Developing bioinspired approaches in undergraduate architecture curricula: Incorporating computational methods

Kihong Ku[1]

[1]Jefferson (Philadelphia University + Thomas Jefferson University), Philadelphia, PA

ABSTRACT: Bioinspiration, biomimicry, biomimetics, are some of the terms being increasingly referenced in the fields of architecture and building engineering in the search for innovation towards sustainability, energy and resource efficiency. Some scholars define biomimetics as an interdisciplinary scientific field and emphasize the complexity of translating an inspiration from nature to a final technological product. The focus is to gain a deeper understanding of functional analogies, processes and mechanisms that aim to abstract fundamental principles beyond morphological analogies which are primarily focusing on the formal aspects.

In this paper, the author examines pedagogical research in bioinspired approaches incorporating computational design methods. This research acknowledges the lack of formalized bioinspired design methods and explains pedagogical case studies to expand the literature. The method is particularly applied in design courses that apply computational methods. The findings suggest that the pedagogical explorations are compatible with methods found in literature and demonstrate that computational tools and methods are important support tools for biomorphic form translations and generations, functional analysis, and prototyping.

KEYWORDS: Bioinspired design, generative design, fiber composites, curricular innovation, sustainability

INTRODUCTION

Biomimicry, bioinspired design, biomimetics are terms often used interchangeably to broadly reference the abstraction of good design from nature (Vincent et al., 2006). Some scholars more specifically differentiate biomimetics, technical biology, bionics as a scientific discipline which concentrates on functional analogies, processes and mechanisms beyond morphological analogies, and define it as interdisciplinary research and development involving biologists, scientists, engineers (Knippers et al., 2016; Pohl and Nachtigall, 2015; Gruber, 2011; Pawlyn, 2011). Biomimetic approaches have been adopted by biologists, engineers, and scientists, to abstract inspirations from nature and develop products and systems that are efficient from an energy and material perspective. Such biomimetic approaches oscillate between biology and technology domains. On the one end, the biologist initiates the research to gain new insights and knowledge of living organisms with the anticipation of potentially translating the findings into downstream technical applications and products. From the other end, an engineer/architect, or technical specialist starts examining an existing successful technical product to improve this product through the transfer of knowledge of natural solutions. While there is a general consensus regarding what these terminologies mean, it has been acknowledged that there is a lack of understanding of design methodologies of biologically based innovation processes (Pohl, 2010; Helms and Vattam, 2009; El Ahmar et al., 2013).

1.0 RESEARCH AIMS AND METHODOLOGY

1.1. Research aims

In this paper, the author adopts the broader notion of bioinspired design to encompass endeavors from biomorphic design to functional translations from biology that may have potential for innovations in architecture. As biomimetics is gaining attention in architectural and engineering research and product development, a number of questions arise about how these approaches apply to the architectural design process and what the role of the architect is in this process. What knowledge and skills can the architect contribute to this process? What tools can assist the architect in biomimetic architectural design? How can biomimetic approaches be taught to enhance architectural education? And can computational tools facilitate this process? To answer these questions, pedagogical research of biomimetic strategies in architectural courses is examined. Computational design and biomimetics were chosen as two compatible domains as it has been demonstrated that computational tools and methods can support modeling and representation of natural growth patterns, swarm behavior, structural analysis, other performance analyses, and physical prototyping capabilities through digital fabrication (El Ahmar, 2013; Menges and Ahlquist, 2011).

1.2. Research methodology

In this paper, literature review establishes a baseline of biomimetic research models and methods in practice and architectural research ranging from lightweight structures pioneered by Frei Otto and his collaborators, to more recent projects that explore the role of innovative materials in biomimetic solutions such as textiles and fiber composites, the design of bioinspired performative building envelope solutions, and the integration of computational design and fabrication processes with bioinspired structures. This review classifies previous approaches by research processes, architectural applications, and support tools. Research processes include a review of bottom-up vs. top-down research approaches and research approaches adopted by design teams to identify, collect, and analyze applicable biomimetic references. Literature provides insights into how biological precedents are filtered from the vast variety of candidates. Architectural applications illustrate the target solutions defined by designers such as structural applications (Pohl, 2010) or building envelopes (López et al., 2017) as evidenced in experimental research prototypes to commercialized applications in buildings. The findings help to support and establish research to design and implementation process frameworks. It is also being discussed what role and to what extent the architect can contribute and lead this research process. Support tools focus primarily on computational design tools that can be adopted by the design team to generate alternative solutions, to map and simulate material properties, to conduct performance analyses and evaluate, and to control and extend fabrication capacities. Based on the findings, a conceptual framework is developed to facilitate biomimetic design teaching within the architectural studio and seminar courses. The framework involves background research on bioinspirations and precedents, including evaluation and translations of morphologies and functional characters, and examines how the research outputs can be applied to an architectural problem of site and program and building systems.

2.0 BIOINSPIRED METHODOLOGIES IN ARCHITECTURE

Literature review classifies previous approaches by research processes, architectural applications, and support tools. Research processes include a review of bottom-up vs. top-down research approaches and research approaches adopted by design teams to identify, collect, and analyze applicable biomimetic references. The pedagogical method explained in this paper is based on the review to facilitate biomimetic design teaching within the architectural studio and seminar courses.

2.1. Knowledge transfer from nature

In this paper, the author includes endeavours from morphological to functional translation from nature to architecture as part of bioinspired design. Gruber (2011) mentions biomimetics involve the transfer of form, morphological characteristics, constructs, and more broadly *natural phenomena which can include surfaces, materials, structures, functions, constructions, mechanisms, principles, processes, etc*. Such properties have to be abstracted and applied to architectural scenarios. Biomimetics are applicable from nanoscale to buildings and to urban conditions. Successful examples include the self-cleaning surface coating product Lotosan which was developed based on the hydrophobic surface microstructure of a lotus leaf, or on the large-scale lightweight construction and material optimizations pioneered by Frei Otto and his successors.

2.2. Biomimetic methods

Pohl (2010) explains that biomimetic research can be either bottom-up or top-down methods. The bottom-up process is initiated by the biologist and can lead to undefined technical possibilities whereas the top-down approach starts from examining an already existing technical product in the market with the goal to improve it. Helms et al. (2009) term the former approach 'solution based' vs. the latter 'problem based'. In both approaches the knowledge transfer from nature to an architectural application occurs through abstraction which has to accommodate the translation at different scales, material, and timescales. Gruber (2011) recommends that the reduction of information, identification of relevant parameters and boundary conditions should be guided through personal interest and intuition rather than strict categorizations in the early stages.

2.3. Architectural applications and design methods

In recent years, a number of architects and architectural researchers have explored the potential of bioinspired approaches for architecture either adopting a bottom-up or top-down approach. Table 1 categorizes selected examples from literature and simplifies and categorizes them by biomimetic research methods, application area in architecture, abstraction methods, and support tools. Examples which purely are concerned with visual and formal interpretations of nature, or urban scale planning examples are not included in the table. The table indicates that most of the current research efforts that involve new materials for building construction remain experimental and are not yet implemented at the full building scale. Biomorphic translations as in the example of a hierarchical structural abstraction of diatom structures (Pohl, 2010) have also been proposed as a strategy to be applied for large scale load bearing structures. This particular example applies the geometric hierarchical pattern into the design of a railway station roof structure with the use of welded steel tubes. The efforts towards developing biomimetic strategies for adaptive façade systems that enhance energy efficiency and human comfort are still in very early stages at this point. López et al. (2017) explain a formalized biomimetic research and design approach for adaptive building façades. Their research discusses the complexity of addressing human comfort and also the complications of developing the abstracted biomimetic idea and finding or developing new potential building materials to implement such concepts.

Table 1: Categorization of biomimetic architectural research applications

Research team	Research method	Application area	Abstraction method	Support tools
Hensel et al. (2010)	Bottom-up	Material systems	Emergence	Computational, prototyping
Dörstelmann et al. (2014)	Bottom-up	Material systems	Structural optimization	Computational, prototyping
Knippers et al. (2016)	Mixed	Material systems	Structural optimization	Computational, prototyping
Pohl (2010)	Bottom-up	Material systems	Structural optimization	Computational, prototyping
López et al. (2017)	Top-down	Façade systems	Analysis of plant's adaptive behavior	Diagrammatic methods
Hertzsch (2010)	Top-down	Façade systems	Analysis of adaptive behavior	Diagrammatic methods

El Ahmar et al. (2013) highlight the need for biomimetic design methodologies and propose a computational architectural design method. The team explains biological principles of adaptation, material systems, evolution, form and behaviour, and emergence, and the importance of the interrelationships and hierarchies of form, structure, material within the organisms. Their model is based on a top-down approach starting with an architectural project brief subsequently followed with biological research for precedents/inspirations which define a genotype that is further refined through the use of computational algorithms, analyses and simulations to translate into a phenotype that goes through iterations for the final output.

3.0 PEDAGOGICAL CASE STUDIES

This chapter explains the author's teaching approach to bioinspired design from two courses, a fifth year undergraduate architecture studio and a fourth year level seminar course which involve computational methods. Both courses did not involve collaborators from the non-architectural disciplines of biology or engineering, but the studio involved two external architect practitioners.

3.1. Courses organization

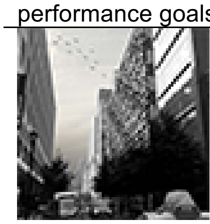
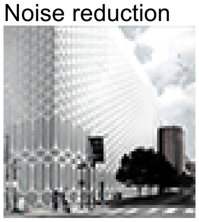
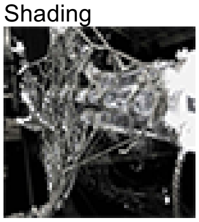
Both courses took a top-down approach for two reasons. First, there was no interdisciplinary partner who could provide access to open ended biological research, and second, from a curricular and personal familiarity standpoint, starting with an architectural target application facilitated the organization of bioinspired design activities into the courses. The studio project focused for seven weeks on retrofitting and designing a bioinspired façade of an existing building and involved 12 fifth year undergraduate students and two external architect practitioners who were partnering with the instructor. The students were grouped into two member teams. The final deliverable for this project included a fabricating a mock-up of a full scale prototype.

The seminar course tasked six fourth and fifth year students to identify and develop biomorphic concepts for architectural column structures through the application of various nature inspired algorithms utilizing Rhino3D and Grasshopper software.

3.2. Studio projects

The studio projects were conducted for the first half of the semester for seven weeks to redesign an existing façade based on bioinspired research which was located in Center City Philadelphia on the Thomas Jefferson University Campus. The façade was a typical masonry clad curtain wall with continuous bands of horizontal windows of a six-story building. For the project, the first task was broad based research of biological precedents that would offer opportunities for improvements of specific performance criteria that the students identified. The students were specifically tasked to focus on functional aspects that could improve the existing performance of the façade including daylighting, thermal comfort, acoustic comfort, etc., rather than simply designing a bioinspired image or aesthetic. Building on research of their selected biological precedents, the students then began designing and developing façade designs and systems concepts. During this process the six student teams were tasked to incorporate various computational approaches including form finding, performance analysis, and digital fabrication. Table 2 demonstrates the various biological characteristics, the architectural performance goals, abstraction methods and computational approaches employed by each team. The final stage led to developing construction details and producing a full scale mock-up.

Table 2: Summary of student projects

Architectural performance goals	Biological performance benchmarks/sources	Abstraction method	Support tools
 Noise reduction	Fennex fox ear	Morphological diagramming	Computational, prototyping
 Shading	Chromatophone cell	Morphological diagramming	Computational, prototyping
 Dynamic shading	Photochromatic cell & spider web	Structural optimization	Computational, prototyping
 Shading	Cactus morphology	Structural optimization	Computational, prototyping
 Daylight transmission and control	Oriental hornet exoskeleton	Analysis of plant's adaptive behavior	Diagrammatic methods
 Water harvesting & shading	Pineapple plant leaves	Functional abstraction	Circle packing algorithms, solar radiation simulation

The specific strategies adopted by each team varied, most teams prioritizing functional abstraction over formal analogies. As outlined in Table 2 the performance goals included noise control, shading, daylight transmission, and water harvesting. In comparison to López et al. (2017), students did not limit their bioinspirations solely to plants which arguably have similarities to buildings which are fixed to specific location and static. Students in contrast referenced chromatophore observed in cephalopods focusing on physiological color change, oriental hornet solar cells which generate electricity from sunlight, and fennex fox ear morphologies which facilitate acoustic amplification, besides various plant references. It is interesting to note that after identifying and abstracting an applicable function from a biological precedent, the teams translated and integrated the mechanisms and processes into a compatible abstracted patterns that could be related to the function. For example, in the case of the project that applied a cactus morphology, a deformed hexagonal pattern was developed in Rhino3D/Grasshopper to incorporate self-shading properties of the cactus skin into a building skin. Fiber composite materials were considered as the material to fabricate the system. In case of the dynamic shading control system, the team combined the characteristics of shape memory alloy and a delauney mesh pattern, creating a biomorphic shape of a spider web which acts as an exoframe for the kinetic shading elements that translate characteristics of photochromatic cells found in octopus. Each team established performance criteria for their façade design and conducted applicable building simulations to verify the performance of their system. However, the complexity of addressing human comfort and energy efficiency simultaneously proved to be challenging. The duration of the project, the knowledge and skill level of the teams, and limited resources including available computational tools and fabrication tools impacted the development process.

3.3. Seminar course projects

The primary goal of this course was to teach algorithmic modeling using Rhino3D and Grasshopper scripting. Students started with learning the basics of parametric modeling, surface operations such as tiling and mesh operations, and scripting of recursive patterns, branching and L-systems, flocking algorithms and cellular automata. In order to teach the analogies of natural patterns, the students were tasked to identify interesting patterns in nature and apply those patterns to a vertical column structure. Figure 1 is an example of a student's selected 3D printed models that applied L-systems and cellular automata algorithms to a vertical column structure which were based on inspirations from bones and the regeneration of cells within a connective network. The results show similarities to a bone structure and are generated based on a limited number of simple rules. Bioinspirations selected by students included specific characteristics, components, and aspects of plants and animals (e.g., snake, armadillo, etc.), which were analyzed in depth to understand morphological aspects and the relationship to specific functions. The students iterated multiple versions of bioinspired algorithms on vertical column structures and 3D printed the resulting geometry.

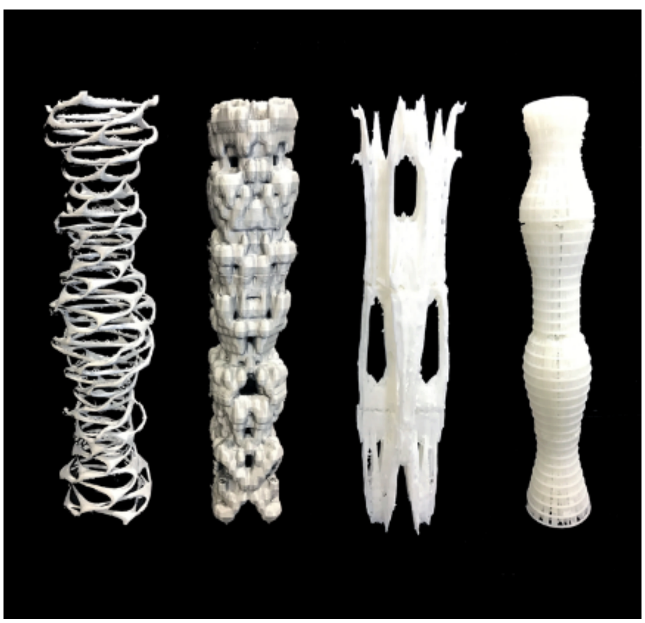


Figure 1: 3D printed structures generated using cellular automata algorithms based on studies of growth of cellular structures (Project credits: Jennifer McElroy).

4.0 DISCUSSIONS

The two different courses discussed above illustrate examples of bioinspired design taught in architectural courses that incorporate computational methods, the former focusing on designing a complex architectural system, the façade, and the latter focusing on generating nature based patterns through algorithmic processes.

4.1. Results

The pedagogical explorations presented here highlight the characteristics of bioinspired architectural design processes by students. While the absence of biologists eliminates the collaborative aspect of working with interdisciplinary partners, students were still able to conduct systematic research on biological precedents through literature and precedents to identify relevant sources of inspiration and evaluate the potential fit for the façade design project. Students approached research from two ends. Initially some students found interesting examples that they tried to justify for the façade design which eventually turned out to be difficult to transfer, and the team accordingly replaced their inspiration with different biological references. For example, one team investigated the armor of boxfish whose hexagon shaped scales and joints provide exceptional strength with potential applications for body armor and flexible electronics. But the application deemed less applicable to the building façade project and thus this team switched their focus towards a dynamic shading function that led to photochromatic cells and spider web examples. In most cases the students established specific functions they desired for the façade design to identify applicable biology precedents. In many cases students changed some of their original assumptions and found more applicable precedents. In terms of form finding, most teams found an applicable pattern geometry (i.e., circle packing, voronoi, etc.) which they manipulated to achieve some level of formal analogy to their biological reference while translating the abstracted functions into the façade scale. The students were given the constraint of using fiber reinforced composites as a material to implement their design into a construction material. Utilizing fiber composite material did not necessarily directly translate the biological characteristics of their selected precedents but it offered an option to develop a light weight composite structure to implement the design concepts.

In comparison, the seminar course allowed students to adopt more simplified strategies of abstracting biological inspirations because they were only concerned with identifying applicable morphological patterns or systems that could be replicated through computational algorithms which resulted in more algorithmic iterations. While this approach has potential to quickly study multiple examples, the abstraction into more complex downstream architectural and technological innovations may also be limited.

4.2. Future Considerations

Comparing the student projects from teaching with approaches from literature exemplify that the author's pedagogical processes were simplified and more flexible in comparison to professional team approaches. The teams did not involve interdisciplinary counterparts and biomimetic abstraction processes allowed somewhat flexible approaches. The ultimate goal of biomimetic approaches is to expand technological innovations that can enhance sustainability and energy efficiency. The historic examples of lightweight construction pursued material efficiency. Complex systems such as façade and building envelopes require more intricate system based approaches to address complicated issues of human comfort in addition to material and energy efficiency to be integrated through biomimetic approaches. The pedagogical explorations highlight a few future areas for improvement to better support bioinspired design processes and teaching: (1) interdisciplinary team building would offer the advantage of expanding rational boundaries between disciplines; (2) computational tools that support analysis of biological examples are typically beyond the scope of tools and knowledge that architect have access to. Interdisciplinary collaborations can help to facilitate cross pollination discipline specific tools, processes and methods; (3) architects and architectural students are well positioned to identify needs for improvement of existing systems and to abstract functional analogies between natural and man-made systems at different scales. Formalizing design methods of such abstraction processes will be helpful; and (4) architectural computational tools that can more efficiently support key capabilities including form finding, simulation of growth patterns, performance analyses, optimization, and digital fabrication will be helpful. Applying these tools in bioinspired design processes requires combining multiple tools iteratively throughout the design and development process. Enhancing computational literacy and skills beyond current levels will help architects and students lead and contribute to bioinspired design processes.

CONCLUSION

The results of the comparison suggest that practice/research and pedagogical approaches are compatible but highlight the challenges of creating interdisciplinary environments in the architectural curriculum. The pedagogical explorations presented were limited in scope of technical development and multidisciplinary team involvement, but the examples show that the biomimetic approaches can be applied at different scopes and scales to encourage innovative thinking in form finding, functional system development, and incorporation of computational design tools and processes. Shortcomings included the lack of interdisciplinary counterparts, lack of understanding of biological material processes which are difficult to translate into abstract architectural design concepts. This put a greater responsibility on the instructors' role. The studio instructors' team supplemented real-world perspectives to offer balanced feedback on the challenges of the architect, changing architectural knowledge and skillsets, and design processes.

Future research will continue to compile biomimetic approaches to define material and computational design strategies in teaching bioinspired experimental structures and performative building envelopes projects. Future plans include engaging with biologists/students to facilitate interdisciplinary experiences and to gain new understanding of the opportunities and challenges of this framework. The long term outcome of this pedagogical research will demonstrate that computational design and biomimetic approaches offer a viable framework to enhance creative and technical design skills of architects.

ACKNOWLEDGEMENTS

This studio projects described in this paper were developed as part of the IDEA Studio curriculum which was funded by a 2015 NCARB Award. The author would like to thank Dylan Beckwith, Kelsey Donato, Victoria Febrizio, Christopher Hreniuk, Lauren Jester, Mathew Lombardo, Adelaide McInnis, Katherine Meier, Christopher Murnin, Sanjeev Rao, Ross Silverman, Maura Turlip, and Jennifer McElroy for their project contributions, and Ryan Lohbauer and Petra Stanev for their significant input into the projects.

REFERENCES

El Ahmar, S, Fioravanti, A, and Hanafi, M 2013, A Methodology for Computational Architectural Design Based on Biological Principles, Stouffs, R and Sariyildiz, S (eds.), *Computation and Performance* – Proceedings of the 31st eCAADe Conference – Volume 1, Faculty of Architecture, Delft University of Technology, Delft, The Netherlands, 18-20 September 2013, pp. 539-548

Gruber, P 2011, *Biomimetics in architecture: architecture of life and buildings*, Springer, Wien;New York.

Helms, M, Vattam, S and Goel, A.K. 2009, Biologically inspired design: process and products, *Design Studies*, 30(5), pp. 606-622.

Hensel, M., Menges, A. & Weinstock, M. 2010, Emergent technologies and design, Routledge, Oxon [U.K.];New York, NY

Hertzsch, E., 2010. Sustainable buildings: biomimicry and textile applications. In *Textiles, Polymers and Composites for Buildings* (pp. 375-397).

Knippers, J, Nickel, K, & Speck, T 2016, *Biomimetic Research For Architecture And Building Construction: Biological Design And Integrative Structures*, Cham: Springer

López, M., Rubio, R., Martín, S. and Croxford, B. 2017, How plants inspire façades. From plants to architecture: Biomimetic principles for the development of adaptive architectural envelopes, *Renewable and Sustainable Energy Reviews*, 67, pp.692-703.

Menges, A. and Ahlquist, S. eds. 2011. *Computational Design Thinking*, John Wiley & Sons.

Pawlyn, M 2011, *Biomimicry in Architecture*, London, RIBA Publications

Pohl, G. 2010, *Textiles, polymers and composites for buildings*. Oxford;Philadelphia;: Woodhead Pub. in association with the Textile Institute.

Pohl, G, & Nachtigall, W 2015, *Biomimetics For Architecture & Design* : Nature - Analogies - Technology, Cham: Springer.

Vincent, J,Bogatyreva, O,Bogatyrev, N,Bowyer, N, Pahl, K 2006, Biomimetics: its practice and theory, *JRSocInterface* 3(9), pp. 471–82