FORM FOLLOWS STRUCTURE: BIOMIMETIC EMERGENT MODELS OF ARCHITECTURAL PRODUCTION

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> "If you want to make a living flower you do not build it physically with tweezers, cell by cell; you grow it from seed. If you want to design a new flower, you will design the seed and let it grow. The seeds of the environment are pattern languages." - Christopher Alexander[1]

INTRODUCTION

The recent evolution of architectural materials and fabrication techniques has created an interesting culture of multiplicity in which methods of assembly are persistently challenged by the invasive use of computer-aided design and manufacturing processes (CAD/CAM). This pervasive development has not only created new formal outcomes, but it has also produced new material processes that are deeply rooted into the morphogenesis of self-organizational and environmentally responsive models. Thus, the synergy existing between emerging materials, modes of renewable energy, and ecological design have all created a new ontology of architectural production in which the science of materials is finally revaluating the traditionalistic notion of material signification via the establishment of new methods of digital morphogenesis and associative cellular arrangement.

What regulates this new framework of complexity? This paper tries to answer the originating question by initially looking at the concept of emergence, and how it might relate to the growth of new complex modes of modularization of architectural production. Ideally, a material process articulated around the Deluzian idea of difference and repetition should be expressed by recognizing the possibility for multiple morphological variations.[2] In fact, while this process might involve redundancy as deep strategy, its morpho-tectonic structure tends to adapt to the existing environment by adjusting its formal outputs. Redundancy is indeed a primary component of any evolutionary system, but we need to understand that it also produces diversity.[3] Thus, within this framework, form ought to be integrated with structure in order to allow for a more realistic functionality of its symbiotic apparatus. The ultimate scope of form-generative processes is to provide guidelines for fabrication; those guidelines are identifiable by looking at examples of self-organizing structures that are characterized by natural apparatuses from which their material performance emerges. This process provides for an integrated set of design strategies where formal relations and biological materials are in constant feedback.

Considering the notion that biological materials are self-assembled and self-generating, this paper also analyzes the importance of biomimetic approaches to the production of new speculative methodologies of assembly in order to understand how certain organisms or biological forms organize themselves. This framework certainly allows for a much deeper understanding of organized complexity through material pattern recognition methods. Yet, those patterns should not be considered another architectural formalization of nature, thus reducible to pure aesthetic, but instead they should propose a more accurate study of those models based on the recognition of methodological reciprocity between elements of structure and form.

Biomimetic structures, in their material and morphogenetic expression, have indeed the effect of controlling the emergence of form. Therefore, in order to generate the concluding premises of my argument, I will examine the methodologies and work of Frei Otto, putting emphasis on his attention for those structural and material processes that seek form finding through the study of biological analogues. Indeed, if you want to design a new flower, you will have to design its seed first. We need to fully understand the new emergent patterns of material practice in order to avoid a regimental return to traditionalist forms of architectural production.

DIFFERENCE AND REPETITION

> "Difference is not diversity. Difference is given, but difference is that by which the given is given, that by which the give is given as diverse. Difference is not the phenomenon but the nuomenon closest to the phenomenon." - Gilles Deleuze[4]

If we look at the architectural production that defines the establishment of modernism, we can certainly recognize a proactive modality in which the functionality of a building is strictly related to its structural modularity. Within this stagnant framework, how can a new production praxis of based on dynamic and generative ecological relations finally emerge?

Before addressing the systematic investigation of the concept of emergence, understood as the way organisms have evolved formally and structurally, I believe that it is opportune to reframe the Deluzian ontology of difference and repetition in order to clarify the significance of morphogenetic variations that underline the argumentation of my paper. Deleuze is a process-oriented philosopher, and when he addresses the modalities of difference and repetition, he is not looking at formal or representational phenomena, but instead he is searching for the inequalities by which the phenomena are methodologically communicated.[5] Deleuze states that: "Everything which happens and everything which appears is correlated with orders of differences: differences of level, temperature, pressure, tension, potential, difference of intensity."[6] Thus, when we look at the symbiotic relationship between form, materials, structure, and program, we should properly examine what causes differentiation among those levels, and how form consequently emerges (experimental morphology).[7]

On the other hand, repetition does not involve resemblance or generality, but it suggests the existence of a process whose modalities of morphogenesis are inherently characterized by analogous genomic sequences. The key here is the recognition of those repetitive conditions and processes that produce morphological difference. While analyzing this framework, it is also important to look at the origins of structuralist ontology. Structuralism is generally defined as the way of looking at the world phenomena while focusing on the recognition of permanent structures and the set of relationships existing between them.[8] This framework takes into consideration the systems of transformations as well as the rules of associations between overarching structures. But, rather than proposing a static catalog of procedural conditions, Deleuze is more interested in recognizing those intrinsic conditions that generate ontological transformations, which eliminate predictable assumptions and open up an internal process of criticism that takes directly control of the already established operational system (also known as deterritorializiation of the predictable).

Fundamentally, this methodology of complexity suggests the adoption of a methodical analysis and understanding of morpho-tectonic changes/variations that might explain the emergence of particular models of architectural production and assembly. This is only possible if we can recognize those discrepancies by which the phenomenon unfolds.

EMERGENCE AND BIOMIMICRY

> "We are everywhere confronted with emergence in complex adaptive systems – ant colonies, networks of neurons, the immune system, the Internet, and the global economy, to name a few – where the behavior of the whole is much more complex than the behavior of the parts."
> – John Henry Holland[9]

Emergence examines the way and method complex systems and patterns arise out of a multiplicity of relatively simple interactions.[10] Emergent architectural and urban structures appear at many different levels of organization and spontaneous order. While addressing issues of self-organization, I believe it is important to understand how natural analogues establish systems of dynamic feedback that associate functionality and materiality with the originating host environment.[11] This process emphasizes the existence of an irreducible intricacy and complexity that generates new systems capable of displaying new properties of interaction and new levels of morphogenetic organization. Along with this framework of dynamic repetition, the Deluzian understanding of systemic correlations of differentiations generates a new intersecting domain where emergent methodological design frameworks can be finally recognized.

Undeniably, this process has forced us to intermingle with other interdisciplinary fields, such as biology, mathematic, and chemistry all of which address the intricate structure of cellular organisms. Sometimes, this process involves looking at simplified geometrical diagrams of organic and compound form that explain the existence, and perhaps the emergence, of particular patterns of form, structure, and material. Interestingly enough, biological organisms show a continuous morphogenetic evolution by virtue of repetition in which form, structure, and chemical composition are not understood as autonomous identities, but they are all properly correlated through dynamic interactions. The example of the Beijing National Aquatic Center has been broadly used to demonstrate how the process of geometric biomimicry can be integrated into the formal and structural design of a large assembly building by means of modularity and repetition (Figure 1).[12] In fact, John Bilmon of PTW Architects said that,

> "The Watercube concept is a simple and concise square form that ultimately uses the water bubbles theory to create the structure and building cladding, and which makes the design so unique. It appears random and playful like a natural system, yet it is mathematically very rigorous and repetitious."[13]

What is truly interesting about this process is the multi-scalar correlation between form, structure, and material, which are all inherently and hierarchically organized to evolve and adapt while interacting with any programmatic and external agent.

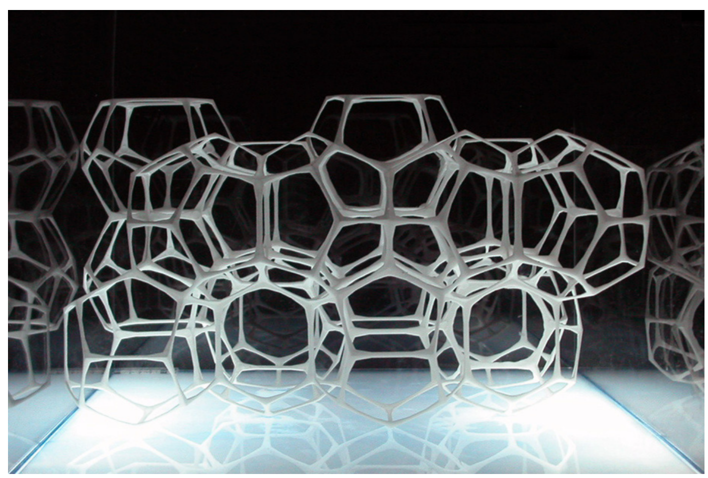

Figure 1. Beijing National Aquatic Center. Its geometric modularity is also found in other natural systems such as crystals, cells, and molecular structures. From, Watercube: The Book, (Barcelona: DPR Editorial, 2008), 188.

This approach, however, requires a major understanding of differentiated structures and complex morphogenetic theories since they inform the recognition of variations; yet, if we can diagrammatically summarize the results of our codification process, then we should be able to classify those elements of spontaneous order by specific generative types. While classification provides the hierarchical layout of the possibilities available, computational devices based on generative algorithms allow us to actually implement those modalities in the form of design definitions, which embodies biomimetic complexity, both at its formal and material levels.

This process of mathematical morphogenesis is not new. In fact, D'Arcy Thompson, in *On Growth and Form*, had already addressed the mathematical and geometric nature of growing cells, stating that form does not arise from the irrationality of chaotic systems, but it arises from the most basic mathematical and physical laws of material aggregation.[14] For example, the dragon fly wing (Figure 2) shows a rather complex organizational system based on the interaction between a primary and a secondary structural vein arrangement, which appears to be seemingly smaller.

Interestingly enough, the intricacy of such a system can be summed into to three mathematical propositions as underlined by D'Arcy Thompson:

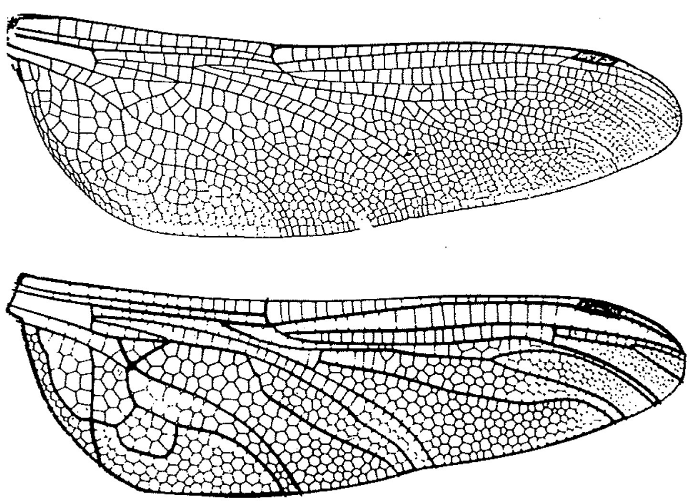

Figure 2. Dragonfly wing pattern showing different layers of geometric organization. From Frei Otto, *Occupying and Connecting*, (London: Axel Menges Edition, 2009), 27.

1) Cells between two close ribs are quadrangular in shape; 2) when two rows of cells appear to be inscribed by two ribs, their adjacency is determined by a 120-degree angle; 3) when the distance between ribs increases, the cells assume hexagonal shapes that share a coequal angle of 120 degree.[15] Thus, it is plausible to say that materials found in nature combine many inspiring properties that allow for sophistication, hierarchical organization, hybridization, resistance and adaptability to emerge, which can all be mathematically explained.[16]

Therefore, with regards to some of the recent studies on emergence, self-organization and material constructions, it is certainly comprehensible how production processes of material optimization based on the biological analogy have increasingly become part of the architectural process of design and assembly.[17] The study of the self organizational aptitude of some material, most of which are based on the engineering design of cellular solids, has already been found in the search for structural form-finding of Frei Otto, whose research has focused on the structural capacities of biomimetic models. Thus, the rest of this paper will look into the theories and modalities of structural and form-finding production as investigated by Frei Otto in order to show the rigorous association between form and structure in biomimetic emergent models of architectural production.

FORM FOLLOWS STRUCTURE: NOTES ON THE WORK OF FREI OTTO

> "It is not *ad hocism*, which is collage, but a methodology of evolving start points that, by emergence, creates its own series of order. When we attempt to trap chaos and convert it to our preconceptions, Order! becomes an enormous effort. We try to eliminate fault or error. We try hard but the effort turns to dullness and the heavy Formal." – Cecil Balmond[18]

New approaches of advanced simulation in design have certainly redefined form-finding processes.[19] The natural morphogenesis analogy based on the structural and self-organizational quality of certain material systems was extensively and methodically analyzed during the early 60's and 70's by German architect and structural engineer Frei Otto, who sought form-finding through an analysis of membranes and meshworks influenced by external and internal vectors of loads and forces.

According to Otto, construction processes should propose a methodology where programmatic and structural issues are symbiotically organized in order to show a clear morphogenetic articulation.[20] This process involves the presence of a feedback system that constantly checks for dynamic performance and structural integrity. Consequently, form becomes the result of a method of procedural integration that takes into account form, hierarchy, as well as the structural manifestations of them.

The work of Frei Otto also shows a lucid interest toward biomimetic analogues because their internal material composition and structure are always synchronically organized so that there is no distinction between form, material, and structure. To address this methodological interdisciplinarity, Otto's practice has developed a strong collaboration with biologists, chemical engineers and mathematicians while expanding his increasing interested toward the process of self-formation of natural elements.[21] However, according to the German architect and engineer, even artificial objects can present characteristics typical of natural components, since most of the manufacturing techniques employed nowadays are modeled after general processes of bio-chemical association.[22] This has essentially triggered an enormous interest toward a more qualitative yet empirical examination of processes of self-formation, but if we look at nature, we do need to understand that things and organism emerge because larger systems (ecosystems) are eventually responsible for what we call morphogenetic changes. Frei Otto is fully aware that the discipline of architecture can't be limited to the production of individual objects, but it has to promote a methodology that occupies and connects the different modalities of construction in a seamless and logical way. Otto looks into various experimental apparatuses that take into consideration patterns and grids established by natural systems and processes of crystallization. He experiments with paths tramped by hoofed animals, the dragonfly wing pattern, the maple leaf, crack patterns, and soap-bubble raft as a way to recognize patterns of instrumental geometry that connect points in space (Figure 3).

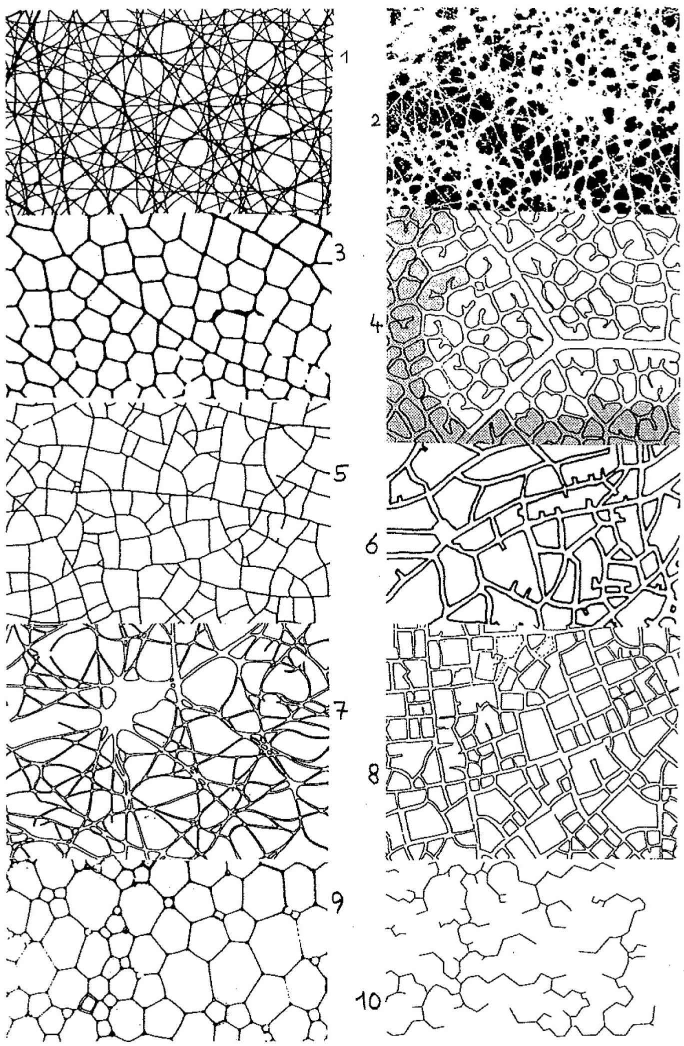

Figure 3. Processes of connection. From Frei Otto, *Occupying and Connecting*, (London: Axel Menges Edition, 2009), 51.

Yet, any interdisciplinary endeavor requires multiple levels of disciplinary knowledge. Another interesting aspect of Frei Otto's work is the recognition of particular task-oriented process that requires the presence of different "specialists" such as architects, biologists, and engineers. As explained by Otto, architects have the responsibility to produce architecture while researching new modes of production. Most specifically, the mission of the architect is to find out if there is indeed a scientific link between nature and the built environment.[23] The task of the biologist is instead to recognize and investigate the processes of physical and mechanical morphogenesis that lead to the emergence of living objects. Essentially, the biologist ought to identify those stages that, while operating by virtue of repetition, generate formal differentiation. Consequently, the task of the engineer is to understand the mathematical underpinning of some of the systems analyzed by the biologist, and to find the structural and physical linkage between geometric models and material systems.[24]

It is interesting to note that Otto's methods of form finding through structural analysis are inherently characterized by the convergence of different procedural systems that, in their interdisciplinary nature, construct a sort of structural pattern language. This pattern language is systemic, and it is also characterized by dimensions, loads, vectors, and biochemical composition. This taxonomical process is essentially similar to the production of typologies, but rather than looking at programmatic peculiarities, Otto investigates the relationship between form and structure, and he does so not to crystallize form, but to generate new form. Phillip Drew in *Frei Otto Form and Structure* wrote that,

> "The logic and clarity of Frei Otto's forms results from his strict and systematic adherence to the rule of natural economy, and subordination of extraneous considerations to the instructions obtained from the process of form discovery. He would never "force" or attempt to pervert the intrinsic structural logic of form to achieve an architectural artifact."[25]

Thus, it is never a question of aesthetics, but instead it is about form-finding as a way to optimize structural systems, creating analogous processes that communicate the concept of self-organization as a procedure guided by biological laws of mutations and selection.

Otto has established a research modality based on a clear understanding of tension structures, lattice domes, suspended structures, pneumatic structures, and structural membranes; all these structures have been analyzed by looking at the morphogenetic qualities of biological analogues, which he accomplished in the production of the Olympic stadium, the Olympiapark in Munich, or the Mannheim Lattice shell just to name a few. In the recent years, Frei Otto has been trying to focus more on the radical optimization of structural components as a way of expanding his vocabulary of form, influencing the work of Santiago Calatrava, Richard Rogers, and Cecil Balmond.[26] Another good example of Otto's more recent approach is the Japan Pavilion at the Expo 2000 in Hannover, Germany, which was designed in collaboration with Shigeru Ban. The pavilion proposed the use a lightweight structural framework entirely made out of paper tubes (Figure 4). This collaboration investigated not only issues of tectonic assembly and structural biomimicry, but also environmental concerns such as recyclability and material reuse.

Figure 4. Japan Pavilion at the Expo 2000. (Image courtesy of © Shigeru Ban Architects).

CONCLUSIONS

While recognizing the presence of new design problematics relative to the increasing use of computational design and manufacturing technologies, this paper has tried to reflect on the importance of biomimetic and emergent models of architectural production as a possible alternative to a current framework characterized by extreme modularization and formal repetition. Emergent and biomimetic approaches combine many inspiring properties that allow for a new modality of architectural production based on sophistication, hybridity, and adaptability.[27]

Yet, while some of these biomimetic models have provided a superficial collection of exuberant solutions, the work of Frei Otto has shown how form can be intrinsically tied to patterns of instrumental geometry found in nature, which show the existence of emergent morphogenetic strategies where the structural composition of materials is actively altering form. Most of the processes of material optimization based on the biological analogy have increasingly become part of this new process aimed toward the making of diversity. While traditional modes of architectural production have shown the presence of a redundant framework based on the assembly of parts independently designed, the biomimetic model can certainly be considered a valid alternative, especially if we reflect on the symbiotic approach and methodologies established by Frei Otto. If we can generate a framework of inherent heterogeneity that takes into account the modalities of the different agents of architectural production, then we can certainly state that form must follow structure.

ENDNOTES

1 Christopher Alexander, "The Environment," in *The Japan Architect*, (Tokyo, 1970), 54.

2 Gilles Deleuze, *Difference and Repetition*, (New York: Columbia University Press, 1995), 3.

3 Lawrence Fogel, *Intelligence Through Simulated Evolution*, (New York: Wiley, 1999), 4.

4 Gilles Deleuze, 222.

5 Ibid, 2-5.

6 Ibid, 222.

7 Experimental morphology is the study of the effects of external factors upon the form of organisms under the effect of genetic mutation. For a more extensive definition of the term see Michael Hensel, Achim Menges, *Morpho-Ecologies*, (London: AA Publications, 2006), 16-17.

8 See Michel Foucault, "Structuralism and Post-Structuralism," in *The Essential Foucault*, Edited by Paul Rabinow, Nikolas Rose, (New York: The New Press, 1994), 80.

9 John Henry Holland, *Emergence: From Chaos to Order*, (Oxford, UK: Oxford University Press, 2000), 2.

10 Michael Weinstock, *The Architecture of Emergence: The Evolution of Form in Nature and Civilization,* (London: John Wiley & Sons, 2010), 10.

11 Michael Hensel, "Computing Self-Organization: Environmentally Sensitive Growth Modelling," in *AD: Techniques and Technologies in Morphogenetic Design*, Vol. 76, No. 2, (May, 2006). 12.

12 Charles Jencks*, The Story of Post-Modernism*, (Chichester, UK: John Wiley & Sons, 2011), 186-187.

13 See excerpts from *Watercube: The Book*, (Barcelona: DPR Editorial, 2008), 60.

14 D'Arcy Thompson, *On Growth and Form*, (Cambridge, UK: Cambridge University Press, 1961), 96.

15 Ibid, 98.

16 See Michael Weinstock, "Self-Organization and Material Construction," in *AD: Techniques and Technologies in Morphogenetic Design*, Vol. 76, No. 2, (May, 2006), 35.

17 See Clement Sanchez, Herve Arribart, and Marie Madaleine Giraurd Guille, "Biomimetism and bioinspiration as tools for the design innovative material systems," in *Nature Materials*, Vol. 4, (April 2005), 277-288; Joanna Aizenberg, "Crystallization in Patterns: A Bio-Inspired Approach," in Advanced Materials, No. 15, (August 2004), 1295-1302; Roland Snook, "Fibrous Assemblages and Behavioral Composites," in *Log 25*, Edited by Francois Roche, (July, 2012).

18 Cecil Balmond, *informal*, (New York: Prestel USA, 2007), 221-222.

19 See Michael Weinstock, and Nikolaos Stathopoulos, "Advanced Simulation in Design," in *AD: Techniques and Technologies in Morphogenetic Design*, Vol. 76, No. 2, (May, 2006), 55.

20 Frei Otto, Bodo Rash, *Finding Form: Toward an Architecture of the Minimal*, (London: Axel Menges, 1996), 15.

21 Ibid, 15.

22 Ibid, 16.

23 Ibid, 18.

24 Ibid, 19.

25 Philip Drew, *Frei Otto Form and Structure*, (Boulder, CO: Westview Press, 1977), 11.

26 See Charles Jencks*, The Story of Post-Modernism*, (Chichester, UK: John Wiley & Sons, 2011); Luigi Prestinenza-Puglisi, *New Directions in Contemporary Architecture*, (Chichester, UK: John Wiley & Sons, 2008).

27 See Achim Menges, "Polymorphism," in *AD: Techniques and Technologies in Morphogenetic Design*, Vol. 76, No. 2, (May, 2006), 79-80.