to resist weather conditions that affect them at all times. Plants, unlike buildings, have developed special means of protection against changing environmental issues (e.g. 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. Analysis of adaptation plants strategies to their environment is the basis of this research. Taking as a reference the Worldwide Bioclimatic Classification System [19], we focus on Europe, where we can see four of the five broad climate types defined: Mediterranean, Temperate, Boreal and Polar. Through these different climate areas we study the different strategies and mechanisms to adaptation. In order to classify and compare the wide range of plant adaptation examples that can be found in nature, we define a Data Collection as well as make easier the application or transfer solutions from nature to architectural solutions. We establish a classification of plant adaptations to their environment: dynamic mechanisms and static strategies [20]. Once several plant adaptations examples have been studied for their possible application to adaptive architectural envelopes, we have found stomata of leaves of particular interest. Stomata are pores, found in the epidermis of leaves used to control gas exchange. These pores are bordered by a pair of specialized parenchyma cells known as guard cells that perceive and process environmental stimuli to trigger cellular responses resulting in stomatal opening or closure [21][22]. We have chosen stomata because they exist in all terrestrial plants and they are a key experimental tool to investigate how plants respond to and drive environmental factors. Moreover, stomata are an example of dynamic mechanisms and, at the same time, static strategies, and thus
demonstrate that the classification proposed is not exclusive and therefore stomata are specimens with an exceptional value in the process of biomimetic inspiration.

<table>
<thead>
<tr>
<th>ENVIRONMENTAL ISSUES</th>
<th>CONTROLLED VARIABLE</th>
<th>STOMATAL MOVEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>humidity or water availability</td>
<td>$\text{CO}_2$ concentration within a leaf</td>
<td>OPENING</td>
</tr>
<tr>
<td>temperature</td>
<td>high concentration</td>
<td>CLOSURE</td>
</tr>
<tr>
<td>atmospheric carbon dioxide concentration</td>
<td>$\text{H}_2\text{O}$ level (turgidity) within a leaf</td>
<td>OPENING</td>
</tr>
<tr>
<td>light intensity</td>
<td>low level</td>
<td>CLOSURE</td>
</tr>
</tbody>
</table>

**Figure 1: Diagram showing stomata as dynamic mechanisms**

On the one hand we consider stomata as dynamic mechanisms due to their valve movements in response to water and carbon dioxide interchanges. Functions of stomata include: interchanging of gases, avoiding lack of water, transpiration and interchanging of temperature. Stomata open in response to a decrease in concentration of dioxide carbon, as well as respond directly to light. Temperature provides another stimulus, at higher temperatures, stomata commonly open, responding to increased carbon dioxide consumption and as close responding to the higher level of carbon dioxide. Finally stomata respond to water or high humidity through guard cells that increase their turgidity and the stomata open [23][24]. In figure 1 we can see how control of stomatal movements depends on the controlled variable within leaf (carbon dioxide concentration and water level) and the external inputs (humidity, temperature, carbon dioxide and light).

<table>
<thead>
<tr>
<th>ENVIRONMENTAL ISSUES</th>
<th>CHALLENGE - FUNCTION</th>
<th>STOMATAL MORPHOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>humidity or water availability</td>
<td>exchange; gain; retain; dissipate; prevent; conserve; transport; lose; regulate</td>
<td>STOMATAL DENSITY</td>
</tr>
<tr>
<td>temperature</td>
<td></td>
<td>STOMATAL PATTERNING</td>
</tr>
<tr>
<td>atmospheric carbon dioxide concentration</td>
<td></td>
<td>ANATOMICAL STRATEGIES</td>
</tr>
<tr>
<td>light intensity</td>
<td></td>
<td></td>
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</tbody>
</table>

**Figure 2: Diagram showing stomata as static strategies**

On the other hand, we consider stomata as static strategies because of their great variability on surface structures around these valve cells, due to functional adaptations to environmental conditions. According to the different challenges at different climate zones, plants have been developed different stomatal morphologies, and these are the key of their environmental adaptations. It is important to understand these principles of adaptation solutions and transferring them into artificial systems for adaptive architectural envelopes rather than simply copying them. We organize this information according to three main concepts (Fig. 2): stomatal frequency or density; stomatal patterning or distribution geometry; and anatomical strategies such as wax morphologies or hair structures to reduce the evaporation of water, or dense coverage with air-filled-hairs to reflect visible light and temperature control [25].
2. Functions and active materials according to environmental issues defined

2.1. Adaptive behaviours

After the analysis of stomata we try to transform this biological inspiration into technical implementation, therefore some adaptive behaviours are suggested to concept designs for architectural adaptive envelopes. Climate data are the starting point in this transfer from biology to architecture, because we try to achieve the adaptability in each type of environment. Thus, we take climatic data given by the Worldwide Bioclimatic Classification System, as well as the season and the daytime or night-time period. At the same time, we take into account the user demands inside the building, and some available standard regulations for buildings are selected, such as ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) and CTE (Código Técnico Edificación), according to the level and type of activity. Since we consider the architectural envelope as an adaptive interface between environmental factors and internal comfort, the following challenges-functions are defined for each environmental issue, based on specific climate data and user demands:

- To regulate humidity: exchange, dissipate or absorb
- To regulate temperature: dissipate, gain, reflect, absorb or conserve
- To regulate carbon dioxide (air quality): filter, exchange or dissipate
- To regulate light intensity: diffuse, reflect or absorb

Previously we looked at why stomata were an example of dynamic mechanisms and at the same time static strategies. Adaptive architectural envelopes can be divided in two approaches as well, and functions defined above suggest two kinds of adaptability (Fig. 3), i.e. adaptive behaviour through dynamic mechanisms or adaptive behaviour through static strategies. The first type of adaptability, based on a movement through dynamic mechanisms, 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 second type, based on material properties through static strategies, changes directly affect the internal structure of a material and 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.

![Diagram of adaptive behaviour for adaptive architectural envelopes](image)

Figure 3: Diagram showing two kinds of adaptive behaviour for adaptive architectural envelopes, according to each environmental issue in different climate areas and user demands inside buildings.
2.2. Active materials

Next question could be: how can we materialize this mechanism into a technical implementation? This materialization will be possible through active materials.

So far, traditional materials such as ceramics, metals or glasses are industrially produced to satisfy the demands of the building sector, so they are homogeneous and uniform in composition, and isotropic, having identical or very similar properties in all directions [26]. Conventional materials and manufacturing processes provide inert solutions, static results or complex high-tech equipments to achieve kinematic systems. Some attempts of kinetic architecture are developed through mechanical and electronic sensing, actuating and regulating devices, resulting in a non energy-efficient architecture.

Unlike traditional materials, smart materials have properties that react to changes in their environment. 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 [27]. Most common smart materials are those relying on electrical stimulus to activate movement. However, this kind of smart-materials have been dismissed for our selection, because we focus on low-tech and low-energy adaptive materials systems, rather than highly automated and mechanical systems. We are interested in those materials that have structural and physical properties to generate movement or kinetically adapt in real time to environmental changes. Active materials, with kinematic behaviours for a better performance that shrink, fold or expand responding to changes and, at the same time, remain stable in their different configurations. We look into active materials that are self-actuating responsive materials with innate characteristics, behaviour and performative capacity to react to environmental changing conditions. These atmospheric conditions act as “green” triggers on active materials with reversible changes. Conifer cones (Fig. 4) could be a good example of our definition of active material because they have repetitive opening and closing cycles as the humidity responsiveness. Conifer cones are biological examples of humidity reactive systems with responsive capacity in the structure of the material itself.

Depending on the two different approaches of adaptive behaviour we can divide the search of materials into: active materials for dynamic mechanisms and active materials for static strategies. In the next section some experiments with active materials will be explained.

. Active materials for dynamic mechanisms:

We try to to work out a system capable of growing or shrinking in size or changing in shape, through the ingrained properties of the material they are made of, without the need for external energy or complex mechanical parts. We look into active materials capable to stretching, expanding, folding or bending, after fabrication depending only on environmental stimulus. In figure 5, a list of possible materials is proposed,
depending on different functions and environmental issues. Thus, we can see a selection of temperature reactive materials, such as thermo-bimetal sheets (two metals joined together which, when heated, expand at different rates, the structure that they form will bend) or thermo-expansive polymer (plastic capable to expand induced by thermal changes). Also humidity reactive materials, such as wood (due to its properties of hygroscopicity and anisotropy continuously is responding to changes in relative humidity by adjusting the bound water content, resulting in constant dimensional movement) or hydrogel (smart gel that swell up when water is added, making an expanded mass). We keep searching for other materials dependent on carbon dioxide or light.

Active materials for static strategies:
We look into active materials with properties to change the internal structure of the material, through changes in specific properties, such as light reflection or absorption properties, or through the exchange of energy from one form to another. Thus, in figure 5 we can see a first selection of temperature reactive materials, such as thermochromic polymers (thermochromism is the property of substances to change color due to a change in temperature) or phase change materials (capable of absorbing, storing and dissipating heat). Also some humidity and light reactive materials, such as hydrogels or photochromic materials.

![Figure 5: Diagram showing a first approach in the research into active materials depending on different functions and environmental issues defined.](image)

3. Experiments in active materials
In this last section we present some experiments in temperature active materials behaviours as actuators for innovative and low-tech design concepts for adaptive architectural envelopes. Using simple shaped elements in simple geometries as a starting point, we observe the response range and behaviour of different materials. These tests show dimensional changes (i.e. opening, closing, expansion, fold and
other transformations) or internal composition changes on element surface, caused by varying environmental issues, and thus, demonstrate the material capacity to rapidly respond to changes in temperature, humidity, carbon dioxide or light.

These experiments have been carried out using 3D printing technologies, because of the huge potential of additive manufacturing to generate structures with complex geometry, through an exceptional accuracy, speed, material property and manufacturing cost, tested in last years [28]. One step further is the 4D printing concept, developed by Skylar Tibbits or H. Jerry Qi and Martin L. Dunn, for example, which allows materials to self-assemble into 3D structures, adding the extra dimension of time. Active fibers can be incorporated into composite materials so their behavior can be predictably controlled when the object is subjected to thermal and mechanical forces [29][30]. This 4D technology provides a new approach to creating reversible 3D surfaces and promises exciting new possibilities, among others the technical implementation for adaptive architectural envelopes we are looking into.

In figure 6 we can see experiments in thermo-expansive polymer. This is a kind of plastic capable to expand induced by thermal changes. Combinations of two plastics of differing coefficients of thermal expansion involve heat sensitive actuation. Other polymers can also be blended to enhance this process such as Ultra High Molecular Weight Polyethylene (UHMWPE) which expands a lot under heating but is hard to process on its own. Images below show the use of an infrared camera to capture the heat distribution triggered through the temperature changes. With this active material we try to achieve a dynamic mechanism capable to open or close, like stomatal movements, to dissipate or gain heat according data climate at different locations. Other architectural application would be create a shading system, by means of a dynamic mechanism that bends under high temperatures. All of these adaptive behaviours try to reduce the amounts of energy to pump heating, or cool, and ventilate our buildings.

Figure 6: Diagram showing some dynamic mechanism ideas to control temperature inside buildings by means of systems with thermo-expansive polymer. Experiments presented have been carried out in the UCL Healthcare Biomagnetics Laboratories (The Royal Institution of Great Britain)

In contrast, in figure 7 we can see some experiments in thermochromic polymers to implement different static strategies such as reflect or absorb sunlight, depending on the polymer colouring. Thermochromic polymer is a kind of plastic, PLA plus an additive, that has the property to change color due to a change in temperature (thermochromism). By means of these materials, that are able to alter their colour in reaction to temperature changes, we propose a strategy to reflect sunlight to reduce temperature inside the buildings located at Mediterranean areas and a strategy to absorb more solar heat to maintain or increase
temperature inside the buildings located at Boreal areas. Like ideas proposed previously, these adaptive behaviours try to reduce and control of energy waste to maintain the comfort inside buildings.

**ADAPTIVE BEHAVIOUR**

<table>
<thead>
<tr>
<th>CLIMATE: Mediterranean (T&lt;25°C)</th>
<th>CHALLENGE: to cope with drought, excessive sunlight and high temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLANT ADAPTATION: static strategy: white waxy cuticles on leaves and stomata</td>
<td></td>
</tr>
<tr>
<td>FUNCTION: to reflect sunlight and reduce water loss</td>
<td></td>
</tr>
<tr>
<td>ADAPTIVE ARCHITECTURAL ENVELOPE</td>
<td>STRATEGY: to reflect sunlight in order to reduce temperatures inside buildings</td>
</tr>
<tr>
<td>CLIMATE: Boreal (T&lt;0°C, T&lt;20°C)</td>
<td>CHALLENGE: to cope with low temperatures</td>
</tr>
<tr>
<td>PLANT ADAPTATION: static strategy: dark colours</td>
<td></td>
</tr>
<tr>
<td>FUNCTION: to absorb more solar heat</td>
<td></td>
</tr>
<tr>
<td>ADAPTIVE ARCHITECTURAL ENVELOPE</td>
<td>STRATEGY: absorb sunlight in order to retain more solar heat and maintain/enhance temperatures inside buildings</td>
</tr>
</tbody>
</table>

**ACTIVE MATERIAL EXPERIMENT**

| MATERIAL: thermochromic polymer |
| COMPOSITION: PLA + additive |
| ADAPTIVE BEHAVIOUR: static strategy |
| ENVIRONMENTAL ISSUE: “GREEN TRIGGER”: temperature |
| MECHANISM / STRATEGY: property change: colour change at a certain temperature. In this case: 37°C |
| NEXT RESEARCH: to experiment polymer from dark opaque to transparent and to reduce temperatures until 29°C to change colour. |

Figure 7: Diagram showing some static strategies ideas to control temperature inside buildings by means of systems with thermochromic polymer. Experiments presented have been carried out in the University of Oviedo Laboratories, in the Construction and Manufacturing Engineering Department.

4. Conclusions

The research focuses on the development and the technical implementation of adaptive architectural envelopes based on the functioning of stomata on the surfaces of leaves. We study the possibilities of fabrication of responsive systems where multiple materials can react to the environment and deform over time such as mechanisms that transform into a predetermined shape, changing property and function after fabrication through deformation of active materials, depending only on environmental stimulus. The environmental issues selected are humidity, temperature, carbon dioxide and light, and some functions (e.g. filter, exchange, diffuse, ...) are proposed for each one, in order to define two kinds of adaptive behaviour: dynamic mechanisms and static strategies. Several experiments with temperature reactive materials, carried out using 3D printing technologies, are presented. Through these experiments we try to explore the interrelationships between active materials and their response to external stimuli, seeking meaningful ways to bridge between the natural inspiration, stomata, and the technical implementation, adaptive architectural envelopes.

The next step in the research is to continue working on experiments with active materials and 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, the goal of the active materials research will be to achieve hybrid materials or active composites which can embody multiple functionalities.

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