Parametric Performative Systems: Designing a Bioclimatic Responsive Skin

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Abstract

This paper assumes the façade as an innovative element of interaction between the inside and the outside: the architectural skin. As in nature, one of its most significant functions is the energy exchange with the environment. Similarly, efficiency increases by passive and active responses to climate conditions and site orientation. This research explores the potential of parametric techniques, programming and digital manufacturing, to design and build a Bioclimatic Responsive Skin (BRS). Firstly, we designed a bio-component applicable to any surface due to its parametric nature. Secondly, we fabricated two non-reactive working prototypes to study the manufacturing and construction details. Thirdly, we integrated the physical and the digital interfaces by using Generative Components™, Arduino, and Ubimash to generate a kinetic responsive model. This prototype was presented at SmartGeometry Workshop and Conference 2010. Finally, Lem3a architecture used this BRS in a real design project for a Sustainable house in New Hope, PA.
1. From Façade to Skin

Technological advances have always influenced Architecture changing the way in which buildings are conceived, drawn and produced. Particularly, the evolution of structural systems makes available a new range of possibilities to organize the space, installations and services. Buildings are not conceived anymore as an aggregation of their parts but as an integration of all of them. This integration of elements produces a combined functionality that transcends the traditional notion of design [1].

One of the ideas that has radically changed in this process is the concept of façade. These days, the façade is not just a neutral elevation that separates the inside and the outside of the building. Far beyond, the façade becomes an active element that makes the building interact with its context and the environment. This element is now considered as a continuous envelope of tectonic, environmental and aesthetical relationship between the interior and the exterior: the skin.

According to the design logic of the architectural skin, the interaction with the environment might be different. Among others categories of interactive models, we might find contextual designs, media façades, and sustainable approaches. In contextual designs for instance, the skin of the building seek to establish a dialog with its surroundings. In this case, the characteristics of the site, cultural aspects or traditional materials, play an important role when designing an architectural skin.

The envelope of the building might also become a media façade. There are different kinds of communicative skins, depending on the technology, the dynamic aesthetic, and the cultural conceptions. The message might be just an advertising or a much more subtle way of interaction with its context. The BIX installation in the Kunsthaus Graz in Austria is a good example of media dynamic skin creating a symbiosis of art, architecture and media [2].
The design logic of architectural skins might be also based on a more sustainable approach. Improving the energy performance of a building is the main objective of this kind of skin. The decisions about the geometrical forms, the materials, or the construction details, are made to moderate the energy exchange. Consequently, the use of additional heating or cooling systems is reduced. We might find architectural exemplars of this sustainable skin based on high-tech and low-tech construction systems (Figure 1). This paper will explore the potential of parametric design techniques, programming, and digital manufacturing to design and build a responsive type of this kind of skin.

2. Bio-Climatic Architectural Skins

At the beginning of this technological Era, this interaction was not completely respectful with the environment. Most of the energy needed to maintain comfort inside of the building was supplied by polluting and consuming machines. We required then a more efficient interaction, so we began looking at Nature.

Living creatures, in their perfection, have developed special structures to preserve their inner medium from the external environmental conditions. One of these structures is the skin. Human skin for example, reacts accurately to external stimuli such as temperature, pressure or light radiation, by masterly designed biological sensors. Nowadays, contemporary buildings try to resemble living organisms, and consequently benefit from an adequate skin, here called “Bio-climatic Responsive Skin” (BRS).

In their book Intelligent Skins, Wigginton and Harris [3] state that providing with a variable envelope to reduce to the minimum the provision for environmental services is essential when designing a building. They argue that purely passive buildings that sit, inert, and maintain comfort, day and night, throughout the year are not efficient enough to face diurnal and seasonal variations [3]. Therefore, the skin should behave differently according to external climatic circumstances to keep an ideal thermal condition inside of the building, without using an additional energy supply to drive a heating or cooling system. We named this responsive behaviour: Active Bioclimatic Strategy. To get this reactive performance in real time the BRS has to be intelligent like human skin is. For example, in summer time with hot weather our inner temperature increases and our skin reacts to reduce it. Opening its pores and sweating the skin refreshes its external layer aiming to maintain constant the temperature of the body. Similarly, an efficient BRS should be smart enough to know what, when, and how to react to changing external inputs to held inside temperature stable.

In order to answer these questions we looked at Victor Olgyay’s article “Design with climate. Bioclimatic approach to architectural regionalism”, where he states that there are two main factors that influence the human bioclimatic comfort: air temperature and relative humidity. In his Bioclimatic Graph he represents where the comfort area is and which are the three parameters
that we can alter to modify air temperature and relative humidity and reach a comfortable environment [4]:

- Speed of airflow
- Solar Radiation
- Evaporation (adding humid air)

If modifying these three factors efficiently we cannot enter in the comfort area, then we have to depend on additional heating or cooling systems. For the BRS design we consider reasonable to control two of these three parameters, speed of airflow and solar radiation. We assume that adding elements that produce humidity such as vegetation, fonts, or pools, might solve the need for an addition of humid air, controlling evaporation.

2.1. How can we control these parameters with the BRS?

1. Incorporating in the design opening systems the BRS might control the speed of airflow by producing natural cross ventilation. Increasing speed of airflow reduces heat by convection, producing a sensation of freshness, and simultaneously increasing evaporation. But we have to control ventilation carefully because an airflow speed higher than 1.52 m/s might be unpleasant for occupants.

Figure 2. Bioclimatic diagram of Victor Olgyay's article [4]
2. *Solar radiation* comes in contact with the surrounding elements heating them and increasing air temperature by radiation. We might have the need to allow solar radiation, and use this energy as a natural heating system, or to avoid it to maintain the inside temperature. Therefore, the BRS should manage solar radiation by integrating a combination of shading devices and heat trap systems to have a flexible performance.

Taking into account diurnal and seasonal variations we might summarise in the next diagram some of the general requirements of the BRS to contribute to maintain the inside comfort of a room:

![Diagram](https://via.placeholder.com/150)

▲ Figure 3. IC diagram. General requirements of the BRS

However, these are not only the factors that affect to the bioclimatic thermo regulation. If we continue looking at nature, we might notice many differences among the skins of animals depending on the climate of the area where they live. The global geometry of the skin, the roughness, the colour, the type of hair, are some of the passive techniques to deal with weather conditions. This peculiarity of the natural world brings up the diversity of skins according to different climates. Similarly, the BRS should have different characteristics depending on the location of the building. This is what we call in this article *Passive Bioclimatic Strategy*.

Passive techniques such as combination of materials, orientation, or form factor are also crucial as architectural strategies to make use of environmental conditions to improve the energy efficiency of a building. [5]. The optimum approach is to find the bioclimatic equilibrium between all these features in order to balance the gain of heat in cold seasons (maximum gain) and hot seasons (minimum gain).

Another important characteristic that we may appreciate in natural skins is *differentiation*. For example, the skin surrounding our eyes is much more sensible and thin than the skin of the palm of our hands. We can find part of our skin with longer hair, different roughness or different sensibility. They have
different needs and, consequently, a different performance. Similarly, we have to think of the BRS as a system based on differentiation to deal with the variable needs at different orientations. This differentiation produces a certain complexity. One way to cope with this complexity is starting with a replicable simple component (cell) that might populate the skin to generate a more versatile structure.

3. Prototypes’ Overview and Development

This generative process of complex geometry leads us to use digital technology to efficiently drive the design method and fabrication. Thinking of fabricating several prototypes we decided to build the digital model using planar surfaces to make easier the manufacturing process.

Parameters, constrains and fabrication should be into the same model to design a BRS aiming to improve energy performance and reduce CO2 emissions. Parametric design methods become essential in order to proficiently integrate the Active and Passive Bioclimatic strategies into the same artefact. We used the software Generative Components™ (GC) as parametric design tool to develop the concept of Bio-panel (BP) applied to a BRS.

According to Active and Passive strategies our BRS must include:

- Opaque panels (shading devices)
- Transparent panels (heat trap system sand natural light)
- Controlled opening systems (ventilation)
- Material and colour combination
- A parametric flexible organization and form factor (triangular components)

The idea of the BRS component, here called Bio-components, comes from an origami game based on identical triangular surfaces, which form a movable structure (Figure 4). The position of the component determines the surface that interacts with the environment. Starting with a triangular geometry makes possible a flexible organization to create any kind of surface from a triangular mesh.

Figure 4. Design logic, origami game
We created each BP from two triangles using different materials (opaque and transparent). We joined these two identical triangles along one of the sides forming a 90° angle. Thus, they rotate simultaneously creating variations in the BP and allowing it to behave differently, according to the circumstances.

Figure 5. Bio-panel performance positions

Figure 6. Bio-panel’s geometrical relationships, GC Symbolic view
The rotation angle of the BP is the variable that determines the performance of the BRS. We translated the entire concept to the GC script in order to establish the geometrical relationships to generate this reactive component (Figure 6).

To control the opening orientation of every BP we organized them in groups of three to form the complete Bio-component that populates a double curve surface. Subsequently, the Bio-component was applied in a triangular mesh introducing two inputs: the base triangle and the rotation of the component, the graph variable (Figure 7).

Once we had the digital model working in GC we proceed to the digital fabrication of a non-responsive prototype to explore construction details and the structural system.

The first physical model was a static representation of the BRS to study the structural system. For this first model we used cardboard (2.5 mm thick) for the structure, and white board and clear acrylic (1.5 mm thick) for the Bio-components. We prepare the digital fabrication planes exporting the digital model from GC to Rhinoceros to unfold the panels and the structural elements. We named them and we send the planes to the laser cuter. It took around 20 minutes to cut 336 panels and 23 beans notching the identification...
number of every piece. This means efficiency in terms of fabrication. The most time consuming task was the assembling process.

![Figure 9. Non-reactive static prototype of the BRS](image)

![Figure 10. Non-reactive static prototype of the BRS](image)
Then, we built a second movable prototype to a bigger scale to explore the rotation system. Basically, we scaled a part of the first version and worked directly with the components. The problem came when we integrate the rotation element. The rotation had associated a translation movement that produced a wrong functioning. Placing the rotation axis in the intersection between the two Bio-panels was the key point to avoid a collateral translation movement. For this movable no-responsive model we used MDF (2.5 mm thick) for the structure and acrylic of several colors (2.5 mm thick).

Finally, we introduced the responsive behavior to make the Bio-components react in real time to external conditions. We developed this third prototype (with Col. Grammatikos, K. (Arup), and Ferraris, F. (Sybarite) at the facilities of the IAAC (Institute for Advanced Architecture of Catalonia) in Barcelona. It was accepted as proposal for the cluster “Parametrics and Physical Interactions” of the SmartGeometry Workshop 2010, supervised by Salim, F. D., Mulder, H., and Jaworski P.
4. Responsive Behavior

First of all, we need to know when to activate the responsive system. For this task, the BRS might be provided with a receiver (receptor) that reads data from the environment. This essential element of a BRS could be an external sensor device or an inherit property of the material. In a continuous loop, the arriving data has to be processed by a logical code of control and the result must be transferred to an actuator.

Finally, the actuator activates the movement of the Bio-component obtaining a responsive system.

As said before, the BRS must be intelligent to have a responsive performance. The element that makes the BRS smart is the Arduino. The Arduino is an open source hardware and software platform able to receive input from different sensors and alter its surroundings by controlling electronic devices [6].

The microprocessor of the Arduino board (hardware) has to be controlled by a code written in Arduino language (software). The Arduino code is based on C and it is the way to establish the bioclimatic behaviour that the BRS needs. Once more we have to rely on digital technology, in this case not only to design the system, but also to integrate the smart control over the designed object.

To build this prototype, we used, apart from the Bio-components and the structural elements, 14 light sensors, one temperature sensor, 3 Arduino
boards (Duemilanove) [7] and 14 servomotors. We organized the work in three specific objectives:

1. Designing the mechanical system to produce the movement of the Bio-components.
2. Designing the version of the BRS to use for the working prototype.
3. Designing the electronic system and the Arduino code to transfer data from the sensors to the actuators.

After studying different options we decided to use a pulling system and gravity to simplify and optimise the mechanical elements. The Bio-component should be connected to the structure with the rotation axis in horizontal position. Then, 3 nylon tensors will pull it up from the free corner of the BP generating a rotation movement. The tensors are connected to an arm that is fixed to the servomotor.

The mechanical system design determined a new simplified configuration of the structure and the rotation hinges. We used the same concept of the previous prototypes but making a planar surface to apply the Bio-components. A double layer structure allowed placing the mechanical groups on top of the Bio-components to permit the pulling system.

Once we designed the mechanical procedure to move the Bio-components, we needed to tell the motors how much they had to rotate the
BP and when. Each mechanical group controlled the movement of one Bio-component (3 BP). An Arduino board can feed a maximum of 6 servos (6 mechanical groups), so we needed 3 boards to control the 14 Bio-components. We organized the control box in 3 electronic groups formed by...
light and temperature sensors and an Arduino board. These electronic groups were capable of reading data from external sources, but they needed the proper formula to process this data according to the BRS needs. Therefore, we wrote an algorithm with Arduino software with the desired movement of the Bio-components and we uploaded this code in each Arduino board.

The process of the Digital fabrication was similar to the previous prototype but using different materials due to the bigger size of this model (1.5 x 0.9 x 0.37 m). We used 16 mm MDF for the structure and 3 mm plywood and clear acrylic for the BP. The prototype has a total of 42 BP, which form 14 Bio-components, and each BP incorporates a hinge (PVC bar ø 3mm) that connects the panel with the structure using two eyebolts.

Completing this prototype we obtained a kinetic physical model of the BRS that reacts to light and temperature. We connected the physical environment with the prototype by means of digital technology. The Arduino code was programmed to know the exact rotation angles of the Bio-components, so there is also a feedback loop between the physical (prototype) and the digital (Arduino) environment.

But we extended these connections to Generative Components™ in order to link up the digital and the physical model. Therefore, we could see in the screen the geometrical modifications of the prototype according to the received environmental data. To get this new association we used Ubimash 3.0, an open source software to connect physical devices with CAD software [8,9]. We connect the Arduino with GC so we implemented the real time changes of the BRS on our digital model as well.
Figure 19. Selection of frames that shows movement of the BRS at the SmartGeometry Exhibition
This versatility to design using the Physical and the Digital environment at the same time opens a new range of possibilities in the parametric design process. We believe that this innovative work methodology will also affect the contemporary digital practice not only in the design of BRS but also in the design of the future interactive design tools.

4. Lem3a Arquitecture Uses the BRS Design Concept for a Sustainable House

We tested the potential of the BRS in a real design project for a sustainable house in New Hope, PA. First of all, we studied the environmental conditions of the site and then, we defined the Passive and the Active Bioclimatic strategies. Then, we decided to use the BRS to cover a group of patios attached to the house, so we utilize this patios as bioclimatic bubbles with 3 main objectives: capturing energy form the environment, accumulating this energy and distributing it around the house (Active Bioclimatic Strategy).

The Passive Bioclimatic Strategy shaped the global geometry of the house using the optimum orientations according to the solar cart of New Hope. We defined a grid based on the angles that produce the minimum gain of heat in summer and the maximum in winter. We worked with this grid, the boundaries of the site and the program, as the core parameters to define the main volume (Figure 21).

As part of the passive system we designed a ventilated skin of
prefabricated concrete (GRC) of different colours combined with green walls, and we included a garden on the roof. In addition, the house was raised up form the ground to improve natural ventilation [10].

All these design decisions were complemented with an Active Bioclimatic Strategy to improve the energy efficiency of the insufficient passive systems. As active strategy we used the BRS to cover part of the house. We used a different skin for a different function like we see in nature. In this case, we created a kind of green house system associated to the main spaces of the house to make use of natural energy. Here, the flexibility to behave differently made of the of the BRS the smart element to manage this energy. We combined the functions of the BRS (shading systems, heat trap systems and ventilation) with humidity control by integrating vegetation and a pool inside of the patios. We also used photovoltaic cells on the opaque panels to produce the power to drive the motors of the Bio-components.
Figure 22. Capturing, accumulating and distributing energy, SET house. Lem3a Architecture
4.1. How can we adapt the digital design concept of the BRS to a real design project?

Due to the parametric nature of the BRS and its component-based system the generation of the Bioclimatic bubbles was really efficient. We just needed to export the geometry of the house into Generative Components™ and use it as a reference to build the new parametric surface that will form the BRS. For this project we used a triangulated surface to increment the form factor of the building according the bioclimatic needs of the site. Finally, we applied the Bio-components into it generating our BRS for each patio.

Figure 23. Parametric design modelling, SET house. Lem3a Architecture

Figure 24. Digital model, SET house. Lem3a Architecture
5. Discussions and future direction
The BRS component based system is a very powerful generative method. The triangular geometrical form of the bio-components and the parametric nature of the tool (GC) permit to create and apply the component to any kind of surface: flat, curved, or doubly curved surfaces. However, the curvature of the mother surface and the size of the components are limited by the rotational free space requirements. Therefore, the existing GC code to generate the triangular mesh base should include a new parameter to redefine the size of the triangles according the curvature. So, the bigger is the curvature, the smaller should be the component. Introducing a new variable to customize the angle that forms the two BP of each component might be another option to cope with this limitation. This alternative does not change the shape of the flap panels of the BPs but the 90° angle that they form.

We should also consider that the control of the BRS might be local or global. Ideally, the BRS should work as a unified system. So far, we have incorporated a sensor device and a statement (Arduino) for each bio-component. Consequently, the future steps will include:

- Organizing the control of the components in groups according to orientation and situation in the global model.
- Declaring in the Arduino code a new relationship of performance between each group that allows the system to behave coordinately.

Finally we should consider that sustainable architecture is not an option anymore. Nowadays, the environmental situation forces us to improve the energy efficiency of buildings. The BRS is an alternative to reduce the use of heating and cooling machines. As a natural skin does the BRS might help to balance the gains and looses of heat. We might think only of new constructions but the reality is that most of the existing architecture need to be more efficient in terms of energy. Including bioclimatic bubbles in these existing buildings using the BRS might be a new way of making them more sustainable.

Concerning future development, we are working to make more efficient the design of the Bio- components with a more sophisticated technology. We aim to integrate the Mechanical and Electronic groups in the same element using advanced micromechanical and microelectronic integration technology. If we got an “all in one product” we will reduce costs and simplify the manufacturing process. Our current cooperation with members of a research group in Microelectronic of the University of Malaga at the Technological Park of Andalusia could be the key of this achievement.

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