A Methodology for Computational Architectural Design Based on Biological Principles

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Abstract. *Biomimicry, where nature is emulated as a basis for design, is a growing area of research in the fields of architecture and engineering. The widespread and practical application of biomimicry as a design approach remains however largely unrealized. A growing body of international research identifies various obstacles to the employment of biomimicry as an architectural design method. One barrier of particular note is the lack of a clear definition and methodology of the various approaches to biomimicry that designers can initially employ. This paper attempts to link biological principles with computational design in order to present a design methodology that aids interested architects within the preliminary design phase.*
Keywords. *Biomimicry; architectural design; design process; case study.*

INTRODUCTION

The influence of ideas derived from nature has always been pervasive throughout the history of architecture. Through a deep exploration into how nature solves problems that are experienced today, beneficial solutions could be extracted and new directions for our built environments could be explored. Through a 3.8 billion year-history of brilliant "designs" and development, nature provides an inspirational source of possible innovation that could enhance the performance and create a more sustainable built environment. Digital modeling and simulation tools together with computational design processes are facilitating the realization of complex forms and materials of many contemporary buildings. They also represent an opportunity to fully explore the potential benefits of biological principles found in nature through deeper understanding of nature's systems and processes (Steadman, 2008).

A truly biomimetic approach (one that does not only mimic shape or form) to architectural design requires the development of novel design methods that integrate environmental factors and influences as well as the modeling of behavior and the constraints of materialization process. This requires an understanding of form, material and structure not as separate elements, but rather as complex interrelations that are embedded in and explored through an integral computational design process. Correlating and combining computational form generation methods and natural principles, suggests a new approach developed for architectural design that is strongly related with biology. This approach aims for a more integral design method to correlate object, environment and subject into a synergetic relationship (Hensel et al., 2010).

RESEARCH AIM

The aim of this paper is to clearly present a design process inspired by biological principles implemented by computational means. The authors attempt to find links and relationships between a number of biological principles and their application in a computational design process.

The paper starts by briefly outlining a set of biological principles found in nature, and then a focus is made on some of them which were selected based on the authors' observations of a number of case studies. This selection does not imply the importance of these principles over others. A number of case studies are analyzed in this paper; one will be presented in full detail while the rest will be cited briefly. The case studies are analyzed based on the selected principles, resulting in a detailed design methodology commonly observed in all of them.

BIOMIMICRY TAXONOMIC CRITERIA

Levels of Biomimciry

In 2007 the Biomimicry Guild defined three levels of biomimicry, which are the form, process and ecosystem. These levels have been further developed by Zari (2007) to clarify the potential of biomimicry in sustainable design as shown in (Figure 1), and they include the organism, behavior and the ecosystem. The organism level refers to a specific animal or plant, and includes mimicking the organism as a whole or just a part of it. The second level refers to mimicking an organism's behavior, and could include how an organism relates to or interacts with its context. The third level is the mimicking of ecosystems as a whole and the general principles that enable them to function successfully. These three levels could be analogous to the three main aspects defining an entity in computational design. The three aspects are meanings, properties, and rules respectively (Carrara et al., 2009). The ecosystem is the highest level and is the one chosen for further study as it includes the most potential to serve as a guide to a sustainable design approach.

It is worth noting that these levels of biomimetic design could be seen from a different perspective that leads to a different classification. They could be perceived as ascending scales, starting from the cellular scale of living organisms; including material

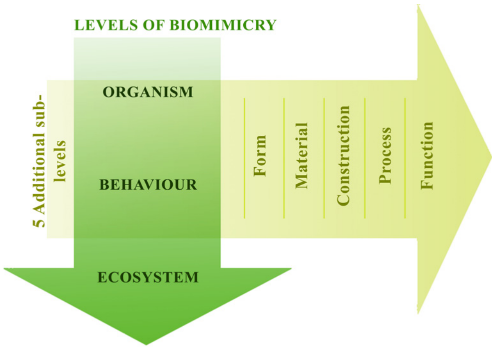

Figure 1
Levels of Biomimicry adopted from Zari (2007).

make-up and cellular growth laws for example. The second scale could include anatomical and structural aspects of the organism itself as a whole. The third scale includes the micro-environment such as the influence and interaction with other organisms and immediate surroundings. The fourth and final scale is the macro-environment including the context and ecosystem within which it survives and develops.

Any of these scales could be beneficially applied in architecture, and not necessarily on the same corresponding scale. For example, studies on a cellular scale (their shape, packing, functions, interactions, etc.) could be useful for the development of nanomaterials, the development of building forms, and even for an urban-scale development (such as applications of cellular automata studies). In addition, studies on a macro-environmental scale and ecosystems could be applied on the scale of the design process of a building as will be explained in this paper.

Ecosystem Principles

By comparing multi-disciplinary understandings of how ecosystems operate, a set of ecosystem principles was developed by Zari and Storey (2007). By analytically comparing related knowledge of ecosystem principles in various disciplines, a set aiming to capture cross disciplinary understandings of ecosystem functioning was developed. These principles are stated as follows. Ecosystems:

- are dependent on contemporary sunlight.

Figure 2
Cross section through the stem of a geraniim illustrating variation in their cross section and different organizations of cells in successive hierarchies. Cells have a structural role (such as supporting the plant itself and resisting wind loads on a macro scale) in addition to distributing carbohydrates, hormones and water in the same time (micro scale) (Castle, 2004) .

- optimize the system rather than its components.
- are attuned to and dependent on local conditions and situations.
- are diverse in components, relationships and information.
- create conditions favorable to sustained life.
- adapt and evolve at different levels and at different rates.

According to Zari and Storey (2007), these general principles could aid designers in evolving design methodologies and aim at the development of a more sustainable built environment. Although the comprehensive application and fulfillment of all ecosystem principles in one single project may be yet difficult to achieve, numerous examples that employ some of them do exist as will be demonstrated.

Selected Biological Principles

The aforementioned ecosystem principles are quite general so it was necessary to classify them in a more specific manner to be more effectively used. The following more specific biological principles are used as analysis criteria for case studies:

- *Adaptation*

Ecological systems as well as living organisms are adaptive. Adaptation is considered one of the most important criteria for sustaining life, both by evolutionary genetic changes in species and by responding to changing environments and circumstances within the lifespan of the organism (Gruber, 2011). How an organism adapts and responds to its environment (its fitness) could be compared to the coherence of a certain building with its surrounding context. In general, it could be compared to the appropriateness of any designed artifact for the reasons for which it was created (Steadman, 2008).

During the design process it could be very time consuming to continuously adapt geometry to changing circumstances. However, current computational parametric design software facilitate this process enabling designs to be more and more flexible and capable of absorbing changes as required (Hensel, 2006). Adaptation could not only be achieved during the design process, but could also be achieved in a higher level if the designed artifact is dynamically capable of sensing and responding to a changing environment.

- *Materials Systems*

To further examine on the ecosystem principle: 'Ecosystems optimize the system rather than its components', we could say that ecosystems use materials and energy in a manner that would optimize the system as a whole rather that each component individually (Zari and Storey, 2007). A focus was made in this paper on nature's *materials systems*. In the aim of material efficiency, natural organisms and ecosystems tend to use materials for more than one function as shown as an example in (Figure 2), which means energy is saved to be used in other functions such as growth, reproduction, health, etc. (Benyus, 1998).

The idea of material systems within the context of architecture does not only refer to the construction system and material components of a building, but also refers to complex interrelationships between material, form, space and structure and the associated processes of fabrication and production, as well as the effects that result from environmental influences (Hensel et al., 2010). All such factors could be fed into a computational setup from the outset, hence directly influencing the design process and end result.

- *Evolution*

Nature's systems and organisms are a result of ever-continuing evolutionary processes. Architecture could be seen as a sort of artificial life and hence subject to the ideas of genetic coding, replication, survival of the fittest etc. (Frazer, 1995). Design could be described as a human activity where the evolutionary mechanisms of nature are able to aid in creating a diversity of new forms. These forms are able to survive the environment within which they are set, and then serve as a basis for further evolution and improved solutions. Through the use of genetic algorithms (GAs), this evolutionary design process aids in resolving multiple (and often conflicting) criteria by producing outputs that learn from experience of previous generations (Rosenman et al., 1994).

- *Form and Behavior*

From the ecosystem principle: 'Ecosystems optimise the system rather than its components' the relationship between form and function is emphasized, and as a result, form and behavior are equally important. Forms of natural organisms are maintained by changing their behavior as their needs require. This is a two-way relationship that is context-dependent. The form of an organism will affect how it behaves in the environment, and a certain behavior will have different outcomes in different environments. Form and behavior are linked and affect each other (Weinstock, 2004). In terms of architecture, the required behavior of a building (its function) should affect its form, and the resulting form affect the actual behavior. In addition, both form and behavior affect and are affected by the environment.

- *Emergence*

According to the principle: 'Ecosystems are diverse in components, relationships and information', relationships operate in various hierarchies. They are complex; hence emergent effects tend to occur (Zari and Storey, 2007). In the 1970s, the phenomenon of emergence was discovered and it offered a new precision to the study of evolution and complexity, and it is applicable to a wide range of disciplines and scales. An emergent entity has behaviors or properties that could not have been foreseen by observing any of the properties of its constituent parts. In a qualitative manner, the emergent entity always exceeds the sum of its parts (Wiscombe, 2006).

The variations of any biological form should not be seen separately from its materials or structure. The overall performance of natural organisms emerges from the complex hierarchies of their materials. Form, structure, and material all affect one another and the properties of an organism could not be determined by the properties of any of them alone(Hensel et al., 2010). Analogously, the building is also a result of the complex interrelationships between its form, materials and structure, and we could not predict its final behavior by studying any of these aspects alone. This results in increased creativity since results are often new and unexpected.

CASE STUDIES

A number of case studies were analysed, where the previously stated principles served as analysis criteria. All case studies were analysed in the same manner, but only the first one is presented in detail while the rest are breifly cited.

FAZ Pavilion Frankfurt, 2010

This pavilion (Figure 3) is based on the biomimetic research projects: Responsive Surface Structure Phase I and Responsive Surface Structure Phase II in the Institute for Computational Design (ICD) at the University of Stuttgart. The team includes Prof. Achim Menges, Steffen Reichert, and Eva Menges. The research was based on the study and exploration of a surface that could passively respond to humidity changes, based on inspiration from Conifer cones (Menges and Reichert, 2012).

- *Adaptation*

The initially moist Conifer cones contain seeds necessary for reproduction which are released when the cones are dry and therefore opened. What is really interesting is that even if the cones are not anymore attached to the tree, they continue to open and close as humidity levels change. This is due to the

Figure 3
FAZ Pavilion in an open state (top) and closed state (bottom) (Menges and Reichert, 2012).

cone's material itself which is capable of interacting with the environment even if its tissues are no longer living.

The envelope of the FAZ Pavilion adapts and responds to changing weathers. When the humidity is relatively low on sunny days, the envelope is fully opened, and when it rains for example or the humidity simply increases, a response is triggered and the skin is closed automatically (Figure 4).

Figure 4
Left: Conifer cones in open and closed states. Right: a responsive system component was developed that can adapt its shape by being based on a four-, five-, six- or seven-sided polygon (Menges and Reichert, 2012). Iva Kremsa, Kenzo Nakakoji and Etien Santiago, Performative Wood Studio (Achim Menges), Harvard University Graduate School of Design (GSD), Cambridge, Massachusetts, 2009.

- *Material System*

The ability of the cones to continuously open and close is due to the structure of the scales' material itself. The scales consist of two layers; an outer one made of parallel, long densely packed thick-walled cells that react to changing humidity by expanding or contracting, and an inner layer that almost doesn't change. Therefore the research focused on mimicking this material structure by developing bilayered materials that could react in a similar way.

The anisotropy and hygroscopicity of wood is similar to that of cones and therefore synthetic wood composites were studied and developed. 'Anisotropy denotes the directional dependence of a material's characteristics, and Hygroscopicity refers to a substance's ability to take in moisture from the atmosphere when dry and yield moisture to the atmosphere when wet' (Menges and Reichert, 2012). The dimensional change of wood is directly proportional to changes in moisture content. Given a specific piece of wood, a certain increase in moisture content will always cause the same swelling or shrinking. When different synthetic veneer composites are combined, they could be physically programmed to differently respond to humidity changes (Figure 5).

- *Evolution*

An integrative computational design process (Figure 6) was developed by the project team, in order to manage multiple design criteria such as the reciprocity of individual elements and overall system responsiveness, the associated micro and macro thermodynamic variations, material's anatomy and characteristics, and constraints of fabrication and assembly.

The overall form of the structure was a result of an evolutionary algorithmic process based on continuous changes to the design variables, evaluation of generated results, and then the results are fed back to the system to produce new improved solutions. This algorithmic process enables a quite simple prototype, to adapt its morphology, material

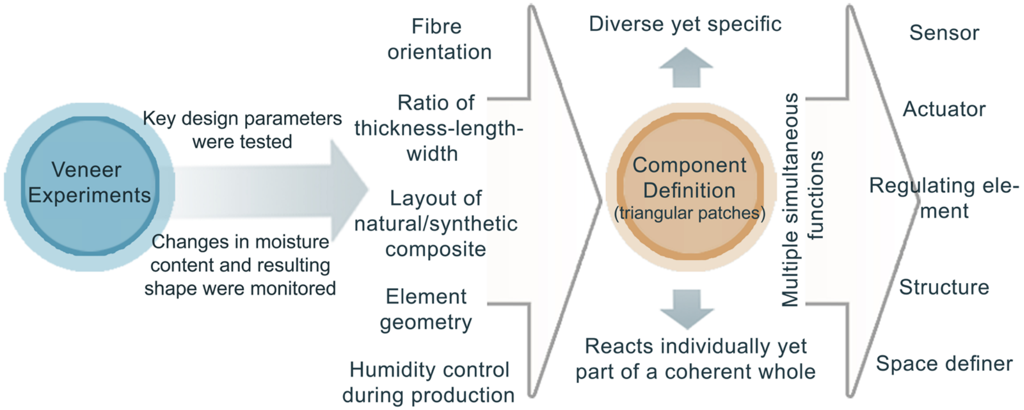

Figure 5
The composite system elements can be programmed to materially compute different shapes within variable humidity-response ranges by adjusting these five parameters during the production phase.

density, curvature and other aspects in response to contextual requirements and overall form. It results in the integration of structural and responsive elements as one system.

- *Form and Behavior*

The overall surface curvature plays an important role in the intricate interaction between system and environment. It contributes to structural capacity, as well as providing different orientation and exposure of each element to relevant environmental influences (such as sunlight, thermal energy and global airflow), thus affecting the behavior of the system. In addition, the required behavior was set from the outset as performance criteria and therefore resulted in the produced form.

- *Emergence*

A full scale prototype was fabricated representing a skin, structure, and a regulating responsive envelope all together. This high level of integration of form, material, and structure resulted in an emer-

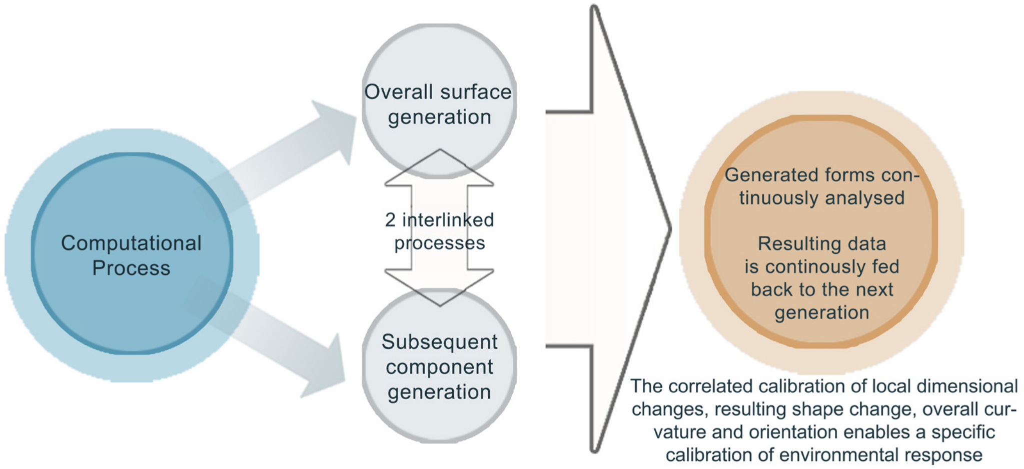

Figure 6
Algorithmic computational process.

gent system whose behavior and properties could not have been predicted by any of its constituents acting alone. This case study presents an example of ecologically embedded architecture that is continuously interacting with its environment and context.

Other Case Studies

- ICD/ITKE Research Pavilion, 2012
  This pavilion is a result of the collaboration between the Institute of Computational Design (ICD), and Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart, along with biologists of the University of Tübingen [1].
- Fiber Bridge, 2009
  This project is the March dissertation of Christina Doumpioti at the AA School of Architecture, London (Hensel et al., 2010), [2].
- Patagonia Shelter, 2007
  The project was designed by a team of the Emergent Technology and Design Group students (at the Architectural Association, London) in the land of Hacienda Quitralco in Chilean Patagonia within one week [3].
- AA Membrane Canopy, 2007
  The project was developed, designed and constructed by the Emergent Technology and Design master students at the Architectural Association School of Architecture, London, in collaboration with structural engineers from the London branch of Buro Happold [4].
- Piraeus Tower (Redesign) Athens, 2005
  A Master of Science dissertation by Ioannas Douridas at the AA School of Architecture, London (Hensel et al., 2010).

PROPOSED METHODOLOGY

Through the analysis of the case studies, it has been observed that they share some common patterns in their design methodology. This paper attempts to propose a generalized and simplified methodological framework (Figure 7) to aid designers in applying the previously mentioned biological principles within a computational process. The applicability of each biological principle is explained in terms of the design procedures by which it has been implemented.

As any typical design process, it starts by analyzing the project brief and highlighting its main objectives, requirements and influences in terms of function, structure, environment, context, etc. For the design project to be *adapted* to 'the reasons and environment in which it was created' as mentioned earlier, we should explicitly express these reasons or requirements into quantitative measurable performance profiles. These will serve as fitness criteria determining the acceptance or rejection of the resulting design outputs of the computational process, ensuring the achievement of a minimum threshold predefined by the designer. Ideally, one would hope to achieve all requirements at high levels, but often this is not the case. Practically, priorities have to be made between these requirements which are sometimes even conflicting.

The designers should then choose an appropriate material (which could be wood, bricks, concrete, fibers, metals, nano-materials, etc.) or a combination of more than one material and use them in designing a basic repetitive unit/component (as a cell) that will form the overall artifact. Physical tests might be necessary to determine the characteristics of these components, it structural limitations, and necessary fabrication methods. All these aspects in addition to the geometrical description of the component itself should contribute to design and definition of the 'genotype', which is the initial design seed (digital model) that will be subject to an algorithmic growth process (genotype is the 'description' of the species transmitted through biological heredity (like a recipe) (Steadman, 2008)). By taking all these material-related aspects into consideration from the beginning, and allowing them to influence the design process, a complex interrelationship is formed between the *material system, form and structure.*

An optional step that could be done in parallel is the study of a certain organism for inspiration. Such an inspiration could be of its behavior, material composition, structural aspects, etc. This inspiration could serve a certain design objective that

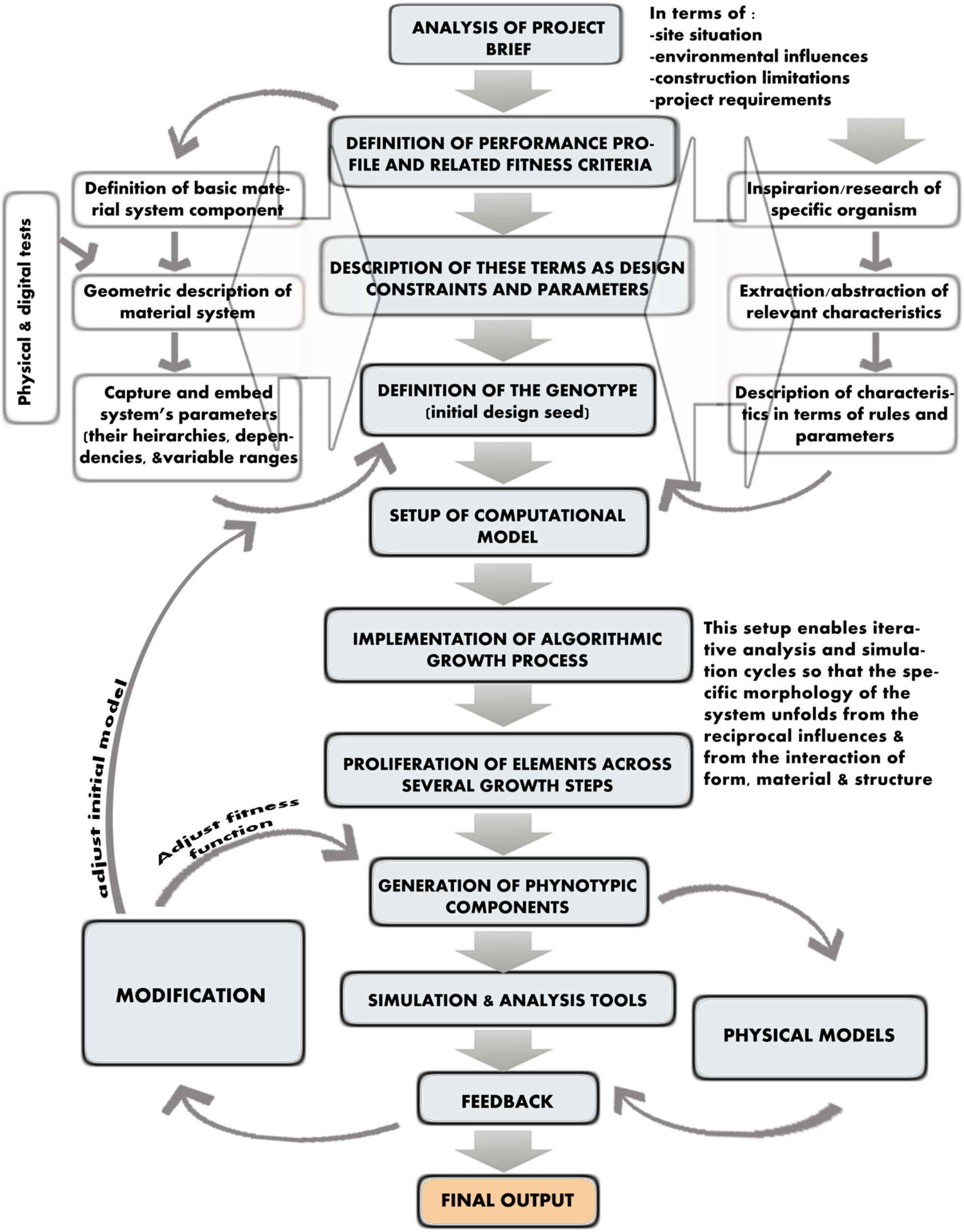

Figure 7
Proposed methodology for a preliminary design phase.

was prioritized from the beginning such as energy efficiency, structural capacity, or any other design problem related to the project. This specific phase is more elaborated by The Biomimicry Institute [5]. Designers should extract relevant characteristics of this organism then abstract them for geometrical and mathematical description, also contributing to the definition of the genotype.

The genotype is then subject to an algorithmic growth process using genetic algorithms, where several generations of digital models (phenotypes) are created (Phenotype: the physical embodiment of what is described in the individual organic body (like a realised recipe), (Steadman, 2008)). From each generation the 'fittest' models (the ones with most accordance with the performance criteria set earlier) are selected using a fitness function for further *evolution* and improvement. After a number of generations, the designers could choose the resulting models with the highest performance criteria for further testing. This could include more elaborate environmental or structural simulations, or fabrication of physical models for even more accurate testing. The feedback from these tests often require modifications either to the fitness function, performance criteria (such as re-prioritizing their importance), or even to the genotype itself.

The required behavior affected the development of forms through the evolutionary process, and in turn the resulting forms are tested for their actual behavior. The results are then fed back into the system as modifications producing new improved forms. The process is never a linear one, including constant feedback loops and modifications between *form* and *behavior* until a satisfactory output it finally reached. The result is an *emergent* form, with complex interrelations between form, material and structure, and with properties that could not have been foreseen in any of them independently.

CONCLUSION

The presented methodology is highly simplified and abstracted. It aimed at achieving certain biological principles in the design process to aid in producing a more sustainable output. Even if a specific organism is not mimicked (although this would have added much more value to the process and consequently the product), the process is still biomimetic as it applies clear biological principles present in nature. The methodology implies a certain sequence of occurrence of these principles within the design process. However, there is no clear line defining the end of one and the beginning of another. They usually overlap and sometimes we could go back and forth between them depending on the project at hand.

It aids in developing an architecture that is produced as a result of the existing environmental, materialization, and special requirements, and therefore specifically tailored to its location and conditions. It also supports imagination and unexpected results due to the algorithmic growth process. Another benefit is support for extra complexity. For the structures to become more flexibly adaptable, their complexity will have to increase.

Some might claim that the increasing software development in computational design gradually diminishes the human role in design. Although the presented design approach heavily depends on computer software and technology, the architect's role remains significant. It is most evident for example in analyzing the project brief at the beginning, setting priorities and fitness criteria, defining a material system, analyzing a certain organism then transferring the inspired ideas into computationally applicable solutions, creating the genotype, choice of suitable simulation software for evaluation, feeding back results into the system then finally choosing a satisfying result.

It is important to note that the application of a real 'material system' in a full building scale is not yet feasible. Unlike our buildings, there is no sudden difference of material in natural organisms. The change is soft by gradually altering the properties of materials themselves. However, this methodology could be applied on small-scaled design artifacts such as sheds, shelters, pavilions and furniture. It could be also applied in parts of whole buildings.

Another point worth mentioning is that this process does not specify certain software to be used. There are various text-programming languages (TPLs) as well as visual programming languages (VPLs) that could be used to apply this methodology.

Biomimicry is an approach that provides inspiration for answers to human problems by observing and analyzing nature's designs and processes. Technological advances in computational design software together with environmental, structural and other simulation means, offer very useful tools that enable us to further explore the potential of nature's solutions. This paper attempted to facilitate this design approach for architects by the means of an elaborated methodology for the preliminary design process.

This paper is also a part of an on-going research in which the authors attempt to practically apply the presented methodology in the design process for further development and evaluation of its potential.

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