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"Biomanufacturing the future: Biodigital Architecture & Genetics"

Alberto T. Estévez

Abstract

Biomanufacturing is a type of manufacturing or biotechnology that uses biological systems to produce biomaterials and biomolecules for using in medical and food industry. Biomanufacturing products are recovered from natural sources, such as animal or plant cells. The cells used during the production may have been naturally occurring or derived using genetic techniques. Since the year 2000 we began to apply this with architectural objectives, founding the Genetic Architectures Research Group & Office, and the Master of Biodigital Architecture, at the ESARQ, the School of Architecture of UIC Barcelona (Universitat Internacional de Catalunya). Research, practice and teaching come together on architecture and design, with the application of biology and digital tools, where biolearning and digital organicism are key words. The Biodigital Architecture and Genetics is the field where we began to work, exploring questions through interdisciplinary endeavours involving fields such as material science, biology, genetics, art, architecture, civil engineering, design, computer graphics, and human-computer interaction. We are exploring knowledge frontiers… And for really arriving to knowledge frontiers one main interdisciplinary cross-point is where genetics meets biology & digital, applied to architecture in our case (and also applied to art, civil engineering, design). This is the cross-point where we are, the cross-point that this paper is about, also presenting one of our last projects, the Scales Biodigital System Pavilion: the pavilion begun with the electron scanning microscope research of fish scales, and finished with the design of a digital manufactured pavilion that reacts to water without artificial motors, as a natural alternative without electricity or batteries.

Keywords: Biomanufacturing; Biodigital Architecture; Genetics; Digital Organicism; Biolearning

1. "Where do we come from? What are we? Where are we going?"

1.1. Introduction

It is no longer a secret: we have the urgent need of a more sustainable environment. Our response to this is to research, to teach, to work as architects and designers, since 2000, founding as a set -respectively- the Genetic Architectures Research Group & Ph.D., the Biodigital Architecture Master's Degree, and the Genetic Architectures Office, as a professional office. All based at the ESARQ, the School of Architecture of UIC Barcelona (the Universitat Internacional de Catalunya) [1].

Knowing the natural automatic building power that nature has, used for bio-architecture, and knowing the artificial automatic building power that the new technologies have, used for digital-architecture, we create the world's 1st (real) genetic architecture laboratory and the 1st digital fabrication workshop at a Spanish school of architecture. There, the real application of genetics to architecture became our main objective, with geneticists working together with architects for the first time in history: specifically, the scientific research in progress and its technological genetics application for obtaining living building materials (biomanufacturing), bioluminescence and bioheat for human use.

We also started to publish books, as the *Genetic Architectures I*, *II* and *III* (in 2003, 2005, 2009) [2, 3, 4], to organize events, as the *International Conferences of Biodigital Architecture & Genetics* (in 2011, 2014, 2017) [5, 6, 7], to do the *Genetic Architectures Seminars* (from 2001 until today), or to participate in numerous exhibitions (in Barcelona, Valencia, Bilbao, Florence, Beijing, etc.); having the Biodigital Architecture Master's Degree; and on the other side doing a lot of projects of architecture and design, such as - for example- a skyscraper (Barcelona, 2008), a kindergarten (Vilobí, 2009), a museum (Piñola, 2010), a urban design project (Barcelona, 2011), a market (Casablanca, 2012), a urban passage (Bilbao, 2012), a park (Cornella, 2013), an antenna tower (Santiago de Chile, 2014), a multifunctional building (Hard, 2014), or apartment buildings (Innsbruck, 2014, 2016-17), etc. [8].

Projects that can only be done with digital tools, and with digital manufacturing; projects that offer a more empathetic approach to users, solved with the richness given by the values of organic forms, continuity, unity, cohesion, coherence and complexity, but also harmony in all its parts in relation to the whole (this is the definition of beauty, and of intelligence in architecture too); projects that consider the new bio & digital techniques (Fig. 1).

Fig. 1. Alberto T. Estévez - Genetic Architectures Office, *Multifunctional building* (Hard, 2014), *Market* (Casablanca, 2012), *Antenna tower* (Santiago de Chile, 2014): projects that can only be done with digital tools, and with digital manufacturing.

So, Biodigital Architecture & Genetics is the field in which we work, making that research, practice and teaching come together on architecture and design, with the application of biology and digital tools, where biolearning and digital organicism are key words. We are exploring questions through interdisciplinary endeavours involving fields such as material science, biology, genetics, art, architecture, civil engineering, design, computer graphics, and human-computer interaction. We are exploring knowledge frontiers… And for really arriving to knowledge frontiers one main interdisciplinary cross-point is where genetics meets biology & digital, applied to architecture in our case (and also applied to art, civil engineering, design). This is the cross-point where we are, the cross-point that this paper is about.

1.2. "Green is not a color"

We need to "live Green", in "Green architecture", in "Green cities", in a "Green planet", for a planetary sustainability! And genetics (biomanufacturing) becomes a cornerstone of our "Green future"; precisely because it is at the cross-point between nature and computation; because is the science that can command both, from "inside".

All this becomes justified towards the "green economy" that mankind needs from today. Because, this is our reality: our Mother Earth now cries out to us because of the harm we have inflicted on her by our irresponsible use and abuse of her goods. We have come to see ourselves as her lords and masters, entitled to plunder her at will. The violence present in our hearts is also reflected in the symptoms of sickness evident in the soil, in the water, in the air and in all forms of life. We have forgotten that we ourselves are dust of the earth; our very bodies are made up of her elements, we breathe her air and we receive life and refreshment from her waters.

This is our reality. We all generate small or great ecological damage, so, we are called to acknowledge our contribution, smaller or greater, to the destruction of our planet. For human beings… to destroy the biological diversity; for human beings to degrade the integrity of the earth by causing changes in its climate, by stripping the earth of its natural forests or destroying its wetlands; for human beings to contaminate the earth's waters, its land, its air, and its life – these are crimes, against the natural world, against mankind, and against the future.

This is our reality, the same in Europe, in America, in Asia… Our planet's forests lose double the surface size of Portugal every year: 16 million hectares of trees disappear yearly. This is our reality, with so much contradictions: for example, we read on the newspapers how 78,000 people have signed up in only two weeks to a journey of no return to Mars. The mission (of billions of Euros) plans to install a permanent colony on Mars in a survival as dangerous as capricious, when is our planet that needs "permanent colonies" on the deserts, to give them life again, and even for a much lower price and less dangerous than in Mars. But, of course, it is more "cooler" to go forever to Mars than to the Sahara. Contradictions, also such as if we ask ourselves if we would prefer to live in a forest or in a harbour landscape of boxes. But our cities are more similar to a harbour landscape of boxes than to a forest.

Fig. 2. Alberto T. Estévez, *Green Barcelona Project*, Barcelona, 1995-98: creation of a huge urban park with green interconnected roofs.

But we can change our reality… with life! Starting as the *Green Barcelona Project* (Barcelona, 1995-98), with the creation of a huge urban park with green interconnected roofs (Fig. 2), towards a new contemporary understanding of landscape, of nature, of cities… Alive buildings for an alive city, such as the project *Genetic Barcelona Pavilion* (Barcelona, 2007), a genetic reform soft and eatable of the *Mies German Barcelona Pavilion*, a genetic research on growth control which makes live cells grow for architectural material and habitable spaces. (We can) let the houses grow! (*Sporopollenin houses*, Barcelona, 2009-10). (We can) let the buildings grow! (*Housing structure*, Havana, 2009-10). (We can) let the cities grow! (*Built island*, Garraf, 2009-10).

Genetics brings to architecture an almost infinite horizon of possibilities. For example, there is nothing more democratic than being able to buy your house in a supermarket, in the form of a "seed" of sporopollenin, which, after its corresponding genetic research, after "planting" it, grows alone as a space with the extreme durability of sporopollenin. Or to realize the millennial myth of living in a tree, whose branches -after planting them- allow for free the growth of new habitats (Fig. 3).

1.3. Biomanufacturing the future

"Let it grow!" This is the meaning of biomanufacturing, knowing the key concept of genetics applied to architecture and design. The question is to recognize how "natural" DNA is a biological information chain, with its transcription in four letters, and how "artificial" software is a digital information chain, with its transcription in zeros and ones, and how it can be linked: DNA as a "biological software", and software as a "digital DNA". Of course this is nothing easy and depends only of research funds. The control of this chains of information allows the structure, form and skin "emergence" with biological processes or with digital processes, in understanding of the advantages of this genetic and biodigital architecture, done with materials that emerges, that "grows" alone thanks to self-organization systems, biological or digital, when DNA and software are the new materials of a new architecture, and when genetic and cybernetic systems are the new systems of a new architecture.

Only a few things have so much potential to solve the problems of sustainability as biomanufacturing. That is when "biomanufacturing the future" becomes a necessity. And providentially this is now facilitated by an increasing better knowledge of genetics. At last, it is the very nature that teaches us for millions of years the “right way”, the most efficient processes. In order to take advantage of them, we just have to be especially sensitive to such learning, the biolearning. Because, just when the infinite possibilities that digital has today have been consolidated, it has begun to be a serious concern, based on the problems of its materialization and manufacturing, in the search of a digital reality, of “the material”, the ideal and adequate matter for the digital world. Where is a cheap, sustainable and definitive material for the digital machines of the Computation Era? Thanks to genetics, if “genetics takes command”, “life” will be the matter for stopping the artificial non-biodegradable stratigraphy of Anthropocene, for dissolving the non-biological human impact on our planet, for having the guaranty of its sustainability. Yes, we have genetics, an infinite horizon for research, but towards a utopian matter… we have it already: the DNA.

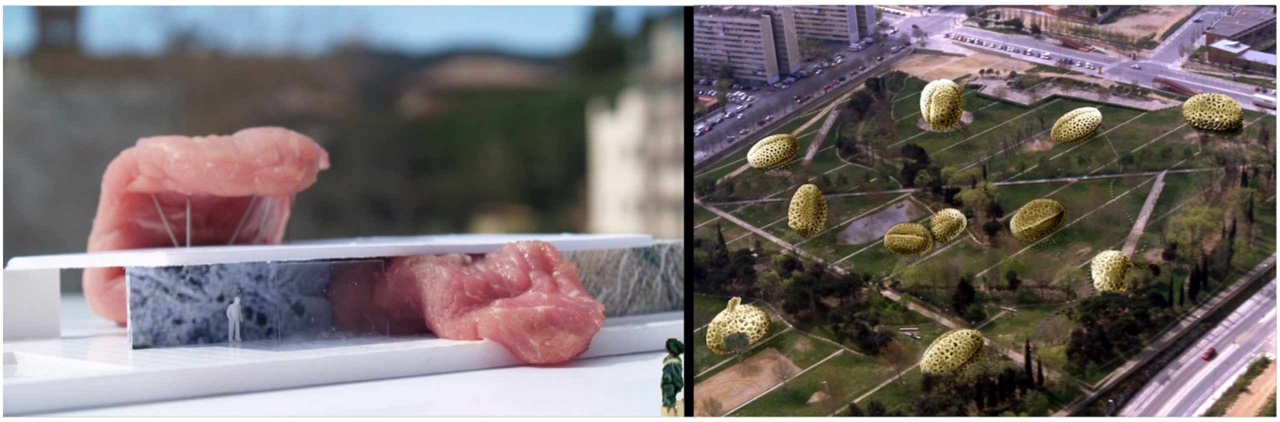

Fig. 3. Alberto T. Estévez, *Genetic Barcelona Pavilion* (with Marina Serer), Barcelona, 2007, and *Sporopollenin houses*, Barcelona, 2009-10.

Fig. 4. Alberto T. Estévez, *Genetic Barcelona Project* (1st phase), 2003-06: the magic light of the GFP lemon trees. Center, image of a possible world. Right, real comparison between a lemon tree leaf with GFP and another without GFP from the same tree type: above photo taken with conventional reflex camera, and below photo taken with special UV camera (author’s images and photos).

2. Architecture & Genetics comes together

About genetics, one of the real results that we can also mention now is for instance our research about the application of genetics to architectural objectives, such as the *Genetic Barcelona Project* (Fig. 4).

In January of 2003, talking with the geneticists in our group about the use of GFP in research, it came to the question of “what else can the GFP be used for other than being an indicator?” As an architect it was clear to me: “for illuminating architectural spaces!” At that moment we began research for getting trees to work as “lamps” (biomanufacturing!) illuminating streets, plants illuminating homes, vegetation illuminating the roadsides without electricity: the creation of plants with natural light by genetic transformation for urban and domestic use had emerged. So, in October of 2005, we successfully obtained the first 7 lemon trees with luminescent leaves, provided by GFP. These transformed lemon trees get their green fluorescent protein through the expression of the GFP gene. (The natural source of this gene was originally a jellyfish called *Aequorea victoria*). We started with the GFP, since it is the most studied one, as geneticists use it as a common cellular marker. The functionality of the objectives was clear: the trees were made with the objective of being of architectonical and urban use; it was the first time in architectural history that geneticists had worked for an architect.

The durability results were good: today, more than 10 years later, the leaves have the same luminescence, and the initial little lemon trees continue to grow depending on soil availability. They can be also multiplied by planting their branches, becoming non-manufactured (biomanufactured) “lamps”, for free! But from the beginning the lightning efficiency was very poor and needed special light input in order to achieve enough brightness.

So, through a second phase of this project, to make more efficient and useful bioluminescent vegetation, we arrived at “Biolamps”: in 2007 we started to research bacterial bioluminescence for urban and domestic use. We also were involved with the research of how to achieve bioluminescent plants with a bacterial genes group that is the responsible for bioluminescence at the same time. In this phase, in 2008 we began to create “Biolamps”, a kind of “batteries” with bioluminescent bacteria that are originally found in abyssal fish. With them, we created the first systematically fully illuminated living light apartment without electricity. For the first time in architectural history -without an electrical installation- a whole home was illuminated using bioluminescence (Fig. 5).

Paradoxically, the second phase of this bioluminescence research was very effective for lighting, not as the GFP lemon trees, but too problematic in terms of durability: every 10 days the “biobatteries” needed to be changed. And a “lamp” that could guarantee the required air-tightness, oxygen, and food was too complicated to manufacture compared with a simple bioluminescent plant or tree. So, we are now in the third phase, trying to introduce the genes responsible for bioluminescence in ornamental plants.

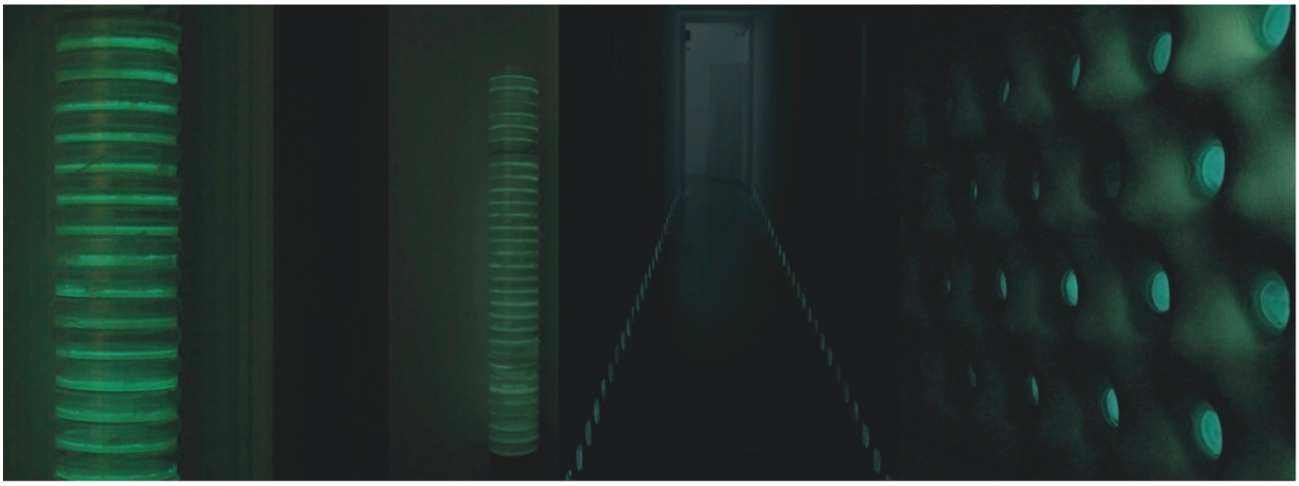

Fig. 5. Alberto T. Estévez, *Genetic Barcelona Project* (2nd phase), 2007-10: “Biolamps”: the first systematically fully illuminated apartment with living light (human eye view: photos by the author, taken with a conventional reflex camera).

3. *The Scales Biodigital System Pavilion*

3.1. Introduction to the pavilion

Motivated and grounded in what has been said so far, we are going to present a case study, one of the last projects of Alberto T. Estévez and of the Genetic Architectures Research Group & Office, the *Scales Biodigital System Pavilion*: the idea of its creation begins first with the initial fascination with fish scales, which will lead to its investigation using a scanning electron microscope (SEM). Such microscopic investigations are carried out by the main author of these lines since the year 2007, because he considers relevant to an architect the moment in which the initial amorphous masses of the growing cells begin to organize themselves genetically to resist strength, that primal moment when nature makes emerge the first forms with structural characteristics. Then, in addition, to that scale of thousands of microscope magnifications, is when unusual landscapes are discovered, surreal, full of seductive and inspiring capacity.

Meanwhile, on the other hand, there has been a growing fashion that in recent years has “devastated” the world of architecture and design, due to the contagion of the fascination for digital, electronic and mechanical interactivity, of movements driven by electric motors applied to the architecture and the design. However, it is not seen that the solution to planetary sustainability comes from the hand of planting thousands of electric motors through the facades and spaces of our buildings. Things have to be solved in a much more "natural" and simple way, and counting rather with the characteristics that nature offers for "free". This prompted that the pavilion was configured almost like a manifesto in favour of this idea: a pavilion of scales that would open and close without motors or electric energy, simply by means of the own gravitational forces.

Then, connected to the scales system enjoyed by the fishes, there was an approximation also to that same system of scales but existent in the vegetal world. Concluding then -in this biolearning way- that nature not only solves similar functions in a hugely varied way, but also it solves radically different functions with similar systems, in this case scales systems.

This is how while design this pavilion began to appear a series of patterns, from natural solutions such as fish scales, pinecones, palm trunks, etc. These patterns emerge due to individual necessities, usually required to cover specific areas: in this case of the pavilion, the interruption of the continuous lines/joins between panels that could suppose weak points for water leaks. To cover, by definition means pieces overlapping. To avoid the continuity lines generated by the orthogonal grid, a displacement gap is produced in the piece generation points (scale, branch, petal). This will result in a quincunx structure to which apply a Voronoi structure that will turn into a diamond/rhombus structure.

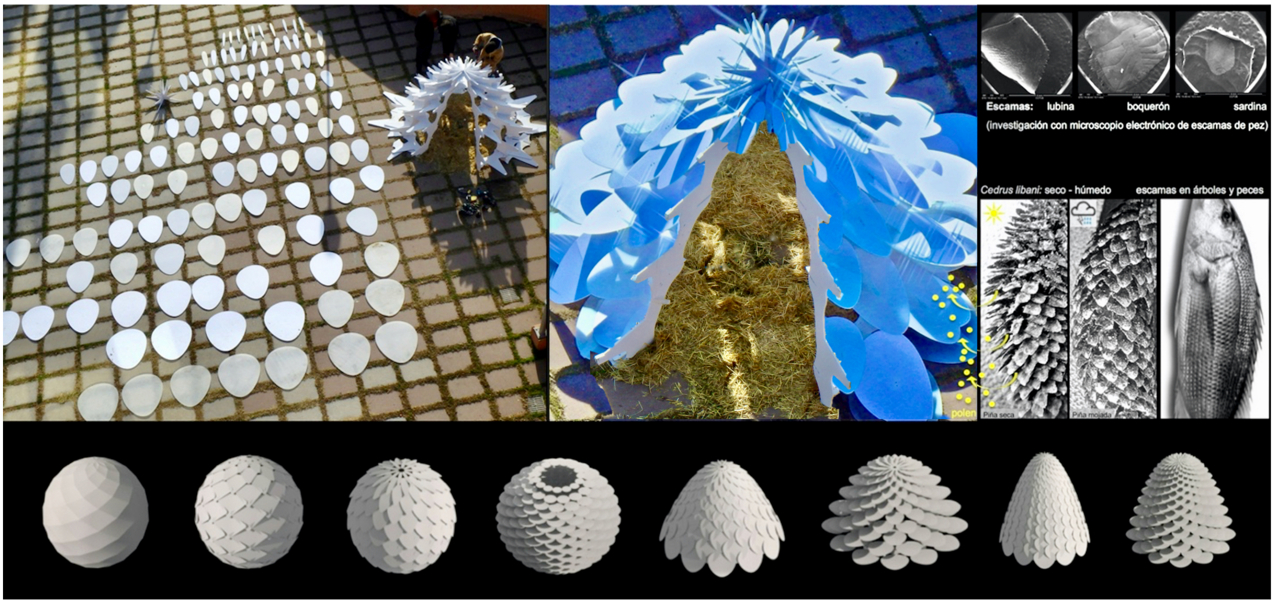

Fig. 6. Alberto T. Estévez - Genetic Architectures Office & Research Group, *The Scales Biodigital System Pavilion*, ESARQ School of Architecture, UIC Barcelona, 2015: (electron microscope research + biolearning + biodigital design + real fabrication = biomanufacturing).

Of course, it is possible to generate rectangular patterns without leaving openings, such as the tiles of a roof (Fig. 6), but this involves the use of two different pieces, and therefore is a more complex solution, which would require more resources, discriminated in case of a natural process (of nature).

3.2. Digital graphic research: “what can be drawn, can be manufactured”

The diamond structure is geometrically equivalent to a rectangular/orthogonal one, with the only difference of having two pairs of different angles. On the other hand, the value to consider for this situation is an external direction to the pattern. The diamond structure breaks both vertical and horizontal lines, in the same way an orthogonal one would do it with a diagonal one. There is a perspective problem: in fishes, as a natural example, scales are oriented in base to the direction of movement, following the minimum resistance aerodynamic line. In plants and fruits is usually gravity the one that defines direction, gathering water in the palm’s case. Based upon this geometric order, an application problem arises when modeling in Rhinoceros3D: all surfaces are two-dimensional elements composed by two coordinates (U and V) and therefore they define a "rectangle". The limits of the diamond structure will generate triangles, an extra shape that appears as a result of the exceptions that is the encounter of the pattern with the limits. Due to this, a subdivision's paneling tool like Lunchbox or Toolbox can't be applied in a straight and simple way. To solve this problem, and thanks to the isotropic geometry of the pavilion, two columns are selected in the original pattern (they are made of every type of panel in the pavilion) and a polar array is applied to enclosure the space. (The Lunchbox subdivision generates some irregularities that later manifested in significant differences in the scales sizes). Once achieved the diamond paneling (also depending on the original parametric surface based on a parabolic revolution), every scale is redrawn to achieve the overlapping. This scales pivot over an interior structure, which also works as support for the whole pavilion. The oscillation happens around the end of the interior structure, on several so-called spines that emerge from the interior structure that will be later defined. The oscillation points have to be calculated through the mass center point of the scale while in horizontal position. For this reason, is necessary to simulate the rotation of the scales based on the angle between the normal vector of the scale while closed and the perpendicular vector to the ground. This operation implies a dozen of different angles and distances but becomes relatively simple thanks to the parametrization of the model (the operation of the Grasshopper definition allows parameterizing the pavilion to its last stage of manufacture).

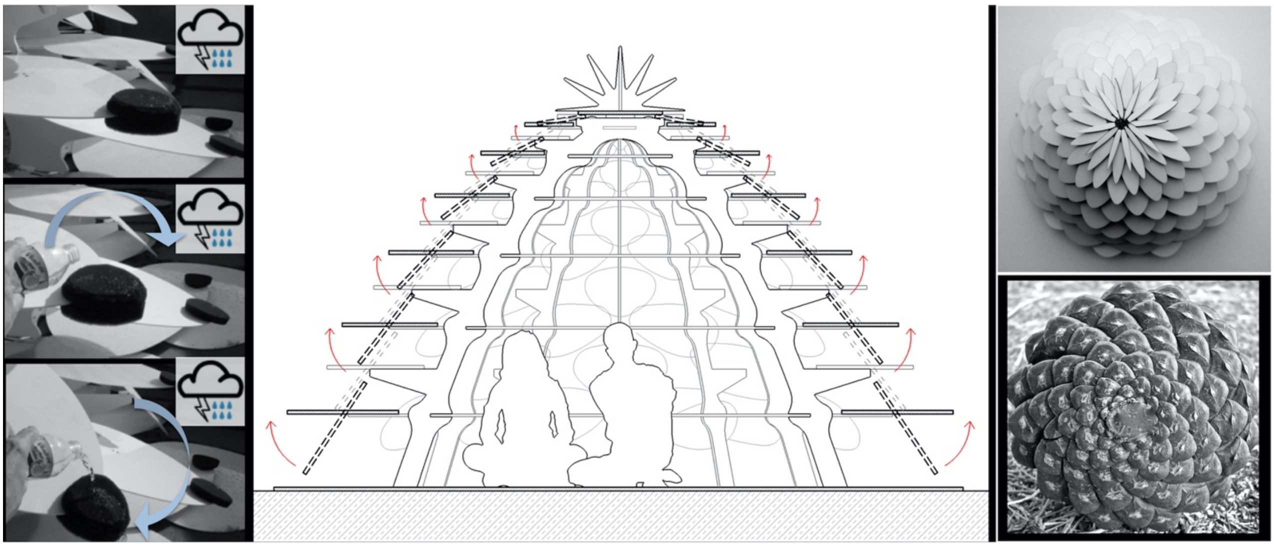

Fig. 7. Alberto T. Estévez - Genetic Architectures Office & Research Group, *The Scales Biodigital System Pavilion*, ESARQ School of Architecture, UIC Barcelona, 2015: (electron microscope research + biolearning + biodigital design + real fabrication = biomanufacturing).

The interior structure, is simpler geometrically speaking (Fig. 7), but became harder to parameterize due to the multiple details within. The structure is a waffle system made of horizontal and vertical-polar ribs. As mention, the details of this structure are not geometrically challenging, but they do produce multiple problems and errors: they subdivide the surface in the correct number of ribs, they apply variable thickness as they grow, they associate the spines to the mass centres, and add tongue-and-groove joints, they apply fillets to the profile… To define the non-parallel gap between the inner surface that defines the structure thickness an evolutionary algorithm was needed -Galapagos- considering these genes: scale 2D (XY), scale 1D (Z), movement in Z axis. Their fitness values are based in: minimizing intersection between the surfaces to 0, equalizing the height of interior edges, and maximizing its thickness to generate intersections with the horizontal ribs. Structure and scales proceed from the same surface (existing since the beginning of the process), but its geometry is completely different. Therefore, when trying to relate both geometries special attention is needed to organize the data flow. For this situation, due to an accessible number of columns and rows, a gene pool is introduced to help reorganizing the data structure in an interactive way until the values are coincident. These very same values in a bigger scale can be handled by any algorithmic solver, changing the order of the elements until the result is without errors or intersections.

In order to unify the tongue-and-groove joints, the spines and the scales in a unique continuous piece, contour 2D Boolean operations were applied over the composing parts. Thanks to these operations' simple geometries like rectangles, trapezoids and arcs produce a rather complex shape. On the other hand, this operations produce really small segments that later will make almost impossible to apply fillets to all the unions of the rib: radius is larger than the segment to fillet. The reconstruction of the curve is not a possibility because it would apply roundness even in the undesired places, like the ones in contact with the ground. To improve the result, different phases of fillets were applied with different growing radios to approximate and soften the joints as maximum as possible.

The second part of the definition is related to define the materiality and fabrication aspect of the project. It reinforces the theory that detailed and complicated (not complex conceptually talking) definitions "break" easily. In an intricate gears machinery a single small piece is potentially an error which can disable the whole definition. At that point detail and effort to solve errors should be considered in the workflow. In consequence, these are poorly flexible definitions that only serve a single purpose and hardly can be applied to other projects. On the other hand, it is worth to mention that this "detailed" property allows pushing the parametric aspect until the final fabrication process.

This hugely facilitates the adjusting capabilities in all the project, and thus favouring prototyping, testing and experimenting in much defined boundaries (Fig. 8). The unrolling, numbering and distribution of the pieces to fabricate are also included inside of the definition, only leaving out of it the very last step of nesting with RhinoNest.

Also, it has to be mention that in any moment the three-dimensionality of the objects themselves is needed due to the fact that all of them will be 2D cut with a CNC machine, which dramatically improves computing performance. Exceptionally the thickness of the objects is needed for the tongue-and-groove joints. However, these three-dimensional values are subsequently incorporated into the definition to produce infographics of the project.

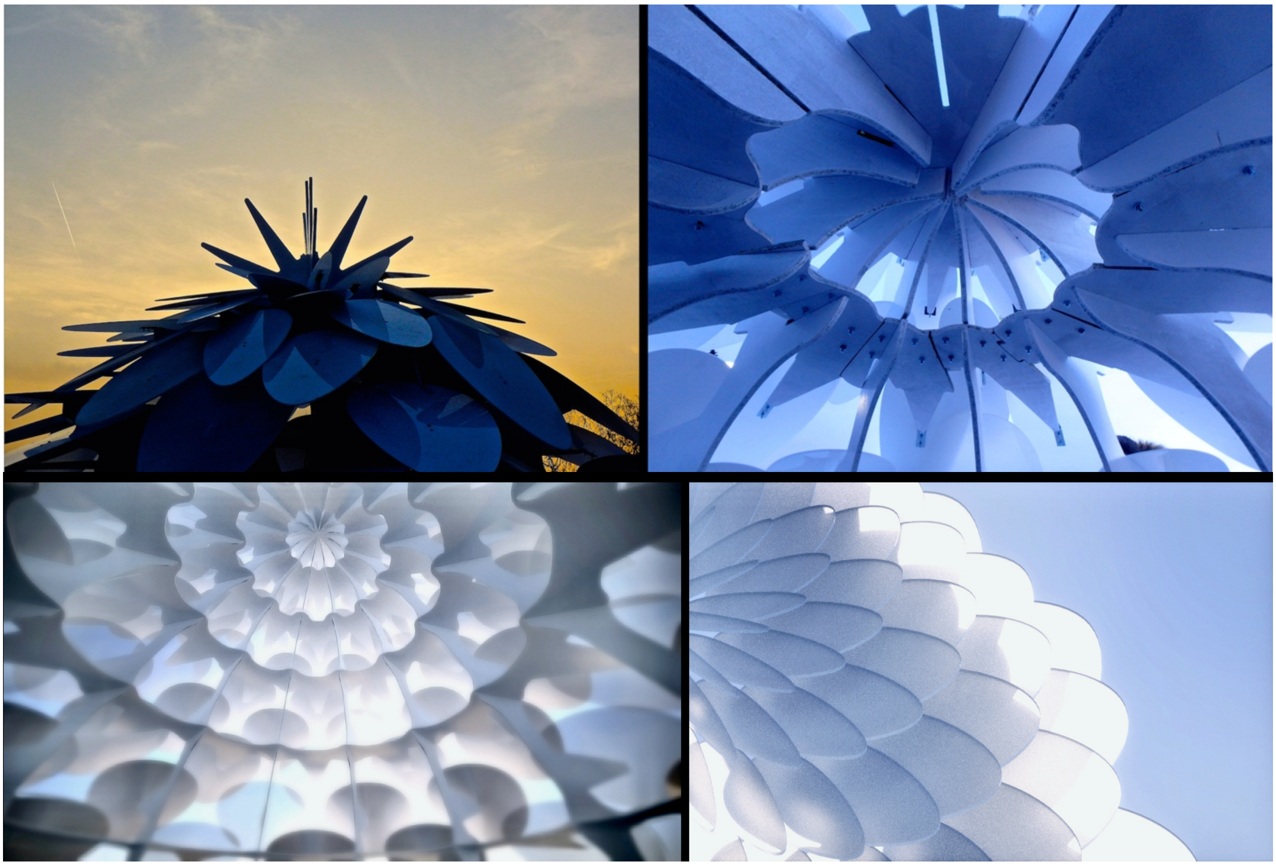

Fig. 8. Alberto T. Estévez - Genetic Architectures Office & Research Group, *The Scales Biodigital System Pavilion*, ESARQ School of Architecture, UIC Barcelona, 2015: (electron microscope research + biolearning + biodigital design + real fabrication = biomanufacturing).

3.3. Conclusions

In short, this pavilion, which includes research from the Genetic Architectures Research Group & Office, and applies it in a real way in a constructed architectural work, defines a whole project methodology: it starts from a study of fish scales, as biolearning, for the resolution of facades. This includes the use of the scanning electron microscope. In the second instance, we study pinecones, also resolved with scales, that includes the interesting mechanism of opening in dry weather, to let the pollen fly, and of closing in rainy weather, so that rain does not drag the pollen to the ground, losing then its fecundating capacity. On the other hand, the Fibonacci sequence is studied in the conformation of the scales of those pinecones, which allows a dome-shaped space. All this concludes by translating this research to a digital design and digital manufacturing for their real application. While creating a system that does not require motors for the ventilation operations of open and close. Almost as an answer by natural systems, non-motorized, face to the fashion to fill with electrical sensors the buildings to make them kinetic. This is achieved by placing the scales horizontally in equilibrium, with sponges at its ends, so that the rainwater acts as a counterweight on the sponges closing the pieces of the facade. They will again open automatically when the sponge is dried. Finally, each step involves a research, from biology to a genuine digital graphic research that must be done in order to design what we want to obtain. And also a digital manufacturing research must be done, for creating its materiality with digital tools. And at last everything must fit with the constructiveness of the whole pavilion.

All this requires not only deepening the knowledge of digital tools, but also maintain a certain transversal and interdisciplinary perspective, for an enrichment of the understanding of architecture.

And all this is not a whim. In order to give an idea about the urgency of the problem that our planet is suffering, an action was started, as a permanent manifesto that could be extended to all cities: the urban action Wake up Nature! Yes, we have to wake up to nature, but also we have to wake nature up. Or maybe it is nature that is already awake and watches us (Fig. 9)…

Fig. 9. Alberto T. Estévez, urban action *Wake up Nature! (Wake up kid!)*, Barcelona, 2012-13.

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