This is the translated into English and revised version (with corrected inaccuracies).
For references, cite the published version as:

Alberto T. Estévez, et al. "Del microscopio electrónico a la estrategia digital en arquitectura", *Blucher Design Proceedings*, vol. 3, num. 1, pp. 734-742, São Paulo, November 2016. ISSN: 2318-6968. DOI: 10.5151/despro-sigradi2016-530.

"From the electron microscope to a digital strategy in architecture"

Alberto T. Estévez

Abstract

The organization of an amorphous mass of cells into an initial structural level is relevant for the architect. As living beings do, architecture must also respond to structural and economic stresses following the law of efficiency. We can learn this process from nature (i.e., bio-learning). However, the initial structural level can only be observed using a microscope. Thus, the microscope becomes a useful tool for architectural research. This paper presents examples of this approach through which we seek to discover, analyze and evaluate the microscopic structures of plants and animals. Based on the knowledge we gain, we use computational strategies, including morphogenetic ones, to digitally design architectural projects.

Keywords: Bio-learning; Computational strategies; Bio-digital architecture; Parametricism; Digital organicism.

Introduction (and methodology)

This article describes several interdisciplinary studies and architectural projects designed by the author of this writing, within the framework of the Genetic Architectures Research Group & Office of the ESARQ (the UIC Barcelona School of Architecture). This group unites researchers from the fields of architecture and design, biology (e.g., genetics), art history and philosophy.

Today, understanding the moment when amorphous masses of cells organize themselves into an initial structural level is relevant for the architect. Architecture should also respond to structural, physical, economic and efficiency stresses, as living beings do. How to respond is something that we can learn from nature (i.e., bio-learning). However, the initial structural level can only be observed using a microscope. Therefore, this tool becomes valuable to architectural research. Here, we present examples of this approach. First, we attempt to discover, analyze and evaluate the microscopic structures of animals and plants. On the basis of this knowledge, the digital design of real architectural projects can emerge based on computational strategies that are also morphogenetic.

The research that is described involves the use of a scanning electron microscope (SEM). Such a microscope can produce high-resolution images with a substantial depth of field, which enables a large zone of the sample object to appear within the range of focus. In our case, because of our methodological interest in bio-learning (which stems from the advantages that living beings enjoy in the form of efficiency and empathy), all of the samples are biological (Estévez, 2015). Using SEM, the samples can be examined and photographed with a large magnification (up to several thousand times), as required by a given time point and with respect to the previously mentioned level of interest, i.e., the level at which the emergence of an amorphous material into its initial structure and geometry occurs.

Specifically, we use an FEI Quanta 200 SEM. At the outset, the word discover appears. Surprising landscapes repeatedly arise before our eyes, landscapes that have never been seen before, unknown morphologies that, from the human perspective, can even seem emotionally charged. Then, these discoveries are analyzed and evaluated with respect to their bio-economy and their applicability to architecture. Thus, we proceed from electron microscope scanning to 3D modelling, in which algorithms are defined and a subsequent digital reproduction is created. In this way, we attempt to make the digital design of real architecture projects emerge, even though this process implies conducting research on how a design should be drawn and how it may be produced. There are no direct paths to realizing the desired project idea because both a project's usability and its constructability are involved, which vary according to the scale used. This difficulty involves the conceptual parallel that exists in the natural environment, where cell DNA (as a natural software) determines an organism's morphogenesis, and in the digital environment, where various software applications (i.e., artificial DNA) appear as computational strategies that are also morphogenetic (Hensel - Menges - Weinstock, 2004): *from the electron microscope to a digital strategy in architecture.*

Bamboos, sponges and trees

What occurs to an original form when, in the course of its natural cell growth, it genetically transforms itself into a structure? Fractality occurs independent of whether plants (in this example, bamboo) or animals (in this example, sponges) are considered. Using SEM, we can observe how bamboo consist of bamboos that in turn consist of even smaller bamboos or how sea sponges consist of sponges that consist of smaller sponges (Fig. 1).

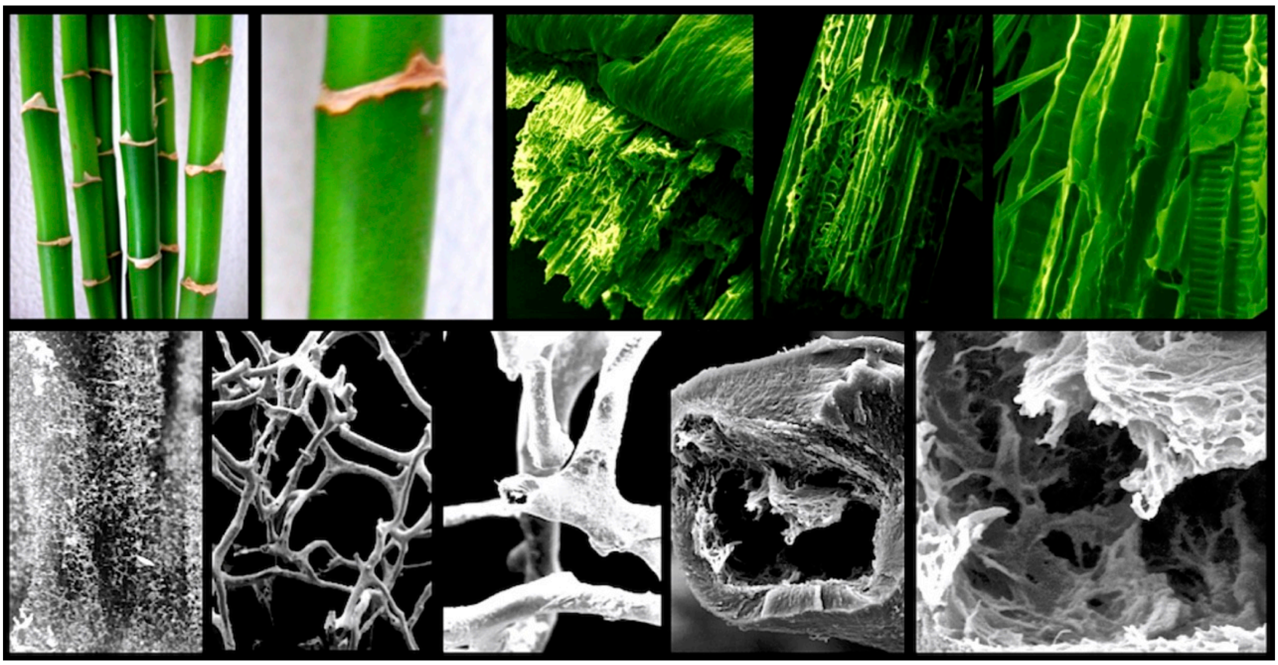

Figure 1. SEM photos done by Alberto T. Estévez, to display structural fractality, 2008-09. Top row, bamboo (x1, x10, x200, x400, x3000). Bottom row, sea sponges (x1, x100, x400, x3000, x7000).

The architect cannot be indifferent to this fact. Until recently, our structures have been based on pillars, slabs and walls. Today, thanks to new digital 3D printing technologies, we can also design structures that use this triple level of internal fractality, which facilitates an economical use of material in the search for greater structural efficiency (and lightness).

Let us bear this idea of fractality in mind as we proceed. "I captured the purest and most pleasant images of Nature. Nature, who is always my Teacher. (…) The great book, which is always open and which we must make an effort to read, is that of Nature; the other books are taken from this one and contain the errors and interpretations of men. (…) Everything comes from the great book of nature (…). This tree next to my workshop: this is my teacher!" (Puig-Boada, 1981). Ultimately, these words of Antonio Gaudi are based on the concept of bio-learning, which today has become a planetary imperative for global sustainability. Architects increasingly understand the change of reference that this concept implies, which can also be recognized in Toyo Ito's development of Gaudi's idea of the teacher-tree:

"Learning from the Tree
1. Trees create order in the process of growth over time.
2. Trees create order through the repetition of simple rules.
3. Trees create order through the relationships that surround them.
4. Trees are open to their surroundings.
5. Trees are fractal systems." (Ito, 2009)

Yes –trees and fractals– our buildings should look more like trees and fractals than anything else. Today, realizing this ambition is possible through the tools that the digital world provides. In fact, this idea resulted in a project for a fractal-based telecommunications antenna building.

This building is a tower that functions as a supporting structure for antennas. It is also by definition an urban landmark (a designation often applied to buildings of this type) that establishes a new typology of the tower-antenna that is self-sufficient with respect to its energy demands (Figure 2).

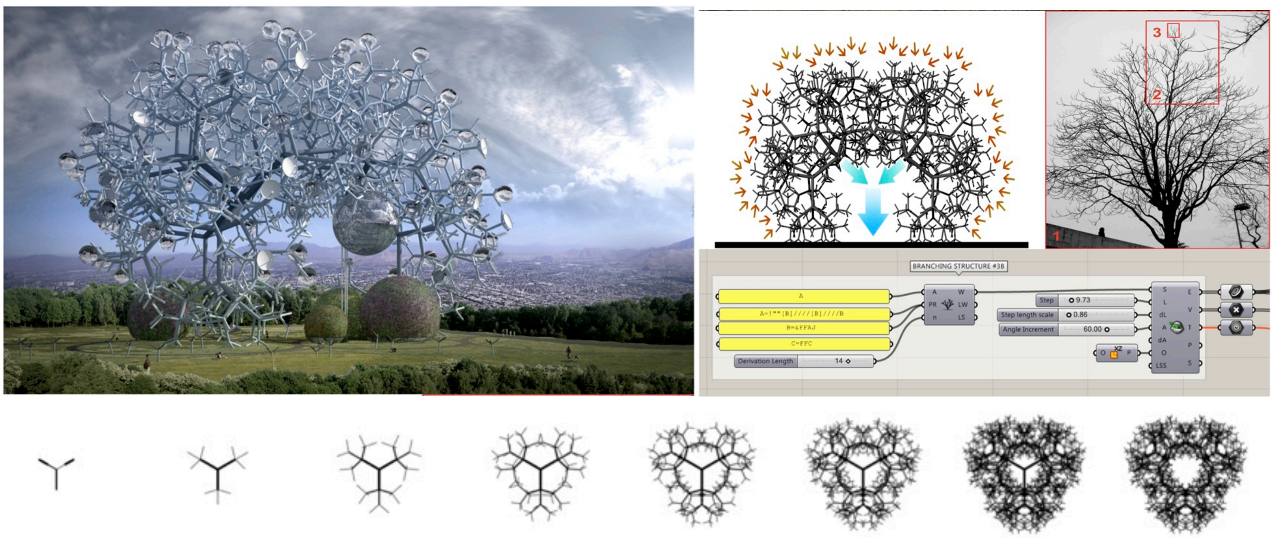

Figure 2. Alberto T. Estévez - Genetic Architectures Office, *Air-purifying and energy self-sufficient fractal telecommunications antenna*, Santiago, Chile, 2013-14: 8 generations, 3,276 bars, 60° angles.

The structure's energy self-sufficiency is achieved through spheric solar gain (BetaTorics). In addition, the building has hollow tubes with fans and filters that circulate clean air, thus helping decrease pollution. The design is based on a fractal structure that was "bio-learned" from trees and from the tooth of a lion (also fractal). "Planted" in its surroundings, the structure exhibits uniquely therapeutic and playful characteristics. The structure was digitally created using fractal geometry (L-System), thus facilitating the control of its parts. It is "automatically" harmonious, organic (i.e., organized), formal and conceptually understood without any break in continuity. It is based on a coherent system that in all parts reflects a harmonious whole, as do natural fractal structures.

Rhinoceros3D, Grasshopper and Rabbit were used to develop the fractal system, the most important components of these being L-System and Turtle. The L-System option met the requirements for developing the project with greater functional and structural ease. Therefore, the project was defined by a succession of bars that were multiplied by three in each of eight generations and reproduced using a system of 60° angles that provides shape to what is nearly a sphere. The sphere functions as a dome when some of its endpoints begin to cross. Of equal importance is that the generation of knots is constant. Therefore, all of the knots can be resolved with the same piece: a bar that is divided in three with 30° angles relative to the perpendicular plane of the original bar and with 120° angles between the pieces.

A constant system of proportions and color gradation is also introduced. As the recursions in the fractal increase, the longitude and width of the bars decrease. All of the generations produce 3,276 bars with 0.34-1.06 m diameters. The last generation of bars (2,187 in total) receives the antennas and the energy self-sufficiency equipment.

Another project was an oceanfront skyscraper. The project began with an analysis of the microscopic structure of sea sponges (Figure 3). This analysis led to digital research using programming and parametric instruments to extract genetic and structural rules. Finally, the architectural design emerged independently because the structure was capable of producing and shaping itself fractally and digitally.

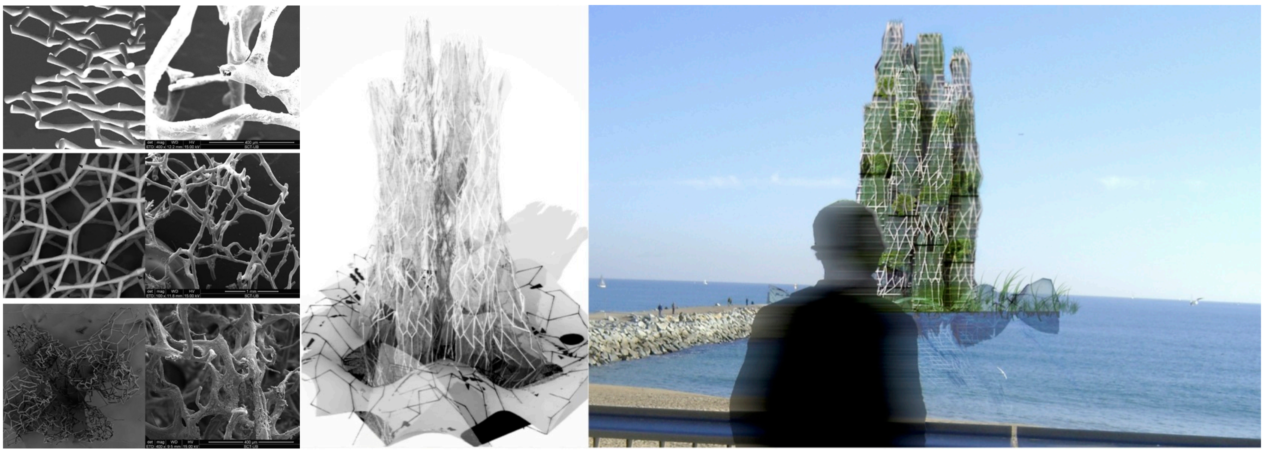

Figure 3. Renderings of 3D scripting files (left) that reveal the implications of the genetic and structural rules determined through the microscopic study of sea sponges (right, x400, x100, x400) using parametric instruments for Alberto T. Estévez - Aref Maksoud's *Biodigital skyscraper* design, Barcelona, 2008-09.

Simultaneously, real biological symbiosis was pursued so that the natural sea sponge structure could be used as a light screen in the form of lattices on the facades (Figure 4).

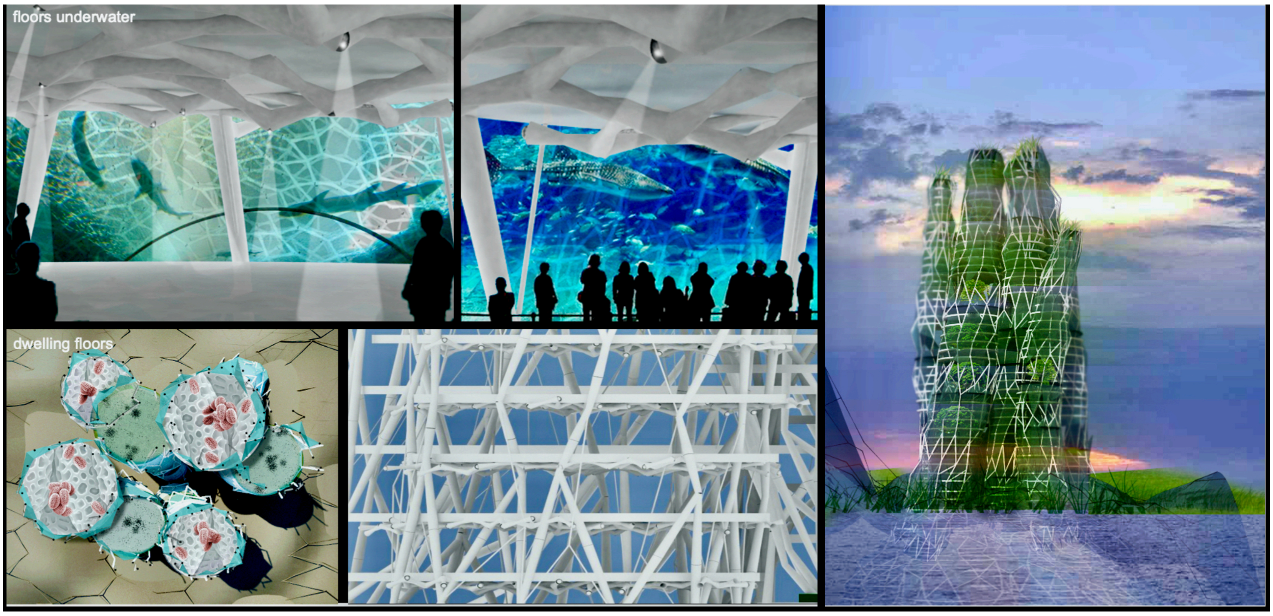

Figure 4. Alberto T. Estévez - Aref Maksoud, *Biodigital skyscraper*, Barcelona, 2008-09.

De *Datura ferox*, dragonflies and other insects

There are many examples of natural organisms whose geometric structure on a larger or smaller scale resembles a Voronoi diagram (Figure 5).

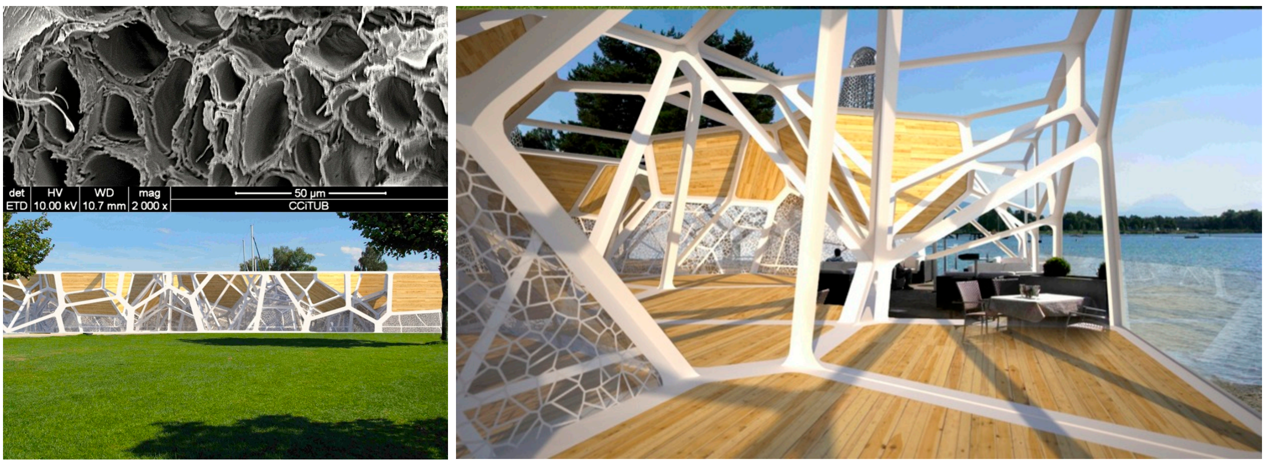

Figure 5. Top left, SEM cross section of a *Datura ferox* spike (x2000): the image reveals the plant's structural resemblance to a Voronoi diagram (Alberto T. Estévez). Bottom and right, Alberto T. Estévez - Genetic Architectures Office, *Multifunctional building*, Hard, 2014.

We focus on these patterns because they appear in nature, both in the plant world (in this example, *Datura ferox*) and in the animal world (in this example, dragonflies) and because of our interest in the digital dump. One such case under development is a project to reform an entire urban area, including a park and a multifunctional building.

Thus, to meet baseline requirements, to accommodate adjustments in project conditions and to achieve uniqueness and continuity, a Voronoi cell system was used. It was also used because it automatically generates designs and resolves problems using a simple geometry (i.e., points that mark the center of each cell) of controllable patterns. Elongated, lineal, large and apparently orderly views or more heterogeneous and extensive patterns can be created for a square or a similar location.

In addition, the study of Voronoi patterns (for example, of dragonfly wings) reveals a quality that results from expressing differences between structure, edge and other conditions (Figure 6). This insight represents an important discovery that was only possible by observing biological samples. Therefore, the Voronoi diagram levels were drawn subordinate to one another, which enables continuous lines to emerge (that were wider because they defined themselves as first steps). These lines were defined using a succession of points that define parallel curves.

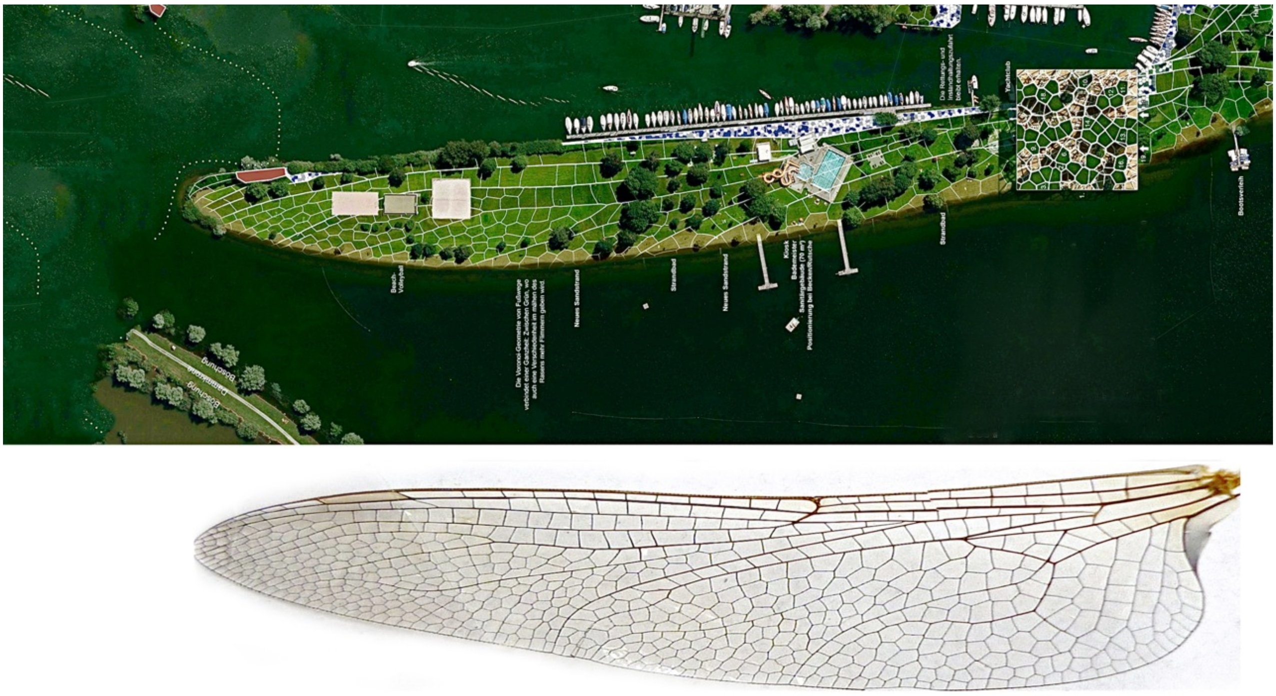

Figure 6. Alberto T. Estévez - Genetic Architectures Office, *Park and multifunctional building*, Hard, 2014: the richness of space, diversity and hierarchized routes are the result of a study that draws on biology.

he Voronoi pattern organized the park pathways with coherence, unity and diversity, parceling areas according to use and creating private areas. The cells in the more urban areas with hard pavement were subdivided into three successive fractal levels down to the small scale of the flagstone. Alternatively, the cells were enlarged to form kiosks on the second level of the subdivision or benches on the third level. The transition between the more urban spaces and the green areas was resolved with gradients between the cells of the second level.

Finally, continuing the Voronoi fractal, a multifunctional atrium building (with a restaurant, a cafeteria, offices, changing rooms, storehouses, and amenities) was proposed. The park entrance was situated at the oceanfront promenade, and Voronoi rules were followed in creating a three-dimensional form: the cell edges are the structural elements, whereas their faces are the facade, ground and covering.

Closing and opening the faces of each three-dimensional cell fulfils the proposed program. To this end, the different faces are evaluated based on the value z to organize them as covering, pavement or facade. Certain faces are made of glass with Voronoi lattices, while others are made of boards.

Computational work was required to subordinate cells within others (i.e., to nest the structure inside its own structure three times using the Voronoi Groups component) or to adapt cells to irregular perimeters. For this last requirement, it was necessary to implement components of Boolean evaluation to delimit the coinciding regions (Region Intersection) of two domains: a) a Voronoi pattern that is larger than the whole and b) the project's limits.

To reinforce the idea of cells, the angles are rounded on the inside with their radial length based on cell size. In this way, the organic nature of the cells and the values of continuity and uniqueness, fluidity and dynamism are emphasized.

The same digital strategy was applied in a housing complex project, which was a compact building with several floors (Figure 7).

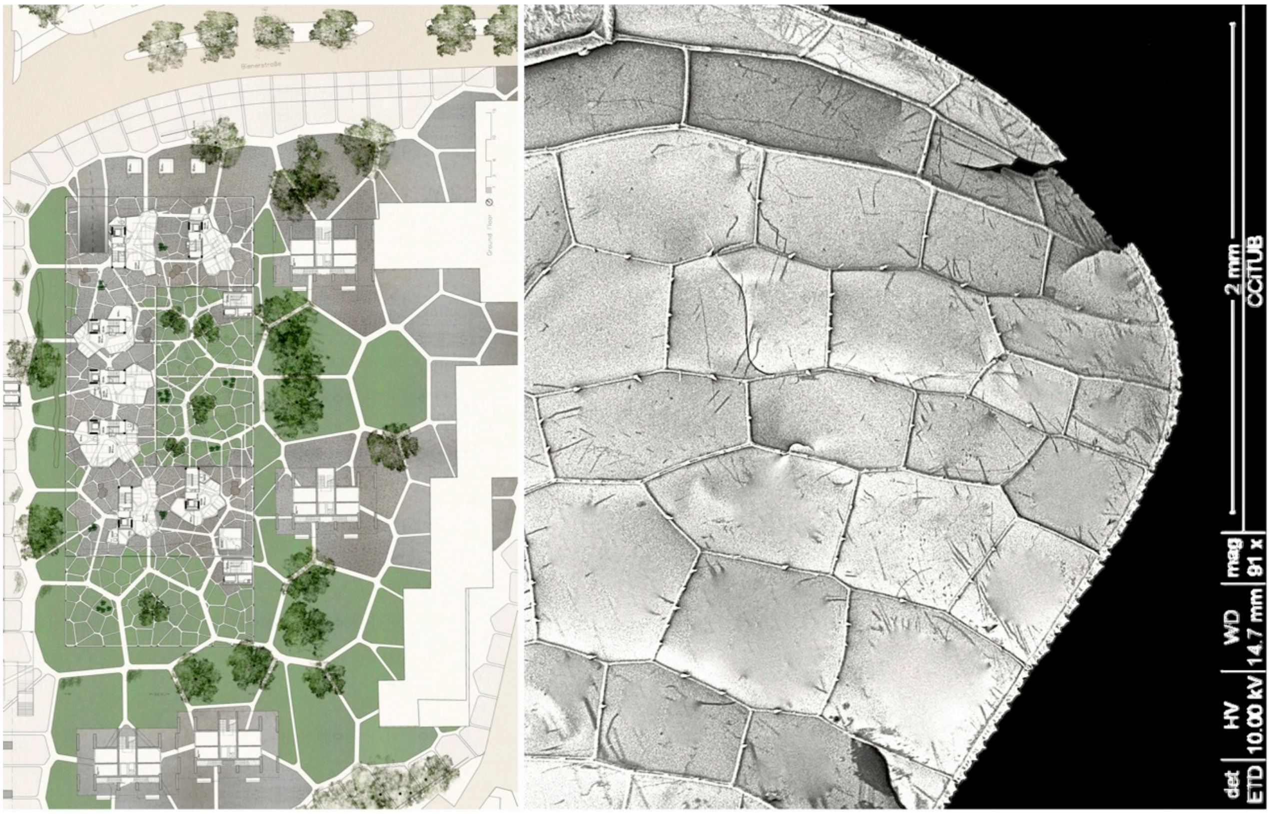

Figure 7. Left, Alberto T. Estévez - Genetic Architectures Office, *Passive solar biodigital housing*, ground floor with different levels of the subordinated Voronoi diagram, Innsbruck, 2014-15. Right, SEM image done by Alberto T. Estévez that shows the structural similarity of a dragonfly wing (x91) to the Voronoi diagram.

This project was entirely designed in accordance with ideas from the field of passive solar architecture, including apiculture and urban vertical agriculture on "floating" green platforms (Figure 8).

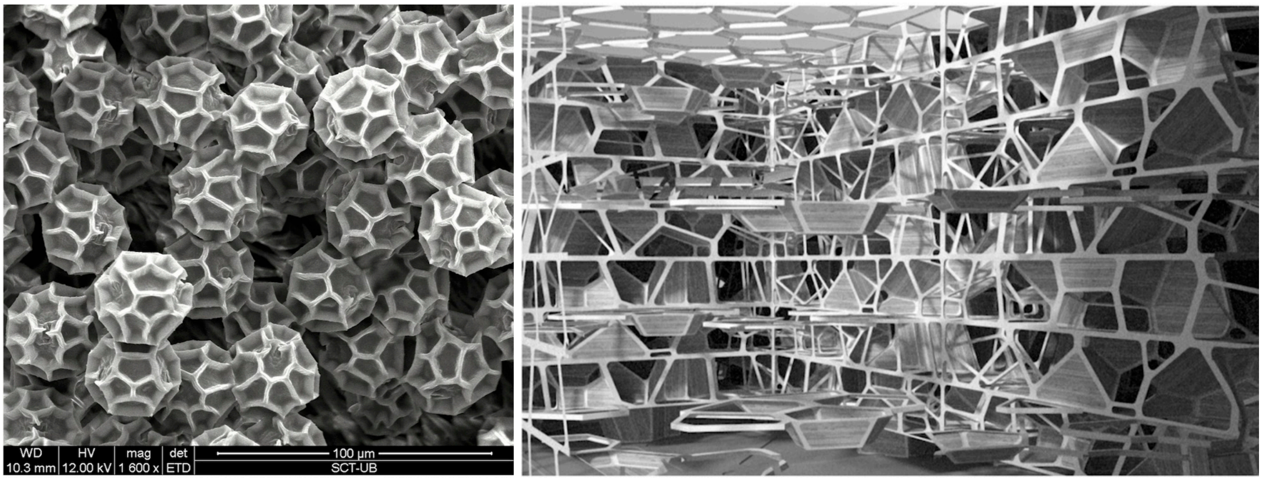

Figure 8. Left, *Aster* pollen grains: SEM image (x1600) done by Alberto T. Estévez that shows the structural similarity to a Voronoi diagram. Right, Alberto T. Estévez - Genetic Architectures Office, *Passive solar biodigital housing*, interior courtyard with “floating” green platforms, Innsbruck, 2014-15.

The management and adaptation of the Voronoi cells is performed in a manner opposite to how it was performed in the previous example of the *Park and multifunctional building*. In the park, the objective was to adapt the cells to irregular and heterogeneous pre-existing limits. However, in this project, the project limits are clearly defined by the regular forms of facades and patios. That is, a Voronoi pattern is used to subdivide the internal space instead of spreading growth towards unknown edges. In addition, in this project, the Voronoi diagrams develop broadly and fully in three dimensions, as was discovered to be the case, for example, in a microscopic section of a cactus (Figure 9).

A particularly interesting aspect of this project is the functional need for verticality and horizontality in the building’s facade and floors. Naturally heterogeneous, the Voronoi pattern contributes to the blurring and fragmentation of these needs. However, the pattern must also recognize and adjust itself to them. Therefore, although the calculation of Voronoi cells is infinite according to its mathematical definition, the pattern’s limits are manifestly represented and controlled in this building through the overlapping of regions in its vertical and horizontal slopes.

To divide the space into cells that facet and fragment the facade, a Voronoi 3D triangulation component is used. The points on which this component is executed arise from randomly populating the volume of each of the building’s elevations. Obviously, the number of points and their arrangement directly affect the façade’s appearance. Therefore, the number of points and the seed that randomly generates their arrangement should be controlled.

The most important factor in adapting a Voronoi pattern's digital format to a geometry that is amenable to manufacture is the duplication of faces. As a result of their adjoining cells, each of the interior faces of the three-dimensional pattern is duplicated. To clean up the excess faces, the center of each face was calculated and associated with the point duplication component. This list of duplicates could be subsequently applied to the list of faces.

The center of the faces was also used to classify and apply the materials (e.g., wood, glass) based on their relative height. The surfaces whose centers are higher than the average height become windows, whereas the lowest surfaces are fashioned into laminated wooden flaps. The faces associated with a normal vertical vector become floor slabs.

Figure 9. Left, SEM images of cactus sections (x1600, x3000, x6000) done by Alberto T. Estévez that exhibit Voronoi diagrams in three dimensions, given that they also appear on the walls perpendicular to the section. Right, Alberto T. Estévez - Genetic Architectures Office, *Passive solar biodigital housing*, outside view with a Voronoi pattern in three dimensions, Innsbruck, 2014-15.

The previously mentioned fragmentation of the facade is controlled through conditionals. The intention was to create recesses, i.e., places that allow light to enter, spaces for high-rise gardens or simply holes in which plants could grow. The relation of the conditionals is the distance from the cell's geometric center to the building's most exterior limit. If the cells meet this minimum distance requirement, they are subjected to a coefficient of 60%, which eventually determines their disappearance (Figure 9).

Last, the filling of the patios, which consist of two hierarchies of Voronoi structures different from those used in the rest of the project, required the most adjustments (Figure 8). The purpose of this open space is to control the density and slenderness of the bars and the size of the platforms used for agriculture. The first Voronoi hierarchy established the structure and is subjected to an evolving algorithm that assesses 1,000 options to determine those that fulfil the minimum slenderness and construction-feasibility parameters. The second hierarchy, or the platforms, is the result of a subdivision within the structure frame because the platforms must sustain themselves on the structural hierarchy. Of course, this circumstance generates a large number of platforms that must be removed as a result of the degree of randomness associated with the facade's proximity.

Pollen, radiolarians and other plants

In this final section, we include similar structures that again emerge from the plant (in this case, pollen) and animal (in this case, radiolarians) worlds. The digital transformation of these structures is particularly interesting because of the way in which the various projects are able to develop by obtaining answers from these natural structures, benefiting the resulting architecture. Thus, from the microscopic study of the common geometry of pollen grains and radiolarians (plants and animals), a graphic study was performed (using various applications, including Rhinoceros3D, Grasshopper, Paracloud and scripting) that ended in the design and digital manufacture of panels at a scale of 1:1, a pavilion and a series of urban interior furnishings and lamps.

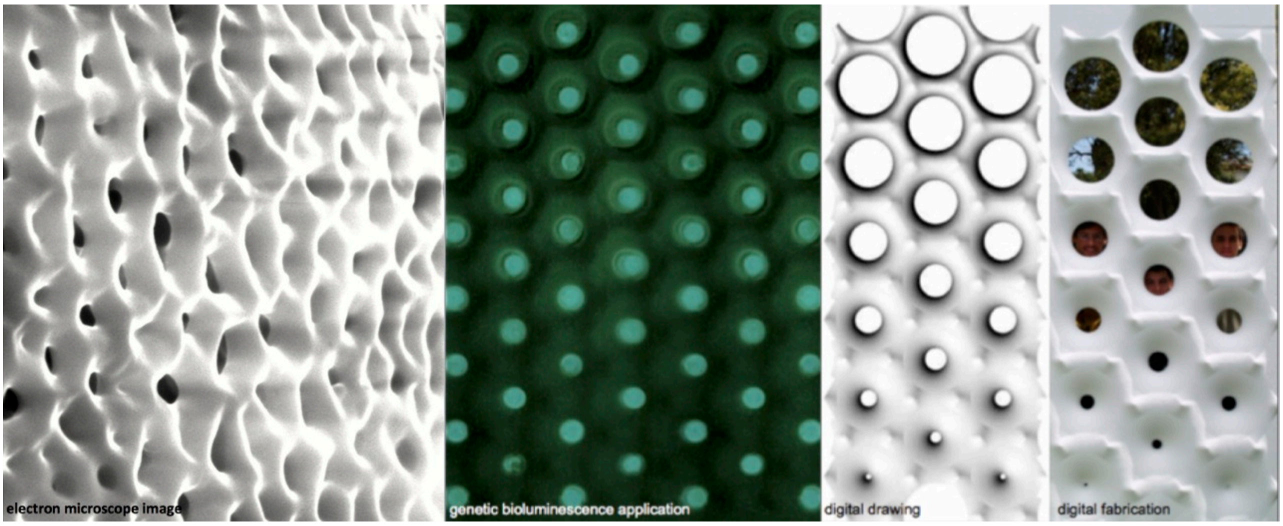

Figure 10. Panels designed by Alberto T. Estévez, 2008. Left, SEM image of pollen (detail) (x12000) done by Alberto T. Estévez. Center left, panels with biolamps application. Center right, model that uses the most convenient solution. Right, digitally manufactured piece at natural scale 1:1.

First, a series of different panels were used that were applicable to different possibilities of space creation, for example, a doctor's office (Figures 10 and 11). In this example, the human needs of privacy and transparency are blended from bottom to top, as produced later by computer-aided design and computer-aided manufacturing (CAD/CAM) technology.

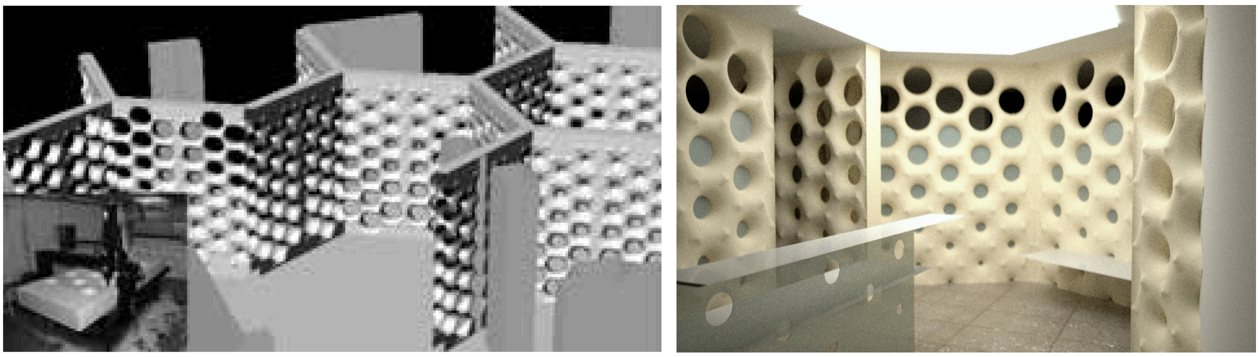

Figure 11. Alberto T. Estévez, *Consulting room*, Barcelona, 2008-09: panels manufactured using a CNC milling machine.

In the process of developing this product line, domes were manufactured, as in the pavilion also presented here (Figure 12). In this case, the modelling, parametric and scripting software continued to be used in addition to a computer numerical control (CNC) milling machine.

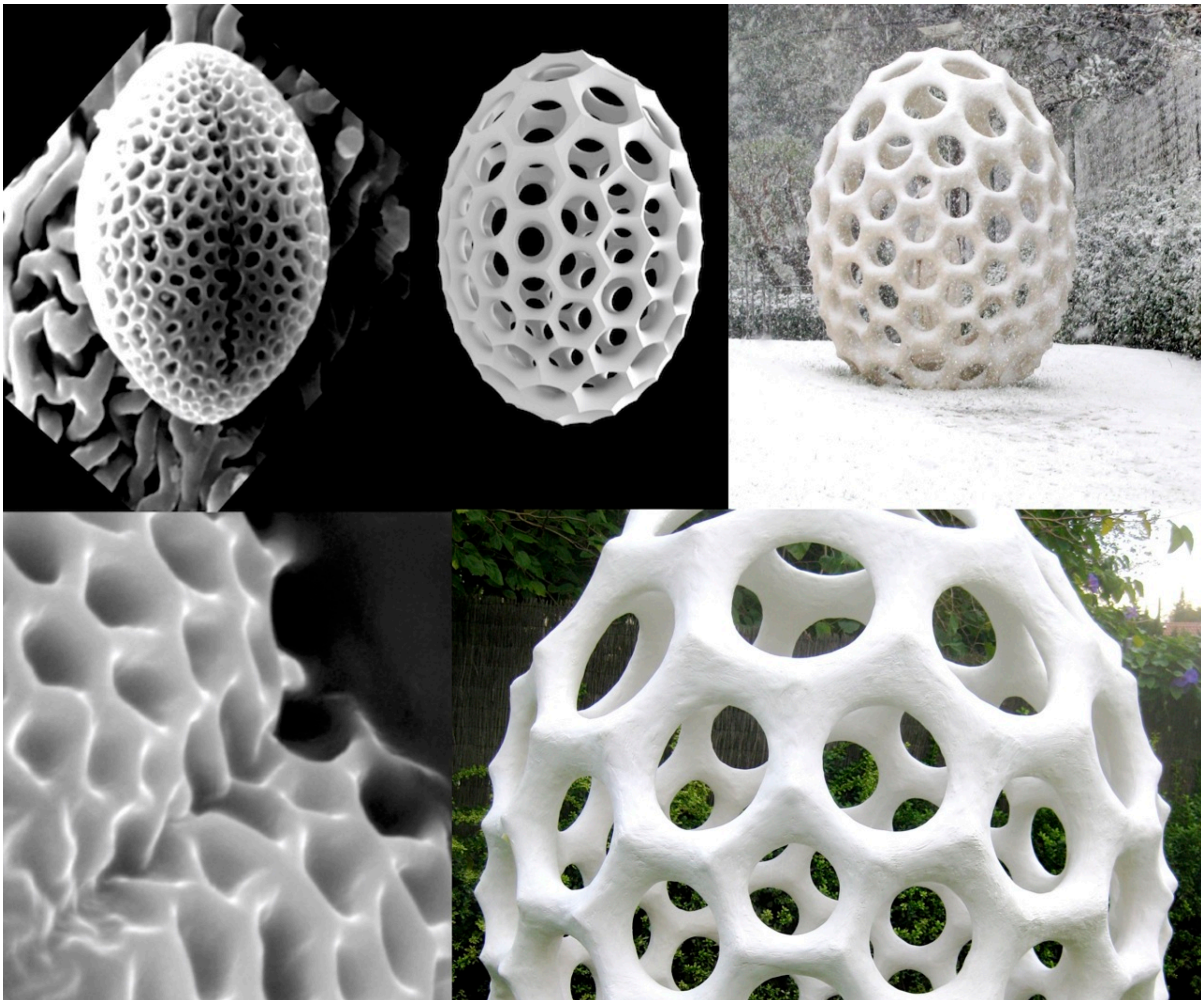

Figure 12. Left, top and bottom, SEM image of a *Prunus dulcis* pollen grain (x6000, x20000) done by Alberto T. Estévez. Top center, final model based on the corresponding graphic study. Right, top and bottom, Alberto T. Estévez, *Biodigital Barcelona Pavilion*, Barcelona, 2008-09.

The ease of changing scale also facilitated the creation of the previously mentioned furnishings and lamps (Figure 13).

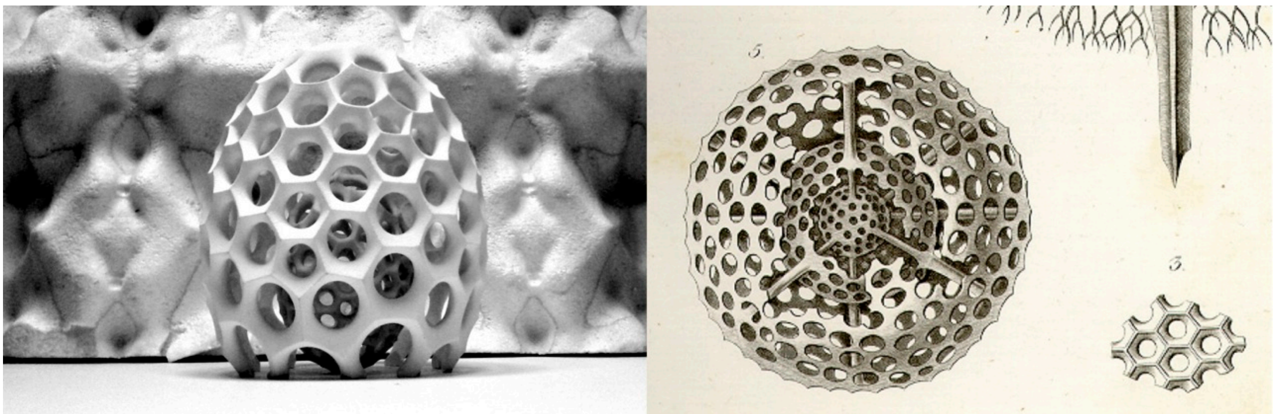

Figure 13. Left: Alberto T. Estévez, lamp manufactured on a natural 1:1 scale with a 3D printer, 2010. Right: extracted image of *Die Radiolarien*, p. 24 (Haeckel, 1862).

Finally, we present a digitally designed and produced bench. In this project, learning by using a microscope to observe the fluidity in plant filaments and stamens continued (Figure 14). Following discovery and analysis, the application of the corresponding parametric strategy was particularly appropriate because of its consistency with the concept of usability that we sought.

Figure 14. Alberto T. Estévez - Genetic Architectures Office, *Biodigital Barcelona Chair*, Barcelona, 2010. Top center, SEM image of a *Viola* stamen (x400) done by Alberto T. Estévez. Left, subsequent graphic study. Right, first example of a digitally manufactured series of benches with real grass, placed in different locations.

In this case, the objective was to use a digital translation to longitudinally sequence without interruption all of the possible ways that a human being might sit (Figure 15).

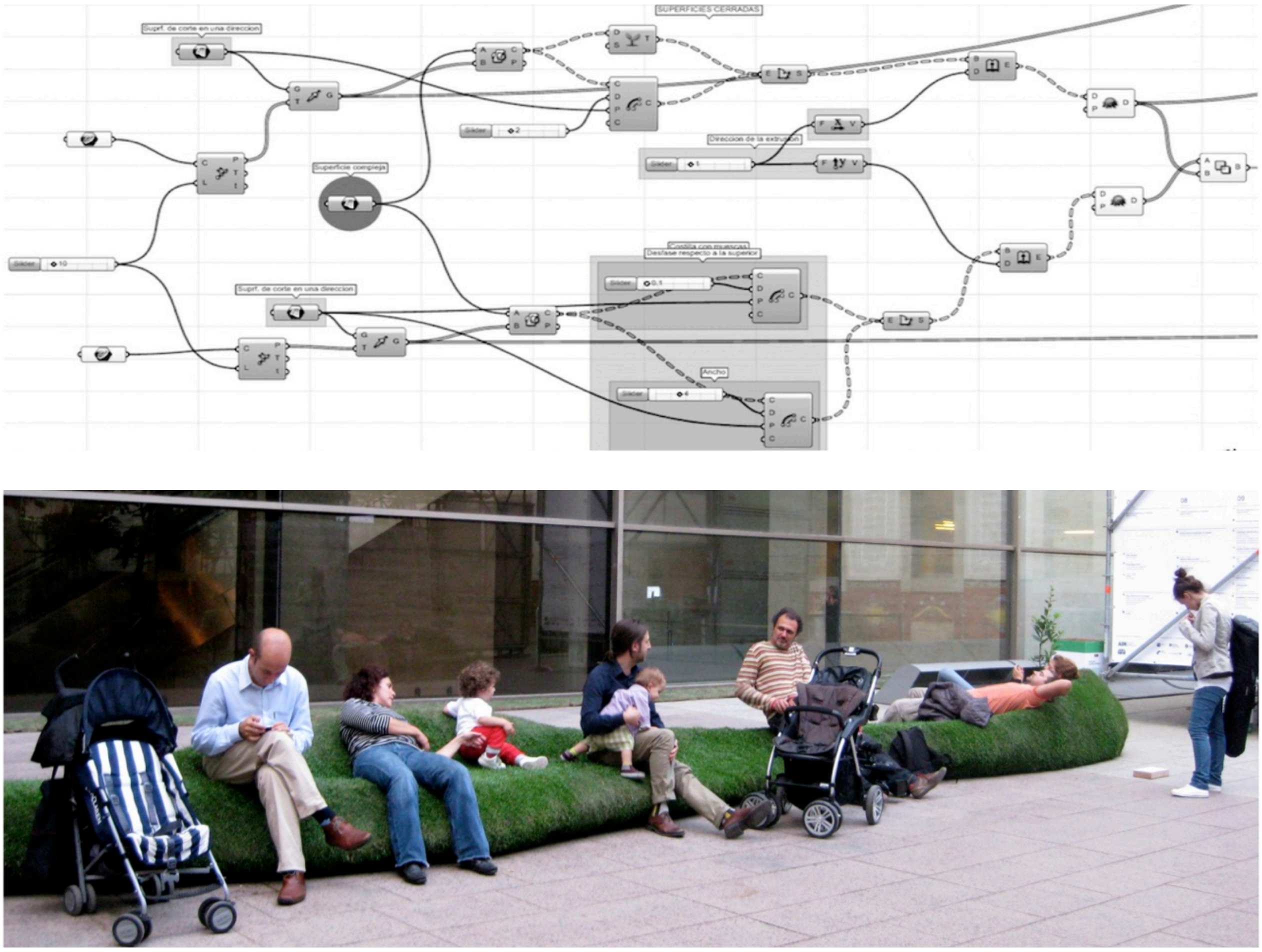

Figure 15. Alberto T. Estévez - Genetic Architectures Office, *Biodigital Barcelona Chair*, Barcelona, 2010, and its definition in Grasshopper (top).

Then, an interior structure was created that was filled with earth and equipped with an automatic watering system, which enabled the structure to be covered with real grass. The grass-covered bench produces agreeable sensations for any user position from sitting to lying down. The design is used to achieve the biological symbiosis of living beings participating in human comfort in real time and integrated into architecture and design for this purpose.

All of these examples are completely based on microscopic structural images - born from them! In fact, on this biological level, everything is only structure. We learn from nature how to appreciate everything (both physically and empathetically) as architectural values: from organicity to continuity, coherence and unity.

These last three values have been defined since Plato as bearers of intelligence and the conditions for attaining the supreme value of beauty. It should be noted that in the architect's professional and academic environment, there are numerous occasions when the approach to architecture discussed here is rejected because it is considered bizarre. In reality, the deeper objectives of such architecture transcend such prejudices.

We must also introduce here other examples in which microscopic research uncovered unknown typologies that would have been difficult to invent without the methodology explained in these pages. For example, the topological *Kindergarten* was developed from an analysis of the surfaces of tiny leaves (i.e., sepals) of flowers. This analysis resulted in the discovery of microscopic landscapes, which inspired the creation of a building that in its entirety serves as a playground for toddlers (among numerous other functions) because of its essential and special architectural DNA (Figure 16).

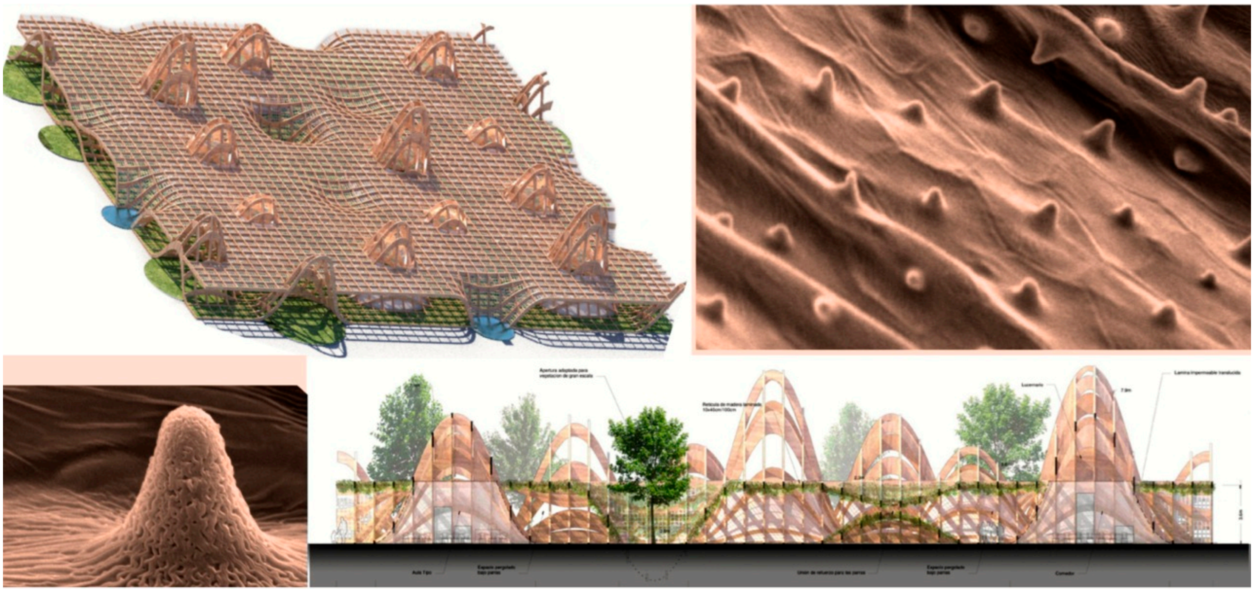

Figure 16. Alberto T. Estévez - Genetic Architectures Office, *Kindergarten*, Vilobí del Penedès, 2009, with SEM images of two plant leaves (sepals) (x800 and x3000, respectively, top right and bottom left) done by Alberto T. Estévez.

The building is an abstract parametric mesh that adapts itself to its environment according to the needs of its users and expands in an "all-over" architecture. The building’s open-use, common space is defined by two meshes of wood (upper: roof-pergola; lower: ground-pavement) that are digitally defined and produced. Classes are held and other activities occur in the single protrusions. In this case, biological symbiosis occurs through the use of a green covering, e.g., a pergola and an arbour, which introduces a playful appearance that unconsciously corresponds with the architectural typology, in this case, a *Kindergarten*, a children’s garden.

Conclusions

This article has briefly presented examples of various projects by our team that suggest a number of digital strategies for the development of actual architectural designs.

Of course, someone could describe these projects using the widely accepted term “parametricism” (Schumacher, 2009). However, another term that could be more accurately used to describe these projects and that should receive greater critical acceptance is “digital organicism” (Estévez, 2005). This terminological discussion, which we only mention in passing because of space limitations, should be developed within another framework. However, it should be stated that parametric qualities represent only one aspect of the approach presented here.

The projects of the Genetic Architecture Office and the work it performs with digital tools and organic forms fuse digital and biological techniques and guide us along pathways that lead to other values: organicity, plasticity, vivacity, complexity, diversity, uniqueness, coherence, fractality, cohesion, harmony and bio-economy. These values are also architectural values! We have learned these values from the lessons taught by the book of nature. We have also learned to transcend the simple, imitative metaphor using the environmental, empathetic and humanizing advantages that biology contributes. The subtlety of each part of a natural microscopic structure has much to offer with respect to the enrichment of architectural structures, their spaces and enclosures.

Our approach is not metaphorical or a mindless mimesis but an empathetic adaptation of nature to human beings that can form the basis of a new, more authentic contextualism in which the tree is the real, most primordial context. Finally, digital tools provide the advantages of control, automatization and manufacturing. These tools will aid us in the pursuit of efficiency and the genuinely integral sustainability (physical, human and social) that efficiency’s achievement implies.

The wide scope of the results presented here can be attributed to the fact that the Genetic Architecture Office operates in a permanent professional-research-teaching relationship with the Genetic Architecture Research Group and the Biodigital Architecture Master’s Program, which have been directed since 2000 by the author at ESARQ (the School of Architecture of UIC Barcelona). This relationship has facilitated the development of a philosophical foundation for the research presented here, including a recognition of the emergent nature of life (DeLanda, 2015). Thus, our research represents transdisciplinary thinking that draws on biology, architecture and design and in which digital instruments serve as a vehicle of creation that fosters construction based on multiplicity and diversity. Such thinking addresses fundamental issues in the field of architecture and design, the objective of which for us is always the improvement of human society.

Therefore, in conclusion, the interest in community and sustainable development ultimately justifies the use of parametric design and digital manufacturing as these tools are applied in the projects presented here, that is, to find paths to a better quality of life. In fact, these projects would not have been possible without direct, permanent collaboration with a team of biologists, who are present at the discussions that concern them and who aid in the use of biology's tools. Similarly, we collaborate with philosophers specialized in the emergent nature of life and bioethics, who provide the team with more profound and more rigorous instrumentation, definitions and arguments. In addition, art historians help us place the task at hand in a historical context and provide comparative references. This collaborative approach facilitates the evaluation of and reflection on our activities in relation to the future of art and architecture.

In fact, those who view our efforts as surreal or bizarre may fail to recognize that in reality, our research expresses our *Zeitgeist*, the spirit of a period increasingly complex, contradictory, interconnected and undermined by unseen opponents.

In the end, the projects described here exemplify how technology used innovatively, creatively, and in an interdisciplinary way offers ways to qualitatively improve the project process (i.e., design research) and perhaps to improve life itself.

Bibliography

DeLanda, M. (2015). *Philosophy and simulation: the emergence of synthetic reason*. London: Bloomsbury Academic.

Estévez, A. T. (2015). *Biodigital Architecture & Genetics: Writings / Escritos*. Barcelona: ESARQ (UIC).

Estévez, A. T. (2005). "Arquitectura biomórfica / Biomorphic Architecture". In A. T. Estévez (Ed.), *Arquitecturas genéticas II: medios digitales y formas orgánicas / Genetic Architectures II: digital tools and organic forms* (pp. 18-80). Barcelona / Santa Fe: ESARQ (UIC) / Sites Books.

Haeckel, E. (1862). *Die Radiolarien (RHIZOPODA RADIARIA).* Berlin: Georg Reimer.

Hensel, M., Menges, A., Weinstock, M. (2004). "Emergence: Morphogenetic Design Strategies". *Architectural Design*. London: Wiley.

Ito, T. (2009). Unpublished lecture (transcription of Alberto T. Estévez). Barcelona: ETSAB (UPC).

Puig-Boada, I. (1981). *El pensament de Gaudí. Compilació de textos i comentaris*. Barcelona: Col·legi d'Arquitectes de Catalunya / La Gaya Ciència.

Schumacher, P. (2009). "Parametricism: A New Global Style for Architecture and Urban Design". In N. Leach (Ed.), *Digital Cities*. London: Wiley.